The Cost and Citation-based Effectiveness of Observational Astronomical Facilities since 1958

Thesis

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THE COST AND CITATION-BASED EFFECTIVENESS OF OBSERVATIONAL ASTRONOMICAL FACILITIES SINCE 1958

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ABSTRACT

This is the first comprehensive, quantitative analysis of the cost-effectiveness of both ground- and space-based astronomical observatories. The effectiveness is based on an analysis of the 15% most highly-cited papers published in the *Astrophysical Journal* and the *Monthly Notices of the Royal Astronomical Society* in the first half of every fourth year from 1958 to 1994, inclusive. The costs include both capital and annual operations costs.

The analysis shows that there has been a progressive swing away from small, ground-based, optical/IR telescopes over the period 1958–1994, in terms of highly-cited papers, so that by 1994 two-thirds of all ground-based, optical/IR results were being produced using telescopes > 2.5m diameter. The Hale 5m was the most effective optical/IR telescope over the whole period, but the AAT matched it in the second half of the period. The VLA was the most effective radio telescope, and the Einstein Observatory and IUE was the most effective spacecraft over the whole period, although the CGRO, ROSAT and HST produced high-quality results at the end of the period.

Large ground-based, optical/IR telescopes were more cost-effective, on average, than smaller telescopes; the two most cost-effective large telescopes over the second half of my period being the AAT and 3m Lick. Ground-based, optical/IR telescopes taken as a whole were more cost-effective than either ground-based radio telescopes or spacecraft observatories. The cost-effectiveness of spacecraft has increased over the last twenty years, however, although the high cost of the HST caused a reduction in overall spacecraft cost-effectiveness in 1994.

Finally, the facilities recommended in the decennial NRC reports are compared with those provided, and some of the reasons for the poor correlation discussed. The thesis ends with general conclusions and a discussion of possible lessons to be learnt.

CONTENTS

Part 1 Effectiveness

Part 2 Costs

<u>Part 3</u> <u>Cost-Effectiveness</u>

2 Ground-Based Optical/Infrared Telescopes

3 Ground-Based Radio Telescopes

Part 4 Historical Overview of Observational Facilities

APPENDICES

INTRODUCTION

Background

A large amount of money has been spent in the USA and British Commonwealth or ESA* on building and operating observational astronomical facilities, both on the ground and in space, but there has, as yet, been no objective analysis of the cost-effectiveness of these various observational facilities to astronomy. Decisions on future investment plans are, instead, made on the basis of recommendations by panels of senior astronomers who, from their experience, judge the past performance of astronomical facilities, and assess the likely benefits to be gained from keeping or modifying those facilities, closing some of them down, and building new facilities.

In this current project I aim to analyse the relative cost-effectiveness of ground- and space-based astronomical observational facilities since the launch of Sputnik in October 1957 in as objective a way as possible, and to compare the cost-effectiveness of ground-based, optical/infrared telescopes of various sizes from the smallest used by professional astronomers to the largest. The effectiveness considered is the astronomical effectiveness and excludes the use of such facilities to promote the 'public perception of science'. Promoting the public perception of science is an important aspect of any work that uses a substantial amount of public money, but a study of that could possibly warrant a PhD in itself. Although such promotion is important, the main aim of providing the facilities is, of course, to advance astronomical research, and it is that aspect that I will examine in this project.

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* The UK has tended to collaborate with British Commonwealth countries and the USA to provide ground-based astronomical facilities, and with ESA member states and the USA to provide space-based facilities. Hence I have analysed the performance of ground-based astronomical facilities in the British Commonwealth and of ESA spacecraft, in addition to analysing the performance of American ground- and space-based facilities.

An analysis of the cost-effectiveness of astronomical facilities since about 1957 will be of historical interest in its own right, providing quantitative data to augment the normal qualitative historical approach. In addition, however, it should help to show how such a quantitative approach could be used to support the committee-based assessment process mentioned above to determine future investment policy.

The USA spends a great deal more money than the British Commonwealth or ESA on astronomical facilities, and a comprehensive committee-based assessment process has been developed in the USA over the last thirty years or so to determine future investments in such facilities. These committees, which have operated under the aegis of the National Research Council (NRC), have been set up about every ten years to recommend on investments for the next ten years. I have, therefore, in the latter part of this thesis, compared the American facilities actually built with those recommended by these NRC decennial committees, and have examined, in broad terms, the main reasons for the difference. My thesis does not look into the detailed workings of these committees or the subsequent decision-making process, as this would be a major area of research in its own right. Furthermore, it would probably best be carried out by people who could have easy access to detailed records of the various committee and sub-committee meetings, and of Congressional committees and of Congress itself, where the major decisions are made.

In the UK a number of committees have been set up over the years to examine the performance of UK astronomical facilities, but these committees have been ad hoc and have been generally concerned with only a limited range of facilities (i.e. ground-based optical/IR, or radio or space-based facilities). Again, time has precluded extending my study to these UK committees, and I have chosen to concentrate on the American committees, as they have been much more clearly structured and America is where most of the money has been spent over the period under consideration.

Citation Analysis*

As mentioned above, my aim is to measure the effectiveness of astronomical observational facilities in as objective a way as possible. Reviewing the astronomy literature, I found that Abt[1,4] used numbers of citations as a measure of effectiveness, whereas Martin and Irvine[2,3] use what they call partial indicators based on numbers of papers, numbers of citations, and peer review. As explained in Part 1 of my thesis, I have used a method based on numbers of citations as a measure of effectiveness, as I believe that:-

(i) Using numbers of papers gives a much less satisfactory indication of quality than using numbers of citations.

(ii) It is not feasible to use peer review over a period of almost forty years. (There were already indications in Martin and Irvine's work that their peer reviewers were having trouble covering a period of only ten years. In addition they could not differentiate between the performance of different telescopes at the same site).

In view of this, the measure of effectiveness that I have adopted is based on analysing those papers that have numbers of citations in the top 15% for any one year. Any measure of effectiveness will have problems associated with it, of course, but I believe that this system is the most appropriate for my study. The potential problems in using such a system (which is explained in more detail in Part 1) are, I believe, relatively small, as shown by the summary analysis in the following table.

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* For a more general discussion of citation analysis and bibliometrics see, for example, Cronin, B., *The Citation Process*, Taylor Graham, 1984, Edge, D., *Hist. Sci.*, 17, 102, 1979, Garfield, E., *Citation Indexing - Its Theory and Application in Science, Technology, and Humanities*, Wiley, 1977, and Dunn, M., *Bibliometrics as a Measure of areas of Strengths and Weaknesses*, SERC.

Possible Problems with Citation Analysis as used by me

Possible Problem[2]	**My Response**
(a) If a paper is published in a field that has very few astronomers, it will probably get less citations, on average, than 'similar quality' papers published in a field that has a large number of astronomers.*	The reason that the number of specialists in one group is very much less than in another is probably because the smaller speciality is, on average, less important to astronomy than the larger one. If that is the case, the higher citation rating of papers enjoyed by the larger group is justified, as their papers will be, on average, of more importance to astronomy.
(b) There are a small number of extremely important papers which may not be referred to as much as expected once the ideas have been accepted, as the referring paper is referred to instead.	I have used a modest hurdle of 15%, so it does not matter in my system whether a paper is in the top 0.1% or the top 10%. So I am almost certain to catch these very important papers.
(c) Some good quality papers are not recognised until a number of years after they have been published.	If this is the case, it would only be of importance to my analysis of papers published in more recent years. It would not be a problem for those years either provided the papers were good enough to be above my modest 15% hurdle level.
(d) Some bad papers may get a high citation rating because they are referred to frequently because they are bad.	I have not come across this in scanning over 1,000 papers in hard copy, but it could probably happen in a few cases. There is no reason to suppose that the bad papers are connected with a particular observatory or spacecraft, and so the effect would be to put random errors into the system rather than bias the results. Such considerations give a warning, however, that I have to be careful in drawing conclusions from very small numbers of papers over just one or two years.
(e) The Science Citation Index underestimates the citations for astronomers with names that are misspelt.	In some of these cases over 10% of the papers can be mis-attributed. As in the case (d) above, this is unlikely to bias the results against any observatory or spacecraft, but it will add random errors into the system.
(f) Excessive self-citations could bias the results.	Abt[1] showed that the number of self-citations was only about 6%, which is unlikely to cause a bias in my analysis of facilities, rather than of astronomers.

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* For a more general discussion of this problem see, for example, McGervey, J.D., *Science*, **183**, 28, 1974, Sullivan, D., White, D.H., and Barboni, E.J., *Social Studies of Science*, 7, 167, 1977, and Cole, J.R., and Cole, S., *Social Stratification in Science*, University of Chicago Press, 1973.

Possible Problems with Citation Analysis as used by me (cont.)

Possible Problem[2]	My Response
(g) The 'halo' effect, where papers written by well-known astronomers attract more references than they really justify.	This is unlikely to affect my results unless these 'top quality' researchers always use the same facilities.

Note (b) and (c) above are less of a problem with the 15% hurdle system that I have used, compared with standard citation analysis. (e), (f) and (g) are less of a problem with my analysis of facilities compared with a standard citation analysis of authors.

Previous Cost-Effectiveness Work

Abt[1] analysed the relative cost-effectiveness of the six telescopes available at the Kitt Peak National Observatory in the late 1960s, and Martin and Irvine[2,3] analysed the cost-effectiveness of some ground-based observatories and telescopes in the 1970s, but these analyses were produced for a limited number of years and a limited number of telescopes, and no attempt was made to compare the cost-effectiveness of these ground-based facilities with those in space. Whilst these studies are of undoubted historical interest they are also substantially out-of-date.

Some work has been undertaken to examine the relative usefulness or effectiveness* of some observational astronomical facilities, but cost has not been considered in these particular studies. In 1985 Abt[4] compared the relative usefulness of the four largest American telescopes available in the late 1970s, and Trimble[5] has recently updated and extended this analysis. Abt[6] has also produced some statistics on the

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* The words 'usefulness' and 'effectiveness' are used interchangeably in this thesis.

relative usefulness of astronomical spacecraft available in the late 1980s and early 1990s, but again cost was not considered.

Hypotheses

In the early years of the space programme a space mission was generally considered to be successful if the launcher worked and the satellite transmitted a reasonable amount of data for a reasonable amount of time. Spacecraft were breaking new ground at that time, and astronomers had very little idea what use space-based instruments would be to astronomical research, even though some preliminary work had been undertaken with sounding rockets. Money was no constraint in these early years of space research, as America poured money into the space programme in an attempt to catch up with the USSR by firstly putting a spacecraft into orbit around the earth, then getting a man in space, sending spacecraft to the Moon and planets, and finally landing a man on the Moon.

So, in the late 1950s and early 1960s money flowed freely into the American spacecraft programme which was required to provide results as quickly as possible. Spacecraft and rocket technology was relatively crude at that time, however, and there was little idea as to what sort of data would be obtained from space, let alone how that data should be analysed. Starting in the mid 1960s, however, the political pressures for instant spectacular results from space started to subside, as the spacecraft and rocket technology started to mature, although it took another ten or twenty years for spacecraft launches to be relatively routine with carefully planned experiment timelining.

Given this background, of which I was well aware, having spent over twenty years in the space business, guided me to several hypotheses which I was particularly keen to test in this project (next page):-

I would anticipate, for example, that there would be a dramatic increase in the cost-effectiveness of American astronomical spacecraft up to about 1980, at least, with maybe a more gradual increase since then. Although ESRO and ELDO* never had the political incentive in the early days of the 1960s to get a satellite into orbit no matter how much it cost, their technology base was also very insecure at that time**, so again *I would expect a relatively poor early cost-effectiveness result which should have improved dramatically with time since then, particularly in the early years.*

Ground-based radio telescopes were first brought on line very much as experimental devices in the late 1940s and early 1950s. At that time, as with spacecraft ten years later, no one was very sure what radio telescopes would find. The designs of radio telescopes matured faster than that of spacecraft, however, as radio telescopes, like all ground-based facilities, could also be repaired or modified at will, whereas spacecraft, until the use of the space shuttle in the 1980s, had to work first time. In addition, ground-based radio telescopes did not have to cope with the risk element that launchers contributed to space research. *So I would anticipate that ground-based radio telescopes would be much more cost-effective than spacecraft at the start of my period in the late 1950s, but that that cost-effectiveness would have increased more slowly than that of spacecraft since then.*

The designs and technology used in the construction of ground-based optical telescopes had seen relatively little change over the last few decades prior to the start of my period, and there was little further change until the late 1970s when radically new designs were gradually introduced for large telescopes. *So I would expect to see only a modest increase in the cost-effectiveness of ground-based optical/IR telescopes upto about 1980, with a somewhat greater increase since then.*

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* The forerunners of ESA.

** Mainly because the Europeans spent a much smaller proportion of their GNP on civil space than the Americans, and also did not have a military space programme to match the Americans.

A key question is how does the cost-effectiveness of these three different systems of spacecraft and ground-based optical/IR and radio facilities compare now, and whether the result is so clear that it should influence the balance of investments in future facilities.

If, as expected, spacecraft are still less cost-effective than ground-based instruments, because spacecraft are still very expensive to build and launch, should that cause a radical movement of resources from spacecraft to ground facilities? It is true that some wavebands can only be observed from space, but that should not give 'carte blanche' to administrators to pour money into space-based observatories if that compromises investments in more cost-effective ground-based facilities. Hopefully my analysis should enable a more informed debate to be carried out into these matters than has been possible hitherto.

Thesis Structure

In Part 1 of my thesis I will examine the relative effectiveness of the various ground- and space-based observational facilities as measured by citation analysis and, in Part 2, I will establish their costs. Then in Part 3 I will analyse the resultant cost-effectiveness of American, British Commonwealth and ESA facilities. In Part 4 I will examine the development of astronomical facilities in the United States over my chosen period, compared with those recommended in the decennial reports of the National Academy of Sciences. I will then finish with a general discussion of the main results.

It has been difficult to know where to stop my thesis as the work described has no natural boundary, although some boundaries have been indicated in the above. As a result, some of the matters discussed in the general discussion at the end of the thesis could well be used as an agenda for further research.

PART 1 EFFECTIVENESS

Summary

In the first section of Part 1 I review three alternative methods of analysing the effectiveness of astronomical observational facilities over my chosen period from 1958 to 1994. As a result, I conclude that a method which involves analysing the 15% most-cited papers in astronomical journals is the most appropriate, being both objective and practical and able to yield quantitative results.

Having chosen a method of measuring effectiveness, I define a detailed methodology (see Table S1) for selecting papers. Such a selection is essential to make my project tractable, as there were about 100,000 astronomical papers published world-wide

TABLE S1
Methodology

	Select	Comments	Section No.
Measure effectiveness	15% most-cited papers		2
Analyse specific journals	ApJ and MNRAS	Consequently limits analysis to stellar, galactic and extra-galactic work and to American and British Commonwealth facilities	2
Choose timescale cadence	One half year in every four	Must treat results for individual spacecraft and new telescopes with caution	2
Characterise & select papers	Select only those papers that analyse new observations or catalogue data		3.2
Define scoring system	Score each facility according to the fraction of the data it supplied to a paper. Total scores for all facilities in any paper = 1.		4.2

over my chosen period. The journals selected (*ApJ* and *MNRAS*) mean that my analysis is limited to stellar, galactic and extra-galactic work (rather than solar or solar system research), using American and British Commonwealth facilities. In addition, the cadence of years chosen (one half year in every four) also implies that I will have to be cautious about drawing conclusions about the usefulness of individual facilities (i.e. of individual spacecraft and new ground observatories) whose output change relatively rapidly with time. For more established facilities, however, there are no such problems, as my cadence of years provided a number of data points for each.

The selection of journals reduced the number of papers from about 100,000 to 50,000, and the selection of years reduced this further to about 6,700. I then looked up the citation numbers for each of these 6,700 papers on a computer database to select the 15% most cited. This gave 1,000 papers which I then analysed in hard copy.

Even though my work is unique in its comprehensive coverage, there have been a number of analyses published covering a small number of observatories over a limited period of time. My results are compared with these at various places in Part 1. The agreement is generally good (see Table S2, next page) with one exception, that of the relative effectiveness of individual spacecraft. This is because of the yearly cadence problem outlined above, although the first 5 of the 26 spacecraft in Abt's list are covered by the first 8 spacecraft in mine, and vice versa.

Although astrophysics rests on work with both ground- and space-based facilities their cost structure is very different, so there is a built-in problem in judging the relative spending priorities between ground- and space-based facilities. Because of this, I deal with these two different type of facilities separately in Part 1.

TABLE S2

Comparisons between my results and those of others

	See	Compared with	Resulting agreement
% of Observational Papers	Sect. 3.2 Tables 6B & C	Abt for ⅓ of 1986, '89 and '94	Excellent
% of Space-based Papers	Sect. 4.1 Tables 8A & B	Ditto	Excellent
% of Papers by Waveband	Sect. 4.1 Table 9	Abt for ½ of 1962, '72 , '82 and '92	Good
Relative effectiveness of 4 large optical telescopes	Sect. 4.3.1 Table 13	Abt for 1980-81 and Trimble for 1990-93	Good
Relative effectiveness of 13 American optical telescopes > 2.0m dia.	Sect. 4.3.1 Fig. 4 Table 14	Trimble for 1990 & first ½ of '91	Good. Best correlation with Trimble's citation numbers rather than numbers of papers
Relative effectiveness of 7 British C'wealth optical telescopes	Sect. 4.3.1 Figs. 5 & 6	Martin & Sinclair 1986, '90, 94 or 1990-95	Good. Best correlation with Martin & Sinclair's no. of highly cited papers rather than no. of papers
Relative effectiveness of 4 medium sized optical telescopes	Sect. 4.3.1 Table 15A & B	Irvine & Martin 1969-78	Good. Best correlation with citation numbers rather than numbers of papers. Good correlation with peer-group rankings
Relative effectiveness of various spacecraft	Sect. 4.3.3 Tables 18A & B + text	Abt for ⅓ of 1986, '89 and '94	Fair

The rise since 1970 in the percentage of highly-cited papers produced using spacecraft data is shown in Figure 1 of Part 1, and a further subdivision of this data by different wavebands is shown in Figures 2A and 2B. I then present my main results divided into ground-based optical/IR telescopes, ground-based radio telescopes, and spacecraft (see Table S3, next page). The individual spacecraft

TABLE S3
Index of my main results

	See	Sample Results
Percentage of highly-cited papers by Ground- and Space-based Observatories as a function of time from 1958 to 1994	Figure 1	Percentage of space-based papers has increased from zero in 1966 to 40% in 1994
Number and Percentage of highly-cited papers by different Wavebands as a function of time from 1958 to 1994	Tables 7A & B & Figs. 2A & B	Percentage of ground-based radio and IR papers has remained approx. constant at about 17% and 8% since 1962 and 1966, respectively. In 1994 the percentage of space-based papers exceeded the percentage of ground-based optical papers for the first time.
Number and Percentage of highly-cited papers by size categories for Ground-based optical telescopes as a function of time from 1958 to 1994	Table 10 & Figs. 3A & B	Percentage of highly-cited optical papers using ground-based telescopes in the 2.55m - 5.08m (100" - 200") class increased from 23% in 1958 to 58% in 1994. The corresponding figures for telescopes in the range up to 0.61m (24") were 21% in 1958 and 1% in 1994.
Individual Opt./IR telescopes:-		The most useful ground-based optical telescope over the whole period 1958–1994 was the 5.1m Hale Telescope, but in the second half of that period the Anglo-Australian Telescope had similar effectiveness results.
Cum. Scores 1958-94	Table 11A	
Av. Scores 1958-74	Table 11B(a)	
Av. Scores 1978-94	Table 11B(b)	
Individual Radio Telescopes:-		The VLA was the most useful ground-based radio telescope over the period 1958–1994.
Cum. Scores 1958-94	Table 16A	
Av. Scores 1978-94	Table 16B(b)	
Individual Spacecraft:-		The Einstein Observatory was the most useful space observatory over the period 1958–1994. In 1994 the best spacecraft were the CGRO, Rosat and the HST. On average the greatest number of highly-cited papers were published 4 to 5 years after launch of spacecraft.
Cum. Scores 1958-94	Table 17	
Cum. Scores 1978-94	Table 17(b)	
Tentative order of merit	Table 20	
Scores as a function of time after launch	Figs. 7A & B	
Most-cited Individual Ground- and Space-Based Facilities:-		The 5.1m Hale Telescope was the most useful facility over the whole period 1958–1994, and also for the second half of that period. The Einstein Observatory Spacecraft was the most useful facility in the second half of that period.
Cum. Scores 1958-94)		
Cum. Scores 1958-74)	Table 21	
Cum. Scores 1978-94)		

results are more tentative than those for individual ground-based facilities, for the reasons already given, although there is no such problem in dealing with spacecraft as a group.

In broad terms, the analysis of Part 1 shows that large ground-based optical/IR telescopes have become more and more important to astronomy over my period, at the expense of smaller telescopes. The effectiveness of spacecraft has improved dramatically over the same period, with no spacecraft in the top three facilities over the period 1958–1974, one spacecraft in the top three over 1978–1994, but all three of the top facilities in 1994 were spacecraft. As far as I can determine, these analyses are unique.

Part 1

1 Effectiveness Measure

How can the effectiveness or usefulness of a particular facility be evaluated or measured? Clearly whatever method is used will be subject to objections.

One possible method is peer evaluation which, in my project, would involve a representative cross-section of astronomers judging the relative usefulness of both ground- and space-based facilities over my chosen period, that is over the years since the launch of Sputnik in 1957. It would be feasible to arrange such an evaluation for a relatively small group of similar facilities over a relatively limited period, as Martin and Irvine have shown[2,3] with radio astronomers judging the relative usefulness of various radio observatories over the previous ten years, and optical astronomers doing the same for optical observatories*. But asking for such judgements over a period of almost 40 years would be fraught with difficulties**, which would be compounded with also trying to inter-compare the relative usefulness of ground- and space-based facilities over various wavebands.

An alternative method would be to judge the effectiveness of facilities by undertaking a simple count of published papers written using data from the various facilities.

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* In Reference 2, Martin and Irvine used peer review to judge the relative rankings of nine radio observatories over the previous ten years, and in Reference 3 they did the same for twelve optical observatories. In Reference 3, however, they pointed out that their peer review group had difficulties in differentiating between the usefulness of the various telescopes at each observatory, so they used the peer review system to judge the relative rankings of the various observatories, not the telescopes. Martin and Irvine did not try to compare radio with optical facilities in this work.

** There is some suggestion that in Reference 3 Irvine and Martin's peer review team were more influenced by the performance of the observatories in the latter part of the ten years being evaluated than in the earlier part (see Section 4.3.1 below). Over a 40 year period such a trend would produce far more of a problem.

This would probably be misleading, however, as some papers are much more important than others, and my study needs to establish not just how much data has been produced but how useful it was. Such a count of published papers might indicate the number of hours the facility has been used, how many different groups of astronomers have used it, or how much data has been produced, but it would not indicate how useful the data was.

Finally, an alternative measure of the usefulness of a particular facility could be based on the number of citations to papers produced using data from that facility. This citation method could be used in either of two ways; either by simply totalling the number of citations to such papers produced using a particular facility, or by counting the number of papers that have a citation greater than a given 'hurdle' value. Unfortunately, there is no reliable database linking papers to the facilities that were used to supply the observational data, so I will have to scan the papers in hard copy. If I analyse the papers published in a given journal over a given period, the total citation method would require all the papers to be analysed, whereas the hurdle method would require only those papers to be analysed that crossed the hurdle, substantially reducing the amount of work involved. The hurdle method also has the advantage of being a compromise between the simple paper count, discussed as the first option above, and the total citation method.

After considering the relative advantages and disadvantages of these various alternative schemes for my project*, I decided to use the 'hurdle' citation method. So

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* Martin and Irvine have produced an excellent discussion of the advantages and disadvantages of most of these methods in Reference 2, but they were interested, in that Reference, in the communities that produced the papers, not the facilities used to produce the data for the papers. As mentioned above, they were also looking at an intercomparison of *similar* facilities over a more limited, more recent period (at the time that they wrote the paper) than I am, so their discussion is not directly relevant to my project, although it is generally valid.

in this study I have analysed only those papers whose citation record is greater than a certain level, thus including only the more important papers. The citation database used was the Science Citation Index made available on the BIDS* computer system.

The analysis covers the period from 1958 (the first full year after the launch of Sputnik) to 1994, although it is recognised that the citation database of papers published in 1994 can only be provisional, as there has not yet been time for their true relevance to be properly appreciated.

Before proceeding to discuss the implementation of my chosen selection system, it is appropriate to discuss possible problems with such a system, and explain why I think it will provide a fair guide to the effectiveness of facilities.

Martin and Irvine[2] argued that the best way to evaluate the performance of research groups (which is what they were trying to do) is to use what they called 'partial indicators', and to use only those results where the partial indicators agreed. The main partial indicators that they used were numbers of papers, number of citations and peer review. I have already explained above why I think that peer review is not appropriate to my study, as it covers 36 years and many different types of facilities (compared with the ten years and more constrained facilities of Martin and Irvine), so

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* BIDS is an on-line computer database produced by Compendex and operated in the UK by Bath Information and Data Services. Although BIDS records cited papers written before 1958, it only records citations to those papers in papers published starting in 1980. Because of this, the numbers of citations to pre-1980 papers is not complete and their citation numbers should not be compared with those of post-1980 papers unless some normalisation is attempted. This is not a problem in this project, however, because of the way I have used the citation data, in only comparing citation numbers for papers published in the same year as each other. This type of normalisation allows me to compare results over the whole of my 36 years.

I will now consider the other partial indicators of numbers of papers and numbers of citations.

My hurdle system is not a citation analysis in the generally accepted sense of the term, as in a normal citation analysis the number of citations are determined and totalled by groups of researchers, or by observatories, etc. In such a normal citation analysis a paper with 100 citations gets a 'score' ten times that of a paper with 10 citations, which in turn gets a score ten times that of a paper with one citation, so papers with large numbers of citations have a very large effect on the results. In my system, on the other hand, papers that have a citation number above the modest hurdle* will get a score of one, and those below that hurdle will get a score of zero, so my results will not be as heavily affected by heavily-cited papers as would a normal citation analysis.

The main aim of my methodology is to try to eliminate the routine papers and select the more effective papers, rather than bias my analysis towards that very small number of heavily-cited, breakthrough papers, which are probably more due to the inspiration of the authors rather than the excellence of the facilities, although the latter may have had an effect. Martin and Irvine were looking at the performance of people, however, and not the facilities, and so conventional citation analysis may have been more relevant to their analysis than mine.

As mentioned above (see Page 7), my system is basically a compromise between a simple paper count and a normal citation analysis although, as there is a citation bias in my system, I would expect my results to be more closely correlated with those produced using a conventional citation analysis than with those based on a simple

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* The size of the hurdle was chosen to ensure that the same modest percentage of papers (15%) pass the hurdle in each time period considered (see Page 11).

paper count. As I show later in this thesis*, this is indeed so in those cases where such a comparison is possible, although my results also compare well with those analyses based on numbers of papers**.

I will now return to the main topic of my thesis and describe the selection system in more detail.

2 Journals and Years

The total number of papers published in astronomical journals is very large, being about 50,000# for just the *Astrophysical Journal* (*ApJ*), the *Astronomical Journal* (*AJ*), and the *Publications of the Astronomical Society of the Pacific* (*PASP*), for the period from 1958 to 1994, so some selection of material is inevitable. I also wished to include a UK publication, to provide a balance to the American data##, and so I

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* The correlation coefficients for a comparison between my results and those of other researchers are as follows, depending on whether those researchers analysed numbers of papers or numbers of citations (see Pages 38–43 below):-

Researchers	No. of papers	No. of citations
Trimble	0.82	0.88
Irvine & Martin	0.89	0.96

** See Table 6C and text on Page 20, Table 8B and text on Page 25, Table 9 and text on Pages 25 & 26, and the text on Pages 38–43).

Although 50,000 is a great number of papers, figures such as these need to be put into context. Abt[7] found, for example, that for the 2,865 Full Members of the American Astronomical Society in 1989, the number of research papers published per astronomer per year was only about 0.5, assuming a paper count of *1/n* per astronomer for each paper that has *n* authors.

About 80% of the papers published in the *ApJ* in the period from 1958 to 1994 were by American authors. Over the same period about 75% of the papers published in the *MNRAS* were by British Commonwealth astronomers[8].

decided, therefore, to analyse papers published in the *Astrophysical Journal* (*ApJ*) and the *Monthly Notices of the Royal Astronomical Society* (*MNRAS*). An alternative approach could have been to analyse the astronomical papers published in 'Nature', but these papers generally also appear in some form in *ApJ* or *MNRAS*, whereas the reverse is not true. So reviewing *ApJ* and *MNRAS* papers probably gives a more complete picture of the progress of astronomy.

It is recognised that, in making such a selection of general astronomical journals, solar and planetary work would not be properly represented, as these topics have their own specialised journals. Because of this, the usefulness of solar telescopes and planetary spacecraft cannot be properly assessed, and such an assessment is considered to be outside the scope of this investigation.

As mentioned above, I only wanted to consider the most important papers, and I also needed to keep the number of papers analysed down to a manageable number (of about 1,000 papers). One solution would be to analyse only the very highly cited papers, say the top 1% of papers, but these may have more to do with the insight of the astronomers writing the papers than the facilities used to produce the data. So, given my target number of about 1,000 papers, I decided to analyse the 15% most-cited papers published in the first half of the years 1958 to 1994, inclusive, at four-yearly intervals, i.e. 1958, 1962, 1966 etc..

Clearly I could have used a larger percentage of papers, but this would have meant less years or less parts of years being analysed, and four-yearly intervals seems reasonable when looking at the trends over 36 years, producing, as it would, ten data points. The alternative of using a lower percentage of papers, but more years, could have been chosen, but this could have meant that I was not looking at papers that truly represented astronomical work as a whole, as I need some relatively routine papers, not just catalogue or discovery papers which predominate in the top 5%, say.

My solution, outlined above, effected what I considered to be a reasonable balance between these various competing factors.

In this Part 1 of my thesis I will identify those facilities used to produce data for these highly-cited papers, in Part 2 I will analyse the costs of these facilities and in Part 3 deduce their cost-effectiveness.

The number of papers to be analysed is listed in Table 1.

TABLE 1
Number of Papers to be Analysed

First ½ of	No. of Papers in ½ Year	No. of Papers to be Analysed (i.e. 15%)
1958	101	15
1962	134	20
1966	325	49
1970	390	59
1974	648	98
1978	807	122
1982	850	128
1986	877	132
1990	1,140	171
1994	1,523	229
Total	**6,795**	**1,023**

3 Papers

3.1 Selection of Papers

It is clearly important to avoid bias at all stages in this study, and in selecting the subset of papers to be analysed the following methodology was adopted.

The 6,795 papers published in the first half of the above years in *ApJ* (including Letters, Supplements and Notes) and *MNRAS* (including Previews, Letters and

Memoirs) were identified, and their citation numbers found in the BIDS database using first author name, year and volume number as search parameters. The BIDS citation numbers do not discriminate between papers written by the same first-named author in the same year with the same volume number, however, as it is not possible to introduce a page number discriminator in the search parameters. In these ambiguous cases, the citation lists of each citing paper were consulted to find out which of the two or more papers was being cited for the same author.

Once the citation numbers were found, the papers were listed in order of citation numbers for each half-year, and the top 15% selected. If there were a number of papers with the same number of citations at this 15% level, then all of these papers were retained, producing a selection of slightly more than 15%.

As the *ApJ* and *MNRAS* papers were considered together, there was not necessarily 15% from each journal, see Table 2.

TABLE 2
Number of papers Analysed

	ApJ		*MNRAS*		
First ½ of	**No. of Papers**	**No. Selected**	**No. of Papers**	**No. Selected**	**Total No. Selected**
1958	75	14 (19%)	26	3 (12%)	17 (17%)
1962	100	14 (14%)	34	8 (24%)	22 (16%)
1966	252	42 (17%)	73	8 (11%)	50 (15%)
1970	317	55 (17%)	73	10 (14%)	65 (17%)
1974	518	87 (17%)	130	12 (9%)	99 (15%)
1978	636	101 (16%)	171	22 (13%)	123 (15%)
1982	653	108 (17%)	197	21 (11%)	129 (15%)
1986	652	111 (17%)	225	23 (10%)	134 (15%)
1990	858	153 (18%)	282	29 (10%)	182 (16%)
1994	1,187	188 (16%)	336	49 (15%)	237 (16%)
Total	**5,248**	**873 (16.6%)**	**1,547**	**185 (12.0%)**	**1,058 (15.6%)**

TABLE 3 (Adapted from Peterson[9])
Source of Cited Papers

	Citing Journal				
	ApJ	*MNRAS*	*AA*[*]	*PASJ*[**]	*SA*[#]
No. of Papers in 1984 →	1,354	484	603	61	229
Source of Cited Papers ↓					
ApJ	41.7%	30.8%	26.7%	26.6%	16.9%
MNRAS	6.0%	15.7%	6.8%	7.8%	4.6%
Ratio *ApJ/MNRAS*	7.0	2.0	3.9	3.4	3.7

The percentage of highly-cited papers selected from *MNRAS* was less than the percentage for *ApJ*, probably because *ApJ* published many more papers than *MNRAS*, and there was a tendency for writers in one journal to quote papers from the same journal, as shown by Peterson[9], see Table 3[##].

The ratio of the number of papers published by *ApJ* to those published by *MNRAS* for the half-years 1958, 1962, ..., 1982 was 2551/704 = 3.62. So, if the quality of the papers was generally the same in both *ApJ* and *MNRAS*, and if there was no self-citation tendency, the ratio of citations to *ApJ*, compared with those to *MNRAS*, should be about 3.6. This is what the independent (i.e. non-American, non-British) journals AA, PASJ and SA showed for the *ApJ/MNRAS* citation ratio (see Table 3), so there appeared to be no significant difference between the quality of the papers in

---

[*] *Astronomy and Astrophysics*

[**] *Publications of the Astronomical Society of Japan*

[#] *Soviet Astronomy and Soviet Astronomy Letters*

[##] This self-citation bias, shown in the first two columns of Table 3 for *ApJ* and *MNRAS*, was not limited to these two journals, but was valid for all of the journals considered by Peterson. It is hardly surprising, of course, as readers of any journal would be expected, generally, to be more familiar with the papers in that journal than those in any other.

ApJ and *MNRAS* and, ideally, my 15% selection criterion should apply equally to both journals.

My average selection rate of papers was 15.6 % (see Table 2) and, if this had applied equally to *ApJ* and *MNRAS* papers, this would have resulted in the number of selected *ApJ* papers being reduced by 56 from 873 to 817, and the number of *MNRAS* papers being increased from 185 to 241. Clearly it would have been possible to ensure that these figures of 817 and 241 were met by taking 15.6 % of papers in each journal separately for each half-year considered, but that is only an improvement over my selection system if the papers in the two journals are as important as each other for each of the half-years considered, which is highly unlikely*. In this study this variation in the relative quality of the papers in the two journals is automatically allowed for, as the ratio of papers selected in the *ApJ* and *MNRAS* can vary freely, resulting in ratios of *MNRAS*/*ApJ* of from 9%/17% in 1974 to 15%/16% in 1994**.

3.2 Characterisation of Papers

It is important to characterise the type of papers being analysed, as some are based primarily on new observations, some have a mixture of new and old observations, and some are theoretical, and this study is only concerned with those facilities used to produce new observations.

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* *MNRAS* tends to publish a greater proportion of results based on British Commonwealth facilities than *ApJ*. In not making such an adjustment, therefore, I may appear to be favouring American over British Commonwealth facilities. Any analysis based on citation indexes has exactly the same problem. There is no satisfactory solution to this, as factoring the *MNRAS* results introduces as many problems as it may appear to solve.

** The highest ratio was 24%/14%, but this was in 1962 when we were dealing with the statistics of very small numbers.

Part 1

I scanned the (nominal) 15% most-cited papers that I had selected and classified them as:-

- (A) Papers based on new observations.
- (B) Papers using previously published catalogue or survey data.
- (C) Papers reanalysing or rediscussing previously published observations.
- (D) Theoretical papers.
- (E) Miscellaneous papers describing laboratory data or instrumentation.

This categorisation is similar to that of Abt[10], except that I separately recorded papers based on catalogue or survey data (category B) from those in category A, whereas Abt did not discriminate between categories A and B in his analysis.

Sometimes a paper could fit plausibly into more than one category. In that case it was put into the most appropriate one, and was not split between categories. For example, a paper mainly discussing previously published results could contain a significant number of new results. In that case it was put into category C, but the source of the new data was recorded and used further in my analysis.

TABLE 4
Number of papers per classification category

Category →	A	B	C	D	E	Total
1958	8	1	2	5	1	17
1962	13	0	1	7	1	22
1966	17	2	3	27	1	50
1970	18	1	8	35	3	65
1974	45	0	12	42	0	99
1978	54	1	10	55	3	123
1982	71	5	12	40	1	129
1986	72	5	14	42	1	134
1990	97	4	15	63	3	182
1994	119	5	11	96	6	237
Total	**514**	**24**	**88**	**412**	**20**	**1,058**
	48.6%	**2.3%**	**8.3%**	**38.9%**	**1.9%**	

The number of the nominal 15% most-cited papers put into each of the above categories is shown in Table 4 (previous page).

Abt's data from his various papers is summarised in Table 5 against each of my categories A to E given above.

TABLE 5
(Data by Abt) 6.10.11.12

(a) Analysis of Papers in *ApJ* (including Supplements) and AJ 12

Year	No. of Papers	Observational	Theoretical	Instrumental or Laboratory Studies
My Category →		A + B + C	D	E
1961	326	53.2 %	44.2 %	2.7 %

(b) Analysis of Papers in *ApJ* (including Letters and Supplements), AJ and PASP 11

Year	No. of Papers	Observational	Theoretical
My Category →		A + B + C + E	D
1960	369	74.5 %	25.5 %
1970	908	65.3 %	34.7 %
1980	1,622*	67.9 %	32.1 %

(c) Journals as (b) but analysed by half-years 10

½ Year	No. of Papers	Observational	Reanalysis	Theoretical	Instrumental or Lab. Studies
My Category →		A + B	C	D	E
1962	182	60.4 %	11.5 %	25.3 %	2.8 %
1972	546	52.9 %	12.6 %	26.2 %	8.2 %
1982	849	61.8 %	9.1 %	27.1 %	2.0 %
1992	1,118	51.2 %	13.6 %	33.3 %	1.9 %
	Mean	56.6 %	11.7 %	28.0 %	3.7 %

---

* Half-year multiplied by two.

TABLE 5 (cont.)

(d) *ApJ* only (including Letters) for first 1/3rd of years[6]

1/3 Year	No. of Papers	Observational	Theoretical (incl. Reanalysis)
My Category →		A + B	C + D + E
1986	420	57 %	43 %
1989	454	50 %	50 %
1994	665	52 %	48 %

My analysis in this paper is concerned with results based on observational work only, i.e. categories A, B and C, and my results are compared with Abt's in Table 6A.

Direct comparisons can be made in just three years (1962, 1970 and 1982), where my results average 58% in comparison with Abt's average of 68%. Abt's figures for those years cannot be strictly compared with mine, however, as his figures (next page):-

TABLE 6 A
Percentage of Category A + B + C Papers

Year	My Data	Ref. 12	Refs. 10 & 11
Journals →	*ApJ & MNRAS*	*ApJ & AJ*	*ApJ, AJ & PASP*
1958	65		
1960			72*
1961		53	
1962	64		72
1966	44		
1970	42		62*
1972			66
1974	58		
1978	53		
1980			65*
1982	68		71
1986	68		
1990	64		
1992			65
1994	57		

---

* A + B + C + E minus 3% for E; 3% being a typical figure for E, see Tables 5(a) and (c).

(a) are for papers in the *ApJ*, *AJ* and *PASP*, whereas mine are for papers in the *ApJ* and *MNRAS*.

(b) are for all papers, not just the 15% most-highly cited papers that I have analysed.

(c) in 1970 are for the whole year, not just ½ a year as in my data.

The nearest selection of papers that Abt has made to mine is in Reference 6 where he restricted his analysis to papers in the *ApJ*, dividing his papers between observational (my categories A and B) and theoretical and reinterpretation (my categories C, D and E). His results compare with mine as shown in Table 6B.

TABLE 6 B
Percentage of Category A + B Papers

	My Data ***ApJ & MNRAS***	**Abt** ***ApJ***
1986	57 %	57 %
1989		50 %
1990	55 %	
1994	52 %	52 %

The agreement for 1986 and 1994 is remarkable, especially when it is realised that Abt's data:-

(a) does not include the *MNRAS*.

(b) does not include the *ApJ Supplement*. (Mine does).

(c) is only for 1/3 of the year, not ½ of the year as in my data.

(d) is for all papers, not just the 15% most-highly cited.

In order to get a clearer comparison with Abt's data, I have modified my data (for this comparison only) by excluding the *MNRAS* and the *ApJ Supplements*, and restricting my data to the first 1/3 of both years. So the only differences remaining between Abt's analysis and mine are (d) above and the subjective element of determining which papers to put into categories A and B, and which to exclude. The results are shown in Table 6C.

TABLE 6 C
Percentage of Category A + B Papers

	My Data ***ApJ***	**Abt** ***ApJ***
1986	59 %	57 %
1994	52%	52%

So in the only case where a direct comparison is possible between Abt's data and the data produced in this study, the percentage of papers put into categories A + B is virtually identical. This gives some confidence that my categorisation of class A + B papers is consistent with Abt's. It also indicates that, in these 1/3 years at least, the percentage of category A + B papers in the 15% most-cited papers is the same as in all papers. This is consistent with Abt's[12] observation that the percentage of citations made to observational papers closely resembles the percentage of observational papers.

4 Results

4.1 Waveband Analysis

I now turn to the main point of my investigation, namely the identification and analysis of the various ground-based telescopes and space-based facilities used to produce important new observations; these new observations being largely in categories A and B, together with some in category C. It is also of interest to see how the wavebands used in astronomical papers have changed with time, as it has become possible to use more and more wavebands for ground- and space-based research.

I first scanned the 626 selected papers in categories A, B and C (see Table 4) to find out whether the source was Ground- or Space-based data, and what wavebands were used. There were problems at the borderlines between wavebands, as they are not sharply defined. Reading the papers, it appeared sensible to include the near IR (up to about 1μm), and the near UV (down to the bottom of the atmospheric window) in the optical region, if optical equipment was used. Abt[10] adopted a similar approach. In the event that more than one waveband was used, each waveband was given partial credit, split equally.

The small number of papers produced using data from the Kuiper Airborne Observatory, balloons and sounding rockets were included with the Space papers.

TABLE 7

Analysis of papers in categories A, B and C

(Numbers are numbers of papers)

(A) Ground Observations

½ Year	Optical	IR	Radio	Cosmic Rays	Total
1958	11	0	0		11
1962	11	0	3		14
1966	17	2	3		22
1970	21.5	0.5	3		25*
1974	30.5	7	10.5		48
1978	30.3	9.8	11.3		51.5**
1982	36.1	10.8	15.3		62.2
1986	35.9	2.4	27.4		65.7
1990	53.5	18.3	18.7		90.5
1994	49.2	14.6	14.8	1.0	79.5**
Total	**296.0**	**65.4**	**107.0**	**1.0**	**469.4**

---

* excludes one survey paper that was based on ground- and space-based data at all wavelengths.

** rounded

TABLE 7 (cont.)

(B) Space Observations
(zero before 1970)

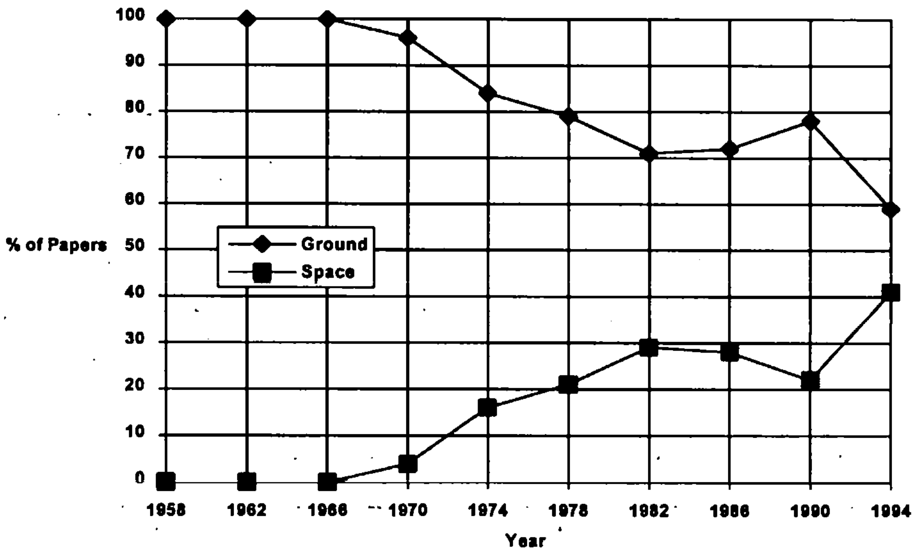
½ Year	γ-rays	X-rays	UV	Optical	IR	μ-wave	Particles	Total
1970	0	0	0	0	0	0	1.0	1
1974	0	4.5	3.5	1.0	0	0	0	9
1978	1	4	7	0	1.5	0	0	13.5
1982	1	16.3	6.8	0	1.8	0	0	25.8*
1986	0.5	11.7	5.2	0	5.9	0	2.0	25.3
1990	2.2	11.2	2.5	0	5.3	2	2.2	25.5*
1994	12.3	16.4	12.1	4.0	4.3	5.5	1.0	55.5*
Total	**17.0**	**64.1**	**37.1**	**5.0**	**18.8**	**7.5**	**6.2**	**155.6**

My results are summarised in Table 7 above.

The trends are shown in Figs. 1 and 2A and 2B (next page) where the data in Table 7 are plotted as percentages of papers in each of the half years considered. As

FIGURE 1

Percentage of highly-cited papers based on ground or space-based observations as a function of time. Space-based papers first appeared in 1970 and now account for about 40% of all observationally-based papers. Figures 2A and B below break down this data further to observations in different wavebands.



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* rounded

FIGURE 2A

Percentage of highly-cited papers based on ground-based observations in various wavebands. The rapid initial decline in the percentage of papers based on optical observations has almost levelled-off by 1994. The percentage of papers based on radio and infrared observations has stayed approximately constant with time after the initial increases in 1958 and 1962, respectively.

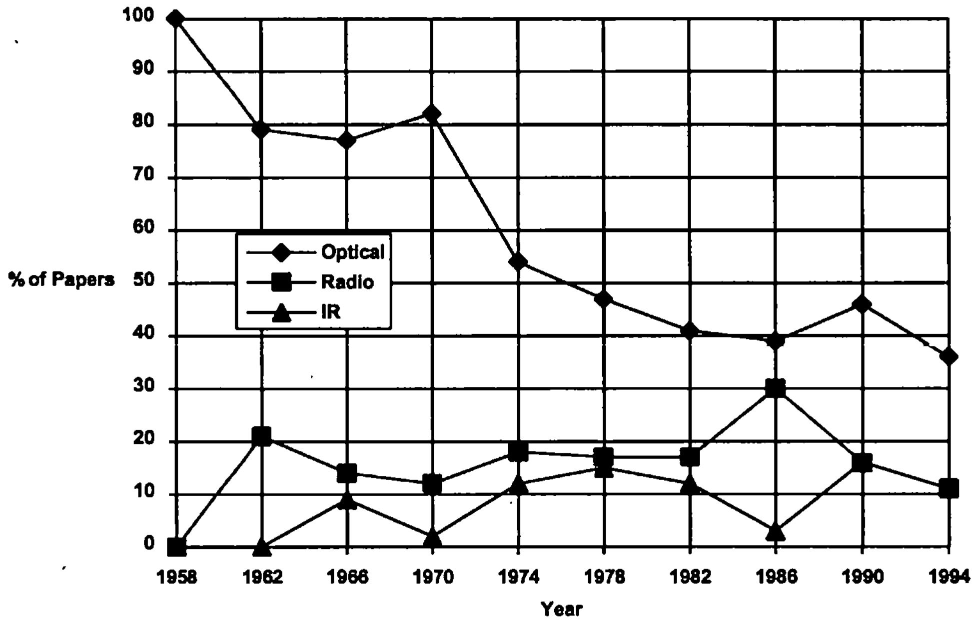
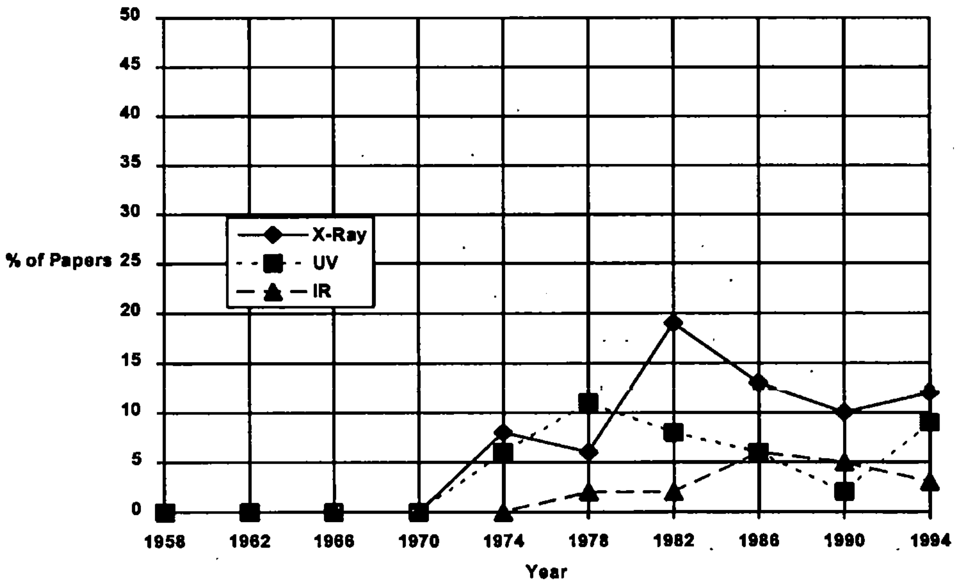


FIGURE 2B

Percentage of highly-cited papers based on space-based observations in various wavebands. Although the results are somewhat variable from one four year data point to the next, the number of papers based on X-ray observations is higher than those using ultraviolet or infrared observations for all but one year, namely 1978.



expected, the percentages of Optical papers has decreased (see Fig. 2A) as first Radio and Ground IR observations became available, and then spacecraft opened up new wavebands, particularly at the short wavelengths of X-rays and UV (see Fig. 2B).

Abt[6] analysed the papers published in the *ApJ* (including Letters but excluding Supplements) in the first 1/3 of 1986, 1989 and 1994, and separated the papers into ground-based, space-based and theoretical. His results compare with mine as shown in Table 8A.

TABLE 8 A
Ratio of Space/Space + Ground Observational Papers

	My Data ***ApJ & MNRAS***	**Abt[6]** ***ApJ***
1986	28 %	27 %
1989		28 %
1990	22 %	
1994	41 %	42 %

As for Table 6B, the agreement for 1986 and 1994 is remarkable, especially considering that Abt's data:-

(a) does not include the *MNRAS*.

(b) does not include the *ApJ Supplement*.

(c) is only for 1/3 of the year, not ½ of the year as in my data.

(d) is for all papers, not just the 15% most-highly cited.

In order to get a clearer comparison between my data and Abt's, I modified my data (for this comparison only) by excluding the *MNRAS* and the *ApJ Supplements*, and restricting my data to the first 1/3 of both years. So the only difference remaining between Abt's analysis and mine is (d). The results are as shown in Table 8B (next page).

TABLE 8 B
Ratio of Space/Space + Ground Observational Papers

	My Data *ApJ*	**Abt**[6] *ApJ*
1986	32 %	27 %
1994	43 %	42 %

So in the only case where a direct comparison is possible between Abt's data and the data produced in this study, the percentage of space-based observational papers is very similar, indicating that, in these 1/3 years at least, the percentage of space-based observational papers in the 15% most-cited papers is similar to that in all papers.

Abt[10] also undertook a similar analysis, of the wavebands used, at 10 year intervals from 1962 to 1992, inclusive. His results (see Table 9) are remarkably similar to mine, especially when considering (next page):-

TABLE 9
A comparison of Abt's with mine data on wavelengths used for observations
(Numbers are percentages of papers)

½ Year	**Source of Data**	**Space**			**Ground**			**Other**
		X-rays	**UV**	**IR**	**Optical**	**IR**	**Radio**	**(Sp. & Gr.)**
1962	DL				79		21	
1962	Abt[10]				78	1	19	2
1970/74*	DL	4	3		69	6	15	3
1972	Abt[10]	8	4		61	6	17	4
1982	DL	19	8	2	41	12	17	1
1982	Abt[10]	8	13	2	49	8	18	2
1990/94*	DL	11	6	4	41	13	14	11
1992	Abt[10]	9	6	4	44	11	20	6

---

* Average of 1970 and 1974, and of 1990 and 1994, as I did not analyse 1972 or 1992.

- the relatively small database involved
- the fact that the mix of journals was different between his and my data (he used *ApJ*, *AJ* and *PASP*).

and
- my data refers to only the 15 % most-cited papers.

4.2 The Scoring System

Following the above analysis, I now scanned the papers in categories A, B and C to find out which telescopes and/or spacecraft had been used as the source of the new observations. The only exception to the 'new observation' rule was that I considered that the small number of papers in category B, which were based on catalogue or survey data, were based upon new observations. If this had not been done, then the extensive work of producing these large databases, which are often not published as papers, would have gone largely unrecognised. (Abt[10] did the same).

Virtually all category A or C papers discussed previous results to some extent, but in the case of category A the main purpose of the paper was to present new results. In the case of category C, however, some papers contained no new observations, and so these were not considered further in my analysis, but some did include some new observations*. If these new observations were judged to be at least 25 % as many as in a typical category A paper, then they were considered further in my analysis and added to my database, with a 'score' (of ≥ 0.25) appropriate to that percentage. In the case of category A, the paper score was always 1.

Some category A papers used more than one telescope and/or spacecraft as the source of their new observations and, in these cases, the score of 1 was shared between the sources. If it was not clear from the paper what the split was between the amount of

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* 'New observations' in category C papers also included newly-analysed catalogue or survey data, consistent with the inclusion of category B papers in my analysis.

data produced from the two or more sources, they were scored equally. If, on the other hand, the split was reasonably clear, then the actual split was used, although sources of data with scores of less than 0.25 were ignored. Sometimes, for example, an author listed his observations, clearly stating which telescope was used for each observation. If, in such a case, the following occurred:-

	Telescope A	0.50 points
	Telescope B	0.25 points
	Telescope C	0.15 points
and	Telescope D	0.10 points

then only the scores of telescopes A and B were recorded, as all scores of below 0.25 were ignored. This is consistent with the case of category C papers in which paper scores of below 0.25 were ignored. A cut-off is required to avoid scoring and analysing many minor sources of new observations; after all I am trying to identify those instruments that have made a *significant* contribution to astronomy, which is why only the 15 % most-cited papers have been analysed.

In the case of category C, the paper score (of ≥ 0.25, but < 1) was multiplied by the telescope (or spacecraft) score, and the resultant figure used only if it was at least 0.25.

Sometimes the source of the new observations, even in category A papers, was not stated. In these cases the author sometimes referred the reader to a previous paper for such information, and the source could then be determined, but occasionally there was no information on the source of the new observations at all. In those few cases I had no alternative but to leave the paper out of any further analysis.

As the source of new observations in category A papers was not always specified, and the category C papers all have scores of less than 1, the total of the scores in any half year is always less than the total of the number of category A, B and C papers in those half years.

4.3 Telescopes and Spacecraft - the Results

4.3.1 *Ground-Based Optical & Infrared Telescopes*

I grouped the optical/infrared telescopes into four aperture categories*, namely:-

(a)	2.55 - 5.08 m (200")
(b)	1.23 - 2.54 m (100")
(c)	0.62 - 1.22 m (48")
(d)	0 - 0.61 m (24")

The percentage of the total scores for each of these groups of telescopes are given in Table 10 (next page) for each half year. They are plotted against time in Figs 3 A and B (pages 30 and 31).

Figure 3B shows that:-

(1) In 1958/62 the most useful group of telescopes (measured by the percentage of the most highly- cited papers) was category (b) (i.e. 1.23 - 2.54 m), followed by categories (a), (c) and (d), in that order.

Text continued on Page 30

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* The split between categories was chosen based on imperial units as, until recently, that was the *lingua franca* for telescope sizes in the USA and British Commonwealth.

TABLE 10

Optical and Infrared Telescopes
Scores and Percentages

	1958	1962	1966	1970	1974	1978	1982	1986	1990	1994
(a) 2.55 - 5.08 m	2.05	2.15	2.50	5.75	5.75	14.48	20.76	14.39	31.29	30.40
	23 %	27 %	19 %	37 %	22 %	47 %	56 %	54 %	54 %	58 %
(b) 1.23 - 2.54 m	3.35	3.75	7.40	6.23	15.68	10.59	14.55	8.20	18.75	12.11
	38 %	46 %	55 %	41 %	61 %	35 %	39 %	31 %	32 %	23 %
(c) 0.62 - 1.22 m	1.60	1.58	3.55	2.08	3.71	3.40	1.66	3.05	8.13	5.33
	18 %	19 %	26 %	13 %	15 %	11 %	4 %	12 %	14 %	10 %
(d) 0 - 0.61 m	1.90	0.66	0	1.33	0.55	2.25	0.25	0.80	0	0.50
	21 %	8 %	0 %	9 %	2 %	7 %	1 %	3 %	0 %	1 %
Total (Optical)	8.90	8.14	13.45	15.39	25.69	30.72	37.22	26.44*	58.17	52.24#

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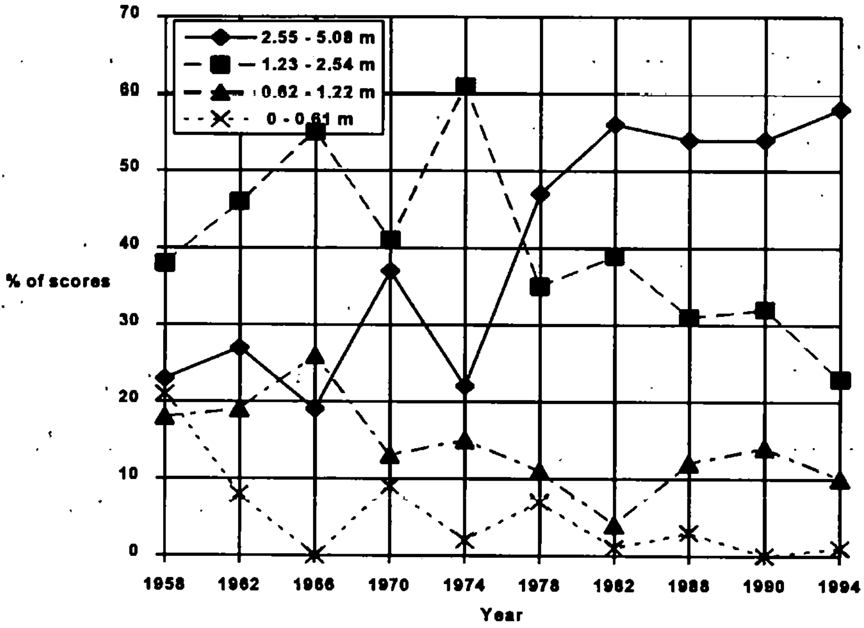
* Lower than 1978 and 1982 because there was a much lower number of Ground IR papers selected in 1986

\# Includes 3.90 (8 %) for one telescope of diameter greater than 5.08 m, i.e. the 9.8 m Keck

FIGURE 3 A

The percentage of scores for optical telescopes in various size categories as a function of time. The lines for each of the four categories are plotted separately in Figure 3B (next page).



(2) The period from 1958 to 1994 saw a sharp increase in the usefulness of the largest telescopes (category (a))*, accompanied by a decline in the relative usefulness of all other categories, so that by 1994 the relative usefulness figures were (from Table 10):-

9.8 m Keck	8 %
2.55 - 5.08 m	58 %
1.23 - 2.54 m	23 %
0.62 - 1.22 m	10 %
≤ 0.61 m	1 %

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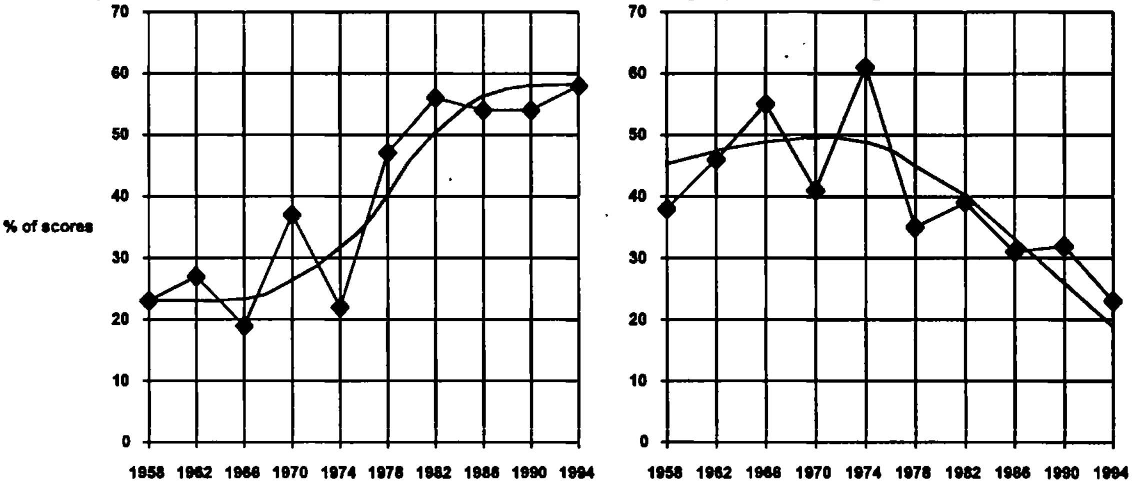
* Abt suggests[13] that the main reason for this was that in the early period (1958 - mid 70s) research work was concentrated on stars and relatively little work was done on galaxies, and for stellar work in those days (b)-size telescopes were almost as effective as the larger (a)-size. Later, however, with the advent of CCDs and modern two-dimensional detectors, the emphasis shifted to galaxies, for which the larger telescope apertures were required. Abt says that the percentage of stellar to extragalactic papers in *ApJ* changed from 50% to 6%, respectively, in 1954, to 33% to 42% in 1994.

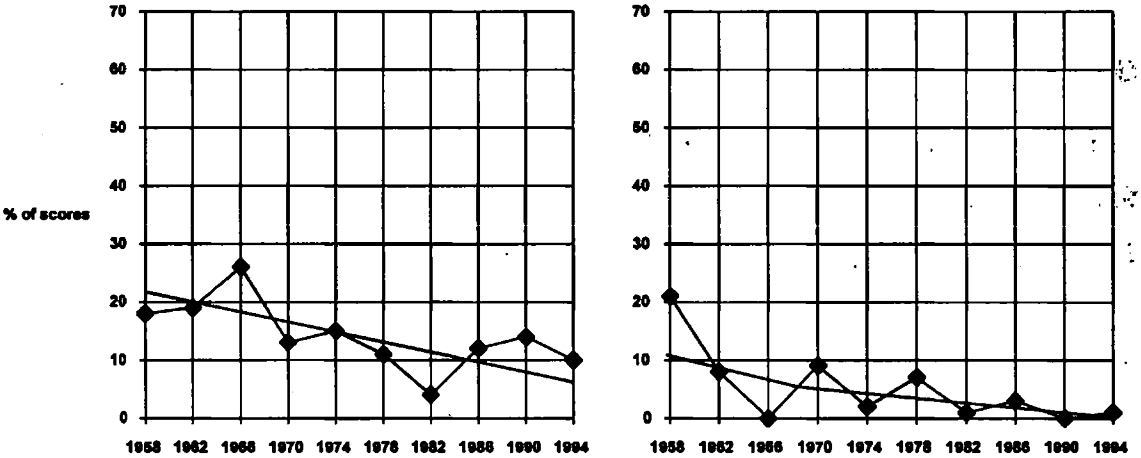
FIGURE 3 B

The percentage of scores for optical telescopes in various size categories as a function of time showing the general trends.



Category (a) Telescopes i.e. 2.55 - 5.08 m :-

Category (b) Telescopes i.e. 1.23 - 2.54 m :-



Category (c) Telescopes i.e. 0.62 - 1.22 m :-

Category (d) Telescopes i.e. 0 - 0.61 m :-

So optical telescopes of ≤ 0.61 m (24") diameter were used for very little leading-edge research by 1994, and about 90 % of the key optical results in that year were produced with telescopes of more than 1.22 m (48") diameter. That is not to say that small telescopes can be dispensed with, however, as they do have a rôle to play in astronomy, enabling novae and supernovae to be found, for example, which are then examined in more detail with larger telescopes. How many such small telescopes is required is another matter, however.

It seems likely that, as a number of new telescopes in the 5.09 - 10.00 metre class come on-line over the next decade or so, the curve for the 2.55 - 5.08 m class of telescopes will start to fall in the same way as that did for the 1.23 -2.54 m class 25 years ago.

It is interesting to speculate as to why the largest telescopes have been so successful, in spite of their relatively small number and the fact that they have to operate through the atmosphere which, until the recent advent of adaptive optics, severely limited their spatial resolution. Is it because they attract the best astronomers, or because they have the best instrumentation, are situated in the best locations, can observe the faintest galaxies, or have the best spectral resolution? Whatever the reason, the trends are clear in Figure 3.

Interestingly, Abt[1] showed that the number of observers (or teams) using the six largest telescopes available at the Kitt Peak National Observatory in the late 1960s increased approximately with aperture. Whether this was because there was more competition for the larger telescopes, and hence their observing time was at a premium, or because the larger telescopes could carry out their observations in a shorter time was not clear. The type of observations for which the various telescopes were used would clearly also be a factor, but an investigation into these various factors is beyond the scope of this present study.

Table 11A (next page) presents the cumulative scores for ground-based optical/infrared telescopes for the whole of the period 1958 – 1994, showing that the Hale telescope has been clearly the most successful optical/infrared telescope over the whole period. This is hardly surprising as it was by far the largest telescope available in 1958. The largest telescope of today, the Keck I, started to show in the results for 1994, but it has been operational for far too short a period (only becoming

TABLE 11
The Most Useful Optical and Infrared Telescopes*

(A) Cumulative performance over the whole period 1958 - 1994

Diameter (in metres)	Year of first use	Name	Cumulative Score** 1958 - 1994
5.08	1948	Hale (Palomar)	27.6
3.89	1975	Anglo-Australian Telescope	18.8
3.05	1959	Shane (Lick)	18.0
2.14	1964	Kitt Peak National Observatory	14.7
3.81	1973	Mayall, KPNO	12.9
4.00	1975	Cerro Tololo Inter-American Obs.	11.8
1.26	1948	Palomar Schmidt	9.5
2.54	1917#	Hooker (Mt Wilson)	9.2
3.80	1979	UK Infrared Telescope	8.5
2.54	1976	Irénée du Pont Telescope	8.0
2.72	1969	Mc Donald Obs, Univ. of Texas	7.0
2.08	1939	Struve, Mc Donald Obs.	6.7
3.58	1979	Canada-France-Hawaii Telescope	6.6
4.20	1987##	William Herschel Telescope	6.4
2.24	1970	University of Hawaii	6.4
4.50	1979	Multi-Mirror Telescope	5.2
1.52	1968	Cerro Tololo Inter-American Obs.	5.2
1.52	1908	Mt Wilson 60 inch	5.1
9.82	1991##	Keck I	3.9
1.27	1969	Kitt Peak National Observatory	3.8
2.54	1984	Isaac Newton Telescope	3.8
1.24	1973	UK Schmidt	3.6
1.52	1970	Whipple Obs., Mt Hopkins	3.3
0.91	1879	Crossley, Lick Obs.	3.2
2.26	1969	Steward Obs., Univ. of Arizona	3.1

Note (i) Minimum qualification for the above Table is cumulative score ≥ 3.00.

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* The large Russian and ESO telescopes do not figure in this table as it is based on papers published in *ApJ* and *MNRAS*, and most of their results are published in other journals. Likewise the results of solar telescopes are published in other specialist journals and so do not figure in the above either.

** For average scores, taking into account the period of operation of the telescopes, see Table 11B.

Decommissioned 1985

##These are the only telescopes to appear in the above list that have been commissioned after 1985. Their scores are remarkably good, considering their limited life so far.

TABLE 11 (cont.)
The Most Useful Optical and Infrared Telescopes

(B) The best average scores

Diameter (in metres)	Year of first use	Name	Average Score	Cumulative Score
		(a) 1958 - 1974		
5.08	1948	Hale (Palomar)	2.04	10.2
3.05	1959	Shane (Lick)	2.00	8.0
2.54	1917	Hooker (Mt Wilson)	1.59	8.0
1.52	1968	Cerro Tololo	1.52	3.0
2.14	1964	Kitt Peak	1.42	4.3
2.08	1939	Struve (Mc Donald Obs.)	1.02	5.1
		(b) 1978 - 1994		
3.89	1975	Anglo-Australian Telescope	3.77	18.8
5.08	1948	Hale (Palomar)	3.49	17.4
4.20	1987	William Herschel Telescope	3.21	6.4
3.81	1973	Mayall, KPNO	2.59	12.9
4.00	1975	Cerro Tololo	2.36	11.8
3.80	1979	UK Infrared Telescope	2.12	8.5
2.14	1964	Kitt Peak	2.08	10.4
3.05	1959	Shane (Lick)	2.00	10.0
3.58	1979	Canada-France-Hawaii Telescope	1.65	6.6
2.54	1976	Irénée du Pont Telescope	1.61	8.0
2.72	1969	Mc Donald Obs.	1.40	7.0
4.50	1979	Multi-Mirror Telescope	1.31	5.2
2.54	1984	Isaac Newton Telescope	1.28	3.8
1.26	1948	Palomar Schmidt	1.20	6.0
2.24	1970	University of Hawaii	1.03	5.2

Notes (i) Minimum qualifications for each of the above Tables B, average score ≥ 1.0, cumulative score ≥ 3.0 and at least two data points (i.e. data for 1958 and 1962, or 1962 and 1966, etc.)

(ii) The lines above separate telescopes into groups, such that the telescope at the top of each group is at least 80 % certain to have a better average score than the telescope at the top of the group immediately below (using the Student's t-test).

operational in 1991) to have yet made a major contribution. Unfortunately, the simple presentation of cumulative scores for each telescope over the period from 1958 - 1994 favours those telescopes, like the Hale, that have been operational for the whole of that period, against those telescopes that have been operational for only part of the period.

Another measure of the usefulness of a telescope could be its *average* score over the years that it has been operational. Such average scores for the whole period 1958 - 1994, however, may favour those telescopes that have been operational only in more recent years, when there are far more astronomers and far more papers published than 20 to 30 years ago* , thus possibly making it easier to get a higher average score. So, I have in Table 11B (previous page) adopted a compromise approach of dividing the period 1958 - 1994 into two halves, and listing the telescopes by average** score in each of those two halves.

The lines in Table 11B divide the telescopes into groups. The average score of each telescope within any group is not significantly different from any other telescope in the same group, whilst the telescope at the top of each group is at least 80 % certain to have a better average score than the telescope at the top of the group immediately

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* Between 1960 and 1990, for example[14,15], the number of papers published in*ApJ* increased by a factor of 9, and the number of American astronomers increased by a factor of 5.

** This average score is the total score (for either of the two periods) for a telescope divided by the number of data points (at 4-yearly intervals) in which published results are expected. This assumes that the first significant published results will appear *two years* after the first year of use of a telescope, which allows time for commissioning the telescope and equipment, analysing the data, writing a paper and getting it published. If that year of first expected publication coincides with one of my 4-yearly data points and no score is recorded, then a zero is included in the statistics from which the average score is produced.

TABLE 12

Telescopes in the 4.50 - 3.80 ("4 metre") metre range

Diameter (in metres)	Year of first use	Name	Average Score	Cumulative Score 1978 - 1994
3.89	1975	Anglo-Australian Telescope	3.77	18.8
4.20	1987	William Herschel Telescope	3.21	6.4
3.81	1973	KPNO (Mayall)	2.59	12.9
4.00	1975	CTIO	2.36	11.8
3.80	1979	UK Infrared Telescope	2.12	8.5
4.50	1979	Multi-Mirror Telescope	1.31	5.2

below it. Clearly the borders of each group are not hard-and-fast, as the telescopes at the bottom of one group are not significantly better than those at the top of the one immediately beneath, but, nevertheless, the lines give some idea of which telescope results are significantly different and which are not.

The results for the two largest telescopes, the Keck and the Hale have been discussed above, but what of the telescopes just below the Hale in the 3.80 - 4.50 ("4 metre") range? They have achieved the results shown in Table 12 above, where both the average scores and the cumulative scores for 1978 – 1994 are shown.

The Multi-Mirror Telescope (MMT) scores very poorly on an average score basis, and the Student's t-test shows that it is 95% certain that the Anglo-Australian Telescope, for example, had a better average score than the MMT over the years 1982 - 1994 (for observations made 1980 - 1992). It is, therefore, not surprising that the MMT is currently having its six mirrors replaced by one large one because the telescope has not been as useful as expected.

The correlation between my results for the Hale telescope and the MMT with their known performance (good in one case, and not so good in the other) clearly indicates that some useful conclusions can be made at telescope level from the above data, provided the results cover quite a number of years. The results for any particular telescope or spacecraft are so variable from one year to another, however, that it would be wrong to draw any conclusions on the usefulness of any telescope or spacecraft on the basis of one year's results.

Of the telescopes in Table 12, it is too early to draw any firm conclusions on the usefulness of the William Herschel Telescope, as its average score is the average of only two points, although it is undoubtedly producing good leading-edge results. Of the *other* telescopes in that table, the Anglo-Australian Telescope seems, at the 80% confidence level, to be the best performer, with the KPNO (Mayall), CTIO and the UK Infrared (UKIRT) all performing at about the same level as each other.

(i) Comparisons Between my Data and other Published Data

Abt[4] analysed papers produced using data from the four largest American optical telescopes that had become operational a number of years prior to 1980. He analysed the papers published in *ApJ* and *AJ* in 1980 and 1981, and their citations in papers published in 1982, 1983 and 1984. Ten years later, in 1995 Trimble[5] updated and extended Abt's analysis by examining papers published in *ApJ*, *AJ* and *PASP* between January 1990 and June 1991, inclusive, that were cited in 1993. In order to get a reasonable amount of data for these telescopes, to compare them with the results of the Abt/Trimble analysis, I have had to average my scores over the period 1982–1994*. These results are compared with those of Abt and Trimble in Table 13 (next page).

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* This seemed reasonable as there was no clear trend in my effectiveness results with time for any of the telescopes in Table 13 over this period.

TABLE 13

The four large telescopes available in 1980

		My Av. Score 1982 - 1994	% of Papers Abt[4] 1980-81	% of Papers Trimble[5] 1990-91	% of Citations Abt[4] 1982-84	% of Citations Trimble[5] 1993
4 m	CTIO	2.95	33	31	29	34
4 m	KPNO (Mayall)	2.69	24	22	27	24
5 m	Palomar (Hale)	2.51	20	27	20	22
3 m	Lick (Shane)	2.02	22	20	23	20

Abt's and Trimble's data for both percentage of papers and citations give the order CTIO, KPNO, and Lick, and my data agrees with that. The position of the 5m Palomar varies, however, between last in Abt's data to second (in papers) and third (in citations) in Trimble's data. My data shows it in third position. The consistency between my results and those of Trimble and Abt is somewhat surprising considering that the years surveyed and journals used in the Abt/Trimble studies were different from those used in my study*. In addition the only statistically significant difference in my study was between the CTIO and Lick in Table 13, the CTIO, KPNO and Palomar scores all being the same, within error.

Trimble went further than Abt by extending her analysis to include all of the telescopes of greater than 2.0m diameter referred to in the 1990-91 papers that she analysed. Because Trimble only used American journals, however, the results for non-American telescopes were unrepresentative (as she acknowledged). In Figure 4 (next page), therefore, I have plotted Trimble's number of citations for each telescope against my average score per telescope for 1982–1994 for all of the American telescopes** in her survey. The correlation coefficient of 0.88 for this comparison of

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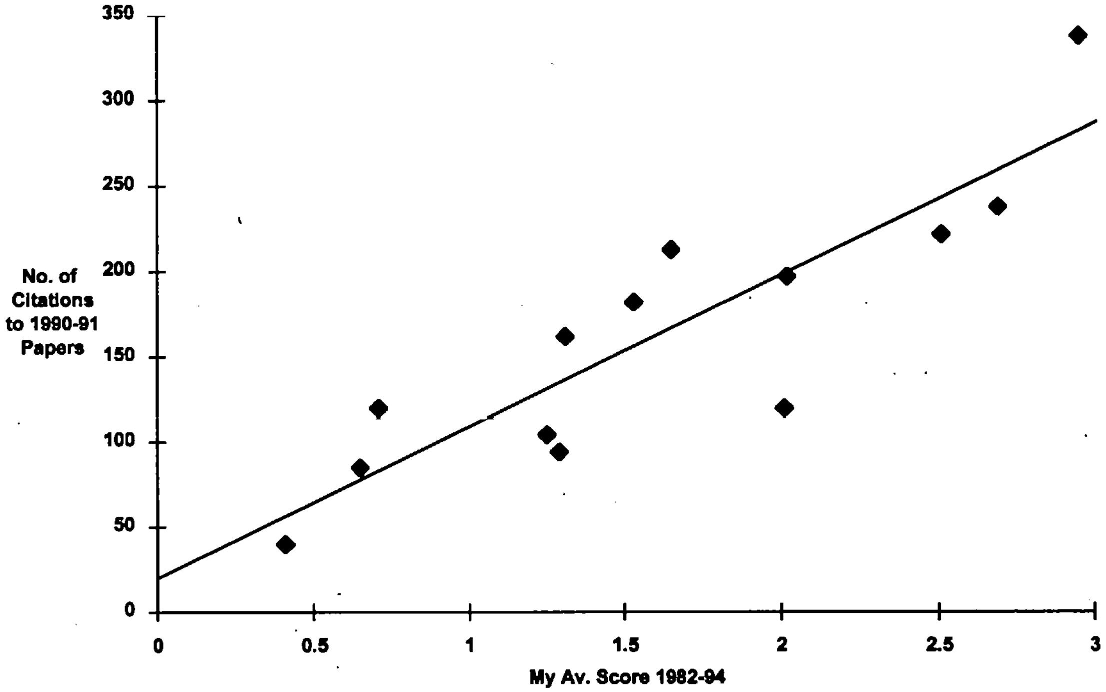
* Although *ApJ* was one of the journals used in both the Abt/Trimble and my own studies, and the number of papers published by *ApJ* is by far the largest of the journals considered.

** Including the CFHT that is only partly American, of course.

FIGURE 4

Number of citations to 1990-91 papers (from Trimble[5]) plotted against my average scores for 1982-94 papers for American telescopes of >2.0 m diameter. Each point represents a different telescope. The correlation coefficient is 0.88, indicating a good correlation between Trimble's citation numbers and my average scores over the periods indicated.



average score v citation number shown in Figure 4 compares with one of 0.82 for a comparison of average score v number of papers. This coefficient of 0.88 is very high considering that Trimble and I used both different journals and different years, and she used total citation numbers whereas I used the 15% most cited papers.

Table 14 (next page) shows the order of telescopes according to my average scores for 1982–1994 and Trimble's citation numbers. The lines indicate where significant differences occur in my average scores*. The resultant grouping into groups of three or four telescopes is consistent with the maximum difference in position noted between Trimble's and my list of three places (for the Irénée du Pont Telescope). In

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* i.e. the average scores for the CTIO 4m, the KPNO 4m and Palomar telescopes are all the same, within error, whereas that for the CTIO 4m is significantly higher than that for the Lick 3.1m.

TABLE 14

A comparison of the order of telescopes using my average scores from 1982 to 1994 and Trimble's[5] citation numbers for papers published in 1990 & 1991

	Order of Telescopes		
	Using my Av. Score	Using Trimble's citation numbers	Difference in order
CTIO 4m	1	1	0
KPNO 4m	2	2	0
Palomar	3	3	0
Lick 3.1m	4	5	-1
Irénée du Pont	5	8	-3
CFHT	6	4	+2
KPNO 2.1m	7	6	+1
MMT	8	7	+1
Univ. of Hawaii	9	11	-2
McDonald 2.7m	10	10	0
IRTF	11	9	+2
Steward	12	12	0
McDonald 2.1m	13	13	0

fact this level of difference would be expected statistically even if Trimble and I had used the same journals and same years, because my data does not allow me to put the telescopes into smaller groups.

In 1996 Martin and Sinclair[16] plotted the number of papers published per year for ground-based optical/IR telescopes in which the UK have a financial interest, effectively complementing the Trimble analysis. In Figure 5 (next page) I have compared the average number of such papers published in 1986, 1990 and 1994, as recorded by Martin and Sinclair, against my average score for the same telescopes for the first half of the same years*. The agreement is very good, with the exception of the point for the UK Schmidt Telescope (UKST) where the number of papers recorded by Martin and Sinclair is much higher than expected using my data.

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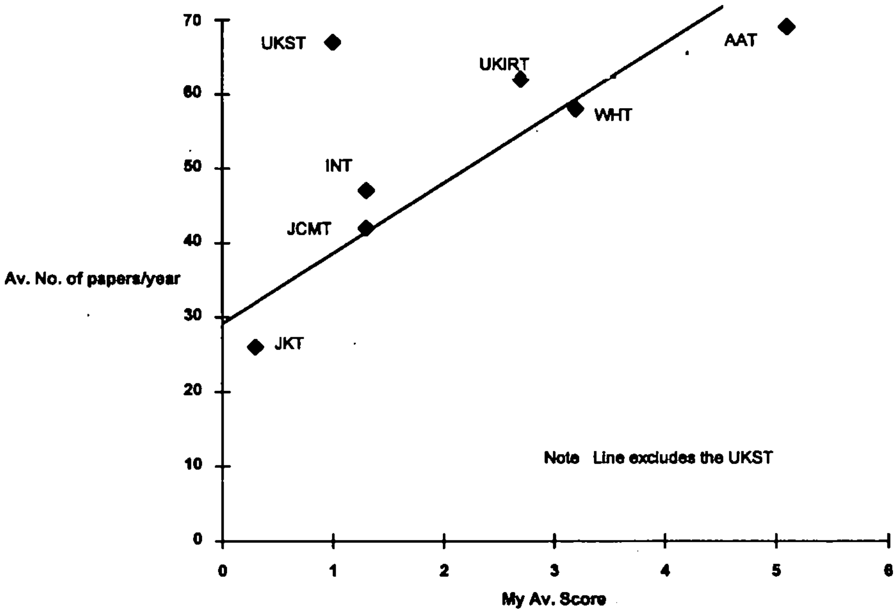
* The JCMT and WHT data is for only 1990 and 1994 in Figure 5, however, as they came on line after 1986.

In the same paper Martin and Sinclair listed those papers that appeared in the 100 most-cited papers each year from 1990 to 1995, inclusive, that had used data from the same telescopes. In Figure 6 (next page) I have redrawn the graph of Figure 5 with the total number of such highly-cited papers over the period 1990-95 as the ordinate*. The point for the UK Schmidt Telescope is no longer anomalous, thus indicating that the UK Schmidt is unique in the telescopes shown in Figures 5 and 6 in having a lower proportion of its papers in the highly-cited category. This is so, whether one uses the 100 most highly cited papers per year from Martin and Sinclair, or the 15% most-cited papers in my analysis.

FIGURE 5

The average number of papers, for 1986, 1990 and 1994, produced using various optical/IR telescopes in which the UK have a financial interest (from Martin and Sinclair[16]), plotted against my average scores for the same telescopes for the same years. Each point represents a different telescope. The JCMT and WHT data relates to 1990 and 1994 only, as they saw first light after 1986. The line is the least-squares line through all the points excluding the UKST (UK Schmidt Telescope) which appears to have too high a number of papers based on my average score.



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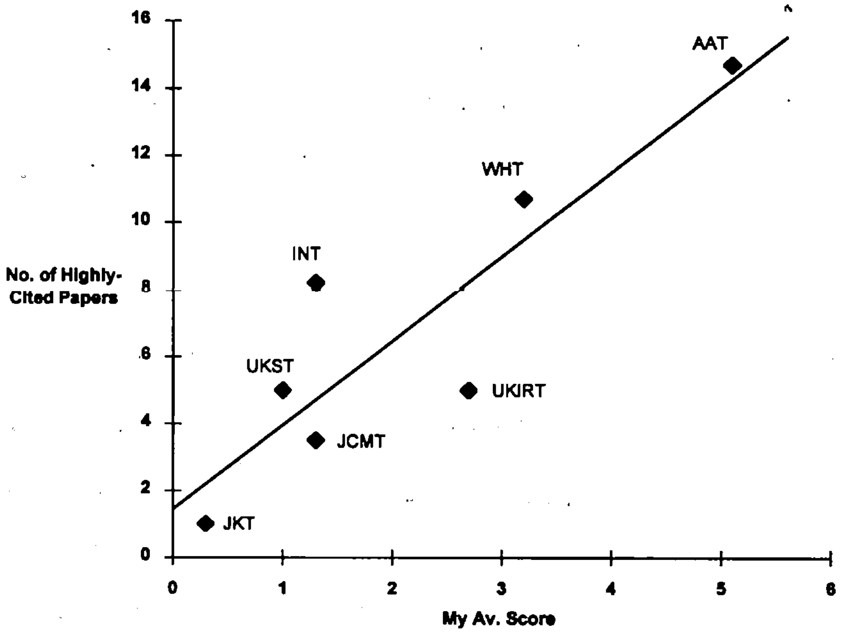
* In the absence of any other information in the Martin and Sinclair paper, I divided the paper score of unity equally between telescopes, when more than one telescope was used to produce data for any one paper.

FIGURE 6

The number of papers in the 100 most cited papers each year totalled over 1990-95, produced using various optical/IR telescopes in which the UK have a financial interest (from Martin and Sinclair[16]), versus my average scores for the same telescopes for the years 1986, 90 and 94. Each point represents a different telescope. As in Figure 5, my JCMT and WHT data relates to 1990 and 1994 only. The line is the least-squares line. The point for the UKST (UK Schmidt Telescope) is no longer anomalous.



The correlation coefficient for the data of Figure 6 is 0.89*, which is very high considering that the data on the two axes relates to different journals and different years**, and Martin and Sinclair's data is for the 100 most-cited papers (i.e. about the top 6%) and mine is for the 15% most cited.

These comparisons between my data and Trimble's, and my data and Martin and Sinclair's, both show a reasonable correlation (with coefficients of 0.82 and 0.70, respectively) when using their paper scores, but the correlation (with coefficients of

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* The correlation coefficient for the data of Figure 5 is 0.70.

** It might appear, at first sight, to have been better to limit both Martin and Sinclair's and my data in Figure 6 to the two years that they have in common, namely 1990 and 1994. Unfortunately, the number of papers per year in both databases is so small as to make this impracticable.

0.88 and 0.89) is very good when using their citation data, even though many of the details of their and my analyses differ.

Finally (in these comparisons between my results and other published results), in 1983 Irvine and Martin[3] published a comparison between the performance of the CTIO 1.5m, KPNO 2.1m, Lick 3m and INT 2.5m telescopes over the period 1969-1978*. In this paper they used three measurements of performance, namely numbers of published papers, numbers of citations to these papers, and assessment by peer review. Their data is compared with mine in Table 15A (next page) for the first two of these criteria.

The correlation coefficients between Irvine and Martin's data and mine were 0.89 when using their numbers of published papers, and 0.96 when using their citation numbers. This higher correlation when comparing my data with citation numbers, rather than with numbers of papers, is the same as that observed with the Trimble and Martin and Sinclair data above. As my data refers to the 15% most-cited papers, this is not too surprising. Although, as pointed out above, my analysis differs from each of these published analyses in many details. What is encouraging, however, is the magnitude of the correlations, showing that, although my data is relatively sparse at individual telescope level per half year, it is reasonably reliable at telescope level when three or four half-year's worth of data are combined.

Irvine and Martin also asked a total of about 50 astronomers from KPNO, Lick and the RGO to rank the scientific contribution of twelve optical observatories (including their own) over the period from 1969 to 1978, giving a score of 1 to the best and 12

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* Martin and Irvine[2] undertook a similar review of radio telescopes, but of the four telescopes they compared, only two were in my geographical area. So I cannot usefully compare that analysis with mine.

TABLE 15

A comparison between my results and Irvine and Martin's[3] for four medium-sized optical telescopes

(A) Irvine and Martin's data on published papers and citations

Telescopes	My Total Scores 1970/74/78	Irvine and Martin's Data: Total no. of papers published 1969-78	Irvine and Martin's Data: Total no. of citations to papers published since 1969
Lick 3m	9.4	422	1460
KPNO 2.1m	8.5	434	1200
CTIO 1.5m	3.0	354	880
INT 2.5m	0	71	190

(B) Irvine and Martin's data on peer review scores

Observatories	My Total Scores 1970/74/78/82	My Total Scores 1974/80/82	Irvine and Martin's peer group rankings*
KPNO	21.3	19.3	2.6
Lick	12.2	7.2	4.3
CTIO	8.1	8.1	4.6
RGO	1.0	1.0	11.0

to the worst observatories. It should be noted that Irvine and Martin's peer group found it difficult to distinguish between the performance of different telescopes at the same observatory, and so they presented their results at observatory level. The results for the KPNO, Lick, CTIO and RGO observatories, that were the subject of their paper, are compared with my total scores for the telescopes at these observatories in Table 15B.

Although the peer group were asked to judge the performance of observatories over the period 1969-78, they were more influenced by the performance of the observatories over the more recent of those years than the earlier years. This can be seen in Irvine and Martin's paper by the fact that the Anglo-Australian Observatory was place third out of twelve, even though the Anglo-Australian Telescope only saw

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* Low scores are best. Self-citation scores are excluded.

first light in 1975. I have extended my data in Table 15B to include 1982, in view of this near-year bias, and the fact that Irvine and Martin's paper was published in 1983, suggesting that the peer group were questioned sometime about 1981. The correlation between my total scores and the peer group rankings is good, being a little better for 1974-82 than for 1970-82, as one would expect if the peer group were somewhat biased towards more recent performances, as suggested above.

All these comparisons between my data and the published data of Abt[4], Trimble[5], Martin and Sinclair[16], and Irvine and Martin[3] are highly encouraging, showing a certain robustness in my data.

4.3.2 *Ground-Based Radio Telescopes*

The two most useful radio telescopes in terms of *cumulative* scores over the periods 1958-1994 and 1978-1994 were (see Table 16, next page) the VLA and the Arecibo dish. This is no surprise as the VLA was still (at the end of my period) the most comprehensive interferometric array located in any one place, and the Arecibo dish was still the largest dish antenna in the world, 20 years after its initial construction. Table 16B (b) indicates that a group of four other telescopes, led by the Five College Millimetre-Wave Observatory and IRAM, have now caught up with the Arecibo dish in producing important results.

4.3.3 *Spacecraft*

The three most useful spacecraft over the period 1958-1994 and 1978-1994 were (see Table 17 next page but one) the Einstein Observatory, IUE and Compton Gamma Ray Observatory which operated at X-ray, UV and γ-ray wavelengths, respectively. Both Rosat and the Hubble Space Telescope (HST), which came next, have only appeared in the 1994 figures, like the Compton Gamma Ray Observatory, as they

TABLE 16

The Most Useful Radio Telescopes

(A) Cumulative performance over the whole period 1958 - 1994

Diameter (in metres)	Year of first use	Name	Cumulative Score 1958 - 1994
—	1978/1981*	VLA	13.0
305	1963	Arecibo	9.4
14	1978	Five College Millimetre-Wave Obs.	7.8
7	1977	AT & T Bell Labs., Holmdel	6.5
11	1967	Kitt Peak	5.7
—	1980	MERLIN	5.0
10.4	1978	Caltech 'scope, Owens Valley	4.2
43	1966	Green Bank (NRAO)	4.0
30	1985	IRAM, Pico Veleta, Spain	3.8
92	1962	Green Bank Transit	3.8
64	1961	Parkes	3.8
1.2		Columbia Univ.	3.0

(B) The best average scores

(a) 1958 - 1974

No cumulative scores of ≥ 3.0

(b) 1978 - 1994

Diameter (in metres)	Year of first use	Name	Av. Score	Cum. Score
—	1978/1981	VLA	3.25	13.0
30	1985	IRAM, Pico Veleta, Spain	1.92	3.8
305	1963	Arecibo	1.88	9.4
7	1977	AT & T Bell Labs., Holmdel	1.63	6.5
14	1976	Five College Millimetre-Wave Obs.	1.57	7.8
—	1980	MERLIN	1.25	5.0
10.4	1978	Caltech 'scope, Owens Valley	1.06	4.2
1.2		Columbia Univ.	1.00	3.0

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* Partial service 1978, full service 1981.

TABLE 17
The Most Useful Spacecraft

Launch Date	Name	Cumulative Score 1958 – 1994	Wavelength
1978	Einstein Observatory	19.5	X-ray
1978	IUE	13.4	UV
1991	Compton Gamma Ray Observatory	11.0	γ-ray
1990	Rosat	10.1	X-ray
1990	Hubble Space Telescope	9.8	UV & Vis.
1983	IRAS	8.3	IR
1989	COBE	6.0	IR & μ-wave
1983	Exosat	5.9	X-ray
1974	Kuiper Airborne Observatory	5.5	IR
1987	Ginga	4.3	X-ray
1972	Copernicus	4.0	UV
1977	HEAO-1	3.8	X-ray
1973	Skylab	3.0	X-ray, UV & Vis.

Splitting the above period into two equal halves gives:-

(a) 1958 – 1974

No cumulative scores of ≥ 3.0

(b) 1978 – 1994

Launch Date	Name	Cumulative Score 1978 – 1994	Wavelength
1978	Einstein Observatory	19.5	X-ray
1978	IUE	13.4	UV
1991	Compton Gamma Ray Observatory	11.0	γ-ray
1990	Rosat	10.1	X-ray
1990	Hubble Space Telescope	9.8	UV & Vis.
1983	IRAS	8.3	IR
1989	COBE	6.0	IR & μ-wave
1983	Exosat	5.9	X-ray
1974	Kuiper Airborne Observatory	5.5	IR
1987	Ginga	4.3	X-ray
1977	HEAO-1	3.8	X-ray
1972	Copernicus	3.0	UV

were not launched until 1990. Rosat is continuing and improving the X-ray survey of the Einstein Observatory, but the HST is the first major optical spacecraft observatory. The first IR spacecraft on the list is IRAS, and the first microwave spacecraft is COBE.

Abt[6] analysed the observational papers in *ApJ* (excluding Supplements) in the first 1/3 of 1986, 1989 and 1994, and produced a list of 26 spacecraft that had appeared as the main sources of space data in those papers. His results are compared with mine in Table 18A for the most-frequently cited spacecraft, where my results are for the 15% most-cited papers in *ApJ* (including Supplements) and *MNRAS* in the first ½ of 1986, 1990 (not 1989) and 1994.

TABLE 18
The Most Frequently-Cited Spacecraft 1986 - 1994
My Data and Abt's compared

(A) Spacecraft Listed by Numbers of Papers
(numbers are numbers of papers)

Spacecraft	My Data	Spacecraft	Abt[6]
Einstein	11.8	IUE	37.8
Compton γ-ray Obs.	11	Einstein	26.5
Rosat	10.1	HST	20.5
HST	9.8	Rosat	19.8
IRAS	8.3	Exosat	18.0
IUE	8.1	Kuiper A'borne Obs.	16.0
COBE	6.0	IRAS	15.8
Exosat	5.9	Compton γ-ray Obs.	11.5

(B) Order of Spacecraft Compared
(numbers are order of spacecraft)

Spacecraft	My Data	Abt	Spacecraft	My Data	Abt
Einstein	1	2	IRAS	5	7
Compton	2	8	IUE	6	1
Rosat	3	4	COBE	7	10
HST	4	3	Exosat	8	5

The order of spacecraft in Abt's and my analyses is similar but by no means the same (see Table 18B). The first 5 of the 26 spacecraft in his list are covered by the first 8 spacecraft in mine, and vice versa, but IUE, in particular, does not show up nearly as well in my list as in his, and Compton does not show up nearly as well in his list as mine.

There is no reason, of course, why the two lists should be the same as Abt's data:-

(a) does not include the *MNRAS*.
(b) does not include the *ApJ Supplement*.
(c) is only for 1/3 of the year, not ½ of the year as in my data.
(d) is for all of the papers, not just the 15% most-highly cited.
(e) is for 1986, 1989 and 1994, not 1986, 1990 and 1994.

Abt made no claim that his list of spacecraft was in any way other than indicative, as he was trying, in Reference 6, to explain the sudden increase in the number of papers in the *ApJ Parts 1 and 2* (i.e. the main journal and letters), producing his list of spacecraft "for general interest" only.

(i) Spacecraft performance with time

The ground-based optical telescopes were listed in Table 11B by their average score. An average score is meaningful for data that shows little change with time, but for spacecraft, that generally have a lifetime of only a few years, the scores change quite noticeably from one four-year point to another. In that case, quoting the average score could be very misleading.

Consider the Einstein Observatory spacecraft, for example, that had the following scores (next page):-

1978	1982	1986	1990	1994	Average
Launch	7.66	6.00	5.50	0.33	4.88

If another spacecraft with exactly the same score profile were to have been launched in 1986, it would have had only two scores recorded, of 7.66 in 1990 and 6.00 in 1994, giving an average of 6.83. Clearly quoting the two spacecraft averages of 4.88 and 6.83 would give the misleading impression that the Einstein Observatory was the worse of the two spacecraft. If averages are misleading, is there another way of finding the most useful spacecraft?

One solution would be to list the spacecraft by their maximum score, but that ignores all the other results for the spacecraft. In addition, the peak could be missed, as the results are sampled for only one half-year in every four. The best compromise is probably to use averages, but to compare satellites with the same number of data points if at all possible, see Table 19 (next page).

Comparing the average scores for satellites that have the same number of data points, and using the largest number of data points possible for each satellite, gives the *tentative* order of merit shown in Table 20 (next page).

It is impossible to judge if figures are statistically significantly different from one another unless their standard deviation or a similar statistic is known. So no judgement can be made on whether the scores of the first four spacecraft in Table 20 are significantly different from one another. The Einstein and IUE spacecraft each have four sets of data, however, enabling a judgement to be made on whether their scores are significantly different.

Unfortunately, because the scores of spacecraft change rapidly with time, their standard deviations have both a time and error element. In order to minimise the

TABLE 19

Spacecraft Scores

Average of Score with Different Numbers of Data Points

4 data points*		**3 data points**		**2 data points**		**1 data point**	
Einstein	4.9	Einstein	6.4**	Einstein	6.8	Compton	11.0
IUE	3.4	IUE	3.2**	IUE	4.1	Rosat	10.1
HEAO-1	1.0	IRAS	2.8	IRAS	3.5	Hubble	9.8
Copernicus	1.0	Exosat	2.0	COBE	3.0	Einstein	7.7
		HEAO-1	1.3**	Exosat	3.0	IUE	5.3
		Copernicus	1.0**	Ginga	2.2	COBE	5.0
				HEAO-1	1.9	IRAS	4.0
				Copernicus	1.5	HEAO-1	3.8
						Exosat	3.0
						Ginga	2.5
						Copernicus	2.0

TABLE 20

Spacecraft - Tentative order of merit

No. of data points:-	**4**	**3**	**2**	**1**
Compton				11.0
Rosat				10.1
Hubble				9.8
Einstein	4.9	6.4	6.8	7.7
IUE	3.4	3.2	4.1	5.3
IRAS		2.8	3.5	4.0
COBE			3.0	5.0
Exosat		2.0	3.0	3.0
Ginga			2.2	2.5
HEAO-1	1.0	1.3	1.9	3.8
Copernicus	1.0	1.0	1.5	2.0

time element, I have taken the *difference* between each pair of results, and tested this difference using the Student's t-test to see if it is significantly different from zero. In the case of Einstein and IUE it is *not* significantly different at the 80% level. The

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* Average of the first 4 scores.

** Average of the first 3 scores.

FIGURE 7 A

Spacecraft scores plotted as a function of years after launch. The scores of each spacecraft increase relatively rapidly to a peak about 4 years after launch and then steadily declines.

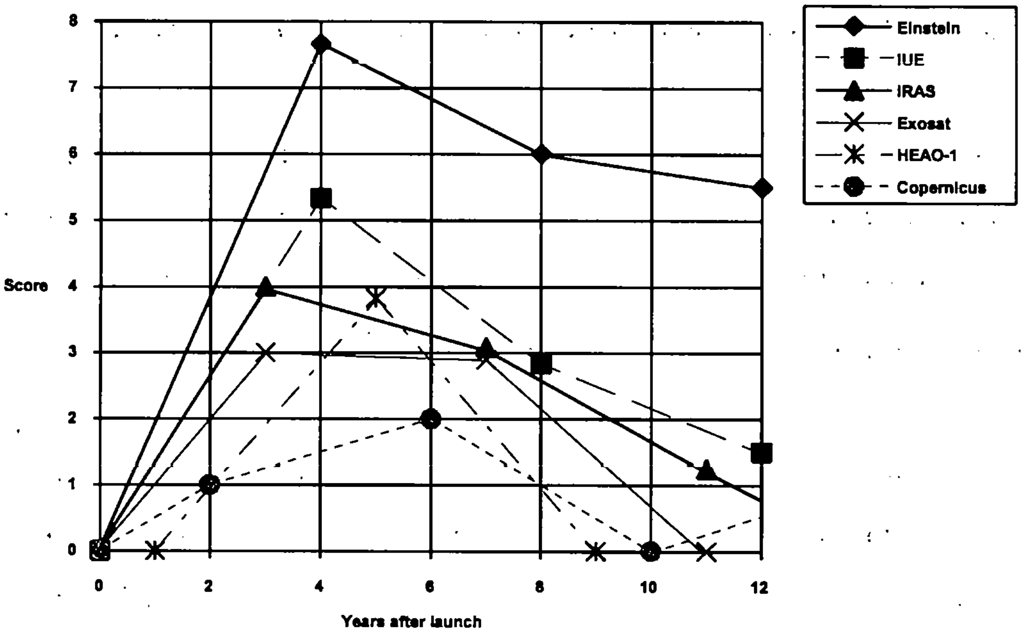
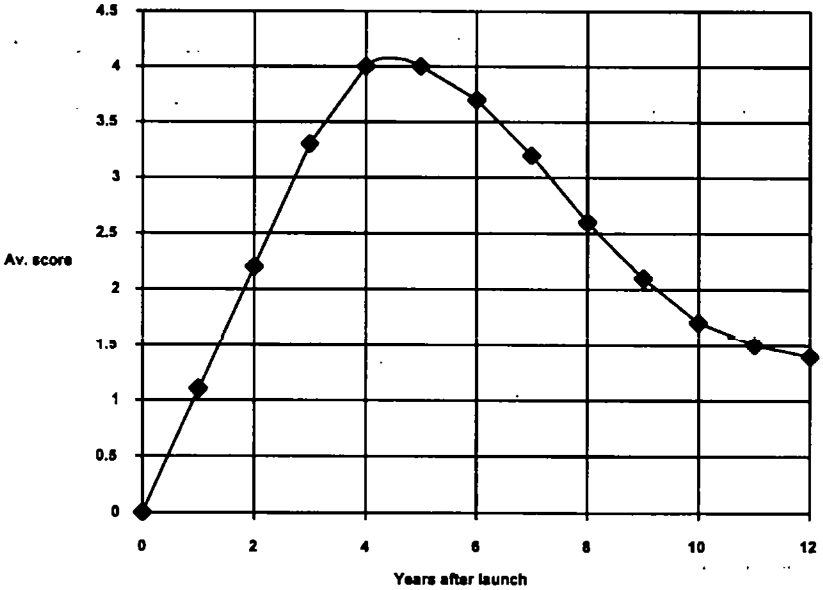


FIGURE 7 B

The average scores of the six spacecraft of Figure 7A plotted as a function of years after launch. The peak in this average score is about 4 or 5 years after launch.



Einstein results *are* significantly better than those of IRAS, however, and the IRAS results are significantly better than those of Exosat, hence the two horizontal lines in Table 20 separating the spacecraft into three groups. The spacecraft in any one of these groups have results that are not significantly different from each other.

There are six spacecraft in Table 19 that have at least three scores recorded, and these six spacecraft should allow a reasonable estimate to be made of the time when a spacecraft's score reaches a maximum. The time dependency of these scores for the six individual spacecraft is shown in Figure 7A (previous page).

Reading off the scores from Figure 7A for each spacecraft for each year, assuming the linear interpolations to be correct, and averaging the results so obtained for the six spacecraft, gives the curve shown in Figure 7B. This shows a maximum score at about 4 to 5 years after launch.

4.3.4 *Consolidated List of Ground and Space Observatories*

The consolidated list of the most useful ground and space observatories is given in Table 21 (next page) for the period 1958 - 1994 and for the two halves of this period, i.e. 1958 - 1974 and 1978 - 1994, in terms of their cumulative scores[*].

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[*] It is difficult to compare the usefulness of ground- and space-based observatories based on average scores, because the scores of spacecraft are very time dependent, peaking about 4 or 5 years after launch. So I have compared their cumulative scores instead.

TABLE 21
The Most Useful Astronomical Observational Facilities in terms of Cumulative Scores

The above Tables 11, 16 and 17 give the following number of ground telescopes or spacecraft with scores of at least 3.00:-

	1958-1994	1958-1974	1974-1994
Ground Optical, IR & Solar Telescopes	26	8	18
Ground Radio Telescopes	12	0	9
Spacecraft & Airborne Observatories	13	0	12

The top six telescopes or spacecraft were, in the above three time periods-:

1958 - 1994

Year of first use		Cumulative score		
1948	5.1m Hale Telescope	27.6	Ground Opt/IR	
1978	Einstein Observatory Spacecraft	19.5		Space
1975	3.9m Anglo-Australian Telescope	18.8	Ground Opt/IR	
1959	3.1m Shane (Lick) Telescope	18.0	Ground Opt/IR	
1964	2.1m Kitt Peak Telescope	14.7	Ground Opt/IR	
1978	IUE Spacecraft	13.4		Space

1958 - 1974

Year of first use		Cumulative score	
1948	5.1m Hale Telescope	10.2	Ground Opt/IR
1959	3.1m Shane (Lick) Telescope	8.0	Ditto
1917	2.5m Hooker (Mt Wilson) Telescope	8.0	Ditto
1939	2.1m Struve (Mc Donald Obs.) Telescope	5.1	Ditto
1908	1.5m Mt Wilson 60 inch Telescope	4.4	Ditto
1964	2.1m Kitt Peak Telescope	4.3	Ditto

TABLE 21 (cont.)

1978 - 1994

Year of first use		Cumulative score		
1978	Einstein Observatory Spacecraft	19.5		Space
1975	3.9m Anglo-Australian Telescope	18.8	Ground Opt/IR	
1948	5.1m Hale Telescope	17.4	Ground Opt/IR	
1978	IUE Spacecraft	13.4		Space
1978/1981	VLA	13.0	Ground Radio	
1973	3.8m Mayall Telescope, KPNO	12.9	Ground Opt/IR	

The key observatories in the period 1958 - 1974 were all ground-based optical observatories, but the major observatory in the period 1978 - 1994 was the Einstein Observatory Spacecraft. There was one other spacecraft (IUE) in the first 6 observatories in this second period, plus one radio telescope (the VLA), but there were still 3 ground-based optical/IR observatories in this first 6. If 1994 were to be representative of the future, however, spacecraft would be even more important, as the top three observatory scores in 1994 were for the Compton Gamma Ray Observatory, Rosat and the Hubble Space Telescope.

5 Conclusions

The above survey of the most highly-cited papers during the period 1958 - 1994 has shown quantitatively for the first time that:-

(1) There was a swing away from small, ground-based optical/infrared telescopes over the period 1958 - 1994 such that, by 1994, virtually no important results were being obtained from professional optical/infrared telescopes of 0.61 metres (24 inches) or less in diameter. Two-thirds of all important, ground-based, optical/infrared results were being produced in 1994 with telescopes in excess of 2.54 metres (100 inches) diameter.

(2) The 5 metre Hale telescope produced the most consistently good results of any ground- or space-based observatory over the period 1958 – 1994, although the Anglo-Australian Telescope matched it in the second half of that period.

(3) The Einstein Observatory Spacecraft produced the most consistently good results of any spacecraft over the period 1978 – 1994, closely followed by IUE.

(4) Significant* useful results were first obtained:-

- in 1962 using ground-based Radio Telescopes.
- in 1974 using ground-based IR Telescopes.
- in 1974 using Spacecraft (at all wavelengths).

but there has been no general increase in the relative usefulness of the ground-based Radio and IR observatories since 1962 and 1974, respectively. In 1994, however, there were, for the first time, more highly-cited papers based on spacecraft data than on that from ground-based optical observatories. This was the conclusion of a trend that started in 1970 when the first space-based paper entered the database (see Table 7).

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* In this context I take 'significant' to mean ≥ 10% of the total of highly-cited papers.

PART 2 COSTS

Summary

I have assessed the effectiveness of ground- and space-based astronomical observatories in Part 1, and in Part 2 I will establish their costs, prior to analysing their cost-effectiveness in Part 3. I treat ground-based optical/IR telescopes, ground-based radio telescopes and spacecraft separately. For each grouping I establish a list of observatories that have been available at sometime during my chosen period, the start and finish date of operations if they fall within that period, the capital costs of the facilities and their annual running costs.

In Part 1 above I identified a number of telescopes and spacecraft because they were mentioned in the papers that I analysed, but there were many more telescopes and spacecraft available than these. The task of establishing a catalogue of such facilities, together with the start and finish date of their operational period, was non-trivial, as there are no such catalogues available, except for those that list the largest facilities.

Because of the choice of journals that I analysed in Part 1, I limit myself in the remainder of this thesis to considering American and British Commonwealth ground-based telescopes, and American, ESA and British spacecraft. For the same reason, I exclude solar and solar system spacecraft. Even with these limitations, I identified 220 ground-based professional optical/IR telescopes of at least 0.61m diameter, 156 professional ground-based radio telescopes, and 27 observatory spacecraft.

Even though I consulted an extensive literature (see Appendix 1) to produce my list of available facilities, there is clearly a risk that I have not found all of the available telescopes. As far as optical/IR telescopes are concerned, I show in Section 2.1, however, that my number of such telescopes down to an aperture of 1.5m agrees with published figures. Nevertheless, the problem of a possible underestimate in the number of smaller telescopes is addressed, and the effect is included as an error in my analysis.

Having established a reasonably reliable list of available telescopes and spacecraft, I then establish their capital and annual running costs.

As far as ground-based optical/IR telescopes are concerned, I establish their capital costs by consulting the decennial reports of the National Academy of Sciences produced under the chairmanship of Whitford (1964), Greenstein (1972) and Field (1982), along with many other sources (see Table 25 footnotes). My analysis shows that the capital costs vary as the diameter to the power 2.4, in agreement with Abt's result for a much smaller number of telescopes (namely 7). In addition, my analysis shows that the capital costs of post-1980 telescopes with an aperture of greater than 2.3m are only about 40% of the capital costs of the earlier telescopes. This is due to a number of factors, including the introduction of:-

(a) active optics, which allows the use of much thinner and less-massive mirrors, which in turn simplifies the design of the telescope mount

(b) alt-azimuth mounts

(c) mirrors with a small f-number, which allow the construction of much smaller and simpler observatory buildings.

Interestingly, there was no such reduction in cost for post-1970 telescopes, compared with earlier telescopes, because there were no such radical changes in design over that period.

I follow this analysis of the capital costs of optical/IR telescopes with an analysis of their annual operations costs. Here my source of data was the National Science Foundation, which provided me with annual costs from 1955 for Kitt Peak and Cerro Tololo, which I supplemented with data from the Greenstein, Field, Bahcall and McCray reports. I also had access to PPARC cost files and numerous observatory annual reports. All this annual cost data needed extensive analysis to understand and rectify inconsistencies and omissions, and make sure that I was comparing like with like. This is described in detail in the main text of my thesis and in Appendices 4, 6 and 7.

Abt showed that the annual running costs of the optical telescopes at KPNO varied as the aperture to the power 2.1, and Irvine and Martin showed that this relationship also appeared to hold for telescopes between observatories, by analysing the annual costs of the CTIO, KPNO, Lick and RGO observatories for three years during the 1970's. My data confirm this relationship for a further six observatories, over dates ranging from 1974 to 1994. I also found that the annual costs of some, but not all, of the observatories were decreasing with time, even though their complement of telescopes had stayed essentially constant.

I continue my analysis in Part 2 in a similar vein to the above, with an analysis of the capital and annual costs of both ground-based radio telescopes and spacecraft. This shows, for example, that the annual running costs of radio observatories is approximately related to their total capital costs.

The total of the annual plus amortised capital costs over my chosen period was about \$6,200m* for spacecraft, about \$3,500m for ground-based optical/IR observatories, and about \$2,700m for ground-based radio observatories. By chance, the total costs for the ground-based observatories are exactly the same as that for spacecraft. Although the totals were the same, only 13% of the total cost of ground-based observatories were amortised capital costs, the remainder being annual costs, whereas 74% of the total spacecraft cost were amortised capital costs.

Interestingly, the initial capital cost of the HST (i.e. excluding the cost of in-orbit repairs and refurbishment) was about the same as the total capital costs of all the

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* All costs in this summary are in 1992 dollars.

ground-based optical/IR and radio telescopes that were in operation at some time during my period of 36 years.

An index of the Figures and Tables giving my main results is given in Table S4.

TABLE S4
Index of my main results

	See	Results
Optical/IR		
Cumulative number of telescopes as a function of aperture for 1956 and 1992	Figure 8	Linear relationship shown between log (cum. number) and log (aperture) for apertures below about 2m in 1956 and about 4m in 1992
Initial (capital) costs versus aperture for telescopes in use up to and including 1980	Figure 15	Approx. linear relationship shown between log (initial cost) and log (aperture), with a slope of 2.45
Initial costs versus aperture for telescopes in use for the first time (or under construction) from 1981 to 1996	Figure 16	Approx. linear relationship shown between log (initial cost) and log (aperture), with a slope of 2.33
Comparison of the best-fit lines of Figures 15 and 16	Figure 17	Initial costs of large telescopes that saw first light after 1980 are shown to be about 40% of those for earlier telescopes
Average annual operating costs for observatories compared with $\Sigma d^{2.1}$ for all their telescopes (where d is the diameter)	Table 33B	Abt's relationship of annual costs $\alpha\ d^{2.1}$ is found to be valid between observatories, confirming Irvine and Martin's earlier results for a smaller number of observatories
Radio		
Initial costs versus dish diameter for radio telescope dishes designed to operate at frequencies in the range from 1 to 15 GHz.	Figure 21	Approx. linear relationship shown between log (initial cost) and log (aperture), with a slope of 2.2
Comparison between the total annual operating costs of radio observatories and the product of their capital costs and operational years.	Table 48	Annual costs are shown to be about 14% (± 7%) of the capital costs of radio observatories

TABLE S4 (cont.)
Index of my main results

Spacecraft

Total programme costs per spacecraft programme	Table 60	The costs of the various spacecraft observatories vary from about $2,850m for the HST (up to 1992) down to about $28m for Explorer 11 (both at 1992 rates)

Total

Total of the annual and written-off capital costs for ground- and space-based observatories	Table 62	The total of the annual and written-off capital costs for ground-based observatories from 1956 to 1992 is about the same as that for space-based observatories. Whilst 87% of these costs for ground-based observatories are annual costs, the figure for space-based observatories is only 26%.

1 Introduction

The above analysis has only considered those ground- and space-based facilities that have been used to produce highly-cited papers in the periods and journals concerned. There are, of course, many more ground- and space-based observational facilities than these, and they also need to be considered when looking at the total observational resources that have been available to professional astronomers during the period under consideration.

In Part 1 I analysed papers published in the *ApJ* and *MNRAS* which were, inevitably, mainly based on observations made using American or British Commonwealth facilities. In the following analysis, therefore, I have restricted myself to facilities owned by institutions from these countries*, and have ignored papers produced using European (except for the UK), Japanese, Russian and South American observatories and spacecraft. So the numbers of papers are slightly reduced from those considered in Part 1 above.

2 Ground-Based Optical/Infrared Telescopes

2.1 Number of Telescopes Available

The American and British Commonwealth Optical/Infrared Telescopes available at sometime between 1956 and 1992 (i.e. two years before the beginning and end of our period) are listed in Appendix 1, Table A**. This listing stops at an aperture of 0.61m as it is impracticable to list the innumerable telescopes of smaller size.

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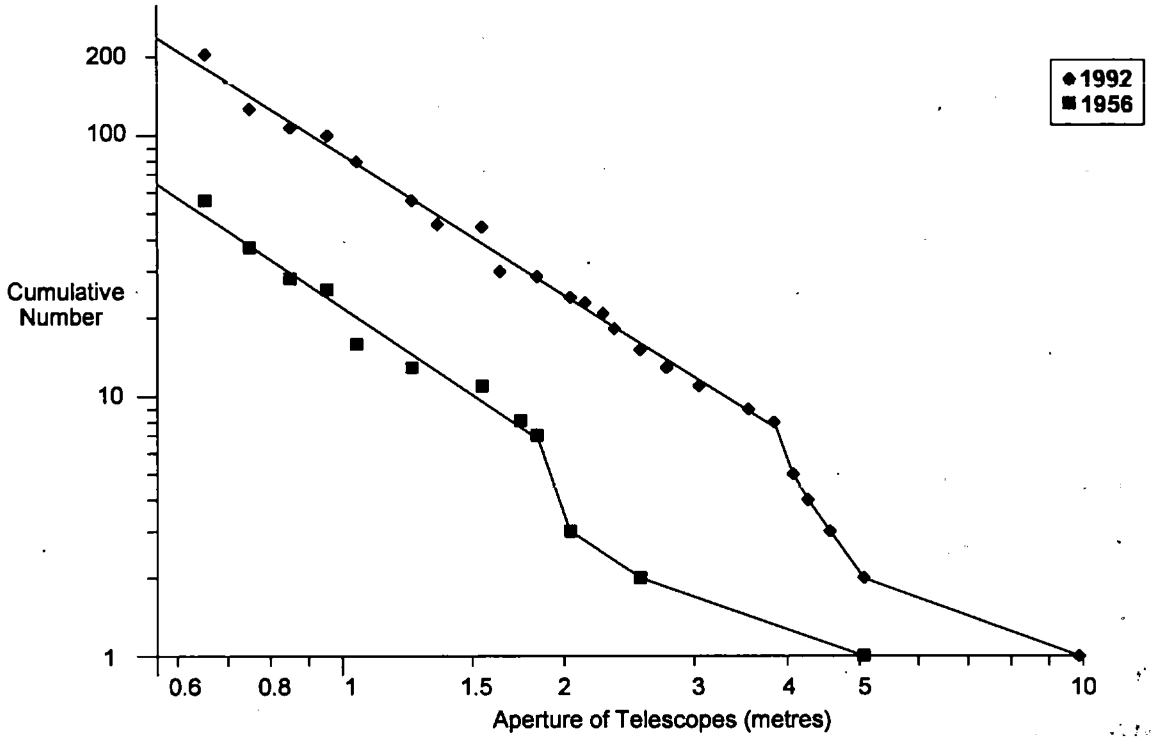
* I have also included Mexico and Israel because of their close links with the USA.

** Called Appendix 1A for simplicity.

FIGURE 8

The cumulative number of Optical/Infrared telescopes plotted as a function of aperture. Only USA and British Commonwealth telescopes are included. The linear part of the graph for 1956 and 1992 is parallel, within error.



The cumulative numbers* of telescopes available in 1956 and 1992, taken from Appendix 1A, are plotted on a logarithmic scale in Figure 8 against log (aperture). The relationship of log (cumulative number) to log (aperture) is basically linear for both years, if the largest telescopes are ignored. Interestingly, the slope of the linear part is the same, within error, for both 1956 and 1992.

It proved to be very difficult to compile the list of telescopes in Appendix 1A as can be seen from the extensive Bibliography that had to be consulted, and it is obviously questionable as to how many telescopes have been missed in my list. Telescopes of aperture of about 2.5 m and above are well-known, but the listing becomes more and more difficult as the aperture size decreases. Krisciunas[17] produced a graph similar to Figure 8 for Optical/Infrared Telescopes available *world-wide* in about 1986 which showed a total of 63 telescopes of aperture 1.5 m or more. My *world-wide* data, of

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* This is the cumulative number of telescopes with apertures of at least those shown on the horizontal axis of Figure 8.

which that in Appendix 1A is a sub-set, showed 65 telescopes of aperture 1.5 m or more available in 1986, giving confidence that my data is sensibly complete, at least down to this aperture in 1986.

The number of highly-cited papers produced using optical/infrared telescopes has increased over the period 1956 to 1992 (see Table 10) from about 9 to 52, and the number of telescopes available has also increased over the same period (see Figure 8). A key question is evidently "Has the number of papers increased at the same rate as the number of available telescopes?"

Table 10 showed, for example, that the number of highly-cited papers based on data from telescopes of aperture 2.55 - 5.08 m aperture (i.e. Category (a)) increased from 2.05 in 1958 to 30.40 in 1994, which is reduced to 28.40 when ESO telescopes are ignored. Over the period 1956 to 1992 the number of such telescopes available in American and British Commonwealth observatories has increased from 1 to 12 (see Appendix 1A), so the number of highly-cited papers per telescope is approximately the same for these two years being about 2.1 for 1958/56* and 2.4 for 1994/92. Data for different telescope sizes and years is given in Table 22 (next page), and the ratio of the number of papers Np to number of available telescopes N_t is plotted in Figure 9 against year for each telescope size category (see page 67).

Figure 9 shows that the ratio N_p/N_t has stayed effectively constant over the duration 1958 - 1994 for each of the size categories of telescopes considered.

The average number of telescopes in categories (c) and (d) appear to have increased very little since 1976 (see Table 22(a)), suggesting that I may have missed a number of these smaller telescopes that have become recently available (because their size no

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* The first-quoted year is the year when the papers were published, and the second year is the year when the telescopes were available.

TABLE 22

(Optical/IR, American & British Commonwealth Telescopes only)

(a) Number of telescopes available (N_t)

category ↓		1956	1960	1964	1968	1972	1976	1980	1984	1988	1992
(a)		1	2	2	2	3	6	10	10	11	12
(b)		12	12	15	21	28	31	34	35	38	38
(c)	min.*	27	35	44	57	70	80	83	84	89	94
	max.	37	45	54	67	79	86	89	89	94	94
	Average	32	40	49	62	74½	83	86	86½	91½	94
(d)	part.** min.	13	18	22	41	55	63	64	65	65	68
	max.	23	27	31	48	62	67	67	68	68	68
	Average	18	22½	26½	44½	58½	65	65½	66½	66½	68

(b) Number of highly-cited papers (Np)

category ↓	1958	1962	1966	1970	1974	1978	1982	1986	1990	1994
(a)	2.05	2.15	2.50	5.75	5.75	14.48	20.01	14.39	30.29	28.40
(b)	3.35	3.75	7.40	6.23	15.68	10.59	14.55	8.20	18.75	11.36
(c)	1.60	1.58	3.55	1.58	3.71	3.40	1.66	3.05	8.13	4.33
(d) part	0	0	0	1.33	0.25	1.50	0	0.30	0	0

(c) Ratio of Number of highly-cited papers (N_p) to Number of Available Telescopes (N_t)#

category ↓	1958	1962	1966	1970	1974	1978	1982	1986	1990	1994
(a)	2.1	1.1	1.3	2.9	1.9	2.4	2.0	1.4	2.8	2.4
(b)	0.27	0.31	0.49	0.30	0.56	0.34	0.43	0.23	0.49	0.30
(c)	0.050	0.040	0.072	0.025	0.050	0.041	0.019	0.035	0.089	0.046
(d) part	0	0	0	0.030	0.004	0.023	0	0.005	0	0

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[*] In Appendix 1 there are a number of telescopes for which the first year of use is not clear, shown, for example, as ≤ 1976. In such cases I can assume that the first year of use is that shown, in this case 1976, or the first year that I have analysed, i.e. 1956; the truth being generally somewhere between these two years. The min. figure in the above table assumes the later year (i.e. 1976 in my example), the max. figure assumes 1956.

[**] This refers to the fact that only telescopes of 0.61 m aperture are listed in Appendix 1, and the numbers of papers referred to elsewhere in this table are only those produced using telescopes of this aperture.

[#] Average numbers used for categories (c) and (d) part.

TABLE 22 (cont.)
(d) Average Statistics

Category	N_p/N_t Average	N_p/N_t σ_{n-1}
(a)	2.03	0.62
(b)	0.37	0.11
(c)	0.047	0.021
(d) part	0.006	0.011

longer warrants publicity). It seems a strange coincidence, however, that the lines for 1956 and 1992 in Figure 8 are parallel to each other, and that the ratios in Figure 9 have not changed with time, suggesting that if my numbers of smaller telescopes are too low in recent years the error may not be too large. Having said that, there is no reason why the two lines in Figure 8 should be parallel, and the points in Figure 9 are widely scattered, so even relatively large errors in numbers of telescopes could be disguised.

Table 23 shows the numbers of telescopes available at the beginning, middle and end of my period, taken from Table 22(a), and various ratios of these numbers.

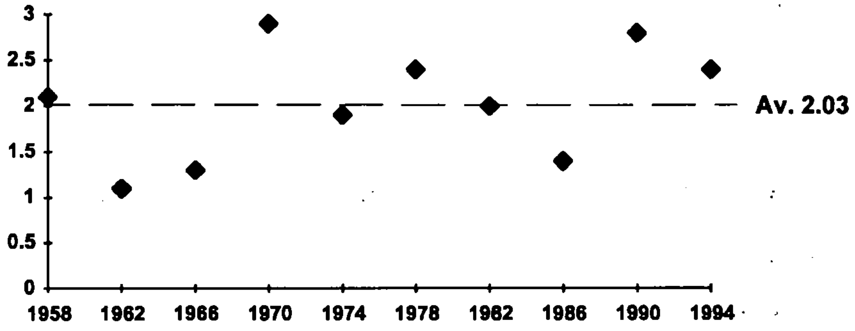
The number of available telescopes in category (a) is probably correct for the period 1956–1992, and the number of telescopes in the other categories is probably reasonably accurate for the period up to 1976. In that case, the main question mark in Table 23 is over the number of telescopes in 1992 for the categories (b), (c) and (d), and hence the ratio (iii)/(ii) for these categories.

TABLE 23
Numbers of Available Telescopes

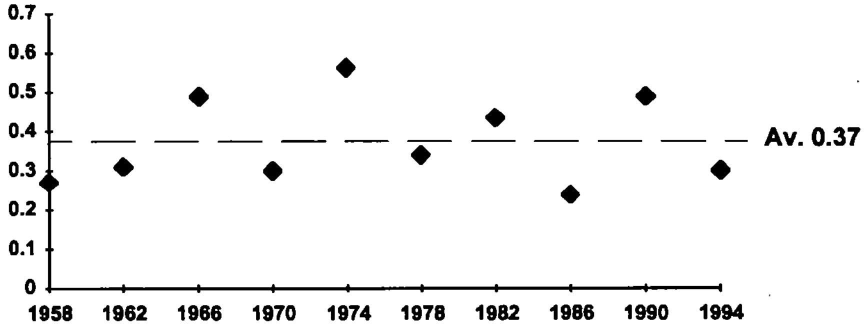
category	(i)	(ii)	(iii)	Ratios		(iii)/(ii)
↓	1956	1972/76	1992	(ii)/(i)	(iii)/(ii)	(ii)/(i)
(a)	1	4.5	12	4.50	2.66	0.59
(b)	12	29.5	38	2.46	1.29	0.52
(c) Average	32	78.8	94	2.46	1.19	0.48
(d) part Average	18	61.8	68	3.43	1.10	0.32

FIGURE 9

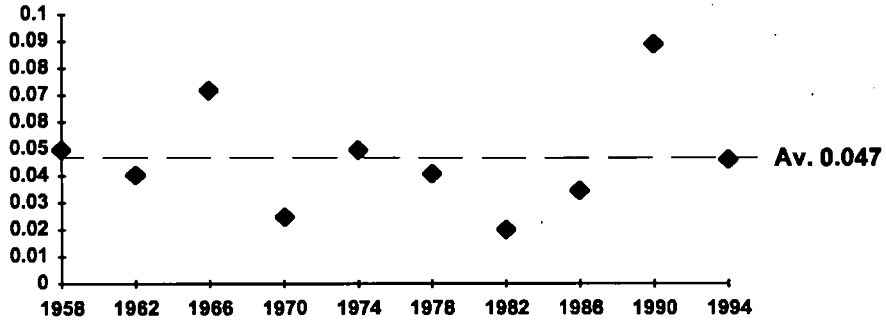
Graphs of the ratio of the number of highly-cited papers (N_p) to number of optical/infrared telescopes available (N_t) for United States and British Commonwealth observatories plotted against year. The ratio for each telescope size category (a) to (d) are basically constant with time.



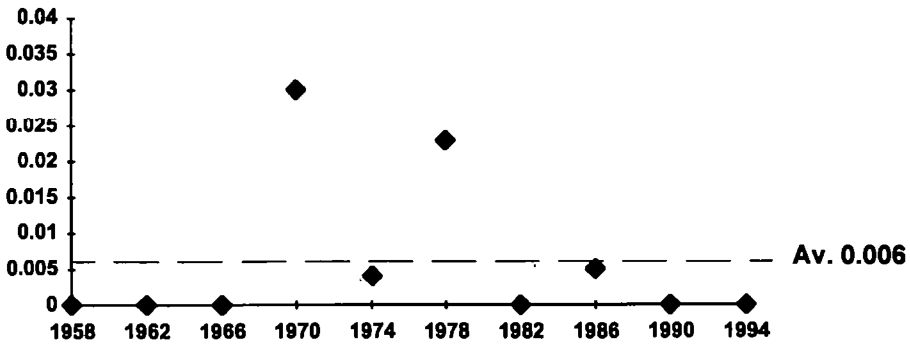
(a) 2.55 - 5.08 m



(b) 1.23 - 2.54 m



(c) 0.62 - 1.22 m



part cat. (d)
0.61 m

The rate of increase in the number of category (a) telescopes is 59% in the second half of the period 1956–1992, compared with the first half of this period (see Table 23). Assuming, *for illustration purposes only*, that this figure should be 59% for the other categories also (and not 52%, 48%, and 32%, see Table 23), and that the numbers of telescopes in 1956 and 1972/76 are correct, would give 43, 114 and 125 telescopes in categories (b), (c) and (d), respectively, in 1992, compared with my numbers of 38, 94 and 68. These new 'guesstimates' would have the effect of reducing the ratios of N_p/N_t by 12%, 18% and 46% respectively for 1994. Applying these 'correction factors' to the figures in Table 22(c) progressively from 1978 to 1994 would change the N_p/N_t averages of Table 22(d) as follows:-

Category	N_p/N_t Average
(b)	decrease from 0.37 to 0.36
(c)	decrease from 0.047 to 0.044
(d) part	no change, at 0.006

So these average ratios are insensitive to such possible underestimates in the number of the more recent, medium and small telescopes.

Looking at the average of N_p/N_t in Table 22(d), there is a suspicion that it may vary as the receiving area of the telescopes* and, to check this out, the receiving area was calculated for each of the available telescopes listed in Appendix 1A. The total areas A for all of the available telescopes in each size category are given in Table 24 over the period 1956 - 1992, together with the ratio of N_p/A (i.e. Number of papers to Total area of telescopes available in each size category).

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* I have ignored the obscuration by the secondary mirror in these calculations as the effect is small and similar in scale for all reflectors, at least when considered as a group.

TABLE 24

(a) Total receiving areas (in m^2) of all available Optical/IR telescopes in each size category

category ↓	1956	1960	1964	1968	1972	1976	1980	1984	1988	1992
(a)	20	27	27	27	34	69	114	114	127	133
(b)	30	30	37	51	68	76	86	90	100	100
(c) Average	18	22	28	38	46	52	54	54	57	64
(d) part Average	5	7	8	13	17	19	19	19	19	20

(b) Ratio of Number of papers to Total of telescope receiving areas, i.e. $N_p/A \times 10^{-2}$

category ↓	1958	1962	1966	1970	1974	1978	1982	1986	1990	1994
(a)	10.3	8.0	9.3	21.3	16.9	21.0	17.6	12.6	23.9	21.4
(b)	11.2	12.5	20.0	12.2	23.1	13.9	16.9	9.1	18.8	11.4
(c)	8.9	7.2	12.7	4.2	8.1	6.5	3.1	5.6	14.3	6.8
(d) part	0	0	0	10.2	1.5	7.9	0	1.6	0	0

(c) Average Statistics[*]

Category ↓	N_p/A Average	N_p/A σ_{n-1}	N_p/A Average	N_p/A σ_{n-1}	N_p/A Average	N_p/A σ_{n-1}
	1958-1994		1958-1974		1978-1994	
(a)	16.2	5.8	13.2	5.7	19.3	4.4
(b)	14.9	4.6	15.8	5.4	14.0	3.9
(c)	7.7	3.5	8.2	3.1	7.3	4.2
(d) part	2.1	3.7				

Table 24(c) shows that the ratio N_p/A is basically constant for each telescope size category over the period 1958 - 1994, except for category (a) where the ratio has increased from an average of 13.2, in the first half of the period, to 19.3 in the second half. The average ratios for telescope size categories (a) and (b) over the whole period 1958-1994 are basically the same as each other, but they are higher than for category (c) which, in turn, is higher than for category (d). If the cost of

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[*] All numbers in this Table are x 10^{-2}. The effect of a possible increase in the number of telescopes in categories (b), (c) and (d) to 43, 114 and 125 in 1992, as outlined above, would be to reduce the Average N_p/A ratio of categories (b) and (c) from 14.9 to 14.5 and from 7.7 to 7.3 for the period 1958-94. The effect on the Average N_p/A ratio for category (d) telescopes is only in the second place of decimals.

building and operating telescopes were to vary as the receiving area, then category (a) and (b) telescopes would be equally useful per unit cost, but both would be better than category (c) telescopes which, in turn, would be better than category (d). So how do the costs of optical/IR telescopes vary with size?

2.2 The Relationship between Telescope Size and Cost

2.2.1 Initial Costs

There have been a limited number of papers or reports analysing the effect of size on the cost of optical/IR telescopes. In particular, the 1964 Whitford report[18] showed that the initial costs (including telescope building, dome, mounting and optics) increase as the square of the telescope diameter (see Figure 10, next page), whereas Abt[1] showed that, for the seven telescopes which were part of the American National Optical Observatory on Kitt Peak* in the late 1970s, the initial costs (defined in the same way as in the Whitford report) varied as the aperture to the power 2.37 (see Figure 11, next page but one). Abt also found that the annual costs (including instrumentation, operations, maintenance and 1/75th of the initial costs) varied as the aperture to the power 2.1.

I will now analyse the 1964 Whitford report and the subsequent surveys published by the American National Academy of Sciences in 1972/73[14] (the Greenstein report) and 1982/83[19] (the Field report) to provide a more detailed and up-to-date analysis of how the *initial* costs of optical/IR telescopes vary with aperture. I will also include the cost data from Abt's report[1] and from other publications. All of the cost data to be analysed is summarised in Table 25 (next page but two).

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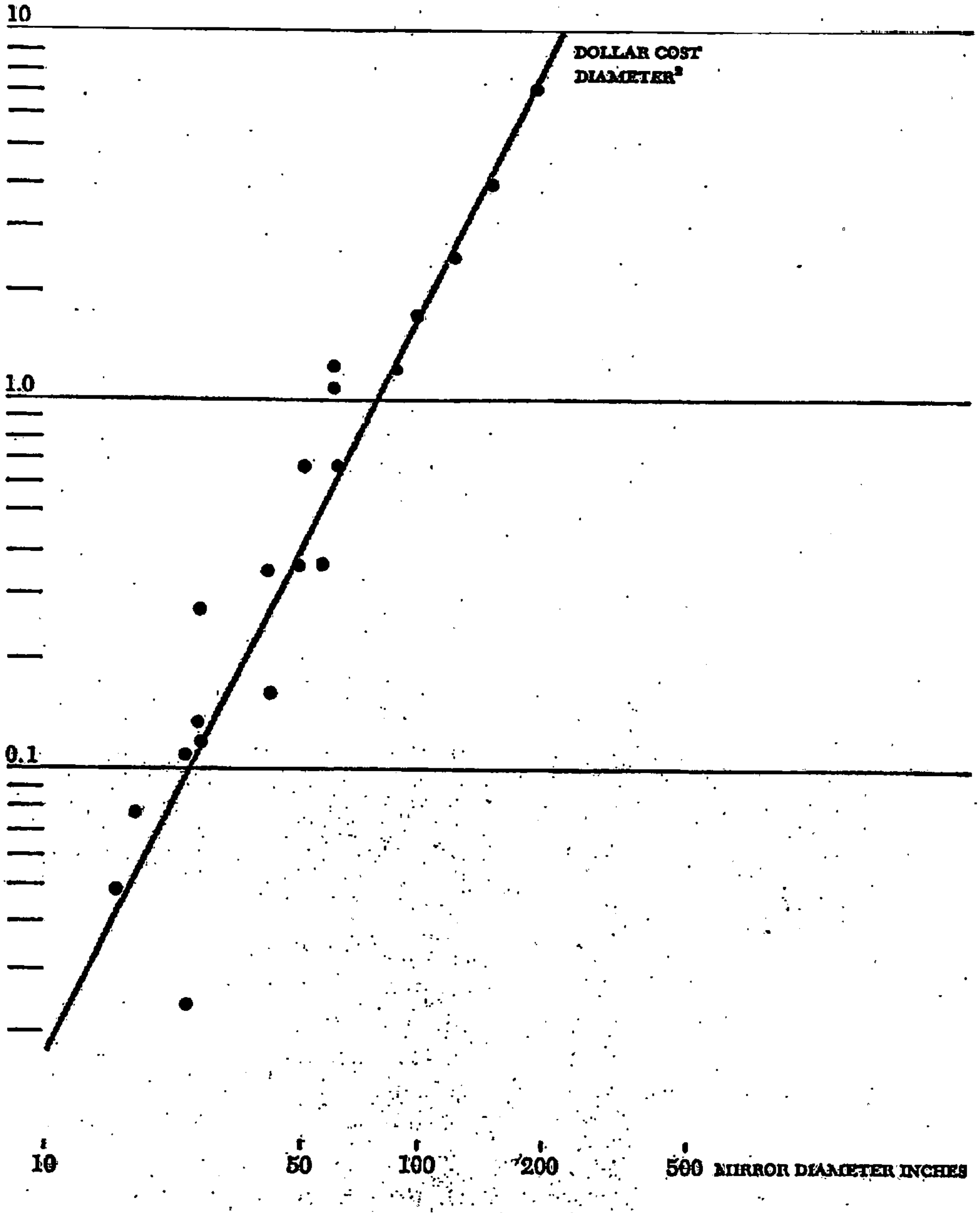
* Telescopes of diameter 4.0 m, 2.1 m, 1.3 m, 0.9 m (two telescopes), and 0.4 m (two telescopes).

FIGURE 10

Plot of initial (or capital) cost against aperture from the 1964 Whitford report[18] showing that cost is approximately proportional to aperture squared.

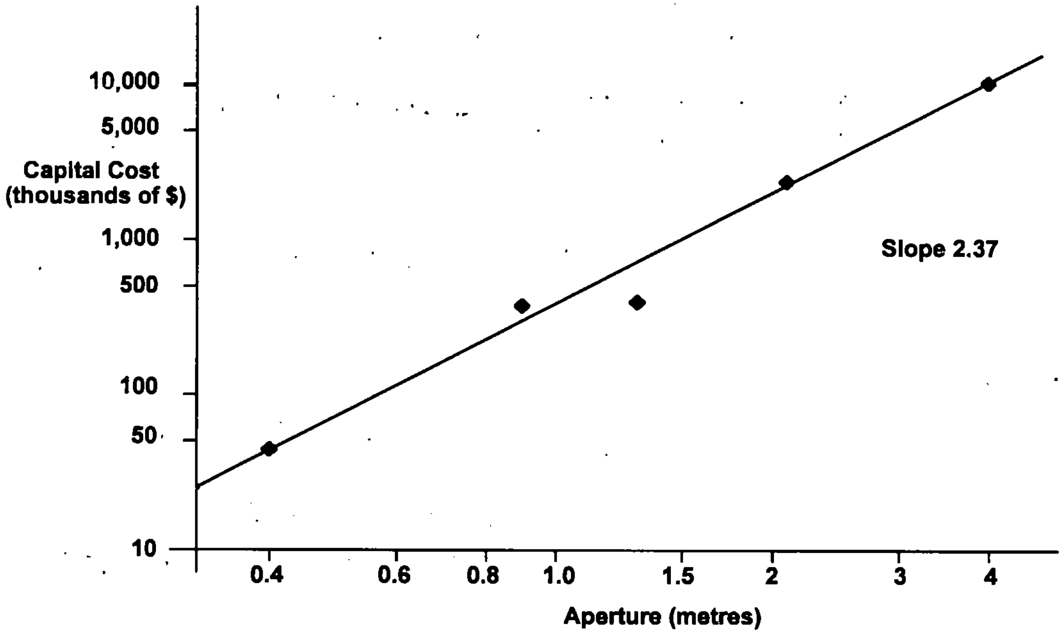


Costs of optical telescopes as a function of aperture, in millions of 1963 dollars. The data are from Table F (p.105, Appendix) and include optics, mounting, and dome. Land costs, site development, and auxiliary instruments are not included.

Note The Table F referred to above is my Table 27 (see later)

FIGURE 11

The relationship of capital (or initial) costs to telescope aperture for KPNO optical telescopes according to Abt[1]



(i) Costing Assumptions

The initial costs of any large telescope facility are notoriously difficult to analyse as, not only has inflation occurred since the facility was completed, but there was also inflation during the time that the facility was being constructed.* As a result, the costs usually quoted on completion of the facility are at a mixture of price levels. For example, the Anglo-Australian Telescope cost $A 15,932k** spread over the years 1967 to 1975. This figure is the total of the yearly expenditure in Australian

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* There are other problems in analysing telescope facility costs, as it is often not clear what has been included and what excluded. For example, are the costs of focal-plane instrumentation and site works included? Are internal manpower costs on initial design and on project management included? In this analysis I have given preference to cost data that clearly only include the telescope building, dome, mounting and optics, in the event that two different references have two different costs (at the same price level) for the same facility.

** This cost, quoted in the AAT Annual Report for 1976/77, is higher than the $A14.1m quoted in Table 25, as the $A15,932k includes the cost of site works and instrumentation, whereas the $A14.1m does not.

TABLE 25
Costs

(A) Optical and Infrared Telescopes
(reflectors unless otherwise stated)

	Date of First use	Initial Costs in $million[1]				Current or Last Location
		1963[2]	Historic[3]			
		Ref.1	Ref.2	Ref.3	Other[4]	
9.82 m	1991				94.0[5]	Keck I, Mauna Kea
(a) 2.55 - 5.08 m (200") diameters						
5.08 m	1948	8.50 6.95[8]	5.5[6]	6.0	6.0[7]	Palomar (Hale) Telescope
4.50 m	1979			7.5	16[9]	Multi-Mirror Telescope (MMT)
4.20 m	1987				24[10]	William Herschel Telescope (WHT)

Reference 1 Whitford, A.E., et al., "Ground-Based Astronomy; A Ten-Year Program", National Academy of Sciences - National Research Council, Washington DC., 1964.

Reference 2 Greenstein et al., "Astronomy and Astrophysics for the 1970's", Vol. 1 (1972) and Vol. 2 (1973), National Academy of Sciences, Washington DC.

Reference 3 Field et al., "Astronomy and Astrophysics for the 1980's", Vol. 1 (1982) and Vol. 2 (1983), National Research Council, National Academy Press, Washington DC.

Note This table is self-contained with its own References 1, 2 and 3, as given above, and its own footnotes shown as numbered superscripts. These latter superscripts should not be confused with the references in the main text which are also shown as numbered superscripts.

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[1] These costs are for the instrument including dome building, mounting and optics, but excluding instrumentation and site development costs.

[2] At 1963 price levels.

[3] At the price levels pertaining to the year(s) in which the money was spent. This expenditure was often spread over a number of years.

[4] Other references, as indicated in the footnotes.

[5] Sky and Telescope July 1990.

[6] In 1971 the replacement cost was estimated at $25 million.

[7] Cost in 1928, Astronomy December 1992.

[8] Two figures are given in different tables. According to the text of this reference, the second figure is the result of an adjustment to allow a like-by-like comparison with other data in this reference.

[9] In 1985 dollars, Sky and Telescope July 1985, (or $10.8m in 1979 prices).

[10] Sky and Telescope August 1990.

TABLE 25 (cont.)

		Ref.1	Ref.2	Ref.3	Other	
4.00 m	1975		10.0		10.4[11] or 10.0[12]	Cerro Tololo Inter-American Obs.
3.89 m	1975				18.6[13]	Anglo-Australian Telescope (AAT)
3.81 m	1973			11.1	10.7[14] or 10.5[15] or 11.1[16]	Mayall, KPNO
3.80 m	1979				8.6[17]	UKIRT, Mauna Kea
3.58 m	1979			30.0	28.0[18]	Can.-Fr.-Haw. (CFHT), Mauna Kea
3.05 m	1959	2.17 2.40[22]	3.0	3.0	2.5[19] or 2.8[20]	Shane, Lick Obs.[21]
3.00 m	1979			10.0	10.0[23]	NASA IRTF, Mauna Kea
2.72 m	1969		5.9	5.9		Mc Donald Obs.

(b) 1.23 - 2.54 m (100") diameters

		Ref.1	Ref.2	Ref.3	Other	
2.54 m	1976			10.0		Irénée du Pont Telescope, Las Campanas
2.44/2.54 m	1967/1984				2.3[24]	Isaac Newton Telescope (INT), La Palma
2.34 m	1988				2.0[25]	Hiltner Telescope, MDM Obs., Kitt Peak
2.30 m	1984				2.0[26]	Mt. Stromlo & Siding Spring Obs.
2.29 m	1977			1.6	1.6[27]	Wyoming IR Telescope, Jelm Mountain

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[11] Private Communication, S.Tuttle (NSF) to DL, June 1986.

[12] Sky and Telescope Feb. 1975.

[13] $A14.1m, excluding computer, instrumentation and site costs. Anglo-Australian Telescope Annual Report 1976-77.

[14] Private Communication, S.Tuttle (NSF) to DL, June 1986.

[15] Abt PASP, 1980, 92, 249.

[16] Irvine, J., and Martin, B.R., Social Studies of Science, 13, 1983, 49.

[17] PPARC private communication.

[18] Bull. Am. Astr. Soc., 1978, Vol. 10.

[19] "Eye on the Sky, Lick Observatory's First Century", by Osterbrock, D.E., Gustafson, J.R., and Unruh, W.J.S., California University Press, 1988.

[20] Irvine, J., and Martin, B.R., Social Studies of Science, 13, 1983, 49.

[21] In "ESO's History", by A. Blaaw, European Southern Observatory, 1991:- 1957-60 estimate of costs for build-to-print of a repeat 3.05m Lick $3.5 m.

[22] Two figures are given in different tables. According to the text of this reference, the second figure is the result of an adjustment to allow a like-by-like comparison with other data in this reference.

[23] Bull. Am. Astr. Soc., 1978, Vol. 10.

[24] This is the initial cost (£0.96m) in 1967. The cost of moving the INT to La Palma, replacing the main mirror, and building facilities on the mountain, cost £7.5m (or $11.4m) in 1983. Data from Irvine, J., and Martin, B.R., Social Studies of Science, 13, 1983, 49.

[25] Sky and Telescope July 1989.

[26] Sky and Telescope Oct. 1981.

[27] Sky and Telescope June 1978.

TABLE 25 (cont.)

		Ref.1	Ref.2	Ref.3	Other	
2.26 m	1969		2.5	2.0	2.0[28]	Steward Obs., Univ. of Arizona, Kitt Pk.
2.24 m	1970		4.2			Univ. of Hawaii, Mauna Kea
2.14 m	1964	2.5 1.2[31]	2.5	2.9	2.38[29] or 2.9[30]	Kitt Peak National Obs.
2.14 m	1979				1.30[32]	San Pedro Martir Obs., Univ. Nac. Aut. de Mexico
1.88 m	1935				0.35[33]	David Dunlap Obs., Univ. of Toronto
1.55 m	1964	1.2		1.0		US Naval Observatory, Flagstaff
1.27 m	1965				0.402[34] or 0.68[35]	Kitt Peak National Obs.
1.26 m	1948	0.60 0.675[37]				Palomar *Schmdt.*, (48" x 72" nominally)[36]
1.24 m	1973				1.8 1.2[38]	UK *Schmidt*, Siding Spring, (48" x 72")

(c) 0.62 - 1.22 m (48") diameters

1.22 m	1961	0.36				Dominion Astrophysical Obs., Canada
1.08 m	1973			0.305		Charlottesville, Virginia
1.07 m	1970			0.25		Lowell Obs., Flagstaff, Arizona
1.0 m	1964	0.35				Siding Spring
1.0 m	1980			0.25		Lick Obs., Univ. of Calif., Mt. Hamilton
0.91 m	1950	0.25				Cerro Tololo
0.91 m	1956	0.124				McDonald Obs., Univ. of Texas
0.91 m	1958	0.139				Pine Bluff Obs., Univ. of Wisconsin
0.91 m	1960	0.275			0.379[39] or 0.49[40]	KPNO, No. 1 *(closed 1989)*
0.91 m	1966				0.379[39] or 0.49[40]	KPNO, No. 2

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[28] "Realm of the Long Eyes", by Kloeppel, J.E., Univelt, 1983.

[29] Abt PASP, 1980, **92**, 249.

[30] Irvine, J., and Martin, B.R., Social Studies of Science, **13**, 1983, 49.

[31] Two figures are given in different tables. According to the text of this reference, the second figure is the result of an adjustment to allow a like-by-like comparison with other data in this reference.

[32] Sky and Telescope Vol. 60.

[33] Sky and Telescope October 1985.

[34] Abt PASP, 1980, **92**, 249.

[35] Irvine, J., and Martin, B.R., Social Studies of Science, **13**, 1983, 49.

[36] In "ESO's History", by A. Blaaw, European Southern Observatory, 1991:- 1957-60 estimate of costs for build-to-print of a repeat Palomar Schmidt $0.6 m.

[37] Two figures are given in different tables. According to the text of this reference, the second figure is the result of an adjustment to allow a like-by-like comparison with other data in this reference.

[38] £480,000, Sky and Telescope, March, 1973.

[39] Abt PASP, 1980, **92**, 249.

[40] Half of the $0.98m quoted for both 0.91 m telescopes in Irvine, J., and Martin, B.R., Social Studies of Science, **13**, 1983, 49.

TABLE 25 (cont.)

		Ref.1	Ref.2	Ref.3	Other	
0.61 m (24") diameter						
0.79 m	1964			0.03		NASA refl., Lowell Obs., Flagstaff
0.76 m	1972			0.3		Manastash Ridge, Univ. of Washington
0.66 m	1873			0.05		Clark *refractor*, USNO, Washington
0.61 m	1949	0.216				Curtis *Schmdt*, Cerro Tololo, (24" x 36")
0.61 m	1953			0.035		Arizona Univ., Flagstaff, Arizona
0.61 m	1964				0.58[41]	Lick Obs., refl., Mount Hamilton
0.61 m	1970			0.10		US Naval Obs., Flagstaff, Arizona
0.61 m	1970			0.08		US Naval Obs., Washington

Additional Information

(i) Telescopes outside geographical area

3.58 m	1989	13 or 14[42]	NTT, ESO, La Silla, Chile
3.57 m	1976	40[43]	ESO, La Silla
2.54 m	1989	7.0[44]	Nordic Opt. Tel., La Palma

(ii) Estimated costs of telescopes not completed in 1992

9.8 m	93.3[45]	Keck II
8 m x 2	176[46]	Gemini
3.5	10[47]	ARC, Apache Point, New Mexico
3.5	10[48]	WIN Telescope, Kitt Peak

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[41] Irvine, J., and Martin, B.R., Social Studies of Science, 13, 1983, 49.

[42] Cost $13m according to Sky and Telescope Sept. 1989, or $14m according to Astronomy Now Nov. 1990.

[43] At 1989 rates. Sky and Telescope September 1989.

[44] Sky and Telescope January 1990, and Astronomy February 1990.

[45] Astronomy August 1992.

[46] Cost of two 8 metre Gemini Telescopes $176m at 1992 rates.

[47] Astronomy November 1986.

[48] Astronomy June 1989.

dollars for every year from 1967 to 1975, inclusive, in dollars of the year concerned, and so is not just in 1975 Australian dollars.

For the purpose of this study, I will assume that all telescope costs quoted in the literature are at a price level for the year in which the telescope was completed, unless otherwise stated This is the only feasible assumption, as otherwise I would need to know the payment profile for the years that each facility was under construction, and it is virtually impossible to find that for most facilities. An idea of the effect of making this assumption is given by the following example.

Consider two identical telescopes A and B that took 6 and 8 years to build respectively, that were both started on the same day. Assume an equal expenditure of funds with time in unescalated dollars for each telescope, and an inflation rate of 6% per year, every year. Then, for example, for telescopes costing $60m each we would have the financial profiles shown in Table 26.

TABLE 26

	Telescope A		**Telescope B**	
	$ m		**$ m**	
Year	**Unescalated**	**Actual**	**Unescalated**	**Actual**
1	10.0	10.0	7.5	7.5
2	10.0	10.6	7.5	8.0
3	10.0	11.2	7.5	8.4
4	10.0	11.9	7.5	8.9
5	10.0	12.6	7.5	9.5
6	10.0	13.4	7.5	10.0
7			7.5	10.6
8	___	___	7.5	11.3
Total	**60.0**	**69.7**	**60.0**	**74.2**

In this case, I would be quoting the cost of Telescope A as $69.7m in Year 6 dollars and Telescope B as $74.2m in Year 8 dollars. But the Year 6 dollars need escalating by two years inflation to get $78.3m for Telescope A in Year 8 dollars. It would thus appear as if Telescope A cost $4.1m (5.5%) more than Telescope B in Year 8 dollars, whereas the real costs ($60m in Year 1 dollars) were exactly the same. Such errors of about 5% obviously become larger, the larger the rate of inflation and the larger the difference in time taken to construct the telescopes The effect is generally small, however, compared with other sources of error, and it was particularly low until the second half of the period 1956-92 under consideration, as inflation did not exceed 6.0% in the USA and the UK until 1973 and 1970, respectively. What cannot be ignored, however, is the effect of inflation since the telescopes were completed, which in some cases was over 40 years ago.

(ii) The 1964 Whitford Report[18]

The 1964 Whitford report estimated the initial costs of all the optical/IR telescopes at 1963 prices. As mentioned above, the report concluded that the initial costs for optical/IR telescopes vary as the square of the aperture (see Figure 10), but it included (see Table 27, next page) preliminary costs for facilities not then near completion, and estimated costs for the 100" (2.54m) Mt Wilson and 200" (5.08m) Palomar telescopes that had been constructed many years earlier. (Although the 200" was completed in 1948, most of the money was spent before the hiatus caused by the American entry into the Second World War in 1941). Ignoring these preliminary and estimated costs* (and that for the specialist lunar telescope in Whitford's list) produced the graph shown in Figure 12** (next page but one), which indicates a 1963

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* As cost-to-completions estimated a number of years prior to the completion of a major facility are notoriously unreliable.

** Although the costs of the two Schmidts shown in the first cost column of Table 25, plus the small 0.46m/0.71m Palomar Schmidt (see Table 27), are plotted in Figure 12, the best-fit (regression) line shown in Fig. 12 ignores them. This is because it is difficult to know which dimension of the Schmidt to use as a fair comparison with the mirror diameter of a normal reflector. Should it be the diameter of the correcting lens or that of the mirror? The horizontal bars shown in Fig. 12 for each of the Schmidts indicate both of these dimensions.

This subject of how to characterise the Schmidt telescopes is discussed in Appendix 3. There I show that (bottom of next page):-

TABLE 27

Table F from the 1964 Whitford report

TOTAL COSTS FOR LARGE OPTICAL TELESCOPES Corrected to Jan. 1963
From National Average Cost Index Factors for Equipment.
Includes—Dome-Building; Telescope Mount; and Complete Optics
Does Not Include—Land; Site Development; Observing Instruments and Auxiliaries

APERTURE INCHES	OBSERVATORY	SPONSOR	FUNDING AGENT	TELESCOPE TYPE AND MOUNTING		YEAR OPER.	COSTS OR (EST) 1963 $ THOUSANDS
16	KPNO	AURA	NSF	Cass	Off-axis	1961	(55)
18/28	Palomar	CIT/CIW	Private	Schmidt	Fork	1958	(80)
24/36	Portage Lake	U. Mich.	State	Schmidt	Fork	1958	216
24	Palomar-Mt. Whitney	CIT Lunar	NASA	Cass	Fork	Const.	25
36	KPNO	AURA	NSF	Cass	Off-axis	1960	275
36	McDonald	U. Chicago	State	Cass	Fork	1957	124
36	Washburn	U. Wis.	State	Cass	Fork	1958	139
40	Mt. Stromlo	Australia	Aus. Gov.	Cass/coudé	Off-axis	1963	350
40	European Southern	Australia Group	Aus. Gov.	Cass/coudé	Fork	Prelim.	(160)
48	Dominion Obs.	Victoria	Canada	Cass/coudé	Fork	1961	360
48/72	Palomar	CIT/CIW	Private	Schmidt	Fork	1948	675
60	U.S. Naval Obs.	Naval Obs.	USN	Cass	Fork	Const.	(1,200) (800 + Opt.)
60	Palomar	CIT/CIW	—	Cass/coudé	Fork	Prelim.	(650)
60	Chile Obs.	AURA	NSF	Cas/PF/coudé	Off-axis	Prelim.	(1,050)
84	KPNO	AURA	NSF	Cass/coudé	Fork	1963	(1,200)
100	Mt. Wilson	CIW	Private	Newt/Cas/cou	Yoke	~~1908~~ 1917	(1,680) (Old est.)
120	Lick Obs.	U.C.	State	PF/Cas/cou	Fork	1959	2,400
150	KPNO	AURA	NSF	PF/Cas/cou	Yoke	Prelim.	(3,880)
200	Palomar	CIT/CIW	Private	PF/Cas/cou	Yoke	1948	6,950

Note The above data was used to plot Figure 12, after *excluding* the preliminary estimates and those for the 24" lunar telescope and for the 100" and 200" telescopes, as explained in the text, but *adding* the cost of the 36" Cerro Tololo telescope (taken from Table C of the same Whitford report).

(i) the best dimension to use, based on the cost of the Schmidts, is 0.3a + 0.7b, where a is the diameter of the corrector plate and b is the diameter of the main mirror.

and (ii) using this dimension has no significant effect on the data and conclusions of this thesis.

FIGURE 12

Initial Costs (at 1963 rates) plotted against aperture for ground-based optical/infrared telescopes using the data shown in Table 27, based on the 1964 Whitford report. The following modifications have been made to the Whitford data in producing this plot (as explained in the text):-

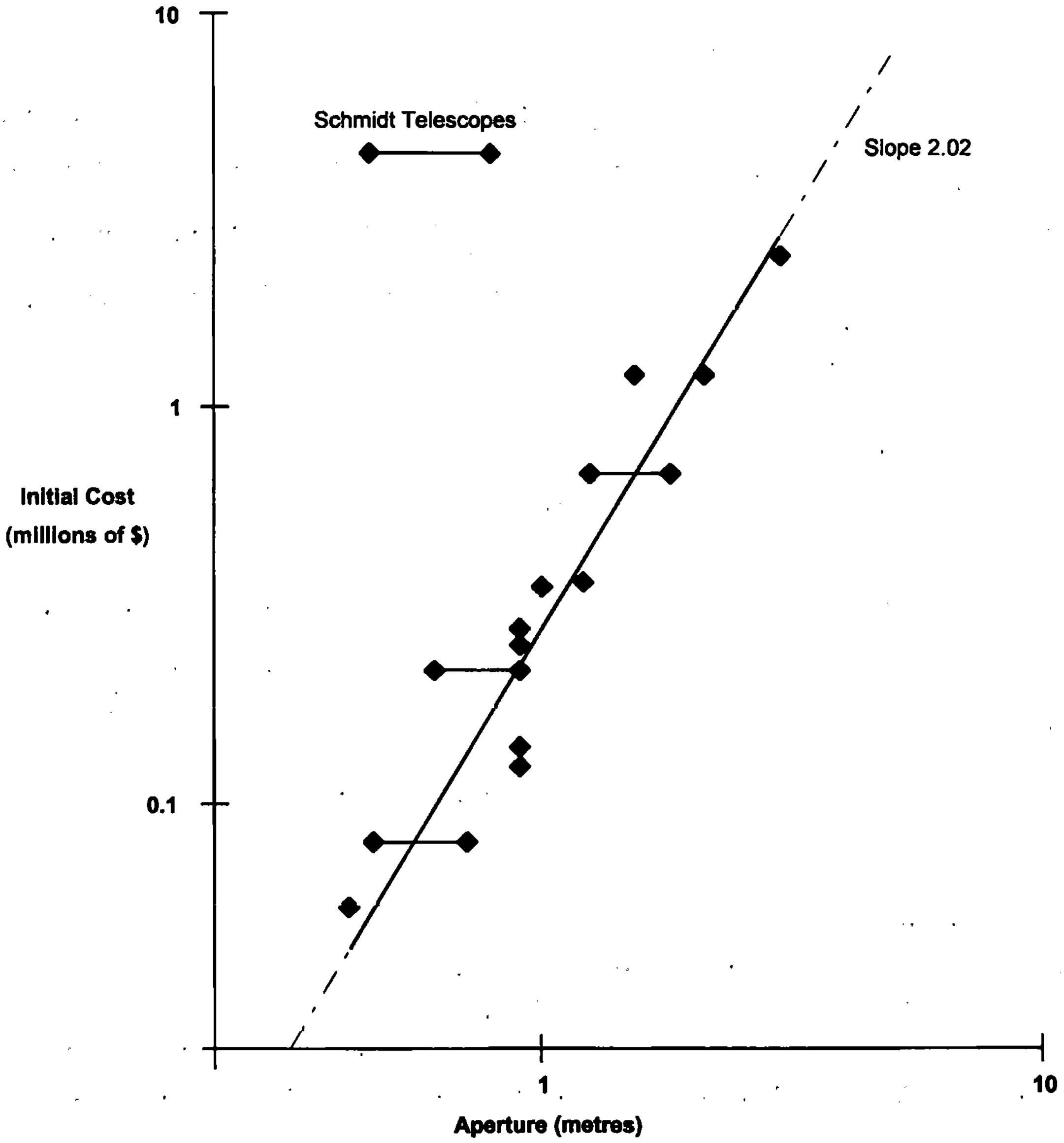
(i) The *estimated* costs of the 200" Palomar and 100" Mt Wilson telescopes have been ignored

(ii) *Preliminary* cost estimates and the costs of the 24" *lunar* telescope have been ignored

(iii) The cost of the 36" Cerro Tololo telescope has been added (taken from a different table in the Whitford report).

(iv) The points for the Schmidts have been plotted with a bar indicating the difference between the primary mirror and corrector plate diameters. The least-squares regression line shown on the graph does not use this Schmidt data, however, as I am unsure as to which Schmidt diameter to use. Whitford, on the other hand, plotted just the corrector plate diameters and used these in plotting his best fit regression line shown in my Figure 10.

In spite of these modifications to Whitford's data, the slope of my least squares regression line is, to one place of decimals, is the same as Whitford's shown in Figure 10.



cost for the 200" Palomar telescope of \$7.3m which is, within error, the same as the \$6.95m 1963 cost suggested by Whitford.

There are indications in the 1972 Greenstein report for the National Academy of Sciences[14] that the Whitford figure of \$6.95m in 1963 dollars for the 200" Palomar telescope is appreciably too low, however* . In this 1972 Greenstein report it was estimated that it would cost about \$25m in 1971 dollars to replace the Palomar 200 inch with "modern (1971) auxiliary instrumentation", although a separate cost was not indicated for this instrumentation which is clearly excluded from the cost estimate in the 1963 Whitford report. \$25m at 1971 rates is equivalent to \$18.7m at 1963 rates, assuming the inflation figure given in Appendix 2. So which figure is correct at 1963 rates, \$18.7m or \$6.95m? or maybe neither.

To try to resolve this question and clearly establish the dependency of cost with telescope aperture, I will now review the costs for optical/IR telescopes published in the 1964 Whitford report[18], in the 1972 Greenstein[14] and 1982 Field[19] reports, and in any other publication that give the costs of such telescopes as listed in the footnotes of Table 25.

(iii) The 1972 Greenstein Report[14]

Inspection of the data in Table 25 for those telescopes whose costs are listed in the 1964 or 1972 reports, excluding for the moment the 200" Palomar telescope, we find that:-

(i) The \$2.40m cost deduced by the Whitford report for the 3.05m Lick Telescope, at 1963 rates, has been increased by the 1972 report to \$3.0m at 1959

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* The initial estimate in 1928 for the Palomar 200" was \$6.0m, including \$252k for the mirror blank. When the contract for the latter was cancelled in 1931, \$639k had already been spent, and no 200" blank had been produced[20]. So the \$6.0m, at 1928 rates, was probably exceeded, implying a 1961 cost of considerably more than \$6.0m, once inflation has been taken into account for the intervening 33 years.

rates. This latter figure is repeated in the 1982 report, whilst Osterbrock[21] quoted a cost of $2.5m spread over the period of construction of the telescope and Irvine and Martin[3] quoted a cost of $2.8m. I will thus plot an error bar for this telescope, running from $2.40m at 1963 rates to $3.0m at 1959 rates (which will also cover the Osterbrock figure). This is equivalent to from $3.2m to $4.3m at 1971 rates, using the inflation figures given in Appendix 2.

(ii) The 2.72m McDonald Telescope is quoted in both the 1972 and 1982 reports as having cost $5.9m at 1969 rates, which is equivalent to $6.5m at 1971 rates.

(iii) The 1972 report quotes a cost of $2.5m at 1969 rates for the 2.26m Steward Observatory Telescope, whereas both the 1982 Field report and Kloeppel's book[22] quote $2.0m at the same 1969 rates. This range equates to from $2.8m to $2.2m at 1971 rates, which defines the size of the error bar plotted.

(iv) The 2.14m Kitt Peak Telescope has cost figures ranging from $1.2m at 1963 rates to $2.9m at 1964 rates. The $1.2m was calculated by Whitford based on an original cost of $2.5m, but, unfortunately, Whitford does not give details of his calculation. Abt, on the other hand, who had access to detailed costings of Kitt Peak telescopes, clearly stated that his figure of $2.38m, at 1964 rates, is for the telescope building, dome, mounting and optics. In addition, the figures in the 1972 and 1982 reports are similar to Abt's, so I will thus ignore the $1.2m of the Whitford report and draw an error bar from the Abt figure of $2.38m to the $2.9m quoted in the 1982 report. This equates to from $3.1m to $3.8m at 1971 rates.

(v) The cost of the 1.55m US Naval Observatory Telescope is quoted at $1.2m by Whitford at 1963 rates, and $1.0m at 1964 rates by the 1982 report. This equates to a range of from $1.6m to $1.3m at 1971 rates.

(vi) Whitford quoted $0.275m as the cost of the No.1 0.91m Kitt Peak Telescope in 1963 dollars, whereas Abt quoted $0.379m. Abt's figure is half the total cost of the No. 1 and 2 0.91m Kitt Peak telescopes that were completed in 1960 and 1966. The cost, in absolute terms, of producing just the first of these telescopes would be higher than 50% of the total cost of both, if it had to carry the full design and development costs. On the other hand, the second telescope was paid for when inflation over the intervening six years had made the dollar worth less, and so his 50/50 split between the two telescopes is probably fair. Using a similar 50/50 split of the $0.98m figure for both telescopes in the Irvine and Martin paper[3] gives a figure of $0.49m for the cost of each. I will thus plot the cost of the No.1 telescope as an error bar running from $0.275m at 1963 rates to $0.49m at 1960 rates, i.e. $0.37m to $0.69m at 1971 rates.

In addition, Whitford quoted $0.055m as the cost of one of the 0.41m Kitt Peak Telescopes at 1963 rates (see Table 27), whereas Abt[1] quoted a figure of $0.045m. I will use both figures, giving an error bar running from $0.074m to $0.060m at 1971 rates.

All other data in the Whitford and 1972 reports are assumed to be correct, in the absence of contradictory evidence, and the figures escalated to 1971 rates. The resulting plot is shown in Figure 13 (next page), where the best-fit (regression) line (excluding the Schmidts) implies a 1971 cost for the 200" Palomar Telescope of $22m. This indicates that the $25m estimated in the 1971 was correct (within error), and the Whitford figure of $6.95m at 1963 rates ($9.3m at 1971 rates) was an under-estimate.

Figure 13 is based on the data in Figure 12, corrected for inflation between 1963 and 1971. In addition, in Figure 13, (a) the Whitford report data has been modified, as explained above, and (b) cost data for three large new telescopes have been included that came on line in the meantime (the 2.72m McDonald, the 2.26m Steward, and the 2.24m University of Hawaii). Analysis shows that the effect of (a) was to increase the slope of the regression line in Figure 12 from 2.02 to 2.26, and the effect of (b) was to increase the slope further to the 2.43 shown in Figure 13* .

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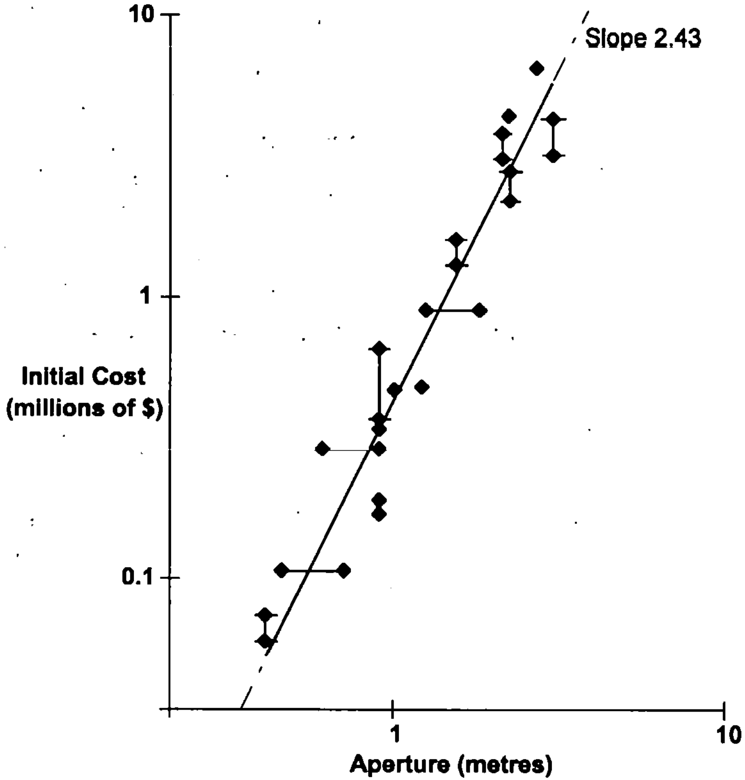
* The 200" Palomar is excluded from both of these graphs.

FIGURE 13

Initial costs at 1971 rates plotted against aperture for ground-based optical/infrared telescopes using data based on the 1964 Whitford and 1972 Greenstein reports, as explained in the text. The slope of the least-squares regression line has increased from 2.02 in Figure 12 to 2.43 here.



(iv) Consolidated Data

There are a number of telescopes listed in the final two cost columns of Table 25 which did not have costs quoted in either the 1964 Whitford report or the 1972 Greenstein report. Table 28 (next page) is a *consolidated* listing of all this data* and that discussed above, corrected to 1992 prices. This data in Table 28, excluding that for the Schmidts**, is plotted in Figure 14; the slope of the best-fit regression line being 2.19.

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* Except for the MMT, which is excluded from this analysis as it is of a radically different design, and the 1873 Clark refractor as it is very old and is the only refractor in Table 25. I have included the costs for four telescopes that have been completed since 1992 (or are still being built at the time of writing i.e. 1996), and three telescopes outside my geographical area, to include cost data for as many modern telescopes as possible.

** Because of their radically different construction.

TABLE 28
Consolidated List of Initial Costs at 1992 Rates

Date of First use	Dia. in metres	Initial Costs in $million	Current or Last Location
1991	9.82	96.9	Keck I
1948	5.08	76.2*	Hale Telescope
1987	4.20	29.6	William Herschel Telescope (WHT)
1975	4.00	26.0/27.1	Cerro Tololo Inter-American Obs.
1975	3.89	48.4	Anglo-Australian Telescope (AAT)
1973	3.81	33.1/35.0	Mayall Telescope, KPNO
1979	3.80	16.6	UK Infra-Red Telescope (UKIRT)
1979	3.58	54.1/57.9	Canada-France-Hawaii (CFHT), Mauna Kea
1959	3.05	11.1/14.9	Shane Telescope, Lick Obs.
1979	3.00	19.3	NASA IRTF, Mauna Kea
1969	2.72	22.5	Mc Donald Obs.
1976	2.54	24.6	Irénée du Pont Telescope, Las Campanas
1967	2.44	9.7	Isaac Newton Telescope, Hertsmonceaux
1988	2.34	2.37	Hiltner Telescope, MDM Obs., Kitt Peak
1984	2.30	2.7	Mt Stromlo and Siding Spring Obs.
1977	2.29	3.7	Wyoming IR Telescope, Jelm Mountain
1969	2.26	7.6/9.5	Steward Obs., Univ. of Arizona, Kitt Peak
1970	2.24	15.2	Univ. of Hawaii, Mauna Kea
1964	2.14	10.8/13.2	Kitt Peak National Observatory
1979	2.14	2.5	San Pedro Martir
1935	1.88	5.3	David Dunlap Obs.
1964	1.55	4.5/5.5	US Naval Observatory, Flagstaff
1965	1.27	1.8/3.0	Kitt Peak National Observatory
1948	1.26/1.83	2.8/3.1	Palomar *Schmidt*
1973	1.24/1.83	3.8/5.7	UK *Schmidt*, Siding Spring
1961	1.22	1.67	Dominion Astrophysical Obs., Canada
1973	1.08	0.96	Charlottesville, Virginia
1970	1.07	0.90	Lowell Obs., Flagstaff, Arizona
1964	1.0	1.60	Siding Spring
1980	1.0	0.43	Lick Obs., Univ. of Calif., Mt. Hamilton
1950	0.91	1.16	Cerro Tololo
1956	0.91	0.58	McDonald Obs., Univ. of Texas
1958	0.91	0.64	Pine Bluff Obs., Univ. of Wisconsin, Madison
1960	0.91	1.28/2.40	Kitt Peak Nat. Obs., No. 1 Telescope
1966	0.91	1.64/2.12	Kitt Peak Nat. Observatory, No. 2 Telescope
1964	0.79	0.14	NASA refl., Lowell Obs., Flagstaff, Arizona
1972	0.76	1.00	Manastash Ridge Obs., Univ. of Washington
1949	0.61/0.91	1.00	Curtis *Schmidt*, Cerro Tololo
1953	0.61	0.19	Arizona Univ., Flagstaff, Arizona
1964	0.61	2.64	Lick

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* As deduced from Figure 13, i.e. $22m at 1971 prices.

TABLE 28 (cont.)

Date of First use	Dia. in metres	Initial Costs in $million	Current or Last Location
1970	0.61	0.36	US Naval, Flagstaff, Arizona
1970	0.61	0.29	US Naval Obs., Washington
1958	0.46/0.71	0.37	Palomar *Schmidt*
1961	0.41	0.21/0.26	Kitt Peak National Observatory

Additional Information

(i) Telescopes outside geographical area

1989	3.58	14.7/15.8	New Technology Telescope, ESO, La Silla
1976	3.57	45.3	European Southern Observatory, La Silla
1989	2.54	7.9	Nordic Optical Telescope, La Palma

(ii) Estimated costs of telescopes not completed in 1992

	9.8	93.3	Keck II
	8.0	88	Gemini[*]
	3.5	12.8	ARC, Apache Point
	3.5	11.3	WIN, Kitt Peak

A key question is how much the costs of building new telescopes has gone down in recent years because of the use of modern design and manufacturing techniques (e.g. the use of segmented mirrors, spin casting and active optics). To examine this I have plotted the data of Figure 14 (next page) on two graphs, one (Figure 15) being for telescopes that saw first light up to and including 1980, and one (Figure 16) for those that saw first light in 1981 and later. The slopes of the regression lines are the same within error on both graphs (i.e. 2.45 and 2.33, respectively) and, at a typical diameter for the telescopes in Figure 16 of 4 metres, the regression lines of Figures 15 and 16 give costs of $36m and $15m, respectively, so the new techniques appear to have reduced the costs to about 40% of the original costs. This, incidentally, is very similar to the situation with the 3.6 metre New Technology Telescope at the

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[*] The two 8.0 m Gemini Telescopes are estimated to cost $176m.

FIGURE 14

Initial costs at 1992 rates, taken from my consolidated list of Table 28, plotted against aperture for ground-based optical/infrared telescopes *in use (or under construction) up to and including 1996.*

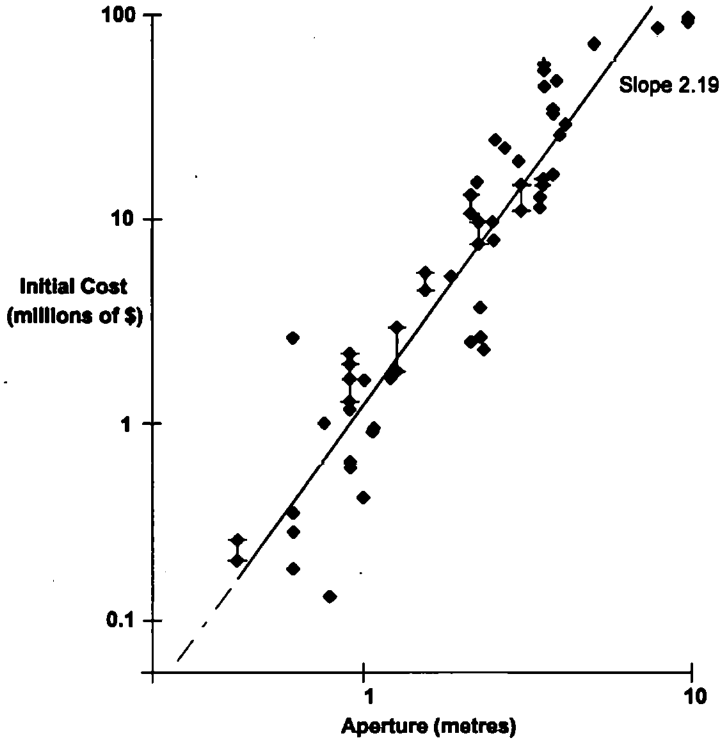


FIGURE 15

Initial costs at 1992 rates, taken from my consolidated list of Table 28, plotted against aperture for ground-based optical/infrared telescopes *in use up to and including 1980.*

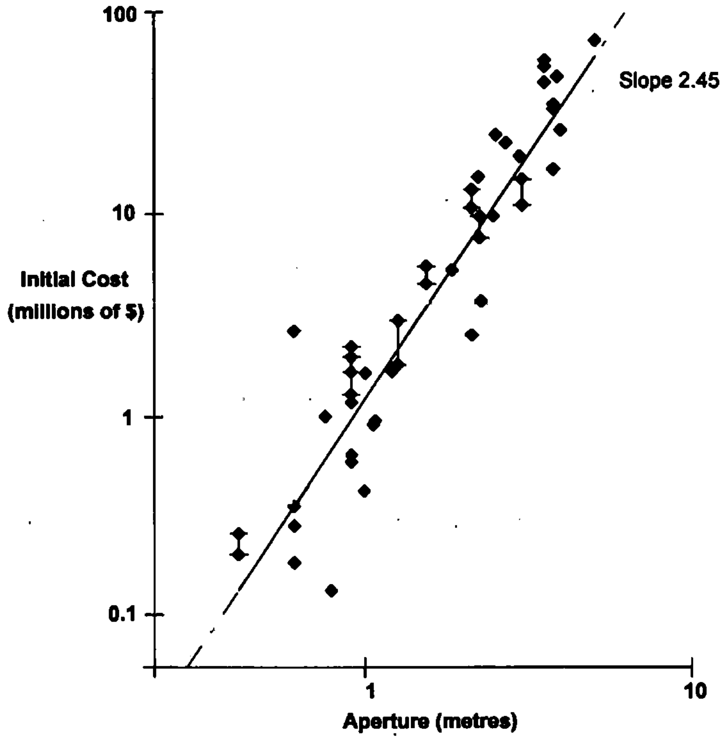
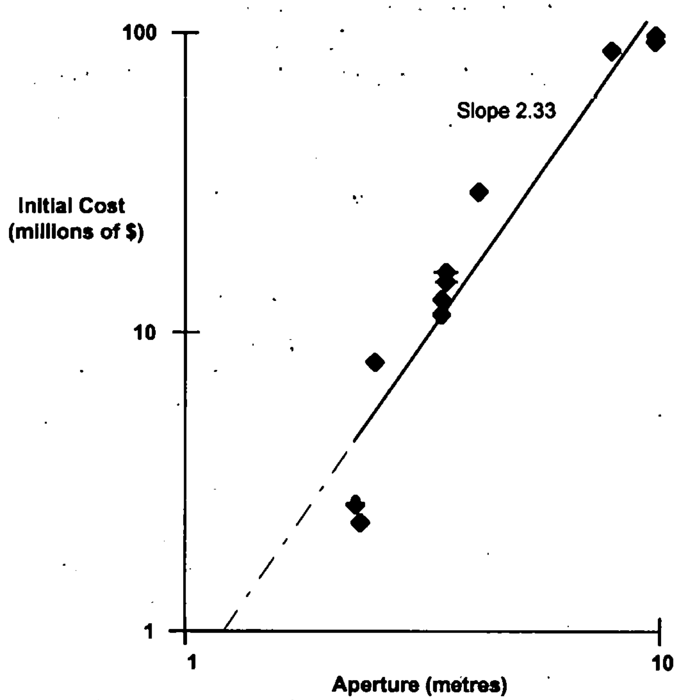


FIGURE 16

Initial costs at 1992 rates, taken from my consolidated list of Table 28, plotted against aperture for ground-based optical/infrared telescopes *in use for the first time (or under construction) from 1981 to 1996.*



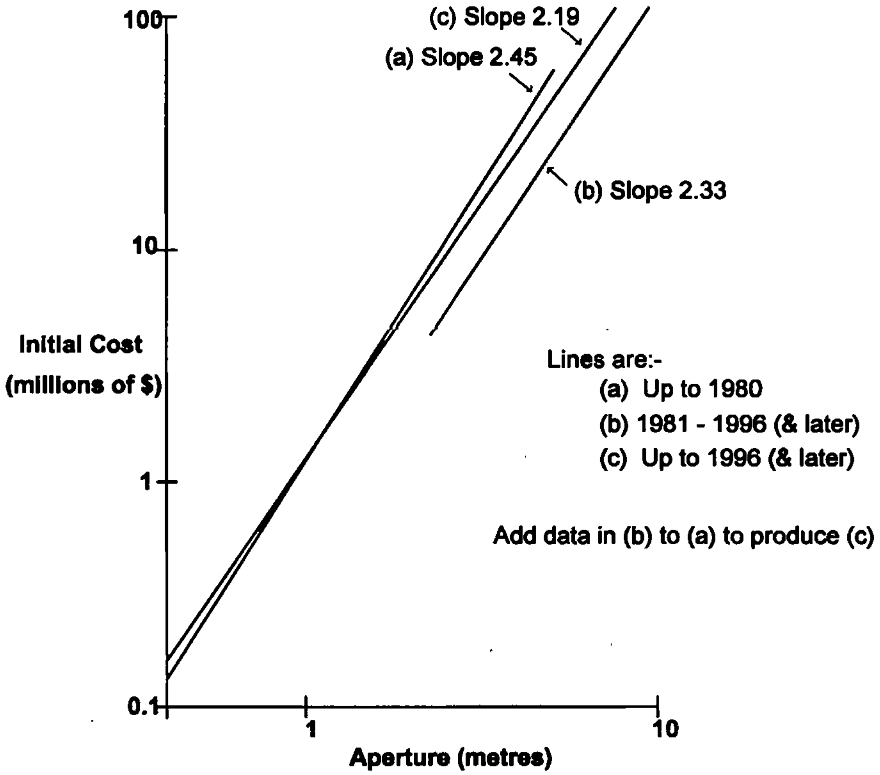
European Southern Observatory, completed in 1989, whose cost was only 30% of that of the original 3.6 metre[23] telescope at the same observatory which had been completed in 1976 .

The slope of the line in Figure 15 for all telescopes up to 1980 was 2.45, but in Figure 14 for all telescopes up to 1996 (and later) it was 2.19, whilst for telescopes from 1981-1996 (and later) the slope was 2.33 (see Figure 16). This apparent inconsistency, where adding data with a regression line of slope 2.33 to one of slope 2.45 produced a regression line of slope 2.19, is because the 1981-96 (and later) line is offset downwards compared with the other two lines, see Figure 17 (next page), and it covers only large telescopes (minimum size 2.30m).

It is also important to check whether the costs of optical/infrared telescopes have changed in the period before 1981 and, to do this, I have compared the costs up to 1970 with those shown in Figure 15 up to 1980.

FIGURE 17

The least-squares regression lines for ground-based optical/infrared telescopes are reproduced here from Figures 14, 15, and 16, above, to show their relative position. This shows how the slope of the regression line is reduced from (a) 2.45 to (c) 2.19 when data is added with a regression line of slope 2.33. The relative positions of (a) and (b) show that large post-1980 telescopes of line (b) are, on average, less expensive than pre-1981 telescopes of line (a).



The slope of the regression line for telescopes up to and including 1970, see Figure 18 (next page), is 2.45, which is identical with that for telescopes up to and including 1980. Not only are the slopes of the lines identical, however, but so is the position of the lines, within error*, so the cost of telescopes up to and including 1970 are similar to those from 1971 to 1980.

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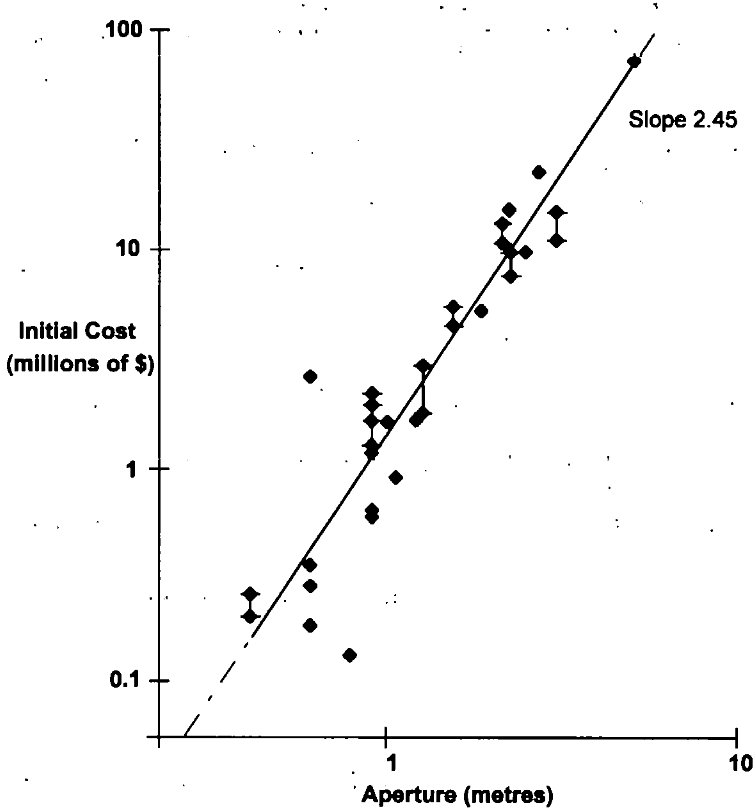
* Compare the position of the lines in Figures 15 and 18 relative to the topmost point, which is the same point on each plot.

FIGURE 18

Initial costs at 1992 rates, taken from my consolidated list of Table 28, plotted against aperture for ground-based optical/infrared telescopes *in use up to and including 1970.*



It is interesting to note that the period covered by Figure 18 is the same as that covered by Figure 13, but with 11 more telescopes included in Figure 18. In spite of these extra telescopes the regression lines are almost identical*.

It is tempting to see if I can produce an analysis limited to telescopes available up to and including 1960 but, unfortunately, I have only 7 such telescopes in my list, and the error will be too large.

So, in conclusion, I have (next page):-

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* Compare the position of the lines in both Figures relative to the pair of points for the smallest telescope, which are the same points on each plot.

Figure No.	**Telescopes Available (First Year of Operation)**	**Slope**	**Downward Movement of regression lines***
18	up to and including 1970	2.45	—
15	up to and including 1980	2.45	Nil
16	1981 - 1996 (and later)	2.33	Costs reduced by 60%

Within error, these slopes are all the same at 2.4, and are the same as the slope of 2.37 (see Figure 11) deduced by Abt for the seven telescopes at the Kitt Peak National Observatory that became available between 1960 and 1973. In the following, therefore, I have worked with the regression line of Figure 15 for telescopes up to and including 1980, and that of Figure 16 for telescopes after 1980. Although such a step-function change in costs did not occur in 1980, of course, the effect in the following analysis of using the wrong synthetics for telescopes just on either side of 1980, whilst being important at the individual telescope level, is of no consequence in determining the total cost of all telescopes.

Table 28 shows the actual costs, at 1992 values, of some of the telescopes listed in Appendix 1A. If I use the regression lines of Figures 15 and 16 to estimate the cost of the other telescopes in Appendix 1A, I obtain a total initial cost for all the telescopes in Appendix 1A of about $840 million, at 1992 rates, of which 71% are known costs from Table 28**, with only about $240m or 29% estimated. Assuming an error of ± 50% on the estimated amount gives a total cost of $840m ± $120m.

The analysis of Table 23 indicated that the numbers of smaller-sized, post-1978 telescopes deduced from Appendix 1A may be on the low side, however, although such a possible underestimate had little effect on the average values of N_p/A for the various telescope categories. Nevertheless, such a possible underestimate is a potential source of error and needs to be evaluated. If the numbers of telescopes

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* i.e. change in costs, relative to Figure 18.

** Including the costs from Table 25 of the MMT, the Clark refractor, and the modification and removal costs of the INT, which are not included in Table 28.

deduced from Table 23 were correct, and the extra numbers were evenly distributed* throughout their respective categories, then these extra telescopes would have cost about $40m. This assumes that most of these extra telescopes had been purchased since 1980 at about ½ of the average price of the previous decades (as indicated by Figure 17). This implies that the total cost could be somewhere between $840m and $880m. I will take an average value of $860m ± $20m which, when the previously estimated error of ± $120m is included, becomes $860m ± $120m**.

2.2.2 Annual Costs

The total costs of running an observatory consist essentially of two elements, namely the initial (or capital) costs and the annual (or running) costs. The initial costs have been analysed in Section 2.2.1 above, where they have been shown to vary as the telescope diameter (d) to the power 2.4. I will now consider the annual costs.

Data on the annual costs of operating individual optical/IR telescopes, or even those for complete observatories, is very sparse and difficult to interpret for a number of reasons:-

Costs of Running Observatories

- In the United States, in particular, many observatories have more than one source of funding. Many university observatories, for example, are funded by the National Science Foundation (NSF) or NASA, by state funds and/or by private donations, so looking at only one of these sources of funding can be very misleading.

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[*] It is unlikely that the extra numbers would be evenly distributed for category (b), in particular, as the telescopes that have not been publicised are likely to be towards the lower-sized end of the range. My assumption is probably valid to a first approximation, however.

[**] This is the root mean square of ± $120m and ± $20m = ± $122m, or ± $120m in round numbers.

- If the observatory is not a stand-alone facility from a cost point-of-view, some valid costs may not be charged to the observatory. University observatories, for example, may use staff who are covered by other university budgets. In the UK the situation was clarified in 1993/94 by changes in the Dual Support arrangements of funding university observatories[24], but this change only took place at the end of my period.

Costs of Running Individual Telescopes

- There is often more than one telescope at any given observatory and splitting the cost of that observatory between the various telescopes is difficult. **Direct** costs, such as those for instrumentation, improvements, maintenance, etc., are relatively easy to attribute (assuming that the observatory keeps appropriate records), but splitting the **indirect** costs, like the observatory administration charges, for example, between the different telescopes in a reasonable manner is not only difficult but highly subjective.

The best set of data that I have been able to obtain on the annual running costs of ground-based observatories is that shown in Tables 29 and 30 for the American National Observatories. Table 29 is in real-year dollars and Table 30 in 1992 dollars. This data has been derived in Appendix 4 from data supplied[25] mostly by Tuttle of the NSF.

The last major telescope to become operational at the KPNO was the 3.8m Mayall in 1973, and one would expect to see a jump in the operations cost of the observatory at about that time. In fact the reverse happened (see Table 30) indicating that, although I have done my best in Appendix 4 to eliminate the capital costs of all the telescopes in Tables 29 and 30, there must still be significant capital costs included in the pre-1974 figures. Because of this, I will ignore all pre-1974 costs in the following parametric analysis.

TABLE 29

Operating Costs of the National Astronomical Research Centres in the USA as derived in Appendix 4

(Numbers are commitments in real-year dollars, i.e. 1970 figures are in 1970 dollars, in millions)

	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970
(i) NOAO											
Kitt Peak (KPNO)*		2.00	2.32	2.65	2.97	3.29	3.61	3.95	5.21	4.88	5.60
Cerro Tololo (CTIO)								0.5	1.0	1.6	1.90
Total (NOAO)		2.00	2.32	2.65	2.97	3.29	3.61	4.45	6.21	6.48	7.50
(ii) NRAO (Green Bank)	~1.0	~1.0	~2.0	3.3	3.3	3.38	4.72	4.98	7.21	7.28	5.86
(iii) NAIC (Arecibo)					~1.2	~1.3	~1.3	~1.3	~1.4	~1.5	1.55
Total	**1.0**	**3.0**	**4.32**	**5.95**	**7.47**	**7.97**	**9.63**	**10.73**	**14.82**	**15.26**	**14.91**

	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981
(i) NOAO											
Kitt Peak (KPNO)	6.32	6.77	6.86	6.63	6.53	7.14	7.40	7.76	8.25	8.93	9.44
Cerro Tololo (CTIO)	2.28	2.50	2.70	2.60	2.95	3.45	3.50	3.89	4.35	4.83	5.81
Total (NOAO)	8.60	9.27	9.56	9.23	9.48	10.59	10.90	11.65	12.60	13.76	15.25
(ii) NRAO (Green Bank & VLA)	6.90	6.8	6.9	7.2	8.1	8.4	9.4	9.6	11 ?	12.53	14.79
(iii) NAIC (Arecibo)	2.47	2.55	2.70	3.20	3.20	4.05	5.00	4.28	4.63	4.99	5.41
Total	**17.97**	**18.62**	**19.16**	**19.63**	**20.78**	**23.04**	**25.30**	**25.53**	**28.23**	**31.28**	**35.45**

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* Excluding the solar observatory.

TABLE 29 cont.

	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992
(i) NOAO											
Kitt Peak (KPNO)	9.54	9.87	11.72	12.0	11.8	10.75	10.56	10.95	12.03	12.71	11.77
Cerro Tololo (CTIO)	6.06	6.48	6.71	6.2	6.2	5.45	5.11	5.36	6.2	6.2	7.29
Total (NOAO)	15.60	16.35	18.43	18.2	18.0	16.20	15.67	16.31	18.23	18.91	19.06
(ii) NRAO	14.84	15.90	20.26	17.65	16.63	16.83	16.26	18.30	19.60	21.20	26.60
(iii) NAIC (Arecibo)	5.32	5.11	6.11	6.05	5.70	5.88	5.82	6.15	6.22	6.39	6.55
Total	**35.76**	**37.36**	**44.80**	**41.90**	**40.33**	**38.91**	**37.75**	**40.76**	**44.05**	**46.50**	**52.21**

TABLE 30
Operating Costs of the National Astronomical Research Centres in the USA
(Numbers are commitments in 1992 dollars, in millions)

	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970
(i) NOAO											
Kitt Peak (KPNO)*		9.6	10.9	12.3	13.5	14.7	15.6	16.6	21.0	18.6	20.2
Cerro Tololo (CTIO)								2.1	4.0	6.1	6.9
Total (NOAO)		9.6	10.9	12.3	13.5	14.7	15.6	18.7	25.0	24.7	27.1
(ii) NRAO (Green Bank)	~5.0	~5.0	~9.0	15.3	15.0	15.1	20.4	20.9	29.1	27.8	21.1
(iii) NAIC (Arecibo)					~5.6	~5.6	~5.6	~5.6	~5.6	~5.6	5.6
Total	**5.0**	**14.6**	**19.9**	**27.6**	**34.1**	**35.4**	**41.6**	**45.2**	**59.7**	**58.1**	**53.8**

	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981
(i) NOAO											
Kitt Peak (KPNO)	21.9	22.7	21.6	18.8	17.0	17.6	17.1	16.7	15.9	15.2	14.6
Cerro Tololo (CTIO)	7.9	8.4	8.5	7.4	7.7	8.5	8.1	8.4	8.4	8.2	9.0
Total (NOAO)	29.8	31.1	30.1	26.2	24.7	26.1	25.2	25.1	24.3	23.4	23.6
(ii) NRAO (Green Bank & VLA)	23.9	22.8	21.8	20.4	21.1	20.7	21.7	20.6	21 ?	21.3	22.8
(iii) NAIC (Arecibo)	8.6	8.5	8.5	9.1	8.3	10.0	11.6	9.2	8.9	8.5	8.3
Total	**62.3**	**62.4**	**60.4**	**55.7**	**54.1**	**56.8**	**58.5**	**54.9**	**54.2**	**53.2**	**54.7**

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* Excluding the solar observatory.

TABLE 30 cont.

	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992
(i) NOAO											
Kitt Peak (KPNO)*	13.9	13.9	15.8	15.7	15.1	13.3	12.5	12.4	12.9	13.1	11.8
Cerro Tololo (CTIO)	8.8	9.1	9.1	8.1	7.9	6.7	6.1	6.1	6.7	6.4	7.3
Total (NOAO)	22.7	23.0	24.9	23.8	23.0	20.0	18.6	18.5	19.6	19.5	19.1
(ii) NRAO	21.6	22.4	27.4	23.0	21.3	20.8	19.3	20.7	21.0	21.8	26.6
(iii) NAIC (Arecibo)	7.7	7.2	8.2	7.9	7.3	7.3	6.9	7.0	6.7	6.6	6.6
Total	**52.0**	**52.6**	**60.5**	**54.7**	**51.6**	**48.1**	**44.8**	**46.2**	**47.3**	**47.9**	**52.2**

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* Excluding the solar observatory.

The last major telescope to come on line at the CTIO was the 4.0m in 1975. Inspection of the data in Table 30 indicates that, here again, I have been unable to eliminate all capital costs prior to 1976 as the 1972 & 1973 costs, for example, are about the same as the 1976 & 1977 costs, after a temporary reduction in 1974 & 1975. I will thus ignore all pre-1976 CTIO running costs in this parametric analysis also.

The average annual costs of running the KPNO and CTIO observatories since the installation of the 3.8m and 4.0m telescopes respectively were, in 1992 dollars from Table 30:-

KPNO	for 1974 - 1992	$14.9m
CTIO	for 1976 - 1992	$ 7.8m

We now wish to examine how these KPNO and CTIO annual operations costs, which consist of a mixture of direct and indirect costs (as defined above), can be explained by the operations costs of the different telescopes at the two different observatories.

Abt[1] showed that the annual **direct** costs of operating the optical/IR telescopes of the KPNO in 1974 was $306k (see Table 31, next page). This compares with a total 1974 budget of $6.63m for KPNO* in 1974 rates (see Table 29). The difference between the annual cost that Abt quotes of $306k and the total annual cost of the optical/IR KPNO of $6.63m is vast. This difference represents the **indirect** costs of the observatory which Abt did not attempt to attribute to individual telescopes.

Plotting Abt's data on **direct** annual costs against telescope aperture (see Figure 19**, next page but one) shows that they are proportional to $d^{2.1}$.

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* Excluding the costs of the KPNO solar observatory.

** This is not the same as the annual cost graph in Abt's paper, that also had a slope of 2.1, as his graph was for the direct costs + 1/75th of the capital costs, whereas Figure 19 is for direct costs only.

TABLE 31

Abt's Data[1] for the Kitt Peak National Observatory in 1974

Telescope Costs and Expenses

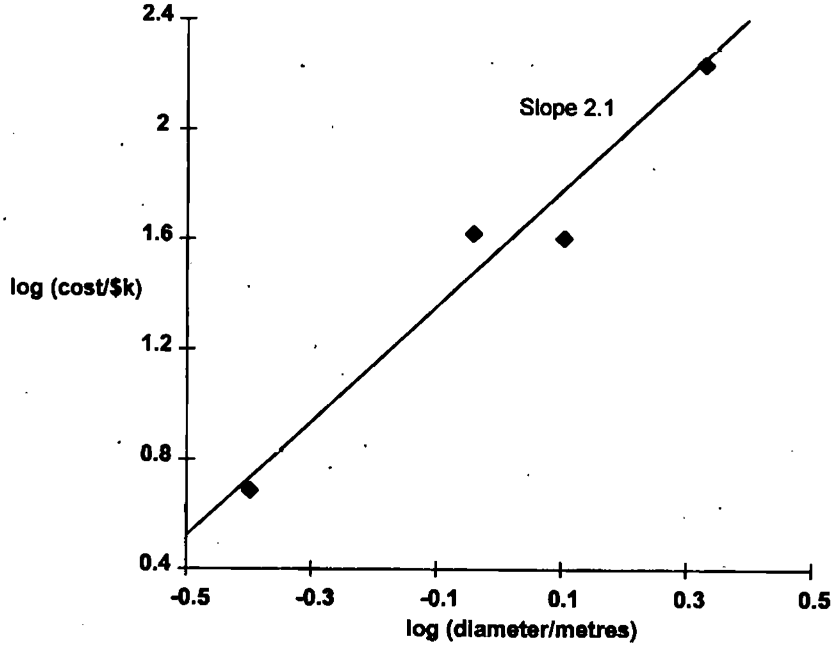
	Telescope (meters)			
	0.4 (mean)	0.9 (mean)	1.3	2.1
Instrumentation and improvements (FY74)				
Building and dome	–	1,200	385	11,536
Controls and console	-	3,500	1,332	5,172
Computer systems	–	3,500	4,000	11,314
Research and development	-	50	3,173	37,955
Instruments	–	700	–	35,351
Total, instr. & Imp.	-	8,950	8,890	101,328
Operations & maintenance (FY74)				
Telescope operators	-	-	-	23,000
Instrument support	-	3,100	2,200	3,600
Technical assistance	575	9,500	7,800	8,600
Janitor & maintenance	575	3,750	3,500	7,800
Electronic maintenance	-	3,200	3,200	3,600
Electricity	1,050	3,900	4,800	12,000
Dry ice, liquid air, liquid He, etc.	525	3,100	4,000	3,400
General supplies, plates	125	3,250	3,000	4,200
Magnetic tapes	1,000	1,500	1,000	2,000
Travel support	1,000	1,500	2,000	3,000
Total O&M	4,850	32,800	31,500	71,200
Total Annual (direct) costs	4,850	41,750	40,390	172,530

Note The total annual direct costs of the observatory were $306,120. (To get this figure the numbers in the first two columns have to be doubled, as there were two 0.4m and two 0.9m telescopes, before adding them to the numbers in the last two columns).

As the 1/75th of the capital costs are rather small, however, the slope of his graph and that of Figure 19 are the same to the first place of decimals.

FIGURE 19

The relationship of direct annual costs to aperture for KPNO telescopes in 1974 according to Abt[1]



Irvine and Martin[3] used Abt's $d^{2.1}$ relationship* to estimate the annual costs of operating the 2.1m telescope at the KPNO, the 1.5m at the CTIO, the 3.0m at the Lick Observatory, and the 2.5m INT at the RGO, in 1970, 1974 and 1978, from the total annual observatory operating costs as shown in Table 32A. They first reduced those for the KPNO by 30%** to eliminate the "solar, planetary and space work", and by 20% to eliminate "various central facilities used by astronomers to process observations obtained on telescopes other than those on Kitt Peak". They did *not* reduce either the CTIO or Lick costs, as these costs were reckoned to be completely attributable to stellar astrophysical work, but for the RGO they deducted 30% for

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* They also assumed that not just the direct operating costs + 1/75th of the capital costs varied as $d^{2.1}$, but that the indirect costs varied as $d^{2.1}$ also. In view of the difficulty of apportioning indirect costs, this seems a reasonable assumption, however.

** Irvine and Martin's basic cost data for the KPNO was the same as mine for the three years that they considered, but I only reduced the KPNO figure by 15% to eliminate the KPNO solar observatory in Tables 29 and 30.

TABLE 32

Approximate Annual Operating Costs from Irvine and Martin[3]

(A) Irvine and Martin's Data as presented (in real-year costs)

		CTIO	**KPNO**	**Lick**	**RGO**
Total observatory operating costs	1970		£2.68m	£0.37m	£0.70m
	1974		£3.33m	£0.57m	£1.35m
	1978	~ £2.1m	£4.77m	£0.90m	£2.00m
Reduce* by to get:-		0 %	50 %	0 %	60 %
Estimated costs of stellar astrophysics work at the observatory	1970		£1.34m	£0.37m	£0.28m
	1974		£1.67m	£0.57m	£0.54m
	1978	~ £2.1m	£2.39m	£0.90m	£0.80m
Percentage of the stellar astrophysics costs apportioned to the particular telescope being assessed		9.8%	17.2%	82%	72%
Estimated annual cost of the telescope being assessed	1970		£0.23m	£0.30m	£0.20m
	1974		£0.29m	£0.47m	£0.39m
	1978	~ £0.21m	£0.41m	£0.74m	£0.58m

(B) Above Costs converted to 1992 Dollars

		CTIO	**KPNO**	**Lick**	**RGO**
Total observatory operating costs	1970		$23.2m	$3.2m	$6.1m
	1974		$22.1m	$3.8m	$9.0m
	1978	~ $8.7m	$19.7m	$3.7m	$8.2m
	Average	**~ $8.7m**	**$21.7m**	**$3.6m**	**$7.8m**
Multiply by to get:-		9.8%	50% x 17.2%	82%	40% x 72%
Annual operating cost of telescope		$0.85m	$1.87m	$2.95m	$2.25m
Telescope diameter d (in metres)		1.52	2.14	3.05	2.44
$d^{2.1}$		2.41	4.94	10.40	6.51
Annual cost/$d^{2.1}$		0.35	0.38	0.28	0.35

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* See text.

"work on positional astronomy and providing certain national services (the National Almanac and Time Services)", and they deducted another 30% for "support services to telescopes overseas". This then gave them an estimate of the annual observatory costs attributable to stellar* astrophysics work (see Table 32A). They then split these annual costs between the various telescopes at a given observatory by assuming that operating costs are proportional to $d^{2.1}$ for each telescope. So, for example, $d^{2.1}$ for the 1.5m at the CTIO is 9.8% of the total of the $d^{2.1}$ values of all the telescopes at the CTIO. Thus 9.8% of the total annual operating costs at the CTIO are attributable to this telescope. Using this methodology they observed that, roughly:-

Cost of 3.0m Lick = 2.0 x Cost of 2.1m KPNO
Cost of 2.5m INT = 1.5 x Cost of 2.1m KPNO
Cost of 1.5m CTIO = 0.5 x Cost of 2.1m KPNO

as one would expect if the costs were proportional to $d^{2.1}$, *indicating that Abt's $d^{2.1}$ relationship is not only valid between telescopes within an observatory but also approximately between observatories.*

I have, in Table 32B, converted Irvine and Martin's cost figures into dollars at the prevailing sterling/dollar exchange rates of 1970, 1974 and 1978, and escalated them to 1992 dollars. I also show, in this table, the values of $d^{2.1}$ for the four telescopes concerned, and the ratio of annual** operating costs/$d^{2.1}$ which are, indeed, very similar, with an overall average# of \$0.33 million x metres$^{2.1}$.

Irvine and Martin were interested in comparing the cost of operating the INT (when it was at Herstmonceux) with those of similar size telescopes elsewhere. I, on the other hand, am trying to build up a picture of annual observatory costs over my

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* Stellar in this context includes galactic and extragalactic work.

** Direct and indirect.

\# i.e. ΣAnnual operating costs / $\Sigma d^{2.1}$ for the four telescopes.

geographical area of the United States and the British Commonwealth. Irvine and Martin's paper shows, however, that in doing this I must take into account that the two national observatories of the KPNO and the RGO have costs included in their annual accounts other than those used solely for operating 'stellar' telescopes. So my data for the KPNO above, which averaged $14.9m over 1974-92, needs reducing if I am to compare like-with-like. I had already reduced the KPNO base costs by 15% to eliminate the costs of the KPNO solar observatory (see Appendix 4), but they should be actually reduced by 50% to eliminate all 'non-stellar' costs as indicated by Irvine and Martin.

The annual operating costs of UK owned and/or shared facilities are analysed in Appendix 6 based on data in the PPARC report of 1995[26], data supplied by Le Masurier of PPARC[27], data in the PPARC files, and the reports of the various observatories[28,29,30]. In addition, the annual operating costs of the Mount Wilson and Las Campanas Observatories and of the Canada-France-Hawaii telescope on Mauna Kea are analysed in Appendix 7, using data taken from their annual reports[31,32]. All this data, and my data for the KPNO and CTIO discussed above, are summarised in Table 33A, together with Irvine and Martin's data for the Lick and RGO observatories.

The values of the ratios of $\dfrac{\text{Annual observatory operating costs}}{\sum d^{2.1}}$ are remarkably similar for the various observatories (see Table 33B), *with an overall average value the same as Irvine and Martin's of \$0.33 million x metres*$^{2.1}$. The ratio for the Las Campanas Observatory is so low, however, compared with that for the other observatories, that one has to wonder if all the costs have been included in the Carnegie Annual Report. Maybe there are other sources of funds, or maybe the split between Las Campanas and Mount Wilson is not correct, although the Mount Wilson

TABLE 33

(A) Average Annual Operating Costs for Optical/IR Observatories in 1992 Dollars

Observatory	Location	Period	Av. Cost (in \$m)
KPNO	Kitt Peak	1974 - 92	8.8*
CTIO	Cerro Tololo	1976 - 92	7.8
UKIRT	Mauna Kea	1980 - 92	6.0
ING	La Palma	1988 - 94	9.5
AAO	Siding Spring	1975 - 94	4.7
Mt Wilson	Mt Wilson	1974 - 83	2.4
Las Campanas	Las Campanas	1977 - 83	1.5
CFH	Mauna Kea	1981 - 94	5.5
Lick	Mt Hamilton	1970/74/78	3.6
RGO	Herstmonceux	Ditto	3.1**

(B) Annual Observatory Operating Costs as a Function of $\Sigma d^{2.1}$ of all their Telescopes#

Observatory	Av. Annual Cost in 1992 \$ millions	$\Sigma d^{2.1}$ of all Telescopes (d in metres)	Annual Cost/$\Sigma d^{2.1}$
KPNO	8.8	24.5	0.36
CTIO	7.8	21.5	0.36
UKIRT	6.0	16.5	0.36
ING	9.5	28.2	0.34
AAO	4.7	18.9	0.25
Mt Wilson	2.4##	9.1	0.26
Las Campanas	1.5	7.8	0.19
CFH	5.5	14.7	0.37
Lick	3.6	12.1	0.30
RGO	3.1	9.1	0.34
Total	**52.9**	**162.4**	**Average 0.31**
			σ_{n-1} = **0.06**

Overall Average $\dfrac{\Sigma \text{Av. Annual Costs}}{\Sigma\Sigma d^{2.1}} = \dfrac{52.9}{162.4} =$ **\$0.33 million x metres$^{-2.1}$**

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* 14.9 x (0.50/0.85)

** 7.8 x 0.40

\# Telescopes of diameter of < 0.6m ignored.

\#\# This figure includes the costs of running the solar telescopes. On the one hand, the ratio in the last column indicates that this cost is very small as the ratio is close to the overall average figure of 0.33, but the low ratio for its associated observatory at Las Campanas indicates that the cost may not be insignificant. I have assumed the cost is small in deriving the total of this column.

figure is on the low side also. Whether this Las Campanas ratio is correct or not, however, the effect on the overall average ratio will be very small, as the value of $\Sigma d^{2.1}$ for Las Campanas is only 5% of the total value of 162.4 shown in Table 33B.

I can now use this overall average ratio of 0.33 ± 0.06* from Table 33B to estimate the total annual running costs of all the optical/IR telescopes in Appendix 1A in 1992 dollars, based on their diameters.

The values of $\Sigma d^{2.1}$ for all the telescopes in Appendix 1A that were available in 1992, for example, and their consequential running costs, are shown in Table 34 by telescope category.

TABLE 34

Estimated 1992 Operating Costs of Telescopes in Appendix 1A, excluding the Keck

Telescope Category	$\Sigma d^{2.1}$		**∴ Cost in 1992 $m (from $\Sigma d^{2.1}$ x 0.33)**
(a)	194		64
(b)	134		44
(c)	73		24
(d) part	24		8
		Total	**140**

So the total annual running costs in 1992 was about $140m, excluding the costs of the Keck, as it was not in any of the telescope categories in Table 34.

The range of telescope diameters for the observatories in Table 33, from which I deduced the ratio of 0.33, covers those for all the telescopes in Appendix 1A with the exception of the 5m Palomar and the 9.8m Keck. The Palomar telescope is only just

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* Strictly speaking this ± 0.06 is the error about the average of 0.31, not about the overall average of 0.33, but it is a good enough estimate of error for the present purposes.

outside the range, however, but the Keck is way outside, so we have to be very careful about estimating the Keck's annual costs using the 0.33 factor.

Figure 17 showed that, on average, in the period since 1980 the capital costs of telescopes of a given diameter are about 40% of those in earlier decades. The cost of the Keck is even below the post-1980 line[*], however, as its capital cost was about 30% of the typical pre-1981 costs, although it is unlikely that this 70% reduction would transfer directly into a similar reduction in running costs. Now using $d^{2.1}$ x 0.33, deduced from Table 33, the 1992 running cost of the Keck would appear to be \$40m, but with a 70% reduction this would become \$12m[**]. I cannot find any data in the literature on the running cost of the Keck, so I will be cautious and use a figure half way between these two figures of \$26m ± \$14m, giving a maximum and minimum of \$40m and \$12m respectively (see Table 35)[#].

I also need to consider the effect of a possible under-estimate in the number of smaller telescopes in Appendix 1A. If the number of telescopes in categories (b), (c) and (d) part in 1992 were 43, 114 and 125, instead of 38, 94 and 68, respectively (see Table 23 and associated text), and if the extra telescopes were evenly distributed in size within their categories, then we would have the maximum operational costs shown in the last column of Table 35 (next page), instead of the original figures taken from Table 34 shown in the first column of Table 35.

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[*] The point for Keck I, which was the only Keck available in 1992, is the upper of the pair of points at the top right of Figure 16. (The other point is for Keck II).

[**] The 0.33 factor already covers a mixture of old and new telescopes (see Table 33A), so the full reduction by 70% for a completely new instrument appears unlikely, and a figure somewhere between \$40m and \$12m seems most probable.

[#] This inaccurate estimate for the annual running costs of the Keck will have little effect on the total running costs of all the optical/IR telescopes over the period from 1956 to 1992, which I will estimate shortly, as the Keck was only operational for two of those years.

TABLE 35
Estimated Annual Operating Costs for 1992

Telescope Category	**Annual Operating Costs in 1992 $s (in millions)** **Minimum**	 **Maximum**
Keck	12	40
(a)	64	64
(b)	44	50
(c)	24	29
(d) part	8	15
Total	**152**	**198**

Table 36 (next page) shows the known 1992 operating costs and the known total operating costs over various durations for the observatories previously listed in Table 33.

The average of the maximum and minimum estimated operating costs for 1992 given in Table 35 is \$175m, of which \$40m was known (see Table 36), giving \$135m estimated, i.e. \$109m + \$26m for the Keck. The error in the ratio used to calculate these estimated operating costs was ± 0.06 in 0.33, giving an error in the \$109m of $\pm\frac{0.06}{0.33}\times\$109\text{m}$, i.e. ± \$20m, excluding the error in estimating the operating cost of the Keck. To this error of ± \$20m, we must add ± \$23m to cover the estimated range of from \$152m to \$198m shown in Table 35, giving an rms error of ± \$30m*.

So the total annual operating costs, excluding major capital costs, of all the optical/IR telescopes in American and British Commonwealth observatories in 1992 was \$175m ± \$30m, at 1992 prices.

These annual operating costs for 1992 are based on the known operating costs of Table 36 and on the $\Sigma d^{2.1}$ x 0.33 synthetic for telescopes of unknown operating cost, using the telescopes listed in Appendix 1A, plus an allowance for unknown

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* i.e. rms error of ± \$20m and ± \$23m.

TABLE 36

Known 1992 and Known Total Operating Costs for Optical/IR Observatories in 1992 $s

Observatory	**Location**	**Operating Costs (in $m)** **For 1992 only**	 **Sum over time***
KPNO	Kitt Peak	6.9**	295#
CTIO	Cerro Tololo	7.3	191.6
UKIRT	Mauna Kea	6.0	78
ING	La Palma	9.5	47.5
AAO	Siding Spring	4.7	87.8
Mt Wilson	Mt Wilson	?	24
Las Campanas	Las Campanas	?	16.8
CFH	Mauna Kea	6.0	72.0
Lick	Mt Hamilton	?	10.8
RGO	Herstmonceux	?	9.3
	Total	**40.4**	**832.8**

telescopes. On a similar basis, the operating costs of optical/IR telescopes in my chosen geographical area over the whole period from 1956 to 1992 totalled about $3,300 million in 1992 dollars. This compares with total capital costs for the same telescopes of about $860 million ± $120 million, also in 1992 dollars (see Section 2.2.1 above).

I now need to estimate the likely error on this cumulative operating cost of $3,300m.

The error in the 1992 operating costs consisted of two parts (i) the error associated with the Keck plus that associated with a possible underestimate in the numbers of the smaller telescopes and (ii) the error produced by an estimated error of ± 0.06 in the 0.33 ratio. (i) gives an error of ± $100m and (ii) gives an error of:-

$$\pm \frac{0.06}{0.33} \times \$(3,300 - 830)\text{m} \approx \pm \$450\text{m}$$

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* These are the known totals over time up to and including 1992. These figures are not all complete, however, as they sometimes do not go back to the start of operations at an observatory.

** 11.8 x (0.50/0.85)

\# After using the ratio (0.50/0.85)

where $830m are the known operating costs (see Table 36). The root mean square of these two errors of ± $100m and ± $450m is ± $460m, or ± $500m in round numbers.

To get an estimate of the *total* cost of such optical/IR observatories in the period 1956–1992 we need to add to this $3,300m ± $500m a *proportion* of the $860m ± $120m capital costs of the telescopes that were in use for at least some time during this period. To do this we first need to estimate the useful lifetime of optical/IR telescopes, so that we know how much of their capital costs to include in our period.

2.3 Telescope Lifetimes

The oldest telescopes that produced useful results in this study are those given in Table 37, which indicates that they had an average useful lifetime* of about 75 years.

TABLE 37
The Oldest Telescopes used to Produce Data for the 15% Most-Cited Papers

(i) Year of first use	Dia. in metres	Telescope	(ii) Date of last paper	Hence Useful Life (ii) - (i) in Years
1879	0.91	Crossley reflector	1978	99
1888	0.91	Lick refractor	1958	70
1908	1.52	Mt Wilson	1978	70
1917	2.54	Hooker, Mt Wilson	1982	65
1918	1.83	Dominion Obs., Canada	1990	≥ 72
			Average**	**75**

These were the only pre-1920 telescopes referred to in the most-cited papers that I analysed. In addition to these, however, there were other pre-1920 telescopes of size ≥ 0.91m that did not appear in my list of most-cited papers, even though they were available in 1956, at the start of my period. They were:-

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* "Useful lifetime" in this context being the lifetime during which the telescope produced results that were analysed in the 15% most-cited papers.

** Assuming a figure for the Dominion telescope of 72 years.

Year of first use	**Dia. in metres**	**Telescope**
1891	1.52	Rockefeller Telescope
1910	1.07	Lowell Observatory
1897	1.02	Yerkes refractor
1911	0.94	University of Michigan

So only 5 out of 9, or 56%, of these early telescopes of aperture ≥ 0.91m appeared in my list of telescopes used to produce the most-cited papers.

For comparison with more modern telescopes, I arbitrarily took those telescopes that saw first light in the period 1948-1968, inclusive, with an aperture of ≥ 0.91m. Only 56% of these telescopes appeared in my list of telescopes used to produce the most-cited papers. So the fact that four pre-1920 telescopes did not appear in my list is not unusual, and I could assume a useful life for all 9 of these pre-1920 telescopes of about 75 years.

Telescopes are probably closed down more quickly now than a few decades ago but this figure of 75 years for the average useful life of a large telescope is probably about correct when considering the period 1956-92 as a whole.

2.4 Total Costs

I now need to calculate how much of the $860m ± $120m capital costs to write off during the period 1956–92, given this average telescope lifetime of about 75 years. The total costs of the optical/IR telescopes for 1956–92 is then this write-off figure plus the operational costs of $3,300m ± $500m for the same period.

I could apply the lifetime of 75 years to each of the telescopes in Appendix 1A on an individual basis and add up the number of years that are covered for each telescope by my period, but this is not really necessary in order to get an approximate estimate of the total capital costs that should be attributed to the period 1956–92. The largest such estimate would be

$$\frac{\$(860 \pm 120)\text{million x } 37 \text{ years}}{75 \text{ years}} \approx \$(420 \pm 60)\text{m}$$

but this would only be valid if all the telescopes were useful during the whole of my period. A fairer estimate, taking into account the start and finish dates of real telescopes is probably about half of this figure, or about $210m, with an error of about ± $80 bearing in mind the assumptions made[*]. This figure of $210m ± $80m is very small compared with the total operating costs of $3,300m ± $500m.

So the total costs (direct and indirect annual costs, and apportioned capital costs) of the optical/IR telescopes in American and British Commonwealth observatories that were operational some time during the period 1956-92 is approximately $3,500 million ± $500 million[**] *at 1992 prices.*

3 Ground-Based Radio Telescopes

The American and British Commonwealth Radio Telescopes available at some time between 1956 and 1992 are listed in Appendix 1B which is divided into:-

(a) Dish antennae that generally operate at ≤ 30 GHz (≥ 1cm wavelength) and that can move about two axes.

(b) Fixed dishes or those that can move only in declination.

(c) Dishes optimised for millimetre wavelengths.

(d) Submillimetre-wave dishes.

(e) Dish interferometers.

(f) Miscellaneous antennae and arrays.

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[*] I have assumed that the ratio could be anywhere from 1/3 to 2/3. This ± $80m is the root-sum-square of ± $70m and of the error of ± $30m in the $210m.

[**] Root-sum-square of ± $500m and ± $80m in round numbers.

The purpose of the separate listings is to try to list like-with-like, as far as possible.

Although I have consulted an extensive Bibliography to produce these listings, there are, no doubt, a number of telescopes which have been missed. As in the case of the Optical/IR telescopes above, however, I believe that the majority of the larger and more-expensive facilities have been listed, as these are generally well publicised, although a number of smaller facilities may be missing. This list should enable me, therefore, to produce a reasonably reliable estimate for the *total* cost of available radio telescope facilities, and to indicate the individual costs of the *major* facilities.

3.1 Initial Costs

The initial costs for a number of radio telescopes are listed in the 1964 Whitford report[18] and the 1972 Greenstein report[14]. These, together with those costs quoted elsewhere, are given in Table 38 (next few pages) and analysed in this section. As in the case of optical/IR telescopes, these costs exclude the costs of land and site development. This may be thought to be unfair in comparison with the costs of spacecraft where I have included the costs of launch vehicles, for example, although I have excluded the costs of purchasing and building the launch sites. So my general rule, applied across-the-board, was to exclude the purchase and development costs of land.

3.1.1 Dish Antennae operating at ≤ 30 GHz and Moveable about Two Axes

(i) The Jodrell Bank 76 metre

The 1964 Whitford report suggests that the Jodrell Bank 76 m radio telescope would have cost \$5m to \$10m to build in 1963 (see Table 38(a)), although it had been

TABLE 38

Costs of Radio Telescopes

(Excluding those used solely for solar work)

(a) Dish antennae[1,2]

(min. dish diameter 10 metres)

Dia. (m)		Date of First use	Initial Costs in $million				
			1963[3]	Historic[4]			
			Ref. 1	Ref. 2	Ref. 3	Other	
76		1957	5 to 10			1.79[5]	1957 Mark 1, Jodrell Bank, UK
						1.59[6]	1971 modified and called Mark 1A
64		1961	2.5		1.37[7]		Parkes, Australia
64	T[8]	1966	12	12			NASA Mars Antenna, Goldstone

Reference 1 Whitford, A.E., et al., "Ground-Based Astronomy; A Ten-Year Program", National Academy of Sciences - National Research Council, Washington DC., 1964. (Data taken mainly from Table E of this report).

Reference 2 Greenstein et al., "Astronomy and Astrophysics for the 1970's", Vol. 1 (1972) and Vol. 2 (1973), National Academy of Sciences, Washington DC.

Reference 3 Robertson, P., "Beyond Southern Skies", Cambridge University Press, 1992.

Note This table is self-contained with its own References 1, 2 and 3, as given above, and its own footnotes shown as numbered superscripts. These latter superscripts should not be confused with the references in the main text which are also shown as numbered superscripts.

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[1] Movable in both right ascension and declination, using either an equatorial or altazimuth design. Those fixed dishes, or those that can only move in declination, are listed in Table (b) below. Those dishes operating at frequencies > 30 GHz (< 1cm wavelength) are listed in Tables (c) and (d) below.

[2] Although outside our geographical area, the 100m Effelsberg radio telescope cost 34m DM, or about $9.0m, in 1972.

[3] At 1963 price levels.

[4] At the price levels pertaining to the year(s) in which the money was spent. This expenditure was often spread over a number of years.

[5] £640k. "Astronomer by Chance", by B. Lovell, Oxford University Press, 1992. Note. The £/$ exchange rates used in the above table are those prevailing at the time.

[6] £664k Modification cost, quoted in "Astronomer by Chance" by B. Lovell, Oxford University Press, 1992. He suggests on Page 222 of this book that it would have cost £20m to build the telescope in 1986. In the Millennium bid this was increased to £30m at 1995 rates. (NRAL private communication).

[7] The cost of A£610k was equivalent to about $1.37m. Total costs including laboratory, residential buildings, roads and site services was about A£900k.

[8] T in this column stands for Tracking, R for Radar and D for radome. See Appendix 1B for more details.

TABLE 38 (cont.)

(a) Dish Antennae cont.

Dia.		Date of	Initial Costs in $million				
(m)		First use	1963	Historic			
			Ref. 1	Ref. 2	Ref. 3	Other	
46	R	1959	0.35	0.35		0.35[9]	Stanford, California
46		~ 1966				0.822[10]	NRL, Sugar Grove, West Virginia
46		1965	2.7		4.0		Algonquin Obs., Ontario, Canada
43		1965	13.5	13.5	13.0	14.0	Green Bank, West Virginia
40		1968		1.6		1.2[11]	Caltech., Owens Valley, Big Pine
38 x 25		1964			0.7	0.67[12]	Mark II, Jodrell Bank
38 x 25		1966			0.4	0.39[13]	"Mark III", Nantwich, UK,
37	D	1963	1.9				MIT Lincoln Lab.
36		1971		0.5			Vermilion River, Illinois
26		1959	0.46				Lincoln Lab., MIT, Millstone Hill
26 (84 ft)		1957	0.25	0.25			NRL, Maryland Point, Washington
26	T	1958	0.75	0.75			Caltech, Goldstone, California, (DSN)
26	T	1960	0.75	0.75			Caltech, Goldstone, California, (DSN)
26*		1959	0.375	0.375			Univ. of Michigan, Portage Lake
26		1959	0.375				Howard Tatel 'scope, Green Bank
26* (85 ft)		1961	0.375				Harvard Coll. Obs., Ft. Davis, Texas
26		1962	0.35	0.35			Univ. of California, Hat Creek
18		1956	0.275				Agassiz Station, Harvard College Obs.
15		1951	0.10	0.10			Naval Research Lab., Washington
15	R	1960	0.30				MIT
12	T	1959	0.30				Ohio State Univ., Delaware
10		1956	0.025				Caltech., Owens Valley, Big Pine
10		1960	0.045				Univ. of California, Hat Creek

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[9] Sky & Telescope Dec. 1961.

[10] Sky & Telescope June 1965. This is the cost for the antenna and mounting (i.e. metalwork) only.

[11] Sky & Telescope April 1965. This is the contract price of the dish only.

[12] £0.24m. At 1962 rates. NRAL private communication.

[13] £0.14m. At 1963 rates. NRAL private communication.

* All telescopes shown with a * in this table were used mainly for solar observations.

TABLE 38 (cont. ii)

(b) Fixed dishes (including those that can move only in declination)

(min. dish diameter 10 metres)

Dia. (m)	Date of First use	Initial Costs in $million 1963 Ref. 1	Historic Ref. 2	Ref. 3	Other	
305	1963	4.00	9.00	9.00	8.30[14]	Arecibo. Puerto Rico[15]
92**	1962	0.90	0.90	0.90	0.85[16]	Green Bank, West Virginia[17]
30	1974				0.6	Higuillales, nr. Arecibo, Puerto Rico

(c) Dishes optimised for Millimetre Wavelengths

(Optimum Freq. > 30 and ≤ 300 GHz; Min. dish diameter 6 metres)

Dia. (m)	Date of First use	Initial Costs in $million (Historic) Ref. 2	Other	
36[18]	1966	6.5	15.0[19]	Haystack Hill, Westford, Massachusetts
32	1990		8.8[20]	Mullard Labs., Cambridge, UK
11[21]	1967	1.0		NRAO, Kitt Peak, Arizona

(d) Submillimetre-wave Dishes

(Optimum Freq. > 300 GHz; Minimum dish diameter 6 metres)

Dia. (m)	Date of First use	Initial Costs in $million (Historic)	
15	1987	18.8[22]	JCMT (James Clerk Maxwell Telescope), Mauna Kea

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[14] S. Tuttle (NSF) to DL, Private Communication, June 1996.

[15] Upgraded in 1972-74 at a cost of $8.8m. ($5.8m for resurfacing + $3.0m for installation of a radar capability).

** Can move in declination.

[16] Sky & Telescope February 1988 and March 1989.

[17] Resurfaced in 1970 at a cost of $0.65m. Dish collapsed and completely destroyed in 1988. (Sky & Telescope, March 1989).

[18] Has a radar capability and operates within a radome.

[19] Sky & Telescope December 1964.

[20] £4.9m. Including the cost of integrating it into MERLIN. (NRAO private communication).

[21] Protected by a radome.

[22] PPARC private communication.

TABLE 38 (cont. iii)

(e) Dish Interferometers (listed in reverse date order)[23]

Date of First use	Number of Dishes	Dia. of Dishes (m)	Initial Costs in $million	
1988/93	10[24]	25	87.65[25]	VLBA, USA, including Hawaii, & the Virgin Islands
1980	3	25	12.9[26]	Cheshire/Powys, UK
1977/81	27	25	78.6[27]	VLA, Socorro, New Mexico
1972	8	14	5.5[28]	Five km (or Ryle) Telescope, Mullard Labs., Cambridge
1971	5	18	2.0[29]	Stanford Univ., California
1968	2[30]	9	0.07[31]	Half-mile Telescope, Cambridge, UK
1967*	96	14	0.63[32]	Culgoora, Australia
1966	3[33]	26	1.4[34]	Green Bank, West Virginia
1964	3	18	1.54[35]	One Mile Telescope, Cambridge, UK
< 1964	4	9	0.10[36]	Stanford, California
1958	2	27	0.97[37] or 2.0[38]	Owens Valley, Big Pine, California

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[23] In 1991 the *estimated* cost of building a 6 off 6m dish *sub*-millimetre interferometer was about $50m. (Astronomy, March 1991).

[24] These dishes were all newly constructed for this array. Most other very large arrays are arrangements of the existing telescopes listed in table (a) above. As such, these very large arrays are not listed separately in this table of interferometers to try to avoid 'double counting'.

[25] See Appendix 4. (In 1984 the estimated cost was $70m, plus an annual operating budget of $5.0m; Sky & Telescope June 1985).

[26] £5.6m This is the cost of MERLIN; that is the cost of these three dishes, a nominal payment to RRE for the 25m Defford dish (built in 1965), and the interconnection costs of MERLIN. (NRAL private communication). This cost excludes the costs of the Jodrell Bank and Cambridge dishes.

[27] 'Sky & Telescope' Dec. 1980, and 'Astronomy' Aug. 1987.

[28] £2.2m. MRAO private communication.

[29] Probably only hardware cost as design done in-house. Bull.Am.A.S.,6, 1974. Ref. 2 also quotes a cost of $2.0m.

[30] Plus 2 more in 1972.

[31] £30k. In 1968. MRAO private communication.

[32] Hey, 'The Evolution of Radio Astronomy', Paul Elek, 1973.

[33] One of these three dishes is the original Howard Tatel Telescope (see Table (a) above). A second antenna was added in 1964, and a third shortly after.

[34] Ref.2.

[35] £550k. MRAO private communication.

[36] Ref.1.

[37] Ref.1.

[38] Ref.2.

TABLE 38 (cont. iv)

(f) Miscellaneous Antennae and Arrays (in reverse date order)

Date of First use	Initial Costs in $million	Size	Place
1983	0.35[39]	5 km	Low Freq. Synth., Cambridge
1975	0.055[40]	1.4 km	151 MHz Synth. (or 6C), Cambridge
1968*	0.06[41]	16 log periodic, 3.3 km array	Univ. of Maryland, Clark Lake
1967	0.05[42] or 0.10[43]	4 acre dipole array	Scintillation Telescope, Cambridge
1967	1.1[44]	1,600 m each arm	Molonglo Cross, Univ. of Sydney
1962	0.605[45] or 2.0[46]	79[47] x 21 m focusing para.	Perkins Obs., Ohio State, Delaware
1962	0.30[48] or 0.40[49]	180 x 120 m cyl. paraboloid	Univ. of Illinois, Vermilion River
1958	0.14[50]	700 m cyl. paraboloid	Radio star interf., (4C), Cambridge
1958	0.03[51]	1,000 and 30 m arms	Galactic radio telescope, Cambridge
1957*	0.20[52]	Two 24 x 14 m trih. corner reflectrs.	Boulder, Colorado
1952	0.02[53]	4 element interferometer, 100 x 12 m	2C Telescope, Cambridge[54]

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[39] £230k. MRAO private communication.

[40] £25k. MRAO private communication.

[41] Ref.2.

[42] £18k. MRAO private communication.

[43] £37k. B. Lovell, 'Astronomer by Chance', Oxford University Press, 1992, pg 294.

[44] Hey, 'The Evolution of Radio Astronomy', Paul Elek, 1973.

[45] $300k antenna, $175k receivers and instrumentation, $30k prime focus lab. and feed antenna, and $100k buildings, roads and other site facilities (Sky & Telescope July 1963).

[46] Ref.2. The extra cost over $0.605m is due, presumably, to the cost of increasing its size from 79m to 104m in 1970.

[47] Increased to 104m in 1970.

[48] Ref.1.

[49] Ref.2.

[50] £50k. MRAO private communication.

[51] £10k. MRAO private communication.

[52] Ref.2.

[53] £6k. MRAO private communication.

[54] Later called the 3C Telescope.

completed in 1957 at a cost of just £640k*, equivalent to about $1.8m at 1957 exchange rates (see Appendix 5). The main construction work on this telescope took place between 1952 and 1957, and so, assuming that this £640k was in 1955 prices on average, and inflating the cost to 1963 rates produces a figure of £800k or $2.24m. This is nowhere near the Whitford figure of $5m to $10m. Even allowing for the uncosted time of the University people and the fact that the contractor may have lost money, it seems unlikely that the total cost exceeded $3.0m at 1963 rates.

In 1971 the 76 m dish** at Jodrell Bank was modified at a cost of £664k. Inflating both the original construction cost of £640k and this £664k to *1992 rates* gives a total cost of £8.1m + £4.5m = £12.6m. Lovell suggests[33] that it would have cost about £20m to build such a telescope in 1986 prices, which were increased to £30m at 1995 prices in the NRAL Millennium bid[34]. These latter two figures are both equivalent to about £27m at 1992 prices, or just over double the actual cost of £12.6m, after allowing for inflation. Lovell attributes this difference to the fact that material and construction costs for major civil engineering structures have increased at a faster rate than the normal inflation rate since the 1950's, but this must already have happened by 1963 if the Whitford estimates are to be believed. Lovell's suggested reason may have been a factor in the late 50's/early 60's, but the uncosted time of University staff and the fact that the contractor may have lost money on the original construction may also have contributed to the low initial construction cost. The use of one or two government surplus items also kept the original cost down. The Whitford and the more-recent Lovell estimates may have been over-estimates, of course, and so it seems best, therefore, to use a range of costs going from the actual costs of £12.6m, at 1992 rates, to the more recent Lovell/Jodrell Bank estimates of

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* The source of this, and other costs in this section, are given in the footnotes to Table 38.

** I often refer to the cost of 'dishes', 'antennae' or 'telescopes' in Section 3. These terms are used interchangeably in this thesis when discussing costs, unless stated otherwise. This enables me to refer to the cost of '15 GHz dishes' rather than of 'telescopes using dishes operating at 15 GHz', for example.

£27m at 1992 rates. This is equivalent to a range of from $22m to $48m, at the same rates.

(ii) Other Telescopes

Comparing the costs quoted in the Whitford report with those quoted elsewhere for dish antennae (see Table 38(a)) we find that there are two other significant discrepancies:-

(i) The $2.5m quoted in the Whitford report at 1963 rates for the Parkes telescope equates to about $2.3m at 1961 rates (the year of completion). This compares with A£610k, or $1.37m quoted as the actual cost by Robertson[35] in his book on Australian astronomy, or A£900k, or $2.0m if the costs of the laboratory, residential buildings, and site services are included. It seems likely, therefore, that the costs quoted by Whitford are based on this latter figure, although Whitford categorically states that he tried to eliminate site costs as far as possible. As I wish to exclude these costs also, I will use the Robertson figure of $1.37m suitably escalated for price increases.

(ii) The 46m Algonquin telescope was still under construction when the Whitford report was written, and so I will use the $4.0m cost quoted by Robertson, rather than the $2.7m quoted by Whitford which could only have been a predicted cost.

There are some telescopes listed in Table 38(a) whose costs were not listed in the Whitford report. Of these, only the 40m Caltech telescope has two significantly different cost figures quoted in two different references, however, and this was justified for this telescope as the lower figure was for the dish only. So Table 38(a) shows no other cost inconsistencies than those already discussed.

(iii) Consolidated Data

The costs for dish antennae quoted in Table 38(a) above are given in Table 39(a) (next page) in *1992 dollars* based on the above analysis. These costs, which are plotted against diameter on a log/log plot in Figure 20 (page after Table 39), show a considerable scatter about a linear relationship compared with the equivalent graph for optical/IR telescopes of Figure 14. This scatter is because some of the dishes represented in Figure 20 were build for satellite tracking or communication purposes, where operations must be performed under extreme weather conditions when it would be acceptable to temporarily close down a radio telescope. In addition, the required surface tolerances for dishes represented in Figure 20 vary greatly, as the points cover dishes operating at maximum frequencies of from 0.4 GHz (for the 46 m Stanford antenna) to up to 30 GHz, see Appendix 1B. The points for the dishes at both ends of this frequency scale (i.e. high frequencies of ≥ 15 GHz or low frequencies of ≤ 1.0 GHz) are designated in Table 39(a) and Figure 20[*] , together with those points representing dishes designed to operate in extreme weather conditions (as T for Tracking, R for Radar and D for fitted Radome). The regression line drawn through the remaining points, covering the frequency band from > 1.0 to < 15 GHz, has a slope of about 2.2. For clarity these remaining points, and their associated regression line, are reproduced in Figure 21 without the T, R, D and high- and low-frequency points of Figure 20. Here the liner relationship is much clearer.

There is a suggestion, looking at the points representing the high-frequency (≥ 15 GHz) radio telescopes in Figure 20, that the slope for such telescopes is higher than the 2.2 slope for the > 1 to < 15 GHz telescopes. In fact, the best-fit regression line through these high-frequency points has a slope of 3.7 (see Figure 22A). The largest

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[*] Most of the costs in Table 39(a) relate to the costs of telescopes of the original build standard. So the frequency of operation of the telescope in that original configuration is generally used to analyse those costs, not its current frequency which is often higher because of later modifications (of unknown cost).

TABLE 39

Consolidated List of Initial Costs of Radio Telescopes at 1992 Rates

(Excluding those used solely for solar work)

(a) Dish antennae

Dia. in metres		Date of First use	Initial Cost in $million	
76		1957	22 - 48	Mark 1A, Jodrell Bank, UK
64		1961	6.6	Parkes, Australia
64	T[*]	1966	56	Mars Antenna, NASA, Goldstone, California
46	R, L	1959	1.6	Stanford, California
46		~ 1966	> 3.5	Naval Research Lab., Sugar Grove, West Virginia
46	H	1965	18	Algonquin Obs., Lake Traverse, Ontario, Canada
43	H	1965	60	Green Bank, West Virginia
40	H	1968	6.5	Caltech., Owens Valley, Big Pine, California
38 x 25		1964	3.1	Mark II, Jodrell Bank
38 x 25		1966	1.7	Nantwich, UK
37	D	1963	8.8	MIT Lincoln Lab.
36		1971	1.7	Vermilion River, Illinois
26		1959	2.1	Lincoln Lab., MIT, Millstone Hill, Mass.
26 (84 ft)		1957	1.2	Naval Research Lab., Maryland Point, Washington
26	T	1958	3.5	Caltech, Goldstone, California
26	T	1960	3.5	Caltech, Goldstone, California, (DSN)
26	H	1959	1.7	Univ. of Michigan, Portage Lake
26		1959	1.7	Howard Tatel 'scope, Green Bank, West Virginia
26 (85 ft)		1961	1.7	Harvard Coll. Obs. Field Station, Ft. Davis, Texas
26		1962	1.6	Univ. of California, Hat Creek
18		1956	1.3	Agassiz Station, Harvard College Obs.
15	H	1951	0.5	Naval Research Lab., Washington
15	R	1960	1.4	MIT
12	T, L	1959	1.4	Perkins Obs., Ohio State Univ., Delaware, Ohio
10		1956	0.12	Caltech., Owens Valley, Big Pine, Calif.
10		1960	0.20	Univ. of California, Hat Creek

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[*] T in this column stands for Tracking, R for Radar, D for radome, L for low frequency and H for high frequency. See the text and Appendix 1B for more details.

TABLE 39 (cont.)

(b) Fixed dishes (including those that can move only in declination)

Dia. in metres	Date of First use	Initial Cost in $million	
305	1963	55.0*	Arecibo. Puerto Rico
92	1962	6.5**	Green Bank, West Virginia
30	1974	1.7	Higuillales, nr. Arecibo, Puerto Rico

(c) Dishes designed for Millimetre or Sub-Millimetre Wavelengths
(Maximum Freq. > 30 GHz)

Dia. in metres	Date of First use	Initial Cost in $million	
36	1966	28 - 65	Haystack Hill, Westford, Massachusetts
32	1990	9.4	Mullard Labs., Cambridge, UK
15	1987	23	JCMT, Mauna Kea
11	1967	4.2	NRAO, Kitt Peak, Arizona

(d) Dish Interferometers

Date of First use		No. of Dishes	Dia. of Dishes in m	Freq. in GHz	Max. Dist. in km	Initial Cost in $m (a)	Estimated Dish Cost Only (see text) (b)	Ratio (b)/(a)
1988/93	VLBA	10	25	43	8,000	88	10 x 3.9 = 39	0.44
1980	MERLIN	3+	25	24	150	22	3½ x 3.9 = 14	0.64
1977/81	VLA	27	25	24	25	152	27 x 3.9 = 105	0.69
1972	Five km	8	14	30	5	18	8 x 1.1 = 8.8	0.49
1971	Stanford	5	18	10	0.2	6.9	5 x 0.65 = 3.3	0.48
1968	Half-mile	2	9	1.4	0.8	0.3	2 x 0.08 = 0.16	0.53
1967	Culgoora	96	14	0.08	3	2.6		
1966	Green Bank	3	26	8-15	5	6.1	3 x 1.5 = 4.5	0.74
1964	One Mile	3	18	1.4-5	1.6	7.0	3 x 0.65 = 2.0	0.29
< 1964	Stanford	4	9	1.4		0.5	4 x 0.08 = 0.32	0.64
1958	Owens Valley	2	27	3-11	0.5	7.6	2 x 1.6 = 3.2	0.42

Average ratio (excluding special case of the VLBA) = 0.55 ± 0.14 (1σ) ≈ 0.5

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* 38.5 + 16.5 (i.e. total cost of improved dish, see text)

** 4.25 + 2.25 (i.e. total cost of improved dish, see text)

TABLE 39 (cont. ii)
(e) Miscellaneous Antennae and Arrays

Date of First use	Initial Costs in $million	Size	
1983	0.50	5 km	Cambridge Low Freq. Synth.
1975	0.14	1.4 km	151 MHz Synth. (or 6C), Cambridge
1968	0.24	16 element, 3.3 km array	Univ. of Maryland, Clark Lake
1967	0.32	4 acre dipole array	Scintillation Telescope, Cambridge
1967	4.61	1,600 m Molonglo Cross	Sydney
1970	7.19	104 x 21 m focusing paraboloid	Perkins Obs., Ohio State Univ.
1962	1.65	180 x 120 m cyl. paraboloid	Univ. of Illinois, Vermilion River
1958	0.71	700 m cyl. paraboloid	Cambridge interf. array (4C)
1958	0.15	1,000 and 30 m arms	Cambridge galactic array
1957	1.03	Two 24 x 14 m corner reflectors	Boulder, Colorado
1952	0.11	4 element interf., 100 x 12 m	2C Telescope, Cambridge

moveable dish in the world, the 100 m Effelsberg antenna in Germany, has not been included in my analysis, as it is not in my stated geographical area, but including it temporarily could help to clarify the gradient for high-frequency telescopes. Effelsberg was originally built to operate at a maximum frequency of 15 GHz[#] and, as such, is a higher-frequency telescope in the terms of Figure 20. The Effelsberg telescope originally cost 34m DM, or about $9m in 1972, which is equivalent to about $30m in 1992 rates. This would have put it exactly on the regression line in Figure 20, and including it in my analysis (as point E in Figure 22B) reduces the slope of the regression line for high-frequency dishes to 2.4.

Now the 43 m dish at Green Bank (G in Figures 22A & B) is a special case, because it is the only equatorially-mounted large dish antenna. This equatorial mounting of such a large dish would have increased its costs over that for equivalent Alt-Azimuth designs. Excluding the point for the 43 m, and including that for the 100 m Effelsberg (which *is* of Alt-Azimuth design), reduces the slope of the regression line for the high-frequency telescopes to 2.3 (see Figure 22C) which is, within error, the same as that shown in Figures 20 & 21 for medium frequency telescopes.

[#] Although it has since been upgraded to operate at higher frequencies.

FIGURE 20

Initial costs at 1992 rates, taken from my consolidated list of Table 39, plotted against dish diameter for dish-type radio telescopes that generally operate at ≤ 30 GHz (≥ 1 cm wavelength), and which can move about two axes. The least-squares regression line is only plotted through the medium frequency points (15 GHz > ν > 1.0 GHz), however, and it also ignores those points for antennae with extra capabilities (shown as T, R or D). The regression line is reproduced, with the medium frequency points only, in Figure 21.

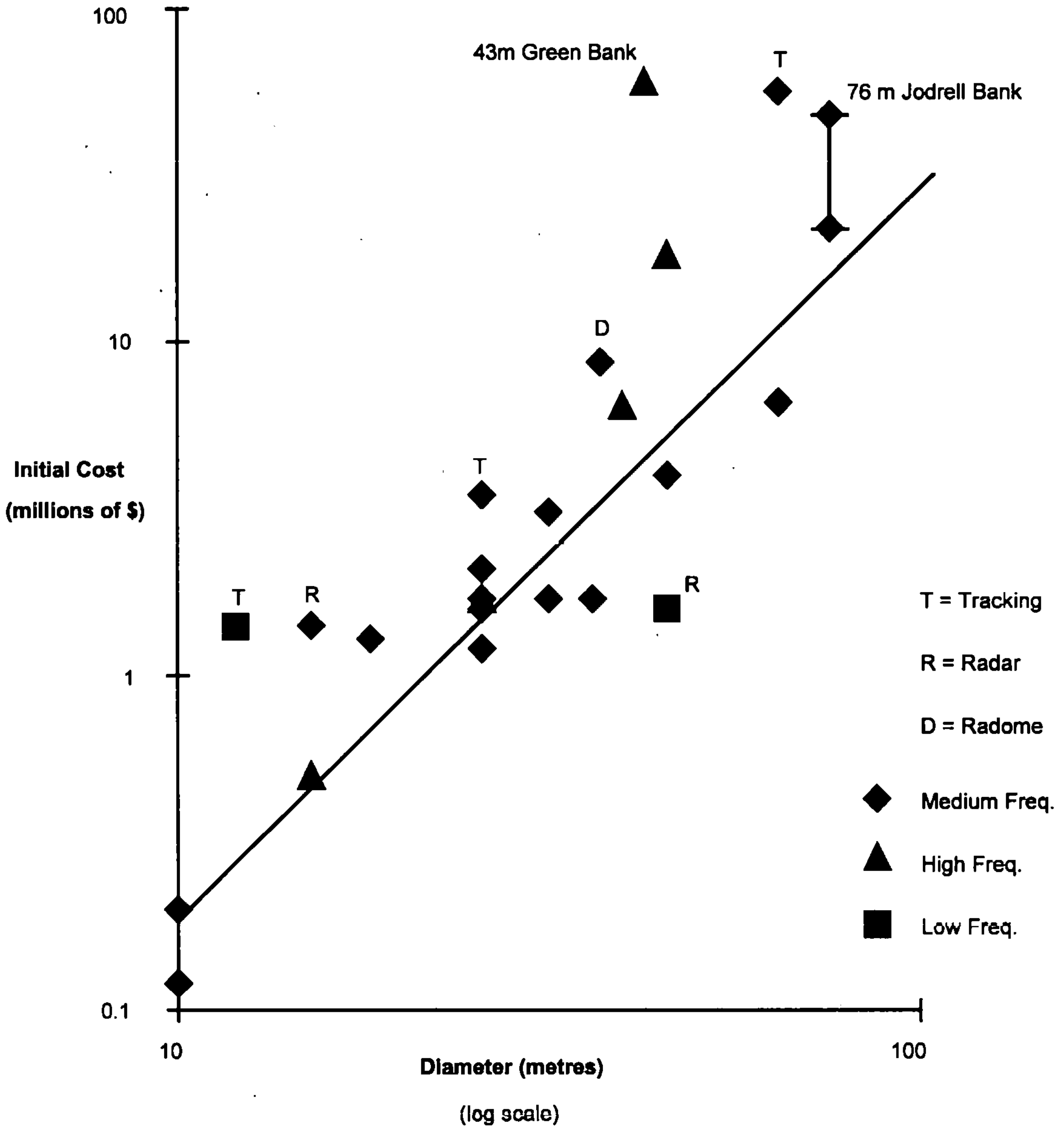


FIGURE 21

Initial costs at 1992 rates, plotted against dish diameter, for dish-type radio telescopes that originally operated at maximum frequencies of > 1 and < 15 GHz. The points are the medium-frequency points of Figure 20, excluding those designated T, R or D in Figure 20. The least-squares regression line below is reproduced in Figure 20.

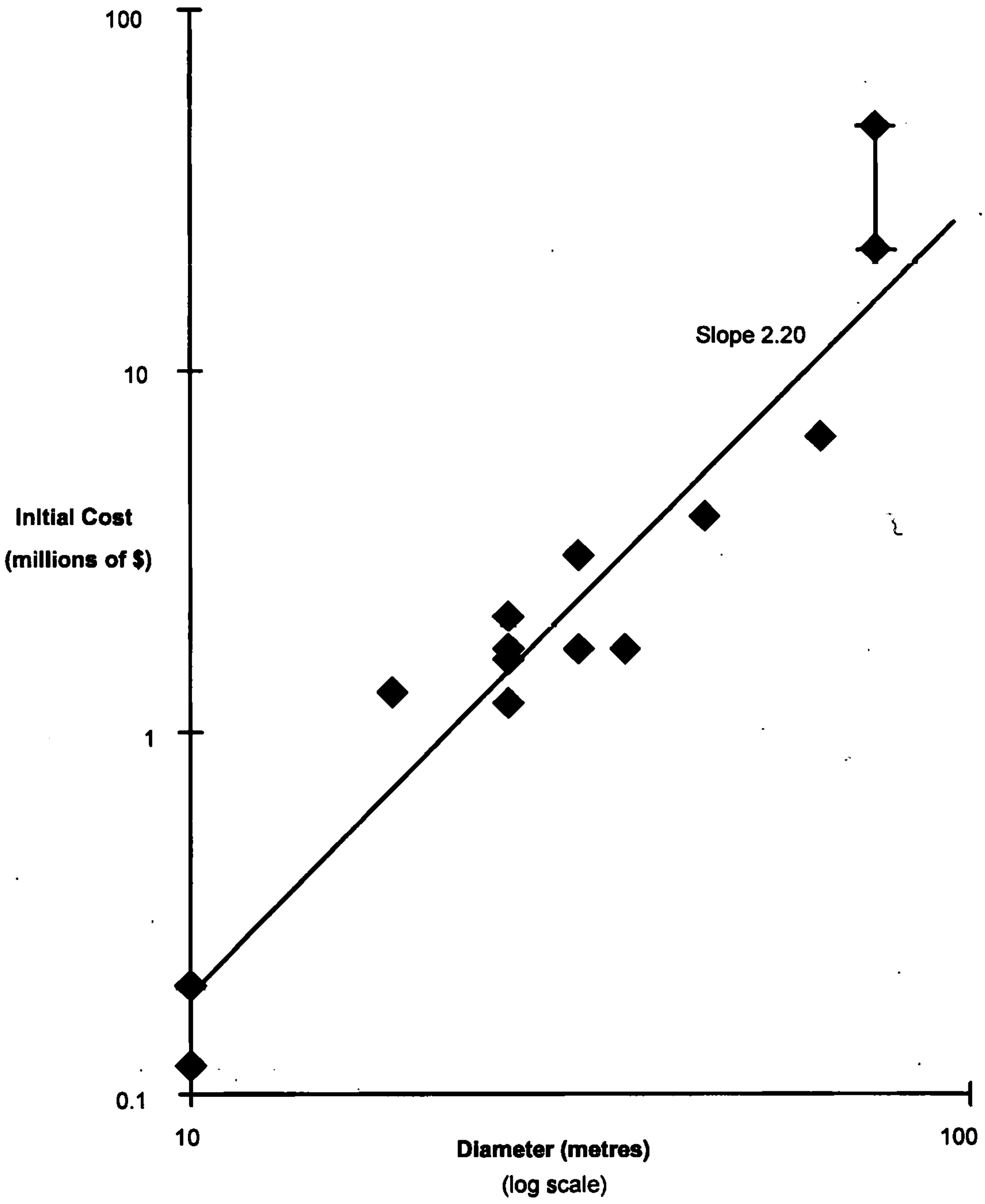
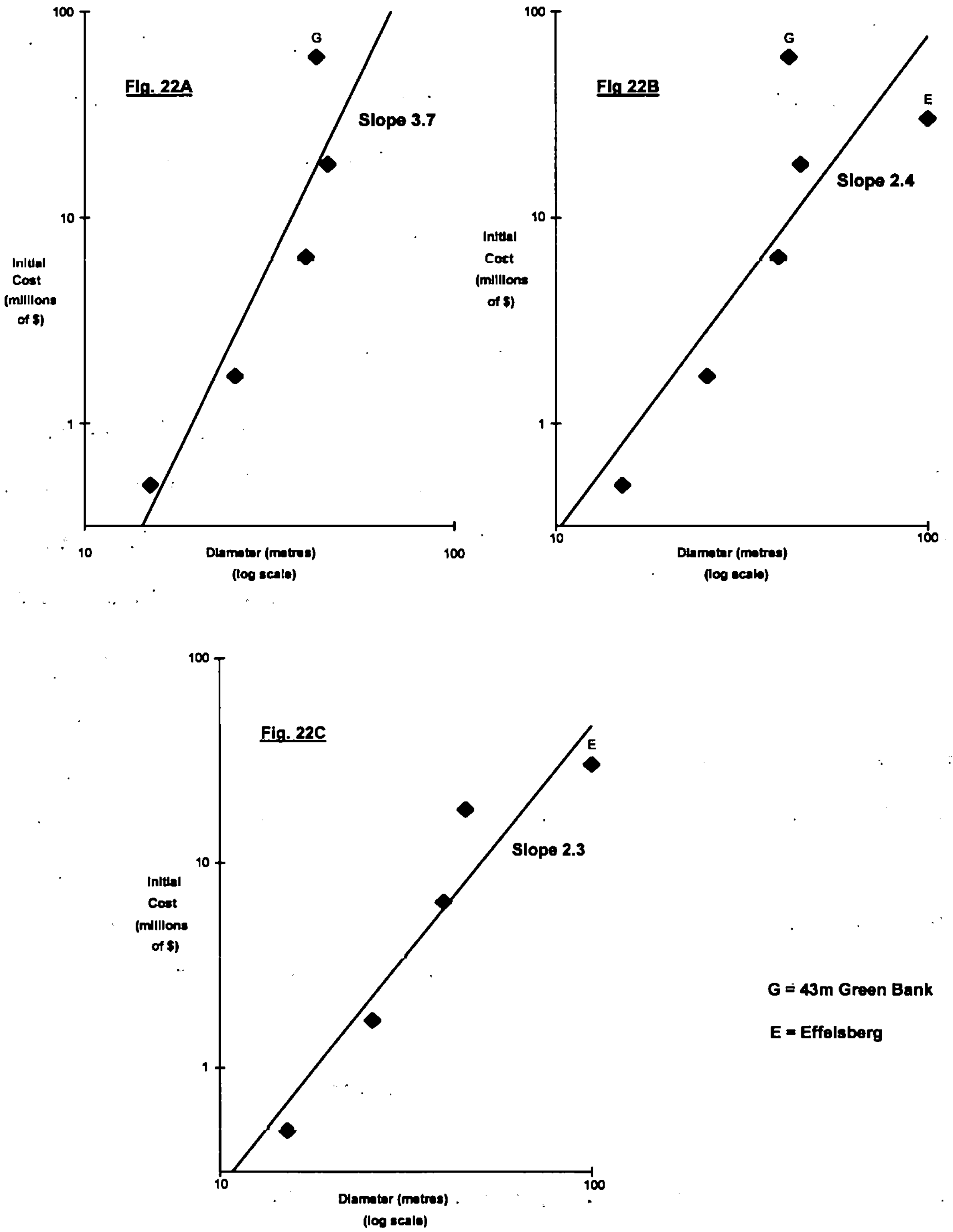


FIGURE 22

Initial costs at 1992 rates, plotted against dish diameter, for dish-type radio telescopes that originally operated at maximum frequencies of ≥ 15 and ≤ 30 GHz. The three different graphs, Figs. 22A to C, show the effect of including the 43m Green Bank radio telescope, the Green Bank and Effelsberg telescopes, or the Effelsberg telescope, respectively.



The points representing the possible cost of the 76 m Jodrell Bank telescope are clearly above the regression line in Figure 20, and yet, as mentioned above, the point for the Effelsberg dish would have been on the line. The Effelsberg telescope was constructed 15 years after the 76 m Jodrell Bank telescope and it also operates at a higher frequency than the 76 m. This clearly questions the recent high cost estimates for a rebuild of the Jodrell Bank instrument (the upper of the two points in Figures 20 & 21), and, in particular, questions Lovell's suggestion, mentioned above, that construction costs have out-stripped general inflation. As the Effelsberg design is completely different from that of the Jodrell Bank dish, however, this point must remain open.

(iv) Summary

So the slope of the regression line for medium frequency dishes (15 GHz > ν > 1.0 GHz) is about 2.2, and that for high frequency dishes (30 GHz ≥ ν ≥ 15 GHz) is about 2.4 or 2.3, depending on whether I include the 43m equatorially-mounted Green Bank antenna or not. In all these cases I have ignored the special Tracking (T), Radar (R) or Radome-covered (D) antennae in producing the regression lines

In 1964 Whitford[18] undertook a similar analysis, also excluding the T, R and D antennae, and found a slope of 2.5 for both the medium and high frequency dishes treated together. I have disagreed with one or two of Whitford's costs, as discussed above, and have added more up-to-date data, but it is encouraging to see a relatively close agreement between the slopes of my regression lines and that of Whitford's.

3.1.2 Fixed Dishes or Dishes that can move about only One Axis

The main two telescopes in this category (Appendix 1B(b)) are the fixed 305 m diameter Arecibo dish, and the 92 m Green Bank dish that could move about only one axis.

The Whitford report quotes a cost for the Arecibo telescope of \$4.0m (Table 38(b)), but the Whitford report was written before the telescope was finished. A more reliable figure is the \$8.3m quoted by Tuttle of the NSF, which was rounded up to \$9.0m in the other two references quoted in Table 38. The maximum operating frequency for Arecibo was increased to about 5 GHz in 1972-74 at a total cost of \$5.8m*. So the cost *at 1992 prices* was about \$38.5m (based on Tuttle's \$8.3m figure) for the original design, plus about \$16.5m for the modifications, or about \$55.0m in total, as shown in Table 39(b).

The 92m Green Bank telescope was also resurfaced in 1971 to enable it to operate at the same higher frequencies of about 5 GHz, resulting in a total cost in 1992 prices of about \$4.25m + \$2.25m = \$6.5m.

Interestingly, the Jodrell Bank 76 m had also been resurfaced in 1971 to enable it to operate at frequencies up to about 5 GHz, and its modification costs compared with those of Arecibo and the Green Bank 92 m are as follows, in 1992 prices:-

Dia. in metres	**No. of Axes of Movement**	**(i) Orig. Cost**	**(ii) Mod. Cost**	**Total Cost**	**[(ii)/(i)] x 100%**
305	0	\$38.5 m	\$16.5 m	\$55.0m	43 %
92	1	\$ 4.25m	\$ 2.25m	\$ 6.5m	53 %
76	2	\$14.3 m	\$ 8.0 m	\$22.3m	56 %

The percentage extra cost for each of these frequency upgrades is very similar.

Figure 23 shows, inter alia, the total costs of these three telescopes plotted against diameter on a log/log plot. Both the \$22.3m figure mentioned above and the higher \$48m figure, discussed in Section 3.1.1(i), are plotted for the Jodrell Bank telescope, as on Figures 20 and 21. The bold line in Figure 23 is the regression line from Figures 20 & 21.

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* This excludes the cost of the radar system which was also installed at the same time.

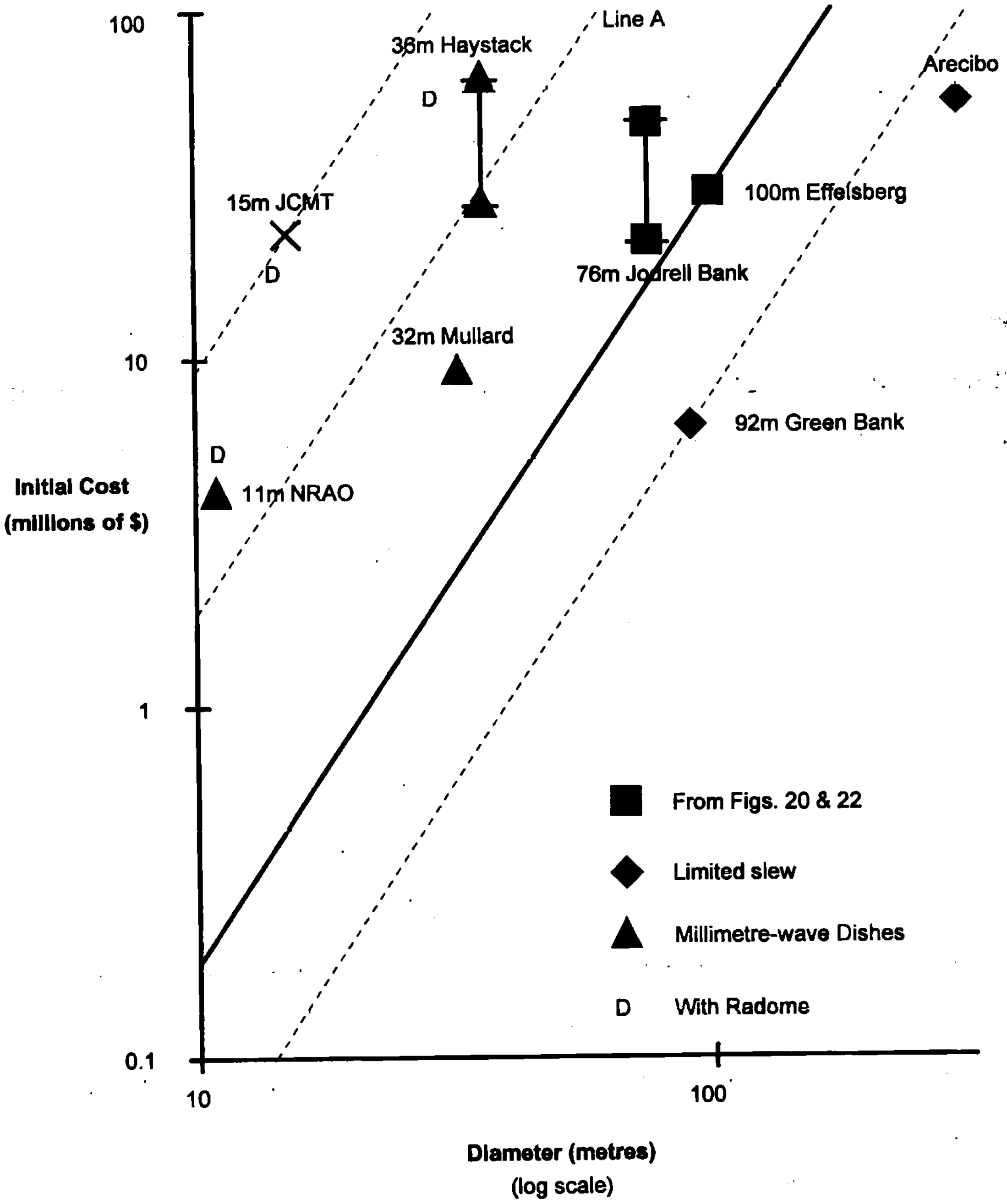
FIGURE 23

Capital costs at 1992 rates plotted against dish diameter, for various large and/or very high frequency telescopes. The solid line is the regression line from Figure 21, and the dotted lines are drawn parallel to it.

The fixed Arecibo dish is less expensive than the single-axis 92m Green Bank instrument, when normalised for diameter differences, which is, in turn, less expensive than the two-axis Jodrell Bank and Effelsberg telescopes.

The 32m Mullard telescope is the least expensive of the four very high frequency instruments, probably because it is the only one without a radome, and the JCMT is the most expensive, probably because it operates at the highest frequency of these four telescopes.

Line A is the best-fit line constrained to be parallel to the solid line, for the three millimetre-wave dishes.



The points for both the Arecibo and 92 m Green Bank telescopes are below the bold line for the telescopes of Figures 20 and 21, as the Arecibo and Green Bank instruments do not have a two axis tracking capability. Using this bold line for guidance, to take account of diameter differences, the Arecibo telescope appears significantly less expensive than the Green Bank instrument, which is what one would expect for the fixed-dish Arecibo telescope when compared with the moveable-dish Green Bank instrument.

3.1.3 Dishes designed to operate at > 30 GHz

The costs of the 36 m Haystack radio telescope are quoted as $6.5m in the Greenstein report, but as $15.0m in Sky & Telescope. I have no further data to indicate which is correct and so both costs are quoted in Table 38(c) and escalated to 1992 rates in Table 39(c). These costs at 1992 rates for the Haystack telescope, and those for the 32 m Mullard telescope at Cambridge, the 11 m telescope at Kitt Peak, and the JCMT on Mauna Kea are plotted in Figure 23. The JCMT (Tables 38(d) & 39(c)), which is the only one of these telescopes designed to operate at submillimetre wavelengths, appears, as expected, to be the most expensive relative to the bold line on Figure 23. The fact that the JCMT was constructed at such a remote observatory as Mauna Kea would also have added to its cost. The 32 m Mullard antenna appears to be the cheapest of this group, partly because it is the only one not protected by a radome.

3.1.4 Dish Interferometers

A number of factors need to be considered in trying to analyse the costs of dish interferometers. The main ones being the:-

(a) Number of dishes

(b) Maximum frequency of operation

The first question that has to be addressed, to be able to estimate the unknown costs of some interferometers, is "what proportion of the cost of an interferometer is due to the cost of the dishes?"

In Tables 38(e) and 39(d) there are three interferometers which use 25 metre diameter dishes operating at approximately the same maximum frequency (in the range 24 - 43 GHz). They are the VLBA, MERLIN and the VLA. The three MERLIN dishes (listed under Cheshire/Powys in Table 38(e)) were bought for about £1m ($2.3m) each from the VLA production run which, when escalated to 1992 prices, becomes about $3.9m each. MERLIN originally cost $12.9m to build in 1980 (or $22m at 1992 prices), including the cost of three of the VLA-type dishes, plus an undisclosed nominal payment for the 25 m Defford dish. Assuming that the latter payment was half of that for a VLA dish, the 25 m dish costs included in MERLIN would be about $14m at 1992 prices, or 64% of the total cost (see the last column of Table 39(d))*.

If the VLA paid the same as MERLIN for each of its 27 dishes, this would have cost about $105m in 1992 prices. In fact, the VLA cost a total of $78.6m in 1979, or about $152m in 1992 prices. So the dishes would have accounted for about 69% of the total VLA cost (Table 39(d)). A similar calculation for the VLBA, assuming that the dishes cost the same as for the VLA, produces a total dish price of 44% of the total cost.

Interconnecting the VLA dishes and the MERLIN array was *relatively* straightforward and inexpensive compared with the interconnection of the 10 VLBA dishes over distances of up to 8,000 km. In addition, one of the VLBA dishes was installed on Mauna Kea, which is a relatively expensive site because of its inaccessibility, and one was installed on the Virgin Islands. Linking these two

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* In this calculation I have ignored the costs of the Jodrell Bank Mark I, II and III telescopes as they were already operational and were not included in the quoted MERLIN costs.

overseas sites into the mainland network, which was itself highly dispersed, probably explains why the dish portion of the total VLBA construction costs is lower than for the VLA and MERLIN (Table 39(d)).

One other interferometer listed in Table 39(d) operated at about the same maximum frequency as the above, namely the Five Kilometre Cambridge Telescope consisting of eight 14m dishes. Using the VLA dish price adjusted for the smaller size (assuming that the costs vary as the diameter to the power of 2.2) results in a total dish cost of about $8.8m, or about 49 % of the total cost.

These estimates of the dish costs of the MERLIN, VLA, VLBA and Cambridge Five Kilometre telescopes are based on the costs to MERLIN of about $3.9m (in 1992 rates) of each of the three 25m VLA dishes. Using the regression lines of Figures 22B and C, however, give costs of $2.8m and $2.0m, respectively, for such 25m dishes. It thus appears as though the cost of the VLA dishes to MERLIN may have been on the high side, possibly because of high transportation costs and/or unfavourable sterling/dollar exchange rates, for example. If these costs were on the high side, then so are the ratios for the VLA, VLBA and Cambridge 5km in the last column of Table 39(d). As $3.9m/$2.0m is about 2.0, so these ratios could have been over-estimated by a factor of two. This would reduce the ratios from 0.69, 0.44 & 0.49 (Av. 0.54) to 0.35, 0.22 & 0.25, respectively, (Av. 0.27).

The second question to be addressed is "what effect has the maximum frequency of operation of an interferometer on its capital cost?"

The other interferometers listed in Table 39(d) (all with maximum operating frequencies < 24 GHz) fall broadly into three categories, determined by their maximum frequency of operation, namely (next page):-

Max. Freq. **5 - 15 GHz**	**Max. Freq.** **~ 1.4 GHz**	**Max. Freq.** **0.08 GHz**
Stanford 5 x 18m	Half-mile	Culgoora
Green Bank	Stanford 4 x 9m	
One-mile		
Owens Valley		

Using the regression line of Figure 21 to deduce the dish prices for the four 5 - 15 GHz interferometers listed in the first column above gives the results shown in Table 39(d). This gives an average dish/total cost ratio for these interferometers of 0.48, which indicates that the ratios in the last column of Table 39(d) for the VLA, VLBA and Cambridge 5km may be more nearly correct than the numbers reduced by a factor of two that had been suggested above.

The regression line of Figure 21 is for dishes that can operate at a maximum frequency of between 1.0 and 15 GHz. Those interferometers listed in the second column above that operated at a maximum frequency of about 1.4 GHz are near the bottom of this 1 - 15 GHz operating range, and so using the regression line of Figure 21 may indicate too high a cost for these dishes. We know from Section 3.1.2 above that it cost about 50% to increase the maximum frequency of operation from 1.4 to 5 GHz for the Arecibo, 92 m Green Bank and 76 m Jodrell Bank telescopes, but the extra cost of building such 5 GHz telescopes from scratch would be less than this. Assuming that the increase is 25% (or about half of the 50%) produces the dish costs for the Half-mile and the 4 x 9m Stanford interferometers shown in Table 39(d), yielding ratios of 0.53 and 0.64.

The radio telescopes represented in Figure 20 had maximum operating frequencies of from 0.4 GHz upwards. Unfortunately this lowest figure of 0.4 GHz (for the 46m Stanford telescope) is still much greater than the maximum operating frequency of 0.08 GHz for the Culgoora interferometer so we cannot use this cost to deduce the cost of the Culgoora dishes. *For interest*, we can do the calculation the other way round, of course, assuming that the cost of the dishes is about 50%* of the total cost of the Culgoora interferometer. This produces a cost of about $14k (at 1992 prices) for each of the 0.08 GHz, 14 metre dishes. This compares, for example, with an average cost of about $400k for 14 metre dishes operating at about 5 GHz (deduced from the regression line of Figure 21), and about $1.1m for those operating at about 24 GHz (calculated from the cost of the MERLIN dishes).

These relative costs are explained by the fact that dishes operating at 24 GHz or 5 GHz have to have a continuous plated reflecting surface, the 24 GHz dishes being made to a higher surface tolerance, hence their higher cost. Dishes operating at 0.08 GHz, on the other hand, do not need to be plated at all and can have an open-weave type of construction, which substantially reduces the overall mass of the dish, making it much easier to move, resulting in a relatively low cost.

3.1.5 Total Initial Costs

Table 39 lists the initial costs of many of the radio telescopes listed in Appendix 1B, and the data analysed in Sections 3.1.1 - 3.1.4 above can now be used to estimate the initial costs for the remainder. Although the costs deduced for any individual telescope may be in serious error, the total cost for all the telescopes in Appendix 1B**, which is what we want, should be approximately correct.

(i) Dish Antennae operating at ≤ 30 GHz and Moveable about 2 Axes

The following assumptions were made in order to estimate the total initial (or capital) costs of the telescopes listed in Table (a) of Appendix 1B:-

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* This is the rounded average figure for the 5 - 15 GHz interferometers taken from Table 39(d).

** Excluding those used solely for solar work.

- The cost of the 76 m Jodrell Bank telescope is the average of the $22m and $48m figures discussed in Section 3.1.1 above.

- Telescopes of unknown cost, with maximum operating frequencies of < 15 GHz*, are assumed to have costs shown by the regression line of Figure 21.

- Those telescopes of unknown cost, with maximum operating frequencies of ≥ 15 GHz, are assumed to have costs shown by the regression line in Figure 22C.

- All telescopes whose primary purpose is satellite tracking, communications, or solar research, are assumed to spend 10% of their useful time on stellar or galactic research, and their costs are factored by this amount.

- The 64 m NASA tracking antennae at Madrid and Tidbinbilla are assumed to have the same cost as the 64 m NASA Mars tracking antenna.

- The various 26 m DSN tracking antennae are assumed to have the same cost as the two 26 m Goldstone tracking antennae.

- The costs of the 34m NASA DSN dishes are calculated from the costs of the 64m and 26m DSN dishes.

Using these assumptions, the total costs of all the radio telescopes listed in Appendix 1B(a) is about $213m at 1992 prices. The largest individual error is the ± $13m uncertainty in the cost of the 76 m Jodrell Bank telescope.

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* There are two relatively small telescopes operating at maximum frequencies of < 1.0 GHz and, making the above assumption, they are estimated to have a total cost of $1.6m. In reality the cost will be less than this, but the error cannot be more than $1m.

Probably the most contentious assumption that I have made concerns the use of the regression lines in Figures 21 & 22C to obtain the costs of some of the telescopes. The total cost of the telescopes deduced in this way was only $34m, however, so the effect of some uncertainty in this figure on the total figure of $213m will be relatively small.

(ii) Fixed Dishes or Dishes that can move about only One Axis

The costs of the Arecibo and 92 m Green Bank telescopes will dominate the costs of the other telescopes listed in Appendix 1B(b) as they are by far the largest. One of the next largest, the 67m Jodrell Bank antenna, was a very cheap and simple affair built for a few thousand £s in 1947, and two of the other dishes were of only 12 m and 11 m diameter. The total costs of the Arecibo and Green Bank telescopes was $61.5m at 1992 prices (see Table 39(b)), so it is unlikely that the total cost of all the telescopes in this group would exceed $70m.

(iii) Dishes designed to operate at ≥ 30 GHz

(a) Millimetre-Wave Telescopes

The costs of the 36 m Haystack Hill and the 32 m Mullard telescope will dominate the costs of the other telescopes listed in Appendix 1B(c) because they are by far the largest.

The largest unknown is the cost of the Haystack telescope which is quoted as $28m or $65m at 1992 prices (see Section 3.1.3 and Table 39(c) above); I have taken the average of $47m. The cost of the Mullard telescope is known, together with that of the 11m Kitt Peak telescope, but the cost of the other telescopes have been estimated using the best-fit line A in Figure 23*. The position of this latter line is highly inaccurate, but the total costs of the telescopes deduced by using it is only $20m, or about the error in the cost of the Haystack telescope.

The total costs of all the telescopes in this category was estimated as $81m, based on the above assumptions.

(b) Submillimetre-wave Telescopes

The cost of the JCMT is known and, assuming that costs vary as the diameter to the power of 2.2, the cost of the CSO telescope would be about $10m at 1992 rates. This gives a total cost for both telescopes of about $33m.

(iv) Dish Interferometers

The analysis in Section 3.1.4 above showed that, on average, the cost of dish interferometers can be calculated by assuming that the cost of the dishes is about 50% of the total costs of the interferometer. The total cost of all the interferometers listed in Appendix 1B(e)**, using this synthetic for those interferometers of unknown cost, is about $386m, $311m of which is attributable to interferometers of known cost.

(v) Miscellaneous Antennae and Arrays

There is no reliable way of estimating the total cost of this group of telescopes (see Appendix 1B(f)) as it includes telescopes of such radically different designs. Fortunately, however, these telescopes are generally of very low cost (see Table 39(e)), and the costs that I have appear to be for a reasonably representative group of

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* This line is the least-squares fit line for the three telescopes of known price, constrained to have a slope of 2.2.

** Including the cost of only the first 4 antennae of the GMRT, as only these 4 had come on line by my last year of 1992.

telescopes. The 11 telescopes for which I have cost data cost a total of $16.7m and, assuming that they are representative of the total of 34 telescopes in the group, the total cost of the group would be approximately $\frac{34}{11}$ x $16.7m = $52m.

(vi) Summary

The total costs of the radio telescopes listed in Appendix 1B is thus approximately, in 1992 prices:-

		$m
(a)	Dish antennae; < 30 GHz; 2 axes	213
(b)	Fixed or 1 axis dishes	70
(c)	Millimetre-wave dishes	81
(d)	Submillimetre-wave telescopes	33
(e)	Dish interferometers	386
(f)	Miscellaneous antennae and arrays	52
	Total	**835**

Of this total of $835m, $640m are known costs from Table 39 and so only $195m or 23% are estimated. Assuming that there is a ± 50% error in this estimating gives an error of ± $98m. In addition the costs of the 76m Jodrell Bank telescope is uncertain in Table 39 by ± $13m, and the cost of the 36m Haystack telescope is also uncertain by ± $19m. The root sum square of these errors of $98m, $13m and $19m is ± $101m. These errors do not include any allowance for telescopes that I may have missed, however, which could possibly have cost another $100m ± $50m. This latter error has probably been kept within tolerable proportions because most of the expensive telescopes have probably been listed, even though many of the smaller ones may have been missed.

So the total capital costs of radio telescopes that have been available at some time during my period is about $940m ± $110m[*].*

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[*] $835 + 100 \pm \sqrt{(101^2 + 50^2)} = 935 \pm 110$, or $\approx 940 \pm 110$, in round numbers.

The question now arises as to how much of this total cost should be 'charged' to the period 1956-1992 under consideration.

Lifetimes of radio telescopes have been generally shorter than those of optical telescopes during my period. In the early years of the 1950's, when designs were changing fast, radio telescopes were often closed down after just 10 years of use, although today, with much more stable and mature designs, lifetimes of some decades can be envisaged.

The most expensive telescopes in categories* (a), (b) and (c) have been operational since the 1950's or 60's, and so their costs can be largely written off during my period. Similarly, most of the telescopes in category (f) are old, and their cost can also be largely written off during my period also. The two microwave telescopes in category (d) are new, however, and lifetimes of 20 - 30 years could be envisaged before a major rebuild is required.

The main question is how much of the cost of the dish interferometers (category (e)) should be written off during my period?

The major new dish interferometer available in 1992 (the last year of my period) is the VLBA, which had one dish available in 1988 with further dishes becoming available over the following few years. The other major cost item in category (e), the VLA, had been operational for over a decade and could probably carry on for another 20 - 30 years, but it would need refurbishment relatively soon. For the purpose of this analysis, therefore, I will assume a write-off of the VLBA and VLA over 30 years from their date of first use.

The rate of commissioning the VLBA dishes was:-

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* These categories are those listed in the above summary table.

1988	1989	1990	1991	1992
1	1	3	2	3

So the number of dish-years up to 1992 was 1 x 4 + 1 x 3 + 3 x 2 + 2 x 1 = 15 out of a total lifetime of 10 x 30 = 300 dish-years. So 5 % of the total cost of the VLBA could be attributed to my period.

With a 30 year lifetime of the VLA, and with an average commissioning date of its dishes as 1979, I will write off $\frac{1992-1979}{30} \equiv 43\%$ of its cost in my period.

In summary, Table 40 shows the portion of the above $835m capital costs that can be written off during 1956-1992, with suggested upper limits, but this $835m is thought to have been underestimated by possibly about $100m ± $50m. Most of this $100m-worth of telescopes are probably relatively new, however, replacing some of the telescopes listed in Appendix 1B, and I will assume that only half of this $100m should be written off during my period. In this case the total write-off would be about:-

$$\$\{531 \pm 45 \pm 101 \times \frac{531}{835} + 50 \pm 25\}\text{m} \approx \$580\text{m} \pm \$80\text{m}$$

where:- *(see next page)*

TABLE 40

Proposed Write-off of Radio Telescope Capital Costs (in 1992 Dollars)

	Baseline	$m	Upper Limit	$m	Error $m
(a)	80 % x $213m	170	Increase 80% to 90%	192	± 22
(b)	80 % x $70m	56	Ditto	63	± 7
(c)	80 % x $81m	65	Ditto	73	± 8
(d)	$\frac{5\text{yrs} + 4\text{yrs}}{2 \times 25\text{yrs}}$ x $33m	6	Reduce 25 yrs to 20 yrs	8	± 2
(e)	VLBA 5 % x $88m	5	Reduce 30 yrs to 20 yrs	8	± 3
	VLA 43 % x $152m	65	Ditto	99	± 34
	Others 80 % x $146m	117	Increase 80% to 90%	131	± 14
(f)	90 % x $52m	47	Increase 90% to 100%	52	± 5
	Total	531	Root Sum Square Error		± 45

±45 is the error in working out how much of the 531 to write off (see Table 40)

$\pm 101 \times \frac{531}{835}$ is the error in estimating the costs of the telescopes listed in Appendix 1B reduced by the write-off factor of 531/835

and 50 ± 25 is the extra amount to write off to cover unknown telescopes

This \$580m ± \$80m write-off for radio telescopes compares with the \$210m ± \$80m write-off for optical telescopes for the same period (see Section 2.4 above).

3.2 Annual Costs

The annual operating costs for the American National Radio Observatories of the NRAO and of the NAIC (at Arecibo) are shown in Tables 29 & 30 above. These costs have been derived from Appendix 4 where the major capital costs have been stripped out.

3.2.1 The National Radio Astronomical Observatory (NRAO)

The NRAO now consists of the observatories at Green Bank, South Virginia, whose first major telescope became operational in 1959, the VLA, whose 27 dishes became operational progressively over the period from 1977 to 1981, and the VLBA, which became operational over the period from 1988 to 1993. The major telescopes at the observatories are listed in Table 41 (next page).

Table 41 shows that the last major facility at Green Bank was completed in 1966, and so I will, for the moment, ignore all costs up to this date in order to simplify my analysis. The operational costs for the NRAO in Tables 29 & 30 first included those for the VLA when it started (partial) operation in 1977, so the costs for Green Bank are not clear from that date.

TABLE 41
Major Telescopes at the National Radio Astronomical Observatories
(In date order)

Dish Size (in metres)	First Used	Max. Freq. (in GHz)	Cost (in 1992 $s)	Notes
(a) Green Bank				
26	1959	10	1.7	Howard Tatel Telescope
92	1962	1.4	)	Can move only in declination
	1966		)	Backing structure strengthened
	1970	5	) 6.5	Resurfaced
	1988		)	Collapsed
12	< 1964	1.4	small	Limited movement
26	1964	8/15	) 6.1	Linked to Howard Tatel Telescope
26	1966	8/15	)	Ditto
43	1965	15/30	60	
	Total Cost		**74**	
(b) VLA				
27 off 25m dishes	1977 - 81	24	**152**	21 km interferometer
(c) VLBA				
10 off 25m dishes	1988 - 93	43	**88**	8,000 km interferometer

The operational costs of Green Bank varied over the period 1967-1976 from $4.98m in 1967 to $8.4m in 1976 in real-year dollars (see Table 29), an increase of 69%, but this increase was completely due to inflation. In 1992 dollars the operations costs were thus basically constant over this period, averaging $23.0m. There were wide fluctuations about this average, however, going from a maximum of $29.1m in 1968 (in 1992 dollars) to a minimum of $20.4m in 1974 (see Table 30).

The operations costs for the NRAO progressively increased in real-year dollars from $8.4m in 1976, the last pre-VLA year, to $14.79m in 1981, when the VLA was complete, an apparent increase of 76 %. But inflation over this period was 60 %, so the real increase was small ($22.8m - $20.7m in 1992 dollars, see Table 30). Clearly there had been an attempt, during this period, to keep the NRAO budget increase due to the addition of the VLA to an absolute minimum, by reducing the Green Bank operating costs as far as possible. Interestingly, over the same period of 1976 to 1981, the operational costs of the NOAO on Kitt Peak had been reduced in real terms by 17 %, indicating that there was pressure to reduce costs there as well over this period.

The first of the ten VLBA dishes became operational at Pie Town, New Mexico, in 1988, and a second became operational (at Kitt Peak) in 1989. The VLBA was completed in 1993.

The average operations cost of the NRAO (Green Bank + VLA) over the period from 1981, the first year of full VLA operations, to 1987, the last year before the VLBA started to come on-line, was \$22.8m/year at 1992 prices. This is the same, within error, as the average (\$23.0m/year) for the period 1967-76 before the VLA started (limited) operations, so the cost of operating the VLA had been met completely by reducing the operations costs of Green Bank over this period.

The average cost of operating the American National *Optical* Observatories on Kitt Peak and Cerro Tololo are shown in Table 42 (next page) split into two periods of approximately equal length. This shows that the average cost of operating the KPNO had reduced by 15 % in 9½ years and of operating the CTIO had reduced by 20 % in 8½ years. Over the period of 12½ years between 1967-76 and 1981-87 (mid-point to mid-point) we could therefore expect a reduction of about 25 %* in the annual costs of operating the NRAO, assuming a similar improvement to that for the NOAO. In fact, the VLA has been added to the NRAO over this period at no change in cost, so the annual operations costs of the VLA could be estimated as about 25 % x \$23m, or about \$6m/year at 1992 rates. If the operational costs of Green Bank had

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* $\frac{1}{2} \times (\frac{15\%}{9\frac{1}{2}} + \frac{20\%}{8\frac{1}{2}}) \times 12\frac{1}{2} \approx 25\%$

TABLE 42

Average Annual Operating Costs in 1992 dollars of American National Observatories

		Av.		Av.	Reduction	In Years*
(a) Optical						
KPNO	1974-83	$16.1m	1984-92	$13.7m	15 %	9½
CTIO	1976-84	$ 8.6m	1985-92	$ 6.9m	20 %	8½
(b) Radio						
NRAO Green Bank	1967-76	$23.0m				
NRAO Gr Bk + VLA			1981-87	$22.8m		
NAIC Arecibo	1975-83	$ 8.9m	1984-92	$ 7.2m	19 %	9

been *severely* curtailed over this period, however, then the operational costs of the VLA would obviously be higher.

The VLBA was brought on line over the period 1988-93, causing the progressive reduction in costs of the NRAO, which had reached a minimum of $19.3m (in 1992 dollars) in 1988, to be reversed, reaching an average of $27.1m (in 1992 dollars) over the period 1992-95. This implies annual VLBA operations costs of about $27.1m – $19.3m ≈ $8m. The 92m Green Bank dish collapsed in 1988, however, so the operational costs of Green Bank in 1989 et seq. would be lower than for pre-1988, implying annual VLBA operations costs of > $8m.

3.2.2 NAIC, Arecibo

The 305m diameter radio telescope at Arecibo was completed in 1963, and it was substantially modified, and a 30.5 m antenna added at Higuillales 10 km away, in 1972-74.

The Arecibo facility was originally paid for and operated by the Department of Defense (DoD) and responsibility only handed over to the NSF in 1969. In addition,

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* Mid-point to mid-point.

some of its later modifications and operational costs were borne by NASA and by an NSF budget line devoted to studying the Earth's atmosphere (see Appendix 4). The operations costs listed in Tables 29 & 30, therefore, are not the complete costs, but only those paid for by the NSF astronomy programme*.

The NSF 1969 cost figure is uncertain because that was the year of the transfer of Arecibo from the DoD to the NSF, and the refurbishment and addition of the extra antenna in 1972-74 means that the operations costs deduced in Tables 29 & 30 for those years may be unreliable also. Because of this I have, for the present, ignored these early operations costs, and have analysed the Arecibo costs over the period from 1975 to 1992 only, giving an average figure of $8.0m at 1992 rates.

So we have, in summary:-

		Av. annual operating costs (in millions of 1992 dollars)
Green Bank	1967-76	23.0
Green Bank + VLA	1981-87	22.8
Green Bank + VLA + VLBA	1992-95	27.1
Arecibo	1975-92	8.0

The average of the annual Arecibo operations costs in the second half of this 1975-92 period was about 19 % lower than those for the first half (see Table 42 above), in line with the reductions observed at the KPNO and CTIO.

3.2.3 JCMT

The annual operational costs of the JCMT on Mauna Kea, which became operational in 1987, are analysed in Appendix 6. They average $6.1m (in 1992 dollars) over the period 1987/88 to 1992/93.

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* During the period 1983-87 the contributions of NASA and the NSF atmospheric budget line to the operations costs (see Table A4.1 of Appendix 4) averaged a total of $1.42m, against an average NSF astronomy contribution of $5.77m.

3.2.4 NRAL, Jodrell Bank

The annual costs of operating the National Radio Astronomy Laboratory (NRAL) centred at Jodrell Bank were about $3.2m in 1978 and $6.2m in 1991-94 (both costs in 1992 dollars, see Appendix 7). These costs were for operating the telescopes listed in Table 43.

TABLE 43
Telescopes at the UK National Radio Astronomical Laboratory

Telescope	**Dia. (m)**	**Capital Cost (1992$)**	**First Used**	**Included in 1978 costs?**	**Included in 1991-94 costs?**
Mark I, Jodrell Bank	76	~ 35	1957	✓	✓
Mark II, Jodrell Bank	38 x 25	3.1	1964	✓	✓
Mark III, Jodrell Bank	38 x 25	1.7	1966	✓	✓
Defford	25	) 22	1965	✓	✓
Cheshire/Powys	3 off 25m	)	1980	–	✓
Cambridge	18	*	1964	–	–
Cambridge	32	9.4	1990	–	✓

The main difference between 1978 and 1991-94 configuration being the extension of the MTRLI (Multi-Telescope Radio-Linked Interferometer) into MERLIN in 1980, with the addition of three 25 metre dishes, and the replacement of the 18 metre dish at Cambridge in 1990 with a new 32 metre dish.

3.2.5 MRAO, Cambridge

The annual costs of operating the Mullard Radio Astronomy Observatory (MRAO) at Cambridge was about $2.2m in 1978 and $1.5m in 1991 (in 1992 prices, see Appendix 7). Most of the 1991 cost was for operating the Ryle Telescope. The telescopes concerned are listed in Table 44 (next page).

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* Cost not included as this dish was part of the One Mile telescope at Cambridge.

TABLE 44
Telescopes at the Mullard Radio Astronomical Observatory

Telescope	Capital Cost (1992$)	First Used	Included in 1978 costs?	Included in 1991-94 costs?
8 off 14m dishes, Ryle (or 5 km) Telescope	18	1972	✓	✓
3 off 18m dishes, One Mile Telescope	7	1964	✓	–
Cambridge Low Freq. Synthesis Telescope (7C)	0.5	1983	–	✓
151 MHz Synthesis Telescope (6C)	0.14	1975	✓	–
Cosmic Anisotropy Telescope		1992	–	*

TABLE 45
Summary of Telescope Types Available at the Radio Observatories for which I have Annual Costs

	Single Dishes		Dish Interferometers		Other
	Two axes	One axis	On one site	Multisite	
Green Bank	43m	92m & 12m	3 off 26m		
VLA			27 off 25m		
VLBA				10 off 25m	
Arecibo					305m fixed dish
JCMT					Very high tolerance 25m dish in special enclosure
NRAL	76m & 2 off 38m x 25m			4 off 25m & 1 off 32m	
MRAO			8 off 14m		

3.2.6 Total Annual Costs

The radio telescopes discussed in Sections 3.2.1-5 above cover a broad range of types and sizes (see Table 45) which, to a first approximation, are representative of the radio telescopes listed in Appendix 1B. We should be able, therefore, to use a cost synthetic deduced from their annual operational costs to estimate the annual operational costs of all the telescopes in Appendix 1B, to a fair approximation.

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* Includes 1991 construction costs, not operational costs.

Abt[1] had shown that the annual operating cost of optical telescopes at KPNO was proportional to $d^{2.1}$, where d is the diameter of the primary mirror, and Irvine and Martin[3] had shown that this relationship was valid, not only for telescopes within an observatory, but also approximately between observatories. Unfortunately, there is no similar published analysis of annual operating costs versus dish diameter for radio observatories (where dish antennae are used), and it is not possible to undertake such an analysis with my data, because there are too many different types of antennae, as the following analysis shows.

Although the Arecibo telescope is a unique instrument, and the JCMT telescope is quite unlike any of the other telescopes in Table 45, it should be possible, in principle, to compare the annual operations costs of the dishes at the other observatories. Unfortunately, in order to undertake an analysis (see Table 46, next page) I have had to make four assumptions, which there is no way of checking.

It may be thought, nevertheless, to be encouraging that the ratios in the final column of Table 46 vary only by a factor of 5. Unfortunately this range is relatively insensitive to the power of the diameter used* around d^2, and so it cannot safely be used to optimise that power.

So, because we have to consider a much broader range of types of radio telescopes than optical telescopes, and because I do not have enough data to identify the values of all the cost-driving parameters involved, I cannot use a simple parameter based on dish size to estimate the annual operations costs. I have, therefore, opted to use the parameter of capital cost**, as it is universal to all types of telescopes, to deduce the operational costs for all the telescopes in Appendix 1B. It is clear that this will only be a very crude approximation at individual telescope level, but it is probably adequate for estimating the total annual costs at total telescope level.

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* If I use a power of 1.5, for example, instead of 2, the range of the ratios is 5.7 rather than 5.0.

** Both Whitford[18] and Greenstein[14] used this capital cost parameter to estimate the operations costs of radio telescopes (see Sections 3.2.3 and 5.1 of Part 4).

TABLE 46

Analysis of Annual Operations Costs of the Radio Telescopes listed in Table 45 (excluding the Arecibo telescope and the JCMT)

Assume that the annual operations cost of :-

(i) a radio telescope of dish diameter d is proportional to d^2 for a dish that can be moved about two axes, and to ½ of that amount for a dish that can be moved about only one axis

(ii) an interferometer consisting of n dishes each of diameter d, all on one site, is proportional to $\sqrt{n} \times d^2$.

(iii) an interferometer consisting of n dishes each of diameter d, on different sites, is proportional to $n \times d^2$.

Then we have:-

Observatory	Years	Operations Costs proportional to (a)		Actual Annual Operations Costs in 1992 $ in millions (b)	Ratio (b)/(a) x 10^3
Green Bank	1967-87	$43^2 \approx$	1,800		
		$\frac{1}{2} \times 92^2 \approx$	4,200		
		$\frac{1}{2} \times 12^2 \approx$	100		
		$\sqrt{3} \times 26^2 \approx$	1,200		
		Total (Green Bank)	7,300	20*	2.7
VLA	1981-87	$\sqrt{27} \times 25^2 \approx$	3,200	~ 6	1.9
VLBA	1994-95	$10 \times 25^2 \approx$	6,300	~ 10	1.6
NRAL	1991-94	$76^2 \approx$	5,800		
		$2 \times \frac{1}{2} \times (38^2 + 25^2) \approx$	2,100		
		$4 \times 25^2 + 32^2 \approx$	3,500		
		Total (NRAL)	11,400	6.2	0.5
MRAO	1991	$\sqrt{8} \times 14^2 \approx$	600	1.4	2.3

Table 47 (next page) shows the annual operations costs deduced in Sections 3.2.1-5 above, together with the capital costs and the ratio of the one to the other. As expected, this ratio is highly variable, from 0.04 for the VLA to 0.27 for Green Bank and the JCMT. The figures for the Max Planck and Westerbork observatories, which are also shown in this table for comparison purposes, indicate that the Green Bank and JCMT figures are not unusually high, however, so maybe the VLA figure is unusually low.

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* Average of 23 for 1967-76 and 23 - 6 (for VLA) = 17 for 1981-87.

TABLE 47
Annual Operational and Capital Costs in 1992 Dollars (in millions)

	Operational Costs/yr (i)	Capital Costs (ii)		(i)/(ii)
Green Bank	20	74		0.27
VLA	~ 6	152		0.04
VLBA	~ 10	88		0.11
Arecibo	8	55		0.15
JCMT	6.1	23		0.27
NRAL, Jodrell Bank	4.7*	57**		0.08
MRAO, Cambridge	1.8#	22##		0.08
Total	**57**	**471**	**Ov.Av.**	**0.12+**
Max Planck Inst.	12++	33		0.36
Westerbork	9++	31		0.29

The VLA and VLBA figures have been deduced *very approximately* from the total NRAO figures, as described in Section 3.2.1 above. The overall average ratio in Table 47 is relatively insensitive to these VLA and VLBA costs, however. For example, even if the operational costs for the VLA were double, the average operational cost for Green Bank would only reduce from $20m/year to $17m/year, and the overall average ratio in Table 47 would only increase from 0.121 to 0.127.

A number of assumptions have been made in producing the operational costs listed in Table 47 as explained in Sections 3.2.1-5 above. In particular, the averages for Green Bank and Arecibo ignore the costs during the early years of these observatories, so the average ratio of 0.12 in Table 47 is only approximate for the observatories listed. A more complete figure can be obtained by taking the total operational costs for each of these observatories from their year of opening or 1956, whichever is the later up to and including 1992, and dividing them by the sum of the

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[*] Average of 3.2 for 1978 and 6.2 for 1991-4.

[**] Average of 43 for 1978 and 71 for 1991-4.

[#] Average of 2.2 for 1978 and 1.4 for 1991.

[##] Average of 25 for 1978 and 19 for 1991.

[+] Overall average, i.e. 57/471

[++] Data from Ref. 2, after subtracting the cost of researchers.

capital cost of each of their telescopes multiplied by the number of years that each of them has been operational. These figures for $\frac{\sum C_o}{\sum (C_c \times t)}$ for the period 1956-92, which are given in Table 48*.

TABLE 48

Σ Operational Costs (C_O) and Σ {Capital Cost (C_C) x Operational Years (y)}

(Cost figures in 1992 dollars in millions)

	$\sum C_o$ upto 1992	$\sum (C_c \times t)$ all telescopes	$\frac{\sum C_o}{\sum (C_c \times t)}$
Green Bank + VLA + VLBA	668	4097	0.16
Arecibo	218	1404	0.16
JCMT	31	115	0.27
NRAL, Jodrell Bank	132	1509	0.09
MRAO, Cambridge	56	607	0.09
Total	**1105**	**7732**	**Av.** 0.15**
			σ_{n-1} 0.07
			Overall Av.# 0.14

If I now calculate the values of $C_c \times t$ for all of the telescopes in Appendix 1B over the period 1956-92, I can multiply them by the overall average ratio of 0.14## from Table 48 to obtain an estimate of their total operations costs. The totals of $C_c \times t$ for the various categories of telescopes in Appendix 1B are given in Table 49.

In calculating these values, I have assumed that all those telescopes for which I do not have a closure date were still operational in 1992, even though I know that some of the earlier telescopes had been decommissioned by then: unfortunately I do not know when. To a first approximation, however, I have assumed that this

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[*] The ratio (b)/(a) deduced from Table 46 for Green Bank + VLA + VLBA is 2.1 x 10^3, which is 4.2 times the ratio for NRAL in that table. In Table 48 the ratio of the figures in the last column for these two observatories is 1.8, indicating that the latter figures are more consistent than those in Table 46. So the methodology of Table 48 not only produces more consistent results than that of Table 46, but it relies on less assumptions, and it can be used for all types of radio observatories.

[**] i.e. average of the ratios for the five observatories.

[#] i.e. 1105/7732

[##] Both Whitford[18] and Greenstein[14] assumed that the annual operations cost of radio telescopes was about 0.10 times their capital cost (see Sections 3.2.3 and 5.1 of Part 4)

TABLE 49

$\Sigma(C_C \times t)$ for all the telescopes in Appendix 1B

(units are \$m x yrs, where the dollars are 1992 dollars)

(a)	Dish antennae; < 30 GHz; 2 axes	5,739
(b)	Fixed or 1 axis dishes	1,661
(c)	Millimetre-wave dishes	1,686
(d)	Submillimetre-wave telescopes	155
(e)	Dish interferometers	4,187
(f)	Miscellaneous antennae and arrays	1,404
	Total	**14,832**

overestimate is balanced by the costs of the telescopes that my survey has missed. On this basis the total operational costs of all radio telescopes in my geographical area up to and including 1992 would be about \$(14,832 x 0.14)m ≈ \$2,100m.

About half of this \$2,100 (i.e. \$1,105m, see Table 48) is known to be correct, so the error of ± 0.07* in the ratio 0.14 applies only to the remainder (i.e. on \$2,100m – \$1,105m ≈ \$1,000m). This gives an error of ± \$500m. So the total operational costs over the period 1956 – 1992 are estimated to be \$2,100 ± \$500m.

*We can now add the write-off capital costs over 1956-92 of \$580m ± \$80m (see Section 3.1.5) to these total operational costs over the same period, to give the total costs (annual costs and apportioned capital costs) of American and British Commonwealth radio observatories from 1956 to 1992 of approximately \$2,700m ± \$500m** at 1992 prices. This compares with \$3,500m ± \$500m for optical/IR observatories over the same period (see Section 2.4).*

4 Spacecraft

Spacecraft have been funded in a different way to ground-based optical and radio telescopes, at least as far as the UK is concerned. In the case of ground-based

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* Strictly speaking this ± 0.07 is the error about the average of 0.15, not about the overall average of 0.14, but it is a good enough estimate of the error for the present purposes.

** $\sqrt{(500^2 + 80^2)}$, in round numbers.

telescopes, the British approach has been towards collaboration with countries of the British Commonwealth, having decided some time ago not to join the European Southern Observatory. In the case of space, however, British policy has been towards European collaboration in the guise of ESRO and ELDO, which were reorganised and joined to form into ESA about twenty-five years ago. So the observatory spacecraft which I will consider, and which are listed in Appendix 1C, are those built for NASA, ESA and for bilateral or multilateral projects that included the USA or UK. Spacecraft devoted to solar system research are excluded for the reasons explained in Section 1.

4.1 ESA Spacecraft Costs

There are 6 spacecraft listed in Appendix 1C which involve ESA as either sole authority or in a shared programme with NASA. They are:-

100% ESA Programmes:-	TD-1A Cos-B Exosat Hipparcos
ESA Collaborative Programmes:-	IUE HST

BNSC gave me access to their library facilities which contained ESA Budget Reports from 1975 to 1995 inclusive, minus those for 1979, and ESA Quarterly Reports to Council (QRC's) starting in 1989. In addition, ESA provided[36] me with data on the actual expenditure and Cost-at-Completions of a number of programmes from 1974 to 1988.

The annual costs of each of the major scientific programmes, as given in the annual ESA Expenditure Sheets or Budget Reports, are shown in Table 50 (next page), which include internal and external ESA costs, launch and post-launch operations.

TABLE 50
ESA Science Budgets and Expenditure in real-year MAU's
(Budgets are in normal type and expenditure*, where known, is in italics)
(Payment Authority, including Administration and Other Costs, Launch and Post Launch Operations)

	1975	1976	1977	1978	1979**	1980	1981	1982	1983	1984	1985	1986	Total#
Cos-B	8.9	6.2	5.1	2.6	2.0	0.5	2.2	0.8					##
GEOS 1	26.3	21.4	14.1	4.4	4.0	3.0							##
IUE	3.6	4.5	4.3	3.7	4.0	4.2	3.8	3.2	4.6	5.1	5.0	5.0	
ISEE	2.6	8.8	16.7	1.7	1.0	0.4	0.1	0.1	0.1	0.2			31.7
Exosat	*1.1*+	*3.2*	*9.6*	*28.9*	*32.0*	*30.5*	*21.4*	*15.9*	24.7	6.9	6.1	12.8	
HST Development			*1.9*	*10.4*	*19.4*	*19.6*	*26.0*	*18.1*	*13.0*	*13.6*	*12.8*	*12.7*	
HST Operations							*0.6*	*0.5*	*1.3*	*1.8*	*2.3*	*2.6*	
GEOS 2				12.1			1.9		0.2				14.2
Ulysses				*1.5*	*5.0*	*17.7*	*24.4*	*24.5*	*14.9*	*10.3*	*12.1*	*7.0*	
Giotto							*3.8*	*26.6*	*34.2*	*35.9*	33.1	12.6	
Hipparcos						*0.1*	*1.0*	*6.1*	*15.2*	*41.8*	*56.9*	*83.7*	
ISO												*0.9*	
Misc. Projects	0.5	0.7	1.4	1.8		2.9	1.2	1.7				0.2	
Next Science Project		0.4	3.6							0.3	0.8	1.3	
Science Management				0.6		0.6	0.7	0.8	1.3	1.2	2.0	2.6	
Space Science	3.4	4.6	5.5	6.7		7.3	7.5	8.5	10.2	10.5	11.1	13.0	
Contingency/Exch. Losses						1.9	0.5						
Total	**46.4**	**49.8**	**62.2**	**74.4**		**88.7**	**95.1**	**106.8**	**119.7**	**127.6**	**142.2**	**154.4**	

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* Actual expenditure is recorded, where known. Otherwise I have had to rely on budgets, although the differences between expenditure and budgets are generally small (see text).

** 1979 budget values are estimated. Where expenditures are recorded, however, these are actual figures.

Starting in 1975, for Projects not continuing after 1986.

Totals meaningless for these spacecraft as their programmes started well before 1975.

+ Figure for 1974 + 1975.

TABLE 50 (cont.)
ESA Science Budgets and Expenditure in real-year MAU's
(Budgets are in normal type and expenditure, where known, is in italics)
(Payment Authority, including Administration and Other Costs, Launch and Post Launch Operations)

	1987	1988	1989	1990	1991	1992	1993	1994	1995	Total*
IUE	5.1	5.7	5.6	6.1	4.9	4.7	4.5	4.8	5.5	**97.9**
Exosat	12.1	1.7	1.2	1.0	0.3					**209.4**
HST Development	*10.6*	*24.7*	18.4	10.9	12.4	10.9	7.5	3.9	0.5	**247.3**
HST Operations	2.2	*1.9*	2.2	3.3	3.0	3.6	3.6	3.7	3.6	**36.2**
Ulysses	*2.6*	*7.0*	12.8	17.0	4.4	3.0	2.3	3.1	2.8	**172.4**
Giotto	1.2									**147.4**
Hipparcos	*76.5*	*40.8*	24.0	19.3	0.7	0	6.7	2.0	0.7	**375.5**
ISO	*20.1*	*88.9*	90.2	93.6	68.9	37.5	46.4	51.3	38.4	**536.2**
STSP (Soho/Cluster)			6.3	30.9	109.2	163.8	148.0	137.4	68.8	**664.4**
Huygens					16.1	16.3	45.3	60.9	40.4	
XMM							5.5	41.8	109.3	
Integral									6.3	
Rosetta									40.0	
Misc. Projects	1.5	1.6	4.3	6.3	2.7	4.4	1.0	0.9	0.8	
Next Science Project	5.7	9.6	12.5	6.9	6.8	9.6	10.3	5.1	6.8	
Science Management	3.1	5.4	5.7	5.8	6.6	4.6	5.5	6.7	7.9	
Space Science	15.0	17.3	16.7	16.8	16.8	11.3	12.4	13.0	13.0	
Contingency/Exch. Losses	3.0			10.5						
Total	158.7	204.6	199.9	228.4	252.8	269.7	299.0	334.6	344.8	

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* Both pages. For spacecraft launched in early 1996 or earlier.

TABLE 51
ESA Expenditure v Budgets (in real-year MAUs*)

	Years**	Expenditure (i)	Budget (ii)	(i) - (ii)	(i) - (ii) in %
Exosat	1974-82	110.6	114.8	–4.2	–3.7
HST Development	1977-88	163.4	173.2	–8.9	–5.2
HST Operations	1981-88	13.2	14.0	–0.8	–5.7
Ulysses	1978-88	122.0	125.5	–3.5	–2.8
Giotto	1980-84	100.5	102.6	–2.1	–2.0
Hipparcos	1980-88	322.1	313.9	+8.2	+2.6
ISO	1986-88	109.9	115.0	–5.1	–4.4
				Average	–3.0

It is clearly preferable to use actual expenditure in my analysis, rather than budgets, and these expenditures are included, where possible, in Table 50. In the years where I have both the budget and expenditure data, the differences are generally small, however, averaging only 3.0%, as shown in Table 51.

The latest ESA Cost-at-Completions, produced on the same basis as the Expenditure and Budget Reports (i.e. including the same items), and given in the QRC's, are shown in Table 52 (next page). (The bold numbers indicate the last time a particular programme was included in the QRC's.)

Unfortunately, the:-

(i) TD-1A programme had been completed prior to 1975, and so no data is included in Table 50 for that programme

(ii) Cos-B spacecraft was launched in 1975, and so only in-orbit costs are shown in Table 50 (with the exception of 1975 which probably included some spacecraft costs)

(ii) IUE programme was started prior to 1975, and so the costs are not complete in Table 50

so we will have to find other data for these spacecraft.

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* Millions of Accounting Units. These were originally the same as US dollars, but they are now equivalent to $1.29US.

** Excluding 1979.

TABLE 52
Cost-at-Completion Estimates[#] (in MAU) for major ESA Scientific Programmes
(from ESA Quarterly Reports to Council)

Date of Report →	Q3 1989	Q4 1990	Q3 1992	Q4 1994	Q4 1995
HST Development	202	207	222		
HST Operations	33	50	54		
Ulysses	166	169			
Hipparcos	358				
ISO	405	429	489	584	597
STSP			667	751	762
Huygens				243	246

In the meantime, however, I have compared the latest Cost-at-Completion estimates in Table 52 with the total costs up to the end of 1995 from Table 50 for those spacecraft that have been launched up to 1992 and where the Cost-at-Completions should now be clear. These comparisons are summarised in Table 53.

The Cost-at-Completion (CaC) estimate for the HST was on the low side, probably because the CaC does not include the cost of the hardware for the 1993 repair mission (which Table 50 does), and the CaC for Hipparcos was slightly lower than

TABLE 53
A Comparison of Cost-at-Completions from Tables 50 and 52

	Launched	Stopped Using	Cost-at-Completions from Table 52 Est. in	(i) MAU	Total Costs up to end '95 from Table 50[*] (ii) MAU	Ratio (ii)/(i)
HST Dev.	1990		1992	222	246	1.11
HST Ops.			1992	54	35 + costs for post) '95 in-orbit ops.)	
Ulysses	1990		1990	169	170	1.01
Hipparcos	1989	1993	1989	358	373	1.04

[#] The data in the Cost-at-Completion estimates includes:-

For previous years	Actual costs in real-year Accounting Units
For the current year	The current year's budget
For future years	Forecasts at the current year's price levels

[*] Corrected such that all post-CaC expenditure is at the rates of the CaC.

the eventual out-turn, possibly because of the unanticipated cost of the rescue mission (after the spacecraft had been put into the wrong orbit by the launch vehicle). The two figures for Ulysses were almost the same as each other, however.

Having gained some confidence in my data, I will now consider the HST and Hipparcos costs, which I will take from Table 50 as this data is the most recent. These costs, excluding the modification costs for the 1993 HST repair mission*, were, in real-year MAU's:-

	Cost at Launch**	**Launch Date**
HST	231 MAU	1990
Hipparcos	346 MAU	1989

To these must be added the in-orbit costs of:-

HST	15 years (estimated) x 3.6 MAU at 1993 rates (av. of 1991-'95 figures)
Hipparcos	27 MAU Total for 1990-'93 inclusive (in-orbit operations terminated in 1993)

The spacecraft capital costs taken from Table 50 are at a mixture of annual rates, just like the capital costs considered in Sections 2 and 3 above for ground-based telescopes. The HST figure of 231 MAU, for example, is at rates varying from 1977 to 1990, and the Hipparcos figure of 346 MAU is at rates varying from 1980 to 1989. Inflation will only be considered from the date the spacecraft was launched, in the same way as the capital costs of ground-based telescopes were only escalated after the telescope construction was completed (because annual expenditure during construction of ground-based telescopes was usually not available, see Section 2.2.1).

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* Excluded as the repair was carried out after the end of my period.

** Including preparations for the operational phase (i.e. in the case of HST I have included the costs that were in the operations budget line up to and including 1990).

This treatment of inflation, which ignores inflation during construction, gives an advantage to spacecraft like the HST, that had been in development for a long time, compared with spacecraft like Hipparcos that had a more normal development period. For example, if I take the Costs at Launch for the HST and Hipparcos, i.e. 231 and 346 MAU respectively, and escalate them to 1992 rates* I obtain:-

HST	259 MAU
Hipparcos	404 MAU

If, on the other hand, I escalate each of the annual costs (up to launch) to 1992 rates I obtain:-

HST	365 MAU
Hipparcos	463 MAU

Now $$\frac{463}{404} \times 259 = 297 \text{ MAU} \quad \text{and} \quad \frac{365 \text{ MAU}}{297 \text{ MAU}} = 1.23$$

So, in this example, the HST is underestimated by 23% in real terms compared with Hipparcos, because of the HST's exceptionally long development phase. Unfortunately, I do not know the annual costs during construction for NASA spacecraft and for virtually all of the ground-based telescopes, so I cannot adopt the ideal approach of escalating each of their annual building costs. As explained in Section 2.2.1 above, however, this is not very important if the development periods are all about the same or if inflation during development is low. If, on the other hand, the development periods are very different and inflation is high, then errors of up to about the above level of 23% are possible. It should be emphasised, however, that the HST was a special case as, not only did it have by far the longest development phase of the spacecraft under consideration, but the programme took place during a period of very high inflation. So the 23% is exceptional, and errors of about 10% are more normal.

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* Using the Wiesbaden index to account for price and exchange rate variations between the Member States (see Appendix 8).

ESA also provided[36] me with a Table showing the total estimated cost, produced in January 1996, of a number of scientific programmes in which all the past, present and future years' expenditures were calculated at 1994 rates, see column (i) of Table 54. I have also escalated all the annual figures in Table 50 to 1994 rates, with the results shown in column (ii) of Table 54. The agreement between the two sets of data in Table 54 is generally very good.

TABLE 54
1996 Cost-at-Completions
(*All expenditures* in 1994 MAU)

	ESA Calculations January 1996 (i)	My Calculations based on Table 50 (ii)	Ratio (ii)/(i)
Exosat	444	441	0.99
HST (incl. Ops.)	462	462 + costs for post '95 in-orbit ops.	1.00*
Ulysses	289	288	1.00
Giotto**	242	244	1.01
Hipparcos	534	548	1.03

So far, of the six ESA programmes in which I am interested, I have discussed the costs of just two, namely the HST and Hipparcos, although Table 54 shows that the costs in Table 50 for another, namely Exosat, are basically correct.

The following costs of Exosat and IUE have been deduced from Table 50 (in real-year MAU's):-

	Cost at Launch	Launch Date	Operations Costs#
IUE	16 MAU	1978	82 MAU Total for 1979-'95
Exosat	167 MAU	1983	26 MAU Total for 1984-'86

---

* 1.08 if the costs of the post '95 in-orbit operations are included in column (ii).

** Excluding the extended mission.

\# The operations costs for the year of launch are included in the Cost at Launch figure, as they are not quoted separately in the ESA budget document.

The cost of IUE at launch is not complete, however, as the programme was started before my first Budget year of 1975, and the costs at launch of TD-1A and Cos-B, the other two programmes in which I am interested, are missing from Table 50 as these programmes were started even earlier.

In the ESA Bulletin, Bonnet[37] gave a plot of total costs at launch, as estimated in January 1985, for each of the ESA scientific missions launched after 1975, although there was no cost scale on the plot.

In Table 55 I have compared the Cost-at-Completions for a number of satellites, as at 31st December 1984, excluding post-launch costs, with Bonnet's graph, which has enabled me to deduce the scale of his graph.

TABLE 55

Total Costs (in MAU) up to the time of launch

		Costs at launch*	∴ Costs at 1984 prices** (i)	From Bonnet's graph (arbitrary units) (ii)	Ratio (i)/(ii)
Known total costs:-					
	Launched				
Exosat	1983	167	177	7.3	24
Predicted total costs:-					
	Predicted launch				
Giotto	1985	134	134	5.8	23
Ulysses#	1986	119	119	4.5	26
HST#	1986	147	147	5.3	28
Hipparcos	1988	269	269	8.8	31
				Average	26

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* Costs include:-

For Exosat Real-year costs

For others Real-year costs up to and including 1984. Estimated costs at 1984 prices for 1985 et seq.

** Only escalation after launch is included. All corrections for inflation in MAU's in this thesis are made using the Wiesbaden Index (see Appendix 8), unless otherwise stated.

\# Joint programmes with NASA.

On the same graph Bonnet has plotted the costs of Cos-B and IUE (ESA costs only), for which I do not have Cost-at-Completions, as 6.1 and 2.0 in arbitrary units. Using the average 'scale factor' deduced in Table 55, this yields approximate costs at launch for these two programmes in 1984 prices as 159 and 52 MAU, respectively, or 232 and 76 MAU in 1992 prices.

So now we have costs for all of the six spacecraft required, except for TD-1A which has not figured in any of the above data because it was launched very early (in 1972). It was of about the same mass of Exosat, however, and so a cost of the order of 250 MAU could be assumed*, plus maybe 10 MAU/yr for the two years of operations, all at 1992 rates.

Putting all the data in this section together gives the costs shown in Table 56 for the 6 ESA spacecraft listed in Appendix 1C.

TABLE 56
Costs in 1992 MAU's

	Up to Launch	Operations
TD-1A	~ 250	~ 20 MAU total for 2 years
Cos-B	232	49 MAU total** for 7 years
Exosat	259	36 MAU total for 3 years
Hipparcos	404	29 MAU total for 4 years
IUE (ESA costs only)	76	107 MAU total for 17 years
HST (ESA costs only)	259#	3.3 MAU/yr for 15 yrs (est. lifetime)

The last few rows of Table 50 show a list of non project-specific costs which average out at about 10% of the project costs. These non project-specific costs generally relate to the running of the ESA Scientific Programme Directorate, not ESA HQ or supporting technology, and, as such, should really be charged to the scientific programmes. To take account of this, I have increased each of the costs shown in

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* The Exosat cost at launch was 259 MAU, and the in-orbit costs totalled 36 MAU over 3 years, both at 1992 rates.

** Taken from Table 50 and escalated to 1992 rates.

Excluding costs of modifying the hardware for the repair mission of 1993.

Table 56 by 10% when these costs are incorporated with the NASA and other costs discussed below.

4.2 NASA Spacecraft Costs

We are interested in the costs of the NASA Observatory Spacecraft listed in Appendix 1C, which start with spacecraft in the Explorer, Orbital Astronomical Observatory (OAO) and High Energy Astronomical Observatory (HEAO) series, and are followed by spacecraft of individual design like IUE, IRAS, etc.

4.2.1 The Greenstein Report

The annual costs of the Explorer and OAO series of spacecraft are given in the Greenstein Report[14] as follows:-

Greenstein Table No.	Years Covered	Spacecraft Programme Costs Include
9.23	1965 - 69	Spacecraft, incl. launchers but excl. tracking
9.24 & 9.30	1960 - 70	Spacecraft only
9.26	1962 - 71	Launchers only
9.29	1968 - 70	Tracking only

Unfortunately, there is only one budget line to cover all the Explorer spacecraft of which 40 had been launched by 1970 and of which I need the financial data for just 5, so this Explorer data is of limited use to my project. The data on the OAO spacecraft series is more relevant, however, as I need the costs of all of the spacecraft in this series.

There is a problem in producing composite spacecraft programme costs from data in the above-mentioned Greenstein Tables because of their different cut-off dates. It is also not clear how much, if any, of the internal NASA costs are included. Table 9.23, for example, lists the costs of all of the NASA astronomy programmes (including solar and planetary spacecraft, sounding rockets, etc.) individually under 'direct' costs, and then lists 'indirect' costs for all these programmes lumped together. Greenstein points out that the vast majority of these indirect costs would be incurred by NASA, whether there was an astronomy programme or not, so he suggests that the direct costs in the various tables listed above are virtually the whole costs.

Greenstein's direct costs are, however, just the marginal costs of a programme (i.e. the extra costs incurred by NASA in adding these astronomical programmes to a larger existing programme base). This is convenient for these astronomical programmes, as it keeps their apparent programme costs to a minimum, but it is hardly fair, as a similar attitude could be taken by every NASA programme, and then the indirect costs would be charged to none of them. It is not clear what a fair indirect charge would be to the astronomy programme, and so I propose, therefore, to add 10% to the direct costs of the NASA observatory programmes to cover the indirect costs of managing them (as for the ESA programmes above). To avoid confusion, however, I will only make this increase of 10% at the end of this section.

Notwithstanding the above problems, the Greenstein report provides *annual* costs for the OAO spacecraft programme, including the cost of launchers, from 1960 - 70. In addition it provides *total* programme costs (including the costs of launchers) for Explorer 38, Explorer 42 (i.e. SAS -1), and OAO-2.

4.2.2 The Field Report

The Field Report[19] of 1982 carries on where the Greenstein Report finished off and provides annual costs of the OAO and HEAO programmes up to 1980, but only in graphical form and excluding the costs of launchers. Nevertheless it gives annual cost figures until these programmes were complete.

4.2.3 The NASA Historical Data Book

Volumes 1, 2 and 3 of the NASA Historical Data Book by Ezell[38] provide annual cost data for the OAO and HEAO programmes up to and including 1978, but excluding the cost of launchers. This data is compared with that from the Greenstein report in Table 57 (next page) for the OAO programme, and with the Field report in Table 58 (next page but one) for the HEAO programme.

4.2.4 The OAO Spacecraft Programme

There were four spacecraft launched in the OAO series as follows (see Appendix 1C for more details):-

	Year Launched	**Stopped Using**	**Launcher**
OAO-1	1966	Failed	Atlas-Agena
-2	1968	1973	Atlas-Centaur
-B	1970	Failed	Ditto
-3	1972	1980	Ditto

The costs listed in Table 57 are total programme costs in real-year dollars for both the successful and failed spacecraft. The latter were deliberately included, as the risks of launch vehicle or spacecraft failure is an important factor to be considered when looking at the alternatives of ground- or space-based observatories.

The first few lines of Table 57 show the spacecraft-only costs as listed in the various reports. Although these figures are similar from report to report, they are not the same in any two reports. Nevertheless, they are sufficiently close to warrant using the average figures shown in Line E.

TABLE 57
NASA Costs in real-year $s for the OAO Series of Spacecraft

Line	Source	Includes	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970
A	Greenstein Tables 9.24 & 9.30	S/C* only	0.4	6.8	34.8	31.8	35.6	31.4	22.3	27.7	40.4	36.9	33.3
B	NASA HDB** Vol.1, p 153	S/C only	0.3	11.6	32.9	39.5	35.3	31.8	22.7	28.0	45.8		
C	Ditto Vol.1, p 205	S/C only	0.3	7.4	38.2	39.3	35.6	32.6	22.3	27.7	44.8		
D	Ditto Vol.3	S/C only										36.4	33.3
E	Av. of lines A, B ,C, & D above	S/C only	0.3	8.6	35.3	36.9	35.5	31.9	22.4	27.8	43.7	36.7	33.3
F	Greenstein Table 9.26	L/V#, Agena			3.4	4.3	15.1	~10.0	8.5	5.4			
	Ditto	L/V, Centaur								6.6	10.0	8.8	5.6
G	Line E + F	S/C & L/V	0.3	8.6	38.7	41.2	50.6	41.9	30.9	39.8	53.7	45.5	38.9
H	Greenstein Table 9.23	S/C & L/V						40.9	30.8	33.7	54.3	45.2	(37.2)##
I	Greenstein Table 9.29	Tracking									4.9	3.4	2.9
	Total (Line G + I)	**S/C, L/V & Tr.**	**0.3**	**8.6**	**38.7**	**41.2**	**50.6**	**41.9**	**30.9**	**39.8**	**58.6**	**48.9**	**41.8**

Note The Field Report data on spacecraft costs is not included in this table as it only gave the data in graphical form, and it was not significantly different from the above, within the limited accuracy of the graph.

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* Spacecraft.

** Historical Data Book.

Launch Vehicle.

Numbers in brackets are NASA Estimates.

TABLE 57 cont.
NASA Costs in real-year $s for the OAO Series of Spacecraft

Line	Source	Includes	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980
D	NASA HDB Vol.3	Spacecraft	23.2	13.4	5.7	2.3	2.2	2.3	2.6	2.0		
F	Greenstein Table 9.26	L/V, Centaur	1.5									
I	Greenstein Table 9.29	Tracking	(2.8)	[3][*]	[3]	[3]	[3]	[3]	[3]	[3]		
	Total	**S/C, L/V & Tr.**	**27.5**	**16.4**	**8.7**	**5.3**	**5.2**	**5.3**	**5.6**	**5.0**	**[5.0]**	**[5.0]**

The Grand Total of the last line (last page and this) is $490m

TABLE 58
NASA Costs in real-year $s for the HEAO Series of Spacecraft

Line	Source	Includes	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981
A	Greenstein Tables 9.24 & 9.30	Spacecraft only	13.4									
B	Field Report, Pg 410	Spacecraft only	13	20	6	42	59	40	19	11	4	0
C	NASA HDB[**] Vol.3	Spacecraft only	13.4	21.8	4.9	42.9	59.2	39.4	25.2			

Note The data from the Field Report is only approximate as it was taken from a graph.

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[*] Numbers in square brackets are my estimates.

[**] Historical Data Book.

The first spacecraft was launched by an Atlas-Agena but, when it failed, it was decided to launch the remaining OAO spacecraft using Atlas-Centaurs. All these launcher costs are shown in Line F, and the consequent spacecraft plus launcher costs in line G. These are very similar to the spacecraft plus launcher costs shown in line H, which are taken directly from the Greenstein report, except for 1967 where Greenstein had included the cost of only one of the two launch vehicles. The grand totals, including tracking cost, are shown in the last line.

The data in Table 57 raises one or two interesting questions. For example:-

- Why are there spacecraft costs shown after the launch of the last spacecraft in 1972? Are they to cover technical assistance from the spacecraft designers?
- Why are the launcher costs so low in 1971 and non-existent in 1972, the year of the last launch? Was the launch vehicle manufacturer paid in advance?
- Were there any preparation costs for the tracking system prior to the first successful launch in 1968?

Fortunately, whatever the answers to these questions, the effect would be insignificant on the total programme costs which total $490m in real-year dollars.

As discussed above for ESA programmes, these costs should be escalated after launch, but not during the development programme, to provide a valid comparison with my costs for ground-based telescopes. The average launch date of the four OAO spacecraft was 1969, and escalation from then produces a total cost of $1,871m in 1992 prices.

In addition to annual costs for the OAO programme, the Greenstein report gave a cost of $80m in real-year dollars for the total cost of the OAO-2 spacecraft, including launcher. If all four OAO spacecraft had cost the same amount, the total programme cost would have been $320m, not the $490m calculated above. I will now examine whether these figures are compatible.

It is evident, looking at Table 57, that the cost of the Atlas-Agena launch vehicle, which cost $46.7m for one launch, compared with $32.5m for three Atlas-Centaurs, was very high. We will therefore look at the spend profile of just the spacecraft budget line, ignoring the cost of the launchers for the moment, to avoid this distorting effect. That spacecraft-only profile was, in real-year dollars:-

1960 - 66	$170.9m
1967 & 68	$ 71.5m
1969 & 70	$ 70.0m
1971 & 72	$ 36.6m
1973 & later	$ 17.1m

with launches in 1966, 68, 70 and 70.

The first spacecraft was designed and built in the period 1960-66 and was launched in 1966. Subsequent spacecraft, although different in detailed design, were based on the design of OAO-1, and so their design and development timescale and costs would have been less than for OAO-1. The design and development period for OAO-1 was about 5 years. Thus, assuming a design and development period for each of the subsequent spacecraft of 4 years, with a launch cadence of two years, there would have been two spacecraft in design and development during 1967-68, two during 1969-70, and one during 1971-72. Assuming that each of these spacecraft cost the same, to a first approximation, the above data would suggest spacecraft costs of $71.5m, $70.0m or $73.2m, that is $71.6m on average.

The three Atlas-Centaurs cost $32.5m, or about $10.8m each, so the typical cost of one of these spacecraft (OAO-2, or -B, or -3) plus launcher would be $71.6m + $10.8m = $82.4m, which is identical to the Greenstein figure of $80m for OAO-2, in round numbers.

This simple analysis shows that the real cause of the apparent discrepancy between the 4 x $80m = $320m and the $490m, previously mentioned, was the high initial design and development cost of OAO-1, and the high cost of the Atlas-Centaur that was not used after the first launch.

4.2.5 The HEAO Spacecraft Programme

There were 3 spacecraft launched in the HEAO series as follows (see Appendix 1C for more details):-

	Year Launched	**Stopped Using**	**Launcher**
HEAO-1	1977	1979	Atlas-Centaur
-2	1978	1981	Ditto
-3	1979	1981	Ditto

The cost data in the NASA Historical Data Book for 1972-78, supplemented by that in the Field report for 1979-80 (see Table 58), gives a total spacecraft-only cost of $222m at real-year rates.

In answer to my request, NASA HQ provided[39] me with total programme costs (including development, launch and operations costs) for programmes starting in the early 1970's and later.* Their cost for the HEAO programme was $244m, including launchers, which is compatible with the above $222m, excluding launchers. The $244m escalated from the average launch date of 1978 is $524m at 1992 rates.

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* This excluded the OAO programme, unfortunately, as their database did not go back to the 1960's.

4.2.6 Early Explorer Spacecraft

As mentioned above, Greenstein only gave annual costs for the Explorer programme as a whole, which is very much larger than the astronomy Explorer programme in which we are interested. Fortunately, however, Greenstein gave the total costs (including launcher) of Explorer 38 (otherwise known as RAE-1) and Explorer 42 (or SAS-1), see Table 59. In addition NASA gave me the total cost of the SAS-1, -2, and -3 programme, as shown in Table 59, but they were unable, unfortunately, to break down this total cost by spacecraft.

4.3 Summary of Spacecraft Costs

NASA provided me with their costs for IUE, IRAS, COBE, CGRO and EUVE (including launchers) and these, together with the ESA and NASA costs discussed above, are included in Table 60 (next page). The ESA costs in Table 56 have been converted to US dollars in Table 60, using the average exchange rate of 1AU ≡ $1.15 US, and all the ESA and NASA costs have been increased by 10% to cover the overheads mentioned previously.

TABLE 59
NASA Costs for Explorer Spacecraft (including launchers)

Spacecraft	**Launch**	**Stopped Using**	**Launcher**	**Cost (in $m)** **In real-yr $s**	 **In 1992 $s**
RAE-1 or Explorer 38	1968		Thor-Delta	15	60
RAE-2 or Explorer 49	1973		Ditto		
SAS-1 or Explorer 42	1970	1973	Scout	13	47
SAS-2 or Explorer 48	1972	1973	Ditto		
SAS-3 or Explorer 53	1975	1979	Ditto		
		Total of SAS programme		**51**	**166**

TABLE 60
Total Programme Costs of Orbital Astronomical Observatories

(Costs, in millions of 1992 US dollars, include spacecraft, launcher and operations)

Spacecraft	Launched	Approx.[*] Mass (kg)	Programme Costs[**] ESA	NASA	Total	Estimated Error in Costs (±)
Explorer 11	1961	40		28[1]	28	50 %
OAO-1, 2, B, 3	1966-72	2,000		2,058	2,058	10 %
RAE-1, 2	1968, 73	300		132[2]	132	10 %
SAS-1, 2, 3	1970-75	170		183[#]	183	5 %
TD-1A	1972	500	340		340	25 %
ANS	1974	140			55[1]	50 %
Ariel V	1974	140			55[1]	50 %
Cos-B	1975	300	355		355	10 %
HEAO-1, 2, 3	1977-79	2,800		576[#]	576	5 %
IUE	1978	700	231	74[#]	350[3]	10 %
Ariel VI	1979	150			55[1]	50 %
IRAS	1983	1,100		132[#]	275[4]	25 %
Exosat	1983	500	373		373	5 %
Hipparcos	1989	1,100	548		548	5 %
COBE	1989	2,500		199[#]	199	5 %
Rosat	1990	2,400			320[5]	10 %
HST	1990	9,000	340[6]	2,510[7]	2,850	$270m[8]
CGRO	1991	16,000		633[#]	633	10 %
EUVE	1992			253[#]	253	10 %
			Grand Total		9,638	$375m (rms)

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[*] This is the average mass when there is more than one spacecraft.

[**] These are total programme costs, not the average spacecraft costs, when there is more than one spacecraft.

[1] Estimated from the cost of SAS-1.

[2] Double the cost of RAE-1.

[#] Culler to DL, private communication, June 1996, escalated to 1992 rates and multiplied by a factor of 1.1 (see text).

[3] Includes an allowance for UK costs.

[4] Includes an allowance for NL and UK costs.

[5] $300m at 1990 rates, see Beatty, J.K., Sky and Telescope, Aug. 1990.

[6] Costs up to 1990, plus the cost of two years operations. The cost of the 1993 repair is excluded as it is outside my timeframe.

[7] Based on the cost at launch of $1,500m (Sky & Telescope Oct. 1990), i.e. $1,600m at 1992 rates, plus operating costs for 2/3 of 1990, 1991 & 1992 at $250m/yr (text of speech by Daniel Goldin given in San Antonio, Texas, 17.1.96). Total of $2,250m multiplied by the 1.1 factor. This estimate excludes the cost of the repair mission (and associated hardware) as the mission only took place after my cut-off date of 1992.

[8] This root-sum-square error is based on ± $200m in the $1,600, ± $50m/yr in the $250m/yr and ± 10 % of the ESA costs.

There are the costs of some spacecraft in Table 60 that had to be estimated from the costs of similar spacecraft, and these estimates will only be roughly correct. In addition, there are third-party costs which could only be estimated even more approximately. Fortunately, the total of such spacecraft and third-party costs estimated in this way totalled only $977m, or about 10% of the total costs of $9,638m.

The analysis above has shown that errors in the programme costs listed in Table 60 range from a few percent (see Tables 53 & 54) up to maybe 50 % where I have had to estimate the costs of one satellite programme from the costs of another.. My estimate of these errors is given in the last column of Table 60 which give a root-sum-square error of $375m in the total programme costs of about $9,600m.

The costs in Table 60 include both capital and annual operating costs which I now wish to separate.

The known spacecraft operating costs are listed in Table 61 (next page). Excluding the special case of the HST, the annual operating costs for the other spacecraft were quite similar, ranging from $8.5m/year to $15m/year. Interestingly, there seems to be no correlation between spacecraft size or spacecraft cost and annual operating costs for spacecraft in the range 300 to 2,000 kg. In round numbers the operating costs of spacecraft of this size averaged about $10m/year.

I do not know the annual operating costs for smaller spacecraft, but this $10m/spacecraft/year figure cannot apply to simple spacecraft whose total programmes cost only about $30m or so. In fact, the small early NASA spacecraft (Explorer 11 and SAS - 1, 2 and 3) and the early European national spacecraft (ANS and Ariel V and VI) probably cost no more than about $5m/year to operate.

TABLE 61
Spacecraft Operating Costs in 1992 $US millions

	Number of Yrs. of Operations*	Approx. S/C Mass (kg)	Total Programme Cost**	Operating Cost*	Operating Cost per year
Cos B	7	300	355	62	8.9
Exosat	3	500	373	45	15
IUE	14	700	350	119	8.5
Hipparcos	3	1,100	548	28	9.3
OAO	0 + 5 + 0 + 8#	2,000	515##	147	11.3
HST	2.6	9,000	2,850+	760	275

At the other end of the scale, the Compton Gamma Ray Observatory (CGRO) is the heaviest spacecraft observatory ever launched, and yet its capital cost was only about ¼ of the capital cost of the HST. Assuming that the CGRO cost ¼ of the cost of the HST to operate, its annual operating costs would be about $70m.

The total operating costs up to and including 1992 of all of the spacecraft listed in Table 60, based on the above assumptions, is about $1,588m of which $1,116 or 70 % are 'known' costs. Assuming an error of ± 25 % in the $1,588m - $1,116m = $472m estimated costs gives an error of ± $118m. Unfortunately, the operations costs of the HST at $250m/yr (x 1.1) are included in the list of known costs, and there may well be an error of up to ± $50m/yr (x 1.1) in this figure. The root-sum-square of this HST error (± $150m over the 2¾ years that the HST had been operational up to the end of 1992) and the ± $118m for the other spacecraft is ± $191m, or about ± $200m in round numbers. So the operating costs total about $1,600m ± $200m over the period up to and including 1992. This implies that the capital costs are about $9,600m (± $375m) – $1,600m (± $200m) = $8,000m (± $425m rms), or ± $400m in round numbers.

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* Up to and including 1992.

** Including launchers and operations.

These are the figures for the four spacecraft.

This is the total programme cost divided by four.

+ Upto the end of 1992 only.

The next question is how much of these capital costs should be written off before the end of 1992.

In the case of ground-based telescopes, I wrote-off their capital costs over their lifetimes of several decades. In the case of spacecraft, however, whose lifetimes are generally only a few years, a different approach is required if we are not to have peculiar cost-effectiveness results, with the cost-effectiveness defined as:-

$$\frac{\text{No. of highly - cited papers / year}}{\text{Annual cost}}.$$

Consider the IRAS spacecraft, for example, which had a useful lifetime of less than one year. Because of this very short lifetime, virtually all of the papers based on IRAS data were published *after* it the end of its useful life. So, if I wrote-off its capital costs over its lifetime, as I have done for ground-based telescopes, then in its one year of operation it would have a virtually zero cost-effectiveness (as virtually no IRAS papers were published that year), and for every following year its cost-effectiveness would be infinite (as all papers produced in those years would have no associated facility costs). Although IRAS is an extreme example, as the spacecraft's lifetime was very short, Figure 7B shows that there were, on average, still many papers being published 12 years after the launch of spacecraft, even though the spacecraft in Figure 7 have an average lifetime of only 6 years* . So there is a good case for writing-off the capital costs of spacecraft over a longer period than their useful life. That being so, how long a period should I use?

The answer, unfortunately, has to be somewhat arbitrary, but 12 years seems a fair compromise as (next page):-

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* This mean lifetime of 6 years is heavily biased by the 18 year lifetime of IUE. The median lifetime for those spacecraft in Figure 7 is, in fact, just 3 years.

(i) The average score 12 years after launch for the spacecraft of Figure 7 has reduced to one third of its peak score

and (ii) The scores of half of the spacecraft in Figure 7A have fallen to zero before the end of this 12 year period.

There will clearly be papers published after the end of the spacecraft write-off period, but there will also be papers published after ground-based observatories have been closed down, so both the ground- and space-based observatory write-off schemes will be similar in this respect. It is important, however, that I choose a write-off period for spacecraft such that most of the papers are published whilst we still have a cost to attribute.

Whilst taking 12 years as a baseline, I will analyse the data for 10 and 15 year write-off periods to see how sensitive the results are to this parameter. Fortunately, it transpires that the results are very *insensitive* as to which of these write-off periods I choose, see Part 3, Section 4 below.

For any spacecraft with a known or planned lifetime of more than 12 (10 or 15) years, I will use that known or planned lifetime.

Money is money, and it is basically irrelevant as to whether the money was provided for capital funding or for in-orbit operations. So I will write-off the *total* spacecraft costs over the 12 (10 or 15) year period, rather than just the capital costs. I will write-off the costs linearly over time, as for the ground observatories.

Using the methodology described, the total costs (capital and operational costs) written-off for American, ESA and UK spacecraft from 1956 to 1992 is approximately \$6,200m ± \$500m in 1992 prices. This error takes into account (a) the error in the spacecraft programme costs shown in Table 60, and (b) a write-off period ranging from 10 to 15 years.

These Spacecraft costs are compared with those for Optical/IR and Radio Telescopes in Table 62.

TABLE 62
Total Costs for Ground- and Space-Based Observatories in Millions of 1992 Dollars

(A) Total Capital Costs

	Capital Costs of all known telescopes or spacecraft	of which % known	Add costs for unknown telescopes or spacecraft	∴New total costs for 'scopes or spacecraft available sometime during 1956-92	of which written-off up to and including 1992
Optical/IR Observatories	840 ± 120	71 %	20 ± 20	860 ± 120	210 ± 80
Radio Observatories	840 ± 100	77 %	100 ± 50	940 ± 110	580 ± 80
Spacecraft	8,000 ± 400	90 %			

(B) Total Annual Operational Costs
(including the above allowances for unknown telescopes or spacecraft)

	Total Annual Operational Costs for the Period 1956-92	
	Costs	of which % known
Optical/IR Observatories	3,300 ± 500	25 %
Radio Observatories	2,100 ± 500	53 %
Spacecraft	1,600 ± 200	70 %

(C) Total of Annual and Written-Off Capital Costs

	For 1956-92
Optical/IR Observatories	3,500 ± 500
Radio Observatories	2,700 ± 500
Spacecraft	6,200 ± 500

The total spacecraft costs over the period 1956-92, see Table 62C, is about the same as the total for all ground-based observatories over the same period. The balance between capital and annual expenditure is quite different, however, for ground- and space-based observatories, with spacecraft being much more expensive to purchase, but much cheaper to operate than ground-based facilities. ***On this basis it would pay to spend a little more on the capital cost of a spacecraft if it could be made to operate significantly longer in orbit.***

PART 3 COST-EFFECTIVENESS

Summary

In Part 1 I have assessed the effectiveness of ground- and space-based facilities from 1958 to 1994, and in Part 2 I have calculated their total annual costs, including both annual operating and written-off capital costs. In Part 3 I have used the data from Parts 1 and 2 to compare the cost-effectiveness of these various facilities.

I start Part 3 by comparing the relative cost-effectiveness of different sizes of ground-based optical/IR telescopes (later referred to as optical/IR telescopes) over the period from 1958 to 1994, and conclude that, in the second half of this period, the larger telescopes are not only the more effective (see Part 1), but they are also more cost-effective than the smaller telescopes (see Table S5, next two pages). I then analyse the trend in cost-effective performance of optical/IR telescopes as a group over the period from 1958 to 1994, and find that it has increased by about 50%.

Finally in this section on optical/IR facilities I examine the cost-effectiveness of individual observatories and telescopes. Over the second half of my period, the Anglo-Australian Telescope and the 3.1m Lick are the most cost-effective of the large telescopes, and, in the smaller 1.2m–2.5m range, both the Palomar Schmidt and UK Schmidt have done very well. This is probably because these two Schmidts, along with the ESO Schmidt (which is outside my geographical area), are the largest telescopes permanently providing wide-field survey images. As such they are a unique resource and their data is invaluable to a very large number of astronomers.

I then turn to radio observatories and evaluate their cost-effective performance as a group from 1958 to 1994. Their results are more variable from one four-year data

TABLE S5
Index of my main results

	See	Results
Optical/IR		
Cost-effectiveness of category (a), (b), (c) and (d) telescopes for the total period 1958–1994 and for the first and second halves of that period.	Table 63 & Figure 24	Category (a) and (b) telescopes are of similar cost-effectiveness over the period 1958-1994 as a whole. In the first half of the period, category (a) telescopes are less cost-effective than category (b), whereas in the second half of the period it is the other way round. Category (d) telescopes are less cost-effective than category (c), which are less cost-effective than categories (a) and (b), over the whole period 1958-1994.
Cost-effectiveness of total optical/IR facilities as a function of time from 1958 to 1994.	Table 64 & Figure 25	The cost-effectiveness of optical/IR facilities increases over the period 1958-1994, from an average of about 0.4 highly-cited papers per million dollars* in 1958, abbreviated to 0.4hcp/$m, to about 0.6hcp/$m in 1994.
Cost-effectiveness of individual category (a) and (b) telescopes over the period 1978–1994.	Table 66	The most cost-effective category (a) telescopes for 1978-1994 are the AAT and the 3.1m Lick, and the most cost effective category (b) telescopes are the Palomar Schmidt, the 2.5m Irénée du Pont, the 2.1m KPNO and the UK Schmidt.
Radio		
Cost-effectiveness of total radio facilities as a function of time from 1958 to 1994.	Table 68 & Figure 26	The cost-effectiveness of radio facilities increases over the period 1958-1994, from an average of about 0.1hcp/$m in 1958 to about 0.3hcp/$m in 1994.
Spacecraft		
Cost-effectiveness of total space facilities as a function of time from 1958 to 1994.	Table 70 & Figures 27B & 27C	The cost-effectiveness of space facilities increases over the period 1970-1994, from zero in 1970 to about 0.2hcp/$m in 1994. If the HST is ignored, the latter figure becomes about 0.3hcp/$m.

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* All dollars mentioned in this table are at 1992 prices.

TABLE S5 (cont.)
Index of my main results

Cost-effectiveness of individual spacecraft	Tables 71 & 72	The most cost-effective spacecraft are Rosat, COBE, CGRO, IUE and the HEAO series. The HST's very high capital and annual operating costs have resulted in a very low cost-effectiveness value of 0.05hcp/$m.
Total		
Comparison of the cost-effectiveness of optical/IR, radio and space facilities as a function of time from 1958 to 1994	Figure 28	Optical/IR facilities are more cost-effective than radio or spacecraft facilities over the period 1958-1994. Radio facilities are more cost-effective than spacecraft except in 1990 and 1994 when there is no significant difference.
Cost-effectiveness of individual ground- and space-based facilities over the period 1978–1994:-		
Highly-productive facilities	Table 73A	The most cost-effective, highly-productive facilities are the 2.1m KPNO and the AAT, followed by the 3.1m Lick and the WHT.
Moderately-productive facilities	Table 73B	The most cost-effective, moderately-productive facilities are the Palomar Schmidt, the 2.5m Irénée du Pont, and the UK Schmidt. (These could possibly be matched, or even exceeded, by two or three of the six modest size radio telescopes whose costs I could not determine).
Cost-effectiveness of the total of ground- and space-based facilities as a function of time from 1958 to 1994	Figure 29	Although the cost-effectiveness of the total facilities varies with time, the trend is flat.

point to another than for optical/IR facilities, but, as for the latter, the cost-effectiveness of radio observatories increases with time. Although the cost data for radio observatories is quite reliable when considering them as a group, the cost data for individual medium- and small-sized observatories is not as clear, and so I cannot reliably evaluate the cost-effectiveness for many of these smaller facilities.

The cost-effective performance of space-based observatories is analysed in the next section, where I start by evaluating the change with time over my chosen period. Here the increase with time is much clearer than for the optical/IR and radio facilities, which is what one would expect, as, at the start of my period, spacecraft were still very much experimental devices. In 1994, however, this steady trend of increasing cost-effectiveness of spacecraft with time is put into reverse by the relatively poor cost-effective performance of the Hubble Space Telescope, due both to its high capital and annual operational costs.

I follow this spacecraft trend analysis with an evaluation of the cost-effective performance of individual spacecraft, where Rosat, COBE, CGRO, IUE and the HEAO series of spacecraft are found to top the list.

Finally, I compare the relative cost-effective performance of optical/IR, radio and space observatories over time, and find that the optical/IR facilities have consistently out-performed the other two. This is also shown at individual facility level where four of the first five most cost-effective, highly-productive facilities are optical/IR telescopes, led by the 2.1m KPNO and Anglo-Australian telescopes.

I conclude Part 3 by showing that, although the cost-effective performance of optical/IR, radio and space facilities have all increased with time from 1958 to 1994, the cost-effectiveness of the total of these facilities has not increased at all. This apparent inconsistency is the result of a change in the mix of facilities over the period, with more relatively low cost-effective spacecraft in the total in the later years pulling down what would otherwise have been a steady increase in total cost-effective performance.

1 Introduction

In Part 1 of this thesis I have produced estimates of the usefulness or effectiveness of observational astronomical facilities over the period 1958 to 1994 by analysing the 15% most cited papers in *ApJ* and *MNRAS*, and in Part 2 I have produced estimates of the annual costs over a similar period*. In this Part 3 of my thesis I will draw all this data of Parts 1 and 2 together, and will produce my cost-benefit analysis for American and British Commonwealth, ground- and space-based, observational facilities.

2 Ground-Based Optical/Infrared Telescopes

2.1 The Effect of Size

I will firstly analyse the cost-effectiveness of ground-based, optical/IR facilities as a function of size; the cost-effectiveness being measured as the number of highly-cited papers per unit cost.

The capital costs of optical/IR observatories has been shown in Section 2.2.1 of Part 2 above to vary as $d^{2.4}$ and the annual operations costs have been shown in Section 2.2.2 of Part 2 to vary as $d^{2.1}$. As their written-off capital costs are only just over 5% of the total annual costs over my period, however, we can assume, to a first approximation, that the total of the annual plus capital costs vary as $d^{2.1}$. So the cost-effectiveness index becomes simply $N_p/d^{2.1}$, where N_p is the number of highly-cited papers and d is the telescope diameter** .

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* As mentioned in Section 4.3.1 of Part 1, I have examined the facilities that were first available two years before the papers were published, to allow time for the facilities to be fully commissioned, the data to be analysed, and the papers to be written, refereed and published.

** This approximation of using $d^{2.1}$, rather than $d^{2.1}$ plus a factor times $d^{2.4}$, produces a maximum error of 0.1 in the $N_p/\Sigma d^{2.1}$ figures shown in Table 63. It is therefore valid as a first approximation.

TABLE 63

Cost-Effectiveness Index $N_p/\Sigma d^{2.1}$ for the various telescope categories as a function of time

(All figures are x 10^{-2}, for d in metres)

category	1958	1962	1966	1970	1974	1978	1982	1986	1990	1994
(a)	6.7	5.3	6.1	14.1	11.7	14.3	12.1	8.7	16.3	14.6
(b)	8.3	9.3	14.7	9.1	17.2	10.4	12.3	6.5	13.3	7.9
(c)	7.1	5.7	10.1	3.4	6.4	5.2	2.4	4.2	10.6	5.3
(d) part	0	0	0	8.4	1.2	6.5	0	1.0	0	0

Average Statistics

	1958-1994		1958-1974		1978-1994	
Category	**Average**	σ_{n-1}	**Average**	σ_{n-1}	**Average**	σ_{n-1}
(a)	11.0	4.0	8.8	3.9	13.2	2.9
(b)	10.9	3.4	11.7	4.0	10.1	2.9
(c)	6.0	2.7	6.5	2.4	5.5	3.1
(d) part	1.7	3.1	1.9	3.7	1.5	2.8

The values of this cost-effectiveness index $N_p/\Sigma d^{2.1}$ for each telescope size category* are given in Table 63** for each of my four year data points. The average of these indexes for the whole of my period, and for the first and second halves of this period, are also shown in Table 63. They show a clear improvement in the average values from the first to the second halves of my period for category (a) telescopes, but the apparent reductions shown between the first and second halves of my period for the other three telescope categories are not statistically significant.

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* These size categories are:-

(a)	2.55 - 5.08 m (200")		
(b)	1.23 - 2.54 m (100")		
(c)	0.62 - 1.22 m (48")		
(d) part	0.61 m (24")	see Section 4.3.1 of Part 1.	

** Including half of the possible missing telescopes deduced from Table 23. This is consistent with the approach taken with Table 35, where I have used the average of columns 2 and 3 of Table 35 as the best estimate; column 2 having no allowance for unknown telescopes and column 3 having the full allowance.

In this Section 2.1 I am interested in the effect of size on the cost-effectiveness of optical/IR telescopes, but part of the variation in Table 63 from one four year point to another is due to fluctuations in the cost-effectiveness of my whole population of optical/IR telescopes over the years. To eliminate this variation I have normalised my cost-effectiveness figures of $N_p/\Sigma d^{2.1}$ (shown un-normalised in Table 63) by making them add up to 100% for each year. These relative cost-effectiveness figures for the whole of my period 1958-1994, and for the second half of that period, i.e. 1978-1994, are plotted in Figure 24 (next page) against the logarithm of the average of the telescope diameters in each of the telescope size categories. This average diameter is the average of the diameters of the actual telescopes in each of the categories, not the average of the range.

Table 63 and the plots of {relative cost-effectiveness} versus {log(telescope diameter)} of Figure 24, show that:-

- *Category (a) and (b) telescopes are of similar cost-effectiveness when considering the period 1958-1994 as a whole. In the first half of my period, category (a) telescopes are less cost-effective than category (b) telescopes, whereas in the second half of my period category (a) telescopes are more cost-effective than category (b).*

- *Category (c) telescopes are less cost-effective than categories (a) and (b).*

- *Category (d) telescopes are the least cost-effective.*

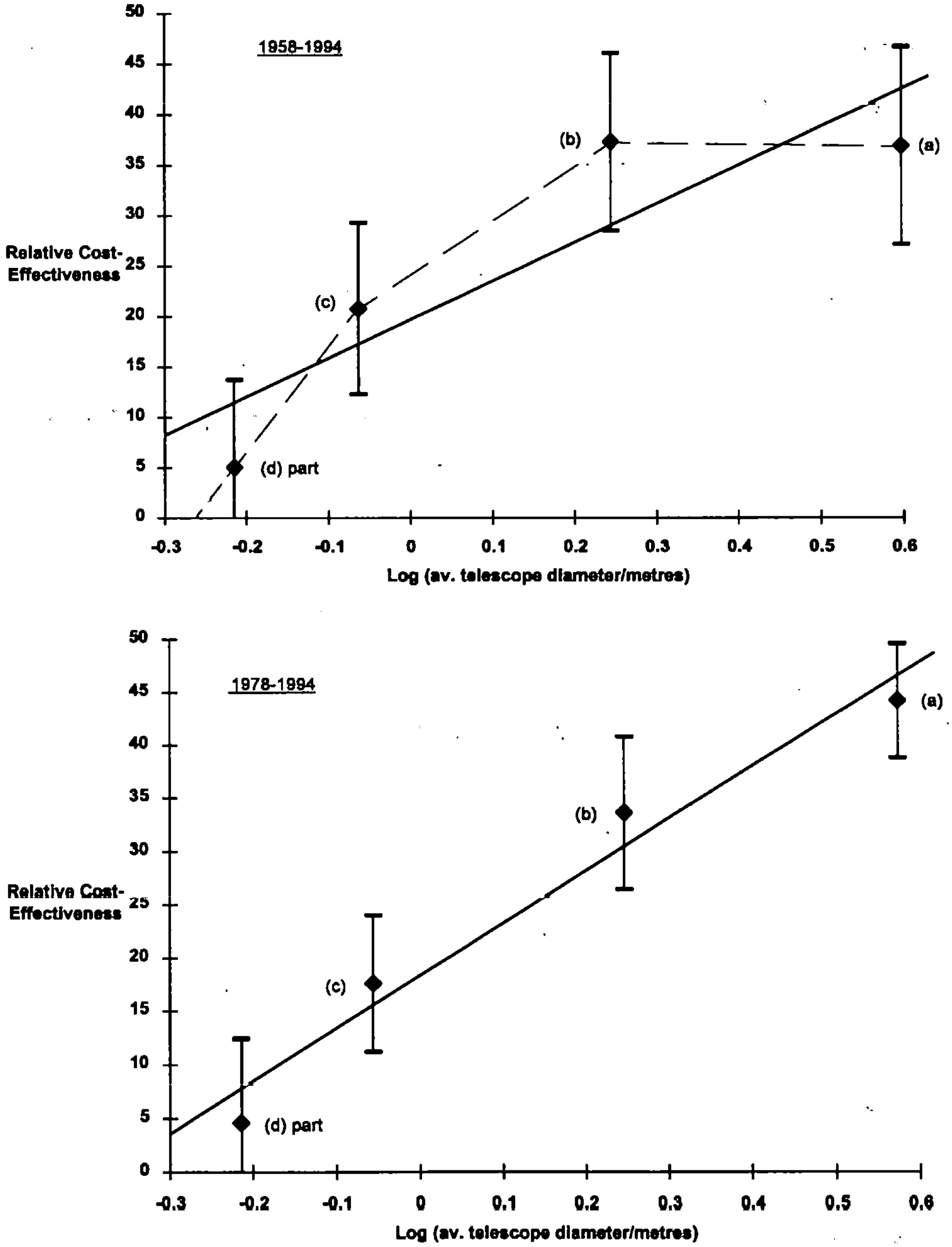
It is interesting to speculate as to why the largest telescopes have been so successful, in spite of the fact that they have to operate through the atmosphere which, until the recent advent of adaptive optics, severely limited their spatial resolution. Is it

FIGURE 24

Average relative cost-effectiveness scores (see text) for my four telescope categories*, with the telescope categories being characterised by the logarithm of the average size of telescopes in each category.

The first graph below indicates that a linear relationship is not the most accurate fit to the points, although a linear relationship seems a fair approximation for the second graph.

The *general* trend of increased cost-effectiveness with increased telescope size is clear for both the whole of my period (top graph) and the second half of my period (bottom graph), with the exception that there is no difference in the cost-effectiveness of category (a) and (b) telescopes in the top graph. The change between the two graphs is because of the clear increase in the cost-effectiveness of category (a) telescopes between the first and second half of my periods (see Table 63), from being less than that for category (b) to more than that for category (b), whereas the cost-effectiveness of telescopes in the other three categories has not changed with time.



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* The telescope categories (a) to (d) part are indicated on the graph.

because they attract the best astronomers, or because they have the best instrumentation, are situated in the best locations, can observe the faintest galaxies, or have the best spectral resolution?

Interestingly, Abt[1] showed that the number of observers (or teams) using the six largest telescopes available at the Kitt Peak National Observatory in the late 1960s increased approximately with aperture. Whether this was because there was more competition for the larger telescopes, and hence their observing time was at a premium, or because the larger telescopes could carry out their observations in a shorter time was not clear. The type of observations for which the various telescopes were used would clearly also be a factor, but an investigation into these various factors is beyond the scope of this present study.

It is also interesting to speculate as to why the cost-effectiveness of the largest telescopes has increased over my period. Abt suggests[13] that the main reason was that in the early period (1958 - mid 70s) research work was concentrated on stars and relatively little work was done on galaxies, and for stellar work in those days (b)-size telescopes were almost as effective as the larger (a)-size. Later, however, with the advent of CCDs and modern two-dimensional detectors, the emphasis shifted to galaxies, for which the larger telescope apertures were required. Abt says that the percentage of stellar to extragalactic papers in *ApJ* changed from 50% to 6%, respectively, in 1954, to 33% to 42% in 1994.

The cost-effectiveness of large telescopes could also have improved if the annual costs had been reduced over my period. Such an effect would not have been evident in the simple analysis of this section, however, because I have not used real costs. I assumed, instead, that the total annual costs vary approximately as $d^{2.1}$.

There is some evidence in Section 3.2 of Part 2 that the true annual operations costs of *some* observatories have reduced with time, and in Figure 17 that the capital costs of telescopes have also reduced with time. But I have no evidence in this thesis that these reductions have been different for different sizes of telescopes. So it is not clear whether the improvement of the cost-effectiveness with time of the largest telescopes relative to the smaller telescopes would have been any different if I had used real costs, rather than a cost synthetic based on $d^{2.1}$.

2.2 Optical/IR Observatories Considered as a Whole

In the above Section I compared the cost-effectiveness of my four different categories of optical/IR telescopes using the fact that the annual plus amortised capital costs vary, to a first approximation, as $d^{2.1}$, where d is the diameter of the primary mirror. In this analysis I did not need to use any cost data directly, as I could simply use the $d^{2.1}$ relationship. Clearly this approach cannot be used when comparing the cost-effectiveness of ground-based optical/IR facilities with both ground-based radio facilities and space-based facilities, and in this case I have to use real costs.

In Table 64 (next page) I have calculated the cost-effectiveness of the total of ground-based, American and British Commonwealth, optical/IR observatories as follows (column numbers in brackets):-

(i) The number of highly-cited papers produced per half-year using data from optical/IR telescopes. These figures are the total figures for all categories of telescope in Table 22(b), plus 3.90 for the Keck in 1994 as that was not included in Table 22(b) (because the Keck was not in any of the classes).

(ii) *Known* operating costs per year for various optical/IR observatories (see Table 30 and Appendices 6 & 7). These costs sometime pre-date those shown in Table 33A as Table 64 includes start-up (non-capital) costs that Table 33A does not.

TABLE 64

Calculation of the Cost-Effectiveness of all Ground-Based, American and British Commonwealth, Optical/IR Observatories (see text)

(all costs are in 1992 $millions)*

Year Papers Published	Number of papers in ½ year (i)	Known operating costs/yr (ii)	$0.33\Sigma d^{2.1}$ for other telescopes** (iii)	Total annual op^{g}. costs = (ii)+(iii) (iv)	Add 6% of (iv) as write-off costs to get (v)	Cost-effectiveness $\frac{N_p}{C} = \frac{2\times(i)}{(v)}$ (vi)
1958	7.0	—	33 ± 6	33 ± 6	35 ± 6	0.40 ± 0.07
1962	7.5	—	39 ± 7	39 ± 7	41 ± 7	0.37 ± 0.07
1966	13.5	8	45 ± 8	53 ± 8	56 ± 8	0.48 ± 0.07
1970	14.9	16	54 ± 10	70 ± 10	74 ± 10	0.40 ± 0.06
1974	25.4	29	62 ± 11	91 ± 11	96 ± 12	0.53 ± 0.07
1978	30.0	33	65 ± 12	98 ± 12	104 ± 13	0.58 ± 0.08
1982	36.2	32	93 ± 17	125 ± 17	133 ± 18	0.54 ± 0.09
1986	25.9	40	93 ± 17	133 ± 17	141 ± 18	0.37 ± 0.05
1990	57.2	39	103 ± 20	142 ± 20	151 ± 21	0.76 ± 0.12
1994	48.0	40	135 ± 30	175 ± 30	186 ± 32	0.52 ± 0.09

(iii) The *estimated* operating costs per year for those observatories not covered by (ii), using the $0.33 \times \Sigma d^{2.1}$ synthetic deduced from Table 33B. The figure for the Keck in this column for 1994 is the average figure of $26m/year deduced from Table 35.

The error quoted in column (iii) is the rms total of two errors, namely:-

(a) the error associated with a possible underestimate in the numbers of smaller telescopes, plus, for 1994 only, the error in estimating the cost of operating the Keck

and (b) the error produced by an estimated error of ± 0.06 in the 0.33 factor (see Part 2, Section 2.2.2).

(iv) *Total* annual operating costs = (ii) + (iii)

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[*] As mentioned above, the costs shown against any of the years in this table are for the facilities as they existed two years previously.

[**] Including $26m in 1994 for the Keck.

(v) Total annual costs = {Total annual operating costs} x {1 + ξ} where ξ is a factor to cover the write-off of capital costs. This factor ξ is 0.06 as, in Table 62:-

$$\frac{\text{The total write-off costs up to 1992}}{\text{The total annual operating costs up to 1992}} = \frac{210}{3300} = 0.06$$

There is an error of $\pm\frac{70}{210} \times 0.06 = \pm 0.02$ in the 0.06 factor for write-off costs (see Section 2.4 of Part 2), so the figure in column (iv) should be multiplied by 1.06 ± 0.02. This error of ±0.02 can be ignored, however, as it is far smaller than any of the other errors shown in column (iv).

(vi) The cost-effectiveness N_p/C given by:-

$$\frac{\text{No. of highly-cited papers/ year}}{\text{Total annual cost}} = \frac{2 \times (\text{i})}{(\text{v})}$$

This cost-effectiveness parameter N_p/C, in number of highly-cited papers per million 1992 dollars, is plotted in Figure 25 (next page) which shows, on average, a gradual increase in cost-effectiveness with time for these ground-based, optical/IR telescopes.

The cost-effectiveness results from 1958 to 1982 in Figure 25 show no great variation about the regression line, but the points for 1986, 1990 and 1994 show quite a large variation. This is mainly due to the low paper scores in 1986 and 1994 and high ones in 1990, although the addition of the costs of the Keck to the costs in 1994 has also helped to reduce the cost-effectiveness score for that year.

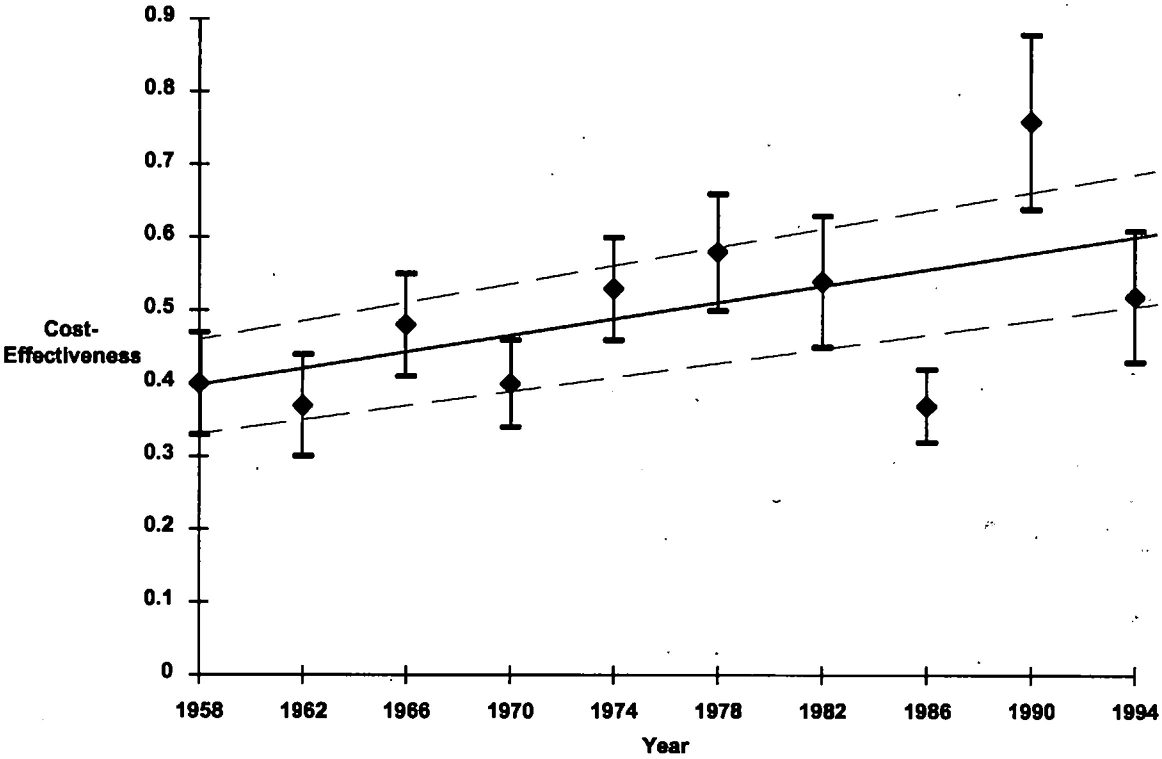
The variation in the paper scores between 1986, 1990 and 1994 is mainly attributable to variations in the scores in the *ApJ*, because the *ApJ* publishes many more papers than the *MNRAS*. There is no clear reason for the peak in 1990 and the low scores in the years on either side, however. These variations appear to be random. In fact the

FIGURE 25

Plot of the cost-effectiveness as a function of time for ground-based, American and British Commonwealth, optical/IR observatories, where the cost -effectiveness is defined as:-

$$\frac{\text{No. of highly-cited papers / year}}{\text{Total annual cost in millions of 1992 dollars}}$$

The error bars are for the errors calculated in Table 64. They take account of errors in the total annual costs due to errors in (a) estimating the total number of telescopes, and (b) estimating the total annual costs for those telescopes where that is not known, using the 0.33 x $\Sigma d^{2.1}$ relationship. The latter is by far the largest error source, as all the largest and most expensive telescopes are known, with only the number of the smaller, less-expensive telescopes being uncertain. So the error bars show essentially systematic errors due to an error in the 0.33 factor. The dotted least-squares regression lines are for the points at either end of the error bars.



scores in the *MNRAS* did not show a peak in 1990, as the score for 1994 was slightly higher than that for 1990.

One possible explanation of the apparent 50% increase from 1958 to 1994 in the cost-effectiveness of optical/IR telescopes shown by the best-fit line in Figure 25 is not that the telescopes are more cost-effective, but that it is easier to get papers published in 1994 than in 1958. To check on this, I divided the number of *ApJ* papers with

American* authors[8] by the number of full-time American astronomers. Taking data for the latter from Greenstein[14] and Bahcall[15], I found that each astronomer appeared to publish about 30% more papers in the 1980s than in the 1960s. Using the number of members of the American Astronomical Society[7,14], however, the ratio of number of papers per astronomer appears to have stayed constant.

It is not clear if the definition of full-time American astronomers in both the Greenstein and Bahcall reports is the same, and I do not know if the percentage of Foreign members of the AAS is the same for the two different periods (which I have implicitly assumed in the above). Given these and other uncertainties, the measure of number of papers per astronomer, that I have used to estimate whether it is easier to publish now than twenty or thirty years ago, can only be very approximate. The two alternative figures of 30% or 0% increase in the number of papers per astronomer from the 1960s to the 1980s show that it is possible, however, that *some* of the 50% increase in the cost-effectiveness of optical/IR observatories indicated in Figure 25 could be caused by this effect. But at least part and possibly all of the 50% increase in cost-effectiveness may be real.

2.3 Individual Optical/IR Observatories Compared

I will now compare the cost-effectiveness of various optical/IR observatories in this section, and will compare the cost-effectiveness of individual telescopes in Section 2.4 below.

In Table 33 (in Section 2.2.2 of Part 2) I listed the known annual costs of a number of optical/IR observatories. In Table 65 (next page) I have calculated the cost-effectiveness of these observatories as follows (column numbers in brackets):-

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* Including 50% of papers with joint American-Foreign authors.

TABLE 65

Cost-Effectiveness of Various Ground-Based Optical/IR Observatories in Rank Order

Observatory	Location	Period (i)	Av. number of papers in ½ year (ii)	Av. annual cost (in 1992 \$m) (iii)	Cost-effectiveness $\frac{N_P}{C} = \frac{2\times(ii)}{(iii)}$ (iv)
AAO	Siding Spring	1978 - 94	4.5	5.0	1.79
Lick	Mt Hamilton	1974 - 82	2.6	3.8	1.37
KPNO	Kitt Peak	1978 - 94	5.9	9.3	1.26
Las Campanas	Las Campanas	1978 - 86	0.9	1.6	1.17*
Mt Wilson	Mt Wilson	1978 - 82	1.3	2.5	1.00
ING	La Palma	1990 - 94	5.0	10.1	0.99
CTIO	Cerro Tololo	1978 - 94	3.2	8.1	0.79
UKIRT	Mauna Kea	1982 - 94	2.1	6.4	0.66
CFH	Mauna Kea	1982 - 94	1.7	5.8	0.57
RGO	Herstmonceux	1974 - 82	0	3.3	0

Note This list is not exhaustive as I do not know the annual cost of the Palomar and Mc Donald Observatories, for example.

(i) As mentioned in Section 4.3.1 of Part 1, I have taken the period of availability of facilities as two years before the date when the papers were published**. So, strictly speaking, in column (i) of Table 65 I should take the years of Table 33, when I know the average costs of the various observatories, add two years to the start and finish dates, and then look up the paper scores for that period. Unfortunately, because I am working with papers at four-yearly intervals, this cannot be done exactly, and so I have taken the nearest four-yearly data points as the start and finish dates of the periods in column (i).

(ii) Column (ii) shows the average number of highly-cited papers published per half-year over the periods shown in column (i).

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* The average annual cost figure for the Las Campanas Observatory may be too low (see Section 2.2.2 of Part 2), and, if this is so, this ratio will be too high.

** To allow time for the facilities to be fully commissioned, the data to be collected and analysed, and the papers to be written, refereed and published.

(iii) The average annual costs shown in column (iii) are the average annual operating costs shown in Table 33 multiplied by 1.06 to cover the write-off of capital costs.

(iv) The cost-effectiveness N_p/C shown in column (iv) given by:-

$$\frac{\text{No. of highly-cited papers/year}}{\text{Total annual cost}} = \frac{2\times\text{(ii)}}{\text{(iii)}}$$

The lines drawn in Table 65 indicate where significant differences occur in the cost-effectiveness values for the years shown.

The only published analysis that examined the relative performance of a reasonable number of optical/infrared telescopes over recent times, and that mentioned an order of merit that resembled one based on cost-effectiveness, has been that by Trimble[5] *. Although she did not estimate the cost-effectiveness as such, she did discuss one 'order of merit' which was based on the number of citations per unit area of the primary mirror (ignoring any area lost due to holes or obstructions). This is very close to a cost-effectiveness figure, assuming that the total annual costs are approximately proportional to d^2, where d is the diameter of the primary mirror.

In her paper Trimble analysed the citations of papers published in 1990-91 using data from telescopes of > 2.0m diameter. She found, after allowing for the different areas of their primary mirrors, that the order of the *telescopes* in which she was most interested was the Lick 3.05m, CTIO 4.0m, KPNO 3.8m, and Palomar 5m, in order of decreasing citation number per unit area. Although she did not mention it, the 2.1m KPNO telescope had the highest citation score per unit area of all the telescopes in her list, and if this is included with the 3.8m KPNO telescope (as they are at the same observatory) it would modify her 'order of merit'. There were six telescopes in

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* This is the same paper as that discussed in Section 4.3.1 of Part 1.

her list[*] that are included in my list of observatories in Table 65, and her list of *telescopes*, in order of citation numbers per unit area, would compare with my list of *observatories*, in order of cost-effectiveness, as follows:-

Order[**] of *telescopes* deduced from Trimble's paper (using Citation Nos./unit area)	**My order of *observatories* using** $\frac{\text{No. of highly-cited papers/ year}}{\text{Total annual cost}}$
KPNO 3.8m + 2.1m	Lick
Lick 3.05m	KPNO
CTIO 4.0m	Las Campanas
Las Campanas 2.5m	CTIO
CFH 3.6m	CFH

As the total annual costs are approximately proportional to d^2, the above order deduced from Trimble's paper is approximately the order of cost-effectiveness (although she did not claim it to be so). A better estimate of the cost-effectiveness would be produced using $d^{2.1}$ instead of d^2, but such a change does not affect the above order in this case. So there is some similarity between the order of telescopes/observatories in terms of their cost-effectiveness deduced from Trimble's data and mine, even though the two lists above have been produced using different parameters. In addition to using different parameters, she was comparing telescopes and I am comparing observatories, and her data was for papers published in American journals in 1990-91, and mine is for papers published in American and British journals in the various periods shown in Table 65. So it may be somewhat surprising that the above two orders of merit are so similar.

My data covers more observatories than those represented in Trimble's paper (as well as more years), however, and the best observatories, of those listed in Table 65,

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[*] I have not included Trimble's data for non-American telescopes, as she admits that her results tend to be biased against them because of her choice of journals. Trimble did not include the Mount Wilson 2.5m telescope as it had been moth-balled some years previously.

[**] This list is not in Trimble's paper. I have deduced it from her data.

appears to be the Anglo-Australian Observatory, although the results for the first six observatories in that table are not significantly different.

The RGO at Hertsmonceaux in the 1970's comes out very poorly in Table 65 as none of the telescopes was used to produce any of the most-highly cited papers over the period 1974-82. This is consistent with the very poor performance of the largest of the RGO telescopes of the time, the INT, found by Irvine and Martin[3]. The more recent performance of the INT has much improved, however, since it was moved to La Palma in 1984, being part of the ING in Table 65.

Unfortunately I do not know the annual costs of the Palomar and Mc Donald Observatories, and so these have been excluded from the above. An estimate of the cost-effectiveness of individual telescopes at these observatories can be deduced, however, using the $d^{2.1}$ relationship. This will be undertaken in the next section, in comparison with all the other optical/IR telescopes covered by my study, which will, therefore, give more comprehensive results.

Before turning to the cost-effectiveness figures for individual optical/IR telescopes, it is probably worth recording here the difficulties that I have experienced in obtaining the annual costs of optical/IR observatories. For completeness, I will also include radio observatories and spacecraft in this brief summary.

- Tuttle of the NSF provided me with most of the annual expenditure data for the American National Observatories (both optical/IR and radio)[25] which is analysed in Appendix 4. Organisations generally provide data that can be found relatively easily and, because of this, it is usually not exactly what was asked for or required. In this particular case with the NSF data, the greatest difficulty I had was in trying to find out what National Solar Observatory costs were included in the NOAO figures, so that I could eliminate these NSO costs from my analysis. I asked S. Wolff (Director of the NOAO) for help here[40] but, although she showed a great interest in my work, I received no information.

- PPARC allowed me access to some of their financial files (see Appendix 6), but a comparison between their data and figures in the UKIRT[28], JCMT[41], ING[29] and AAO[30] annual reports, and in the OIM report[26], showed a number of possible discrepancies. I raised these with PPARC at all levels up to K. Pounds but received no clarification. I received, instead, a written response from Le Masurier that said[42] "Unfortunately the information is just not available. I suppose that with some serious investigation, it could be traced, but we would probably need to hire Touche Ross or someone to do it!"

- Approximate cost data was provided by Stannard of Jodrell Bank[34] and Baldwin of the MRAO, Cambridge, see Appendix 7, but in his reply, Baldwin said[43] "(running costs are) not the whole of the annual grant, since that included the capital for most of the smaller telescopes. A large fraction of the grant is for salaries and one would need to decide which posts, or parts thereof, were for running the telescopes and which were for new developments or for doing science with them. I think that the breakdown would not be easy except for the most recent years". What Baldwin described was a common problem for universities on both sides of the Atlantic in trying to determine a fair estimate of the costs of running their observatories.

As I pointed out in Section 2.2.2 of Part 2:- "In the United States, in particular, many observatories have more than one source of funding. Many university observatories, for example, are funded by the National Science Foundation (NSF) or NASA, by state funds and/or by private donations, so looking at only one of these sources of funding can be very misleading (in trying to understand their costs)." In addition "If the observatory is not a stand-alone facility from a cost point-of-view, some valid costs may not be charged to the observatory.

University observatories, for example, may use staff who are covered by other university budgets. In the UK the situation was clarified in 1993/94 by changes in the Dual Support arrangements of funding university observatories[24], but this change only took place at the end of my period."

- Published data in the Greenstein[14] and Field[19] Reports, and in the NASA Historical Data Book, Vols. 1, 2 & 3 [38], provided much of the data on annual spacecraft costs for NASA spacecraft. Unfortunately, this data stopped in 1981, and subsequent less complete data was supplied by NASA[39] (see Section 4.2 of Part 2).

- BNSC allowed me access to their files which provided a good database on ESA spacecraft costs since 1975. My subsequent questions were answered in detail by ESA[36], giving me the most complete and unambiguous set of data of all those discussed in these paragraphs. Unfortunately, the costs of the earlier European and UK spacecraft could only be deduced much less accurately (see Section 4.1 of Part 2).

Although these problems and their solutions have been discussed in Part 2 and a number of the Appendices, as indicated above, I thought it useful to summarise them here to give an indication of the problems experienced in obtaining unambiguous cost data of good quality. It also shows, in the case of PPARC, that they do not *seem* to have a good understanding of the costs for which they are responsible.

2.4 Individual Optical/IR Telescopes Compared

I will now calculate the cost-effectiveness of individual optical/IR telescopes according to the following methodology:-

(a) For those telescopes included in the observatories listed in Table 65, I will use the $d^{2.1}$ factor to divide up the total annual observatory costs shown in column (iii) of that table between the various telescopes of each observatory.

(b) For those telescopes from observatories *not* listed in Table 65, I can assume that the total annual costs are equal to $1.06 \times 0.33d^{2.1}$ in millions of 1992 dollars, when d is in metres. The 1.06 figure allows for a write-off factor of 0.06, and the 0.33 factor is taken from Table 33B.

This analysis results in the cost-effectiveness figures shown in Table 66 (next page) for the second half of my period* where I have listed the category (a) and (b) telescopes separately for ease of inter-comparison of similar telescopes. These figures in Table 66 are the average annual scores given in Table 11B(b) of Part 1 divided by the annual costs just derived. Obviously the order of telescopes by cost-effectiveness is very different from the order in Table 11B(b), as the criteria are different, although the Anglo-Australian Telescope still heads the list of category (a) telescopes.

It is interesting to note from Table 66 that, although the *average* cost-effectiveness of category (b) telescopes is lower than that for category (a) telescopes, the cost-effectiveness of four category (b) telescopes is higher than that for any of the category (a) telescopes. The difference in cost-effectiveness between each of these four category (b) telescopes and the AAT is not significant, however.

It is tempting to compare Trimble's analysis of telescopes referred to above with my data at telescope level, but this has already been done in terms of effectiveness in

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* I have chosen to analyse the second half of my period as most of the known observatory costs in Table 65 are for this period. As a result, a similar analysis for the first half of my period would have been somewhat speculative.

TABLE 66

Cost-Effectiveness of Various Optical/IR Telescopes for 1978 – 1994 in Rank Order

Diameter (in metres)	Year of first use	Name	Av. number of papers in ½ year (i)	Av. annual cost (in 1992 $m) (ii)	Cost-effectiveness $\frac{N_P}{C} = \frac{2\times(i)}{(ii)}$
		Category (a) Telescopes 2.55 – 5.08 m			
3.89	1975	Anglo-Australian Telescope	3.77	4.3	1.76
3.05	1959	Lick	2.00	3.1	1.27
2.72	1969	Mc Donald Obs.*	1.40	2.9*	0.98
4.20	1987**	William Herschel Telescope	3.21	7.2	0.89
3.81	1973	KPNO	2.59	6.2	0.83
4.00	1975	CTIO	2.36	6.9	0.68
5.08	1948	Palomar*	3.49	10.6*	0.66
3.80	1979	UK Infrared Telescope	2.12	6.4	0.66
3.58	1979	Canada-France-Hawaii Telescope	1.65	5.8	0.57
3.0	1979	NASA IRTF, Mauna Kea*	0.71	3.5*	0.41
4.50	1979	Multi-Mirror Telescope*	1.31	8.3*	0.32
				Average	**0.82**
		Category (b) Telescopes 1.23 – 2.55 m			
1.26/1.83	1948	Palomar Schmidt*	1.20	1.01*	2.39
2.54	1976	Irénée du Pont Telescope	1.61	1.40	2.30#
2.14	1964	KPNO	2.08	1.84	2.26
1.24/1.83	1973	UK Schmidt	0.71	0.72	1.97
2.24	1970	University of Hawaii*	1.03	1.91*	1.08
2.54	1984	Isaac Newton Telescope	1.28	2.52	1.02
2.26	1969	Steward Obs., Univ. of Arizona*	0.62	1.94*	0.64
2.34	1988**	MDM, Kitt Peak*	0.50	2.09*	0.48
		plus 31 others (all with average paper scores of < 0.50)			
				Average	**0.55**

Note Minimum qualification for the above table is average paper score ≥ 0.50 and at least two data points. There were no category (c) or (d) telescopes with an average paper score of ≥ 0.50, and so none are listed in the above table.

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* Costs deduced using the 1.06 x $0.33d^{2.1}$ relationship, see text.

** The number of papers based on data from ground-based optical/IR telescopes appears to increase over about the first ten years of operation[16], before levelling out. If that is also true of highly-cited papers, the cost-effectiveness figures for these telescopes may well get better with time. My data is not sufficiently complete to show whether this is so or not.

\# As mentioned in the footnote to Table 65, the average annual cost of the Las Campanas Observatory, where the Irénée du Pont Telescope is situated, may be too low. If this is the case, this cost-effectiveness ratio will be too high.

Section 4.3.1 of Part 1, and, as her paper gives no data on costs, such an analysis would provide nothing new from that shown in Part 1.

Too much should not be read into the results of Table 66 for those telescopes marked with an asterisk, as the costs for those telescopes have been deduced using the 1.06 x $0.33d^{2.1}$ relationship which may not be accurate enough at individual observatory or telescope level*. It would be unfair to leave these telescopes out of my analysis completely, however, which I have done in Section 2.3 above, and so I have included them with this note of caution.

Different readers will note different things in Table 66, depending on their own particular experience. What I find particularly interesting is:-

(1) The Anglo-Australian Telescope has done particularly well compared with other category (a) telescopes.

(2) Both Schmidt telescopes have done very well in category (b).

(3) The performance of the Isaac Newton Telescope has improved since its modification and move from Herstmonceux to La Palma (compare the RGO results in Table 65 with the INT result in Table 66).

The relative performance of the 3.05m Lick Telescope may appear surprising to some astronomers although, as mentioned in Section 2.3 above, Trimble also found that this Lick telescope had a higher figure of merit (in terms of citations per unit surface area of the primary mirror) than that of the CTIO 4.0m, KPNO 3.8m, and Palomar

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* It is accurate enough when looking at groups of observatories or telescopes, however.

TABLE 67
A Comparison between the Cost-Effectiveness of the 3.05m Lick and the 3.81m KPNO Telescopes according to my analysis and that of Trimble

	My Results for 1978-94*			Trimble's Results for 1990-91*		
	Av. No. of papers in ½ year (i)	Av. annual cost (in 1992 $m) (ii)	Cost-effectiveness $\frac{N_P}{C}=\frac{2\times(i)}{(ii)}$	No. of citations (iii)	Area of mirror (in m^2) (iv)	Citations per unit area $\frac{(iii)}{(iv)}$
3.05m Lick	2.00	3.1	1.27	197	29	6.8
3.81m KPNO	2.59	6.2	0.83	238	46	5.2

5m. In both my analysis and Trimble's, the reason why the Lick did so well, however, was because it had a low annual cost (in my analysis) or smaller mirror area (in Trimble's analysis), not that it had a higher paper score or number of citations compared with these other three large American telescopes. This is shown in Table 67 for the 3.05m Lick compared with the 3.8m KPNO telescope, as an example**. So the Lick 3.05m is the best American category (a) telescope in terms of its *cost-effectiveness*, even though other large American telescopes, particularly the 5m Palomar and the 3.8m KPNO telescopes, have done better in terms of *effectiveness* (see column (i) of Table 66). As most astronomers tend to think of effectiveness of facilities, without considering the cost, they would probably expect the Palomar 5m telescope, in particular, to beat the Lick 3m, which it has. In terms of cost-effectiveness, however, the Lick 3m appears to be the best large American telescope.

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* Dates of published papers.

** The effect is similar between the Lick and the 4m CTIO, and between the Lick and 5m Palomar telescopes.

3 Ground-Based Radio Telescopes

3.1 Radio Observatories Considered as a Whole

In Table 68 (next page) I have calculated the cost-effectiveness of ground-based, American and British Commonwealth, radio observatories as follows (column numbers in brackets):-

(i) The number of highly-cited papers produced per half-year using data from radio telescopes.

(ii) *Known* operating costs per year for various radio observatories (see Table 30 and Appendices 6 & 7).

TABLE 68
Calculation of the Cost-Effectiveness of Ground-Based, American and British Commonwealth, Radio Observatories (see text)
(all costs are in 1992 $millions)

Year Papers Publ^d	No. of papers in ½ yr (i)	Known operating costs/yr (ii)	0.14 x capital costs for other telescopes (iii)	Total annual op^g. costs = (ii) + (iii) (iv)	Write-off costs (v)	Total annual costs (vi)	Cost-effectiveness $\frac{N_P}{C} = \frac{2\times(i)}{(vi)}$ (vii)
1958	0	—	1 ± 1	1 ± 1	0 ± 0	1 ± 1	0
1962	2.0	8	4 ± 2	12 ± 2	4 ± 0	16 ± 2	0.25 ± 0.03
1966	3.0	25	10 ± 5	35 ± 5	8 ± 1	43 ± 5	0.14 ± 0.02
1970	1.9	40	24 ± 12	64 ± 12	13 ± 1	77 ± 12	0.05 ± 0.01
1974	9.4	37	29 ± 15	66 ± 15	14 ± 1	80 ± 15	0.24 ± 0.05
1978	9.5	36	34 ± 17	70 ± 17	18 ± 2	88 ± 17	0.22 ± 0.03
1982	14.1	38	35 ± 18	73 ± 18	24 ± 2	97 ± 18	0.29 ± 0.06
1986	23.2	44	36 ± 18	80 ± 18	25 ± 3	105 ± 18	0.44 ± 0.08
1990	14.3	40	41 ± 21	81 ± 21	27 ± 3	108 ± 21	0.26 ± 0.05
1994	9.2	47	47 ± 24	94 ± 24	28 ± 3	122 ± 24	0.15 ± 0.03

(iii) The *estimated* operating costs per year for those observatories not covered by (ii), using the 0.14 x capital cost synthetic deduced from Table 48.

The error quoted in column (iii) is based on an error of ± 0.07 in the 0.14 figure used to multiply the capital cost (see Table 48).

(iv) *Total* annual operating costs = (ii) + (iii)

(v) A figure to cover the write-off costs of capital expenditure consistent with the assumptions of Table 40.

The error quoted in column (v) is ± 10%, as the error in write-off costs deduced in Section 3.1.5 (vi) of Part 2 was ± \$60m in \$580m total of write-off costs.

(vi) Total annual costs = Total annual operating costs (iv) + annual capital write-off costs (v).

The error quoted is the root mean square of the errors in (iv) and (v) which, in practice, is equal to the error in (iv), as that in (v) is much smaller.

(vii) The cost-effectiveness N_p/C given by:-

$$\frac{\text{No. of highly-cited papers/ year}}{\text{Total annual cost}} = \frac{2 \times \text{(i)}}{\text{(vi)}}$$

This cost-effectiveness parameter N_p/C is plotted in Figure 26 (next page) which shows, on average, a gradual increase in cost-effectiveness with time for these ground-based radio telescopes.

The radio telescopes of the late 1940s and early 1950s were relatively simple, being inexpensive to build and operate, and it was not until the late 1950s and the 1960s that large expensive radio facilities became available. (For more details of these developments, see Part 4). This was very different from the case of ground-based

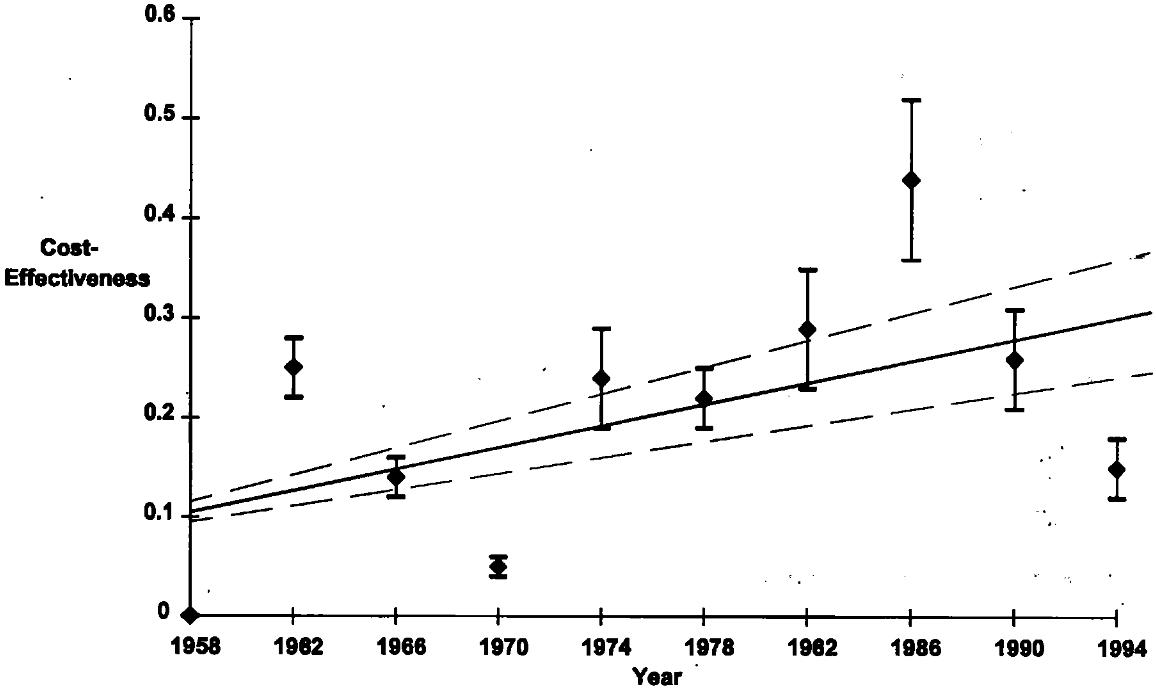
FIGURE 26

Plot of the cost-effectiveness as a function of time for ground-based, American and British Commonwealth radio observatories, where the cost -effectiveness is defined as:-

$$\frac{\text{No. of highly-cited papers/year}}{\text{Total annual cost in millions of 1992 dollars}}$$

The error bars are those calculated in Table 68. In practice they signify the errors in estimating the total annual cost for those telescopes where that is not known. They are, therefore, essentially systematic.

The dotted least-squares regression lines are for the points at either end of the error bars.



optical/IR telescopes that had gradually increased in number and complexity since the time of Galileo. So the annual operations costs of radio telescopes increased from nearly zero in 1956* to about $77m in 1968 (see Table 68) for my chosen geographical area, whereas those for optical/IR telescopes increased from a comparatively large $35m in 1956 to $74m in 1968 (see Table 64).

A comparison of Figures 25 and 26 shows that there is more variability in the cost-effectiveness results for radio telescopes in the early years of 1962 to 1970, than

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* As explained in the footnote to Section 1, the cost figures are for the year two years in advance of the year of publication of the papers. So the 1956 cost figure of $1m is, for example, shown in Table 68 against the 1958 year in which the papers were published.

there was for optical/IR telescopes over the same years. In fact, the large reduction in cost-effectiveness between 1962 and 1970 for radio telescopes was caused primarily by the rapid increase in annual costs, just described, without there being a corresponding increase in the number of highly-cited papers (see Table 68). There was a large increase in number of papers in 1974, however, with little increase in costs, thus causing a significant increase in cost-effectiveness that year.

There was another large reduction in cost-effectiveness between 1986 and 1994 for radio telescopes but, unlike that between 1962 and 1970, this was caused primarily by a large reduction in the number of highly-cited papers, rather than a large increase in costs. This reduction was true of highly-cited, radio-based papers in *ApJ*, but not for the *MNRAS*, where the number of such papers in 1994 was actually higher than in 1990 or 1986. So the reduction in the total of *ApJ* and *MNRAS* papers from 1986 to 1994, shown in Table 68, appears to be due to random effects, rather than indicating clear signs of a decrease in the usefulness of ground-based radio telescopes over that period. Obviously, analysis of all the half-years from 1986 to 1994 could help to clarify this, but that would require the review of as many papers again as I have reviewed in this study (i.e. just over 1,000, see Table 1). This current study is looking at trends over the whole period from 1958, however, rather than concentrating on any particular part of that period, so I will leave that analysis to others who may be more interested in recent developments.

3.2 Individual Radio Observatories Compared

I will now compare the cost-effectiveness of various radio observatories in this section.

Unfortunately, I know the annual costs of only a limited number of radio observatories (see Table 47 above). Their cost-effectiveness is calculated in Table 69 (next page) as follows (column numbers in brackets):-

TABLE 69

Cost-Effectiveness of Various Ground-Based Radio Observatories

Observatory	Period (i)	Av. number of papers in ½ year (ii)	Av. annual cost (in 1992 $m) (iii)	Cost-effectiveness $\frac{N_P}{C} = \frac{2\times(ii)}{(iii)}$ (iv)
Green Bank	1970 - 94	1.17	22	0.11
VLA	1982 - 94	3.25	~ 11	~ 0.6
Arecibo	1978 - 94	1.88	10	0.38
JCMT	1990 - 94	1.30	7	0.37
NRAL (Jodrell Bank)	1978 - 94	1.15	6	0.38
MRAO (Cambridge)	1978 - 94	0.18	2.5	0.14

(i) The annual operating costs shown in Table 47, which are used to calculate the annual costs in Table 69, are for a limited number of years. As a result, the number of highly-cited papers given in Table 69 is limited to those published in the periods shown in column (i).

(ii) These are the average number of highly-cited papers published per half-year in the periods shown in column (i).

(iii) The average annual costs are the average annual operating costs shown in Table 47 plus a figure to cover the write-off capital expenditure consistent with the assumptions of Table 40.

(iv) The cost-effectiveness N_p/C given by:-

$$\frac{\text{No. of highly-cited papers/ year}}{\text{Total annual cost}} = \frac{2\times(\text{ii})}{(\text{iii})}$$

The cost-effectiveness of the Arecibo, JCMT and NRAL observatories listed in Table 69 are identical, within error. As far as the other observatories are concerned:-

(a) The annual costs and number of papers for Green Bank are fairly reliable, and so its cost-effectiveness (with a maximum yearly figure of 0.24) appears to be significantly lower than the average of the other observatories listed in Table 69.

(b) The annual costs of the VLA are not known with any certainty, and so its cost-effectiveness is only known approximately.

(c) In the case of the MRAO, the average number of papers is very low and so the resultant cost-effectiveness figure is very unreliable. I do not know the annual cost of the MRAO before 1978, but if I assume that it has not changed over my total period, its cost-effectiveness over the period 1958 - 1994 would be 0.32. This is the same as that of the Arecibo, JCMT and NRAL observatories, within error.

In summary, therefore, it appears that the cost-effectiveness of all the observatories listed in Table 69 are the same, within error, with the exception of Green Bank which seems to be on the low side.

There is too much uncertainty about how to divide up the observatory costs in Table 69 between the various radio telescopes at each facility for me to try to compare the cost-effectiveness at individual radio telescope level.

4 Spacecraft

4.1 Spacecraft Considered as a Whole

In Section 4.3 of Part 2 I discussed what write-off period to use for spacecraft costs and concluded that 12 years, or the useful lifetime of the spacecraft, whichever is the longer, should be used. I also proposed to investigate what effect choosing 10 years or 15 years would have on my results.

In Table 70 below I have calculated the cost-effectiveness of American, ESA and UK spacecraft as a whole*, using these three different write-off periods of 10, 12 and 15 years, with the results shown in Figure 27A (next page). Table 70 and Figure 27A show that each of these three write-off periods produces similar results, on average, and so my selection of 12 years is not a major sensitivity.

In Figure 27B I have plotted the cost-effectiveness using a 12 year write-off period. The error bars (and dotted regression line) showing the effect of the errors shown in Table 60 (in Section 4.3 of Part 2) for total programme costs. Again the effect of the errors is relatively small.

TABLE 70

Calculation of the Cost-Effectiveness of US, ESA and UK Space-Based Observatories

(all costs are in 1992 $millions)

Year papers publ^d	Number of papers in ½ year	Total annual costs using various write-off periods**			Cost-effectiveness N_P/C using various write-off periods		
		12 yrs	10 yrs	15 yrs	12 years $\frac{N_P}{C}=\frac{2\times(i)}{(ii)}$	10 years $\frac{N_P}{C}=\frac{2\times(i)}{(iii)}$	15 years $\frac{N_P}{C}=\frac{2\times(i)}{(iv)}$
	(i)	(ii)	(iii)	(iv)	(v)	(vi)	(vii)
1958	0	0	0	0	0	0	0
1962	0	0	0	0	0	0	0
1966	0	2 ± 1	3	2	0	0	0
1970	0	139 ± 14	140	139	0	0	0
1974	4.0	194 ± 16	202	183	0.04 ± 0.00	0.04	0.04
1978	6.0	229 ± 17	248	212	0.05 + 0.01/- 0.00	0.05	0.06
1982	16.8	303 ± 17	319	273	0.11 + 0.01/- 0.00	0.11	0.12
1986	16.8	163 ± 9	191	169	0.21 ± 0.01	0.18	0.20
1990	14.0	125 ± 7	87	134	0.22 + 0.02/- 0.01	0.32	0.21
1994	42.2	652 ± 59	693	649	0.13 + 0.02/- 0.01	0.12	0.13

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* Excluding the Kuiper Airborne Observatory, Sounding Rockets and Balloons as I do not know their costs, and they are not spacecraft anyway, although they do operate above much of the atmosphere and therefore have some of the advantages of spacecraft. This analysis also excludes solar and planetary spacecraft, as any stellar or galactic work is incidental to their main mission. This is consistent with excluding ground-based solar telescopes from my earlier analysis.

** Write-off of capital and operational costs over 12 (10 or 15) years, or the useful lifetime of a spacecraft, whichever is the longer. For simplicity, the errors, which are deduced from uncertainties in the total programme costs shown in Table 60, are only shown for the 12 year write-off period.

FIGURE 27

Plots of the cost-effectiveness as a function of time for American, ESA and UK space-based observatories, where the cost-effectiveness is defined as:-

$$\frac{\text{No. of highly-cited papers / year}}{\text{Total annual cost in millions of 1992 dollars}}$$

The best-fit lines in each of the graphs exclude the zero points for 1958, 1962 and 1966, but include that for 1970.

FIGURE 27A

The three different plots are for 10, 12 and 15 year write-off periods for spacecraft programme costs. These different write-off periods do not produce markedly different results, in general.

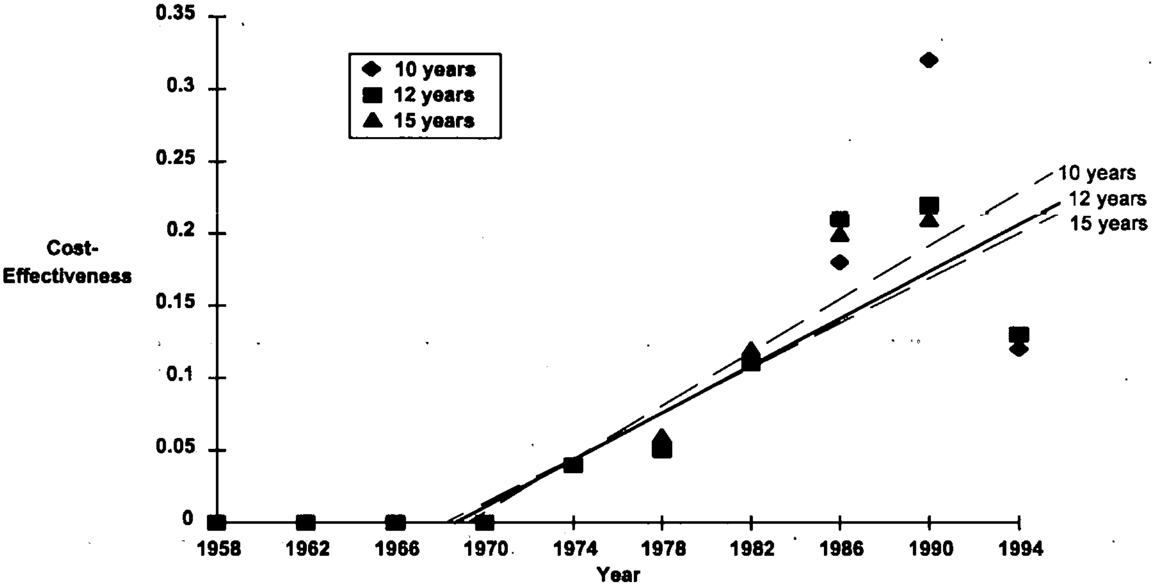


FIGURE 27B

This Figure gives more detail for a 12 year write-off period. The error bars are for errors in estimating spacecraft programme costs (see Table 60). Unlike the cases for Figures 25 and 26, however, these errors in Figure 27B are random. The dotted least-squares regression lines are for the points at either end of the error bars. All Spacecraft are included, *including* the HST.

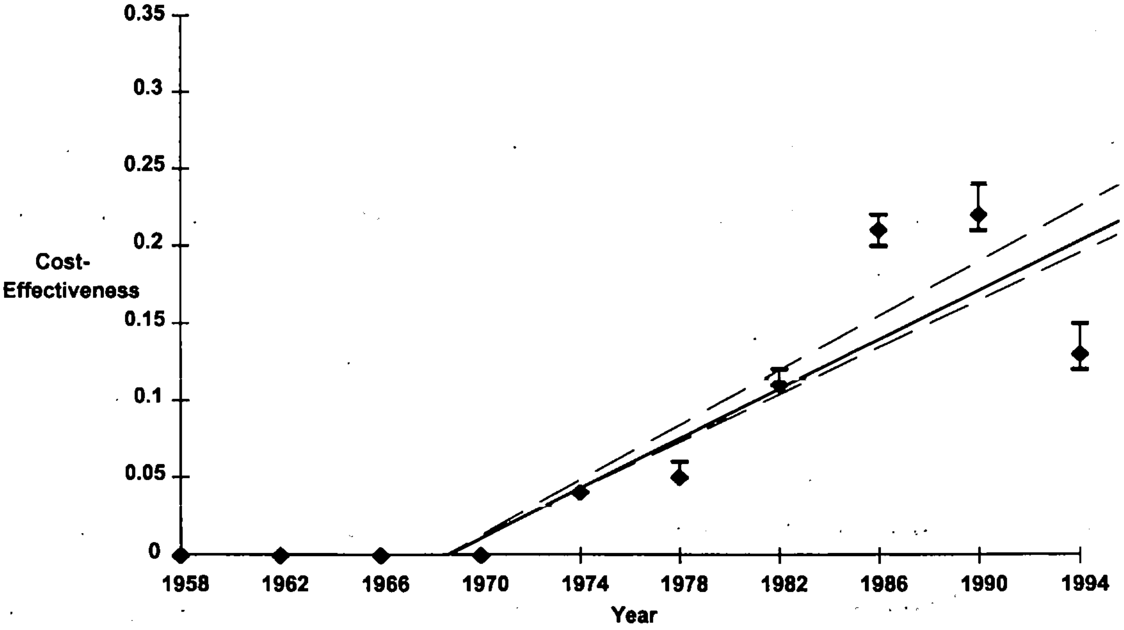
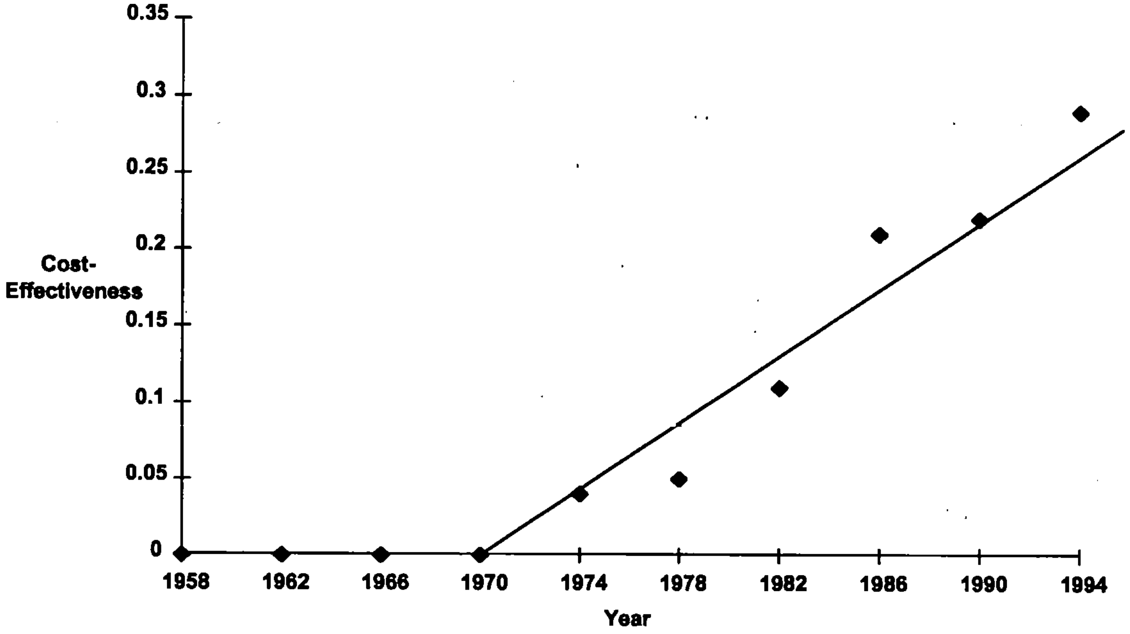


FIGURE 27C

This plot is the same as Figure 27B, with the error bars omitted for simplicity, except that the HST is *not* included in this new plot. The effect of the HST in reducing the average spacecraft cost-effectiveness for 1994, the only year that it appears in Figure 27B, can be clearly seen by comparing the two Figures.



Inspection of columns (i), (ii) and (v) of Table 68 shows that the cost-effectiveness of spacecraft shown in Figure 27B can be divided into three phases, i.e.:-

(a) An increase in cost-effectiveness from 1970 to 1982 due to an increase in the number of highly-cited papers which more than compensates for the increase in total annual costs due to new facilities being brought on line.

(b) An increase in cost-effectiveness from 1982 to 1990 due to a decrease in total annual costs whilst the number of highly-cited papers stays approximately constant. The decrease in cost is mainly due to costs of the OAO series of spacecraft falling out of the cost statistics, as they were launched many years previously.

(c) A decrease in cost-effectiveness from 1990 to 1994, even though the number of highly-cited papers has increased *three-fold*. This decrease in cost-effectiveness is because the increase in number of papers did not match the *five-fold* increase in costs.

The dramatic increase in costs is mainly (but not solely) due to the introduction of the HST into the figures for the first time.

If the HST-based papers and costs are eliminated from the data, the cost-effectiveness figure for the remaining spacecraft for 1994 is more than doubled with the results shown in Figure 27C. The real problem with the HST is not with the number of highly-cited papers, which is good (although it is not outstanding, see Table 19 earlier), but with its very high capital *and* annual costs, as recognised by NASA.

4.2 The Effect of Adding *Astronomy and Astrophysics* to the Analysis

As explained in Section 4 of Part 2, because the UK is a member of ESA, I have included ESA spacecraft in my analysis, whereas in the case of ground-based observatories I have not included (non-UK) European observatories. Because of this, there is a possible problem with the analysis of spacecraft cost-effectiveness*, as many European spacecraft results are included in *Astronomy and Astrophysics (AA)* which I have not included in my analysis. The following gives an idea of the order of magnitude of the underestimate of the cost-effectiveness of ESA spacecraft as a result of not considering *AA* in my analysis.

The total of spacecraft scores for the papers published in *ApJ* and *MNRAS* from 1974 to 1994 were, for spacecraft from various organisations:-

Spacecraft source → *Papers published in* ↓	**NASA**	**ESA**	**Joint NASA/ European**	**Other**	**Total**
ApJ	48.3	3.0	37.2	32.2	120.7
MNRAS	1.0	3.9	4.4	5.0	14.3

In terms of percentages these figures are:-

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* But not that for ground observatories.

Spacecraft source → *Papers published in* ↓	**NASA**	**ESA**	**Joint NASA/ European**	**Other**	**Total**
ApJ	40	2	31	27	100
MNRAS	7	27	31	35	100

So the largest (and only significant) difference between *ApJ* and *MNRAS* is, as expected, between the percentage of papers produced using data from NASA and ESA spacecraft. *There is no significant difference for joint NASA/European programmes (e.g. IUE, IRAS, Rosat and HST).*

We can now calculate the approximate effect of including *AA* in our analysis, *assuming that the proportion of papers produced using data from NASA and ESA spacecraft is the same for AA as for MNRAS*[*] . The spacecraft scores given above are:-

Spacecraft source → *Papers published in* ↓	**NASA**	**ESA**
ApJ	48.3	3.0
MNRAS	1.0	3.9
Total	**49.3**	**6.9**

Now, the ratio of the number of citations achieved by papers published in *AA* (including Supplements) to those in *MNRAS* from 1975 to 1984 is, according to Peterson[9]:-

$$\frac{AA}{MNRAS} = \frac{10{,}934}{7{,}413} = 1.5$$

I will now add 1.5 times the *MNRAS* figures to cover *AA* to give the following:-

Spacecraft source → *Papers published in* ↓	**NASA**	**ESA**
ApJ	48.3	3.0
MNRAS	1.0	3.9
Total	**49.3**	**6.9**
1.5 x MNRAS for *AA*	1.5	5.9
New Total	**50.8**	**12.8**

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[*] As a matter of interest, the percentage of space-based, highly-cited papers to total observational, highly-cited papers in *MNRAS* had increased from zero in 1970 (as per *ApJ* also) to 24% in 1990 and 21% in 1994.

So the ratio of ESA to NASA spacecraft scores has increased from $\frac{6.9}{49.3} = 0.14$ to $\frac{12.8}{50.8} = 0.25$, an increase of 80%. The effects of this are included below.

4.3 Individual Spacecraft Compared

I will now consider the cost-effectiveness of individual spacecraft or spacecraft programmes*, using my analysis of *ApJ* and *MNRAS* papers as the baseline case, but considering the possible impact of adding data from *AA* as discussed above. The change caused by adding the hypothetical *AA* data will be treated as a bias error on the basic data.

In Table 71 (next page) I have calculated the cost-effectiveness of American, ESA, UK and joint spacecraft as follows (column numbers in brackets):-

(i) The total number of highly-cited papers in *ApJ* and *MNRAS* in half years at four-yearly intervals.

(ii) The effect of adding hypothetical *AA* data to my database as outlined in Section 4.2 above, increasing the numbers for ESA-only programmes by 80%. The numbers for joint programmes have not been increased, however, as the analysis in Section 4.2 above shows that this would not have been justified.

(iii) This is the total of the annual costs of the various programmes at four-yearly intervals. The errors are those due to errors in programme costs (see Table 60).

(iv) The cost-effectiveness N_p/C given by:-

$$\frac{\text{Total No. of highly-cited papers}}{\text{Total of annual costs}} = \frac{2 \times \text{(i)}}{\text{(iii)}}$$

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* When spacecraft are part of a series, I do not know the costs of the individual spacecraft but only that of the total programme.

TABLE 71

Calculation of Cost-Effectiveness of Various Spacecraft Observatories (see text)

Spacecraft	Progr.*	Launched	Total No. of papers**		Total of annual costs##	Cost-effectiveness $\frac{N_p}{C} = \frac{2\times(i)}{(iii)}$
			Basic (i)	Modified# (ii)	(iii)	(iv)
Explorer 11		1961	0		7 ± 3	0
OAO-1, 2, B, 3		1966-72	6.0		549 ± 55	0.02 ± 0.00
RAE-1, 2		1968, 73	0		33 ± 3	0
SAS-1, 2, 3		1970-75	2.0		45 ± 2	0.09 ± 0.00
TD-1A	E	1972	1.0	1.8	85 ± 21	0.02 + 0.02/-0.01
ANS	J	1974	0		15 ± 8	0
Ariel V & VI	UK+	1974	2.0		30 ± 15	0.13 ± 0.07
Cos-B	E	1975	0		87 ± 9	0
HEAO-1, 2, 3		1977-79	23.3		144 ± 7	0.32 ± 0.02
IUE	J	1978	13.4		72 ± 7	0.37 ± 0.04
IRAS	J	1983	8.3		69 ± 17	0.24 ± 0.06
Exosat	E	1983	5.9	10.6	93 ± 4	0.13 + 0.10/-0.01
Hipparcos	E	1989	0		46 ± 2	0
COBE		1989	6.0		17 ± 1	0.71 ± 0.04
Rosat	J	1990	10.1		27 ± 7	0.75 ± 0.21
HST	J	1990	9.8		415 ± 60	0.05 ± 0.01
CGRO		1991	11.0		53 ± 5	0.42 ± 0.04
EUVE		1992	1.0		22 ± 2	0.09 ± 0.01

The errors shown in column (iv) are those given in column (iii) modified by the error caused by adding *AA* data to the database. The latter effect is treated as an error as the *AA* data is only estimated. As it turns out, however, this correction only had to be applied to the results for just two spacecraft, namely TD-1A and Exosat, as these were the only ESA-only spacecraft with non-zero paper scores.

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* American programmes unless otherwise stated. E means ESA, J is for Joint Programmes between the USA and European countries (UK, NL or Germany) or between the USA and ESA, and UK is a UK-only programme (although NASA provided the launcher for Ariel V free of charge).

** In half years at four-yearly intervals.

No number means no change from column (i).

In millions of 1992 dollars, at four-yearly intervals.

+ Although this is a UK-only programme, it is unlikely that adding *Astronomy & Astrophysics* to the database would significantly affect the score, as most UK astronomers preferred to publish in the UK or the USA rather than Europe.

There are also errors, not included in column (iv), due to the variability of the number of highly-cited papers from one 4 year data point to the next. As explained in Section 4.3.3 of Part 1, these cannot be sensibly represented by quoting standard deviations, as these would also include an element due to the natural variations with time of the type shown in Figure 7B. As in Section 4.3.3, I have used a null test to check on whether the cost-effectiveness values are significantly different between any two spacecraft programmes.

TABLE 72
The Most Cost-Effective Spacecraft Observatories

Spacecraft programme	Year of (first) launch	Cost-effectiveness N_p/C
Rosat	1990	0.75
COBE	1989	0.71
CGRO	1991	0.42
IUE	1978	0.37
HEAO series	1977	0.32
IRAS	1983	0.24
Exosat	1983	0.13
Ariel V & VI	1974	0.13

The various spacecraft programmes are shown in Table 72 above in order of their cost-effectiveness deduced in Table 71. The line indicates where significant differences occur in the cost-effectiveness scores, and is the result of using the null test just described between spacecraft that have at least two data points. The methodology used is identical to that used in Section 4.3.3 of Part 1, except that the parameter now used is cost-effectiveness, rather than just the number of highly-cited papers.

It is noticeable from Tables 71 and 72 that:-

(a) The most-recent programmes are the most cost-effective in general, as one would expect, as the early programmes were very much trail-blazers and, as such, were relatively expensive.

(b) The HST is an exception* in being a recent programme with a poor cost-effectiveness score.

(c) Hipparcos also appears to be an exception as being a recent programme with, in its case, no highly-cited papers, but this is because the main Hipparcos database was only published in 1997.

5 A Comparison of Ground- and Space-Based Observatories

The cost-effectiveness of Optical/IR, Radio and Space-Based Observatories, previously plotted separately in Figures 25, 26 and 27, are compared in Figure 28 (next page) over the period 1956-1994 of my study. This shows that, over the period as a whole, ground-based optical/IR observatories are better, in cost-effectiveness terms, than either radio observatories or spacecraft. Over the same period, ground-based radio observatories have also had a higher cost-effectiveness rating than that of spacecraft, although in 1990 and 1994 the difference was not significant. In 1994, if the HST result is ignored, the spacecraft cost-effectiveness has, for the first time, overtaken that of radio observatories.

I will now examine how individual ground-based telescopes and/or observatories have performed compared with individual spacecraft or spacecraft programmes. I will concentrate on the second-half of my period (i.e. on 1978-1994) as cost data is very

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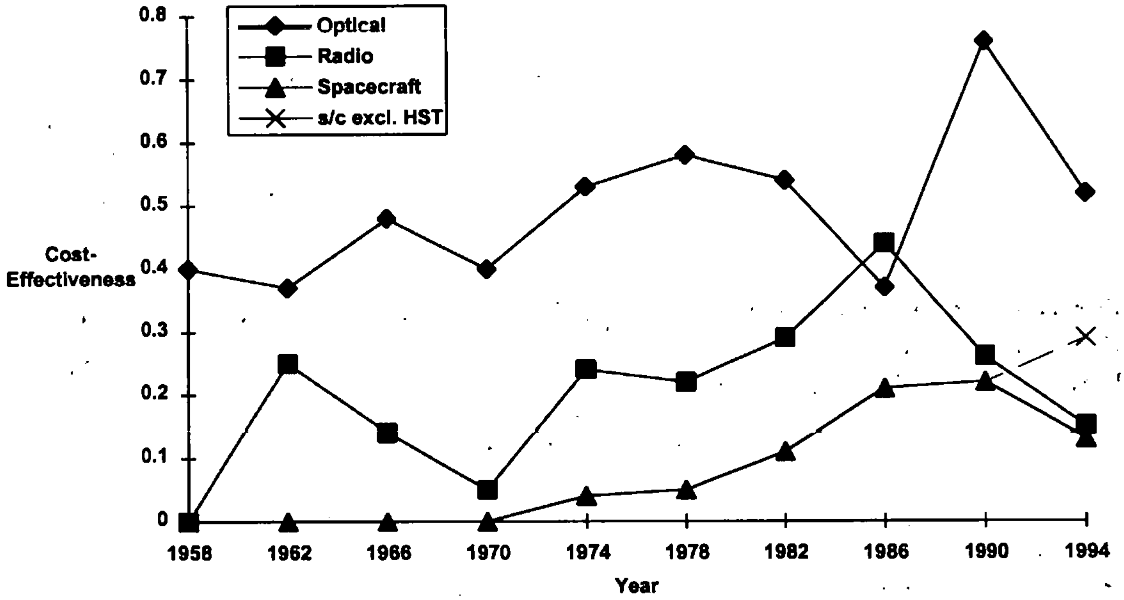
* The EUVE cost-effectiveness is also low, but EUVE was only launched in 1992. This is too close to the last year of 1994 for which I analysed papers, however, to get a fair assessment of its performance.

FIGURE 28

Plots of the cost-effectiveness as a function of time for ground-based optical/IR and radio observatories and spacecraft, where the cost -effectiveness is defined as:-

$$\frac{\text{No. of highly-cited papers / year}}{\text{Total annual cost in millions of 1992 dollars}}$$

The cost-effectiveness of spacecraft excluding the HST is shown by the cross.



sketchy in the first half, and no radio telescopes or spacecraft had significant paper scores in the first half*.

A number of points need to be considered when drawing up such a composite list, namely:-

(a) What is the minimum level of cost-effectiveness that should be included? In the list of spacecraft I was unable to distinguish, within error, between any of the first 5 spacecraft in Table 72 that had cost-effectiveness values of ≥ 0.32**. I thus decided to use 0.30 as the minimum cost-effectiveness score# in my composite list.

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* No radio telescopes or spacecraft had cumulative paper scores ≥ 3.00 in the first half of my period, compared with 9 radio telescopes and 12 spacecraft in the second half. The corresponding figures for optical/IR observatories were 8 in the first half of my period and 18 in the second half (see Table 21).

** This was mainly because two of these 5 spacecraft had only one data point, and so no error value could be established for them, and one spacecraft had only two data points, yielding a naturally high standard deviation.

\# These cost-effectiveness scores are $\frac{\text{No. of Highly-Cited Paper Scores per Year}}{\text{Annual Cost in millions of 1992 dollars}}$

(b) What is the minimum average paper score (per half year) that I should use? The distribution of such paper scores for facilities with a minimum cost-effectiveness score of 0.30 are:-

	Max. av. paper score	**No. of telescopes, observatories, spacecraft or spacecraft programmes with av. paper scores per half year of:-**		
		≥ 2.00	**≥ 1.00 & < 2.00**	**≥ 0.50 & < 1.00**
Ground-based optical/IR telescopes	3.77	8	7	4
Ground-based radio 'scopes/observatories	3.25	1	3	0
Spacecraft/spacecraft programmes	11.0	5	0	0

The minimum average paper score chosen must be somewhat arbitrary, but any facility that has an average paper score of less than 0.50 per half year is not producing consistently significant results, so I decided to exclude such facilities from my list. I then divided the 28 facilities with values of at least this 0.50 figure into highly-productive facilities, with an average paper score per half year of ≥ 2.00, and moderately productive facilities, with an average paper score per half year of ≥ 0.50 but < 2.00. The results are shown in Tables 73A and B (next two pages). As in previous tables in this thesis, I have drawn lines to separate those facilities where the results are significantly different at the 80% level.

Table 73A shows that the most cost-effective, highly-productive facilities were the 2.1m KPNO optical telescope and the Anglo-Australian Telescope, followed by the 3.1m Lick and the William Herschel Telescope. Interestingly, as I mentioned in Section 2.3 above, the 2.1m KPNO telescope also had the highest citation number per unit area* of all the American optical telescopes of ≥ 2.0 m diameter in Trimble's study[5].

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* Of the primary mirror.

TABLE 73

The Most Cost-Effective Ground- and Space-Based Facilities for 1978 – 1994

TABLE 73A

Highly-Productive Facilities

(with average paper scores per half year of ≥ 2.00)

Facility	Category	Av. number of papers in ½ year (i)	Av. annual cost (in 1992 $m) (ii)	Cost-effectiveness $\frac{N_p}{C} = \frac{2\times(i)}{(ii)}$
2.1 m KPNO	Optical/IR telescope	2.08	1.84	2.26
3.9 m AAT	Ditto	3.77	4.3	1.76
3.1 m Lick	Ditto	2.00	3.1	1.27
4.2 m WHT	Optical/IR telescope	3.21	7.2	0.89
3.8 m KPNO	Ditto	2.59	6.2	0.83
Rosat	Spacecraft	10.1	27	0.75*
COBE	Spacecraft	6.0	17	0.71
4.0 m CTIO	Optical/IR telescope	2.36	6.9	0.68
5.1 m Palomar	Ditto	3.49	10.6	0.66
3.8 m UKIRT	Ditto	2.12	6.4	0.66
VLA	Radio telescope	3.25	~11	~0.6
CGRO	Spacecraft	11.0	53	0.42*
IUE	Ditto	3.4	18	0.37
HEAO Series	Spacecraft Programme**	7.8	48	0.32

Table 73B shows that the Palomar and UK Schmidt telescopes are two of the three most cost-effective, moderately-productive facilities. These excellent cost-effectiveness results for the two Schmidts is because they have high paper scores for telescopes of such relatively modest apertures. This is probably because they, along with the ESO Schmidt (which is outside my geographical area), are the largest telescopes permanently providing wide-field survey images. As such they are a unique resource and their data is invaluable to a very large number of astronomers.

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* Only one data point so result only indicative.

** The costs of the individual spacecraft within this programme are unknown, so I have had to analyse their cost-effectiveness performance as a group.

TABLE 73 (cont.)
The Most Cost-Effective Ground- and Space-Based Facilities for 1978 - 1994

TABLE 73B
Moderately-Productive Facilities
(with average paper scores per half year of ≥ 0.50 but < 2.00)

Facility	Category	Av. number of papers in ½ year (i)	Av. annual cost (in 1992 $m) (ii)	Cost-effectiveness $\frac{N_p}{C} = \frac{2 \times (i)}{(ii)}$
1.3/1.8 m Palomar Schmidt	Opt./IR telescope	1.20	1.01	2.39
2.5 m Irénée du Pont	Ditto	1.61	1.40	2.30*
1.2/1.8 m UK Schmidt	Ditto	0.71	0.72	1.97
2.2 m University of Hawaii	Ditto	1.03	1.91	1.08
2.5 m INT	Ditto	1.28	2.52	1.02
2.7 m Mc Donald Obs.	Ditto	1.40	2.9	0.98
2.3 m Univ. of Arizona	Ditto	0.62	1.94	0.64
3.6 m Can.-Fr.-Haw.	Ditto	1.65	5.8	0.57
2.3 m MDM, Kitt Peak	Ditto	0.50	2.09	0.48
3.0 m NASA IRTF	Ditto	0.71	3.5	0.41
Arecibo	Radio telescope	1.88	10	0.38
NRAL (Jodrell Bank)	Radio observatory**	1.15	6	0.38
JCMT	Radio telescope	1.30	7	0.37
4.5 m MMT	Opt./IR telescope	1.31	8.3	0.32

Note There is too much uncertainty in the annual costs at individual radio telescope level for me to include any but the largest radio facilities above. No conclusion should be drawn, therefore, from the omission of any particular radio telescope from this table. In the case of optical/IR telescope and spacecraft, however, the above list is complete for facilities meeting the stated criteria.

6 Cost-Effectiveness of All Facilities

The regression lines in Figures 25, 26 and 27 show that the cost-effectiveness of optical, radio and space facilities have all increased over the duration of my study,

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* The average annual costs of the Las Campanas Observatory, where the Irénée du Pont Telescope is situated, may be too low (see Section 2.2.2 of Part 2) and, if this is so, this ratio will be too high.

** The costs of the individual telescopes are unclear, so I have had to treat the observatory as a whole.

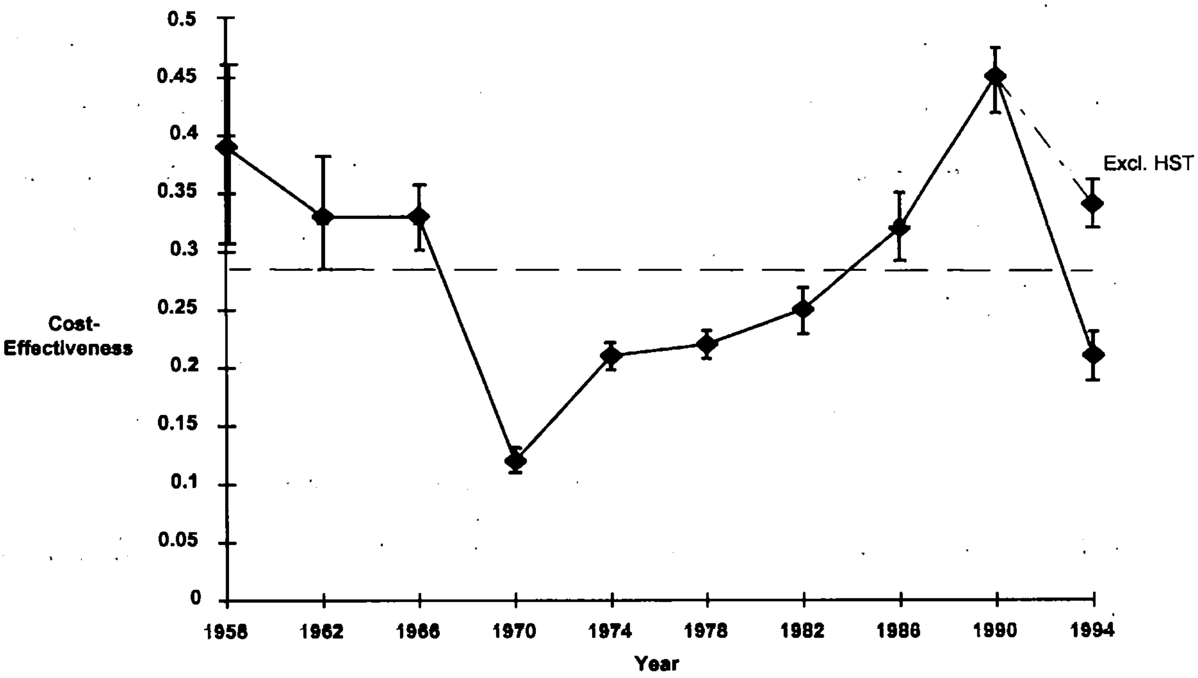
FIGURE 29

Plot of the cost-effectiveness as a function of time for the total of optical, radio and space facilities, where cost -effectiveness is defined as:-

$$\frac{\text{No. of highly-cited papers/ year}}{\text{Total annual cost in millions of1992 dollars}}$$

showing that there is no change with time. The horizontal dotted line is the average cost-effectiveness for the total period 1958–1994. As in Figures 25-27, the error bars indicate the errors in estimating costs. The total cost-effectiveness figure excluding the HST is also shown.

Although there have been changes in the cost-effectiveness of the total facilities during the period 1958–94, there has been no long term trend (see text for discussion).



suggesting, at first sight, that the cost-effectiveness of the total of these facilities has also increased over this duration. The consolidated results for all these facilities plotted in Figure 29 shows that this is not so, however. The reason for this apparent inconsistency is as follows:-

In the early years (1958 and 1962) virtually all the observational facilities were ground-based optical facilities, and so the cost-effectiveness of the total of the optical, radio and space facilities was approximately equal to that of the optical facilities alone. As the years progressed, however, first lower cost-effective radio facilities, and then lower cost-effective space facilities came on line. These 'watered down' the increasing cost-effectiveness of the optical facilities to keep the cost-effectiveness of the total facilities approximately constant.

So, although the cost-effectiveness of ground-based optical/IR facilities, ground-based radio facilities and spacecraft have all increased over the period from 1958 to 1994, the cost-effectiveness of the total of the facilities has not.

Although there was no *over-all* change in the cost-effectiveness of the total facilities over the period 1958–94, Figure 29 shows that their cost-effectiveness was not constant over this period. The changes were as follows (see Sections 2.2, 3.1 and 4.1 above for more details of the optical/IR, radio and spacecraft results, respectively):-

(i) From 1958 to 1970 the cost-effectiveness of the total facilities reduced as radio facilities were gradually brought on line that were of lower cost-effectiveness than the optical/IR facilities. The decrease was made worse because the cost-effectiveness of the radio facilities themselves also decreased over the period from 1962 to 1970.

(ii) The cost-effectiveness of radio facilities recovered in 1974 to their 1962 levels, and then, from 1974 to 1986 the cost-effectiveness of space and radio facilities increased. This caused the curve of Figure 29 to gradually increase.

(iii) In 1990 the cost-effectiveness of ground-based optical/IR facilities increased from their poor figure of four years before, further boosting the curve of Figure 29.

(iv) Finally, in 1994, the cost-effectiveness of optical/IR, radio and space facilities all reduced, causing a rapid decline in the curve of Figure 29. If I ignore the figures for the HST, however, the spacecraft figures are higher in 1994 than in 1990, but this is not sufficient to offset the reduction of the total curve of Figure 29 caused by the reduced cost-effectiveness of the optical/IR and radio facilities compared with 1990.

This complex interaction of changes in the cost-effectiveness of optical/IR, radio and space facilities has resulted in the 'switchback' nature of the curve in Figure 29 which, on average, has shown no overall change in the cost-effectiveness of the total facilities over the period 1958–94.

7 Conclusions

The analysis of the cost-effectiveness of ground-based optical/IR, ground-based radio and space facilities above has shown that:-

(i) Ground-Based Optical/IR Facilities

- Category (a) and (b) telescopes are of similar cost-effectiveness when considering the period 1958-1994 as a whole. In the first half of the period, however, category (a) telescopes are less cost-effective than category (b) telescopes, whereas in the second half of the period category (a) telescopes are more cost-effective than those in category (b).

- Category (c) telescopes are less cost-effective than categories (a) and (b) over the whole period 1958-1994.

- Category (d) telescopes are the least cost-effective over the whole period 1958-1994.

- There is an increase in the cost-effectiveness of the total optical/IR facilities over the period 1958-1994, from an average of about 0.4 highly-cited papers per million dollars[*] in 1958, abbreviated to 0.4hcp/$m, to about 0.6hcp/$m in 1994[**].

- The most cost-effective category (a) telescopes over the period 1978-1994 are the Anglo-Australian Telescope and the 3.1m Lick, and the most cost-effective category (b) telescopes are the Palomar Schmidt, the 2.5m Irénée du Pont, the 2.1m KPNO and the UK Schmidt.

(ii) Ground-Based Radio Facilities

- There is an increase in the cost-effectiveness of the total radio facilities over the period 1958-1994, from an average of about 0.1hcp/$m in 1958 to about 0.3hcp/$m in 1994.

- The cost data obtained is not sufficient to draw conclusions about the cost-effectiveness of individual radio telescopes.

(iii) Spacecraft Observatories

- There is a clear increase in the cost-effectiveness of total spacecraft observatories over the period 1970-1994, from zero in 1970 to about 0.2hcp/$m in 1994. If the HST is ignored, the latter figure for the remaining spacecraft becomes about 0.3hcp/$m.

- The most cost-effective spacecraft observatories are Rosat, COBE, CGRO, IUE and the HEAO series of spacecraft.

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[*] All dollars in this Section 7 are at 1992 rates.

[**] These figures are from the regression line of Figure 25. They are not the actual figures for 1958 and 1994.

- Although the HST has generated data for a very high number of highly-cited papers, its very high capital and annual operating costs have resulted in a very low cost-effectiveness value of 0.05hcp/$m.

(iv) Comparison of Optical/IR, Radio and Space Facilities

- Ground-based optical/IR facilities are more cost-effective than ground-based radio or spacecraft facilities over the period 1958-1994.

- Ground-based radio facilities are more cost-effective than spacecraft up to and including 1986, but in 1990 and 1994 the cost-effectiveness of radio and space facilities are not significantly different.

- The most cost-effective, highly-productive facilities* were the 2.1m KPNO optical telescope and the Anglo-Australian Telescope, followed by the 3.1m Lick and the William Herschel Telescope.

- The most cost-effective, moderately-productive facilities** were the Palomar Schmidt, the 2.5m Irénée du Pont, and the UK Schmidt. (These could possibly be matched, or even exceeded, by two or three of the six modest size radio telescopes whose costs I could not determine, as explained in Section 3.2 above.)

(v) All Facilities

- The cost-effectiveness of the total of ground- and space-based facilities has not changed, on average, over the period 1958-1994, even though the cost-

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* Defined as facilities with an average half-year paper score of ≥ 2.00.

** Defined as facilities with an average half-year paper score of ≥ 0.50 but < 2.00.

effectiveness of ground-based optical/IR, ground-based radio and space-based facilities have all improved over this period.

PART 4

HISTORICAL OVERVIEW OF OBSERVATIONAL FACILITIES
Concentrating on Recommended American-Owned Facilities, Political and Financial Constraints, and Facilities Built

Summary

The analysis in Parts 1 to 3 above has indicated which observational astronomical facilities have been the most cost-effective over the period since the launch of Sputnik in 1957. Over this period astronomy as a subject has changed out of all recognition, and in Part 4 I outline the developments in observational facilities that have facilitated that change. This essentially puts the facilities discussed in Parts 1 to 3 into their historical context, outlining some of the political and financial constraints under which they have been developed and operated. Most of the investments in my chosen geographical area have been in American-owned facilities. Fortunately, American facilities have been the subject of decennial reviews, and this enables a comparison to be made between the facilities recommended in these decennial reviews and those actually provided. It is an aim of this Part of my thesis to undertake this comparison. I have also mentioned, for completeness, key facility developments in the British Commonwealth, but a parallel analysis of these is not possible as there were no regular reviews in these countries as a whole, covering both ground- and space-based facilities, along the lines of the American decennial reviews.

I start Part 4 by *outlining* the developments in ground-based astronomy and sounding rockets just before the launch of Sputnik in 1957. This essentially sets the scene for the period under review. In that section, as in the remainder of Part 4, I concentrate on facility developments, rather than on the astronomical results achieved with those facilities. My book[44] summarises some of these astronomical results for those readers who may be interested.

I follow my outline of the pre-Sputnik era with an overview covering the period from Sputnik up to the Whitford report of 1964. This Whitford report, which is the first of the decennial American reviews, surveyed American-owned astronomical facilities available in 1964, and recommended new facilities that should be developed over the following ten years. I summarise these recommendations and then move forward to the year of publication of the Greenstein report (in 1972) to see which of these Whitford recommendations had been implemented. I then repeat the cycle with the recommendations of the Greenstein report, and the Field report of 1982. In the latter case I review the situation in 1991 at the time of publication of the Bahcall report.

My main conclusions from this survey are given in Table S6.

TABLE S6
Index of my main results

Period	See	Main Developments
Pre-Sputnik	Section 2.1	Radio astronomy is the fastest changing part of astronomy. Jodrell Bank 76m radio telescope is commissioned. IGY planned. Optical astronomy still based on photography.
1957–1964	Section 2.2.1	Early sounding rocket results. American spacecraft programme limited to space spectaculars which have little relevance to extra-solar system research. Early European plans for space-based research.
	Section 2.2.2	Kitt Peak National Observatory founded. Many new radio astronomy facilities built, including the 305m Arecibo dish and the 92m Green Bank transit telescope.
	Section 4.2.2	NSF budgets increase at 39% per annum.
1964–1972	Section 4.1	Early American and ESA observatory spacecraft results. These American spacecraft were largely funded before the major funding cuts in NASA starting in 1966.
	Section 4.2.1	CTIO founded. KPNO developments continued. First telescope installed on Mauna Kea. Under-provision of large American optical telescopes compared with Whitford's recommendations of 1964, but an over-provision of medium and small telescopes.
	Section 4.2.2	Whitford's recommendations for radio astronomy facilities largely ignored. Smaller instruments were provided, however, including the 43m dish at Green Bank, and the 36m and 11m millimetre-wave dishes at Haystack and Kitt Peak, respectively.

TABLE S6 (cont.)
Index of my main results

1964–1972 cont.	Section 4.2.2	Money for astronomical research much tighter than pre-Whitford, although there was still an increase above the rate of inflation.
1973–1982	Section 6.1	The VLA, the highest priority recommendation in the 1972 Greenstein report, was built, although none of the other recommended radio astronomy facilities were provided.
	Section 6.2 & 5.1	Greenstein's second priority recommendation, the construction of a 10-15m diameter MMT, was not implemented. The other ground-based optical recommendations were largely followed, however. CCDs were beginning to be used as detectors for optical telescopes, substantially improving their sensitivity.
	Section 6.3	Greenstein, in his last top priority recommendation, supported the planned four spacecraft HEAO programme. Because of severe funding constraints, however, NASA were compelled to cancel one of these spacecraft and severely descope the other three.
	Sections 5.2 & 6.4	The Large Space Telescope (now called the Hubble Space Telescope) was given a low priority by the Greenstein committee in 1972. Following complaints, its priority was substantially increased in 1974, however. It was approved in 1977 for a launch in 1983.
1983–1992	Section 8.1	CCDs were developed with a good sensitivity at both X-ray and IR wavelengths.
	Section 8.2	A number of ESA and European-American spacecraft were launched. The first American only spacecraft (COBE) of this period was not launched until 1989, however. The HST (with ESA involvement) was then launched in 1990, and the CGRO in 1991. The launch of AXAF, Field's top priority major new programme, was delayed until the late 1990s. The 1982 Field committee also made a number of other recommendations for new spacecraft. These were not implemented, however, because of funding constraints.
	Section 8.3	The VLBA, Field's main radio facility recommendation, was built. Field's recommended 10m diameter submillimetre-wave telescope (the CSO) was also built, but as a joint project with Caltech. Money was saved by deferring maintenance and the purchase of new equipment for the VLA, for example. The Bahcall report of 1991 criticised this decision and suggested that it should be rectified urgently.
	Section 8.4	Field's recommended 15m diameter New Technology Telescope was shelved and the NSF-funded adaptive optics programme cut-back. No major Federally-funded optical/IR telescope was completed in this period. The privately-funded 9.8m Keck saw first light in 1991, however, as did the WHT on La Palma in 1987.

1 Introduction

The above analysis in Parts 1 to 3 gives detailed information on the costs and benefits of astronomical observational facilities over the period since the launch of Sputnik. In this final Part of my thesis I wish to put the development of these facilities into their historical context, by outlining some of the political and financial constraints on astronomical developments in the period 1956-1992*, and discuss the effectiveness and cost-effectiveness of the key facilities provided. My book[44] gives a fuller account of some of the astronomical results obtained over this period with these facilities.

I will concentrate in this analysis on the developments of astronomical facilities in the United States, as the developments there have generally set the tone for developments elsewhere. That is not to say that that has always been the case across the whole of astronomy since 1956, as the Americans were somewhat late into the field of radio astronomy, following the pioneering work in the UK, Australia, and the Netherlands, but I have to constrain my survey in some way to make it handleable. Although I will concentrate on the development of American facilities, however, I will include discussion of other facilities when it seems appropriate to do so.

I will take as the basis for my analysis the series of more-or-less ten-yearly reviews of American astronomical facilities published by Whitford in 1964[18], Greenstein (1972/73)[14], Field (1982/83)[19], and Bahcall (1991)[15]. I will compare the facilities available at the time of these reports with those recommended ten years previously.

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* As explained in Section 4.3.1 of Part 1 I am concerned, in this thesis, with papers published in the years 1958-1994. Generally speaking, the authors of these papers used data from facilities that were available at least two years before the date that the papers were published.

It should be emphasised that this review, like the remainder of this thesis, is looking at the past, to see how facilities as a whole have developed in the way that they have, and how useful they have been. My thesis does not aim to predict future developments, although some of the trends in the late 1980s and early 1990s could be used to give an indication of where to invest in the immediate future.

2 Pre-Whitford

2.1 Pre-Sputnik

The first papers analysed in this thesis were published in the first half of 1958, which was just after the launch of Sputnik 1 on 4th October 1957. The first successful American satellite, Explorer 1, was not launched until 31st January 1958*, and so my first set of papers were essentially for the pre-Sputnik era. I will outline in this Section the astronomical facilities available at that time but, before doing that, it is worth briefly comparing the structure of astronomy pre-Sputnik with that of today.

It is often said that astronomy in the 1990s is an integrated subject where astronomers are equally adept at using data of any wavelength from any ground- or space-based data source. Whether that is now true or not, the situation was certainly not like that in 1957. In those days there were optical *astronomers*, radio *engineers* experimenting with radio telescopes, and *physicists* and *engineers* using rockets to see what they could find out about the Sun and the Earth's upper atmosphere**. Broadly speaking, these three different areas of research were not integrated in 1957, and there was no investment plan for astronomy as a whole at that time. So, over-laying my analysis below, there were changes in the structure of astronomical research from

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* Local Time, or 1st February GMT.

** The flavour of those days is very well described in References 33 and 45 for radio astronomy, and Reference 46 for sounding rockets.

the 1950s to the 1990s, resulting in a much more integrated subject now, with resources provided in a more structured way.

These changes, which now involve more planning of resources than in the past, mirror those in other parts of society, where industry, for example, is much more tightly organised and focused on profit than ever before, and where government advisory committees abound to help to improve the planning of state resources. The change to planned resources in astronomy is also because astronomy has become a much larger spender of government money than in the mid-1950s.

I will now return to my main theme and briefly summarise, in this Section, the astronomical facilities available at the time of the launch of Sputnik 1 in 1957. This will set the scene for developments since then, which are the subject of my thesis.

I will start with radio astronomy, as this was the fastest changing part of astronomy over the period up to the launch of Sputnik 1.

2.1.1 *Radio Astronomy*

Most radio telescopes available in the mid-1950s were either single dishes or arrays of various types, a number of which followed the Mills Cross design. The Naval Research Laboratory's 15 m dish, which started operation in 1951, was unique for many years as it operated up to the very high frequency of 30 GHz. Then in 1957, the fully-steerable 76m Jodrell Bank dish was completed to operate at a maximum frequency of 1.4 GHz. Table 74 (next page) lists this and all the other large radio telescopes available in the USA and British Commonwealth at some time in the period up to and including 1957.

TABLE 74

American and British Commonwealth Radio Telescopes Available up to and incl. 1957

Dish antennae

(min. dish diameter 10 metres)

Dia. (m)	Date of First use	Max. Freq. (GHz)	
76	1957	1.4	1957 Mark 1, Jodrell Bank, UK
26	1957	10	Naval Research Lab., Maryland Point
18	1956	2	Agassiz Station, Harvard College Obs.
15	1951	30	Naval Research Lab., Washington
10	1956		Caltech., Owens Valley, Big Pine, Calif.

Fixed dishes (including those that can move only in declination)

(min. dish diameter 10 metres)

Dia. (m)	Date of First use	Max. Freq. (GHz)	
67	1947	0.2	Jodrell Bank
11	1953	1.4	Potts Hill, Sydney, Australia

Dish Interferometers

Date of First use	Number of Dishes	Dia. of Dishes (m)	Max. Sep$^{n.}$ of Dishes (km)	Max. Freq. (GHz)	
1957*	64	6	0.4	1.4	'Chris-Cross', Fleurs, Sydney

Miscellaneous Antennae and Arrays (in reverse date order)

Date of First use	Max. Freq. (GHz)	Size	
1957*	0.06	Two 24 x 14 m trih.corner reflrs.	Boulder, Colorado
1956	0.02	1,100 m each arm	Mills Cross, Fleurs
1954	0.02	460 m each arm	Mills Cross, Carnegie Inst.
1954	0.08	460 m each arm	Mills Cross, Fleurs
1952	0.08	4 element interf., 100 x 12 m	2C Telescope, Cambridge

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* Used mainly for solar work.

2.1.2 *Optical Astronomy*

In comparison with the relatively new area of radio astronomy, the tried and tested field of optical astronomy saw much more modest developments in the years up to the launch of Sputnik.

On the facilities side, the most important new development was the completion of the 5.1 m Palomar reflector in 1948 which is still today the largest optical telescope in mainland America. In the same year the 1.2 m Palomar Schmidt was also completed which was used to produce the 6° x 6° survey plates for the National Geographic-Palomar Sky Survey, photographing stars and nebulae down to magnitude 21. This survey, which was completed in 1958, has been extensively used ever since as an archival source of unrivalled quality for its era*, resulting in a number of highly-cited papers which are included in the data of Part 1.

I will now outline developments in astronomical facilities both ground- and space-based, from the launch of Sputnik 1 in 1957 up to the publication of the first of the decennial American reports on astronomical facilities, the Whitford report[18], in 1964.

2.2 1957-1964

2.2.1 *Space-Based Observatories*

Prior to the launch of Sputnik 1 space research had been carried out by Aerobee and other sounding rockets that provided a few minutes per launch of observations above most of the earth's atmosphere. Sounding rockets continued to be used for space research after the launch of Sputnik, whilst the majority of the early spacecraft were used for space spectaculars (e.g. sending spacecraft to the Moon and planets) as part

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* Although a new survey has recently been completed using the same instrument down to magnitude of 22.

of the politically-motivated space race between the USA and the USSR. All these spacecraft, whatever their purpose, carried some scientific experiments, however, and so the first American spacecraft, Explorer 1, was able to discover the inner Van Allen radiation belt around the Earth[47]. This discovery, in February 1958, was a big surprise and showed astronomers that spacecraft could make radically new discoveries with relatively simple instrumentation. A few months later, in May 1958, the Langley Aeronautical Laboratory of NACA (National Advisory Committee for Aeronautics), spurred on by the results of sounding rockets and the early developments of spacecraft, recommended that space-based telescopes be flown in space operating at UV, X-ray and γ-ray wavelengths[48].

At this stage the only celestial X-ray source known was the Sun and, based on its observed X-ray intensity, most astronomers thought that it would be impossible for many years to come to measure X-rays from any other astronomical source[49], except possibly for solar-induced X-rays from the Moon, until, that is, X-ray telescope sensitivities were dramatically improved. One or two astronomers disagreed, however, pointing out that radio astronomy had shown that a number of objects that were optically dim could generate large amounts of energy at radio wavelengths. Maybe such surprises would occur at other wavelengths also.

Whilst these discussions were going on, NASA was established and commenced operation on 1st October 1958, with the remit to establish American superiority in the civilian space programme[50].

The American scientific community was generally sceptical about the rôle of NASA, believing that the NASA manned space programme would siphon off funds from scientific research[49]. In addition, the astronomical community in general did not wish to change from their traditional method of working, which usually involved working alone or in small groups, to working in large teams. As a result, most of the new breed of space astronomers were physicists with little or no astronomical background, very much like the physicists and engineers who undertook the early sounding rocket work, and the radio and radar engineers who developed radio astronomy after the war.

In early 1960 Giacconi, Clark and Rossi suggested, in an internal AS and E report[51], that supernova remnants and other specified types of object may emit detectable X-rays. Two years later they were to discover, using an Aerobee sounding rocket experiment, the first celestial X-ray source (other than the Sun), which had an intrinsic X-ray luminosity of about 10^{10} times that of the Sun[52]. The discovery of this source, Sco X-1, was followed by the discovery with the next Aerobee, launched in October 1962, of a source that was shown in 1963 to be the Crab nebula[53]. Finally, in 1963, building on the experience of sounding rockets, Giacconi suggested to NASA that an X-ray satellite observatory be built. In the meantime, in 1961 Krauschaar and Clark of MIT had also detected γ-rays in space using the spacecraft Explorer 11, although the position of the source could not be determined with any accuracy[54].

2.2.2 *Ground-Based Observatories*

The main development in astronomy using ground-based observatories in the period 1957–1964 was the discovery of the first quasar by Maarten Schmidt in 1963[55,56]. This was the result of coordinated radio and optical observations that were to become the norm in years to come.

The discoveries of the very intense X-ray source Sco X-1 (see Section 2.2.1 above) in 1962, and of quasars in 1963, were the first indications that the universe was not the stable, steadily–evolving place that it had been thought to be, but was one where very high-energy, rapidly-changing sources also existed.

It was at this stage in the early 1960s that Whitford was asked to chair a committee to examine the status of ground-based astronomy, and to recommend what ground-based facilities should be provided over the following ten years. It is interesting to note that space-based facilities were not included in his brief, indicating that space-based astronomy had not then been integrated with the mainstream, ground-based subject.

By 1964 only one spacecraft observatory had been flown (Explorer 11) that was primarily dedicated to studying the universe beyond the solar system, so most such space-based observations were still being made from sounding rockets. In the case of ground-based observatories, however, there was a gradually expanding family of optical and radio telescopes becoming available.

The most important development in optical facilities in the period up to the publication of the Whitford report in 1964 was the foundation of the Kitt Peak National Observatory by AURA (Association of Universities for Research in Astronomy). The first permanent telescope, an 0.9m reflector, was installed there in 1960, and in 1964 a 2.1m f/2.6 reflector was also completed. The only other telescope with a diameter of > 2.0m installed in this period in the USA was the 3.1m Shane reflector of the Lick Observatory on Mount Hamilton, bringing to 5 the number of American telescopes with diameters of > 2.0m (see Table 75, next page). The largest telescopes in the British Commonwealth (including the UK) in 1964 were the 1.9m reflectors in Canada, South Africa and Australia completed in 1935, 1948 and 1955, respectively.

As far as radio telescopes are concerned, a number of new telescopes had been completed in the USA and British Commonwealth, as shown in Table 76 (page 240). Some of the telescopes shown in that table were devoted, as indicated, to solar work, and are included only for completeness, and some antennae were built by NASA as part of their Deep Space Network (DSN) to communicate with distant spacecraft.

TABLE 75

American and British Commonwealth Optical and Infrared Telescopes with Apertures ≥ 1.22m (48") Available up to and including 1964

Telescopes available up to and including 1957 are shown in normal text, and those new telescopes available after 1957 are shown in bold.

	Date of First use	Location
(a) 2.55 - 5.08 m (200") diameters		
5.08 m	1948	Hale Telescope, Palomar Mountain, California
3.05 m	**1959**	**Shane Telescope, Lick Obs., Mt. Hamilton, California**
(b) 1.23 - 2.54 m (100") diameters		
2.54 m	1917	Hooker Telescope, Mt Wilson, California
2.14 m	**1964**	**Kitt Peak National Observatory, Arizona**
2.08 m	1939	Struve Telescope, McDonald Obs.
1.88 m	1935	David Dunlap Obs., Univ. of Toronto, Richmond Hill, Ontario
1.88 m	1948	Radcliffe reflector, Pretoria Obs., South Africa
1.88 m	1955	Mt Stromlo Obs., Australia
1.83 m	1918	Dominion Astrophysical Obs., Canada
1.75 m	1932	Perkins reflector, Lowell Obs.
1.55 m	1937	Wyeth Telescope., Oak Ridge Station, Harvard College Obs.
1.55 m	**1962**	**IR Telescope, Univ. of Calif. and Caltech., Mt Wilson Obs.**
1.55 m	**1964**	**US Naval Observatory, Flagstaff**
1.52 m	1891	Rockefeller Telescope, Boyden Station, Bloemfontein
1.52 m	1908	Mt Wilson
1.27 m	1954	Mt Stromlo Obs., Australia
1.26 m	1948	Palomar Schmidt

These DSN facilities are included as NASA allowed them to be used for astronomical observations from time to time when they were not used for spacecraft communications.

The major new radio facilities opened in the period were the 64m antenna (the largest radio dish in the southern hemisphere) installed at Parkes, Australia, the 305m fixed dish located at Arecibo, Puerto Rico, and the 92m transit telescope at the new United States Radio Observatory at Green Bank, West Virginia. The Arecibo telescope,

TABLE 76

American and British Commonwealth Radio Telescopes that became available for the first time between 1958 and 1964 inclusive

Dish antennae

(min. dish diameter 10 metres)

Dia. (m)	**Date of First use**	**Max. Freq. (GHz)**	
64	1961	5	Parkes, Australia
46*	1964	1.5	Sagamore Hill, Hamilton, Massachusetts
46	1959	0.4	Stanford, California
40	1964	1.4	Carnegie Institution, Washington
38 x 25	1964	3	Mark II, Jodrell Bank
37	1963	6	MIT, Lincoln Lab.
26	1959	1.2	Lincoln Lab., MIT, Millstone Hill, Westford, Mass.
26	1958	3	Sagamore Hill, Hamilton, Massachusetts
26	1958	1.0	Caltech, Goldstone, California; part of NASA's DSN
26	1960	2.4	Caltech, Goldstone, California; part of NASA's DSN
26	1962	2.3	Caltech, Goldstone, California; part of NASA's DSN
26	1959	1.4	Dominion Obs., Penticton, White Lake, Canada
26*	1959	16	Univ. of Michigan, Portage Lake
26	1959	10	Howard Tatel Telescope, Green Bank, West Virginia
26	1960		Woomera, Australia; part of NASA's DSN
26*	1961	10	Harvard Coll. Obs. Field Station, Fort Davis, Texas
26	1961		Johannesburg, South Africa; part of NASA's DSN
26	1962	10	Univ. of California, Hat Creek
26	< 1964	1.7	Gilmore Creek, Fairbanks, Alaska
26	< 1964	1.7	Rosman, North Carolina

plus 15 dishes of ≥ 10 metres and < 26 metres diameter

Fixed dishes (including those that can move only in declination)

(min. dish diameter 30 metres)

Dia. (m)	**Date of First use**	**Max. Freq. (GHz)**	
305	1963	0.6	Arecibo. Puerto Rico
92**	1962	1.4	Green Bank, West Virginia

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* Used *mainly* for solar observations.

** Can move in declination.

TABLE 76 (cont.)

Dishes designed for Millimetre Wavelengths

(Maximum Freq. > 30 and ≤ 300 GHz; Min. dish diameter 6 metres)

Dia. (m)	Date of First use	
9	1964	Haystack, Massachusetts

Dish Interferometers (listed in reverse date order)

Date of First use	No. of Dishes	Dia. of Dishes (m)	Max. Sep$^{n.}$ of Dishes (km)	Max. Freq. (GHz)	
1964	3	18	1.6	1.4	One Mile Telescope, Cambridge, UK
< 1964	2	9	0.8	0.5	Chena Valley, College, Alaska
< 1964	2 & 1	26 & 18	1.0	1.1	NBS, Boulder, Colorado
< 1964	4	9			Stanford, California
1960	2	25	1	3	Malvern, UK
1959	2	18	0.2	0.08	NBS, Boulder, Colorado
1958	2	27	0.5	3	Owens Valley, Big Pine, California

Miscellaneous Antennae and Arrays (in reverse date order)

Date of First use	Max. Freq. (GHz)	Size	
< 1964	0.03	Two 12 x 12 m corner reflectors	Gainesville, Florida
< 1964	0.02	Three Yagi arrays 12 x 8 m	Bethany, Connecticut
< 1964	0.3	Two 24-element helix arrays, each 2 x 40 m	Bethany, Conn.
< 1964		Rectangular array	Fleurs, Sydney, Australia
< 1964		Radioheliograph*	Culgoora, Australia
1962	2	79 x 21 m focusing paraboloid	Ohio State Univ.
1962	0.6	180 x 120 m cyl. paraboloid	Univ. of Illinois
1961	0.03	3.8 km x 1.5 km dipole array	Clark Lake, California
1960	0.03	12 x 12 m corner reflector	Univ^{s}. of Florida and Santiago, Chile
1959	0.09	920 m linear array of corner refl.	Carnegie Inst., Washington
1959*	3	110 m each arm	Cross, Stanford, California
1958	0.4	Two 2,000 x 1 m corner refl, sep^{n}. 600 m	Potts Hill, Sydney
1958	0.2	700 m cyl. paraboloid	C'bridge radio star interfer. array (or 4C Tel.)
1958	0.04	1,000 and 30 m arms	Cambridge galactic radio telescope array, UK
1958	0.04	116 x 140 m broadside array of 32 x 32 dipoles	Havana, Ill.

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* For Solar work only.

which had the highest effectiveness rating of these telescopes in my analysis (see Table 16, Page 46), was originally paid for by the US Department of Defense to track the ionisation trails left by artificial satellites using radar. It was also designed to measure electrons in the ionosphere[17] using radar, but as time went by it was also used more and more for other radio telescope observations. More interferometers also became operational during 1958-64, a number of which were located at Cambridge producing, inter alia, the invaluable series of Cambridge catalogues of radio sources. The most important of these catalogues being the revised third Cambridge catalogue which was published in 1962[57].

During this period there was still a great deal of experimentation with the design of radio telescopes; two unique designs of the time being those of the University of Illinois and of the Ohio State University. The Illinois telescope was a transit instrument, consisting of a 180 m long x 120 m wide cylindrical paraboloid of wire mesh laid directly on the ground, whereas the Kraus design for Ohio State had both a fixed and moveable element. The fixed element was a 79 x 21 m focusing paraboloid, which received signals reflected from a similar sized planar antenna that could move about a horizontal axis.

It is clear in comparing Tables 76 and 74 that a great many more radio astronomy facilities were installed in the period 1958-64 than in the period before then. This was because the discoveries made using radio observatories in their early years were so spectacular that many major astronomical institutions felt that they must become involved and possess a radio telescope of some sort. The development of optical facilities over 1958 to 1964 was much more measured, however, as can be seen from Tables 75 (page 239) and 77 (next page). In broad numerical terms, Table 77 shows that the number of optical telescopes that were first available during the period 1958-64 was only more than in the period from 1946-57 for telescopes of modest apertures. This table also shows that the number of telescopes of ≥ 0.61m (24")

TABLE 77

American and British Commonwealth Optical and Infrared Telescopes with Apertures ≥ 0.61m (24") Available up to and including 1964

The statistics of Table 75 and for smaller telescopes are:-

Telescope Size Category	Available up to & incl. 1945	New Telescopes Available 1946-57	1958-64	Total 1946-64
(a)	0	1	1	2
(b)	8	4	3	7
(c)	24	8	12	20
(d) part	9	4	9	13
Total	41 (49%)	17 (21%)	25 (30%)	

diameter* that were first available since the war up to 1964 was about the same as those available prior to then, although the two largest telescopes (those at the Palomar and Lick observatories) were both completed after the war (see Table 75).

3 The Whitford Report[18] of 1964

The first major analysis of existing and projected American observational facilities was carried out in the early 1960s by a committee of senior American astronomers, under the chairmanship of Whitford. Their report, which was limited to surveying the situation in ground-based facilities, was published in 1964. In this section 3 I will summarise the main points made by the Whitford report and, in the following section, will describe what happened to its recommendations.

3.1 General Considerations

In Section 3.1 I will summarise the status of existing facilities as perceived by Whitford, and some of the key considerations mentioned in his report in deciding on

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* Telescope size category d(part) is for 0.61m diameter telescopes, and categories (a), (b), and (c) are for larger telescopes, see Section 4.3.1 of Part 1 and Section 2.1 of Part 2.

a balanced future investment programme. The actual programme recommended in the Whitford report is summarised in Section 3.2.

3.1.1 *Optical Facilities*

Whitford concluded that there were not enough large optical telescopes to satisfy the needs of astronomers nation-wide in the early 1960s. In its survey of existing telescopes the report specifically mentioned the 5.1m Palomar, 3.1m Lick, 2.5m Mt Wilson, 2.1m McDonald and 1.5m Mt Wilson telescopes (see Table 75 above), but pointed out that all but the Lick were privately funded and, as such, provided limited opportunities to astronomers not associated with these observatories. Even the Lick had limited access, as it was funded by the State of California. Whitford considered that, of this list, only the 5.1m and 3.1m telescopes were capable of frontier-type research, specifically mentioning that the capability of the 2.5m on Mt Wilson was already being limited by light pollution.

My analysis in Part 1 confirms Whitford's conclusions on the effectiveness of optical telescopes. In particular, the four best optical telescopes that where available when the Whitford report was written were the 5.1m Palomar, 3.1m Lick, 2.5m Mt Wilson and 2.1m Mc Donald, in that order (see Table 11B(a), Page 34).

Whitford suggested that the construction of the planned 3.8m telescope on Kitt Peak should be completed as soon as possible, but pointed out that, although this would help to solve the problem of a limited number of large telescopes, it would be the only federally-funded large telescope available to the "more than 100 observer candidates". Whitford also concluded that a similar situation prevailed for both medium- and small-sized telescopes where there were also not enough available to meet the demands of the early 1960s, let alone those expected over the subsequent ten years when Whitford anticipated that the number of astronomers would at least double.

One of the key questions to be answered before drawing up the recommendations was how to balance the recommendations for different sizes of optical telescopes. In trying to address the question of whether to recommend the construction of a telescope appreciably larger than the 5.1m Palomar, the report considered the possible cost and benefits of such a telescope that would enable astronomers to see much fainter objects, and hence enable them to see much further back in time than with the 5.1m.

Whitford concluded that, although the report's analysis of the capital cost of existing optical telescopes indicated that they increased as the square of the diameter of the primary mirror, the capital cost of giant telescopes of about 400" (10 m) diameter would probably increase as the diameter to the power of 2.5 to 3.0. In Section 2.2.1 of Part 2 I explained that Whitford had included some speculative costs in his report, and modifying these I found that the capital cost of telescopes existing at the time of the Whitford report varied as the diameter to the power 2.3, rather than 2.0. I also showed that the cost of the larger telescopes built after the time of the Whitford report also increased with the diameter to the power of 2.3, rather than 2.5 to 3.0. What would have happened if a 10m telescope had been built as a scaled-up version of the 5.1m, rather than in the radically different way that the 10m Keck was built in the 1980s, is another matter, however, and Whitford was right to be cautious in 1964 and recommend that a design study be made for a 10m or larger telescope, rather than that an immediate start be made on designing and building such a telescope.

Whitford pointed out that the performance of the 5.1m Palomar telescope was compromised in 1964 to some extent because large diffraction gratings could not be produced, and the report suggested that it would probably be more cost-effective to produce larger gratings than to try to build even larger telescopes than the Palomar 5.1m at that time. Furthermore, Whitford mentioned that improvements in the quantum efficiency of detectors (which were then image tubes or photographic emulsions), or finding observing sites with better seeing, could be just as important as building a 10 m telescope.

Finally, Whitford recognised that there were many astronomical observations for which large apertures were not required, namely:-

- Photoelectric photometry of star clusters (to determine their colour-magnitude diagrams)
- Measurements of galactic rotation (using spectrographic radial velocities)
- Spectroscopic studies of gaseous nebulae
- Studies of variable stars and eclipsing binaries
- Narrow-band filter photometry
- Objective prism surveys for stellar identification

Whitford pointed out that astronomers often find that they need additional observations when they start to analyse the results of their observing runs at a remote location, and this can often involve another visit to that remote location. So Whitford concluded that, although it was best to locate the largest telescopes at high altitude sites, it was not a good idea to locate all medium-sized telescopes there also. This led Whitford to conclude that home institutes should have moderate-sized instruments of their own located nearby, allowing astronomers to develop their observational techniques and undertake initial research at their local base, with the remote observatory only being used for the 'final push'. Experience showed, however, that it was pointless to build instruments of greater than about 1.2 m diameter in areas of relatively poor weather (e.g. on the East Coast of the USA), and so Whitford recommended that such instruments should only be built in areas of good weather (e.g. on the West Coast).

3.1.2 *Radio Facilities*

The Whitford report had concluded that although American optical facilities were the best in the world, there were not enough of them even for the number of astronomers then undertaking observations, let alone the expected doubling in the numbers of such astronomers expected by Whitford over the next ten years. In the case of radio facilities, however, Whitford concluded that the situation was the reverse, with the USA having plenty of new facilities, although only a small number of them were frontier-type instruments. In particular, the largest fully-steerable radio dishes were the 76m at Jodrell Bank and the 64m at Parkes, and the largest millimetre-wave telescope (a 22m) was near Moscow. Although the Americans had the 305m fixed dish at Arecibo, the 92m transit instrument at Green Bank and the 180m x 120m cylindrical paraboloid of the University of Illinois, these all had sky and frequency coverage limitations (see Table 78).

What the Whitford report highlighted was the lack of American radio telescopes with adequate resolution, which it defined as being a few arc seconds. Whitford also pointed out that, although the resolution of ground-based optical telescopes had

TABLE 78

Limitations of Existing American Radio Telescopes, according to Whitford

Telescope	**Limitation**
305 m Arecibo	Limited sky and frequency coverage and a major part of its observing time was devoted to geophysical studies
92 m Green Bank	Cannot track. Limited frequency coverage
180 m x 120 m Univ. of Illinois	Cannot track. Frequency coverage limits its resolution to 10'
Caltech & NRAO interferometers*	Limited by small collecting areas to strong sources, and by the speed with which they can acquire data.
43 m Green Bank (soon to be opened)	Resolution limited to a few arc minutes

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* The Caltech interferometer had two 27m dishes and the NRAO facility had two 26m dishes.

reached their limit because of atmospheric turbulence, ground-based radio telescopes had not yet reached this limitation caused by being located at the base of the earth's atmosphere, and so radio telescopes could be built with far better resolution than those then available. The only instruments able to reach high resolution within reasonable cost constraints, however, were interferometers although these had their own limitations (see Table 79).

TABLE 79
Advantages and Disadvantages of Paraboloids and Interferometric Arrays, according to Whitford

		Advantages	Disadvantages
Large paraboloids			
	2-axis movement	Good intensity resolution Small sidelobes	Expensive Poor angular resolution
	1-axis movement*	As above	Can only observe any particular source for a few minutes per day as it crosses the meridian plane of the instrument
	Fixed	As above The cheapest paraboloid option	Very limited sky coverage
Interferometric arrays		Inexpensive Good angular resolution	Sidelobes can be a problem** Intensity resolution limited** Difficult and slow to use

Whitford discussed the development outside the USA of various interferometric arrays designed to produce high resolution, including the 1.6km Molonglo Cross in Australia that was then under construction and various aperture synthesis arrays at Cambridge University. Whitford acknowledged that, although similar devices existed in the USA (see Tables 74 and 76), they were not large enough to produce the required resolution with adequate sidelobe suppression.

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* Transit instruments

** A careful balance is required between increasing the energy collecting area of the array, which brings in more and more weak sources, and filling in the area of the array with more elements to adequately suppress the sidelobes. If the sidelobes of the strong signals are too high, then even if individual elements of the array may be able to detect weak sources, the array will not be able to do so as the weak signals will be lost in the sidelobes of the strong signals.

Whilst emphasising the need to produce radio telescopes with much better angular resolution, the report pointed out that, although high resolution was essential for some work, it was not necessarily required for studying the following:-

- Variable radio sources
- Structure of the Milky Way
- Polarisation
- Individual spectral lines
- Frequency scanning

So, as in the case of optical telescopes, a mixture of different radio telescopes was required.

3.2 Proposed Facilities

3.2.1 *Optical Facilities*

(i) Large (2.5m - 5.1m) Telescopes

The Whitford panel thought that the first priority should be to build three telescopes in the 3.8m - 5.1m aperture range over the next ten years, hence doubling the number of available American 2.5m - 5.1m telescopes. This would just be sufficient to cover the doubling in the number of American astronomers expected over the same period. It was further suggested that these new telescopes be built at three different top-quality sites, and that they use a proven design to enable them to be completed quickly.

At the time of the Whitford report the 7 largest telescopes in the world* were all in the northern hemisphere, and the two largest telescopes in the southern hemisphere, the 1.88m telescopes in Australia and South Africa, were not at top-quality sites. Hence Whitford suggested that one of the new large telescopes be located at a top-quality site in the southern hemisphere.

Whitford also said that each of these three large telescopes should be supported at their locations by an auxiliary telescope, the one in the southern hemisphere being a 1.2m Schmidt. It was thought that there was no need to build another large Schmidt in the northern hemisphere, as the 1.3m Palomar Schmidt was considered to be quite sufficient to meet the foreseeable demand.

The 3.8m telescope planned for the Kitt Peak National Observatory was counted as one of the recommended three new large telescopes. It was suggested that the other two should be of 5.1m diameter.

Whitford's cost estimate (*including* the cost of initial instrumentation and site development, but excluding the annual operations cost) for all three telescopes was $60m in 1963 dollars. This was split as follows:-

2 in northern hemisphere x $18.5m each	$37m
1 in southern hemisphere x $23m	<u>$23m</u>
Total	$60m

Unfortunately this estimate was for three 5.1m telescopes, whereas the report specifically said that one of the three telescopes was the 3.8m planned for Kitt Peak. In addition, Whitford said that the costings were based on figures given in Table F of the report, which were plotted in Figure 21 of the report. In the case of costings for

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* 5.1m Palomar, 3.1m Lick, 2.6m Crimea, 2.5m Mt Wilson, 2.1m McDonald, 2.0m Tautenberg and 1.93m Haut Provence.

the 3.8m - 5.1m telescopes, however, the costs are not those in Table F or Figure 21. Thus the Whitford report was inconsistent in two respects, namely in:-

(i) the size of one of the large telescopes

and (ii) the capital costs of all three large telescopes

The correct Whitford figures should be (using his Table F and Figure 21) for the costs of the basic telescopes, including optics, mounting and dome, but *excluding* auxiliary instruments and site development (in 1963 dollars) :-

	Should be	**Was**
3.8m in northern hemisphere	$3.9m	$8.5m
5.1m in northern hemisphere	$7.0m	$8.5m
5.1m in southern hemisphere	$7.0m	$8.5m
Total	$17.9m	$25.5m

So the costs of the basic telescopes were overestimated, using Whitford's own figures, by about $8m. It is not clear how much of the remainder of the $60m (for auxiliary instruments, site development and other costs) may also have been overestimated, but the fact that the report should have costed one 5.1m and one 3.8m in the northern hemisphere, and not two 5.1m, must mean that some of these costs were too high also, probably giving a total cost of about $45m, rather than $60m.

(ii) Giant (10m - 15m) Telescope

The panel recommended that, as soon as the three 3.8m - 5.1m telescopes were under construction, a feasibility study should be undertaken to examine the possible designs of the largest feasible telescope, and to prepare a cost estimate for the selected design. It was suggested that a 10m, or possibly a 15m telescope may be feasible.

Whitford did not recommend an immediate start on designing and building such a large telescope as it was thought that it would cost about $100m* and take about 15 years to design and build even a 9m - 10m telescope. This seemed a great deal of money and there were other ways of improving the performance of existing large telescopes that should be tried first, as explained in Section 3.1.1 above.

The cost of the feasibility study was estimated as $1.0m spread over 4 years.

(iii) Medium-Size (1.5m - 2.1m) Telescopes

The panel recommended that 4 general-purpose 1.5m - 2.1m telescopes be provided over the next ten years at good, but not necessarily top-quality sites, probably in the West or South-West of the USA. These were in addition to the auxiliary instruments mentioned in Section (i) above. Whitford said that there were 5 American telescopes of this aperture range available at good sites at the time of his report, so this proposal almost doubled that number. It more than doubled the number, of course, if the auxiliary instruments mentioned above are included.

Cost (including the costs of initial instrumentation and site development, but excluding the annual operations cost) for 4 telescopes was estimated at a total of $4.0m, of which 4 x $0.8m was for the telescope (including optics, mounting and dome). This $0.8m cost figure is consistent with the costs in Figure 21 of the Whitford report (see my Figure 10, Page 71) and with my analysis of the cost of other telescopes of the period (see Section 2.2.1 of Part 2).

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* In the event, the 10m Keck, which was built twenty years later, cost about $97m in 1992 dollars (see Table 28, Page 85), or only $21m in the 1963 dollars of the Whitford report. This relatively low cost was partly because the cost of giant telescopes was proportional to the diameter to the power of 2.3, not 2.5 to 3.0, partly because of the radical design of the Keck which considerably reduced the cost, and partly because the Whitford $100m assumed that a completely new observatory site would need developing, whereas the Keck was built at an observatory that had been built by then on Mauna Kea.

(iv) Small (0.9m - 1.2m) Telescopes

Whitford recommended that eight 0.9m – 1.2m telescopes be built in the next decade. These should be fully-equipped research instruments located at dark-sky locations near universities. The report suggested that climatic conditions need be given little weight in deciding which universities to choose, as the advantages gained in having telescopes on or near the university campus more than outweighed the disadvantages of poor climatic conditions for these small telescopes.* These telescopes were research instruments, not teaching instruments which Whitford said should be funded by the universities.

Cost (including the cost of initial instrumentation) for 8 telescopes was estimated at a total of $3.2m, of which 8 x $0.3m was for the telescope (including optics, mounting and dome). This $0.3m cost figure is consistent with the costs in Figure 21 of the Whitford report (see my Figure 10) and with my analysis of the cost of other telescopes of the period (see Section 2.2.1 of Part 2).

Grand total cost of the proposed optical facilities was $68.2m (including the costs of initial instrumentation and site development, but excluding annual operations costs).

3.2.2 *Radio Facilities*

(i) A Large High Resolution Array

The primary instrument recommended in the Whitford report was an array of about one hundred 26m diameter parabolic antennae to study bright extragalactic sources, the structure of the Milky Way, undertake cosmological work, and study the solar

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* Whitford quoted the performance of small telescopes at the Wisconsin, Michigan and Case Institute Observatories, in relatively poor to mediocre climates, as justification for this view.

system. The main requirement was a resolution of about 10 seconds of arc, with acceptable sidelobes, at about 3 cm wavelength, and the secondary requirement was a resolution of about 1 minute of arc at 21 centimetres. The report left open the configuration of the array, suggesting that it could either be a linear array, relying on the rotation of the earth to provide the second dimension, or a cross, or maybe some other unspecified arrangement. It was suggested that the array should be built and operated by the NRAO.

Cost of	dishes	$30m
	electronics	$ 6m
	land and buildings	$ 4m
	Total	**$40m**

Timescale	about 10 years
Start	as soon as possible

These dish costs of 100 x $300k was consistent with the costs of other 26m dishes of the period that cost between $250k and $460k (see Table 38, Page 114).

(ii) A High Resolution Array of Limited Capability

The Whitford panel recognised that the above large, high resolution array would take a long time to build, and suggested an interim solution which could be built more quickly. In addition, the experience in designing, building, testing and using this interim array would be useful for the major array.

Whitford recommended that the interim array should be the already-costed extension to the interferometer of the Owens Valley Observatory of Caltech. At the time, this interferometer consisted of two 27m dishes, and the proposed extension would add four 40m steerable dishes and extend the baseline. In addition Whitford recommended that a further increase to this interferometer be built to add another four 40m dishes, which should allow a best resolution of 10 arc seconds to be achieved.

Cost	First extension	$ 5m
	Second extension	$ 5m
	Total	**$10m**

Timescale	about 6 years (total)
Start	immediately

These costs are consistent with the $970k cost quoted by Whitford for the original 2 x 27m dish Owens Valley interferometer, although Greenstein quoted a cost of about $2m (see Table 38, Page 116) for that interferometer. Taking an average figure of $1.5m for a 2 x 27m dish interferometer, and using the fact that the cost of a dish is proportional to the diameter to the power of 2.2 (see Figure 21, Page 125), gives a cost for a 4 x 40m dish interferometer of about $7m, so the $5m figure estimated by Whitford may have been a slight overestimate.

(iii) A Large Fully-Steerable Paraboloid

The panel recognised that there was a need for a large paraboloid for 21cm studies of the Milky Way, polarisation studies, spectral measurements, monitoring variable sources, and radar studies of the planets. It was recommended that two 92m fully-steerable paraboloids be built to operate at wavelengths as low as 10cm.

Cost	$8m each
Timescale	5 years to complete
Start	as soon as possible

Whitford quoted $5m to $10m as the cost of the 76m Jodrell Bank telescope but, as explained in Section 3.1.1 of Part 2, I think that a figure of about $2m to $3m is more accurate, which is equivalent to about $3m to $5m for a 92m dish. So the Whitford estimate of about $8m for each 92m dish was probably on the high side.

(iv) Smaller Special-Purpose Instruments

The Whitford report wished to see a balance between large, national facilities and a number of smaller, special-purpose facilities at universities. The panel recognised that universities had special problems in spending what were large sums of money for them in this new area, as radio astronomy sometimes fell between physics, engineering and astronomy, with the result that no-one took responsibility for developing such new radio telescope facilities. To ease matters, the panel suggested that money be included in the Whitford programme to enable a number of universities to build small, special-purpose radio telescopes. These could include fully-steerable paraboloids up to 18m in diameter operating at millimetre wavelengths, or the money could be used to add a radar transmitter to an existing antenna, for example. The research fields would be diverse including stellar, solar and planetary work.

Cost 15 universities x $2m each = $30m

(v) The Largest Possible Steerable Paraboloid

At the time of the Whitford report the attempt to build a 180m diameter, fully-steerable antenna at Sugar Grove had had to be abandoned because of major technical difficulties and consequentially escalating costs. Recognising this, the panel recommended that design studies be undertaken at an early date into what could be built as the largest possible steerable paraboloid. A sum of $1m was included for this study.

Grand total cost of the proposed radio facilities was $97m (including the costs of site development, but excluding annual operations costs).

3.2.3 *Annual Operating Costs*

All the Whitford costings given in Sections 3.2.1 and 3.2.2 above exclude the annual operating costs for the new telescopes. Whitford did provide an estimate for these annual operating costs, however, assuming that they were 4% of the capital costs for optical telescopes and 10% of the capital costs for radio telescopes. **This increased the cost of the recommended optical facilities from $68.2m to $73.5m, and of the radio facilities from $97.0m to $130.6m, over the ten years of the Whitford programme.**

My analysis of the actual costs for the KPNO over the period 1974–92 and those of the CTIO for 1976–92, shows that the annual operating costs (Table 33, Page 104) were 17% and 24% of the capital costs (Table 28, Page 85), respectively. Although the 24% figure for the CTIO may be unrepresentative, because of its remote location, the 17% for the KPNO, which should be reasonably representative, indicates that Whitford's 4% was far too low. My figure of 14% for radio telescopes (see Table 48, Page 151) indicates that the Whitford's 10% was about correct, however.

4 1964 – 1972

I will now outline what facilities were provided in the eight years between the date of publication of the Whitford report and that of the next report, the Greenstein report, of 1972[14]. I will start with space-based facilities, as these saw the largest developments in the period, although space-based facilities had not been considered by Whitford. They were included, however, in the Greenstein report and subsequent decennial reports.

4.1 Space-Based Observatories

In 1966 NASA launched their first Orbital Astronomical Observatory (OAO-1) which was to observe sources in the UV, X-ray and γ-ray wavebands. This two ton observatory failed the day after launch, well-illustrating the risk involved in launching one large observatory, rather than a number of smaller ones. In parallel with this catastrophe, NASA were also under increasing pressure in the mid 1960s to reduce their budgets, like other Federal agencies, to help to pay for both the escalating Vietnam war and the results of ethnic unrest in American cities[58].

In spite of these budget pressures, however, the President's Science Advisory Committee endorsed the concept of a series of High Energy Astronomical Observatories in 1967, which was to become the very successful HEAO series. Then, in the following year, the first successful Orbital Astronomical Observatory, OAO-2, was launched, which was the first dedicated UV astrophysical observatory.

The first dedicated X-ray observatory was launched two years later in 1970. This was the 140kg SAS-1, or Uhuru*, which was launched by an American rocket from the Italian San Marco platform off the coast of Kenya. This spacecraft was a revelation, as prior to then X-ray astronomers had had to rely on the few minutes of observation time that a sounding rocket provided, whereas now continuous observations were possible. Over its lifetime of just over two years Uhuru detected a total of 339 discrete sources, 100 of which had accurate-enough locations determined to suggest visible and radio counterparts[59]. This compares with just 40 X-ray sources known at the time of its launch from 8 years of sounding rocket experiments[49].

The early 1970s also saw a fundamental change in the way that astronomy was integrated as a subject. This was best illustrated by the investigation into the nature of Cyg X-1 (the first black hole candidate) requiring, as it did, data from spacecraft

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* Also called Explorer 42.

(Uhuru), sounding rockets, and ground-based optical and radio observatories[60], showing that observers felt that they could use any waveband and any ground or space type of observatory to solve a problem. An analogous situation had occurred with radio astronomy in 1963 with the discovery of quasars. It is interesting, in fact, to compare the gradual integration of radio and X-ray astronomy into mainstream astronomy. Such a comparison is summarised in Table 80, where the development of X-ray astronomy is seen to closely mirror that of radio astronomy with a delay of about 15 years.

My data on highly-cited papers (see Figure 2, Page 23) shows that ground-based radio astronomy first appeared in my database in 1962 and space-based X-ray astronomy first appeared in that database in 1974, i.e. 12 years later, mirroring the lead times indicated by Table 80. In addition, the appearance of X-ray papers in my database in 1974 is broadly consistent with the rapid increase in the number of X-ray papers recorded by the *Astronomischer Jahresbericht* and *Astronomy and*

TABLE 80
The Gradual Integration of Radio and X-Ray Astronomy into Mainstream Astronomy

	Radio Astronomy	X-Ray Astronomy
First tentative observations	1932	1948
Sun discovered as a source	1942	1949
First non-solar X-ray source discovered	1946 (Cyg A)	1962 (Sco X-1)
First optical identification of a source (other than the Sun)	1949 (NGC 5128 M87 & The Crab)	1963 (The Crab)
First major discovery of a new type of source by working with mainstream astronomy	1963 (Quasars)	1971 (Black Hole candidate)
Change from the discovery phase, where the emphasis is on finding new sources, to the understanding phase, where research is integrated with mainstream astronomy	Early 1960s	~ 1978 (when Einstein observatory launched)

Astrophysics Abstracts increasing from 1 in 1962[#] to 311 in 1972. In parallel, the percentage of American astronomers working in the X-ray field increased from 0.8% in 1962 to 11.2% in 1972 [49] [##].

During the period 1964–1972 covered by this section, NASA launched a number of satellites operating in various wavebands, as shown in Table 81, four of which were large spacecraft in the OAO series (although two of these were failures), and three were small Explorer-class spacecraft (one of them being Uhuru). As mentioned above, there was pressure on the NASA budget from about 1966 onwards, and the results of this pressure are shown in Figure 30 (next page) where I have plotted the NASA Physics & Astronomy R&D budget in 1992 dollars as a function of time.

During the early years of the space race, the fact that large sums of money were being spent on the man-in-space and planetary programmes had no adverse effect on

TABLE 81
Astronomical Observatory Spacecraft Launched 1964–1972[*]

Spacecraft[**]	Launched	Stopped Using	Mass (kg)	Launcher	Wavebands Observed
OAO-1	1966	Failure	1,770	Atlas-Agena	
OAO-2	1968	1973	2,000	Atlas-Centaur	UV
Explorer 38, RAE-1	1968		280	Thor-Delta	Radio
SAS-1, Uhuru, Explorer 42	1970	1973	140	Scout	X-ray
OAO-B	1970	Failure	2,000	Atlas-Centaur	
OAO-3, Copernicus	1972	1980	2,220	Atlas-Centaur	UV, X-ray
SAS-2, Explorer 48	1972	1973	190	Scout	γ-ray
TD-1A (ESA s/c)	1972	1974	470	Thor-Delta	UV, X-ray, γ-ray

[#] The early X-ray astronomy papers, like the early radio astronomy papers, were not usually published in astronomical or astrophysical journals like the *ApJ* and *MNRAS*, as the authors in these early days were generally not astronomers but physicists or engineers (see Section 2.1). Between 1962 and 1965, for example, only 18% of the X-ray papers were published in astronomy or astrophysics journals, whereas by 1970 the figure was 73% [49].

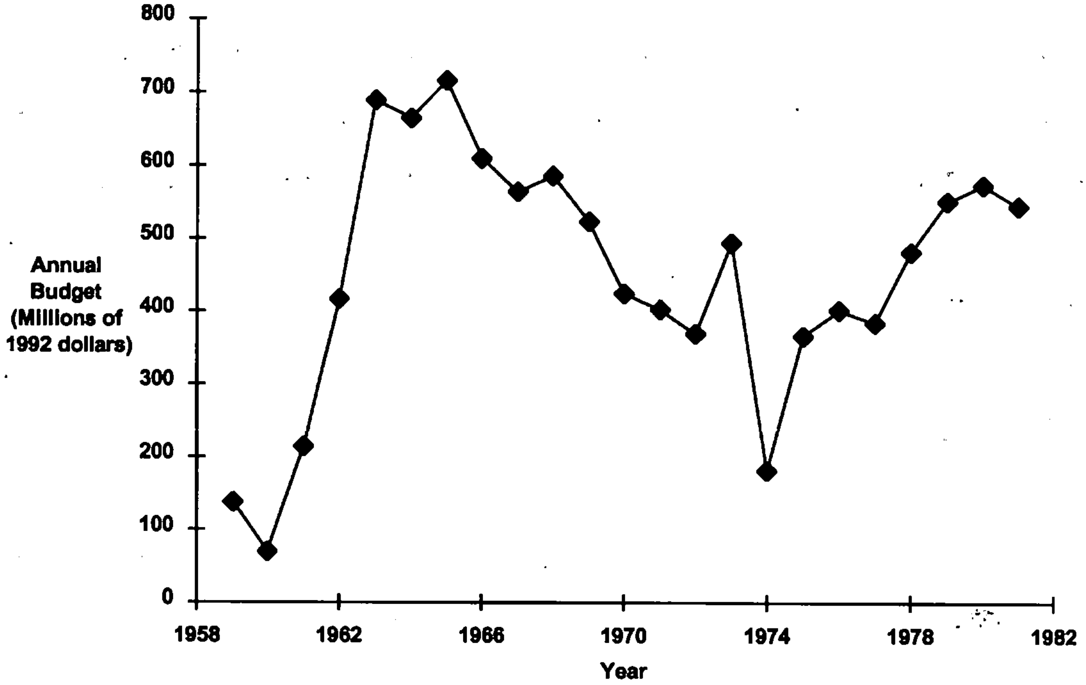
[##] Incidentally, my percentage of highly-cited, X-ray papers in 1974 was 8%.

[*] Excluding solar and solar system spacecraft. All are NASA spacecraft unless otherwise stated.

[**] Where more than one name is given these are alternative names.

FIGURE 30

Plot of the NASA Physics & Astronomy R&D budget in millions of 1992 dollars as a function of time[49, 61]. The effect of the political pressure on NASA budgets starting in 1966 is clearly seen.



the funding of space-based astronomical observatories. In fact, the opposite happened, as shown in Figure 30, as the funding required for space-based astronomical observatories was so low that it was lost in the much higher funding requests for the manned programme, and was generally approved without much discussion. In 1966, however, when total NASA funding was cut, Webb, the NASA Administrator, had to fight hard to avoid money being transferred from the astronomy programme to the man-in-space programme[61]. He was largely successful, although funding for the astronomical programme was inevitably hit with new starts delayed for a number of years, and many tentative programmes were cancelled.

Then in the late 1960s and early 1970s NASA lost their bargaining power as the Apollo programme reached its peak with the landing of the first men on the Moon in 1969. After much discussion of what would be the main programme post-Apollo, President Nixon decided in January 1972 to instruct NASA to build the space shuttle[62]. This decision was to have a major impact on all NASA programmes, because part of the financial justification for building the shuttle involved the phasing out of expendable launch vehicles and launching the vast majority of new spacecraft with the shuttle. This meant that

- spacecraft had to be man-rated (for safety reasons), which increased the cost
- spacecraft could only be launched into a low earth orbit, so if higher orbits were required the spacecraft would have to be provided with extra propulsion

and

- there was pressure to design spacecraft (particularly the Large Space Telescope, or LST) to be updated and repaired in orbit, which also increased the cost.

4.2 Ground-Based Observatories

4.2.1 *Optical/IR Observatories*

I will now turn to the new ground-based facilities that became operational during the period 1964-72, and compare them with those that Whitford had recommended should be made available "within the next decade". As mentioned previously, I have chosen the year 1972 as the end of the period generally discussed in this section, because that was the year in which the Greenstein report was published.

The new optical/IR telescopes of diameter > 1.22m (48") that became operational over the period 1964-72 are listed in Table 82 (next page). In addition, as far as the large telescopes are concerned (i.e. ≥ 2.55m diameter), the 3.8m KPNO telescope was completed in 1973, and the 4.0m CTIO telescope was completed in 1975. So, instead of Whitford's recommended two 5.1m and one 3.8m telescopes, there was one 4.0m, one 3.8m and one 2.7m completed in the large telescope category over the period 1964-75. This means that, although there were three new large telescopes,

TABLE 82

American and British Commonwealth Optical and Infrared Telescopes with Apertures ≥ 1.22m (48") Available for the first time from 1965 to 1972 inclusive

	Date of First use	Location
(a) 2.55 - 5.08 m (200") diameters		
2.72 m	1969	Mc Donald Obs., Mt. Locke, Texas
(b) 1.23 - 2.54 m (100") diameters		
2.44 m	1967	Isaac Newton Telescope, Herstmonceux
2.26 m	1969	Steward Obs., Univ. of Arizona, Kitt Peak
2.24 m	1970	Univ. of Hawaii, Mauna Kea
1.55 m	1965	Catalina Obs., Mt Bigelow, Univ. of Arizona
1.55 m	1972	Infrared Flux Collector, Tenerife
1.52 m	1967	NASA Infrared, Mt Lemmon
1.52 m	1968	Cerro Tololo
1.52 m	1970	Palomar Mountain
1.52 m	1970	Whipple Obs., Mt Hopkins
1.52 m	1971	UCSD-UM IR 'scope, Mt Lemmon
1.32 m	1969	Mc Graw-Hill or MDM Obs., Ann Arbor
1.27 m	1965	Kitt Peak National Observatory

their total collecting area was only 60% of that recommended by Whitford. Nevertheless, my analysis shows that all three of these telescopes were to have a very good cost-effectiveness performance (see Table 66, Page 200).

Whitford had also recommended that one of these three new large telescopes should be located at a top-quality site in the southern hemisphere, and that was achieved as the 4.0m telescope was located at the new Cerro Tololo Inter-American Observatory (CTIO) in the Chilean Andes. This observatory had started operation in 1966 with the installation of a 0.9m reflector, and of the 0.6m Curtis Schmidt that had been moved from Ann Arbor. Two years later, a 1.5m saw first light at Cerro Tololo followed, in 1973, by the 1.0m Yale reflector that had been moved from Bethany, Connecticut, and then, in 1975, by the 4.0m.

The Kitt Peak National Observatory was also developed over the period under consideration, following the installation of a 0.9m reflector in 1960 and of a 2.1m in 1964. A 1.3m and a 0.9m was installed in 1965 and 1966, respectively, followed by the 3.8m Mayall Telescope in 1973. In fact, the KPNO was not alone on Kitt Peak during this period, as the University of Arizona's Steward Observatory had started operations there in 1962, using a 0.9m reflector that had been moved from Tucson. This was followed by the installation of a new 2.3m reflector which saw first light in 1969 at the Kitt Peak Steward Observatory.

These KPNO and CTIO Observatories were largely completed during the period 1964-72, although the 4.0m CTIO reflector was not completed until 1975. The period 1964-72 was also important for the opening of the next major American observatory, namely that on Mauna Kea, following its site testing in 1964[17]. The first major telescope on Mauna Kea was the 2.2m of the University of Hawaii that saw first light in 1970.

In addition to recommending the construction of three large telescopes (in the 2.5-5.1m range), Whitford had also suggested building four medium-sized telescopes in the 1.5-2.1m range at good sites, commenting that there were already five such American telescopes operating in 1964. Interpreting Whitford's Tables, I take these five to be the 2.1m on Kitt Peak, the 2.1m Struve, the 1.8m Perkins, the 1.6m USNO and the 1.5m Mt Wilson. This ignores the 1.6m at Oak Ridge, as the site is not of the specified quality, and the 1.6m Mt Wilson IR telescope, as it was not made to the high specification of normal optical telescopes.

Over the period 1964-72 the following additional medium-sized American telescopes were commissioned in the 1.5-2.5m range* at good sites, excluding IR telescopes with aluminium mirrors:-

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* I have extended the range up to 2.5m to make it contiguous with the range above it.

2.3 m	Steward Obs., Univ. of Arizona, Kitt Peak
2.2 m	Univ. of Hawaii, Mauna Kea
1.6 m	Catalina Obs., Mt Bigelow, Univ. of Arizona
1.5 m	Palomar Mountain
1.5 m	Whipple Obs. (of the Smithsonian Astrophysical Obs.), Mt Hopkins

Extending the period from 1972 to 1974, in this case, introduces no extra telescopes. So five new telescopes were provided in this 1.5–2.5m range, compared with the four recommended by Whitford. Of these five telescopes, only the first two generated an average score of at least 0.50 highly-cited papers per half year in my analysis. The cost-effectiveness of these two telescopes was less than that of the 2.1m KPNO telescope, however, but the 2.1m KPNO was one of the best telescopes from a cost-effectiveness point-of-view (see Table 66, Page 200).

Whitford also recommended that, in addition to four medium sized telescopes in the 1.5–2.1m range, the recommended three large telescopes should each have an auxiliary telescope at the same site. The telescopes provided were the 1.5m at CTIO, the 1.3m at KPNO, and the 0.8m at the McDonald Observatory, meeting Whitford's recommendation, although strictly-speaking the CTIO telescope should have been a Schmidt, taking Whitford's recommendations literally (see Section 3.2.1 (i) above).

Finally, Whitford recommended that eight new small 0.9–1.2m telescopes should be built, whereas, in the event, 14 were provided* in the period 1964-72 (or 17 in the period 1964-1974).

So, in summary, there was an under-provision of large optical telescopes, but an over-provision of medium and small telescopes, compared with those recommended by Whitford. All of the three large telescopes that were built, however, have a good cost-effectiveness rating in my analysis.

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* Again I have extended the range, from 0.9–1.5m, to make it contiguous with the range above it.

4.2.2 *Radio Observatories*

The new radio telescopes that had become operational over the period 1964-72 are listed in Table 83. The largest dish antenna that became operational in this period was the 64m Mars antenna of NASA's Deep Space Network (DSN), which was used mainly for communications with planetary spacecraft, although it was made available from time to time for astronomical observations. It, like most very large radio telescope dishes, had an altazimuth mount, but in 1965 a 43m equatorially-mounted dish was completed at Green Bank which was the largest equatorially-mounted dish available at the time. Its complex equatorial design meant that it was very expensive to build, however (see Table 39, Page 121).

TABLE 83

American and British Commonwealth Radio Telescopes that became available for the first time from 1965 to 1972 inclusive

Dish antennae

(min. dish diameter 10 metres)

Dia. (m)	Date of First use	Max. Freq. (GHz)	
64	1966	3	Mars Antenna, NASA DSN, Goldstone, California
46	~ 1966		Naval Research Lab., Sugar Grove, West Virginia
46	1965	35	Algonquin Obs., Lake Traverse, Ontario, Canada
43	1965	15	Green Bank, West Virginia
40	1968	30	Caltech., Owens Valley, Big Pine, California
38 x 25	1966	2	Nantwich, UK, called "Mark III, Jodrell Bank"
36	1971	2	Vermilion River, Illinois
26	1965		Tidbinbilla, Australia; part of NASA's DSN
26	1965		Robledo, Madrid; part of NASA's DSN
26	1965	1.7	Naval Research Lab., Maryland Point
26	1966	6	Aggasiz Station, Harvard College Obs.
26	1967		Cebreros, Madrid; part of NASA's DSN
26	1967		Honeysuckle Creek, Canberra, Australia
26	1970	2.7	Cornell Univ., New York

plus 8 dishes of ≥ 10 metres and < 26 metres diameter

TABLE 83 (cont.)

Dishes designed for Millimetre Wavelengths
(Maximum Freq. > 30 and ≤ 300 GHz; Min. dish diameter 6 metres)

Dia. (m)	Date of First use	
36	1966	Haystack Hill, Westford, Massachusetts
11	1967	NRAO, Kitt Peak, Arizona
10	1965	AFCRL, Waltham, Mass.
6	1968	Univ. of California, Hat Creek

Dish Interferometers (listed in reverse date order)

Date of First use	No. of Dishes	Dia. of Dishes (m)	Max. Sep$^{n.}$ of Dishes (km)	Max. Freq. (GHz)	
1972	8	14	5	5	Five km (or Ryle), Cambridge
< 1972*	3	18		5	Sagamore Hill, Hamilton, Massachusetts
1971	4	37		0.6	Five College Obs., Amherst, Mass.
1971	5	18	0.2	10	Stanford Univ., California
1968	2**	9	0.8	1.4	Half-mile Telescope, Cambridge, UK
1967*	96	14	3	0.08	Culgoora, Australia
1966	3	26	5	8	Green Bank, West Virginia

Miscellaneous Antennae and Arrays (in reverse date order)

Date of First use	Max. Freq. (GHz)	Size	
1972	0.03	640 dipole, 8 acre array	Gainesville, Florida
1971	0.3	530 x 30 m cyl. paraboloid	Ootacamund, India
1968	0.02	1.3 km x 0.4 km T dipole array	Penticton Obs., Canada
1968*	0.06	16 log per. elements, 3.3 km array	Univ. of Maryland, Clark Lake
1967	0.08	4 acre dipole array	Scintillation Telescope, C'bridge
1967	0.4	1,600 m each arm	Molonglo Cross
1965	0.01	1.2 km x 0.7 km T dipole array	Penticton Obs., Canada

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* Used mainly for solar work.

** Plus two more in 1972.

As radio telescope dish designs improved, so there was a tendency to push their surface tolerances to finer limits to allow observations at shorter wavelengths. This not only improved their resolution, for a given dish size, but also many new interstellar molecules were found because of their lines at millimetre wavelengths. The largest of these millimetre-wave dishes was the 36m at Haystack, which was protected by a radome, but probably the most useful in discovering interstellar molecules was the 11m radio telescope at Kitt Peak. This latter had the dual advantages of a very accurately figured dish surface, and a high altitude observatory, which is important for millimetre-wave observations because of their attenuation by atmospheric water vapour.

A number of dish interferometers were also completed in the period, like the interferometer at Green Bank that consisted of three 26m dishes, and the Five Kilometre Telescope at Cambridge that had eight 14m dishes. Other designs of radio telescope were also built, generally operating at lower frequencies, such as the 1.6km Molonglo Cross of the University of Sydney that operated at 0.4GHz (or a wavelength of 75cm).

Greenstein compared the above radio telescopes built since the Whitford report with the recommendations of that report, and concluded that "It is hardly an overstatement to say that in 1972 essentially none of the Whitford program in radio astronomy had been implemented". None of the radio telescopes recommended by Whitford, and listed in Sections 3.2.2 (i), (ii), and (iii) above, had been, or were being built in 1972, and only the following of the 15 recommended university facilities had been completed, according to Greenstein:-

Dia. (m)	**Date of First use**	**Max. Freq. (GHz)**	
40	1968	30	Caltech., Owens Valley, Big Pine, California
36	1971	2	Vermilion River, Illinois
26	1970	2.7	Cornell Univ., New York
18	1968	5	North Liberty Obs., Univ. of Iowa
6	1968	>30	Univ. of California, Hat Creek

Although Greenstein ignored the Five College and Stanford dish interferometers (see Table 83), he was essentially correct in his conclusion. The main reason for the non-implementation of the main elements of Whitford's radio and optical telescope construction programme was not hard to find. As Greenstein said (p385) in 1972:-

"The fiscal environment in which the Whitford Panel formulated its ten-year program for ground-based astronomy differed markedly from the present one in which the Astronomy Survey Committee worked. The years of preparation of the Whitford report (1963-1964) came at the end of an era when basic research budgets had been climbing 20% per year, NSF budgets 39% per year, and NASA basic research budgets 59% per year."

"The growth rate in current dollars of federally funded astronomy in the period since the Whitford report (fiscal years 1964-1970) has been essentially the same (7.5% per year) as basic research generally (7.4% per year*)."

Nevertheless, even though the financial climate was not as healthy as Whitford had anticipated, and the extensive facility programme that his committee had recommended had not nearly been completed (particularly for radio telescopes), the number of research astronomers had increased at a faster rate than Whitford had anticipated**. As a result, the astronomical community in the USA was said to be desperately short of state-of-the-art astronomical facilities in 1972.

I will now turn to the recommendations of the Greenstein report that covered the next ten years from 1972.

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* 4.5% in constant dollars.

** Whitford had estimated that the number of research astronomers in the USA would increase by a factor of between 2.0 and 2.4 over ten years. It actually increased by a factor of 2.8 [14].

5 The Greenstein Report[14] of 1972

5.1 Recommendations

The Greenstein committee divided its main recommendations into two groups, the first being a group of four recommendations in order of priority, followed by a group of seven. Greenstein estimated that the total cost of implementing all eleven of these recommendations would be about $850m spread over ten years. This would involve an increase of 5.5% per year in astronomical funding in real terms, compared with the 4.5% per year achieved over the years 1964-1970.

The eleven recommendations were:-

1 The Very Large Array

The top priority recommendation involved the construction of a very large radio array (the VLA), consisting of twenty-seven 26m dishes arranged in a Y-shaped pattern, together with increased support for radio facilities at universities and other small research laboratories. The very large array had already been designed in outline, and a cost estimate of $62m in 1970 dollars produced with an estimated five years for construction.

Cost of	VLA	$62m
	5 yrs of operations at 10% of capital costs per year	$30m
	Small programmes 10 yrs x $2.5m/year	$25m
	Total	**$117m**

This recommendation is an up-dated version of the Whitford recommendations listed in Section 3.2.2 (i) and (iv) above.

2 Ground-Based Optical Facilities

Before describing this second recommendation, Greenstein outlined the tremendous developments that had occurred over the previous few years in the design of optical detectors, which were of much higher efficiency than the 1% photon detection efficiency (PDE) of photographic emulsions. The detectors mentioned were image intensifiers, electronographic cameras and integrating television cameras[*]. It was recognised that the use of such detectors, which had PDEs of about 25%, were a far more cost-effective solution to the problem of recording the images of faint objects, rather than building optical telescopes of larger diameter.

As a result of these detector developments, Greenstein recommended that $10m be spent on the development of new electro-optic detectors over the next ten years, and the installation of the best systems on all major US optical telescopes. In addition, it was also recognised that the use of automatic systems for finding and tracking objects would greatly improve the utilisation efficiency of telescopes, and so $5m was earmarked for incorporating such systems on the largest American telescopes also.

There was already a serious light pollution problem for a number of the best American telescopes, including those on Mount Palomar, and it was recognised that there was a need for more large telescopes to be built at remote locations with good seeing, to replace those that were succumbing to such pollution. As a result, a sum of $5m was earmarked to build a conventional 2.5m optical telescope at a remote, non light-polluted site with good seeing, and a similar sum was allocated for another 2.5m optical telescope to support X-ray work, together with a further $5m for one 3-4m ground-based infrared telescope.

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[*] This is just before CCDs were used in astronomy. CCDs were developed in 1969 by Boyle and Smith of Bell Labs., and the first usable experimental devices became available in 1973, the year after the Greenstein report was published.

My analysis of the costs of optical telescopes of the period (see Figure 13, Page 84) indicates a cost of $3.8m for a 2.5m optical telescope, including optics, mounting and dome. Thus the $5m Greenstein estimate for such a telescope allows a reasonable margin of $1.2m for auxiliary instruments and site development. ...

Greenstein also recommended spending $5m on a prototype 3.8–5.1m diameter multimirror optical telescope, followed by $25m for building the largest such multimirror telescope (probably in the 10–15m class) or, if the prototype proved to be unsatisfactory, for the construction of one conventional 5m telescope instead.

Cost of:-

(a) Improved detectors and control systems for large optical telescopes	$15m
(b) Three large telescopes (two optical and one IR)	$15m
(c) Prototype 3.8–5.1m multimirror telescope	$ 5m
(d) Large multimirror or 5m conventional telescope	$25m
Operational costs of (b), (c) and (d) for 5 yrs, at 10% of capital cost per year	$23m
Total	**$83m**

It is noticeable that Greenstein used 10% x capital costs as the annual operating costs of optical telescopes, compared with Whitford's 4% figure. Greenstein's figure is much closer to my figure of 17% for the KPNO, as discussed in Section 3.2.3 above.

3 Infrared Astronomy

A sum of $2m/year for ten years was allocated to increase infrared facilities, in addition to the $5m allocated in Recommendation 2 to pay for a 3–4m ground-based infrared telescope. The $2m/year was for:-

- the development of IR detectors with higher sensitivity
- a survey of high-altitude sites suitable for ground-based IR telescopes
- a sky survey, using balloon-borne detectors, to identify and locate bright infrared sources
- a design study for a very large stratospheric telescope

4 High-Energy Astronomy

Greenstein supported the NASA programme to fly four High Energy Astronomical Observatories (HEAOs). Two of these were planned to be slowly rotating survey spacecraft designed to discover new faint X-ray sources, to measure their positions accurately, and to measure their spectral properties. These two spacecraft were also expected to carry γ-ray and cosmic ray instruments..

The second two HEAOs were planned to be pointable, to enable short-period variations in X-ray intensity of known sources to be measured. The spacecraft would have focusing X-ray optics to provide X-ray imaging and to enable very high accuracy position measurements to be made.

The total cost for four HEAO missions was estimated as $380m

5 Millimetre-Wave Antenna

A 66m diameter telescope, designed to operate at a maximum frequency of 100 GHz, was recommended to provide the high resolution and high sensitivity that research into the structure of interstellar molecular clouds demanded. Such an antenna was also expected to be extremely useful in the study of quasars and planetary emissions.

Cost	Capital	$10m
	5 yrs of operations at 10% of capital costs per year	$ 5m
	Total	**$15m**

The cost of the 36m diameter millimetre-wave Haystack telescope was variously quoted as $6.5m or $15m (see Table 38, Page 115). Assuming that the capital cost is proportional to the diameter to the power 2.2 (see Figures 21 and 23, Pages 125 and 129) gives a cost of about $23m to $57m for a 66m diameter millimetre-wave telescope. The basis of the $10m figure quoted in the Greenstein report is not clear, but Greenstein admits that it "is not well determined". It seems to be an underestimate.

6 Aircraft, Balloons and Rockets

Spacecraft are ideally suited to observational programmes that need large amounts of data and/or observations over many months or years with the same equipment, but aircraft, balloons and sounding rockets still have a rôle to play in simpler observational programmes, or in helping to develop instrumentation for spacecraft. The time from conception of an aircraft, balloon or sounding rocket experiment to making observations is much shorter than for a spacecraft programme, so observations can be made much earlier, and often with more up-to-date equipment, than with spacecraft. With this in mind, it was recommended that the expenditure on aircraft, balloons and rocket experiments in the X-ray, IR and UV bands be doubled. This was estimated to cost an extra $13m/year, or $130m over ten years.

7 Solar Programme

Solar work is not part of my thesis, so I will not consider this item further.

8 Theoretical Work

Theoretical work is not part of my thesis.

9 Optical Space Astronomy Leading to a Large Space Telescope

The Greenstein report was written after the successful launch of OAO-2, but also after the failures of OAO-1 and -B. So the only observatory spacecraft devoted to ultraviolet studies that had been approved, and had not yet been launched, was OAO-3 or Copernicus, which had as its main instrument an 0.8m diameter UV telescope.

Greenstein was unhappy at the lack of any follow-on UV spacecraft after OAO-3, and so the report considered the case for a large space telescope (LST) of 3.0m diameter, covering the UV, visible and near-IR wavebands. Because Greenstein suspected that such an LST was unlikely to fly until the mid-1980s at the earliest, the report speculated on a possible interim programme. This was to both fill the observational gap for UV studies after OAO-3, and to provide some confidence in the design concepts that such an LST would have to use. It was suggested that this interim programme could include either a replacement for OAO-B or a smaller ultraviolet instrument on a Small Astronomy Satellite, plus a 1.5m diameter telescope covering the UV, visible and near-IR wavebands as a forerunner to the LST. The programme was not defined, but it was recommended that spending should continue at the then current level for the UV satellite programme of $35m/year for the next ten years.

10 Large Centimetre-Wave Paraboloid

Greenstein recommended the construction of a 135m diameter radio telescope dish optimised for a wavelength of 2cm, to complement the 66m diameter millimetre-wave dish (see Recommendation 5 above) in its work on interstellar molecules. The report also suggested that the centimetre-wave telescope could work with other large dishes as part of a Very Long Baseline Interferometer (VLBI) to investigate the structure of quasars. It was also recommended that a 6cm radar facility be included with the 135m dish, to enable the surface of Venus and Mars to be mapped.

Cost	Capital (including site acquisition and development, and radar)	$35m
	5 yrs of operations at 10% of capital costs per year	$18m
	Total	**$53m**

11 Astrometry

A programme involving the provision of several modern astrometric instruments was recommended, located in both the northern and southern hemispheres, to allow the accurate, systematic measurement of the positions, distance, and proper motions of stars. Total cost $6m.

Total Cost

The total cost (including operational costs) of the above recommendations over ten years was, in 1970 dollars:-

Rec^{n} No.	Recommendation	$m
1	VLA and smaller radio instruments	117
2	Ground-based optical facilities	83
3	Increased Infrared programme*	20
4	HEAO satellite programme	380
5	66m diameter millimetre-wave radio telescope	15
6	Increased aircraft, balloon and rocket programme	130
7	Increased solar programme	10
8	Increased theoretical programme	30
9	UV/Optical space programme	350**
10	135m diameter centimetre-wave radio telescope	53
11	New astrometry instruments	6
	Total New Money	**844**

This new expenditure (including operations costs up to the end of the ten year period, but excluding the expenditure on solar and theoretical work) compares with that proposed by Whitford as follows, in millions of 1970 dollars# :-

	Greenstein	Whitford
Ground-based optical/IR	109	100##
Ground-based radio	185	175##
Total Ground	294	275
Space (incl. aircraft, balloons & rockets)	510	not considered

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* The cost of a new large ground-based IR telescope is included in Recommendation 2.

** This was not considered to be extra money by Greenstein, so it was not included in the total.

\# It should be emphasised, however, that these are the costs of the new programmes proposed by Whitford and Greenstein, and do not include the costs of programmes that had been already approved.

\## Including $5m at 1963 rates for new auxiliary instruments.

So the new programme is comparable in cost to that proposed by Whitford for ground-based optical/IR and radio astronomy. Greenstein's proposed space-based programme is appreciably more expensive than the new total ground-based programme, however.

5.2 The Large Space Telescope

Greenstein estimated that the total cost of a programme leading to the launch of a 3.0m diameter LST in the early 1980s would be about $1.0bn spread over ten years. This would include the launch of an intermediate LST, probably of 1.5m aperture, but would exclude operations costs. Because the Greenstein committee recognised that it was unlikely that such a sum would be made available, they proposed only the intermediate programme mentioned above (in Recommendation 9) costing $350m over ten years. It seems odd, then, that the design of the HST, albeit with a reduced diameter of 2.4m, should be well under way by the time of the next decennial report (by Field) in 1982. This was because the Greenstein committee radically changed their views on the priority of the LST programme within two years of their report being published. The sequence of events that caused this change in priority is highly instructive, and so will be summarised here.

The Greenstein committee had been asked to prioritise their recommendations, and had been asked by the Bureau of the Budget to reject the idea of building an LST[63]. NASA had not pressed their case for the LST to the Greenstein committee, however, because of "Greenstein's criticism of optical space astronomy and known uneasiness about the potential cost of the telescope". As a result, and in spite of pleading by Field* and Morton, the LST was only included in the Greenstein report as a long-term goal.

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* Interestingly, Field was to chair the next (1982) report after the Greenstein report on astronomical observatories and instrumentation.

The House Appropriations Subcommittee then refused to back the LST programme because of its low priority in the Greenstein report, and by early 1974 the National Academy of Sciences' Space Science Board had concluded that the Greenstein report, which had been published only two years earlier, had already been overtaken by events. Not only had new discoveries been made, which had changed the situation, but the approval of the Space Shuttle in 1972 had meant that most long-term space programmes had to be re-evaluated, allowing for a Space Shuttle launch with the possibility of in-orbit servicing. Bahcall* and Spitzer took this opportunity provided by the Space Science Board to push the case for the LST, and in 1974 persuaded each of the 23 members of the Greenstein committee to back the statement that "In our view, Large Space Telescope has the leading priority among future space astronomy instruments". In addition, Greenstein stated[64] in 1974, when referring to his report, "that had we not had in mind budget limitations, [and] the at that time unsolved technological problems, and had we fully realised the wide range of discovery that we have had even in the last three years, we would not have taken quite so 'conservative' an attitude. Astronomers felt then and feel now that the LST is the ultimate optical telescope and that together with a well-balanced, ground-based program, it will open up new vistas for the human mind to contemplate". So what, two years earlier, had been lukewarm support for the LST, had changed into a glowing endorsement. How much of this change was due to technical progress and how much to lobbying is unclear, but both were clearly involved.

6 1973 - 1982

I will now compare the ground- and space-based facilities that became operational over the period 1973–82 with those recommended as priority items in the 1972 Greenstein report (see Section 5.1 above).

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* Interestingly, Bahcall was to chair the next (1991) report after the Field report on astronomical observatories and instrumentation.

6.1 Radio Observatories

The VLA, which was the subject of the highest priority recommendation in the Greenstein report, was completed on schedule and within budget* in the period under consideration. It consisted of twenty-seven 25m diameter dishes that could operate at a maximum frequency of 24GHz, arranged in a Y-shape, with arms of 21, 21 and 19km in length. Although the cost-effectiveness of the VLA turned out to be modest in comparison with some ground-based optical telescopes and some spacecraft (see Table 73A, Page 220), it has dominated radio astronomy with a very high effectiveness rating (see Table 16B, Page 46).

Greenstein also recommended an increase in funding for radio astronomy facilities at universities and small research laboratories, but this was not implemented. The recommended 66m diameter millimetre-wave antenna was not built either: the largest such antenna completed in the USA during this period (see Table 84, next page) being the 14m dish at the Five College Observatory at Amherst.

The 135m dish recommended by Greenstein to operate in the centimetre band was not built. NASA completed two more 64m dishes, like the Mars antenna that had been completed in 1966 (see Table 83, page 266), at Madrid and Tidbinbilla (Australia) as part of their Deep Space Network and these could be used from time to time for astronomical observations. But the largest new telescope devoted to radio astronomy in the centimetre band was the 30m dish of the Dudley Observatory.

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* The capital cost of the VLA was $78.6m (see Table 38, Page 116) spread *mainly* over the years 1972 to 1978. Assuming that this $78.6m was spent at the average yearly rates of 1975, that is equivalent to $57m at 1970 rates. This compares with the estimate of $62m at 1970 rates in the Greenstein report (see Section 5.1).

TABLE 84

The Main American and British Commonwealth Radio Telescopes that became available for the first time from 1973 to 1982 inclusive

Dish antennae

(min. dish diameter 30 metres)

Dia. (m)	Date of First use	Max. Freq. (GHz)	
64	1973		Madrid, Spain; part of NASA's DSN
64	1973		Tidbinbilla, Australia; part of NASA's DSN
30	1974	5	Dudley Obs., State Univ. of New York at Albany

Dishes designed for Millimetre Wavelengths

(Maximum Freq. > 30 and ≤ 300 GHz; Min. dish diameter 6 metres)

Dia. (m)	Date of First use	
14	1973	Itapetinga, Brazil
14	1976	Five College Obs., Amherst, Mass.
10	1978	Caltech, Owens Valley, Big Pine
9	1976	Battelle Northwest Labs., Rattlesnake Mountain Obs.
7	1977	Bell Labs., Holmdel, New Jersey

Dish Interferometers

Date of First use	No. of Dishes	Dia. of Dishes (m)	Max. Sep^{n}. of Dishes (km)	Max. Freq. (GHz)	
1977/81	27	25	21x21x19	24	VLA, New Mexico
1980	3	25		24	Cheshire/Powys, UK (part of MERLIN)

6.2 Ground-Based Optical/IR Observatories

Greenstein's second priority recommendation involved the construction of a 3.8–5.1m diameter multimirror telescope, followed by the construction of a 10–15m diameter multimirror telescope, or a conventional 5m telescope, if the very large multimirror telescope seemed impracticable at that time. In the event, the 4.5m MMT was completed in 1979 (see Table 85), but neither the 10-15m multimirror telescope nor the 5m conventional telescope were built.

The MMT was not as effective as similar size conventional optical telescopes (see Table 12, Page 36) and, although it was less expensive to build than conventional telescopes of the 1970s, the improved designs of the 1980s and 1990s produced telescopes with similar costs* but without many of the disadvantages of the MMT. As a result the MMT is now being replaced with a telescope of modern design.

TABLE 85

American and British Commonwealth Optical and Infrared Telescopes with Apertures ≥ 1.22m (48") Available for the first time from 1973 to 1982 inclusive

	Date of First use	Location
(a) 2.55 - 5.08 m (200") diameters		
4.5 m	1979	Multi-Mirror Telescope (MMT), Mt Hopkins, Arizona
4.0 m	1975	Cerro Tololo Inter-American Obs., Chile
3.9 m	1975	Anglo-Australian Telescope (AAT), Australia
3.8 m	1973	Kitt Peak National Observatory, Arizona
3.8 m	1979	UK Infrared Telescope (UKIRT), Mauna Kea, Hawaii
3.6 m	1979	Canada-France-Hawaii (CFHT), Mauna Kea, Hawaii
3.0 m	1979	NASA Infrared Tel. Facility (IRTF), Mauna Kea, Hawaii
(b) 1.23 - 2.54 m (100") diameters		
2.5 m	1976	Irénée du Pont Telescope, Las Campanas, Chile
2.3 m	1977	Wyoming IR Telescope, Jelm Mountain
2.1 m	1979	San Pedro Martir Obs., Baja Calif., Univ. Nac. Aut. de Mexico
1.6 m	1978	Mt Mégantic Obs., University Of Montreal, Quebec, Canada
1.5m	1975	Black Moshannon Obs., Rattlesnake Mountain, Penn. State Univ.
1.2 m	1973	UK *Schmidt*, Siding Spring, (48" x 72")

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* Figure 16 (page 88) implies a cost of about $20m at 1992 rates for a modern 4.5m telescope, which is about what the MMT cost.

A key element of Greenstein's recommendation on optical astronomy involved fitting state-of-the-art detectors to all of the major American optical telescopes. This was only partially done.

Greenstein also recommended building two 2.5m optical telescopes, plus a 3–4m infrared telescope. The large CTIO and KPNO telescopes listed in Table 85 were part of the previous ten-year programme of Whitford (see Section 4.2.1 above), so the largest single-mirror, Federally-funded *American* telescopes completed in 1973–82 were (see Table 85) the 3.0m NASA IRTF and the 2.3m Wyoming Infrared Telescope*. So two infrared telescopes were built, instead of the one recommended by Greenstein, but neither of the two 2.5m optical telescopes were constructed.

The third recommendation on Greenstein's list involved an expansion of infrared research, and this was largely achieved as, not only were the two medium-sized IR telescopes mentioned above brought on line, but the Kuiper Airborne Observatory started operation in 1974 and a balloon-based programme was also undertaken.

6.3 Spacecraft

A number of astronomical observatory spacecraft were launched in the period 1973–82 (see Table 86, next page).

Greenstein, in the last of his top priority recommendations, had supported the planned four spacecraft HEAO programme, but the fourth spacecraft was cancelled to save money before the ink was dry on his report. Then in January 1973 NASA announced a reduction in the budget for the HEAO programme of $200m, along with measures on other programmes designed to meet an anticipated major reduction in the NASA 1974 budget. The effect of this on the physics and astronomy R & D budget line is shown in Figure 30 (page 261). Although work on the small SAS-3

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* The 2.5m Irénée du Pont Telescope was not Federally-funded,

spacecraft was allowed to continue, all significant work on the HEAO programme was suspended whilst ways were examined of substantially reducing costs.

The NASA announcement was swiftly condemned by the Council of the American Astronomical Society[65], and an equally rapid response came from NASA suggesting that the mass of each spacecraft should be reduced from 11 to 3 tons. This would enable the original Titan III launcher to be replaced by the much less expensive Atlas Centaur, and would result in a cost reduction for the total programme of 70%. This was the programme that was finally approved.

TABLE 86

American, ESA and British Astronomical Observatory Spacecraft Launched 1973–1982*

Spacecraft**	Launched	Stopped Using	Mass (kg)	Launcher	Wavebands Observed
Explorer 49, RAE-2	1973		330	Thor-Delta	Radio
ANS (NL/USA)	1974	1976	140	Scout	UV, X-ray
Ariel V (UK/USA)	1974	1980	140	Scout	X-ray
SAS-3, Explorer 53	1975	1979	200	Scout	X-ray
Cos-B (ESA)	1975	1982	280	Thor-Delta	γ-ray
HEAO-1	1977	1979	2,700	Atlas-Centaur	X-ray, γ-ray
HEAO-2, Einstein	1978	1981	2,900	Atlas-Centaur	X-ray
IUE (USA/UK/ESA)	1978	1996	670	Thor-Delta	UV
HEAO-3	1979	1981	2,700	Atlas-Centaur	X-ray, γ-ray
Ariel VI (UK)	1979	1982	150	Scout	X-ray

In retrospect, it seems incredible that NASA had originally proposed launching four 11 ton HEAO spacecraft in as many years, when one considers that the mass of the HST is only 9 tons. But the HEAO programme had been conceived in the days of the late 1960's when NASA still had grandiose and far-reaching plans, including a twelve-man space station *and* a reusable space station by 1975, a base in lunar orbit

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* Excluding solar and solar system spacecraft. All are NASA spacecraft unless otherwise stated.

** Where more than one name is given these are alternative names.

in 1976, and a 100-man space station by 1985[66]. The space shuttle was approved in 1972, but the financial crisis of 1973–74 showed that these other plans had no chance of being adopted, at least in the short term. As far as the HEAO programme was concerned, however, once it had been de-scoped, as outlined above, it was completed within its new budget*.

The cost-effectiveness of the HEAO programme as a whole was relatively modest (see Table 73(A), Page 220), however, because of its high cost ($524m in 1992 rates), and because of the relatively poor effectiveness scores of HEAO-1 and -3. On the other hand, the Einstein Observatory spacecraft, or HEAO-2, performed exceptionally well and had an excellent effectiveness rating (see Table 17(b), Page 47), substantially extending our knowledge of the X-ray universe, because it was the first astronomical spacecraft with a true X-ray imaging capability.

6.4 The Large Space Telescope

NASA had been developing plans in the early 1970s for a Large Space Telescope (LST, or what is now known as the Hubble Space Telescope), even though many astronomers opposed it. These astronomers saw the LST as a facility-led, rather than a user-led programme, which would divert limited financial resources from the modest ground observatory programme to a potentially highly-expensive space telescope[63]. The fact that the money would not have been transferred from the space telescope to ground observatories, if the LST did not proceed, cut very little ice with these astronomers.

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* The cost estimate of the original four spacecraft HEAO programme in the Greenstein report was $380m at 1970 rates (see Section 5.1), or about $430m at 1973 rates. The budget was then reduced by $200m in 1973, leaving $230m at 1973 rates. In the event, the new HEAO programme cost $244m at rates varying from 1972 to 1980 (see Section 4.2.5 of Part 2), which is less than the budget of $230m at 1973 rates in real terms.

Greenstein had suggested in 1972 (see Section 5.1) that an interim space telescope programme be considered whilst waiting for the 3.0m LST in the longer term.

In the event, the end-of-life of the UV spacecraft OAO-3 (Copernicus) was extended to 1980, and NASA participated in the international IUE programme to provide a further UV satellite capability. The idea, mentioned in the Greenstein report, of also launching a 1.5m diameter telescope as a precursor to a 3.0m LST, was dropped in 1973, however, in order to keep down the costs of the LST programme[63]. The risk of jumping immediately to a 3m telescope was then thought to be reasonable, now that a space shuttle launch had been agreed, which would allow in-orbit refurbishment of the LST, and a 'Big Bird' military surveillance satellite had been launched that allegedly used similar technology to the LST.

Two years later, however, further budgetary problems forced NASA to reduce the mirror diameter of the LST from 3.0m to 2.4m. Then in 1977 the programme was finally approved by Congress, with estimated costs in the range \$425m to \$475m* (in 1978 dollars), and with a launch date of late 1983. By the time that the Field report was published in 1982, however, substantial technical problems had pushed the LST launch into 1985 with associated cost increases.

7 The Recommendations of the 1982 Field Report[19]

7.1 Introduction

The Field Committee explicitly assumed that approved programmes would be implemented, and that they were to recommend additional programmes for the next decade. This approved programme included, inter alia, the LST, then called the Space Telescope (launch planned for 1985), second generation instrumentation for the Space Telescope (to be installed during the three-yearly servicing missions), and the

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* Including the cost of operations up to the end of one year in orbit.

Gamma Ray Observatory (launch planned for 1988). Field also assumed that a 25m diameter millimetre-wave radio telescope, which was a de-scoped version of the 66m millimetre-wave dish recommended by Greenstein, would also be provided.

Given these assumptions, Field then produced recommendations divided into three major categories, of which only those in the first two categories were costed. The categories were:-

Basic support items for the recommended new programmes
Recommended new programmes
Study work for possible programmes to be started in the longer term

I will now summarise the recommendations in each of these areas in turn. The costs quoted include operational costs, if relevant, during the decade.

7.2 Support Items

(i) Instrumentation and Detectors

At the time of the Field report, $15m/year was being spent from the astronomy budget on the development and installation of improved instruments and detectors at all wavelengths but, as mentioned in Section 6.2, only a limited number of telescopes had had state-of-the-art detectors fitted. It was recommended by Field that this amount of $15m/year should be progressively increased to $30m/year, the extra cost over ten years being $75m.

Clearly much more money was being spent in other non-astronomy areas improving detectors, and particular mention was made by Field of a major military programme to improve infrared detectors. Most of the military developments could not be used, however, until they were declassified, and such early declassification was recommended.

(ii) Theory and Data Analysis

and

(iii) Computational and Physics Laboratory Facilities

These topics are not part of my thesis, and so I will not consider them further.

7.3 Recommended New Programmes

7.3.1 *Major Programmes*

In order of priority:-

1 An *Advanced X-Ray Astrophysics Facility (AXAF)* in space with 100 times the sensitivity and 10 times the angular resolution of the Einstein Observatory. $500m

2 A ground-based *Very Long Baseline Array (VLBA)* of ten 25m diameter antennae located at various points around the USA, giving an angular resolution of 3 x 10^{-3} arc sec. $ 50m*

3 A 15m diameter, ground-based, *New Technology Telescope (NTT)*, with high spatial and spectral resolution, operating in the visible and infrared wavebands from 0.3 to 20 microns. $100m**

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* This includes $15m for operations. The 25m VLA dishes cost about $2.3m each in 1980 dollars (see Section 3.1.4 of Part 2). If the 25m VLBA dishes cost the same, then the VLBA capital cost of $35m would allow $12m for instrumentation and site costs, which could be a little tight.

** The Field committee was undertaking its work at a time when a number of major innovations were being incorporated into the designs of new telescopes (see Section 8.4 below) which would radically

4 A *Large Deployable Reflector (LDR)* in space of 10m diameter, operating in the far infrared and submillimetre wavebands. $300m

7.3.2 Moderate Programmes

In approximate order of priority:-

1 Increased funding for Explorer-class spacecraft to bring the funding back to the level of the early 1970s. The Field report commented that only four Explorer-class observatory missions were approved, namely IRAS, COBE, EUVE and the X-Ray Timing Explorer (XTE), and unless funding was increased these would be the only such spacecraft to be flown in the 1980s. The extra expenditure proposed was $200m.

2 A far-ultraviolet spectrograph in space operating in the waveband from 90 to 120 nm, using a 1m diameter telescope. $150m

3 A space-based VLB Interferometer antenna in low earth orbit to complement and extend the capabilities of the proposed ground-based VLBA. As the VLBA was proposed to be located in the USA, the space-based antenna would not only extend the baseline of that array, but would also allow observations of objects, particularly those in the southern hemisphere, that are not easily visible with the VLBA. $ 60m

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reduce their costs (see Figure 17, Page 89). At that time the committee was not to know how much these innovations would reduce the costs. In the event, however, the largest new telescope built in the 1980s was the 10m Keck which was to cost about $94m (see Table 25, Page 73), mainly spent over the years 1984 to 1990. Assuming that this $94m is at 1987 rates on average, it is equivalent to about $72m at 1980 rates. Assuming also that costs increase as the diameter to the power 2.3 (see Figure 16, Page 88) would give a cost of about $180m for a 15m diameter telescope. So, retrospectively, this $100m Field estimate appears too low.

4 Financial support to ground-based, 2–5m diameter, optical/infrared telescopes which were to be partly funded by private or state funds. $ 20m

5 An advanced solar observatory in space.[*]

6 Cosmic ray experiments using balloons and Spacelab flights. $100m

7 A search for extraterrestrial intelligence (SETI).[*]

7.3.3 *Small Programmes*

Of highest priority:-

1 A 10m diameter, submillimetre-wave radio telescope at a high, dry site. $ 4m[**]

Other important programmes:-

- A two-element, ground-based, infrared interferometer operating in the 2–20 μm band. $ 3m

- A ground-based, high-precision, optical astrometry programme to investigate the design and construction of innovative devices with the aim of measuring relative positions to within ± 0.1 x 10^{-3} arc secs. $ 3m

- A programme to increase the number of new post-docs. in the astronomy departments of US universities.[*]

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[*] Not considered further in this thesis as this topic is outside my area of research.

[**] The 11m diameter NRAO millimetre-wave radio telescope on Kitt Peak cost $1.0m in 1967 (see Table 38, Page 115), or about $2.1m in the 1980 dollars of the Field report. So Field's estimate of $4.0m for a 10m diameter *sub*millimetre-wave telescope seems reasonable.

7.3.4 *Studies*

The Field report also suggested that a number of studies should be carried out to investigate potential programmes that could be started in the longer term. No costs were suggested for these studies, presumably because they were thought to be relatively inexpensive and/or covered within existing general study budgets.

7.4 Total Cost

The total extra cost (including operational costs) of the above costed recommendations over ten years was, in 1980 US dollars:-

	Recommendation	**$m**
Support Items		
(i)	Instrumentation and detectors	75*
(ii)	Theory and data analysis	50#
(iii)	Computational and Physics laboratory facilities	65#
Major New Programmes		
1	AXAF	500
2	VLBA	50
3	NTT	100
4	Large deployable far-IR/submillimetre reflector in space	300
Moderate New Programmes		
1	Additional Explorer-class spacecraft	200
2	Far-UV spectrograph in space	150
3	Space-based VLB interferometer antenna	60
4	Financial support for 2–5m dia. optical/IR telescopes	20
5	Advanced space-based solar observatory	200#
6	Cosmic ray experiments using balloons and Spacelab	100
7	SETI	20#

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[*] Assumed to be 1/3 Optical/IR, 1/3 Radio and 1/3 Space

[#] These figures are included in the $1,910m total but are excluded from later consideration as these subjects are outside the scope of this thesis.

	Recommendation (cont.)	**$m**
Small New Programmes		
1	10m diameter, submillimetre-wave radio telescope	4
•	Ground-based IR interferometer	3
•	High-precision, ground-based optical astrometry	3
•	Increase number of post-docs.	10[#]
	Total New Money	**1,910**[*]

As explained in the footnote, the hashed items in the above table are outside the scope of this thesis. Excluding them we have, compared with the Greenstein and Whitford figures, all in 1980 dollars:-

	Field	**Greenstein**	**Whitford**
Ground-based optical/IR	151	230	210
Ground-based radio	79	390	370
Total Ground	230	620	580
Space (incl. aircraft, balloons & rockets)	1,335	1,080	not considered
Total	**1,565**	**1,700**	

So, although the total cost of the new programme was very similar to that of the Greenstein programme, the proposed investment in new ground-based radio telescopes was very much less than that proposed by either Greenstein or Whitford. This reduced investment in ground-based radio facilities was balanced, however, by the recommendation that $360m be spent on space-based radio facilities.

8 1983 - 1992

8.1 General

The period of the mid to late 1980s and early 1990s covered by this section saw America try to reduce their budget deficit, backed up by the Gramm-Rudman-

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[#] Included in the $1,910m total but are excluded from later consideration as these subjects are outside the scope of this thesis.

[*] There is an arithmetic error in the Field report where this total is shown as $1,720m.

Hollings law, and try to transfer their Federal research funds from pure to applied research, as they were concerned with losing their competitive edge in high-technology products compared with other countries[67]. The financial demands of the Reagan 'star wars' initiative also meant that there was pressure to move funds from civilian to military research.

The Field Committee had recognised in 1982 the tremendous benefits to astronomy because of progress made in detector technology in the 1970s, and it recommended extra funding from the astronomy budget in the 1980s to help produce even more benefits. Early CCDs in the 1970s had arrays of 100 x 100 and then 512 x 320 pixels and, although their quantum efficiency was very high (close to 100%) in visible light, it rapidly reduced at both ultraviolet and infrared wavelengths. In the 1980s, however, CCDs gradually became available with 800 x 800 and then 2,048 x 2,048 pixels in the visible waveband. Smaller arrays were also developed with good sensitivity at shorter wavelengths.

I will now compare the ground- and space-based facilities that became operational over the period 1983–92 with those recommended as priority items in the 1982 Field report. The end of this period almost coincided with the publication of the last (so far) of the National Research Council's decennial reports, that by Bahcall in 1991. So in some of the discussion below I have taken 1991, rather than 1992, as the end of the 'Field decade'.

8.2 Spacecraft

8.2.1 *The Great Observatory Spacecraft*

Two of the four proposed NASA Great Observatory Spacecraft had been approved before the Field report had been published in 1982. The first, the Hubble Space Telescope (then called the LST), was expected to be launched in 1985, and the second, the Compton Gamma-Ray Observatory (then called the GRO), was targeted for a 1987-88 launch. In the event, spacecraft development problems and the Challenger disaster in 1986 pushed the launch of the HST to 1990 and of the CGRO to 1991 (see Table 87).

TABLE 87
American, ESA and British Astronomical Observatory Spacecraft Launched 1983-1992*

Spacecraft	Launched	Stopped Using	Mass (kg)	Launcher	Wavebands Observed
IRAS (NL/USA/UK)	Jan. '83	Nov. '83	1,073		IR
Exosat (ESA)	1983	1986	510	Delta	X-ray
Hipparcos (ESA)	1989	1993	1,130	Ariane 4	Visible
COBE	1989		2,500	Delta	μ-wave
Rosat (USA/Ger./UK)	1990		2,430	Delta II	X-ray, UV
HST (USA/ESA)	1990	Repaired '93	9,100	Shuttle	UV, Vis., IR
Compton γ-ray Obs.	1991		15,900	Shuttle	γ-ray
Extreme UV Explorer	1992			Delta II	UV

The high capital and annual operations costs of the HST (see Section 4.3 of Part 2) badly affected the average cost-effectiveness of spacecraft observatories which, until 1994, had been showing a gradual improvement (see Figure 27, Page 210). These high costs of the HST were mainly because of:-

- the poor initial management of the programme[63]
- the annual budget approval process in the USA which meant that the HST budget had to be approved by Congress each year. This had a disruptive effect on the smooth running of the programme.
- the Challenger disaster which delayed the launch substantially
- the decision to launch the HST with the space shuttle and make the HST upgradable** in-orbit (and hence require it to be man-rated with consequent cost implications).

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* Excluding solar and solar system spacecraft. All are NASA spacecraft unless otherwise stated.

** Although if this had not been done, the problem with the mirror could not have been corrected in orbit.

The problem with the HST was its high costs, not its effectiveness which was very good (see Section 4.3.3 of Part 1). The effectiveness of the second Great Observatory Spacecraft, the CGRO, and of the international Rosat spacecraft were similarly high, however, for programmes costing much less than that of the HST (see Sections 4.3.3 of Part 1 and 4.3 of Part 2).

The third Great Observatory, the Advanced X-ray Astrophysics Facility (AXAF), had been the top priority major new programme recommended by the Field Committee in 1982. This spacecraft was still in its design phase in 1992, however, with a launch planned for the latter part of the 1990s.

The fourth Great Observatory, the Space Infrared Telescope Facility (SIRTF), was only in the conceptual stage at the time of the Field report and was the subject of one of the studies recommended by Field. By 1991 the SIRTF had become the Bahcall Committee's highest-priority, large equipment recommendation.

So, although the NASA Great Observatory programme was still under way in 1991/2, it was running a number of years behind schedule.

8.2.2 The Explorer and Other Programmes

The Field report had observed that, unless funding was increased in the 1980s, only four Explorer-class spacecraft would be flown in that decade, namely IRAS, COBE, EUVE and XTE. Field accordingly recommended a substantial injection of funds into the Explorer spacecraft programme to bring its funding back to the level of the early 1970s. In the event, IRAS was launched in 1983, COBE in 1989 and EUVE in 1992, but the XTE was not launched until 1995, and no other Explorers were launched. So, not only was the Explorer programme not enhanced in the 1980s, but the launch dates of two of the already-approved spacecraft had slipped into the 1990s.

Field had also recommended a suite of other spacecraft programmes including a 10 metre diameter far-IR telescope, a far-UV spectrograph using a 1 metre diameter telescope, and a radio astronomy spacecraft in low earth orbit to extend the baseline of the VLBA. Not only were none of these spacecraft built in the 1980s but none had been approved either. The much less expensive NASA sub-orbital programme continued, however, using balloons, sounding rockets and aircraft, although the Challenger disaster in 1986 interrupted the Spacelab programme.

8.3 Ground-Based Radio Observatories

The construction of a Very Large Baseline Array (VLBA) was the main recommendation of the Field Committee in the field of ground-based radio astronomy. This VLBA, which consists of ten 25 metre dishes spaced across the USA, was built during the 1980s and early 90s, coming on line progressively from 1988 to 1993.

The Field Committee also recommended the construction of a 10m diameter submillimetre radio telescope at a high dry site. Again this was achieved with the building of the 10.4m diameter Caltech. Sub-millimetre Observatory (CSO) on Mauna Kea that entered into service in 1988 with significant financial support from the NSF.

Caltech. also built a millimetre-wave interferometer in the 1980s at Owens Valley. This interferometer, which operated at a frequency intermediate between that of the single-dish CSO which operated in the sub-mm band, and the ten-dish VLBA which operated in the centimetre band, initially consisted of three 10m diameter dishes which had a maximum separation of 300m. Additional dishes have now been added (see Table 88, next page).

TABLE 88

The Main American and British Commonwealth Radio Telescopes that became available for the first time from 1983 to 1992 inclusive

Dish antennae

(min. dish diameter 20 metres)

Dia. (m)	Date of First use	
34	1985	NASA DSN* , Goldstone, Calif.
34	1985	NASA DSN* , Madrid
34	1985	NASA DSN* , Tidbinbilla, Australia
22	1987	Coonabarabran, Australia

Dishes designed for Millimetre Wavelengths

(Maximum Freq. > 30 and ≤ 300 GHz; Min. dish diameter 6 metres)

Dia. (m)	Date of First use	
32	1990	Mullard Labs., Cambridge, UK

Submillimetre-wave Dishes

(Maximum Freq. > 300 GHz; Min. dish diameter 6 metres)

Dia. (m)	Date of First use	
15	1987	JCMT (James Clerk Maxwell Telescope), Mauna Kea
10.4	1988	Caltech Sub-millimetre Telescope (CSO), Mauna Kea

Dish Interferometers

Date of First use	No. of Dishes	Dia. of Dishes (m)	Max. Sep$^{n.}$ of Dishes (km)	Max. Freq. (GHz)	
1988/93	10	25	8,000	43	VLBA, USA
1988	6**	22	6	40	Culgoora, Australia
1984	3#	10	0.3	230	Caltech., Owens Valley

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[*] Can be used part-time for astronomy.

[**] These 6 dishes can be linked to the 64m dish at Parkes and the 22m dish at Coonabarabran to form the Australia Telescope.

[#] There are now seven 10m dishes.

It is not sufficient just to build new facilities, but the existing facilities have also to be properly maintained and fitted with reliable, up-to-date instrumentation if they are to yield the maximum benefit. The 305m diameter Arecibo facility has been upgraded from time to time, although some of its instrumentation was becoming old and in need of replacement in the 1980s. Similarly the other major radio facility, the VLA, was suffering by the time of the Bahcall report because of deferred maintenance. Bahcall also pointed out that if the out-of-date instrumentation and equipment was replaced at the VLA, this would produce a substantially improved performance at modest cost.

The 92m diameter Green Bank dish, which had been completed in 1962, collapsed unexpectedly in 1988. This facility had been built quickly with a short expected lifetime to take advantage of unforeseen developments, but it had continued to be pressed into service well after its expected lifetime had expired. It was a great surprise to astronomers, used to seeing detailed reports proposing new equipment quietly shelved, to see $75m voted by Congress for a replacement facility only a year after the collapse.

8.4 Ground-Based Optical/IR Observatories

The 1980s saw important developments in the designs of large optical/IR telescopes that substantially reduced their capital costs (see Figure 17, Page 89). These included the introduction of:-

- active optics, which allowed the use of much thinner and less massive mirrors, which in turn simplified the design of the telescope mount
- computer-controlled, alt-azimuth mounts
- mirrors with a small f-number, which allowed the construction of much smaller and simpler observatory buildings

The first telescope to include all of these innovations was the Australian Advanced Technology Telescope (ATT).

Whilst these technical developments were under way, American Federal investments in ground-based optical/IR astronomy were severely constrained. In particular, optical/IR astronomy's top priority, 15m diameter New Technology Telescope, recommended by the Field Committee, was shelved[67]. In addition, there were no major Federally-funded optical/IR telescopes brought on line over the 1983-92 period (see Table 89), and the NSF-funded adaptive optics programme was also cut-back because of funding restrictions. In 1988 there were even suggestions that some or even all of the existing NOAO telescopes on Kitt Peak may have to be closed down because of lack of money[68]. In the event, one 0.9m KPNO telescope was closed, whilst the main savings were made by reducing manpower and slowing down the development work on new facilities[69].

TABLE 89

American and British Commonwealth Optical and Infrared Telescopes with Apertures ≥ 1.22m (48") Available for the first time from 1983 to 1992 inclusive

	First light	Location
9.8 m	1991	Keck I, Mauna Kea*
(a) 2.55 - 5.08 m (200") diameters		
4.2 m	1987	William Herschel Telescope (WHT), La Palma
2.7 m	1992	UBC-Laval 'scope, Vancouver
(b) 1.23 - 2.54 m (100") diameters		
2.5 m	1984**	Isaac Newton Telescope (INT), La Palma
2.3 m	1988	Hiltner Telescope*, McGraw-Hill or MDM Obs., Kitt Peak
2.3 m	1984	ATT, Mt. Stromlo & Siding Spring Obs.
2.3 m	1985	Vainu Bappu Observatory, Kavalur, India
2.2 m	1986	Cananea Obs., Mexico
1.5 m	1988	IR Telescope, Rothney Obs., Calgary, Alberta, Canada

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* Not Federally funded.

** Date of first light on La Palma, having been moved from Hertsmonceux.

Ironically, whilst Federally-funded optical/IR astronomy had had such a poor time financially in the 1980s, as far as ground-based facilities were concerned, the privately-funded 10m Keck telescope, whose construction started in 1985 saw first light in 1991.

Bahcall was asked in 1989 why it was that radio astronomy seemed to have a better track record than ground-based optical astronomy in obtaining Federal funding in the 1980s. He replied[70] that it was probably because radio astronomers in the USA worked much more as a community that, once it had agreed on priorities, worked collectively to see them carried out, lobbying as appropriate. The optical astronomers, on the other hand, were much more fragmented as a group, and seemed unable to come to a consensus on priorities. As a result Congressional Committees and the like found it easier to cancel or defer optical/IR projects.

GENERAL DISCUSSION AND CONCLUSIONS

Introduction

In this final section of my thesis I present the general conclusions from my work. It is not my intention here to summarise the various detailed results, which I have already covered in the Summaries to Parts 1, 2, 3 and 4, nor to repeat the detailed conclusions on the effectiveness of facilities, which are given in Section 5 of Part 1, nor the detailed conclusions on the cost-effectiveness of facilities, which are given in Section 7 of Part 3.

The Need for Consensus

My analysis has shown that ground-based optical telescopes have been more cost-effective than either ground-based radio telescopes or space-based observatories, whether considering the period 1958–1994 as a whole or just the last few years in particular (see Figure 28, Page 218). In view of this, it is particularly interesting to see the difficulties that American ground-based optical astronomers have had, compared with their radio astronomy colleagues, in persuading the Administration to fund the ground-based optical facilities recommended by the 1981 Field committee (see Part 4, Section 8.4). Bahcall suggested, as I noted in Section 8.4, that the reason for this lack of success of optical astronomers was because of their lack of consensus on priorities. It may also have helped if they had had a cost-effectiveness analysis available similar to mine but covering recent years in more detail.

This particular example suggests that if astronomical facilities as a whole are to be developed in a sensible and consistent way:-

(i) there needs to be a consensus among astronomers on priorities which is based on facts as far as possible, as decisions based on facts are likely to be more robust than those based on opinions, which can easily change

and (ii) all astronomers who are party to a consensus should then support that consensus and lobby for it actively, whether they argued for it or not in the earlier discussions. They should 'all sing from the same hymn sheet' in their discussions with decision makers or the people who advice such decision makers.

In the USA the decennial committees of the National Research Council produced reports[14,15,18,19] giving the consensus views of the senior astronomers on those committees. If important groups within the astronomical community do not accept that consensus, to such an extent that they lobby actively against it, they are likely to disrupt the approval process to their own detriment, as well as to that of astronomy as a whole. It is therefore essential that every effort be made to involve such pressure groups, as far as possible, in the original decision-making process. How far this was done in the case of the NRC reports discussed in this thesis I do not know, but the number of people involved in the discussions of these committees, or their working groups, was very large*.

A Rôle for Cost-Effectiveness Studies

The NRC reports, excellent though they are, do not seem to have been based on any quantitative cost-effectiveness considerations, which appears to be a significant failing. I would suggest that the NRC, NASA, PPARC and other similar national bodies should, as a matter of routine, keep an up-to-date analysis on an annual basis of the cost-effectiveness of the facilities for which they are responsible, and use this inter alia to monitor the performance of the facilities. This should then be used to assist in making decisions on which facilities to develop and which to close, and the

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* In the case of the Bahcall committee of 1991, for example, there were 300 members of the advisory groups.[15]

results of the annual analyses should be provided to the decennial committees to assist in their analysis and recommendations also. My analysis, and others like it, could *assist* in forming the initial consensus in the discussions of the decennial committees, not necessarily because they are 100% valid for every case under consideration, which they clearly cannot be, but because they can act as a 'straw man' to force people to justify their views, and maybe modify them in the process.

How Successful have the Decennial NRC Committees been? Should They be Imported to the UK?

My analysis in Part 4 shows that the decennial committees of the NRC have only had a very limited success in suggesting which new astronomical facilities should be built by the USA. This may be simply because the total cost of their recommendations far exceeded the amount of money available. Obviously if these committees had limited their recommendations to match the money available, however, assuming the amount was known and that it did not change with political events, which it did (as described in Part 4), then even less money would have been spent. So the committees are bound to push for more money to be spent than is likely to be made available. It is not surprising, therefore that there is not a match between the recommendations of the committees and the facilities actually built, but what is surprising is how poor the match actually is*. At least one could expect that the priority items would be funded, but astronomy over the last forty years has been a rapidly moving science both technically and theoretically, and the priorities are unlikely to have remained constant with time**. Pressure groups also have an effect, as the case of the HST described in

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* Bahcall claims[71], with some justification, that his decennial report of 1991 has been largely successful in so far as most of the recommendations are being implemented, but this post-1991 period is outside the scope of my thesis and so is not discussed further. Maybe the decennial committees have now learnt how to make recommendations which are fundable and supported by the American astronomical community as a whole.

** In addition to the decennial committees, numerous ad-hoc committees have been set up in the USA over the last forty years to analyse and make recommendations on various parts of the astronomy programme. See, for example, the NASA report 'A Long-Range Program in Space Astronomy'

Section 5.2 of Part 4, demonstrates, when the HST was moved from low to high priority following pressure from Bahcall and Spitzer.

In view of these factors it may be thought that the NRC committees are not serving a useful function, and are not worth the amount of time and effort put into them by a large number of senior astronomers. How much effort should be expended in these committees is difficult to determine, but it is clear that such committees do play a useful rôle in bringing astronomers of all persuasions together and forcing them to face the issues involved in recommending an overall facility development programme. It is easy to complain on the sidelines. It is far better to be able to put one's point of view across person-to-person in committee, and then to be involved in deciding on an overall plan, taking into account the differing views from equally clear and persuasive people.

There is no equivalent of the NRC decennial committees in the UK. From time to time similar committees have been established to consider elements of a facility investment programme[24,26], but there is no committee covering both ground- and space-based facilities in the UK on a regular five or ten year cycle. The PPARC astronomy committee may appear, at face value, to perform a similar function, but it differs from the NRC committee in that the PPARC committee is a relatively small *permanent* committee concerned mainly with advising on the running of the current facilities. This is quite different from a committee that sits about every ten years, with sub-committees, working parties and the like, and which has been specifically set up to foresee future needs and developments and to recommend a broad-based investment programme of facilities for the coming ten years. It is interesting that Martin Rees has been recently pushing for such an NRC-like committee structure to be implemented in the UK[74].

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published in 1969 [72], and the NRC report 'A Strategy for Ground-Based Optical and Infrared Astronomy' published in 1994 [73]. These reports are too numerous to review here and, unlike the decennial reports, some are not independent but issued by vested interests.

The Cost-Effectiveness of Spacecraft Observatories. Should Some Money be Transferred to Ground-Based Optical Facilities?

Space facilities have not done very well in my analysis in terms of cost-effectiveness compared with ground-based optical facilities (see Figure 28, Page 218). Although the cost-effectiveness of spacecraft has improved in recent years (if one ignores the HST), spacecraft are still not as cost-effective as ground-based optical facilities, and one has to ask whether enough effort has been expended in both NASA and ESA to reduce the costs of their spacecraft and/or to improve their effectiveness. If that effort *has* been put in, then the idea of transferring some money from space observatories to ground-based optical facilities should be urgently addressed on both sides of the Atlantic. It is often said in the UK that "we cannot change our ESA subscription" but such a change can be implemented if enough ESA Member States agree.

The main costs for spacecraft programmes are the costs of building and launching the spacecraft, not the annual costs of in-orbit operations (see Table 62, Page 177)*. Because of this, the NASA and ESA focus should be on reducing the capital costs and/or extending the in-orbit lifetime of spacecraft, rather than on trying to reduce the annual operations costs. (This is contrary to the situation with ground-based observatories, as explained below).

In the last few years (which have not yet fed through to my database) NASA have, for the first time, implemented a series of 'cheap and cheerful' spacecraft programmes, such as the recently successful Mars Pathfinder spacecraft. On a larger scale NASA are also trying to design a replacement for the HST for about 25% of the costs. But ESA do not, as yet, appear to be implementing such a 'cheap and

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* The HST is an exception, however, as the costs of the three-yearly in-orbit servicing make the annual costs a relatively high proportion of the total programme costs.

cheerful' spacecraft policy, although it has been spoken about on and off for a number of years. In the ESA case this may require a change in their relationship with experimenters for such a policy to be fully effective.

In the USA the spacecraft experiments are paid for by NASA and their procurement is managed by NASA, whereas in the case of ESA the spacecraft experiments are generally paid for by the Member States directly[75] and delivered to ESA 'free-of-charge'. This makes it much more difficult for ESA to control the interfaces between the experiments and the spacecraft bus, and thus control the cost of that bus. If ESA had control of both the experiments and the bus, it would be easier to implement a design-to-cost philosophy.

The 'juste retour' principle[75] has also made it difficult for ESA to keep the costs of their spacecraft down to a reasonable level. In this 'juste retour' system the total value of contracts let to companies in each of the Member States has to equate to the financial contributions of those Member States, which, in the case of the Scientific Programme, are proportional to their GNPs. This principle was imposed by the Member States when ESA was originally set up, in order to ensure that the space industries of each country were treated the same. It helped each country, particularly the smaller ones, to develop a space industry in the early days, but the 'juste retour' system is now generally reckoned to have served its purpose and is in need of reform or abandonment. This system certainly adds to the cost of spacecraft, and conversely its removal would assist ESA in producing more cost-effective spacecraft. Fortunately the Member States have recently agreed to modify the system, although to produce truly cost-effective spacecraft it needs to be eliminated completely.

Investment in Ground-Based Telescopes

Returning now to ground-based optical facilities, my results (Figure 24, Page 186) clearly indicate that, at a national level, money should be directed towards building and instrumenting the largest possible telescopes, leaving universities to fund the smaller telescopes. The one exception at national level is for Schmidt telescopes that, although of modest size, had particularly good cost-effectiveness results (see Table 66, Page 200). Whichever facilities are provided, however, the emphasis should be on reducing the annual costs, rather than unduly constraining the capital costs which are relatively unimportant when amortised over the lifetime of the telescopes (see Section 2.4 of Part 2). A similar situation applies for radio telescopes (see Section 3.2.6 of Part 2).

From a UK point-of-view the excellent cost-effectiveness results of the AAT, WHT, UK Schmidt and INT are most encouraging (see Table 66, Page 200). It is therefore somewhat surprising that a recent decision has been made by PPARC to cease funding the UK Schmidt[76]. Although the reasons for this decision have not been published, I understand from PPARC[77] that it is thought that the UK Schmidt has outlived its usefulness and will shortly be overtaken by CCD-based surveys using other facilities. This clearly shows the limitation of using any survey such as mine, which is based solely on historical data, in trying to make recommendations for future investments. This sort of analysis needs supplementing by information on anticipated technological and other developments in astronomy and associated subjects.

Are there enough Astronomical Facilities?

There has been an underlying concern in the NRC decennial reports that there were not enough up-to-date, Federally-funded astronomical facilities (mainly ground-based optical/IR facilities) for the anticipated number of American astronomers over the decade following the publication of each report (see, for example, Section 3.1.1 of Part 4). Very often the existing facilities were said to be having trouble coping with the number of astronomers working at the time, let alone the increases in numbers anticipated at the time of publication of each report. I do not have enough information on the number of American astronomers that depended on Federally-funded facilities, but it would be of interest to broaden the question to ask whether the number of astronomical facilities in the USA and British Commonwealth as a whole have kept pace with the increase in number of astronomers over the last few decades.

The total number of astronomers in the USA and British Commonwealth has increased by about a factor of 4.0 between 1960 and 1990*. Over this same period the percentage of highly-cited theoretical papers has not changed (see Table 6A, Page 18) so, taking this to indicate that the percentage of theoretical astronomers has stayed approximately constant, there appears to be about four times as many observational astronomers in 1990 compared with 1960.

Over the period from 1960 to 1990 the percentage of highly-cited papers based on data from ground-based optical/IR telescopes has reduced from about 90% to 50%**, those based on data from ground-based radio telescopes has increased from about 10% to 20%**, and those based on data from spacecraft observatories has increased from 0% to about 30%**. I can now estimate whether the numbers of ground-based optical/IR facilities have kept pace with the number of astronomers, assuming that

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* The number of members of the American Astronomical Society increased from 897 in 1959 to 4,995 in 1989 [7,14], and the number of Fellows of the Royal Astronomical Society increased from 1,353 in 1960 to 2,538 in 1991. Not all members of the AAS are active American professional astronomers, and not all Fellows of the RAS are active British Commonwealth professional astronomers. In addition, there will be some people who are members of both societies, and many Fellows of the RAS are geophysicists or amateur astronomers, but, on the other hand, some professional astronomers in the USA and British Commonwealth may not be members of either organisation. As a first approximation, however, if I add the number of members of the AAS to half the number of Fellows of the RAS (to take account of the geophysicists and amateur astronomers) I should get an approximate idea of the increase in the number of professional astronomers in the USA and British Commonwealth over the period of interest. This gives an increase from about 1,570 in 1960 to about 6,260 in 1990, which gives a ratio of 4.0 to 1.

** This is the average for 1986, 1990 and 1994.

these percentages indicate the amount of time spent by astronomers undertaking research with data from each type of facility*.

There appear, from the above figures, to be about $\frac{50\%}{90\%} \times 4.0 = 2.2$ times as many 'full-time equivalent astronomers' using ground-based optical/IR facilities in 1990 compared with 1960, and yet the number of ground-based optical/IR facilities has increased by about a factor of 2.9 for category (c) telescopes, by a factor of 3.6 for category (b) telescopes, and by a factor of 5.5 for category (a) telescopes (see Section 2.1 of Part 2). For the category (a) telescopes the amount of observing time has probably increased by more than this, as most of these telescopes in 1990 were in high mountain locations which have more clear nights per telescope than for the telescopes of 1960. So why has there been a more-or-less continuous cry from astronomers for more and more optical/IR facilities over the last few decades, when the increase in number of facilities has clearly outstripped the increase in numbers of astronomers? Is it because astronomers will always press for more facilities than they have, whether they need them or not, or are the requests justified?

Abt pointed out (see Section 2.1 of Part 3) that the percentage of research work needing large apertures has increased substantially over the last few decades, and this probably explains the claim that the number of large ground-based optical/IR facilities has not kept pace with demand. So the claim for even more large ground-based optical/IR facilities *may* be justified, but, in that case, a number of the smaller telescopes should be closed. This would also make sense from a cost-effectiveness point-of-view as the largest telescopes are, on average, the most cost-effective (see Figure 24, Page 186).

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* I will constrain this analysis to ground-based optical telescopes, as radical changes in the design of ground-based radio telescopes and spacecraft observatories over the period makes a similar analysis for them very difficult.

Endnote

I believe that my analysis in this thesis has produced a great deal of useful data that has never been published or analysed before. These results are of historical interest in their own right, but they could also aid decisions on future investment policy. Extending this analysis for the more recent years, with more journals included, would probably be required, however, before any firm and detailed conclusions could be reached to facilitate future investment decisions.

REFERENCES

1 Abt, H.A., 1980, *PASP*, **92**, 249

2 Martin, B.R., and Irvine, J., 1983, *Research Policy*, **12**, 61

3 Irvine, J., and Martin, B.R., 1983, *Social Studies of Science*, **13**, 49

4 Abt, H.A., 1985, *PASP*, **97**, 1050

5 Trimble, V., 1995, *PASP*, **107**, 977

6 Abt, H.A., 1994, *PASP*, **106**, 1015

7 Abt, H.A., 1990, *PASP*, **102**, 1161

8 Abt, H.A., 1990, *PASP*, **102**, 368

9 Peterson, C.J., 1988, *PASP*, **100**, 106

10 Abt, H.A., 1993, *PASP*, **105**, 437

11 Abt, H.A., 1981, *PASP*, **93**, 269

12 Abt, H.A., 1981, *PASP*, **93**, 207

13 Abt, H.A., to D.L., Private Communication, 18.7.96

14 Greenstein et al., "Astronomy and Astrophysics for the 1970's", Vol. 1 (1972) and Vol. 2 (1973), National Academy of Sciences, Washington DC.

15 Bahcall et al., "The Decade of Discovery in Astronomy and Astrophysics", National Research Council, National Academy Press, Washington DC, 1991

16 Martin, W., and Sinclair, J., *Spectrum*, 1996.

17 Krisciunas, K., 'Astronomical Centres of the World', Cambridge University Press, 1988, ISBN 0-521-30278-1.

18 Whitford, A.E., et al., "Ground-Based Astronomy; A Ten-Year Program", National Academy of Sciences - National Research Council, Washington DC., 1964.

19 Field et al., "Astronomy and Astrophysics for the 1980's", Vol. 1 (1982) and Vol. 2 (1983), National Research Council, National Academy Press, Washington DC.

20 Wright, H., "Explorer of the Universe; A Biography of George Ellery Hale", American Institute of Physics, 1994, ISBN 1-56396-249-7.

21 Osterbrock, D.E., Gustafson, J.R., and Unruh, W.J.S., "Eye on the Sky, Lick Observatory's First Century", Calif. Univ. Press, 1988, ISBN 0-520-06109-8.

22 Kloeppel, J.E., "Realm of the Long Eyes; A Brief History of the Kitt Peak National Observatory", Univelt, 1983, ISBN 0-912183-01-2.

23 Fischer, D., "A Telescope for Tomorrow", Sky and Telescope, Sept. 1989.

24 "Draft Report of the Radio Astronomy Review Panel", SERC, 1992.

25 Tuttle, S., (NSF), to DL, private communication, June 1996.

26 January 1995 Report of the Optical/IR/MM Strategic Review Panel, PPARC.

27 Le Masurier, A., (PPARC), to DL, private communication, April 1996.

28 UKIRT Annual Report for 1992 & 1993.

29 ING Annual Reports from 1989 to 1993, inclusive.

30 AAT/AAO Annual Reports from 1973/74 to 1994/95, inclusive.

31 Carnegie Institution Year Books from 1975 to 1995, inclusive.

32 CFH Annual Reports from 1981 to 1994, inclusive.

33 Lovell, B., "Astronomer by Chance", Oxford University Press, 1992, ISBN 0-19-282949-1.

34 Stannard, D., (Jodrell Bank), to DL, private communication, 21.5.96.

35 Robertson, P., "Beyond Southern Skies; Radio Astronomy and the Parkes Telescope", Cambridge University Press, 1992, ISBN 0-521-41408-3.

36 Jagtman, F., (ESA), to DL, private communication, 25.9.96.

37 Bonnet, R.M., "The New Mandatory Scientific Programme for ESA", ESA Bulletin No. 43, August 1985.

38 Ezell, L.N., "NASA Historical Data Book", Vol.1 NASA Resources 1958 1968, Vol.2 Programs and Projects 1958-1968, Vol.3 Programs and Projects 1969-1978.

39 Culler,G., (NASA), to DL, private communication, June 1996.

40 DL to Wolff, S.C., (NOAO), private communication, 9th December 1996.

41 JCMT Annual Reports for 1987/88 to 1994/95, inclusive.

42 Le Masurier, A., (PPARC), to DL, private communication, November 1996.

43 Baldwin, J.E., (MRAO), to DL, private communication, April 1996.

44 Leverington, D., "A History of Astronomy from 1890 to the Present", Springer-Verlag, 1996, ISBN 3-540-19915-2.

45 Hanbury Brown, R., "Boffin: A Personal Story of the Early Days of Radar, Radio Astronomy and Quantum Optics", Adam Hilger, 1991, ISBN 0-7503-0130-9.

46 DeVorkin, D.H., "Science with a Vengeance", Springer-Verlag, 1992, ISBN 0-387-94137-1.

47 Cornell, J., and Gorenstein, P., (eds.), "Astronomy from Space; Sputnik to Space Telescope", MIT Press, 1983, ISBN 0-262-03097-7.

48 Baker, D., "Spaceflight and Rocketry; A Chronology", Facts on File, New York, 1996, ISBN 0-8160-1853-7.

49 Hirsh, R.F., "Glimpsing an Invisible Universe: The Emergence of X-ray Astronomy", Cambridge University Press, 1983, ISBN 0-521-25121-4.

50 "National Aeronautics and Space Act of 1958", Public Law 85-568, 72, Stat., 426.

51 Giacconi, R., Clark, G.W., and Rossi, B.B., "A Brief Review of Experimental and Theoretical Progress in X-ray Astronomy", internal AS & E Report, ASE-TN-49, Cambridge, Mass., January 15th 1960.

52 Giacconi, R., et al., 1962, *Phys. Rev. Lett.*, **9**, 439.

53 Bowyer, S., et al., 1964, *Nature*, **201**, 1307.

54 Krauschaar, W.L., and Clark, G.W., 1962, *Phys. Rev. Lett.*, **8**, 106, and Kraushaar, W.L., et al., 1965, *ApJ*, **141**, 845.

55 Schmidt, M., 1963, *Nature*, **197**, 1040.

56 Lightman, A., and Brawer, R., "Origins; The Lives and Worlds of Modern Cosmologists", Harvard University Press, 1990, ISBN 0-674-64470-0.

57 Bennett, A.S., 1962, *Mem.R.A.S.*, **68**, 163.

58 Memorandum, "James E. Webb, Administrator, NASA, to the President", Aug. 26, 1966.

59 Forman, W., et al., 1978, *ApJ Suppl.*, **38**, 357.

60 Oda, M., et al., 1971, *ApJ*, **166**, L1; Hjellming, R.M. & Wade, C.M., 1971, *ApJ*, **168**, L21; Rappaport, S., et al., 1971, *ApJ*, **168**, L43; Schreier, E., et al., 1971, *ApJ*, **170**, L21; Braes, L. & Miley, G.K., 1971, *Nature*, **232**, 246; Murdin,

P. & Webster, B.L., 1971, *Nature*, **233**, 110; Webster, B.L. & Murdin, P., 1972, *Nature*, **235**, 37.

61 Logsdon, J.M., (ed.), "Exploring the Unknown; Selected Documents in the History of the U.S. Civil Space Program", Vol. 1, Organising for Exploration, NASA SP-4407, 1995

62 NASA News Release No. 72-05.

63 Smith, R.W., "The Space Telescope; A study of NASA science, technology and politics", Cambridge University Press, 1993, ISBN 0-521-45769-6.

64 *Congressional Record*, 93rd Cong. 2nd sess., July 2, 1974, H.22088-9.

65 *Sky and Telescope*, **45**, Mar. 1973, 139.

66 Chaikin, A., "A Man on the Moon; The Voyages of the Apollo Astronauts", Penguin, 1995, ISBN 0-14-024146-9.

67 Mac Robert, A., *Sky and Telescope*, **75**, May 1988, 469.

68 *Sky and Telescope*, **75**, April 1988, 358.

69 *Sky and Telescope*, **76**, Sept. 1988, 239.

70 *Sky and Telescope*, **79**, Jan. 1990, 19.

71 Bahcall, J.N., "Prioritizing Science: A Story of the Decade Survey for the 1990s", pre-print from the Centennial Volume of the American Astronomical Society, edited by D. De Vorkin.

72 O'Doyle et al., "A Long-Range Program in Space Astronomy; Position Paper of the Astronomy Missions Board", NASA SP-213, July 1969.

73 McCray et al., "A Strategy for Ground-Based Optical and Infrared Astronomy", NRC report, 1994.

74 Rees, M., *Physics World*, Aug. 1997, 15.

75 Bonnet, R.M., and Manno, V., "International Cooperation in Space", Harvard University Press, 1994.

76 *Nature*, **386**, 1997, 635.

77 Le Masurier, A., (PPARC), to DL, private communication, 1st Sept. 1997.

APPENDIX 1

Ground Telescopes and Observatory Spacecraft that have been available sometime between 1956 and 1992 (i.e. 2 years before the start and end of the period 1958-1994)

(The list of Optical and Infrared telescopes below includes all those available in professional observatories in *the USA*[1] *and British Commonwealth* down to, and including, *0.60 m {24"}* diameter)

(A) Optical and Infrared Telescopes
(reflectors unless otherwise stated)

	Date of First use	Current or Last Location
9.82 m	1991	Keck I, Manna Kea[2]

(a) 2.55 - 5.08 m (200") diameters

	Date of First use	Current or Last Location
5.08 m	1948	Hale Telescope, Palomar Mountain, California
4.50 m[3]	1979	Multi-Mirror Telescope (MMT), Whipple Obs., Mt Hopkins, Arizona
4.20 m	1987	William Herschel Telescope (WHT), La Palma, Canary Islands
4.00 m	1975	Cerro Tololo Inter-American Obs., Cerro Tololo, Chile
3.89 m	1975	Anglo-Australian Telescope (AAT), Siding Spring, Australia
3.81 m	1973	Mayall Telescope, Kitt Peak National Observatory, Arizona
3.80 m	1979	UK Infrared Telescope (UKIRT), Mauna Kea, Hawaii
3.58 m	1979	Canada-France-Hawaii (CFHT), Mauna Kea, Hawaii
3.05 m	1959	Shane Telescope, Lick Obs., Mt. Hamilton, California
3.00 m	1979	NASA Infrared Tel. Facility (IRTF), Mauna Kea, Hawaii
2.72 m	1969	Mc Donald Obs., Mt. Locke, Texas
2.7 m	1992	UBC-Laval 'scope, Vancouver

(b) 1.23 - 2.54 m (100") diameters

	Date of First use	Current or Last Location
2.54 m	1917	Hooker Telescope, Mt Wilson, California *(closed down 1985)*
2.54 m	1976	Irénée du Pont Telescope, Las Campanas, Chile
2.44/2.54 m[4]	1967/1984	Isaac Newton Telescope (INT), La Palma

Notes (1) This list excludes solar telescopes and IR tracking telescopes.

(2) The footnotes record only changes in location of telescopes between 1956 and 1992. So the location of telescopes in the final column of the above table may not be the same as their location prior to 1956.

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[1] Including American stations abroad, Mexico and Israel.

[2] This telescope were deliberately left out of category (a), as it was in a size category all of its own

[3] Equivalent light gathering power of its 6 mirrors

[4] The INT was a 2.44 m telescope located at Herstmonceux in 1967. In 1984 its mirror was replaced by a 2.54 m and the telescope moved to La Palma.

(A) Optical and Infrared Telescopes (cont.)

	Date of First use	**Current or Last Location**
2.34 m	1988	Hiltner Telescope, McGraw-Hill or MDM[5] Obs., Kitt Peak
2.30 m	1984	Advanced Technology Telescope, Mt. Stromlo & Siding Spring Obs.
2.3 m	1985	Vainu Bappu Observatory, Kavalur, India
2.29 m	1977	Wyoming IR Telescope, Jelm Mountain
2.26 m	1969	Steward Obs., Univ. of Arizona, Kitt Peak
2.24 m	1970	Univ. of Hawaii, Mauna Kea
2.16 m	1986	Cananea Obs., Mexico
2.14 m	1964	Kitt Peak National Observatory
2.14 m	1979	San Pedro Martir Obs., Baja Calif., Univ. Nac. Aut. de Mexico
2.08 m	1939	Struve Telescope, McDonald Obs.
1.88 m	1935	David Dunlap Obs., Univ. of Toronto, Richmond Hill, Ontario
1.88 m	1948	Radcliffe reflector, Sutherland Obs., South Africa[6]
1.88 m	1955	Mt Stromlo Obs., Australia
1.83 m	1918	Dominion Astrophysical Obs., Canada[7]
1.75/1.83 m	1932/1966	Perkins reflector[8] , Lowell Obs.
1.6 m	1978	Mt Mégantic Obs., University Of Montreal, Quebec, Canada
1.52/1.57 m[9]	1975/1979	Black Moshannon Obs., Rattlesnake Mt., Penn. State Univ.
1.55 m	1937	Wyeth Telescope., Oak Ridge Station, Harvard College Obs.
1.55 m	1962	IR Telescope, Univ. of Calif. and Caltech., White Mountain Obs.[10]
1.55 m	1964	US Naval Observatory, Flagstaff
1.55 m	1965	Catalina Obs., Mt Bigelow, Univ. of Arizona
1.55 m	1972	Infrared Flux Collector, Tenerife
1.52 m	1891	Rockefeller Telescope, Boyden Station, Bloemfontein[11]
1.52 m	1908	Mt Wilson
1.52 m	1965	San Pedro Martir Obs., Baja Calif., Univ. Nac. Aut. de Mexico[12]
1.52 m	1967	NASA Infrared, Mt Lemmon[13]
1.52 m	1968	Cerro Tololo
1.52 m	1970	Palomar Mountain
1.52 m	1970	Tillinghast Telescope., Whipple Obs., Mt Hopkins
1.52 m	1971	UCSD-UM[14] IR 'scope, Mt Lemmon[15]

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[5] Michigan - Dartmouth - MIT

[6] Moved from Pretoria to Sutherland in 1976

[7] New (Cervit) mirror installed in 1974.

[8] Of the Ohio Wesleyan University, the Ohio State University and the Lowell Observatory. The 1.75 m Perkins reflector, which was made in 1932, was moved from the Observatory of the two Ohio Universities in Delaware to the Lowell Observatory in 1961. The mirror was replaced in 1966 by a 1.83 m.

[9] The 152 cm metal mirror was replaced by a 157 cm Cervit mirror in 1979.

[10] Moved from Mt Wilson in 1976.

[11] New mirror installed in 1972.

[12] Moved from Catalina Obs. in 1971. Aluminium mirror replaced by a Cervit mirror in 1981.

[13] Telescope moved to Mt Lemmon in 1973, and metal mirror replaced by a Cervit mirror in 1976.

[14] University of California at San Diego - University of Minnesota

(A) Optical and Infrared Telescopes (cont. ii)

	Date of First use	Current or Last Location
1.50 m	1988	IR Telescope, Rothney Obs., Calgary, Alberta, Canada
1.32 m	1969	Mc Graw-Hill or MDM Obs., Kitt Peak[16]
1.27 m	1954	Mt Stromlo Obs., Australia
1.27 m	1965	Kitt Peak National Observatory[17]
1.26 m	1948	Palomar *Schmidt*, (48" x 72" nominally)
1.24 m	1973	UK *Schmidt*, Siding Spring, (48" x 72")

(c) 0.62 - 1.22 m (48") diameters

1.22 m	1961	Dominion Astrophysical Obs., Canada
1.22 m	1966	Cloudcroft Obs., New Mexico *(closed down 1982)*
1.22 m	1966	Nizamiah Obs., Osmania Univ., Hyderabad
1.22 m	1969	Univ. of Western Ontario Obs., Elginfield, Canada
1.20 m	1975	NASA, Greenbelt
1.2 m	≤ 1991	Table Mountain Obs., JPL., Pasadena
1.08 m	1973	Charlottesville, Virginia
1.07 m	1910	Lowell Obs., Flagstaff, Arizona *(closed down 1964)*
1.07 m	1970	Hall Telescope, Lowell Obs., Flagstaff, Arizona
1.04 m	1934	Ritchey-Chrétien reflector, US Naval Obs., Flagstaff
1.04 m	1968	Yerkes Obs. reflector, Univ. of Chicago
1.04 m	≤ 1991	Table Mountain Obs., Pomona College, Pasadena
1.02 m	1897	Yerkes *refractor*, Univ. of Chicago
1.02 m	1968	Oakland, Illinois
1.0 m	1961	Tonantzintla, Puebla, Univ. Nac. Aut. de Mexico
1.0 m	1963	South Africa Astrophys. Obs., Sutherland[18]
1.0 m	1964	Siding Spring
1.0 m	1966	Yale reflector, Cerro Tololo Obs.[19]
1.0 m	1967	Lindheimer/Dearborn Obs., Northwestern Univ., Evanston, Illinois
1.0 m	1967	Ritter Obs., Univ. of Toledo, Ohio
1.0 m	1969	Prairie Telescope, Mount Laguna, California[20]
1.0 m	1970	Univ. of Arizona IR, Mt Lemmon
1.0 m	1971	Swope reflector, Carnegie Southern Obs., Las Campanas
1.0 m	1971	Wise Observatory, Mitzpe Ramon, Tel Aviv
1.0 m	1973	Mc Cormick Obs., Fan Mountain, Univ. of Virginia
1.0 m	1974	Catalina Obs., Arizona

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[15] Aluminium mirror replaced by a Cervit mirror in 1974

[16] Moved from Ann Arbor to Kitt Peak in 1975.

[17] Aluminium mirror replaced by a Cervit mirror in 1970.

[18] Moved from the Cape Observatory in 1973.

[19] Moved from Bethany, Connecticut in 1973.

[20] Moved from the Prairie Obs., Univ. of Illinois, Oakland, in 1981 when the observatory was closed down. The telescope is now shared between the University of Illinois and the San Diego State University.

(A) Optical and Infrared Telescopes (cont. iii)

	Date of First use	**Current or Last Location**
1.0 m	≤ 1976	Mt. Wilson
1.0 m	~ 1978	Univ. of Tasmania, Hobart, Australia
1.0 m	1980	Nickel Telescope, Lick Obs., Univ. of Calif., Mt. Hamilton
1.0 m	≤ 1982	Vainu Bappu Obs., India
1.0 m	1984	Jacobus Kapteyn Telescope, La Palma
1.0 m	1985	McLellan reflector, Mt John Univ. Obs., NZ
0.97 m	1954	Holcomb Obs., Butler Univ., Indianapolis
0.97 m	1975	Hargreaves reflector, Royal Greenwich Obs., Herstmonceux
0.94 m	1911	Univ. of Michigan, Ann Arbor
0.91 m	1888	Lick *refractor*, Mt Hamilton[21]
0.91 m	1879	Crossley reflector, Lick Obs.
0.91 m	1922	Steward Obs., Kitt Peak[22]
0.91 m	1929	Grubb-Parsons reflector, Royal Obs., Edinburgh
0.91 m	1934[23]	Yapp reflector, Royal Greenwich Obs., Herstmonceux
0.91 m	1939	Goethe Link Obs., Indiana Univ.
0.91 m	1950	Cerro Tololo[24]
0.91 m	1956	McDonald Obs., Univ. of Texas
0.91 m	1957	Union Obs. Annex, Hartebeesport, South Africa
0.91 m	1957	Warner and Swasey Obs., Cape Western Reserve Univ., Ohio
0.91 m	1958	Pine Bluff Obs., Univ. of Wisconsin, Madison
0.91 m	1960	Kitt Peak National Observatory, No. 1 Telescope *(closed down 1989)*
0.91 m	1966	Kitt Peak National Observatory, No. 2 Telescope[25]
0.91 m	1966	Princeton Univ. Obs., Princeton
0.91 m	1968	Tinsley reflector, Fernbank Obs., Georgia
0.91 m	1969	Goddard Space Flight Centre, Greenbelt
0.91 m	1970	Louisiana State Univ., Baton Rouge
0.91 m	1977	Monterey Inst., Carmel Valley, California
0.9 m		Univ. of St. Andrews, Scotland
0.84 m	1971	San Pedro Martir Obs., Baja Calif., Univ. Nac. Aut. de Mexico
0.82 m	1951	ADH Baker - *Schmidt*, South Africa, (32" x 36") *(closed down 1976)*
0.81 m	1943	Perkins Obs., Ohio Wesleyan & Ohio State Universities., Delaware[26]
0.81 m	1964	Leander Mc Cormick Obs., Univ. of Virginia, Fan Mt.
0.8 m	1990	Four College Consortium, Pennsylvania, Mt. Hopkins Obs.
0.79 m	1906	Keeler Telescope, Allegheny Obs., Univ. of Pittsburgh
0.79 m	1964	NASA refl., Lowell Obs., Flagstaff, Arizona[27]

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[21] Lens repolished in 1981 and 1987.

[22] Moved from Tucson, Arizona in 1962

[23] Not in use between 1955 and 1958

[24] Moved to Cerro Tololo in 1966.

[25] The aluminium mirror of this No.2 telescope was replaced by the glass mirror of the No.1 telescope in 1970, and a new glass mirror was installed in the No.1 telescope.

[26] Moved to Delaware in 1962 to replace the 1.75 m Perkins reflector.

(A) Optical and Infrared Telescopes (cont. iv)

	Date of First use	Current or Last Location
0.79 m	1972	Rattlesnake Mountain Obs., Battelle Labs., Washington
0.79 m	≤ 1976	Lab. of Atmospheric & Optical Physics, Southwestern at Memphis
0.76 m	1914	Thaw *refractor*[28] , Allegheny Obs., Univ. of Pittsburgh
0.76 m	1897[29]	Thompson photographic reflector, Greenwich Royal Obs.
0.76 m	1924	Mt Stromlo Obs., Australia
0.76 m	1950	Beck Telescope, Bradley Obs., Agnes Scott College, Georgia[30]
0.76 m	≤ 1954	Univ. of Illinois
0.76 m	1961	South African Astrophys. Obs., Sutherland[31]
0.76 m	1963	Stony Ridge Obs., California
0.76 m	1967	Rosemary Hill Obs., Univ. of Florida, Gainesville, Florida
0.76 m	1967	O'Brien Observatory, Univ. of Minnesota, Minneapolis
0.76 m	1968	Leuschner Obs., Univ. of California at Berkeley
0.76 m	1970	McDonald Obs., Univ. of Texas
0.76 m	1972	Manastash Ridge Obs., Univ. of Washington, Seattle
0.76 m	1972	Behlen Obs., Univ. of Nebraska
0.76 m	1973	New Mexico Institute, Langmuir Lab., Magdalena Mountains
0.76 m	1988	Smithsonian New Generation Small Tel. (NGST), Mount Hopkins
0.76 m	1988	Four College NGST, Mount Hopkins
0.76 m	1988	Fairborn Obs. NGST, Mount Hopkins
0.76 m		Pine Bluff Obs., Univ. of Wisconsin
0.75 m	1988	Automatic Photoelectric Telescope, Mount Hopkins, Arizona
0.72 m	≤ 1933	Flower & Cook Obs., Univ. of Pennsylvania
0.71 m	1893[32]	Greenwich Visual *refractor*, Herstmonceux *(closed down 1971)*
0.71 m	1963	Univ. of Arizona Infrared, Mt Lemmon
0.70 m	1927	McDowell *refractor*, Bloemfontein *(closed down 1974)*
0.69 m	≤ 1970	William Pitt Telescope, Univ. of Kansas Obs., Lawrence, Kansas
0.69 m	1976	Flower & Cook Obs., Univ. of Pennsylvania
0.68 m		Univ. of Sheffield
0.67 m	1884	Univ. of Virginia *refractor*, Leander Mc Cormick Obs., Mt Jefferson
0.67 m	1925	Innes *refractor*, Republic Obs., Johannesburg
0.66 m	1873	Clark *refractor*, US Naval Obs., Washington
0.66 m	1897[33]	Thompson photographic *refractor*, Greenwich Royal Obs.
0.66 m	1925	Yale-Columbia *refractor*, Mount Stromlo, Australia
0.66 m	1959	Mt Stromlo & Siding Spring Obs., Australia

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[27] Was in the custody of the US Geological Survey at Flagstaff until the custody was transferred to the Lowell Obs. in 1972. Its custody was further transferred to the National Undergraduate Research Observatory (NURO) in 1990.

[28] New objective fitted 1985

[29] Not in use between 1947 and 1956

[30] Moved to Hard Labor Creek Obs., Georgia State University in 1989.

[31] Moved from the Cape Obs. in 1972.

[32] Not in use between 1947 and 1957.

[33] Not in use between 1947 and 1957.

(A) Optical and Infrared Telescopes (cont. v)

	Date of First use	Current or Last Location
0.66 m	1968	Tinsley reflector, Univ. of South Florida Obs., Tampa, Florida
0.65 m	1942	*Schmidt* Telescope, Tonanzintla Obs., Mexico, (26" x 31")
0.64 m	1976	Hartung-Boothroyd Obs., Cornell Univ., New York
0.63 m	≤ 1976	Macalester Obs., St Paul, Minnesota

0.61 m (24") diameter

	Date of First use	Current or Last Location
0.61 m	1896	Clark *refractor*, Lowell Obs., Flagstaff
0.61 m	1901	Mc Clean *refractor*, Cape of Good Hope, South Africa[34]
0.61 m	1902	Radcliffe *refractor*, London Univ. Obs., Mill Hill
0.61 m	1912	Sproul Obs. *refractor*, Pennsylvania
0.61 m	1940	Jewett *Schmidt*, Agassiz Station, Harvard College Obs., (24" x 33").
0.61 m	1942	Burrell *Schmidt*, Cape Western Reserve, Kitt Peak[35], (24" x 36")
0.61 m	1949	Curtis *Schmidt*, Univ. of Michigan, Cerro Tololo, (24" x 36")[36]
0.61 m	1959	*Schmidt*, Lowell Obs., Flagstaff
0.61 m	1929	Wilson/Allen Telescope, London Univ. Obs., Mill Hill[37]
0.61 m	≤ 1937	Sproul Obs., Swarthmore College[38]
0.61 m	1940	Francis McMath Telescope, Michigan State Univ. Obs.
0.61 m	1953	Fecker reflector, Arizona Univ., Flagstaff, Arizona
0.61 m	1953	Seyfert Telescope, Dyer Obs., Vanderbilt Univ., Nashville
0.61 m	≤ 1954	Cogshill reflector, Indiana Univ. Obs.
0.61 m	≤ 1958	Agassiz station, Harvard College Obs.
0.61 m	1959	Morgan Telescope, Lowell Obs., Flagstaff, Arizona
0.61 m	1960	Yerkes Obs., reflector
0.61 m	1960	Brigham Young Univ. Obs., Utah
0.61 m	1962	Albuquerque, New Mexico
0.61 m	1963	Mt. Wilson
0.61 m	1964	Lick Obs. refl., Mount Hamilton
0.61 m	1964	Mount Laguna Obs., San Diego State Univ.
0.61 m	1965	UCLA reflector, Ojai, Calif.
0.61 m	1965	Hills Obs., Univ. of Iowa
0.61 m	1965	Corralitos Obs., Las Cruces, Northwestern Univ., New Mexico
0.61 m	1965	Mount Cuba Obs., Delaware
0.61 m	1965	Mees Obs., Univ. of Rochester, New York
0.61 m	1966	Whitin Obs., Wellesley, Mass.

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[34] Previously called the Victoria refractor.

[35] Was first located in 1943 at the Warner & Swasey Obs. at Cleveland, Ohio, before being moved to its Nassau Station at Chardon, Ohio in 1957, and then moved to Kitt Peak in 1979.

[36] Originally located at the Univ. of Michigan Obs. at Ann Arbor, and moved to Cerro Tololo in 1966.

[37] The Wilson Telescope was retired in 1974 and replaced by the Allen Telescope of the same diameter.

[38] Was originally at the Oak Ridge/Agassiz Station of the Harvard College Observatory.

(A) Optical and Infrared Telescopes (cont. vi)

	Date of First use	Current or Last Location
0.61 m	1966	Table Mountain Obs., JPL, Pasadena
0.61 m	1966	Alliance, Ohio
0.61 m	1966	USAF, Hanscom Field, Massachusetts
0.61 m	1966	Perkins Obs., New Canaan, Connecticut
0.61 m	≤ 1967	David Dunlap Obs., Richmond Hill, Ontario
0.61 m	1967	Capilla Peak Obs., Univ. of New Mexico, Albuquerque
0.61 m	1967	Tortugas Mountain Obs., Las Cruces, New Mexico State Univ.,
0.61 m	≤ 1968	Australian National Obs., Siding Spring, Australia
0.61 m	1968	Mt John Univ. Obs., New Zealand
0.61 m	1968	Harriman Obs., Columbia Univ., New York
0.61 m	1968	Univ. of Hawaii, Mauna Kea
0.61 m	1968	Pine Mountain Obs., Univ. of Oregon
0.61 m	1968	Mather Telescope, Fick Obs., Iowa State Univ.
0.61 m	1969	Blue Mesa Obs., Magdalena Pk., Las Cruces, New Mex. State Univ.
0.61 m	1969	NASA-Lowell, Mauna Kea, (operated by the Univ. of Hawaii)
0.61 m	1969	NASA-Lowell, Cerro Tololo
0.61 m	1970	Wallace Obs., MIT, Cambridge, Mass.
0.61 m	1970	Coudé reflector, Lick Obs., Mount Hamilton
0.61 m	1970	US Naval, Flagstaff, Arizona
0.61 m	1970	US Naval Obs., Washington
0.61 m	1970	Perkin Telescope, Van Vleck Obs., Wesleyan Univ., Connecticut
0.61 m	1970	Kodaikanal Obs., India
0.61 m	1971	Univ. of Toronto reflector, Las Campanas Obs., Chile
0.61 m	1971	Bickley Obs., Perth, Australia
0.61 m	1972	Williston Obs., Mt Holyoke College, South Hadley, Mass.
0.61 m	1972	Black Moshannon Obs., Penn. State Univ.
0.61 m	1972	Univ. of Washington
0.61 m	1973	Mount Evans Obs., Univ. of Denver, Colorado
0.61 m	1973	Morehead Obs., Univ. of North Carolina
0.61 m	1973	Goldendale Obs., Washington
0.61 m	≤ 1974	Sommers-Bausch Obs., Univ. of Colorado/NBS, Boulder
0.61 m	1975	Mt John Univ. Obs., New Zealand
0.61 m	≤ 1976	Lab. of Atmospheric & Optical Physics, Southwestern at Memphis
0.61 m	≤ 1976	Univ. of Utah Obs., Salt Lake City
0.61 m	1976	State Univ. of NY, Smithsonian Obs., Mt Hopkins *(cl. down 1990)*
0.61 m	≤ 1980	Univ. of Georgia
0.61 m	1984	Gale Obs., Grinnell College, Iowa
0.61 m	1992	Hopkins Obs., Williams College.
0.61 m		Univ. of Texas refl., Las Campanas
0.61 m		Keele Univ.
0.61 m		Univ. of Newcastle upon Tyne

(B) Radio Telescopes

(a) Dish antennae[39]

(min. dish diameter 10 metres)

Dia. (m)		Date of First use	Max. Freq.[40] (GHz)		
			1964	1992	
76	A[41]	1957	1.4	5	) 1957 Mark 1, Jodrell Bank, UK) 1971 modified and called Mark 1A
64	A	1961	5	20	Parkes, Australia
64	A	1966	3 (1971)	9	Mars Antenna[42], NASA, Goldstone, California
64		1973			Madrid, Spain; part of NASA's DSN[43]
64		1973			Tidbinbilla, Australia; part of NASA's DSN[44]
46[*]		1964	1.5		Sagamore Hill, Hamilton, Massachusetts
46[45]	A	1959	0.4 (1968)		Stanford, California
46		~ 1966			Naval Research Lab., Sugar Grove, West Virginia
46	A	1965	35 (1972)		Algonquin Obs., Lake Traverse, Ontario, Canada
43	E	1965	15	30	Green Bank, West Virginia
40		1964	1.4		Carnegie Institution, Washington
40		1968	30 (1971)	30	Caltech., Owens Valley, Big Pine, California
38 x 25		1964	3	10	Mark II, Jodrell Bank
38 x 25		1966	2 (1972)		Nantwich, UK, called "Mark III, Jodrell Bank"
37	A	1963	6		MIT, Lincoln Lab.[46]
36		1971	2 (1972)	5	Vermilion River, Illinois
34		1985			NASA DSN, Goldstone, Calif.
34		1985			NASA DSN, Madrid
34		1985			NASA DSN, Tidbinbilla, Australia
30		1974	5 (1974)		Dudley Obs., State Univ. of New York at Albany
26	A	1959	1.2	5	Lincoln Lab., MIT, Millstone Hill, Westford, Mass.
26 (84 ft)	E	1957	10	30	Naval Research Lab., Maryland Point, Washington
26		1958	3		Sagamore Hill, Hamilton, Massachusetts
26	E	1958	1.0		Caltech, Goldstone, California; part of NASA's DSN

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[39] Movable in both right ascension and declination, using either an equatorial or altazimuth design. Those fixed dishes, or those that can only move in declination, are listed in Table (b) below. Those dishes operating at frequencies > 30 GHz are listed in Tables (c) and (d) below.

[40] This maximum frequency is not necessarily valid for the whole of the dish area, as sometimes the central area has a higher accuracy tolerance than the remainder of the dish.

[41] A in this column stands for Alt-Azimuth mounting, and E for Equatorial.

[42] Mainly used as a communications antenna for space vehicles as part of NASA's Deep Space Network (DSN).

[43] Deep Space Network.

[44] Partly used for radio astronomy and, since 1985, linked to the 64m Parkes' antenna to form an interferometer.

[*] Used *mainly* for solar observations.

[45] Has a radar facility

[46] Includes a radome.

(a) Dish Antennae cont.

Dia. (m)		Date of First use	Max. Freq. (GHz)		
			1964	1992	
26	A	1960	2.4		Caltech, Goldstone, California; part of NASA's DSN
26		1962	2.3 (1972)		Caltech, Goldstone, California; part of NASA's DSN
26		1959	1.4	7	Dominion Obs., Penticton, White Lake, Canada
26*	E	1959	16		Univ. of Michigan, Portage Lake
26	E	1959	10		Howard Tatel Telescope, Green Bank, West Virginia
26		1960			Woomera, Australia; part of NASA's DSN
26* (85 ft)	E	1961	10		Harvard Coll. Obs. Field Station, Fort Davis, Texas
26		1961			Johannesburg, South Africa; part of NASA's DSN[47]
26	E	1962	10	20	Univ. of California, Hat Creek
26		< 1964	1.7		Gilmore Creek, Fairbanks, Alaska
26		< 1964	1.7		Rosman, North Carolina
26		1965			Tidbinbilla, Australia; part of NASA's DSN
26		1965			Robledo, Madrid; part of NASA's DSN
26 (85 ft)		1965	1.7	40	Naval Research Lab., Maryland Point
26 (84 ft)		1966	6 (1972)		Aggasiz Station, Harvard College Obs.
26		1967			Cebreros, Madrid; part of NASA's DSN
26		1967			Honeysuckle Creek, Canberra, Australia[48]
26		1970	2.7		Cornell Univ., New York
26		≤ 1988			Hobart, Tasmania
25		1965	1.5 (1965)		Royal Radar Establishment (RRE), Defford, UK
24					Hobart, Tasmania
22		1987			Coonabarabran, Australia
20		1968	0.6 (1972)		Table Mountain, Boulder, Colorado
19		1962	3		Stanford Research Institute, Boseman, Montana
19		< 1964	0.4		Chena Valley, College, Alaska
18	E	1956	2		Agassiz Station, Harvard College Obs.
18		1959	16		Dpt of Terr. Magnetism, Carnegie Inst., Washington
18		1959	1.4		Parkes, Australia[49]
18		1961	10		Naval Research Lab., Sugar Grove, West Virginia
18		< 1964	3		Evans Signal Lab., Belmar, New Jersey
18		< 1964	10		Naval Electrical Lab., San Diego, California
18[50]		≤ 1965	22 (1973)	22	Lincoln Lab., MIT, Millstone Hill, Westford, Mass.
18		≤ 1965		8	Lincoln Lab., MIT, Pleasanton, California
18		1968	5 (1972)		North Liberty Obs., Univ. of Iowa
18		< 1972	10 (1972)		Wallops Station, NASA, Virginia

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* Used mainly for solar observations.

[47] Now used as a radio telescope when NASA abandoned it in the early 1970's (*Astronomy* March 1991).

[48] NASA-owned. For communications with manned and unmanned spacecraft.

[49] Moved from Fleurs Observatory in 1963.

[50] This antenna is also used to form a 1.2 km baseline interferometer with the 36 m Haystack dish. Since the late 1970s the 18m dish has been used mainly to determine the motion of the Earth's pole.

(a) Dish Antennae cont.(ii)

Dia. (m)		Date of First use	Max. Freq. (GHz)		
			1964	1992	
18		1972	2 (1972)		Algonquin Obs., Ontario, Canada
15	A	1951	30		Naval Research Lab., Washington
15	A	1960			MIT[51]
15		1962	10		Polar Axis Telescope, Jodrell Bank[52]
15		< 1964	3		Evans Signal Lab., Belmar, New Jersey
14		< 1960	3		Malvern, UK
14		1972		35	Itapetinga Radio Obs., Brazil
12	E	1959	0.9		Perkins Obs., Ohio State Univ., Delaware, Ohio[53]
11		1953			Potts Hill, Sydney, Australia
10	E	1956[54]			Caltech., Owens Valley, Big Pine, Calif.
10	E	1960	8		Univ. of California, Hat Creek
10*		1962	3		State College, Pennsylvania
10		1963	16		Algonquin Radio Obs., Lake Traverse, Ontario

(b) Fixed dishes (including those that can move only in declination)

(min. dish diameter 10 metres)

Dia. (m)	Date of First use	Max. Freq. (GHz)		
		1964	1992	
305[55]	1963	0.6	5	Arecibo. Puerto Rico
92**	1962	1.4	5	Green Bank, West Virginia[56]
67	1947	0.2 (1950)		Jodrell Bank
67[57]	< 1976			Lincoln Lab., Millstone Hill, Mass
30	1974	2.4		Higuillales, nr. Arecibo, Puerto Rico
12	< 1964	1.4		Green Bank, West Virginia
11**	1953	1.4		Potts Hill, Sydney, Australia

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[51] Has a radar capability.

[52] There was also a 15m altazimuth used, since 1964, for tracking spaceprobes and the moon. It was replaced by a 13m dish in 1982 which was used for the same purpose

[53] Air Force Tracking Antenna.

[54] Moved to current site in 1958.

[55] Steel mesh replaced by perforated aluminium panels and an S-band, 2.4 GHz radar system added in 1972-74. The 305 m also operates with the 30 m dish at Higuillales (which has a limiting pointing capability) to form a 10 km baseline interferometer operating at a frequency of 2.4 GHz.

** Can move in declination.

[56] Backup structure strengthened 1966. Resurfaced in 1970 allowing operation at upto 5 GHz.. Dish collapsed and completely destroyed in 1988. (*Sky & Telescope* March 1989).

[57] Has a radar facility.

(c) Dishes designed for Millimetre Wavelengths

(Maximum Freq. > 30 and ≤ 300 GHz; Min. dish diameter 6 metres)

Dia. (m)	**Date of First use**	
36[58]	1966	Haystack Hill, Westford, Massachusetts
32	1990	Mullard Labs., Cambridge, UK
14	1973	Itapetinga, Brazil
14	1976	Five College Obs., Amherst, Mass.[59]
12[60]	1967	NRAO, Kitt Peak, Arizona
10	1965	AFCRL, Waltham, Mass.
10	1978	Caltech, Owens Valley, Big Pine
9	1964	Haystack, Massachusetts
9	1976	Battelle Northwest Labs., Rattlesnake Mountain Obs.
7	1977	Bell Labs., Holmdel, New Jersey
6	1968	Univ. of California, Hat Creek

(d) Submillimetre-wave Dishes

(Maximum Freq. > 300 GHz; Minimum dish diameter 6 metres)

Dia. (m)	**Date of First use**	
15	1987	JCMT (James Clerk Maxwell Telescope), Mauna Kea
10.4	1988	Caltech Sub-millimetre Telescope (CSO), Mauna Kea

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[58] Has a radar capability and operates within a radome.

[59] New radome fitted 1988.

[60] The original 11m dish, protected by a radome, was replaced by a 12m dish in 1983.

(e) Dish Interferometers (listed in reverse date order)

Date of First use	**Number of Dishes**	**Dia. of Dishes (m)**	**Max. Sep$^{n.}$ of Dishes (km)**	**Maximum Freq. in GHz**		
				1964	**1992**	
≤ 1990	2	30				Buenos Aires, Argentina
1988/93	10[61]	25	8,000		43	VLBA, USA
1988	6[62]	22	6		40	Culgoora, Australia
≤ 1985	4[63]	9	0.6		1.4	Dominion Synthesis Tel.
1984	3[64]	10	0.3		230	Caltech., Owens Valley,
1980	3[65]	25			24	Cheshire/Powys, UK
1977/81[66]	27	25	21x21x19	24 (1977)	24	VLA, Socorro
1974	2[67]	6	0.3	38 (1972)	300	Hat Creek
≤ 1973[68]	32 & 2	6 & 14	1			Potts Hill, Australia
1972	8	14	5	5 (1972)		Five km (or Ryle) Tel.
< 1972*	3	18		5		Sagamore Hill, Mass.
1971	4[69]	37		0.6 (1972)		Five College Obs., Mass.
1971	5	18	0.2	10 (1972)		Stanford Univ., California
1968	2[70]	9	0.8	1.4 (1972)		Half-mile Tel., Cambridge,
1967	96	14	3[71]	0.08 ('67)		Culgoora, Australia
1966	3[72]	26	5	8 (1972)	15	Green Bank, West Virginia

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[61] These dishes were all newly constructed for this array. Most other very large arrays are arrangements of the existing telescopes listed in table (a) above. As such, these very large arrays are not listed separately in this table of interferometers to try to avoid 'double counting'.

[62] These 6 dishes can be linked to the 64 m dish at Parkes, and the 22 m dish at Coonabarabran, to form the Australia Telescope.

[63] Now increased to 7.

[64] There are now seven 10m dishes.

[65] These three 25m dishes were part of the VLA production run. These 3 dishes are part of the MERLIN or MTRLI array of radio telescopes in the UK, with a baseline of 230 km. The other dishes that make up MERLIN are the Mark I or Mark II at Jodrell Bank, plus the Mark III, the 25 m dish at Defford (built 1965) and, until 1990, one of the 18 m dishes of the 1 mile telescope at Cambridge. This latter dish was replaced in MERLIN in 1990 by a new 32 m dish at Cambridge (see Table (c) above).

[66] First used with a limited number of dishes in 1977; first used with all dishes in 1981

[67] The first dish was available in 1968 (see Table (c) above). There are now 6 dishes.

[68] For solar work only.

* Used mainly for solar work.

[69] Fixed spherical dishes with moveable feeds (as per Arecibo). Two extra dishes added in 1976.

[70] Plus two more in 1972.

[71] 3 Km diameter circular array

[72] One of these three dishes is the original Howard Tatel Telescope (see Table (a) above). A second antenna was added in 1964, and a third shortly after. A transportable 13 m dish could also be used upto 40 km from the other three dishes. A 14 m transportable dish was added in 1972.

(e) Dish Interferometers cont.

Date of First use	Number of Dishes	Dia. of Dishes (m)	Max. Sep$^{n.}$ of Dishes (km)	Maximum Freq. in GHz 1964	1992	
1964	3	18	1.6	1.4	5	1 Mile (or 5C), Cambridge.
< 1964	2	9	0.8	0.5		Chena Valley, Alaska
< 1964	2 & 1	26 & 18	1.0	1.1		NBS, Boulder, Colorado
< 1964	4	9				Stanford, California
1960	2	25	1	3	5	Malvern, UK
1959	2	18	0.2	0.08		NBS, Boulder, Colorado
1958	2	27	0.5	3	11	Owens Valley, Big Pine,
1957*	64	6	0.4	1.4		'Chris-Cross', Sydney

(f) Miscellaneous Antennae and Arrays (in reverse date order)

Date of First use	Max. Freq. (GHz) 1964	1992	Size	Place
< 1984	0.03 (1984)		1,000 dipole, T-shaped array	Gauribidanur, India
1983	0.15 (1983)		5 km	Cambridge Low Freq. Synth.
< 1989[73]		0.1	Three 1,024 dipole arrays	Ahmedabad, India
< 1980	0.45 (1980)		512 helical antennae, area 3.6 x 3.4 km	Univ. of Texas
1976	0.05		528 dipole array	Univ^{s}. of Florida and Chile,
1975	0.15 (1976)		1.4 km	Cambridge Synthesis (or 6C)
1974	0.1 (1974)	1.2	720 element, helical array, 3.0 km x 1.8 km	Clark Lake
1974	0.03			Cocoa Cross, Clark Lake
1972	0.03		640 dipole, 8 acre array	Gainesville, Florida
1971	0.3		530 x 30 m cyl. paraboloid	Ootacamund, India
1968	0.02 (1972)		1.3 km x 0.4 km T dipole array	Penticton Obs., Canada
1968*	0.06 (1972)		16 log periodic elements, 3.3 km array	Clark Lake
1967	0.08 (1972)		4 acre dipole array	Scintillation Tel. Cambridge
1967	0.4 (1972)		1,600 m each arm	Molonglo Cross, Sydney
1965	0.01 (1972)		1.2 km x 0.7 km T dipole array	Penticton Obs., Canada
< 1964	0.03		Two 12 x 12 m corner reflectors	Gainesville, Florida
< 1964	0.02		Three Yagi arrays 12 x 8 m	Bethany, Connecticut
< 1964	0.3		Two 24-element helix arrays, each 2 x 40 m	Bethany, Conn.

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[73] For analysing the solar wind.

* Used mainly for solar work.

(f) Miscellaneous Antennae and Arrays (cont.)

Date of First use	Max. Freq. (GHz)		Size	Place
	1964	1992		
< 1964		1.4	Rectangular array	Fleurs, Sydney
		0.3	Radioheliograph[74]	Culgoora, Australia
1962	0.05		290 x 290 m broadside array	Lima, Peru
1962	2		79[75] x 21 m focusing paraboloid	Perkins Obs., Ohio
1962	0.6		180 x 120 m cyl. paraboloid	Vermilion River
1961	0.03		3.8 km x 1.5 km dipole array	Clark Lake
1960	0.03		12 x 12 m corner reflector	Univ^{s}. of Florida and Chile
1959	0.09		920 m linear array of corner refl.	Carnegie Inst.
1959[76]	3		110 m each arm	Cross, Stanford, Calif.
1958	0.4		Two 2,000 x 1 m corner refl, sep^{n}. 600 m	Potts Hill, Sydney
1958	0.2		700 m cyl. paraboloid	C'mbrdg interf. array (4C)
1958	0.04		1,000 and 30 m arms	Cambridge galactic array
1958	0.04		116 x 140 m broadside array of 32 x 32 dipoles	Havana, Illinois
1957*	0.06		Two 24 x 14 m trihedral corner reflectors	Boulder, Colorado
1956	0.02		1,100 m each arm	Mills Cross, Sydney
1954	0.02		460 m each arm	Mills Cross, Carnegie Inst.
1954	0.08		460 m each arm	Mills Cross, Sydney
1952	0.08		4 element interferometer, 100 x 12 m	2C Tel., Cambridge[77]
1951	3		185 m[78] linear array	Algonquin Obs.

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[74] For Solar work only.

[75] Increased to 104 m in 1970.

[76] For solar work only.

* Used mainly for solar work.

[77] Later called the 3C Telescope, operating at 0.18 GHz.

[78] Extended to include forty 3 m dishes in a 874 m linear array in 1967.

(C) Observatory Spacecraft

(Includes American, UK or ESA spacecraft programmes, or those with significant American, UK or ESA involvement. Excludes those spacecraft observing the Solar System and defence spacecraft. Also excludes Skylab, Spacelab and captive Shuttle experiments as these were mainly devoted to Solar System research, and were generally used to show what man could do in space.)

Spacecraft#	Year Launched	Stopped Using	Country /Countries	Mass of s/c in kg	Launcher	γ-ray	X-rayUV		Vis.	IR	Radio
Explorer 11	1961		USA	43	Juno II	✓*					
OAO-1	1966	Failed**	USA	1,769	Atlas-Agena	✓	✓	✓		✓	
OAO-2	1968	1973	USA	1,996	Atlas-Centaur		✓	✓			
Explorer 38, RAE-1	1968		USA	276	Thor-Delta						✓
SAS-1, Expl. 42, Uhuru	1970	1975	USA	82	Scout		✓				
OAO-B	1970	Failed	USA		Atlas-Centaur			✓			
OAO-3, Copernicus	1972	1980	USA/UK	2,220	Atlas-Centaur		✓	✓			
SAS-2, Explorer 48	1972	1973	USA	92	Scout	✓					
TD-1A	1972	1974	ESA	472	Thor-Delta	✓	✓	✓			
Explorer 49, RAE-2	1973		USA	330	Thor-Delta						✓
ANS	1974	1976	NL/USA	136	Scout		✓	✓			
Ariel V	1974	1980	UK/USA	134	Scout		✓				

Where more than one name is shown, these are alternative names.

* Indicates that there was an experiment or instrument on board to measure radiation at this wavelength. No attempt is made in this table to distinguish between the relative importance of the various waveband investigations of a particular spacecraft.

** Indicates failed during launch or very soon thereafter, either as a result of a launcher or spacecraft malfunction.

Spacecraft	Year Launched	Stopped Using	Country /Countries	Mass of s/c in kg	Launcher	γ-ray	X-ray	UV	Vis.	IR	Radio
SAS-3, Explorer 53	1975	1979	USA	197	Scout		✓				
Cos-B	1975	1982	ESA	275	Thor-Delta	✓					
HEAO-1	1977	1979	USA	2,722	Atlas-Centaur	✓	✓				
HEAO-2, Einstein	1978	1981	USA	2,948	Atlas-Centaur		✓				
IUE	1978	1996	USA/UK/ESA	669	Thor-Delta			✓			
HEAO-3	1979	1981	USA	2,721	Atlas-Centaur	✓	✓				
Ariel VI	1979		UK	154			✓				
IRAS	Jan. 1983	Nov. 1983	NL/USA/UK	1,073						✓	✓*
Exosat	1983	1986	ESA	510	Delta		✓				
Hipparcos	1989	1993	ESA	1,130	Ariane 4				✓**		
COBE	1989		USA	2,500	Delta					✓	✓*
Rosat	1990		USA/Ger./UK	2,430	Delta II		✓	✓			
Hubble Space Tel.	1990	Repaired 1993	USA/ESA	9,100	Shuttle			✓	✓	✓	
Compton γ-ray Obs.	1991		USA	15,900	Shuttle	✓					
Extreme UV Explorer	1992		USA		Delta II			✓			

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* Microwave.

** Astrometry.

SOURCES FOR ABOVE LISTS

The above lists of ground- and space-based observatories were produced using the following sources:-

(a) Ground-Based Observatories

(i) General

Gingerich, O., (Ed.), "Astrophysics and Twentieth–Century Astronomy to 1950", Part A, Cambridge University Press, 1984.

Kirby-Smith, H.T., "US Observatories: A Directory and Travel Guide", Van Nostrand Reinhold, 1976.

Marx, S., and Pfau, W., "Observatories of the World", Blandford Press, 1982.

Whitford, A.E., et al., "Ground-Based Astronomy; A Ten-Year Program", National Academy of Sciences - National Research Council, Washington DC., 1964

Zombeck, M.V., "Handbook of Space Astronomy & Astrophysics", Cambridge University Press, Second Edition, 1990.

"Astronomy", Vols. 15-20, (1987-1992)

"Astronomical Journal", Observatory Reports in Vols. 61 (1956), 62 (1957), 63 (1958) and 69 (1964).

"Astronomy and Astrophysics for the 1970's", Vol. 1 (1972) and Vol. 2 (1973), National Academy of Sciences, Washington DC.

"Astronomy and Astrophysics for the 1980's", Vol. 1 (1982) and Vol. 2 (1983), National Research Council, National Academy Press, Washington DC.

"Astronomy Now," No. 11, Vol. 2, 1988, and No. 11, Vol. 4, 1990.

"Bulletin of the American Astronomical Society"., Vols. 1 (1969), 2 (1970), 4 (1972), 6 (1974), 8 (1976), 10 (1978), 12 (1980), 14 (1982), 16 (1984), 18 (1986), 20 (1988), 22 (1990), 24 (1992), 26 (1994).

"Sky and Telescope", Vol. 5 (1945-1946), Vols. 21-30 (1961-1965), Vols. 33 & 34 (1967), Vols. 39- 84 (1970-1992), and July 1993 issue.

"The Decade of Discovery in Astronomy and Astrophysics", National Research Council, National Academy Press, Washington DC, 1991.

"The Sky", Vols. 1-5, 1936-1941 (i.e. complete set).

"The Telescope", Series 1, Vols. 1-8, 1931-1932, and Series 2, Vols. 1-8, 1933-1941 (i.e. complete set).

(ii) Optical/IR Only

Beck, R.L., and Schrader, D., "America's Planetarium's and Observatories (a sampling)", Sunset Space Systems Inc., 1992.

Blaauw, A., "ESO's Early History", European Southern Observatory, 1991.

Brück, H.A., "The Story of Astronomy in Edinburgh from its beginnings until 1975", Edinburgh, 1983.

Clerke, Agnes M., "A Popular History of Astronomy during the Nineteenth Century", Adams & Black, 1908.

Evans D.S., and Mulholland, J.D., "Big and Bright: A History of the Mc Donald Observatory", University of Texas Press, 1986.

Gascoigne, S.C.B., Proust, K.M., and Robins, M.O., "The Creation of the Anglo-Australian Observatory", Cambridge University Press, 1990.

Herrmann, D.B., trans. by Krisciunas, K., "The History of Astronomy from Herschel to Hertzsprung", Cambridge University Press, 1984.

Houk, R., "From the Hill: The Story of the Lowell Observatory", Lowell Observatory, 1991.

Howse, D., "The Royal Observatory at Greenwich and Herstmonceux 1675-1975; Vol. 3: The Buildings and Instruments", Taylor and Francis, 1975.

Instituto de Astrofisica de Canarias, "Observatorios Astrofisicos de Canarias", 1985.

King, H.C., "The History of the Telescope", Dover reprint, 1979.

Kloeppel, J.E., "Realm of the Long Eyes: A Brief History of Kitt Peak National Observatory", Univelt, 1983.

Meszaros, S.P., "World Atlas of Large Optical Telescopes", 2nd Ed., 1986, NASA Technical Memorandum 87775.

Moore, P., and Collins, P., "The Astronomy of Southern Africa", Hale, R., 1977.

Müller, P., "Sternwarten in Bildern: Architektur und Geschichte der Sternwarten von der Anfängen bis ca. 1950", Springer-Verlag, 1992.

Putnam, W.L., et al., "The Explorers of Mars Hill: A Centennial History of Lowell Observatory, 1894 to 1994", Lowell Observatory, 1994.

Rudaux, L. and De Vaucouleurs, G., "Larousse Encyclopedia of Astronomy", Batchworth Press, 1959.

Rudd, M.E., "Science on the Great Plains: The History of Physics and Astronomy at the University of Nebraska-Lincoln", University of Nebraska, 1992.

Tatarewicz, J.N., "Space Technology and Planetary Astronomy", Indiana University Press, 1990

(iii) Radio Only

Audouze, J, and Israël, G, (Eds.), "The Cambridge Atlas of Astronomy", 3rd edition, Cambridge University Press, 1994.

Calder, N., "Britain's New Radio Telescopes", The New Scientist, 3rd Oct. 1957, p 23.

De la Cotardière, P., (Ed.), "Larousse Astronomy", Hamlyn, 1987.

Graham Smith, F., "Radio Astronomy", Penguin Books, 1960.

Henbest, N., (Ed.), "Observing the Universe", Basil Blackwell and New Scientist, 1984.

Hey, J.S., "The Evolution of Radio Astronomy", Paul Elek, 1973.

Kraus, J.D., "Radio Astronomy", Second Edition, Cygnus-Quasar, 1986.

Kuiper, G.P., and Middlehurst, B.M., (Eds.), "Telescopes", University of Chicago Press, 1960.

Lovell, B., "The Jodrell Bank Telescopes", Oxford University Press, 1985

Lovell, B., "Astronomer by Chance", Oxford University Press, 1992.

Milne, D.K., and Goddard, D.E., (Eds.), "Parkes; Thirty Years of Radio Astronomy", CSIRO, Australia, 1994.

Robertson, P., "Beyond Southern Skies", Cambridge University Press, 1992.

Sullivan, W.T., III., "The Early Years of Radio Astronomy", Cambridge University Press, 1984.

Verschuur, G.L., "The Invisible Universe Revealed; The Story of Radio Astronomy", Springer-Verlag, 1987.

Wall, J.V., and Boksenberg, A., (Eds.), "Modern Technology and its Influence on Astronomy", Cambridge University Press, 1990.

"NASA Historical Data Book, Vol. 2: Programs & Projects 1958-1968, and Vol. 3: Programs and Projects 1969-1978", Linda Neuman Ezell, NASA, 1988

"Report of the Panel to Review the Future of Radio Astronomy in the UK", Science Research Council, Feb., 1977.

"Report of the Radio Review Panel", SERC, Aug. 1992

(b) Space-Based Observatories

Charles, P.A., and Seward, F., "Exploring the X-ray Universe", Cambridge University Press, 1995.

De la Cotardière, P., (ed), "Larousse Astronomy", Hamlyn, 1987.

King-Hele, D.G., et al., "The RAE Table of Earth Satellites, 1957-1989", RAE Farnborough, 1990

Leverington, D., "A History of Astronomy from 1890 to the Present", Springer-Verlag, 1995.

"Aeronautics and Space Report of the President", 1974 Activities, NASA Washington, 1975, and 1975 Activities, NASA Washington, 1976.

ESA Bulletin No.23, Aug. 1980; No.31, Aug. 1982; No. 43, Aug. 1985; No.44, Nov. 1985.

"NASA Historical Data Book, Vol. 2: Programs & Projects 1958-1968, and Vol. 3: Programs and Projects 1969-1978", Linda Neuman Ezell, NASA, 1988.

APPENDIX 2

Retail Price Indices for the USA and UK

(Base 15.1.74 = 100)

Year	USA	UK	Year	USA	UK	Year	USA	UK
1915		12.6	1959	60.6	48.5	1977	130.6	182.1
1920		25.5	1960	61.7	49.3	1978	140.6	197.0
1925		18.0	1961	62.8	50.8	1979	156.4	223.5
1930		16.2	1962	64.0	53.0	1980	177.6	263.8
1935		16.2	1963	65.1	54.1	1981	195.9	295.2
1940		22.5	1964	66.3	56.0	1982	207.8	320.6
1945		27.0	1965	67.5	58.6	1983	214.4	335.1
1948		31.3	1966	69.8	60.8	1984	223.7	351.9
1949	50.7	32.0	1967	71.9	62.3	1985	231.5	373.2
1950	51.6	32.8	1968	74.9	65.3	1986	235.9	385.9
1951	52.6	35.8	1969	79.1	68.7	1987	244.6	401.9
1952	53.5	39.6	1970	83.7	73.1	1988	254.7	421.7
1953	54.5	40.7	1971	87.2	79.9	1989	266.9	454.6
1954	55.5	41.4	1972	90.2	85.8	1990	281.3	497.5
1955	56.4	43.3	1973	95.7	93.7	1991	293.1	526.6
1956	57.5	45.2	1974	106.4	108.6	1992	302.0	546.4
1957	58.5	47.0	1975	116.0	134.7			
1958	59.5	48.5	1976	122.6	157.1			

Sources

For USA data:-

"Monitoring the World Economy, 1820-1992", OECD, for the years 1949 -1965

"British Industrial Performance, 1987 Edition", National Economic Development Council, for the years 1966 and 1967

"OECD Economic Outlook No. 43, June 1988", OECD, for the years 1968-1987

"OECD Economic Survey: USA 1995", OECD, for the years 1988-1992

For UK data:-

Briggs, A., "A Social History of England", Penguin Books, 1985, for the years 1915-1945

"Economic Trends, Annual Supplement, 1995 Edition", Central Statistical Office, for the years 1948-1992

APPENDIX 3

The Inclusion of Schmidt Telescopes in the Analysis

Papers written using data from Schmidt telescopes have been included in Part 1 of this thesis where I have listed these telescopes by the diameter of their corrector plate, rather than that of their primary mirror. The question addressed in this Appendix is whether there is a more relevant dimension to use and, if so, what effect this has on the data and conclusions made in the main text of this thesis.

The whole purpose of this project is to examine the cost-effectiveness of various observational facilities. It would seem appropriate, therefore, to consider the cost of Schmidt telescopes in trying to decide which diameter to use to characterise them.

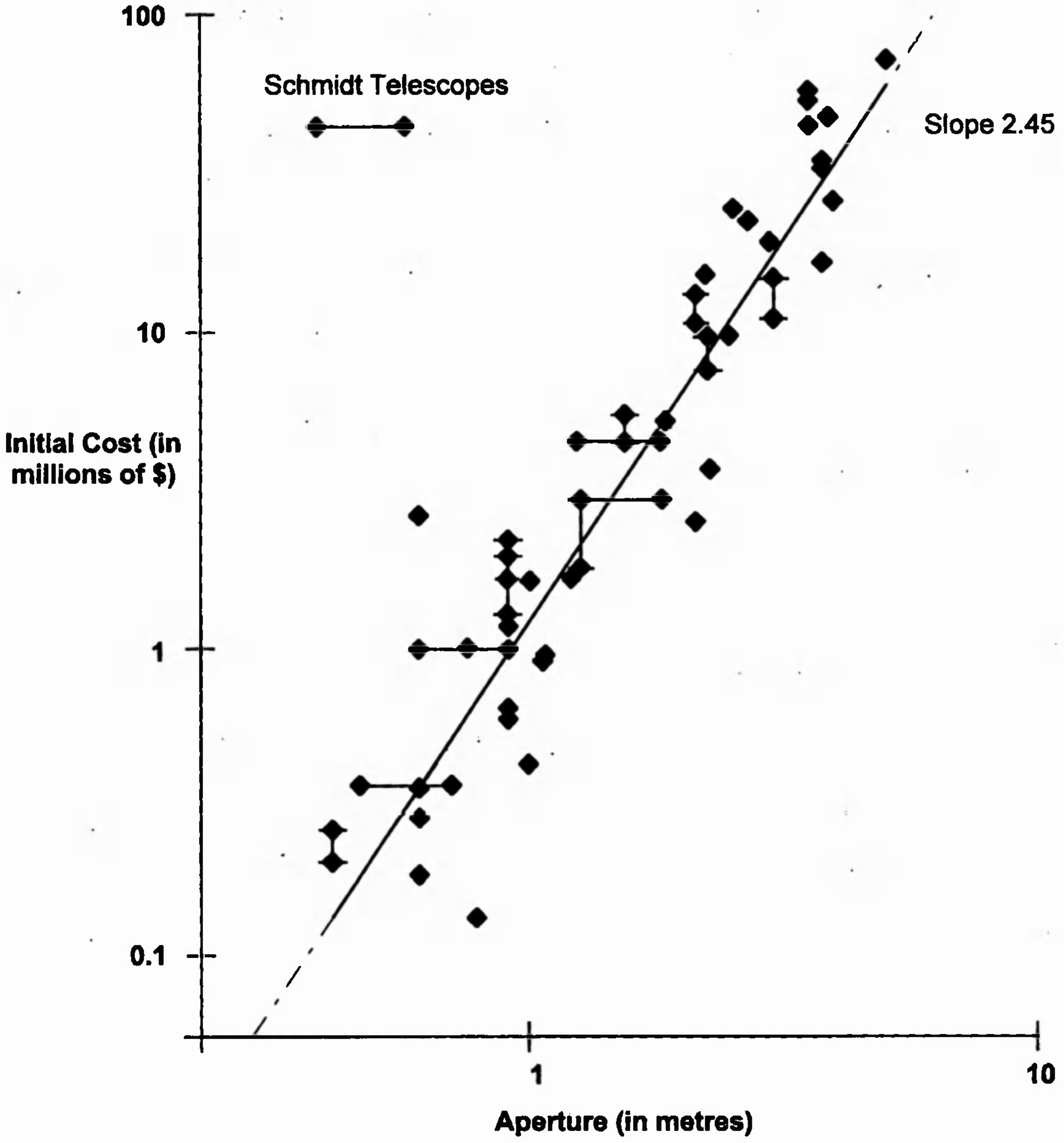
I have ascertained the initial costs of four Schmidt telescopes (see Table 28) which saw first light between 1948 and 1973. The costs of these, added to Figure 15 of the main thesis, are shown in Figure A3.1 (next page), where the regression line makes the following intercepts:-

TABLE A3.1

	(a) Corrector Dia. (m)	(b) Mirror Dia. (m)	(c) Intercept of Regr. Line	Ratio (c) - (a) / (b) - (a)
Palomar Schmidt	1.26	1.83	1.44	0.32
UK Schmidt	1.24	1.83	1.73	0.83
Curtis Schmidt	0.61	0.91	0.88	1.00
Palomar Schmidt	0.46	0.71	0.62	0.64
			Average	0.70

The data in Table A3.1 indicates that the cost of a Schmidt telescope can be determined approximately by calculating $d = a + 0.7(b - a) = 0.3a + 0.7b$, where a is the diameter of the corrector plate, b is the diameter of the main mirror, and using d in place of the diameter on the cost/diameter graph for standard reflectors. If I

FIGURE A3.1
Initial Costs (at 1992 rates) v Aperture
Telescopes in use upto and including 1980: Consolidated List



now list Schmidt telescopes by this diameter d, instead of by the corrector plate diameter that I had used previously, it has the following effect on the data produced in the main text of this thesis:-

Table 10, which shows the number of highly-cited papers, has the following changes:-

Telescopes	Year	Was	Is	Was	Is
cat. (b)	1994	12.11	13.11	23%	25%
cat. (c)	1974	3.71	3.96	15%	16%
	1978	3.40	3.75	11%	11%
	1986	3.05	3.85	12%	15%
	1994	5.33	4.33	10%	8%
cat. (d)	1974	0.55	0.30	2%	1%
	1986	0.80	0	3%	0%

All other numbers in Table 10 remain unchanged, so the net effect of changing the method of characterising Schmidt telescopes on Table 10 is insignificant.

The relative usefulness figures for 1994, for example, change as follows:-

	Was	Is
9.8 m Keck	8%	8 %
2.55 - 5.08 m	58%	58 %
1.23 - 2.54 m	23%	25 %
0.62 - 1.22 m	10%	8 %
≤ 0.61 m	1%	1 %

and similar insignificant changes occur elsewhere in the main text which have no effect on the conclusions reached.

Conclusion

In conclusion, the initial cost data indicates that the best diameter d to use to characterise Schmidt telescopes is given by $d = 0.3a + 0.7b$, where a is the diameter of the corrector plate and b is the diameter of the main mirror. Making this change to the data discussed in Parts 1 and 2 of this thesis has no effect on the conclusions reached.

APPENDIX 4

Annual NSF Funding of Ground-Based Observatories

The Greenstein Report[14] contains annual National Science Foundation (NSF) budget information for the US National Astronomical Observatories of Kitt Peak (KPNO), Cerro Tololo (CTIO), Green Bank (NRAO) and Arecibo (NAIC) from 1963 to 1971 inclusive. Unfortunately, the subsequent US national surveys chaired by Field[19], Bahcall[15] and McCray* contains much more sketchy financial information, often only in graphical form. I therefore contacted the NSF in an attempt to produce a much more consistent and complete set of annual costs for these US National Observatories covering the period from 1956 to 1992 inclusive, and Seth Tuttle sent me a detailed reply[25] in the form of internal NSF memos and budget documents. I have used this NSF information as the basis of my cost analysis, as explained below.

The basic cost data provided by Tuttle is shown in Table A4.1** at the end of this appendix#. The main problems with this data are that:-

(i) There is no KPNO or CTIO data after 1984.

(ii) There is no NRAO data before 1980, nor NAIC data before 1970.

(iii) The costs of the solar telescopes on Kitt Peak are included with the KPNO costs, but I wish to eliminate these solar telescope costs (see Part I, Section 2 of this Thesis).

Tuttle also provided two NSF budget sheets for the NOAO; one for 1987-89 and the other for 1992-94, which I can use to partially complete Table A4.1. This data is shown in Table A4.2, where the costs of running the NOAO HQ (called 'central

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* Mc Cray et al., "A Strategy for Ground-Based Optical and Infrared Astronomy", National Research Council, 1994.

** The list of telescopes shown on page 1 of this table was taken from Appendix 1.

For ease of comparison, all the tables of this appendix are grouped together at the end of the appendix.

costs') and the AURA Management Fee are shown separately from the costs of running the two observatories. Now the KPNO and CTIO costs shown in Table A4.1 include a distribution of these central overheads, so we need to know how the overheads should be distributed before we add the data to Table A4.1. Fortunately, in the McCray report there is data for 1994 both with the central overheads declared separately and with them redistributed amongst the KPNO and CTIO observatories, so I can use a similar overhead structure to produce the modified part of Table A4.1 shown in Table A4.3.

I now reviewed the Greenstein, Field, Bahcall, and McCray reports to try to add more data to that shown in Tables A4.1 and A4.3. This new data is included in Table A4.4*.

I wished to produce cost data that excluded solar, planetary and atmospheric facilities as far as possible, to match the subjects of papers published in the *ApJ* and *MNRAS*. Accordingly, I have deleted the following from Table A4.4 to get the data shown in Table A4.5:-

The High Altitude Solar Observatory
The Sacramento Peak Solar Observatory
The NSO Tucson (or Kitt Peak) Solar Observatory costs where they are separately shown
GONG
NASA funding of Arecibo (this was for planetary radar work)
NSF funding for atmospheric research at Arecibo

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* The only major difference between the data, where it exists, in these Greenstein, Field, Bahcall, and McCray reports, and that provided by Tuttle, is the clear KPNO cost peak in Tuttle's data in 1967, which was shown in Greenstein's report to occur in the following year. The position of this peak is not important in my analysis, however, as I am only interested in trends with time and totals over time, and am not really interested in individual yearly costs.

It is easy to simply delete the above budget lines from Table A4.4 but the resultant total NOAO costs would still include the following solar observatories:-

Upto & including 1984	Tucson (or Kitt Peak)
1985 & 86	Tucson & SPO
1987 - 89	None
1990 & 91	Tucson, SPO & GONG
1992 - 94	None

Fortunately, the SPO budget in 1984 and 1987 was about the same at $2.5m, so taking this figure from the NOAO total for 1985 and 1986 in Table A4.4 would eliminate the SPO for those years. Similarly, the NSF total for Tucson, SPO and GONG in 1988, 89, 92 and 93 averages out at $7.0m and, taking this figure off the NOAO total for 1990 and 1991 in Table A4.4 would eliminate all of these solar observatories for those years. These reductions have been made in Table A4.5, so the NOAO total in that table includes only the Tucson (or Kitt Peak) solar observatory upto and including 1986.

It is also necessary to eliminate major capital expenditure on facilities that were operational by 1992, namely WIYN, Gemini and the Arecibo upgrade shown in Table A4.4. This has been done in Table A4.5.

Table A4.5 is almost what we want, but there are still some problems:-

(i) The Kitt Peak data still includes the Kitt Peak (or Tucson) solar observatory upto and including 1986.

(ii) There are no KPNO and CTIO figures for 1985, 86, 90 & 91.

(iii) The early Green Bank costs are missing (the first large telescope became operational in 1959), and the early Arecibo costs (i.e. from 1963 to 1969) are not known as it was funded by the Department of Defense.

The costs of the early telescopes on Kitt Peak were about (see Table 25 and the accompanying text):-

First Used	Telescope	$m
1960	0.91 m	0.4
1962	McMath solar telescope	4.0*
1964	2.14 m	2.4
1965	1.27 m	0.4
1966	0.91 m	0.4
1973	3.81 m Mayall	10.7

There is an early peak in the funding of KPNO in 1958/59 (Table A4.5) when the major expenditure commitment was probably for the McMath solar telescope. Astronomical observations did not start on the mountain until 1960, however, when the first 0.91 m came into operation. So, if we ignore all of the KPNO costs prior to the first full year of operation of 1961**, we will have automatically excluded the vast majority of the capital costs of the McMath which came into use the following year. Having now effectively deleted the capital costs of the major solar telescope, we need to eliminate the annual running costs of the solar observatory upto and including 1986.

The NSF running costs of the Kitt Peak (Tucson) solar observatory were, compared with the total costs of running KPNO, (data from Table A4.4):-

	KPNO + Solar	Solar alone	Solar/(KPNO + Solar) as %
1987	12.50	1.75	14 %
1988	12.38	1.82	15 %
1989	12.72	1.77	14 %
1992	13.85	2.08	15 %
1993	13.72	2.26	16 %
1994	13.98	2.07	15 %
		Average	15 %

---

[*] Sky and Telescope, 1984, 67, 109.

[**] It is a good idea to ignore the running costs in the first partial year of operation of any observatory, as the start-up costs are often obscured by the costs of commissioning the observatory, which are partially covered by the capital costs.

During these periods of 1987–89 and 1992–94 there were no major capital costs included in the total KPNO or solar budgets, so we can assume that the average running costs of the solar observatory is about 15 % of the total KPNO running costs. I will use this percentage figure for earlier years to delete the running costs of the solar observatory from the running costs of KPNO.

The first full year of operation of the complete complement of major KPNO telescopes was 1974, so for earlier years it would be inappropriate to use this 15 % figure for the annual operating costs of the solar telescopes, as this percentage would be based on a rapidly varying base of non-solar telescopes. Over the period 1974–76, immediately after the installation of the Mayall, the costs of running the solar observatory would be about, using the 15 % figure:-

	$m in real yr. $	**i.e.**	**$m at 1975 rates**
1974	1.17		1.27
1975	1.15		1.15
1976	1.26		1.19
		Average	1.20

So I will use this figure of $1.20m at 1975 rates as the cost of running the solar observatory from 1962 (½ year) to 1973, inclusive. The new KPNO figures, excluding the solar observatory, are shown in Table A4.6.

We also need to deduce the approximate costs of the KPNO and CTIO in 1985, 86, 90 and 91, given their total costs shown in Table A4.5.

CTIO showed no great change in its costs since 1981 (see Table A4.5), averaging $6.2m over the years 1981–94 for which I have data. I have used this average figure for CTIO in 1985, 86, 90 and 91 in Table A4.6, with the consequential costs for KPNO deduced from the known NOAO total.

Table A4.6 now includes all the running costs and capital commitments for the US National Astronomical Observatories from their first full year of operation, except for the early years of Arecibo (from 1964) and of Green Bank (from 1960). We also need to deduct all the major capital commitments from Table A4.6 to get the 'pure' annual running costs.

The last major capital cost at KPNO was during 1963–67 when $10.7m was committed for the 3.8 m Mayall telescope. Over the period 1961–67 the total commitments on new telescopes at KPNO was about (in $m):-

2.14 m	~ 2.0*
1.27 m	0.4
0.91 m	0.4
3.81 m	10.7
Total	13.5

Over the same period (1961–67) the total KPNO costs were $34.29m, so the pure running costs over that period totalled $20.79m, or about $2.97m/yr.

In 1961 the running cost was $2.00m so, assuming a linear increase with time from 1961 to 1967, as more and more telescopes came on line, and an average for that period of $2.97m/yr., the pure running costs would be as shown in Table A4.7.

The last major capital cost at Cerro Tololo was in 1967–69 when $5.45m was committed for the 4.0 metre telescope. Over the same period the total running costs were $8.59m, so the pure running costs over this period totalled $3.14m. For half of this period only the 0.91 metre and the 0.61 metre Curtis Schmidt were operational, with the 1.52 metre become available during 1968. So the likely build up of pure running costs is about $0.5m in 1967, $1.0m in 1968, and $1.6m in 1969 (totalling $3.1m), as shown in Table A4.7.

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[*] Although this telescope cost about $2.4m, some of this money may have been committed prior to 1961.

By far the largest cost* of the various radio telescopes at Green Bank was the $13.5m for the 43 metre dish, which became operational in 1965. The capital cost of the major telescopes at Green Bank were (see Table 38)# :-

Telescope	First Operational	Cost ($m)
26 m dish	1959	0.375
43 m dish	1965	13.5
92 m dish	1962	0.9 + 0.65 (1971)
12 m dish	< 1964	?
3 x 26 m interferometer	1966	1.4

Clearly the vast majority of the Green Bank capital costs were committed prior to 1965, with the figures in Table A4.6 indicating that there was a significant part of the 1963 and 1964 budgets devoted to capital commitments (as the budget reduced significantly in 1965). The 26 metre dish had become operational in 1959 and the 92 metre dish in 1962, but no other major telescope had come on line prior to 1965. So the pure running costs were probably something like those shown in Table A4.7, increasing from $1.0m in 1960 to $3.3m in 1963 and 1964, matching the $3.38m in 1965## .

The costs of $0.65m for resurfacing the 92 metre dish, which had been completed in 1971, were committed before that date. Looking at the cost profiles in previous years, this cost appears to have been committed probably in 1968, so the running cost figure shown in Table A4.7 for 1968 has been reduced accordingly.

Major refurbishment of the Arecibo dish had been undertaken in the early 1970s, and an antenna added at Higuillales, near Arecibo, at a total cost to the NSF of $6.4m (see footnote to Table A4.1). Looking at the annual costs shown in Tables A4.6, it

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[*] Excluding the $75m appropriated in 1989 for the new Green Bank Telescope which is not included in any Tables A4, as it was not operational by 1992.

[#] The lines in the table below separate telescopes of different types - see Table 38.

[##] Inflation was very low in the first half of the 1960's in the USA, running at less than 2.0% per annum.

appears that the refurbishment costs were mostly committed in 1971 and 1972, with pure running costs increasing from about $1.55m (at 1970 rates) before refurbishment to about $3.20m (at 1974/75 rates) afterwards. (The $0.9m figure for 1969 looks like an anomaly, possibly because it is for only part of the transition year when responsibility was transferred from the Department of Defense to the NSF).

The Arecibo refurbishment cost of $6.4m, when taken from the 1971 and 1972 running costs, leaves an average of $2.2m pure running costs per year or, if 1973 is included, an average of $2.55m pure running costs per year. This latter figure looks like a fair transition from the $1.55m* for 1970 to the $3.20m figure for 1974 when the refurbishment was completed. This $2.55m figure at 1972 rates is that recorded in Table A4.7 for 1971, 72 & 73 after correction for inflation.

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* This figure, corrected for inflation, is included as the running cost from 1964 to 1970 in Table A4.7.

TABLE A4.1

Annual Funding of National Astronomical Research Centres in the USA by the National Science Foundation

Source:- Costs in FAX, S. Tuttle, NSF, to D. Leverington, 18.6.96*

(Numbers are commitments in real-year dollars, i.e. 1970 figures are in 1970 dollars, in millions)

	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966
(i) NOAO												
Kitt Peak (KPNO)**	0.05#	0.25#	0.55#	3.10	4.35	0.82	2.00	2.88	3.75##	4.40##	6.92##	5.79##
Cerro Tololo (CTIO)	—	—	—	—	—	—	—	0.05#	1.00	1.00	1.39	1.43
Subtotal	0.05	0.25	0.55	3.10	4.35	0.82	2.00	2.93	4.75	5.40	8.31	7.22

Note

US National Telescopes on Kitt Peak upto and including 1992+

1960	0.91 m	(closed down 1989)
1962	Mc Math Solar Telescope	
1964	2.14 m	
1965	1.27 m	
1966	0.91 m	
1973	3.81 m	Mayall Telescope
1979++	0.61 m	Burrell Schmidt***

US National Telescopes on Cerro Tololo upto and incl.uding 1992+

1966++	0.91 m	
1966++	0.61 m	Curtis Schmidt***
1968	1.52 m	
1973++	1.00 m	Yale***
1975	4.00 m	

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* Contains, inter alia:- C.M.Kellett & S.L.Tuttle, Internal NSF Memo, 15.3.84, on NOAO costs 1955-1984.
NSF Internal Memo (un-named), 9.3.88, on NAIC costs 1970-1988.

** Including solar telescopes on Kitt Peak.

Costs of Study.

Includes amounts for 3.8 metre Mayall telescope. Total cost $10.708m.

+ Down to 0.61 m diameter.

*** The costs of the Burrell and Curtis Schmidts, and of the 1.0m Yale reflector, are excluded from the above, as they were funded separately.

++ Not a new telescope. This is the date of its move to this site.

TABLE A4.1 (cont.)

		1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978
(i) NOAO													
Kitt Peak (KPNO)[*]		12.40[**]	5.98	5.70	6.47	7.22	7.70	7.85	7.80	7.68	8.40	8.70	9.13
Cerro Tololo (CTIO)		1.71[#]	2.33[#]	4.55[#]	1.90	2.28	2.50	2.70	2.60	2.95	3.45	3.50	3.89
Subtotal		14.11	8.31	10.25	8.37	9.50	10.20	10.55	10.40	10.63	11.85	12.20	13.02
Sacramento Peak Solar Obs. (SPO)	NSF Money											0.80	1.29
	USAF Money											0.95	0.33
Total (NOAO) NSF Money			8.31	10.25	8.37	9.50	10.20	10.55	10.40	10.63	11.85	13.00	14.31
(iii) NAIC (Arecibo)													
NSF Money					1.55[##]	6.10	4.69	3.25	3.20[+]	3.20	4.05	5.00	5.48[++]
NASA Money							0.35	2.00	1.00[***]	0.30	0.30	0.30	0.30
Total (NSF Money)		**14.11**	**8.31**	**10.25**	**9.92**	**15.60**	**14.89**	**13.80**	**13.60**	**13.83**	**15.90**	**18.00**	**19.79**

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[*] Including solar telescopes on Kitt Peak.

[**] Includes amounts for 3.8 metre Mayall telescope. Total cost $10.708m.

[#] Includes amounts for 4.0 metre telescope. Total cost $10.449m, of which $5.000m was supplied by the Ford foundation (not shown above).

[##] The 305 metre Arecibo radio telescope had been completed in 1963 using Department of Defense money. Total cost $8.3m.

[+] Resurfacing of 305 m dish completed. Total cost $5.8m; 30.5 metre antenna completed at Higuillales, near Arecibo, to make an interferometer with the 305 m. Total cost $0.6m.

[++] Log-periodic antenna system completed near Islote, Peru. Total cost $1.2m.

[***] Planetary radar installed on 305m dish. Total cost to NASA $3.0m.

TABLE A4.1 cont. (ii)

	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990
(i) NOAO												
Kitt Peak (KPNO)*	9.70	10.50	11.10	11.22	11.61	13.79						
Cerro Tololo (CTIO)	4.35	4.83	5.81	6.06	6.48	6.71						
Subtotal	14.05	15.33	16.91	17.28	18.09	20.50						
NSO SPO NSF Money	1.50	1.66	1.86	2.00	2.10	2.50						
USAF Money	0.33	0.33	0.35	0.37	0.39	0.42						
Total (NOAO) NSF Money	15.55	16.99	18.77	19.28	20.19	23.00	22.83	22.63	22.88	23.10	24.32	25.23
(ii) NRAO												
Green Bank & VLA Ops..		12.53	14.79	14.84	15.90	20.26	17.65	16.63	16.83	16.26	18.30	19.60
VLA Construction		4.50										
VLBA Construction							9.00	8.55	11.40	12.10	12.00	12.40
Total (NRAO)		17.03	14.79	14.84	15.90	20.26	26.65	25.18	28.23	28.36	30.30	32.00
(iii) NAIC (Arecibo)												
NSF Money (Astronomy)	4.63	4.99	5.41	5.32	5.11	6.11	6.05	5.70	5.88	5.82	6.15	6.22
NSF Money (Atmosphere)					1.00	1.12	1.12	1.15	1.05	1.05 (Est.)		
NASA Money	0.30	0.32	0.32	0.32	0.32	0.32	0.34	0.33	0.33	0.33 (Est.)		
Total (NSF Money)**	20.18	29.01	38.97	39.44	41.20	49.37	55.53	53.51	56.99	57.28	60.77	63.45

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* Including solar telescopes on Kitt Peak.

** NSF Astronomy money only (i.e. excluding Atmosphere).

TABLE A4.1 cont. (iii)

	1991	1992	1993	1994	1995
(i) NOAO					
Kitt Peak (KPNO)					
Cerro Tololo (CTIO)					
Subtotal					
NSO SPO NSF Money					
USAF Money					
Total (NOAO) NSF Money	25.91	27.95	27.54	27.74	26.69
Gemini Construction	4.00	12.00	14.00	17.03	41.00
(ii) NRAO					
NRAO Ops.	21.20	26.60	29.81	27.80	29.00
VLBA Construction	11.00	8.70			
Total (NRAO)	32.20	35.30	29.81	27.80	29.00
(iii) NAIC (Arecibo)					
NSF Money (Astronomy)	6.39	6.55	6.93	7.47	
Ditto, Upgrade Costs	2.20	3.90	2.52	1.60	
Total (NSF Money)	**70.70**	**85.70**	**80.80**	**81.64**	**96.69***

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* Excluding NAIC.

TABLE A4.2

NSF Funding of the National Optical Astronomical Observatories (NOAO) 1987 - 1994

Source:- Costs in FAX, S. Tuttle, NSF, to D. Leverington, 18.6.96
(Costs in real-year dollars, in millions)

	1987	1988	1989	1992	1993	1994
KPNO	7.30	7.50	7.78	8.78	8.95	8.59
CTIO	4.94	4.69	4.92	6.79	6.31	6.42
NSO						
Sunspot Total Cost	2.47	2.43	2.43	2.99	2.85	2.44
- USAF Money	0.60	0.60	0.60	0.60	0.60	0.53
∴ Net cost to NSF	1.87	1.83	1.83	2.39	2.25	1.91
Tucson Total Cost	1.33	1.43	1.40	1.67	1.88	1.62
- NASA Money	0.05	0.05	0.06	0.03	0.03	0.03
∴ Net cost to NSF	1.28	1.38	1.34	1.64	1.85	1.59
GONG	0.98	1.01	1.53	2.38	2.56	2.58
Misc.						
Adv. Development Progr.	0.27	0.16				
Future Telescope Technology	1.89	1.75	1.92			
3.5 m WIYN				1.60	0.61	0.33
US Gemini Proj. Office					0.30	1.00
RISE						0.46
Central Costs	5.05	4.40	4.69	5.81	4.98	5.55
- Misc. Credits				1.08	1.11	0.32
∴ Net cost to NSF				4.73	3.87	5.23
AURA Management Fee	0.43	0.43	0.41	0.48	0.48	0.47
Total NSF Costs	**24.01**	**23.15**	**24.42**	**28.79**	**27.18**	**28.58**
c/f Table A4.1	**22.88**	**23.10**	**24.32**	**27.95**	**27.54**	**27.74**

TABLE A4.3

Annual Funding of National Astronomical Research Centres in the USA by the NSF

This is part of Table A4.1 modified in 1987 onwards by the results of Table A4.2

(Numbers are commitments in real-year dollars, i.e. 1970 figures are in 1970 dollars, in millions)

	1987	1988	1989	1990	1991	1992	1993	1994	1995
(i) NOAO									
Kitt Peak (KPNO)*	10.75	10.56	10.95			11.77	11.46	11.91	
Cerro Tololo (CTIO)	5.45	5.11	5.36			7.29	6.69	6.96	
Subtotal	16.20	15.67	16.31			19.06	18.15	18.87	
NSO *SPO* NSF Money	2.56	2.42	2.41			3.03	2.74	2.49	
USAF Money	0.60	0.60	0.60			0.60	0.60	0.53	
Tucson NSF Money	1.75	1.82	1.77			2.08	2.26	2.07	
NASA Money	0.05	0.05	0.06			0.03	0.03	0.03	
GONG	1.34	1.33	2.01			3.02	3.12	3.36	
WIYN						1.60	0.61	0.33	
Gemini, US Proj. Office							0.30	1.00	
RISE								0.46	
Adv. Dev. Progr.	0.27	0.16							
Future Telescope Tech.	1.89	1.75	1.92						
Total (NOAO) NSF Money	24.01	23.15	24.42	25.23	25.91	28.79	27.18	28.58	26.69
Gemini Construction					4.00	12.00	14.00	17.03	41.00
(ii) NRAO									
Green Bank & VLA	16.83	16.26	18.30	19.60	21.20	26.60	29.81	27.80	29.00
VLBA Construction	11.40	12.10	12.00	12.40	11.00	8.70			
Total (NRAO)	28.23	28.36	30.30	32.00	32.20	35.30	29.81	27.80	29.00
(iii) NAIC (Arecibo)									
NSF Money (Astronomy)	5.88	5.82	6.15	6.22	6.39	6.55	6.93	7.47	
Ditto, Upgrade Costs					2.20	3.90	2.52	1.60	
NSF Money (Atmosphere)	1.05	1.05 (Est.)							
NASA Money	0.33	0.33 (Est.)							
Total (NSF Money)**	**58.12**	**57.33**	**60.87**	**63.45**	**70.70**	**86.54**	**80.44**	**82.48**	**96.69#**

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* Excluding solar telescopes.

** NSF Astronomy money only (i.e. excluding Atmosphere).

\# Excluding NAIC.

TABLE A4.4

Annual Funding of National Astronomical Research Centres in the USA by the National Science Foundation

Tables A4.1 and A4.3 as modified by data from the Sources listed in the Note at the end of this Table
(Numbers are commitments in real-year dollars, i.e. 1970 figures are in 1970 dollars, in millions)

	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966
(i) NOAO												
Kitt Peak (KPNO)*	0.05**	0.25**	0.55**	3.10	4.35	0.82	2.00	2.88	3.75#	4.40#	6.92#	5.79#
Cerro Tololo (CTIO)								0.05**	1.00	1.00	1.39	1.43
Subtotal	0.05	0.25	0.55	3.10	4.35	0.82	2.00	2.93	4.75	5.40	8.31	7.22
14.11												
High Altitude Solar Obs.											0.61	1.23
(ii) NRAO (Green Bank)									4.55	4.60	3.38	4.72
(iii) NAIC (Arecibo)##												
Total (NSF Money)	**0.05**	**0.25**	**0.55**	**3.10**	**4.35**	**0.82**	**2.00**	**2.93**	**9.30**	**10.00**	**12.30**	**13.17**

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* Including solar telescopes on Kitt Peak.

** Costs of Study.

\# Includes amounts for 3.8 metre Mayall telescope. Total cost $10.708m.

\#\# Paid for by Department of Defense from 1963 to 1969.

TABLE A4.4 (cont.)

	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978
(i) NOAO												
Kitt Peak (KPNO)*	12.40**	5.98	5.70	6.47	7.22	7.70	7.85	7.80	7.68	8.40	8.70	9.13
Cerro Tololo (CTIO)	1.71***	2.33***	4.55***	1.90	2.28	2.50	2.70	2.60	2.95	3.45	3.50	3.89
Subtotal	14.11	8.31	10.25	8.37	9.50	10.20	10.55	10.40	10.63	11.85	12.20	13.02
High Altitude Solar Obs.	1.05	1.24	1.34	1.43	1.55							
Sacramento Peak Solar Obs. (SPO) NSF Money											0.80	1.29
USAF Money											0.95	0.33
Total (NOAO) NSF Money	15.16	9.55	11.59	9.80	11.05	10.20	10.55	10.40	10.63	11.85	13.00	14.31
(ii) NRAO												
Green Bank & VLA Ops.	4.98	7.86	7.28	5.86	6.90	6.8	6.9	7.2	8.1	8.4	9.4	9.6
VLA Construction							3.0	5.1	13.1	14.0	12.5	13.1
Total (NRAO)							9.9	12.3	21.2	22.4	21.9	22.7
(iii) NAIC (Arecibo)												
NSF Money			0.9	1.55#	6.10	4.69	3.25	3.20##	3.20	4.05	5.00	5.48+
NASA Money						0.35	2.00	1.00++	0.30	0.30	0.30	0.30
Total (NSF Money)	20.14	17.41	19.77	17.21	24.05	21.69	23.70	25.90	35.03	38.30	39.90	42.49

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* Including solar telescopes on Kitt Peak.

** Includes amounts for 3.8 metre Mayall telescope. Total cost $10.708m.

*** Includes amounts for 4.0 metre telescope. Total cost $10.449m, of which $5.000m was supplied by the Ford Foundation (not shown above).

The 305 metre Arecibo radio telescope had been completed in 1963 using Department of Defense money. Total cost $8.3m.

Resurfacing of 305 m dish completed. Total cost $5.8m; 30.5 metre antenna completed at Higuillales, near Arecibo, to make an interferometer with the 305 m. Total cost $0.6m.

+ Log-periodic antenna system completed near Islote, Peru. Total cost $1.2m.

++ Planetary radar installed on 305m dish. Total cost to NASA $3.0m.

TABLE A4.4 cont. (ii)

	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990
(i) NOAO												
Kitt Peak (KPNO)*	9.70	10.50	11.10	11.22	11.61	13.79			10.75	10.56	10.95	
Cerro Tololo (CTIO)	4.35	4.83	5.81	6.06	6.48	6.71			5.45	5.11	5.36	
Subtotal	14.05	15.33	16.91	17.28	18.09	20.50			16.20	15.67	16.31	
NSO *SPO* NSF Money	1.50	1.66	1.86	2.00	2.10	2.50			2.56	2.42	2.41	
USAF Money	0.33	0.33	0.35	0.37	0.39	0.42			0.60	0.60	0.60	
Tucson NSF Money									1.75	1.82	1.77	
NASA Money									0.05	0.05	0.06	
GONG									1.34	1.33	2.01	
Adv. Dev. Progr.									0.27	0.16		
Future Telescope Tech.									1.89	1.75	1.92	
Total (NOAO) NSF Money	15.55	16.99	18.77	19.28	20.19	23.00	22.83	22.63	24.01	23.15	24.42	25.23
(ii) NRAO**												
NRAO Ops.	11 ?	12.53	14.79	14.84	15.90	20.26	17.65	16.63	16.83	16.26	18.30	19.60
VLA Construction	13.3#	4.50										
VLBA Construction						2.5	9.00	8.55	11.40	12.10	12.00	12.40
Total (NRAO)	24.3	17.03	14.79	14.84	15.90	22.76	26.65	25.18	28.23	28.36	30.30	32.00

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* The Figures upto and including 1984 include solar telescopes on Kitt Peak. Starting in 1987 these latter are shown separately under 'NSO Tucson'.

** Excluding the $75m appropriated in 1989 for the new Green Bank Telescope.

\# No figure was quoted for this year in any of my sources. I calculated it assuming that the total VLA cost was $78.6m (see Table 38).

TABLE A4.4 cont. (iii)

<u>(iii) NAIC</u> (Arecibo)	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990
NSF Money (Astronomy)	4.63	4.99	5.41	5.32	5.11	6.11	6.05	5.70	5.88	5.82	6.15	6.22
NSF Money (Atmosphere)					1.00	1.12	1.12	1.15	1.05	1.05 (Est.)		
NASA Money	0.30	0.32	0.32	0.32	0.32	0.32	0.34	0.33	0.33	0.33 (Est.)		
Total (NSF Money)*	**44.78**	**39.01**	**38.97**	**39.44**	**41.20**	**51.87**	**55.53**	**53.51**	**58.12**	**57.33**	**60.87**	**63.45**

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* NSF Astronomy money only (i.e. excluding Atmosphere).

TABLE A4.4 cont. (iv)

(i) NOAO	1991	1992	1993	1994	1995
Kitt Peak (KPNO)*		11.77	11.46	11.91	
Cerro Tololo (CTIO)		7.29	6.69	6.96	
Subtotal		19.06	18.15	18.87	
NSO *SPO* NSF Money		3.03	2.74	2.49	
USAF Money		0.60	0.60	0.53	
Tucson NSF Money		2.08	2.26	2.07	
NASA Money		0.03	0.03	0.03	
GONG		3.02	3.12	3.36	
WIYN		1.60	0.61	0.33	
Gemini, US Proj. Office			0.30	1.00	
RISE				0.46	
Total (NOAO) NSF Money	25.91	28.79	27.18	28.58	26.69
Gemini Construction	4.00	12.00	14.00	17.03	41.00
(ii) NRAO					
NRAO Ops.	21.20	26.60	29.81	27.80	29.00
VLBA Construction	11.00	8.70			
Total (NRAO)	32.20	35.30	29.81	27.80	29.00
(iii) NAIC (Arecibo)					
NSF Money (Astronomy)	6.39	6.55	6.93	7.47	
Ditto, Upgrade Costs	2.20	3.90	2.52	1.60	
Total (NSF Money)	**70.70**	**86.54**	**80.44**	**82.48**	**96.69****

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* Excluding solar telescopes on Kitt Peak.

** Excluding NAIC.

Note Sources for extra data in this Table:-

Greenstein et al., "Astronomy and Astrophysics for the 1970's", Vol. 1 (1972) and Vol. 2 (1973), National Academyof Sciences, Washington DC.

Field et al., "Astronomy and Astrophysics for the 1980's", Vol. 1 (1982) and Vol. 2 (1983), National Research Council, National Academy Press, Washington DC.

Bahcall et al., "The Decade of Discovery in Astronomy and Astrophysics", National Research Council, National Academy Press, Washington DC, 1991.

Mc Cray et al., "A Strategy for Ground-Based Optical and Infrared Astronomy", National Research Council, 1994

TABLE A4.5

Annual Funding of National Astronomical Research Centres in the USA by the National Science Foundation, 1956 – 1992 inclusive

Table A4.4 after eliminating solar*, atmospheric and planetary funding and capital items not completed or in operation by 1992
(Numbers are commitments in real-year dollars, i.e. 1970 figures are in 1970 dollars, in millions)

	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966
(i) NOAO											
Kitt Peak (KPNO)**	0.25#	0.55	3.10	4.35	0.82	2.00	2.88	3.75##	4.40##	6.92##	5.79##
Cerro Tololo (CTIO)							0.05#	1.00	1.00	1.39	1.43
Total (NOAO)	0.25	0.55	3.10	4.35	0.82	2.00	2.93	4.75	5.40	8.31	7.22
(ii) NRAO (Green Bank)								4.55	4.60	3.38	4.72
(iii) NAIC (Arecibo)+											
Total	**0.25**	**0.55**	**3.10**	**4.35**	**0.82**	**2.00**	**2.93**	**9.30**	**10.00**	**11.69**	**11.94**

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* Except for the solar telescopes on Kitt Peak prior to 1985.
** Including solar telescopes on Kitt Peak.
# Costs of Study.
Includes amounts for 3.8 metre Mayall telescope. Total cost $10.708m.
+ Paid for by Department of Defense from 1963 to 1969.

TABLE A4.5 (cont.)

	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978
(i) NOAO												
Kitt Peak (KPNO)*	12.40**	5.98	5.70	6.47	7.22	7.70	7.85	7.80	7.68	8.40	8.70	9.13
Cerro Tololo (CTIO)	1.71#	2.33#	4.55#	1.90	2.28	2.50	2.70	2.60	2.95	3.45	3.50	3.89
Total (NOAO)	14.11	8.31	10.25	8.37	9.50	10.20	10.55	10.40	10.63	11.85	12.20	13.02
(ii) NRAO												
Green Bank & VLA Ops.	4.98	7.86	7.28	5.86	6.90	6.8	6.9	7.2	8.1	8.4	9.4	9.6
VLA Construction							3.0	5.1	13.1	14.0	12.5	13.1
Total (NRAO)							9.9	12.3	21.2	22.4	21.9	22.7
(iii) NAIC												
Arecibo			0.9	1.55##	6.10	4.69	3.25	3.20+	3.20	4.05	5.00	5.48++
Total	**19.09**	**16.17**	**18.43**	**15.78**	**22.50**	**21.69**	**23.70**	**25.90**	**35.03**	**38.30**	**39.10**	**41.20**

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* Including solar telescopes on Kitt Peak.

** Includes amounts for 3.8 metre Mayall telescope. Total cost $10.708m.

Includes amounts for 4.0 metre telescope. Total cost $10.449m, of which $5.000m was supplied by the Ford Foundation (not shown above).

The 305 metre Arecibo radio telescope had been completed in 1963 using Department of Defense money. Total cost $8.3m.

+ Resurfacing of 305 m dish completed. Total cost $5.8m; 30.5 metre antenna completed at Higuillales, near Arecibo, to make an interferometer with the 305 m. Total cost $0.6m.

++ Log-periodic antenna system completed near Islote, Peru. Total cost $1.2m.

TABLE A4.5 cont. (ii)

	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989
(i) NOAO											
Kitt Peak (KPNO)*	9.70	10.50	11.10	11.22	11.61	13.79			10.75	10.56	10.95
Cerro Tololo (CTIO)	4.35	4.83	5.81	6.06	6.48	6.71			5.45	5.11	5.36
Subtotal	14.05	15.33	16.91	17.28	18.09	20.50			16.20	15.67	16.31
Adv. Dev. Progr.									0.27	0.16	
Future Telescope Tech.									1.89	1.75	1.92
Total (NOAO)**	14.05	15.33	16.91	17.28	18.09	20.50	20.33	20.13	18.36	17.58	18.23
(ii) NRAO#											
NRAO Ops.	11 ?	12.53	14.79	14.84	15.90	20.26	17.65	16.63	16.83	16.26	18.30
VLA Construction	13.3	4.50									
VLBA Construction						2.5	9.00	8.55	11.40	12.10	12.00
Total (NRAO)	24.3	17.03	14.79	14.84	15.90	22.76	26.65	25.18	28.23	28.36	30.30
(iii) NAIC (Arecibo)											
Operations	4.63	4.99	5.41	5.32	5.11	6.11	6.05	5.70	5.88	5.82	6.15
Total	**42.98**	**37.35**	**37.11**	**37.44**	**39.10**	**49.37**	**53.03**	**51.01**	**52.47**	**51.76**	**54.68**

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* The figures upto and including 1984 include solar telescopes on Kitt Peak. They are excluded starting with the 1987 figures.

** The Tucson solar observatory is included upto and including 1986, but is excluded thereafter

\# Excluding the $75m appropriated in 1989 for the new Green Bank Telescope.

TABLE A4.5 cont. (iii)

	1990	1991	1992
(i) NOAO			
Kitt Peak (KPNO)*			11.77
Cerro Tololo (CTIO)			7.29
Subtotal			19.06
Total (NOAO)**	18.23	18.91	19.06
(ii) NRAO			
NRAO Ops.	19.60	21.20	26.60
VLBA Construction	12.40	11.00	8.70
Total (NRAO)	32.00	32.20	35.30
(iii) NAIC (Arecibo)			
Operations	6.22	6.39	6.55
Total	**56.45**	**57.50**	**60.91**

Note The above table excludes a number of items previously shown in Table A4.5 for 1991 and 1992, as these items (WIYN, Gemini & the Arecibo upgrade) had not been completed by 1992.

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[*] Excluding the solar telescopes on Kitt Peak.

[**] Excluding the Tucson solar observatory.

TABLE A4.6

Annual Funding of National Astronomical Research Centres in the USA by the National Science Foundation

Table A4.5 after eliminating expenditure prior to the first full year of operation of any observatory and after eliminating expenditure on all solar telescopes

(Numbers are commitments in real-year dollars, i.e. 1970 figures are in 1970 dollars, in millions)

	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970
(i) NOAO											
Kitt Peak (KPNO)		2.00	2.55	3.08[*]	3.71[*]	6.22[*]	5.07[*]	11.66[*]	5.21	4.88	5.60
Cerro Tololo (CTIO)								1.71[**]	2.33[**]	4.55[**]	1.90
Total (NOAO)		2.00	2.55	3.08	3.71	6.22	5.07	13.37	7.54	9.43	7.50
(ii) NRAO (Green Bank)	?	?	?	4.55	4.60	3.38	4.72	4.98	7.86	7.28	5.86
(iii) NAIC (Arecibo)[#]					?	?	?	?	?	0.9	1.55
Total		**2.00**	**2.55**	**7.63**	**8.31**	**9.60**	**9.79**	**18.35**	**15.40**	**16.61**	**14.91**

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[*] Includes amounts for 3.8 metre Mayall telescope. Total cost $10.708m.

[**] Includes amounts for 4.0 metre telescope. Total cost $10.449m, of which $5.000m was supplied by the Ford Foundation (not shown above).

[#] Paid for by Department of Defense from 1963 to 1969.

TABLE A4.6 (cont.)

	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982
(i) NOAO												
Kitt Peak (KPNO)	6.32	6.77	6.86	6.63	6.53	7.14	7.40	7.76	8.25	8.93	9.44	9.54
Cerro Tololo (CTIO)	2.28	2.50	2.70	2.60	2.95	3.45	3.50	3.89	4.35	4.83	5.81	6.06
Total (NOAO)	8.60	9.27	9.56	9.23	9.48	10.59	10.90	11.65	12.60	13.76	15.25	15.60
(ii) NRAO												
Green Bank & VLA Ops.	6.90	6.8	6.9	7.2	8.1	8.4	9.4	9.6	11 ?	12.53	14.79	14.84
VLA Construction			3.0	5.1	13.1	14.0	12.5	13.1	13.3	4.50		
Total (NRAO)	6.90	6.8	9.9	12.3	21.2	22.4	21.9	22.7	24.3	17.03	14.79	14.84
(iii) NAIC												
Arecibo	6.10	4.69	3.25	3.20*	3.20	4.05	5.00	5.48**	4.63	4.99	5.41	5.32
Total	**21.60**	**20.76**	**22.71**	**24.73**	**33.88**	**37.04**	**37.80**	**39.83**	**41.53**	**35.78**	**35.45**	**35.76**

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* Resurfacing of 305 m dish completed. Total cost \$5.8m; 30.5 metre antenna completed at Higuillales, near Arecibo, to make an interferometer with the 305 m. Total cost \$0.6m.

** Log-periodic antenna system completed near Islote, Peru. Total cost \$1.2m.

TABLE A4.6 cont. (ii)

	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992
(i) NOAO										
Kitt Peak (KPNO)	9.87	11.72	12.0	11.8	10.75	10.56	10.95	12.03	12.71	11.77
Cerro Tololo (CTIO)	6.48	6.71	6.2	6.2	5.45	5.11	5.36	6.2	6.2	7.29
Subtotal	16.35	18.43	18.2	18.0	16.20	15.67	16.31	18.23	18.91	19.06
Adv. Dev. Progr.					0.27	0.16				
Future Telescope Tech.					1.89	1.75	1.92			
Total (NOAO)	16.35	18.43	18.2	18.0	18.36	17.58	18.23	18.23	18.91	19.06
(ii) NRAO*										
NRAO Ops.	15.90	20.26	17.65	16.63	16.83	16.26	18.30	19.60	21.20	26.60
VLBA Construction	—	2.5	9.00	8.55	11.40	12.10	12.00	12.40	11.00	8.70
Total (NRAO)	15.90	22.76	26.65	25.18	28.23	28.36	30.30	32.00	32.20	35.30
(iii) NAIC (Arecibo)										
Operations	5.11	6.11	6.05	5.70	5.88	5.82	6.15	6.22	6.39	6.55
Total	**37.36**	**47.30**	**50.90**	**48.88**	**52.47**	**51.76**	**54.68**	**56.45**	**57.50**	**60.91**

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* Excluding the $75m appropriated in 1989 for the new Green Bank Telescope.

TABLE A4.7

Operating Costs of the National Astronomical Research Centres in the USA

Table A4.6 after eliminating expenditure on major capital items

(Numbers are commitments in real-year dollars, i.e. 1970 figures are in 1970 dollars, in millions)

	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970
(i) NOAO											
Kitt Peak (KPNO)		2.00	2.32	2.65	2.97	3.29	3.61	3.95	5.21	4.88	5.60
Cerro Tololo (CTIO)								0.5	1.0	1.6	1.90
Total (NOAO)		2.00	2.32	2.65	2.97	3.29	3.61	4.45	6.21	6.48	7.50
(ii) NRAO (Green Bank)	~1.0	~1.0	~2.0	3.3	3.3	3.38	4.72	4.98	7.21	7.28	5.86
(iii) NAIC (Arecibo)					~1.2	~1.3	~1.3	~1.3	~1.4	~1.5	1.55
Total	**1.0**	**3.0**	**4.32**	**5.95**	**7.47**	**7.97**	**9.63**	**10.73**	**14.82**	**15.26**	**14.91**

	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981
(i) NOAO											
Kitt Peak (KPNO)	6.32	6.77	6.86	6.63	6.53	7.14	7.40	7.76	8.25	8.93	9.44
Cerro Tololo (CTIO)	2.28	2.50	2.70	2.60	2.95	3.45	3.50	3.89	4.35	4.83	5.81
Total (NOAO)	8.60	9.27	9.56	9.23	9.48	10.59	10.90	11.65	12.60	13.76	15.25
(ii) NRAO (Green Bank & VLA)	6.90	6.8	6.9	7.2	8.1	8.4	9.4	9.6	11 ?	12.53	14.79
(iii) NAIC (Arecibo)	2.47	2.55	2.70	3.20	3.20	4.05	5.00	4.28	4.63	4.99	5.41
Total	**17.97**	**18.62**	**19.16**	**19.63**	**20.78**	**23.04**	**25.30**	**25.53**	**28.23**	**31.28**	**35.45**

TABLE A4.7 cont.

	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992
(i) NOAO											
Kitt Peak (KPNO)	9.54	9.87	11.72	12.0	11.8	10.75	10.56	10.95	12.03	12.71	11.77
Cerro Tololo (CTIO)	6.06	6.48	6.71	6.2	6.2	5.45	5.11	5.36	6.2	6.2	7.29
Total (NOAO)	15.60	16.35	18.43	18.2	18.0	16.20	15.67	16.31	18.23	18.91	19.06
(ii) NRAO	14.84	15.90	20.26	17.65	16.63	16.83	16.26	18.30	19.60	21.20	26.60
(iii) NAIC (Arecibo)	5.32	5.11	6.11	6.05	5.70	5.88	5.82	6.15	6.22	6.39	6.55
Total	35.76	37.36	44.80	41.90	40.33	38.91	37.75	40.76	44.05	46.50	52.21

APPENDIX 5

Exchange Rates

(Annual averages unless otherwise stated)

Year	**US$/£**	**Aus[*]$/£**	**Year**	**US$/£**	**Aus$/£**
1949-Nov.67	2.80		1983	1.52	1.69
Upto 1966		£A1.25/£UK	1984	1.33	1.52
1966		2.50[**]	1985	1.28	1.83
Nov.67-72	2.40		1986	1.47	2.21
1972[#]	2.50		1987	1.64	2.35
1973	2.45	1.72	1988	1.78	
1974	2.34	1.61	1989	1.64	
1975	2.21	1.68	1990	1.79	2.38
1976	1.80	1.48	1991	1.77	2.33
1977	1.74	1.57	1992	1.77	2.33
1978	1.92	1.67	1993	1.50	2.22
1979	2.12	1.89	1994	1.50	2.13
1980	2.31	2.03	1995		
1981	2.01	1.75	1996	1.53	1.93
1982	1.75	1.73			

Sources

- "OECD Economic Outlook No. 43, June 1988", OECD, Table R21, for the years 1973-1987.
- "Economic Trends, Annual Supplement, 1995 Edition", Central Statistical Office, for the years 1988-1994.
- E-mail, B. Boyle, Director AAO, to DL, 14.2.97.
- "The Times" of 1.7.96 for 1996 data (mid-year).

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[*] Australian

[**] Australian dollars introduced at the rate of $2.50A/£UK

[#] £ floated in 1972. Prior to then the sterling/US exchange rate was fixed at the rates given above.

APPENDIX 6

Annual Costs of UK Optical/Microwave Facilities

The following analysis is based on the Annual Reports of the various facilities, data contained in the "Report of the OIM Strategic Review Panel" of the PPARC, January 1995 (hereafter called the OIM Report), a private communication from Andrew le Masurier of PPARC, and data in files at PPARC to which I was allowed access. Data from these sources was not always consistent, and I sent a detailed set of questions to PPARC for clarification. Unfortunately, this was not forthcoming and so the following is my interpretation of the data. As a result, figures for individual years below may be open to question, but I believe the picture described to be broadly correct.

A6.1 UKIRT

The annual costs of operating the UKIRT on Mauna Kea, which saw first light in 1979, are given in Table A6.1 (where a blank indicates no data available)

TABLE A6.1
UKIRT Annual Costs
(figures in real-year £s in millions)

	Operations	Staff Cost	Instrumentation
1980/81*	0.60		
1981/82	0.90		
1982/83	1.00		
1983/84	1.59		
1984/85	1.54		
1985/86	2.04		
1986/87	1.75		
1987/88	1.46		
1988/89	1.68		
1989/90	1.36		
1990/91	1.35**		
1991/92			
1992/93	1.50		
1993/94	1.58		
1994/95	1.7	0.8	1.5

---

* UK Financial Year.

** Figure forecast in previous year.

The operations costs from 1980/81 to 1990/91, which were taken from the PPARC files, included a small amount for instrumentation, as did the operations costs for 1992/93 and 1993/94 taken from the UKIRT Annual Report for 1992 & 1993. The operations costs for 1994/95, taken from the OIM Report, included costs for major maintenance, enhancements and upgrades. Unfortunately, only the OIM report gave figures for staff and major instrumentation costs. The staff cost shown in Table A6.1 is for staff in both Hawaii and the UK, and is the average staff cost for recent years at 1994/95 prices.

The operations costs in Table A6.1 are converted to US dollars in Table A6.2 in both real-year dollars and in 1992 dollars. The latter shows no trend with time.

TABLE A6.2
UKIRT Annual Costs
(Figures in $ millions*)

	Operations Costs in	
	real-year $s	**1992 $s**
1980/81**	1.34	2.2
1981/82	1.75	2.7
1982/83	1.69	2.4
1983/84	2.34	3.3
1984/85	2.03	2.7
1985/86	2.71	3.5
1986/87	2.66	3.4
1987/88	2.45	3.0
1988/89	2.82	3.3
1989/90	2.28	2.5
1990/91	2.40	2.5
1991/92	2.53	2.6
1992/93	2.55	2.5
1993/94	2.37	2.3
1994/95	2.57	2.4
	Average#	2.8
	σ_{n-1}#	0.4

Summary

	1992 $s
Operations Costs (Av.)	2.8
Staff Costs	1.1
Instrumentation Costs	2.1
Total	**6.0**

---

* For conversion rates used see Appendix 5.

** UK Financial Year.

Upto 1992/93 only.

Assuming that the staff and instrumentation costs shown in Table A6.1 would have no trend with time either, we can add these to the average of the operations costs to get the total cost shown on the right hand side of Table A6.2 in 1992 \$s.

A6.2 JCMT

The annual costs of operating the JCMT on Mauna Kea, which became operational in 1987, are given in Table A6.3. Unlike the UKIRT, which is a UK facility, the JCMT is funded by the UK (55%), Canada (25%) and the Netherlands (20%), and the figures quoted below are the *total* annual costs, not just those paid by the UK. The costs in the first column of Table A6.3 are taken from the JCMT Annual Reports, and the staff and major instrumentation costs quoted for 1994/95 are taken from the OIM Report. Again the staff costs quoted for 1994/95 are annual average costs.

TABLE A6.3
JCMT Annual Costs
(figures in real-year £s in millions)

	Operations	Staff Cost	Instrumentation
1987/88*	1.13		
1988/89	1.13		
1989/90	1.31		
1990/91	1.18		
1991/92	1.30		
1992/93	1.35		
1993/94	1.74		
1994/95	1.91	1.2	1.5

The operations costs in Table A6.3 are converted to US dollars in Table A6.4 (next page) in both real-year dollars and in 1992 dollars. Like for the UKIRT, the latter figures show no trend with time. Assuming that the staff and instrumentation costs shown in Table A6.3 would have no trend with time either, we can add these to the average of the operations costs, to get the total cost shown on the right hand side of Table A6.4.

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* UK Financial Year.

TABLE A6.4
JCMT Annual Costs
(Figures in $ millions*)

	Operations Costs in real-year $s	1992 $s
1987/88	1.90	2.3
1988/89	1.90	2.2
1989/90	2.20	2.4
1990/91	2.10	2.2
1991/92	2.30	2.4
1992/93	2.30	2.3
1993/94	2.61	2.5
1994/95	2.89	2.7
	Average**	2.3
	σ_{n-1}**	0.1

Summary

	1992 $s
Operations Costs (Av.)	2.3
Staff Costs	1.7
Instrumentation Costs	2.1
Total	**6.1**

The figures in Tables A6.3 & A6.4 are gross costs, not net costs after miscellaneous receipts. (In fact, the 1994/95 operations cost of $2.89m shown in Table A6.4 would be reduced by $0.53m if receipts were included, resulting in a total cost to the international partners of $2.36m, or £1.56m.)

A6.3 Isaac Newton Group - La Palma

The telescopes of the Isaac Newton Group (ING) on La Palma are the WHT (operational 1987) and the INT and JKT (both operational 1984). They are jointly funded by the UK (80%) and the Netherlands (20%).

The annual costs of operating the ING are given in Table A6.5. The 1983/84 to 1987/88 operational costs are taken from the PPARC files, the 1988/89 to 1992/93 costs, which include a small amount for instrumentation, are from the ING Annual Reports, and the 1994/95 figures are taken from the OIM Report. The staff costs is the annual average for UK and the Netherlands staff on both La Palma and in their home facility. The main reason for the rapid increase in operations costs between 1985/86 and 1988/89 is the addition of the WHT which came on line in 1987.

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* For conversion rates used see Appendix 5.

** Upto 1992/93 only.

TABLE A6.5
ING Annual Costs
(figures in real-year £s in millions)

	Operations	Staff Cost	Instrumentation
1983/84*	0.54		
1984/85	0.61		
1985/86	0.75		
1986/87	1.07		
1987/88	1.25		
1988/89	1.72		
1989/90	1.92		
1990/91	2.39		
1991/92	2.48		
1992/93	2.49		
1993/94			
1994/95	3.0	2.6	1.3

The costs in Table A6.6 are those in Table A6.5 converted to US dollars. Unfortunately, it is only possible to apply the staff and instrumentation costs shown in Table A6.5 for 1994/95 to the ING after the WHT became operational in 1987. As a result Table A6.6 starts with the Financial Year 1988/89.

TABLE A6.6
ING Annual Costs
(Figures in $ millions**)

	Operations Costs in real-year $s	1992 $s
1988/89	2.92	3.4
1989/90	3.26	3.6
1990/91	4.25	4.5
1991/92	4.39	4.5
1992/93	4.23	4.2
1993/94	4.4	4.2
1994/95	4.53	4.2
	Average#	4.0
	σ_{n-1}#	0.5

Summary

	1992 $s
Operations Costs (Av.)	4.0
Staff Costs	3.7
Instrumentation Costs	1.8
Total	9.5

---

* UK Financial Year.

** For conversion rates used see Appendix 5.

\# Upto 1992/93 only.

As for the UKIRT and JCMT, Table A6.6 shows that there is no trend in the annual cost of the ING with time (since 1987).

A6.4 Anglo-Australian Telescope/Observatory

The costs of the Anglo-Australian Telescope, which has been operational since 1975, and of the UK Schmidt were quoted separately until the Anglo-Australian Observatory was set up with effect from 1.1.1988 including both of these instruments. The costs of the Schmidt were unclear before this date, but it was known to be much smaller than that of the AAT and so it will be ignored in this section except when it was part of the AAO.

The annual costs of the AAT/AAO are clearly defined in the AAT/AAO Annual Reports going back to the commissioning of the AAT in the period 1973-75. Unfortunately, the accounting procedures changed periodically, and, in particular, depreciation was first included in 1991-92 as an expense. As I have covered the capital costs elsewhere, I have ignored this depreciation cost in my analysis.

The costs in the Annual Reports are quoted in Australian dollars which I need to convert to US dollars. I know the exchange rate from Australian dollars to sterling and to US dollars between 1973 and 1987 and from 1990 to 1994 (Appendix 5), but my sources do not quote Australian dollar exchange rates for 1988 and 1989. Fortunately, I have the UK contributions to the AAT/AAO in £s from PPARC files, and the UK contributions in Australian $s in the AAT/AAO Annual Reports, allowing me to calculate the £/$Aus. exchange rate for every year since 1981/82. These calculated exchange rates are compared with the real exchange rates for 1981/82 to 1986/87 and from 1990/01 to 1993/94 in Table A6.7 (next page). The agreement is generally good, indicating that I am generally comparing like with like.

TABLE A6.7

$Australian to £UK Exchange Rates calculated from the UK contributions to the AAT/AAO given by PPARC in £s and the AAO/AAT Annual Reports in $A, compared with the actual exchange rates.

Year (Mid. Yr. to Mid. Yr.)	PPARC data in £millions	AAT/AAO Annual Reports in $A millions	∴ $A/£	c/f $A/£ Actual
1981/82	0.99	1.74	1.76	1.74
1982/83	1.09	1.92	1.76	1.71
1983/84	1.11	1.84	1.66	1.60
1984/85	1.21	1.80	1.49	1.67
1985/86	0.96	1.90	1.98	2.02
1986/87	0.89	2.00	2.25	2.28
1987/88	0.91	2.45	2.69	
1988/89	1.10	2.78	2.53	
1989/90	1.38	2.67	1.93	
1990/91	1.14	2.89	2.54	2.35
1991/92	1.40	3.18	2.27	2.32
1992/93	1.26	3.32	2.62	2.27
1993/94	1.62	3.20	1.98	2.18

Table A6.8 (next page) shows the gross* annual costs of the AAT/AAO taken from the Annual Reports assuming the real exchange rates from 1973/74 to 1986/87 and from 1990/91 to 1993/94, and the estimated exchange rates for the other years taken from Table A6.7.

Like the other telescopes/observatories analysed above, there is no trend of costs with time for the AAT/AAO in 1992 US dollars, although the year-to-year variation is rather large for the AAT/AAO. Some of this variability is due to varying exchange rates, and it is sufficiently large to obscure the small increase in cost associated with including the UK Schmidt in the figures starting on 1.1.88, which I am told** is about 10% of the total budget.

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[*] i.e. prior to miscellaneous receipts, so these are greater than the total of the UK and Australian Governments' contributions.

[**] E-mail B.Boyle, Director AAO, to DL, 14.2.97.

TABLE A6.8

AAT/AAO Annual Costs

(All figures in millions. For all but the last column they are in real year currencies. The last column is in 1992 $US)

Year (Mid. Yr. to Mid. Yr.)	Costs in $A	Exchange Rate $A/£	∴ Costs in £	Exchange Rate $US/£	∴ Costs in $US	Costs in 1992 $US
1973/74	0.11	1.66	0.07	2.40	0.17	0.5
1974/75	0.73	1.65	0.44	2.28	1.00	2.7
1975/76	1.61	1.58	1.02	2.00	2.04	5.1
1976/77	1.68	1.53	1.10	1.77	1.95	4.7
1977/78	1.74	1.62	1.07	1.83	1.97	4.4
1978/79	2.12	1.78	1.19	2.02	2.40	4.9
1979/80	2.26	1.96	1.15	2.22	2.55	4.6
1980/81	3.29	1.89	1.74	2.16	3.76	6.1
1981/82	3.52	1.74	2.02	1.88	3.80	5.7
1982/83	3.86	1.71	2.26	1.64	3.71	5.3
1983/84	3.65	1.60	2.28	1.43	3.26	4.5
1984/85	3.94	1.67	2.36	1.31	3.09	4.1
1985/86	4.15	2.02	2.05	1.38	2.83	3.7
1986/87	4.08	2.28	1.79	1.56	2.79	3.5
1987/88*	5.15	2.69	1.91	1.71	3.27	4.0
1988/89	5.24	2.53	2.07	1.71	3.54	4.1
1989/90	5.63	1.93	2.92	1.71	4.99	5.5
1990/91	6.02	2.35	2.56	1.78	4.56	4.8
1991/92**	6.79	2.32	2.93	1.77	5.19	5.3
1992/93	6.64	2.27	2.93	1.64	4.81	4.8
1993/94	7.02	2.18	3.22	1.50	4.83	4.8
1994/95	6.79	2.14	3.17	1.51	4.79	4.5
					Average#	4.7
					σ_{n-1}#	0.7

---

* Includes 6 months of Schmidt Operations (i.e. from 1.1.88).

** Starting in 1991/92 depreciation was charged as an expense. As explained in the text, I have excluded it.

\# Excludes 1973/74 & 1974/75 as these costs were for commissioning, and upto 1992/93 only.

APPENDIX 7

Miscellaneous Observatories - Annual Running Costs

A7.1 Mount Wilson and Las Campanas Observatories

The total annual costs of operating the Mount Wilson and Las Campanas Observatories are shown in Table A7.1, with data taken from the Year Books of the Carnegie Institution. Unfortunately, although the costs are clear, what they cover is not.

TABLE A7.1
Annual Costs of the Mount Wilson & Las Campanas Observatories
(Including instrumentation. Figures in real-year $ millions)

Year (Mid Year - Mid Year)	Costs of Operations: Mt Wilson	Costs of Operations: Las Campanas	Costs of Operations: Total (i)	Total (incl. Research) (ii)	Research Costs (i.e. (ii)-(i))
1974-75	1.03	2.14	3.17		
1975-76	1.09	1.75	2.84		
1976-77	1.20	1.06	2.26		
1977-78	1.17	0.70	1.87		
1978-79	1.19	0.79	1.98		
1979-80	1.17	0.83	2.00		
1980-81	1.00	0.96	1.96		
1981-82	1.44	1.21	2.65		
1982-83	1.56	0.91	2.47		
1983-84	1.85	0.98	2.83		
1984-85			3.02	3.74	0.72
1985-86			2.48	3.36	0.88
1986-87			2.81*	3.68	
1987-88			3.15*	4.02	
1988-89			3.17	4.29	1.12
1989-90			3.32	4.09	0.77
1990-91			3.98		
1991-92			3.52		
1992-93			3.53		
1993-94			3.64		
1994-95			3.94		

---

* I could not find these costs in the annual reports to which I had access. They are calculated by taking the average research cost for 1984-85, 1985-86, 1988-89 and 1989-90 (i.e. 0.87) from the total costs, including research, for 1986-87 and 1987-88.

The Mount Wilson Observatory had the following telescopes operational in 1974, the first year in Table A7.1:-

100"	2.54m	Hooker reflector
60"	1.52m	Reflector
150ft	45m	Solar telescope
60ft	20m	Solar telescope

There were also two other telescopes on the mountain (a 1.0m and a 0.6m) but these appear to be owned by other organisations.

The 100" was mothballed with effect from 1.7.85, and the funding of the other three telescopes reduced from the same date (the remainder of the funding of these three telescopes then coming from other organisations). So the Mount Wilson costs in *column 1* of Table A7.1 are for operating the above four telescopes, but when the 100" was mothballed on 1.7.85, and funding was reduced for the other three telescopes, a relatively modest saving of only about $550k was achieved (see column headed 'Total (i)'). This saving seems much too low, leaving some doubt as to how much money was saved, if any, at least in the short term, in reducing the funding of the 60" and the two solar telescopes. In view of the uncertain level of funding of the three telescopes on Mount Wilson after 1985, I have ignored all cost figures after that date in producing the figures in Table A7.2 (next page), which are in 1992 dollars.

In 1974, when Table A7.1 starts, there was only a 40" (1.0m) owned by the Carnegie Institution at Las Campanas, but there was a 100" (2.5m) under construction. The latter was completed in 1976, thus explaining the high first three figures in column 2 of Table A7.1, which I have ignored in listing the annual costs in 1992 dollars in Table A7.2. There are now two other telescopes at Las Campanas, but these are owned by the University of Toronto and the University of Texas, and so can be ignored in this analysis.

TABLE A7.2
Annual Costs of the Mount Wilson & Las Campanas Observatories
(figures in $ millions, at 1992 prices)

Year	Mt Wilson	Las Campanas	Year	Mt Wilson	Las Campanas
1974-75	2.8		1979-80	2.1	1.5
1975-76	2.8		1980-81	1.6	1.6
1976-77	2.9		1981-82	2.2	1.8
1977-78	2.6	1.6	1982-83	2.2	1.3
1978-79	2.4	1.6	1983-84	2.5	1.4

Mt Wilson	Av. 2.4	σ_{n-1} 0.4
Las Campanas	Av. 1.54	σ_{n-1} 0.16

So the average costs of operating one 100", one 60", and two solar telescopes on Mount Wilson was about $2.4m at 1992 prices, and the costs of operating one 100" and one 40" at Las Campanas was about $1.54m.

A7.2 The Canada-France-Hawaii Telescope

The total annual costs of operating the Canada-France-Hawaii (CFH) telescope on Mauna Kea, which became operational in 1979, are shown in Table A7.3. The figures, which are taken from the CFH Annual Reports, show an average cost, when converted to 1992 prices, of about $5.5m.

TABLE A7.3
Annual Costs of the Canada-France-Hawaii Telescope
(Including instrumentation)

Year*	Annual Cost in real year $s	Annual Cost in 1992 $s	Year	Annual Costs in real year $s	Annual Costs in 1992 $s
1981	2.6	4.0	1988	4.9	5.8
1982	3.1	4.5	1989	5.0	5.7
1983	3.5	4.9	1990	5.3	5.7
1984	4.0	5.4	1991	6.5	6.7
1985	3.9	5.1	1992	6.0	6.0
1986	4.2	5.4	1993	6.9	6.7
1987	4.3	5.3	1994	6.1	5.8

Canada-France-Hawaii	Av. 5.5	σ_{n-1} 0.7

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* Calendar years.

A7.3 UK Radio Astronomy Observatories

A7.3.1 National Radio Astronomy Laboratory (NRAL), Jodrell Bank

The annual costs of operating the National Radio Astronomy Laboratory (NRAL) centred at Jodrell Bank were about $3.2m in 1978 and $6.2m in 1991-94, both in 1992 dollars (see Table A7.4). The main difference between the 1978 and 1991-94 configurations being the extension of the MTRLI (Multi-Telescope Radio-Linked Interferometer) into MERLIN in 1980, with the addition of three 25 metre dishes, and the replacement of the 18 metre dish at Cambridge in 1990 with a new 32 metre dish.

The MERLIN array consisted of:-

Telescope	**Location**	**First Available**
Mark I or Mark II	Jodrell Bank	1957 (Mark I) and 1964 (Mark II)
Mark III	Nantwich	1966
25m	Defford	1965
3 x 25m	Cheshire/Powys	1980
18m or 32m	Cambridge	1964 (18m) or 1990 (32m)

TABLE A7.4

Annual Costs of the NRAL, Jodrell Bank

(The costs in the first column are from the references listed in the footnotes. The other costs are calculated from these)

Year	**real year £m**	**real year $m**	**$m 1992 prices**
1978	0.8*	1.5	3.2
1991	3.6**	6.4	6.6
1993/94	3.94#	5.9	5.7
		Average (1991/93/94)	6.2

---

* Martin, B.R., and Irvine, J., Research Policy, 1983, 12, 61. I have deducted the costs of research astronomers from their figures as I wanted only the costs of running the facilities.

** Draft Review of the Radio Astronomy Review Panel, SERC, August 1992.

Private communication from D. Stannard, NRAL, 21.5.96.

A7.3.2 Mullard Radio Astronomy Observatory (MRAO), Cambridge

The annual costs of operating the Mullard Radio Astronomy Observatory (MRAO) at Cambridge was about \$2.2m in 1978 and \$1.5m in 1991 (in 1992 prices, see Table A7.5). This included the cost of operating the following main telescopes:-

Telescope	**First Used**	**In 1978 figures?**	**In 1991 figures?**
8 off 14m dishes, Ryle (or 5 km) Telescope	1972	✓	✓
3 off 18m dishes, One Mile Telescope	1964	✓	–
Cambridge Low Freq. Synthesis Telescope (7C)	1983	–	✓
151 MHz Synthesis Telescope (6C)	1975	✓	–
Cosmic Anisotropy Telescope (CAT)	1992	–	*

TABLE A7.5
Annual Costs of the MRAO, Cambridge
(The costs in the first column are from the references listed in the footnotes. The other costs are calculated from these)

Year	**real year £m**	**real year \$m**	**\$m 1992 prices**
1978	0.5**	1.0	2.2
1991	0.8#	1.4	1.5

According to the Radio Astronomy Review Panel#, most of the 1991 cost was for operating the Ryle Telescope. The cost of operating the CLFST in 1991 was said to be relatively small and, although part of the cost of building the CAT was included in the 1991 figures, this could not have been very much as the total cost of building the CAT was only £240k## (\$420m).

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[*] Includes 1991 construction costs, not operational costs.

[**] Martin, B.R., and Irvine, J., Research Policy, 1983, 12, 61. I have deducted the costs of research astronomers from their figures as I wanted only the costs of running the facilities.

[#] Draft Review of the Radio Astronomy Review Panel, SERC, August 1992.

[##] Private communication from J.E. Baldwin, MRAO, April 1996.

APPENDIX 8

The Wiesbaden Index for ESA Scientific Programmes to account for Price and Exchange Rate Variations

1976	100	1987	226.9
1977	109.5	1988	237.8
1978	120.7	1989	248.9
1979	133.1	1990	258.9
1980	146.9	1991	276.5
1981	160.3	1992	290.9
1982	177.1	1993	311.3
1983	187.7	1994	322.4
1984	199.3	1995	336.4
1985	210.3	1996	350.0
1986	217.9		