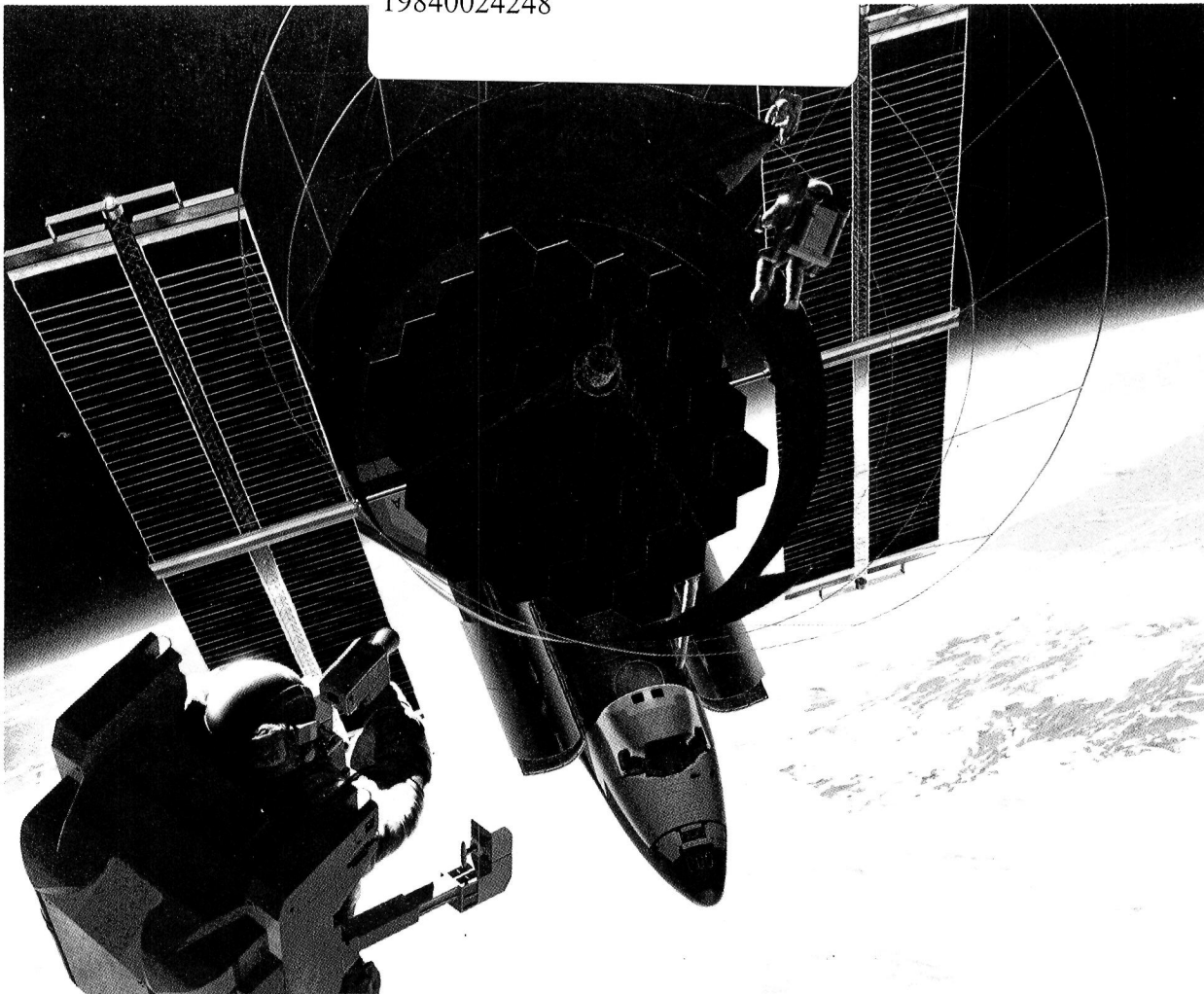NASA Conference Publication 2275

Large Deployable Reflector Science and Technology Workshop

Volume III — Systems and Technology Assessment

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Large Deployable Reflector Science and Technology Workshop

Volume III — Systems and Technology Assessment

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PREFACE

This report describes the technical results of the meeting held June 21–25, 1982, at Asilomar, California, and sponsored by the National Aeronautics and Space Administration (NASA) to evaluate the state of technology for the Large Deployable Reflector (LDR). LDR is a submillimeter/far-infrared (submm/far-IR) telescope which is projected to fly in space in the 1990s. The scientific rationale and technology requirements were defined and systems considerations and generic technology status were assessed.

This report is volume three of three volumes which recorded the proceedings of the NASA LDR Science and Technology Workshop. Volume one is the Executive Summary and volume two is the Scientific Rationale and Technology Requirements.

The workshop was sponsored by the NASA Office of Aeronautics and Space Technology (OAST) and the Office of Space Science and Applications (OSSA). The material for this report was generated by scientists and engineers from private industry, universities, and government agencies.

The technology portion of the LDR Science and Technology Workshop and the report of its findings would not have been possible without the contribution of many people. The participants of the technology panels are listed in appendix A.

Special acknowledgements go to the LDR Science and Technology Workshop Chairman, W. J. Welch; to the Technology Chairman, K. Soosaar, and to the Panel Chairmen: T. Pitts (Systems and Missions); R. Angel (Optics); M. Mikulas (Structures and Materials); F. Tolivar (Sensing and Control); and C. McCreight (Scientific Instruments).

Paul Swanson, Jim Breckinridge, Tom Kuiper, and Bob Freeland deserve special mention for providing valuable input, criticism, and comments.

Finally, special thanks should be given to Mike Kiya, Dave Hollenbach, and Bill Gilbreath for their successful efforts in bringing the LDR Workshop into being, and to Frank Fiore and Bruce Baumrucker of Vectors Unlimited for administrating the workshop.

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C. A. Leidich
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March 30, 1983

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I. INTRODUCTION

A. GENERAL OVERVIEW

The Large Deployable Reflector (LDR) (fig. I.1) will be a 20-m-diam telescope designed for infrared (IR) and submillimeter (submm) astronomical measurements. The LDR will be used to study such diverse astronomical phenomena as stellar and galactic formation, cosmology, and planetary atmospheres. The technology to undertake such an ambitious project is not well in hand, but with sufficient augmentation of the generic technology development efforts currently under way, LDR will be ready in the mid-1990s. This volume will give a summary of the scientific rationale, the functional requirements, the technology assessment, and the future recommendations for LDR developed at this workshop.

Stars and solar systems begin their lives in the cold depth of optically opaque clouds of dust, atoms, and molecules. At far-IR, submm, and radio wavelengths, these clouds are transparent and the feeble radiation originating within them can be seen and properly studied only by telescopes of sufficiently great size and sensitivity. Only a fraction of the radiation from star-forming regions is emitted at radio wavelengths, and, therefore, large, ground-based radio telescopes have limited sensitivity to such sources. These regions radiate primarily in the submm and IR regions of the spectrum; thus, a large instrument such as LDR, operating in space at these wavelengths, is essential in order to observe the physical and chemical processes which are necessary precursors to the coalescence of this material into protostars. With LDR we will be able to witness the growth of Sun-like stars and perhaps to learn whether the formation of planetary systems is a common occurrence in the universe.

The Primordial Nebula from which our solar system formed was probably several times larger than its current size. The large size of the LDR primary mirror (diameter of ~20 m) will give it the angular resolution to resolve similar known or suspected star- and planet-forming regions within 500 light years of the Earth, including the known star-forming molecular cloud in Taurus. LDR will provide a wealth of new data on the early evolution of solar systems.

Current theories postulate that the universe was formed in a gigantic explosion, commonly called the "Big Bang," 15 billion years ago. The Cosmic Background Radiation (CBR) is the remnant of this explosion and is a probe into condition that existed prior to the formation of galaxies. The fluctuations in this background may yield some explanation of the present complex distribution of matter in the universe and of the formation of galaxies and clusters of galaxies. No fluctuations in this background have yet been detected, but LDR will be able to map fluctuations as small as one part in a million and with unprecedented spatial resolution. With this resolution we may be able to study clusters of galaxies to determine whether the galaxies formed first and then were drawn together into clusters or whether the clusters formed first and then the individual galaxies formed.

The reason these important observations have not been made previously is that radiation in the important IR and submm wavelength region is severely attenuated by the Earth's atmosphere. Far-IR and submm radiation carries information vital to the decoding of the structure of stars as they form and to the understanding of the coldest and most distant and highly red-shifted objects in the universe. The results from airplane and balloon-borne observations and, most recently, from the Infrared Astronomical Satellite (IRAS) show that there is an enormous amount of important information to be obtained from a sensitive, high-resolution telescope operating above the Earth's atmosphere at these wavelengths.

In attacking these challenging scientific problems, LDR will be a major component in NASA's long-term commitment to place in space permanent, orbiting astronomical observatories that are sensitive to

Figure I.1.– An artist's conception of a shuttle-deployed LDR.

radiation over the full range of the electromagnetic spectrum. In 1986 NASA expects to place in orbit the Space Telescope (ST), the first large, permanent optical/ultraviolet orbiting observatory. The ST should provide the necessary observations to establish an accurate distance scale for the universe and to chart the evolutionary history of galaxies. Later, the Advanced X-Ray Astrophysics Facility (AXAF) will permit the panoply of high-energy phenomena in the universe to be studied. Between IRAS and LDR will come the Space Infrared Telescope Facility (SIRTF). SIRTF will provide observations of the highest attainable sensitivity at wavelengths from 5 μm to 200 μm. It will extend IRAS's pioneering all-sky survey to fainter, more distant sources and carry out detailed studies of many of the problems to be attacked in a complementary fashion by LDR.

Among this complement of extraordinary observatories, LDR represents a significant departure in design and philosophy. LDR will be the first astronomical observatory to be erected and assembled in space, a distinction that brings with it major challenges to current technology. At the same time, achieving LDR objectives will provide invaluable experience in the art of constructing high-precision, large space structures.

Substantial technical developments are needed to complete the necessary technology base for LDR, but these are now considered achievable in the near-term. In particular, unique challenges lie ahead in the development of ultra-lightweight deployable mirrors, advanced mirror fabrication techniques, and advanced

structures and structural controls for space applications. LDR is only one of the systems which will be possible as a result of these technological advances.

Just as important as the baseline technology issues are the system integration requirements. For example, the Space Transportation System (STS) has constraints on packaging and weight that affect overall telescope size, stability, and control requirements.

Likewise, there will be an effect on testing requirements because of the ultra-lightweight and large size of LDR. Integrated ground testing prior to launch and deployment does not appear feasible. We must, therefore, pursue major improvements in our ability to model and simulate complex space systems with a high degree of confidence and to validate these models with individual technology demonstrations.

The LDR has the potential to be a major springboard for this new generation of space systems for scientific, commercial, and military applications. There is a large degree of confidence within the scientific and engineering community that a 20-m IR and submm telescope in space can be a reality within the next 10–15 years.

B. LDR HISTORY AND STATUS

The impetus for the development of the LDR began in the late 1970s with two parallel proposals — one for study of a large submm telescope by the Jet Propulsion Laboratory (JPL), and the other for study of a large IR telescope by the Ames Research Center (ARC). These proposed studies were united into one project intended to lead to the development of a large-aperture (at least 10-m effective diameter) telescope for far-IR and submm astronomy.

Discussions with university scientists and representatives of aerospace companies working on related problems indicated that such a telescope would be technically feasible in the 1990s; this conclusion was reinforced by technical studies sponsored by NASA. Even at this early stage in its definition, the LDR was among the projects reviewed by the Astronomy Survey Committee ("Field Committee") of the National Academy of Sciences. In 1981, this committee, which was charged with defining a program of astronomical exploration and study extending well into the 1990s, recommended LDR with high priority as a major new NASA Space Program for development in the late 1980s, saying:

> The Astronomy Survey Committee recommends the construction of a Large Deployable Reflector of the 10 m class in space to carry out observations in the far-infrared and submillimeter regions of the spectrum that are inaccessible from the ground. A number of important scientific problems are uniquely accessible to such a Large Deployable Reflector in space. For distances less than 500 parsecs, the projected beam diameter will be less than 1000 AU.

> Direct measurements of the sizes of nearby clouds collapsing to become stars will thus be possible at far-infrared wavelengths, which can penetrate the surrounding clouds of dust that invariably obscure small-scale features at optical wavelengths. In addition, the wavelength regions accessible to an LDR contain spectral lines of atoms, ions, and molecules that reflect a wide range of astrophysical conditions.

> Studies of these features will yield otherwise unobtainable information about the structure and dynamics of planetary atmospheres; the heating, cooling, and chemical composition of the interstellar medium; and, because of the penetrating power of long-wavelength radiation, chemical abundances in the highly luminous, but optically obscured nuclei of active galaxies.

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The sensitivity and high angular resolution of an LDR will also make it possible to study newly forming stars in optically obscured regions of nearby external galaxies enhancing our understanding of galactic evolution of the dynamical processes that stimulate star formation. Such an instrument can also probe the structure of the early Universe and the mechanisms of galaxy formation through studies of small-scale spatial flucturations in the cosmic microwave background radiation.

Because of this strong scientific endorsement for LDR, NASA plans to begin hardware development in the early 1990s, and initial operational capability by the mid-1990s. To meet the technical challenges necessary to begin development on an LDR, an intensive technology program is required prior to the start of the actual flight hardware development.

To this end, a joint NASA-ARC/JPL LDR study team was formed in 1979. Upon completing an extensive industry survey and an initial conceptual design study (won competitively by Lockheed) in 1979, the ARC/JPL study team drafted an LDR Technology Development Plan in 1981.

The most pressing technology area identified in this development plan was the method for fabricating lightweight mirror segments with a surface error of less than 2 μm in large quantities. A segment definition study was won by Perkin-Elmer (PE) for assessing segment technology and providing recommendations for segment development. This study was begun in 1981 and was completed in March 1983.

In addition to the Lockheed and PE contractual efforts, a multidiscipline science and technology consulting team has been formed with participants from both universities and industry. Also, support for LDR from NASA Langley Research Center (LaRC) in the areas of structures and structural analysis has been established.

Finally, a need-to-know with the Defense Advanced Research Projects Agency (DARPA) has been established, and an exchange of information and expertise between DARPA and NASA in the area of large deployable optical technology is continuing.

LDR will be a major national project with far-reaching astronomical and technical ramifications. The Asilomar workshop marked the first major attempt to define the scientific rationale for the LDR and to compare the astronomical requirements with the technical possibilities. The large number (>100) of scientists and technologists involved in the workshop and the wide range of topics discussed are evidence of the excitement and challenge of this project.

A current LDR Bibliography, including information written after this workshop, is included in this volume (appendix B). Other helpful information includes a glossary of terms relating to LDR (appendix C) in this volume.

C. WORKSHOP PURPOSE AND ORGANIZATION

Study activity for LDR began in the late 1970s and by 1981 it was recognized by NASA that major interaction was required between the science and technology communities. The scientific community would define the scientific rationale for LDR as well as conceptually describe a potential instrument complement, and the technical experts would assess the technologies needed for the LDR and plan how to develop those capabilities that are currently beyond the state of the art.

Consequently, NASA sponsored the LDR Science and Technology Workshop at the Asilomar Conference Center, Pacific Grove, California, in June 1982. Over 100 scientists and engineers from universities, NASA centers, Department of Defense agencies, and private industry participated. The organization of the Workshop is shown in figure I-2. Appendix A contains a complete list of all technology workshop participants. The scientific panels were organized around the following topics: Cosmology, Extragalactic and Galactic Structure, Stellar Evolution, Interstellar Medium, and Solar System and Planetary Studies. The technical panels consisted of the following: Systems and Missions, Optics, Structures and Materials, Sensing and Control, and Science Instruments.
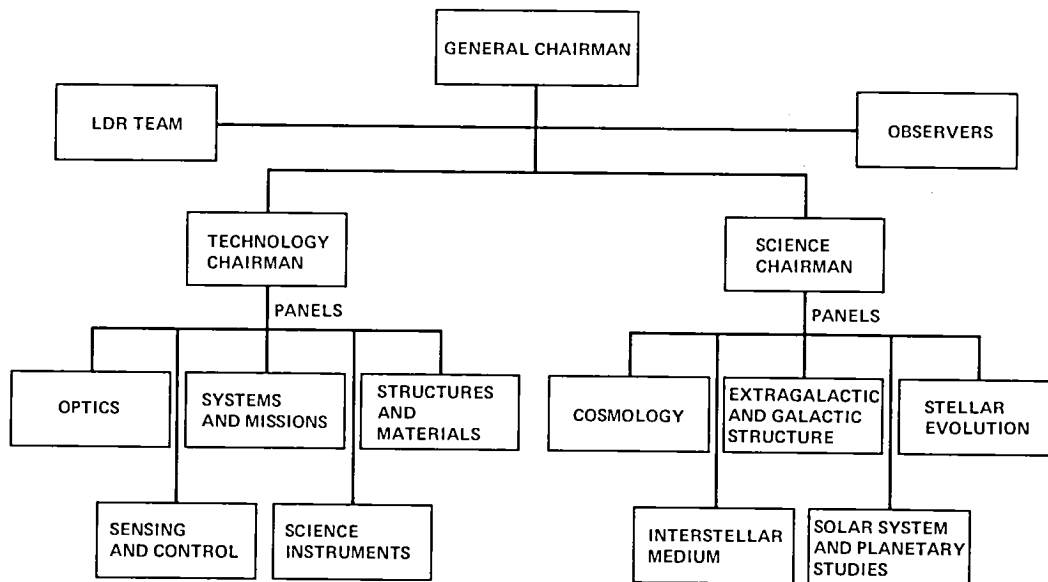
Figure I-2.— Workshop Organization.

Prior to the Workshop, a science team, composed of the Science Panel Chairman and various NASA and JPL scientists, provided the representative LDR Science Performance Goals shown in table I-1. The Systems and Missions Panel then convened 1 day prior to the other technology panels to establish representative LDR systems approaches (System I and System II), also shown in table I-1. These systems requirements served as a starting point for Workshop deliberation, and were iterated between the scientists and technologists during the course of the Workshop, with the Systems and missions Panel acting as the interface.

The final set of Workshop-recommended LDR consensus systems requirements was compiled by Dr. P. Swanson (JPL) and are shown in table I-2. The rationale for changes between the LDR representative systems requirements and the LDR consensus systems requirements is described in this report. The major detailed findings of the science panels shown in figure I.2 are described in Volume II of this report.

TABLE I-1.– LDR REPRESENTATIVE SYSTEMS GOALS

Characteristics	Science performance goals	System I	System II
Diameter, m	30	30	10-15
FOV, arcmin	10	1-10	1-10
F/No (system)	TBD	TBD	TBD
λ-limit, μm	30	30-50	30 (10 desired)
Light-bucket blur circle, arcsec	0.2	TBD	TBD
Sensitivity to background, K	<200	<200	<200
Absolute pointing, arcsec	0.5	0.05	0.1
Jitter, arcsec	0.05	0.02	1.05
Slew, deg/min	20	20	20
Raster scanning	N/A	TBD	TBD
Integration period	N/A	TBD	TBD
Required orbit	None	TBD	TBD
Chopping	Yes	Yes	Yes
Polarization	Limited cross polarization	Limited cross polarization	Limited cross polarization
Sidelobes	Minimize near sidelobes	Minimize near sidelobes	Minimize near sidelobes
Sky exclusion, deg Sun, Earth	45-60	60	45-60
L/D (sunshade)	TBD	TBD	TBD
Limiting noise	TBD	TBD	TBD
Limiting noise level	TBD	TBD	TBD
Cryogenic cooling	Instruments only (0.2 K-50 K)	Instruments only (0.2-50 K)	Instruments only (0.2-50 K)
Lifetime, yr	10 yr total (2-3 yr revisits)	10 total (2-3 yr revisits)	10 total (2-3 yr revisits)
Deployment	Automatic or semiautomatic (one Shuttle)	TBD	Automatic or semiautomatic (one Shuttle)

TABLE I-2.– SUMMARY OF LDR CONSENSUS SYSTEMS REQUIREMENTS

Observational requirement	Functional requirement	Telescope requirement
Observe throughout region obscured by Earth's atmosphere	$30\ \mu m < \lambda < 1$ mm diffraction limited (50 μm acceptable)	rms surface error $<2\ \mu m$ rms slope $<1.5\ \mu rad$
Far-IR studies of: Galaxies at cosmological distances	Spatial resolution comparable to ground-based telescopes	$D > 6.5$ m @ 30 μm
Spiral structure in distant galaxies Giant molecular clouds in nearby galaxies	$\lesssim 1$ arcsec in far-IR $\rightarrow D/\lambda > 2\times 10^5$	$D > 20$ m @ 100 μm
Protostars in our galaxy	Absolute pointing to HPBW/5 Pointing jitter to HPBW/10	$\lesssim 0.06$ arcsec absolute $\lesssim 0.03$ jitter
Observe faint objects at large distances	Sensitivity $\alpha\ D^2$ number of sources $\alpha\ D^3 \rightarrow D$ as large as possible	$D \gtrsim 20$ m
	Spatial chopping to eliminate sky background to 1 part in 10^6	2 Hz, 1 arcmin spatial chopping
	Stray light at detectors below telescope emission	Limits view angle to Sun and Earth
	Minimize telescope background emission	Primary temp ≈ 150 K Secondary temp < 150 K Emissivity < 0.05 @ 100 μm < 0.01 @ 1 mm
Mapping extended sources, planets, molecular clouds, H II regions	$1° \times 1°$ raster scan $\gtrsim 3$ arcmin IFOV	Scan mirror Array detectors Long focal length

Near-IR studies of high red shifted galaxies ($Z \gtrsim 3$)	Spatial resolution $\lesssim 2$ arcsec in 1 to 30-μm range
	$\epsilon < 0.1$ in 1 to 10-μm range
		Light-bucket operation at
		  $\lambda < 30\ \mu m \rightarrow$ surface error $\ll 2\ \mu m$
		Micro roughness
		  $<\lambda/40 = 0.2\ \mu m$ @ 10 μ λ
		       $= 0.2\ \mu m$ @ 1 μ λ

Observe extra solar planets	Sidelobes < -40 dB at $\theta > 10$ arcsec @ $\lambda = 30\ \mu m$	Uniform illumination $\rightarrow -39$ dB @ 10 arcsec Low scatter
Cosmic background	Detector noise limited at $\lambda = 1$ mm (background NEP $<10^{-16}$ WHz$^{-1/2}$)	$\epsilon < 0.01 \rightarrow$ roughness $< 7\ \mu m$
Mission-related requirements	Single Shuttle launch	Deployable structure Segments <4 m diam Mass $<27,000$ kg
	10-yr lifetime Maximize viewing time Revisit capability	>750 km orbit $\gtrsim 20°$/min slew
Maximum detector sensitivity throughout spectral range	Background-limited noncoherent detectors	NEP $\lesssim 10^{-16}$ WHz$^{-1/2}$ @ 10 to 100 μm NEP $\lesssim 10^{-17}$ WHz$^{-1/2}$ @ 100 to 1000 μm

	High-resolution spectroscopy
	  $\Delta\lambda/\lambda < 10^{-6}$, 50 to 1000 μm
		Coherent receivers with
		  $T_{sys} \lesssim 1000$ K
		Cryogenic systems, 0.1 K to 50 K

II. TECHNOLOGY PANEL REPORTS

A. INTRODUCTION

The scientific meetings of the LDR Workshop at Asilomar amplified the scientific rationale for a 10-m-class telescope, recommended by the 1981 Field Committee report. Prior to the Workshop, a science team, composed of the Science Panel Chairmen and various NASA and JPL scientists, provided the representative set of LDR Science Performance Goals shown in table I-1. The Systems and Missions Panel then convened 1 day prior to the other technology panels to establish a representative set of LDR systems approaches (System I and System II), also shown in table I-1. This set of requirements was given to the scientists and technologists during the course of the Workshop, with the Systems and Missions Panel acting as the interface. As shown in figure I-2, the technology portion of the Workshop was divided into five other panels — Optics, Systems and Missions, Sensing and Control, Structures and Materials, and Science Instruments. Appendix A contains a complete list of all participants of the technology portion of this Workshop. The representative set of LDR systems requirements was supplied to each technology panel. The charter for the technology panels was to identify the relevant technologies within their discipline for LDR, and to assess the current and projected state of the art of these technologies.

The general areas of consideration for each panel are shown in table II-1. Wherever the technology fell short of LDR requirements, the technology panels were to recommend development programs for that technology, or alternative technologies, or a change in LDR requirements. This section will describe the findings of each of the five technology panels. Details of the major findings of the science panels shown in figure I-2 are described in volume II of this report.

Appendix B lists the current LDR Bibliography, and appendix C provides a small Glossary.

TABLE II-1.– AREAS OF CONSIDERATION – TECHNOLOGY PANELS

Panels	Areas of concern
OPTICS	Configuration, primary reflector and secondary mirror characteristics, figure control, optical materials, coatings, producibility.
MATERIALS AND STRUCTURE	Support structure, dynamics, deployment, thermal control, vibration control, optical materials, fabrication, testing, thermal shade.
SENSING AND CONTROL	Acquisition, tracking, pointing, vibration control, adaptive optics, figure sensing.
SCIENCE INSTRUMENTS	Photon detectors, arrays, bolometers, mixers, spectrometers, heterodyne receivers, local oscillators, cryogenics, signal processing, smart sensors, cameras, cold electronics, cold optical elements, mechanisms.
SYSTEMS AND MISSIONS	Conceptual design, orbits, budgets, power/weight/volume/telemetry constraints, operations, contamination, simulation, demonstration, second level technologies, technology oversight.

B. SYSTEMS AND MISSIONS PANEL REPORT

1. Chairman's Overview

The Systems and Missions Panel charter was to define systems requirements and technology issues, to act as the interface between the various technology panels, and to provide the interface between the science and technology sides of the Workshop by translating the science goals to technology requirements. The Systems and Missions Panel charter, developed prior to the Workshop, is presented below. These items and others discussed in the Panel deliberations will be summarized in this section.

Representative systems requirements (from science goals — conceptual design approaches)
    Mission considerations/implications
        Orbit/operational considerations
        Power/weight/volume/telemetry constraints
        Deployment/assembly/construction trades
        Lifetime/reliability/refurbishment potentials
        Contamination (technology considerations)
        Automation (technology considerations)
        Smart sensing (technology considerations)
        Cost
    Budgets
        Photon/noise/mass/wavefront error
        Tolerances
        Other
    Performance considerations
        Diffraction — limit versus diameter
        Light bucket
        Chopping
        Other
    Technology assessment implications on systems design testing/demonstration/proof of concept/ simulation

Additionally, this panel was tasked with assessing the typical multidisciplinary systems-missions topics. Examples include contamination and orbits as well as certain technologies which were either not assigned or fully explored by the other panels (such as power and thermal control).

This panel convened 1 day prior to the other technology panels to establish the representative set of LDR Systems Requirements (table I-1) for the science rationale described in Volume II of this report. Two systems approaches, System I and System II, were arrived at after analyzing the goals, and were presented the following day at the plenary session. One approach involved a 30-m-aperture LDR and the other involved a 10-to-15-m-aperture LDR. Following this, all the Technology Panel Chairmen discussed several different LDR configurations other than the baseline (fig. I-3) axisymmetric cassegrain. These included the rectangular aperture (slot), a diluted aperture, a radially degraded aperture, and electrostatically figured membranes. Except for the diluted aperture, all other concepts were recommended for further study.

If the technologists felt that these alternative concepts could be developed in the LDR time frame to satisfy the science goals, they were free to assess the corresponding supportive technologies for them during the week.
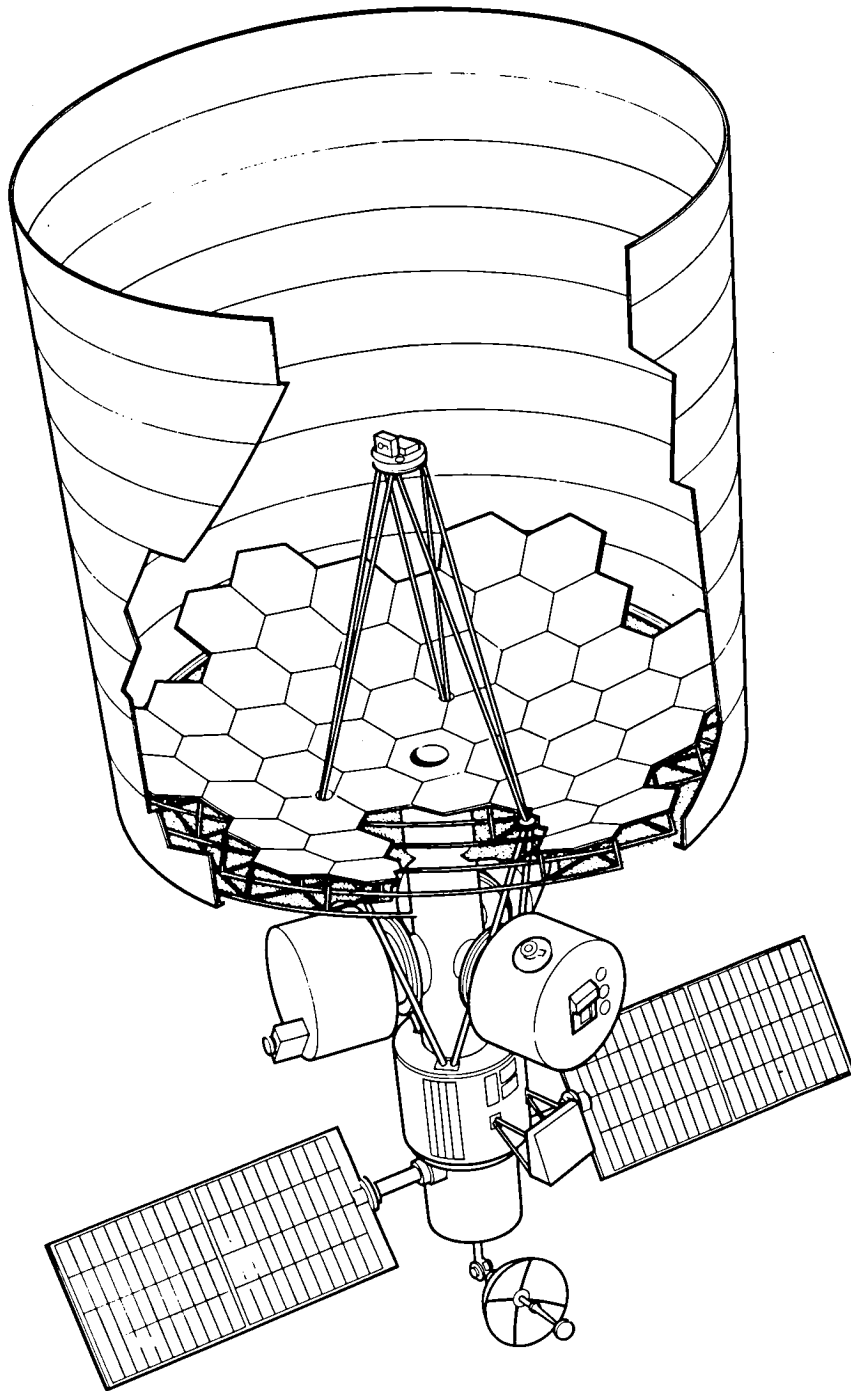
Figure II-1.— LDR representative system concept.

Additionally, in performing its interface role, the Systems Panel heard a number of presentations on specific technologies and concepts, and entertained informal and formal feedback from all the technology panels concerning difficulties with certain goals, alternative approaches, and incompatible requirements. They also received reports from the science side as to the relative importance of the various goals and acceptable performance trades.

2. Systems Requirements Summary

The systems requirements evolved and expanded throughout the week, resulting in the consensus requirements shown in table I-2. The Systems and Missions Panel believes that these requirements are likely to be the most demanding self-consistent set that can be reached if an initial operating capability for LDR in 1995 is to be realized. Although the rationale driving these requirements from a science standpoint is presented in depth in Volume II of this report, brief discussions of the Systems and Missions Panel reasoning and decision process are given here. More complete technical rationales leading to these requirements are presented later in this section and in the other technical-panel reports. While these consensus requirements may not provide scientists with all their initially desired observational goals (e.g., the resolution possible with a 30-m aperture), these requirements do come close to the desired goals and actually offer observational enhancement in some areas. The general optical configuration (mirror sizes, focal numbers and field-of-view (FOV) was driven by a number of systems and technology considerations. For example, a 30-m-aperture telescope would be very difficult, in terms of mass and volume constraints, to fit into a single STS launch. A telescope of this size was judged to be nearly impossible in the near-term by the Panel after considering several factors: (a) the mass, cost, and development schedule of the necessary sophisticated deployment mechanism; (b) the on-orbit stay time needs for erection and resultant extensive life-support requirements and added support mass; and (c) the very stringent mass budget driving all technology disciplines. Hence, a 20-m-diam baseline was subjectively decided to be a reasonable size in the LDR time frame. It was realized that multiple STS launches would facilitate a larger system, but without analysis, the affect of the cost and design of this approach could not be appreciated. Also, the existence of a NASA-manned orbital construction facility would cause this argument to be reconsidered.

During the course of the Systems and Missions Panel, the following was decided: The speed of the system was increased, the primary f number was reduced, and the field was cut from 10 to 3 arcmin to reduce focal-plane size and aperture. (This would lessen instrument development needs and internal heat loads.) In addition, the secondary mirror and spiders were better shielded, and a smaller (1 m), lighter secondary mirror was used to facilitate chopping and to lessen system vibration. As originally felt, the primary reflector collecting area would be the principal total system mass driver; both a diameter (20 m) and a corresponding equivalent area were specified to allow for noncircular configurations, if they prove to be desirable.

Rectangular optics would therefore regain the lost resolution in one dimension (from the original 30-m-aperture goal) and maintain the single STS load ground rule. It is likely that the final selected primary reflector will be composed of segments. The surface and slope specifications are necessary to meet the diffraction limit and light-bucket requirements, respectively.

The exact primary-reflector aperture size was subjectively decided upon and must await analyses (the results of segment development efforts and manufacturing tests) before being fixed.

Considerable debate at the Workshop centered on the diffraction limit, as this will drive the cost and schedule of LDR development. Arguments centered on the particular spectral range embraced by a given science objective; it was decided that the diffraction-limited performance could be relaxed to 50 μm. The light-bucket blur requirement was progressively relaxed from 0.2 to 0.5 to 2.0 arcsec during the course of

the Workshop, as analyses revealed the effect of smaller values. However, if the 2.0-arcsec requirement is to be implemented, 30 μm or better diffraction-limited performance must be provided.

Over much of the LDR operating spectral range, telescope photon emission noise appears to be the limiting factor in sensitivity (see section 6). Thus, successful efforts to reduce optical temperature and emissivity would be very rewarding, particularly in the light-bucket regime.

A number of early LDR concept thermal analyses (Lockheed, JPL, and ARC) have shown that 200 K primary reflectors can be achieved with a primitive shade design. Previous experience of several panel members indicates that ultimate passive control methods can probably reduce 20-m primary reflectors to 130 K or 140 K. Thus, the Systems Panel decided that a goal of 150 K is reasonable. Since the secondary mirror would cause noise equal to that from the primary reflector if its temperature were the same as the primary reflector, it must operate at 125 K, thus reducing its thermal emission by one-half. Because the secondary mirror size and mass is relatively small, active cooling could be employed. Further, the small area suggests that productive efforts in low-emittance coatings are possible. An evaluation of the technologies involved in providing such cooling is given later in this report.

During the Workshop, control requirements did not change appreciably from the preworkshop guidelines. Absolute pointing and jitter needs are compatible with overall resolution requirements. The slew rate was held at a high value to minimize losses in observation time; however, careful programming of observations likely will reduce the need for such high rates and will allow the use of state-of-the-art control momentum gyros (CMG).

The raster scan is a requirement for studying extended sources and could prove difficult to meet while maintaining pointing and jitter requirements. The chopping requirement was quantified following iterations with the Science and Technology Panels. It appears feasible (i.e., acceptable system vibration levels can be achieved) if the secondary mass and size are maintained and a 99% reactionless system is employed. The low-rate tracking requirement needed for following comets was also considered achievable.

The orbit choice (see section 6(C) of this panel report) is based on the desire to obtain the maximum mass (27,000 kg) in operational orbit, for a 10-yr lifetime before significant decay occurs. It is not the optimum choice, particularly from a thermal standpoint, but rather a "straw man" for the present.

The sky coverage and sunshade length to diameter ratio (L/D) are coupled to the observational lifetime. To minimize the sunshade mass, size, and complexity while meeting thermal and off-axis rejection requirements, a large Sun exclusion angle was chosen along with a fairly large Earth avoidance angle. The long lifetime and a carefully planned observing program should assure that all desirable objects are studied for a reasonable time, and that minor losses in observation time are caused by the exclusion angles.

A revisit interval of about 3 yr is needed to install new instruments and provide maintenance and repair. It is probably too long, however, to keep stored cryogen, which may mean that a closed-cycle system must be considered with its resultant high power requirement and vibration input. The cryogenic stations require various temperatures, depending on the particular instrument needs.

Although large quantities of power may be necessary for the present, the instruments (including the cryogenic system) are limited to 1.5 kW to maintain the system mass budget.

3. Budgets

When assessing the consequences of the system requirements on the overall concept, the panel arrived at three budgets: (a) an allocation of available system mass to various subsystems and components, (b) a system photon noise budget, and (c) a wavefront error budget based on the 30-μm diffraction-limited system. The mass budget shown in table II-2 was developed as a baseline for the technology panels to consider. This very cursory mass allocation indicates how difficult it may be to package a 20-m LDR in a single Shuttle launch constrained to 27,000 kg. The 7,000 kg allocated to the primary reflector assumes segments with aerial densities of approximately 22 kg/m^2. This number is well beyond the state of the art and represents one of the leading technological challenges for LDR.

TABLE II-2.– LDR MASS BUDGET

Element	Mass, kg
Primary reflector	7,000
Thermal shade and support structure	720
Tube/truss spiders	600
Secondary mirror and support assembly	50
Control (1.0 kW)	
Actuators	200
Sensors	200
Computer/electronics	200
Pointing system	500
Backup truss for primary reflector	3,000 (cell and back frame)
Equipment, CMG, solar panels (1.0 kW)	3,000
Instruments, cryogenics (1.5 kW)	3,500
Launch and deployment fixtures	2,000
Total	20,970
Propulsion	5,000
Margin	1,030
Total	27,000

The system photon noise budget requires the primary reflector and secondary mirror to be at 150 K and 125 K, respectively. Temperature uniformity on the mirror surface must be kept at $\leqslant$1 K. Scattered light (5 μm to 2 mm) must be $\leqslant$20% of all photon emission from the primary reflector segments. Figure II-2 shows the noise equivalent power (NEP) in W/Hz$^{-1/2}$ as determined by various individual noise sources, compared with the NEP provided by several detectors. The curves for telescope emission apply for an individual mirror, a detector with an area equal to the airy disk at the appropriate wavelength, and assume a 10% bandwidth.

The telescope emissivity shown applies for a highly polished gold mirror surface. The natural backgrounds which ultimately limit telescope performance (i.e., scattered sunlight, zodiacal light, galactic dust emission, and the cosmic background) are also shown.

The bolometer detectors represent the current state of the art. The photodetectors are typical IRAS technology, flight-qualified for use in the mid-1980s. Note that for a 1990s system the photodetector curve may drop an order of magnitude in NEP, equaling present laboratory-device performance. It is seen that
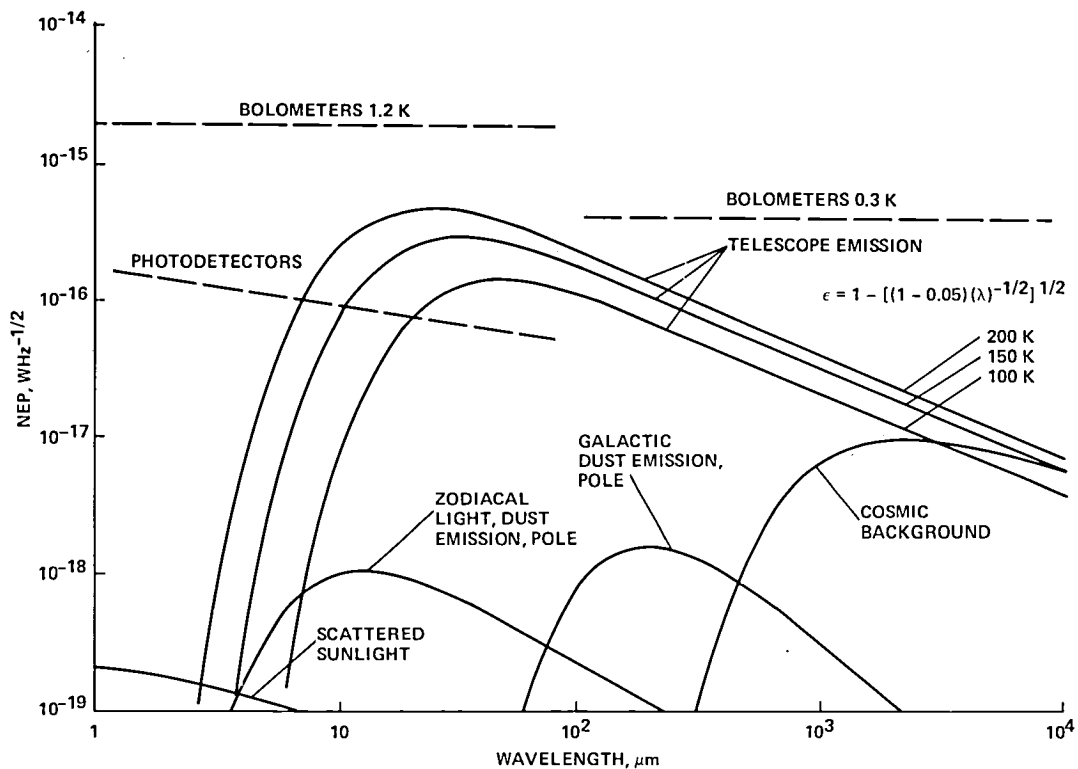
Figure II-2.— NEP versus wavelength (bolometers and photodetectors compared with background).

reducing the mirror temperatures below 200 K significantly increases the region at short wavelengths at which telescope noise emission is below the detector-generated noise and reduces the background noise in the 20-μm region by approximately 30%. In the midwavelength region, cooled bolometric performance is shown. There are presently no heterodyne detectors in this region. It will be necessary to develop heterodyne techniques for LDR in the 100- to 500-μm range. For the long-wavelength region, the heterodyne detector shown is a hot electron (InSb) bolometer with about a 3-MHz bandwidth. Since the telescope and other noise plots are for a 10% bandwidth (30 GHz at λ = 1 mm), when the heterodyne detector is considered, the telescope and other noise curves would be reduced by a square root of the delta f factor, which is two orders of magnitude at λ = 1 mm.

A total wavefront error budget is shown in figure II-3. To provide the required diffraction-limited performance at 30 μm, the total wavefront error must not exceed a 2-μm root mean square (rms). The major sources of the optical errors in the LDR are associated with the primary reflector, secondary mirror, and individual instrument optics. The allocation for each of these individual optical elements is 1.5 μm rms for the primary reflector, 1.0 μm rms for the secondary mirror, and 0.5 μm rms for the science instruments. The overall wavefront quality at cassegrainian focus is 2.0 μm rms. Each of the individual error sources is the result of numerous smaller errors. For example, the primary reflector error of 1.5 μm rms consists of two major components: 1.2 μm rms, which has been allocated to surface errors; and 1.0 μm rms, which has been allocated to alignment sensing and control of the individual panel segments. The surface errors consist of design residuals, which are defined as figure specification tolerances, edge outage, and manufacturing errors. Manufacturing errors include the manufactured radius and subsequent changes in radius of curvature resulting from gravity release, thermal soak, and temperature gradients. In addition, meteorology repeatability and quilting add to manufacturing errors. The total error allocation to each of these four manufacturing errors is 0.5 μm rms.
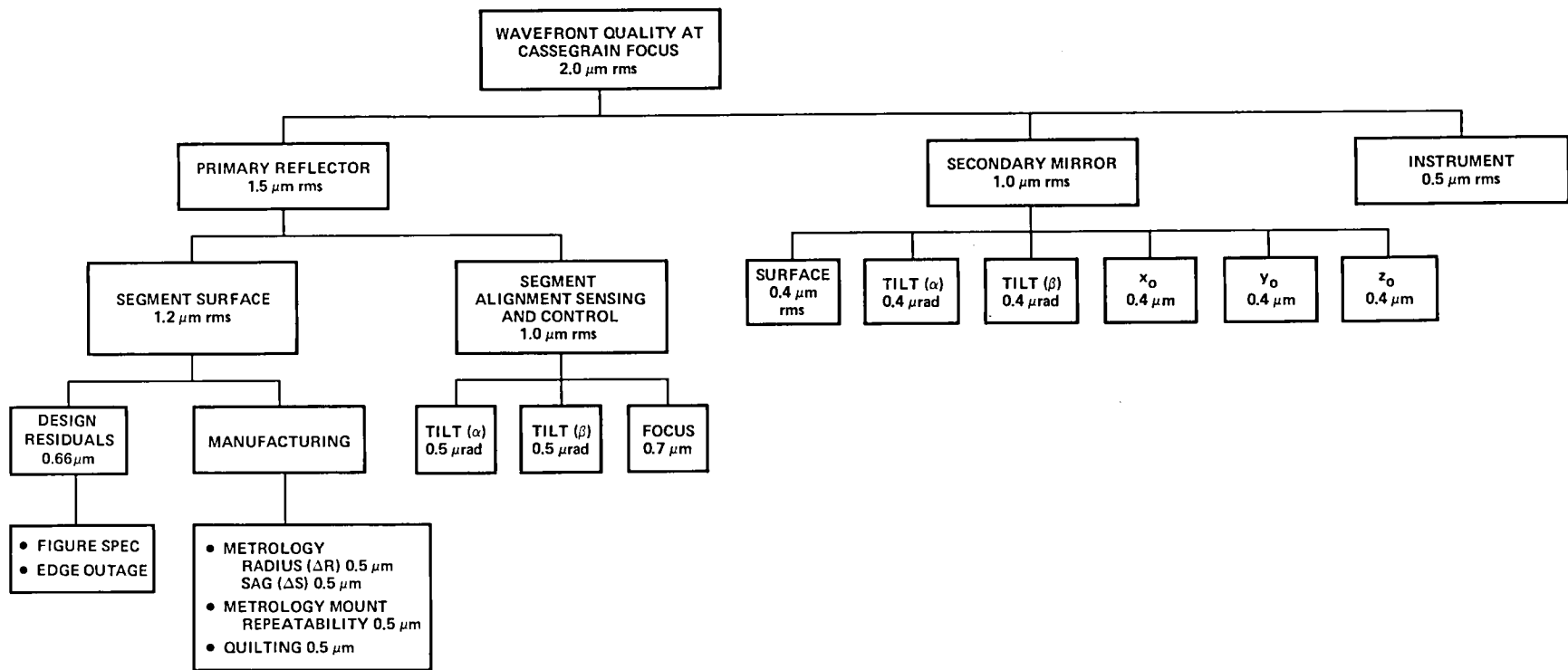
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Figure II-3.— Representative wavefront error budget.

The errors associated with primary-reflector-segment alignment sensing and control total 1 μm rms. This total consists of three major errors: tilt in two axes and focus errors. Error budget allocations of 0.5 μm rms for tilt errors and 0.7 μm rms for focal errors were also made.

Secondary-mirror errors consist of surface errors, tilt, tip, displacement in two axes, and focus. A budget of 4 μm was allocated for each of these secondary-mirror error sources, which total to a secondary error of about 1 μm rms. The third portion of the major sources of optical errors is a 1-μm rms allocation for the individual payload instruments.

4. LDR Representative System Concept

In response to LDR consensus systems requirements and the budgets mentioned above, a LDR representative system concept resulted, as shown in figures I-1 and II-1. The optical configuration is an axisymmetric cassegrain with the focus located near the vertex of the primary reflector. This reflector will be composed of individual segments controlled to form a single image. The exact number and size of the segments are yet to be determined. Fine steering and spatial chopping are accomplished by small rotations of the reactionless, mounted secondary mirror.

Additional optical elements in the scientific instruments are required to form "pupils" and FOV of the desired size, focal lengths, etc. A cylindrical sunshade, probably internally baffled, protects the optics from stray light and varying thermal inputs from the Sun and Earth.

The main structural elements are composed of graphite/composite tubes in a tetrahedral truss arrangement. Control momentum gyros will be used for slew and tracking, and an offset guidestar system will be used for pointing and control. A spacecraft bipropellant rocket will bring the LDR to orbit following Shuttle deployment.

5. Alternative Concepts

The Systems Panel evaluated several alternative systems concepts. A summary of the alternative concepts that were considered are shown in table II-3. The dilute aperture provided high resolution at the expense of mapping capability and was not endorsed by Workshop scientists. All of the other concepts considered were recommended for further study.

6. System Issues and Analyses

Several items were considered to be of particular importance and were specifically addressed by the Systems and Missions Panel. The topics were light-bucket operation, chopping, orbit considerations, light-weight monoliths, sunshade concepts, thermal control technology, and power considerations.

a. *Light-bucket operation*— The light-bucket operation below the diffraction limit corresponds to the geometric optics limit, the primary reflector surface dictates the image quality. The panel concluded that seemingly loose light-bucket image-quality requirements will set more stringent primary-reflector-segment fabrication tolerances than the sharper image-quality requirement demanded for longer-wavelength diffraction-limited operation. The light bucket operation regime is from 1–30 μm; from 1–4 μm, the desired light-bucket blur circle equals 1–2 arcsec.

TABLE II-3.— ALTERNATIVE DESIGNS (COMPARED WITH BASELINE)

Instrument	Science implication	Eased S/C factor	Technology demonstrated	Evolutionary potential
Dilute aperture (interferometer)	Provides high resolution. Poor for mapping of extended sources and spectroscopy.	Framework could be designed for full aperture with missing segments and control mechanisms for reducing weight and volume for single launch compatibility.	Segment fabrication method. Structure and control system. Active thermal system. Attitude and stability control.	Fill in aperture on subsequent flights.
Slot 54 m × 12 m (alternative for full LDR) 18 m × 4 m (interim compromise)	For a given weight, this form allows high resolution in one direction. The sensitivity is 81.584 of equivalent circle for other users (i.e., extended sources and spectroscopy). Diamond shaped aperture permits zone of very low sidelobes to be used.	Same as baseline. Shield more difficult but can point closer to Sun. Light, simply deployed instrument offering some scientific measurements across the range within one Shuttle in 98° orbit.	Alternative to baseline. Segment lubrication method. Thermal design attitude and stability.	Not applicable. Not best core for subsequent completion.
Precision central zone with progressively increased figure tolerance with distance from center	Complex optics design, but might give equal resolution over several optics. Difficult to prevent sensitivity degradation at short λ (especially light bucket). Special aperture stops may be required.	Large reflector provided with minimum mass and assembly risk. Thermal design eased.	All degrees of figure control. Thermal (less stringent). Attitude and stability (reduced requirements).	Outer segments and control devices could be updated later. Additional improved attitude, stability, and thermal controls later.
Off-axis system (circular or slot)	Lower side lobes permits more latitude in secondary and prescription.	None — size is increased.	N.A.	N.A.

Radio telescopes are normally operated at wavelengths at which they are diffraction-limited. Optical telescopes, on the other hand, commonly work in a nondiffraction-limited regime, and we define this regime as the light-bucket mode. This corresponds to the geometric optics limit, in which surface slopes dictate the image quality. A rough understanding is needed of the implications that light-bucket image quality specifications have on the segment surface quality and segment active control system.

Some insight can be gained by considering the properties of an arbitrarily large corrugated flat panel. At short wavelengths, the slopes of the corrugations will determine the angular spread of reflected light. However, at wavelengths much longer than the depth of the corrugations, the effects of the corrugations become negligible, and the panel acts as a truly flat reflector. Thus, we see that the image quality of a mirror may uniformly decrease with shorter wavelengths (in a diffraction-limited region) until, at sufficiently short wavelengths, the image quality becomes so poor as to be independent of wavelength (geometric optics).

This process can be understood in a semiquantitative fashion using a statistical model for the surface errors, as described by Beckmann and Spizzichino. One assumes that the surface errors, z, are Gaussianly distributed:

$$W(z) = \frac{1}{\sqrt{2\pi}\sigma} \exp -\frac{z^2}{\sigma^2} \tag{1}$$

Thus, the surface height errors are characterized by the rms error σ. The second function that must be specified is the correlation of surface heights at two separate points as a function of their separation τ. This is independent of the surface height distribution. Taking the roughness as isotropic, we write

$$C(\tau) = \frac{z(x,y)z(x,y,\tau)dA}{\int z^2 \, dA} \tag{2}$$

and we then define the correlation length, T, assuming $C(\tau)$ is Gaussian

$$C(\tau) = \exp -\frac{\tau^2}{T^2} \tag{3}$$

Thus, we have reduced all complexities of real surfaces to two parameters, σ and T. Remember that these simplifying assumptions may not be valid, particularly the modeling of T. Thus, any conclusions are clearly approximate and model-dependent.

Defining $g = (4\pi\sigma/\lambda)^2$, Beckmann and Spizzichino give the physical optics diffracted field from a point source for the above surface. For small angles they find:

$$|A(\theta)|^2 = \exp(-g)|\phi_0(\theta)|^2 + \frac{\pi T^2}{\lambda^2} \exp -g \sum_{m=1}^{\infty} \frac{g^m}{m!m} \exp -\frac{K^2\theta^2 T^2}{4m} \tag{4}$$

where $K = 2\pi/\lambda$ and $\phi_0(\theta)$ is the diffraction-limited field ($\sigma = 0$) of the system. For $g \ll 1$ we have the normal diffraction pattern, and for $g \gg 1$, we find the irradiance

$$|\phi(\theta)|^2 = \frac{T^2}{16\pi\sigma^2} \exp -\left(\frac{T\theta}{4\sigma}\right)^2 = \frac{1}{8\pi\theta_0^2} \exp -\frac{1}{8}\left(\frac{\theta}{\theta_0}\right)^2 \quad ; \quad \theta_0 = \left(\frac{2\sigma}{T}\right)^1 \tag{5}$$

This is indicated in figure II-4. The fraction of energy within a cone of half angle, θ', is given by

$$F(\theta') = \exp(-g) \int_0^{\theta'} |\phi_0(\theta)|^2 \, \theta \, d\theta \, d\phi + \exp(-g) \left[1 + \sum_{m=1}^{\infty} \frac{g^m}{m!} \exp \left[- \left(\frac{KT\theta'}{2} \right)^2 \frac{1}{m} \right] \right] \tag{6}$$

When $g \gg 1$,

$$F(\theta') = 1 - \exp \left[-\frac{1}{8} \left(\frac{\theta'}{\theta_0} \right)^2 \right] \tag{7}$$

We now return to the LDR. We assume that the mirror is made of segments with a diameter, $2a = 2$ m, and a full diameter, $D = 20$ m. Assuming that the segments are fabricated individually and that the ensemble has no alignment errors, the mirror can be approximately characterized by the individual segments σ and T.

Further, assuming that the surface is well polished, so that no high-frequency correlations exist and only low-frequency figuring errors (focus, astigmatism, coma) exist, numerical modeling indicates

$$\frac{a}{4} \lesssim T \lesssim \frac{a}{2} \tag{8}$$

We will make the "optimistic" $T = a/2 = 0.5$ m. With these assumptions, we can calculate the image diameter containing 80% of the energy as a function of λ and t. Representative results are shown in figure II-5. From equation (7),

$$\theta[80\% \text{ diameter}] = 10.1 \, \sigma/T \tag{9}$$

We can check this result by doing an explicit calculation for the simplest aberration, focus. Assume that the surface error in a segment is given by

$$z = \alpha_{20} R^2$$

It is apparent that the rms surface error introduced is

$$\sigma = \frac{1}{(12)^{1/2}} \alpha_{20} a^2 \tag{9a}$$

Since the maximum slope error is $f_{max} = 2\alpha_{20}a$, the 80% energy image diameter found by geometric optics in the light-bucket mode at short wavelengths) is given by $0.8 = (0.8)^{1/2}\alpha_{20}a$ or, expressed in terms of the rms surface error:

$$\theta(80) \cong 25 \frac{\sigma}{a} \tag{10}$$
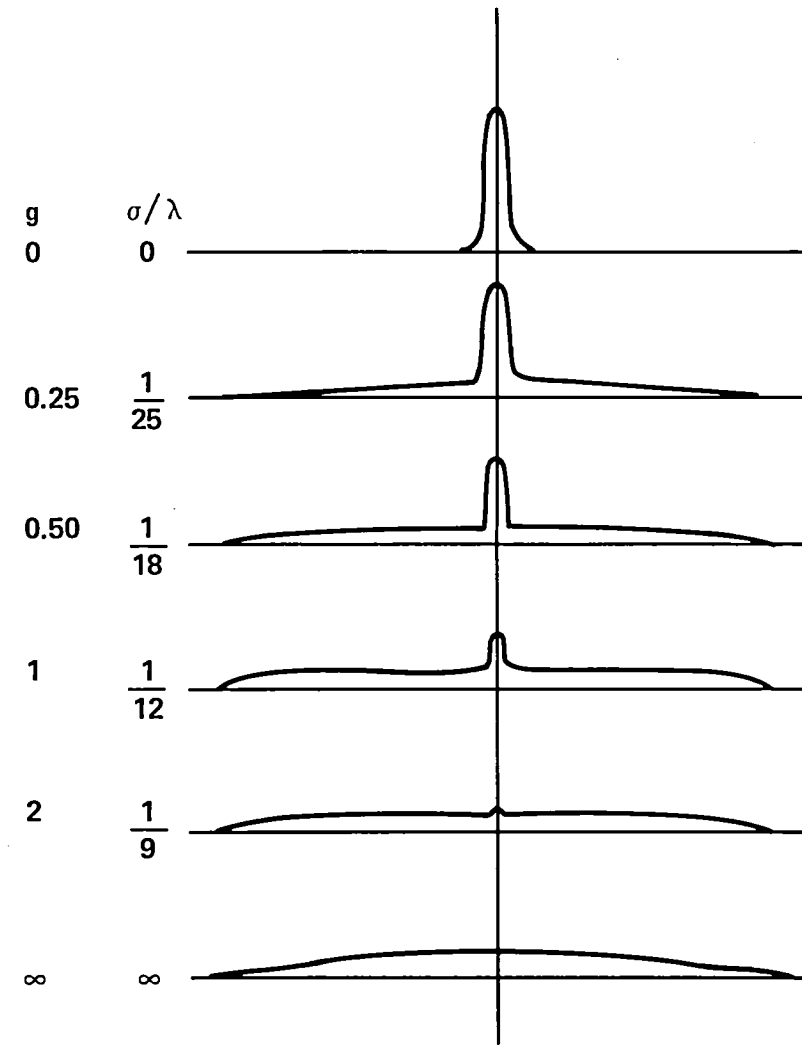
Figure II-4.— Image spread as a function of g.

Equating this to equation (9), we see that for the simplest possible aberration, we can directly calculate an effective correlation length:

$$T \approx \frac{a}{2.5}$$

Since all other figure errors will have shorter correlation lengths, we see that our assumption that $T = a/2$ is indeed optimistic, but not too far from the results of an explicit, nonstatistical calculation.

We see from figure II-5 that there is a definite degradation of resolution as we move into the geometric-optics regime. This follows from the fact the $T \ll D$. In the context of this model, when $T \cong 0.16\,D$ the minimum will disappear.
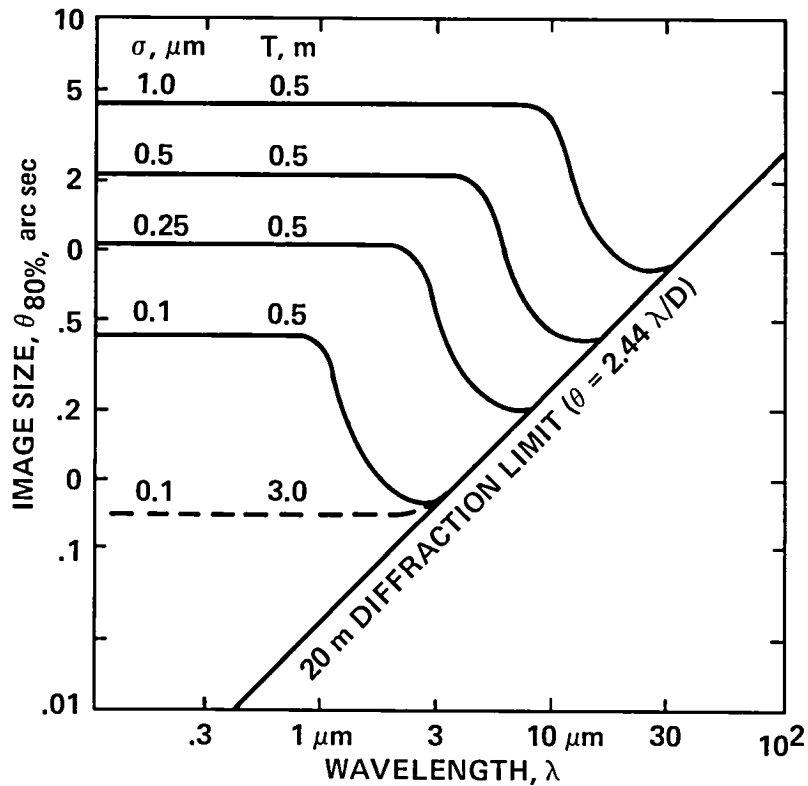
Figure II-5.— Image size versus wavelength.

Larger segments (under the same assumptions) will increase T and thus improve the light-bucket image quality. It seems likely that increasing segment size will increase σ more rapidly than T for a given surface-density segment, so reducing segment size appears more likely to reduce geometric image size rather than increasing segment size. This further improves performance at longer wavelengths.

This trend brings out the importance of the assumption that the segments should be perfectly aligned. As one goes to smaller segments, the difficulty of control increases. At some point the segment control-system errors become objectionable. Note that controls employing edge sensors will have a correlation length $T \gg a$ (see, e.g., the University of California Ten Meter Telescope Report #64 by Mast and Nelson), whereas direct-sensing schemes such as trilateration (Lockheed) or star sensing, will probably have $T \cong a$. More details on the optical effects of segmentation are discussed in the University of California Ten Meter Report #68 by Mast, Nelson, and Welch.

b. *Chopping*— Chopping methods were discussed with the LDR configuration, and tentative conclusions were reached, including the following:

1. Chopping by a moving mirror within the optical train may not be required for many LDR investigations. The required chopping frequency may be sufficiently low in these cases that chopping by moving the entire telescope would suffice.

2. A stable thermal environment will alleviate the chopping requirements for LDR.

3. If the thermal environment is sufficiently stable, the need for chopping may result from other circumstances (e.g., detector properties) than from background variations.

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4. Chopping by wobbling the secondary mirror may not be necessary or desirable, and alternative schemes (e.g., reimaging systems) should be explored.

Chopping is required in the IR range for work from within the atmosphere because one is attempting to detect a weak signal in the presence of large and fluctuating background emission from the atmosphere and optics. With existing systems it is possible to detect signals at the level of $\lesssim 10^{-6}$ of the background power.

On these existing telescopes, chopping is most successfully carried out by "wobbling" the secondary mirror of the telescope to look on and off the source at ~5 to 40 Hz and detecting the resulting a.c. signal (fig. II-6). This has the additional benefits of decreasing $1/f$ noise in detectors and electronics. Potential disadvantages of this scheme for LDR are the unfavorable dynamical consequences of wobbling the large and massive secondary mirror and the possible resulting degradation of image quality.

Several methods of chopping other than wobbling the secondary mirror can be considered. The best method is to move the entire telescope so that the instrumental emission is not modulated. This can be done
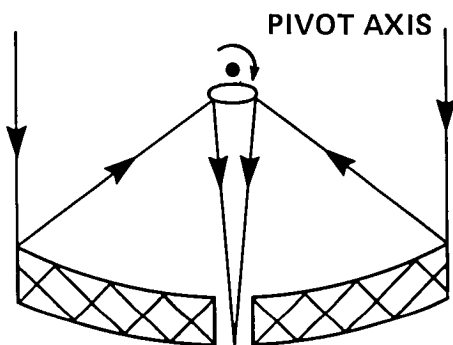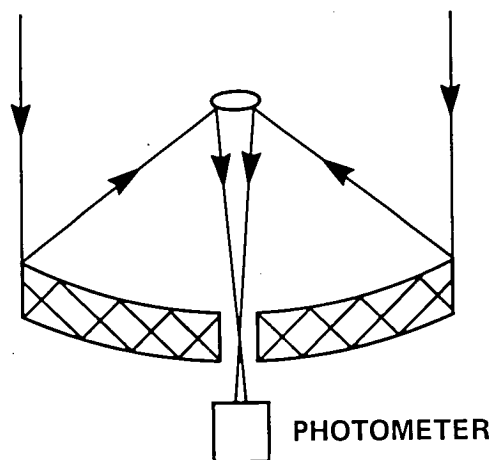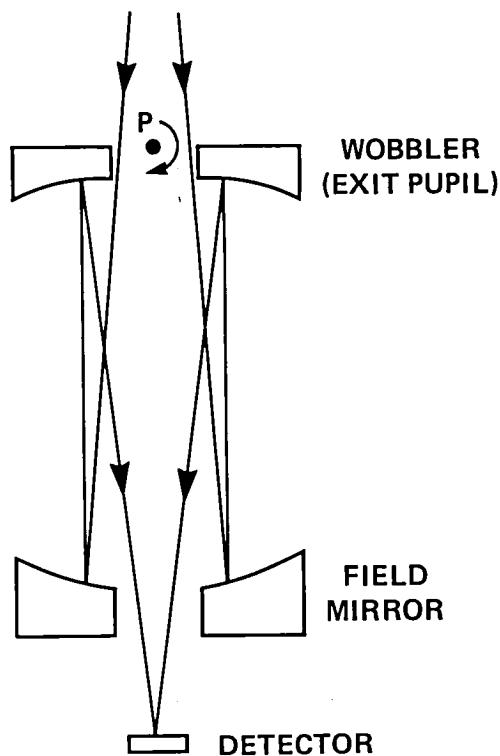
Figure II-6.— Methods of chopping.

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only at very low frequencies. At higher frequencies, it is possible to drop within a reimaging photometer (see fig. II-6), wherein an image of the primary reflector is formed by a third field mirror mounted on a fourth mirror, which is wobbled to execute the chopping. This scheme has been used with some success for ground-based IR work. An additional advantage for LDR is that in this scheme the detector always sees the same portion of the primary reflector and thus is insensitive to problems resulting from temperature gradients across the primary reflector. However, the detector does see different portions of the field mirror (which could be cooled for LDR) and the secondary mirror during the chop cycle.

LDR presents a unique situation with regard to the issue of chopping. The reasons for this are at least twofold. First, the absence of atmosphere means that the dominant background will be due to telescope emission. This should vary relatively slowly (see further discussion below). On the other hand, detection of signals $\lesssim 10^{-6}\%$ of full power will still be desired. Note that for the typical observation parameters ($\lambda = 50 \ \mu m$, $\Delta\lambda/\lambda = 0.1$, emissivity = 0.05, mirror temperature = 200 K, diffraction-limited observation), the background photon flux from the LDR optics will be $\geqslant 10$ arcsec^{-1}. Second, it is very likely that monolithic detector arrays will be widely used for observations on LDR. These will permit the use of the outer portion of an image (or a spectrum) to define a background level. This is equivalent to chopping, but with no loss of image quality. However, the array would have to be very well characterized and very stable to work in the power regime (source power $\lesssim 10^{-6} \times$ background power) in this mode. Of course, not all LDR investigations will be in that mode. The background power will certainly vary for LDR, both temporally and spatially across the focal plane. Thus, some form of chopping by varying the look angle will be required.

The choice of methods (moving the entire telescope, moving a smaller mirror wobbling the secondary mirror, or using a reimaging photometer) will depend on the nature of the scientific investigation, the time scale of the background variations, and the detector characteristics. In practice, several methods will probably be used on LDR, and all options should be left open at present because the relevant parameters of the system and the detectors are totally unknown.

It is possible to assess the chopping problem by computing the maximum allowable temperature fluctuation, ΔT_{max}, averaged over a time $t_c = 2/f_c$, which would lead to fluctuations in power over that time that are greater than those due to the fundamental fluctuations in the background power. In other words, if we chop at frequency f_c and the average temperature fluctuates randomly by more than Δt_{max} in time intervals $t_c = 2/f_c$, we will experience excess noise. This is shown in figure II-7 for a typical LDR observation with the parameters described in the figure. In this case, chopping at 1 Hz requires the average temperature to be constant to ~ 1 mK over $\sim 1/2$-sec time scales (fig. II-7, right axis). Alternatively, if the background subtraction is done by the use of an array, ΔT_{max} is the maximum allowable random spatial variation in the effective background temperature across the focal plane.

All of the influences that might produce a temperature change are not well defined at present, but ΔT_{max} can be usefully compared with the average temperature change $\langle \Delta T \rangle$ expected over the same time interval ($t_c = 2/t_c$) because of the orbital variation of mirror temperature. This is also done in figure I-9, assuming an overall variation of 5 K in half an orbital period (50 min).

Note that $\langle \Delta T \rangle \gg \Delta T_{max}$ does not necessarily imply that this will be excess noise, because the first-order temperature gradient will be linear with time and produce a constant offset with no associated noise. Referring to the left axis of figure II-7, for example, we see that if the gradient is linear to one part in 100, which is conceivable over a short time, then it will not introduce any excess noise, even at chopping frequencies as low as 0.1 Hz. This example was worked out for a broad spectral band and for a high value of the orbital temperature gradient. Under other circumstances, ΔT_{max} could be a much larger fraction of $\langle \Delta T \rangle$.

Figure II-7, therefore, suggests that if chopping is required only to deal with background variations resulting from orbital temperature gradients, chopping frequencies (in the range in which the whole telescope
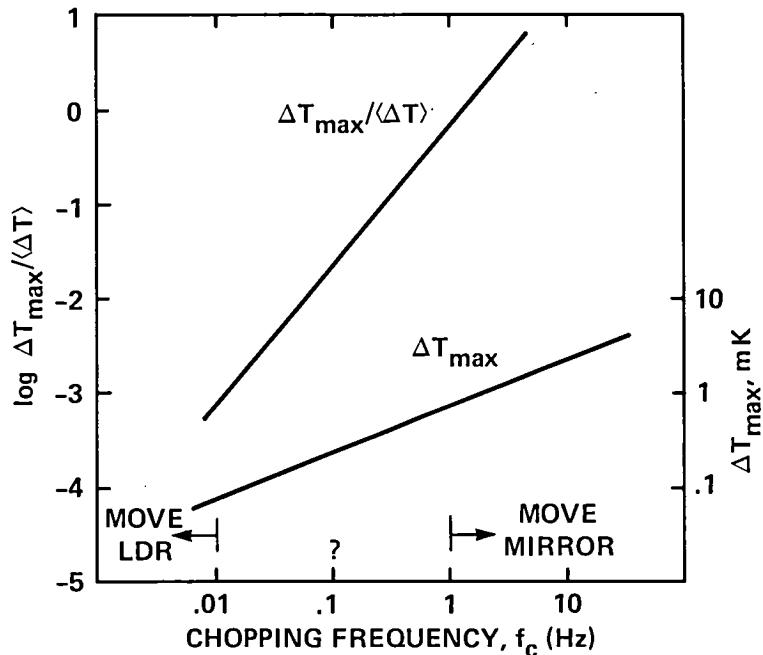
ALLOWABLE TEMPERATURE FLUCTUATIONS (ΔT_{max})
AVERAGED OVER TIME $t_c = 2/f_c$ IF EXTRA
NOISE $\leq$ BACKGROUND NOISE, ARE COMPARED WITH
EXPECTED VARIATIONS, $<\Delta T>$, DUE TO ORBITAL
EFFECTS

CONDITIONS: $T = 200K$
$\lambda = 50\mu m$
$\Delta\lambda/\lambda = 0.2$
$\epsilon = 0.04$
DIFFRACTION-LIMITED FOV, 5°
PEAK ORBITAL TEMPERATURE VARIATION
$(<\Delta T> \equiv \dfrac{5K}{50min} \times t_c)$

Figure II-7.— Effect of LDR mirror temperature variations on chopping requirements.

might be moved) of 0.01 Hz or lower may be used and frequencies in excess of 1 Hz will not be commonly required.

c. *Orbit considerations*— From a scientific standpoint there are no strong preferences affecting the choice of LDR orbit, at least from a "preproject technology program" view. However, orbit choice does strongly affect the following mission aspects and deserves attention when design tradeoffs are considered: sky-viewing constraints, telescope thermal design, detector radiation environment, spacecraft propulsion, and mission timeline (slewing, propulsion, thermal control maneuvers). Current baseline LDR orbit options are as follows. First, the altitude should be about 700 km. A higher altitude would increase ionizing radiation exposure and a lower altitude would require more frequent orbit-sustenance rocket boosts. The LDR observatory spacecraft must have a low-jerk, low-acceleration, storable propellant propulsion system. Existing $N_2O_4N_2H_4$/unsymmetrical dimethyl hydrazine or equivalent rocket technology is adequate, as used, for example, to trim Viking orbits at Mars. To permit Shuttle revisits, either deboost or natural orbit decay may be used, depending upon operational considerations. Although STS could reach LDR operational direct orbits for revisit maintenance and for repair and instrument change-out (by using several orbiter maneuver

subsystem (OMS) kits), LDR should support the dedicated launch. It may be more cost-effective to deboost and reboost the LDR from a low STS orbit for such periodic maintenance, especially if a manned orbital facility is operational when LDR is flying.

Second, a Sun-synchronous (i.e., approximate polar) inclination would be best for thermal and sky-viewing purposes, but requires a Western Test Range (WTR) launch and an observatory mass limit of 32,000 lb for a single Shuttle launch. Low-inclination (28° to 54°) orbits Eastern Test Range (ETR) launch) are acceptable and are used as a present baseline. Maximum mass, then, is 65,000 lb. Figures II-8 and II-9 and unpublished data from S. Bolton and JPL show the effects of inclination and altitude on viewing constraints.

Third, other orbit parameters are not critical, although the mission timeline may be strongly affected by them. Mission sequence planning has become costly and is a fruitful field for future technical improvement to increase flexibility and reduce cost. Modest system-technology efforts in this area are generic and worthwhile.

d. *Lightweight monoliths for LDR—* The current state of the art of mirror lightweighting was discussed. In most cases, the process of completing the surfacing before lightweighting was standard practice. It appears that the monolith design concept discussed is applicable to LDR. The mirror segments were selected as the leading technology driver. Because there was considerable inter-Panel concern over the possibility of achieving the baseline mass for the primary reflector, included is the following discussion of the current state of the art in mirror lightweighting.

Recent work at the Itek Corporation has led to the development of a family of ultralightweight mirrors fabricated from solid mirror blanks. The process includes developing an optimum monolith design concept applicable to LDR. The process involves procuring a mirror blank of sufficient thickness, figuring the front surface of the mirror to match the design surface, and finally, lightweighting the mirror via machine and acid etching.

Experimental efforts have included the development of the following optical components: (1) small samples 6 in. deep and >90% lightweighted; (2) 27-in.-square Pyrex plates 1 in. thick and >85% lightweighted; (3) 9-in.-diam fused silica segments, >95% lightweighted; and (4) 24-in., nominally circular, fused silica, 5-in.-deep segment, 90% lightweighted. In most of these cases, the process of completing the surfacing prior to lightweighting was standard practice. Item 4 included a thermal test at nominally 100 K to determine thermal deformations at cryogenic temperatures (i.e., 0.1 λ at $\lambda = 6328$ Å).

With these data in hand, a concept for an LDR optical segment at 1.5-m-diam was investigated. This segment would be fabricated from a fused silica blank, nominally 2 in. thick, slumped to the nominal radius of the primary reflector of LDR. The surface of this segment would be finished to match the requirements of its location in the overall primary reflector surface. After final polish, the segment would be lightweighted by machining out approximately 90% of the glass, leaving the basic monolithic structure (i.e., a 4-in. triangular web with 2-in.-deep webs. The last step in the process would be to acid-etch the piece to relieve stresses and reduce the weight to the 10-kg/m² requirement. Analysis has indicated the fundamental resonance of the piece to be 30 or 40 Hz, which appears to be consistent with current LDR requirements.

Larger segments, 2 m in size with ≅ 10-Kg/m density, are also available with some reduction in natural frequency.

e. *Sunshade concepts—* A representative sunshade concept was derived by the Systems and Missions Panel for a 60° viewing exclusion angle from the Sun and for a 45° exclusion angle from the Earth. Sunshade geometry, viewing constraints, stray light and thermal analyses, and orbit choice were all recommended for further study (fig. II-10).

ORBIT

CONSTRAINTS

INC = 57°
Ω = 180
ALT = 300 km

60° ANG. AWAY FROM SUN
1° ANG. AWAY FROM EARTH's LIMB
β = ~ 80°

RIGHT ASCENSION (deg)

SUN

ORION

ORBITAL PLANE

45

45

45

45

GALACTIC CENTER

RIGHT ASCENSION (hrs)   SUMMER SOLSTICE
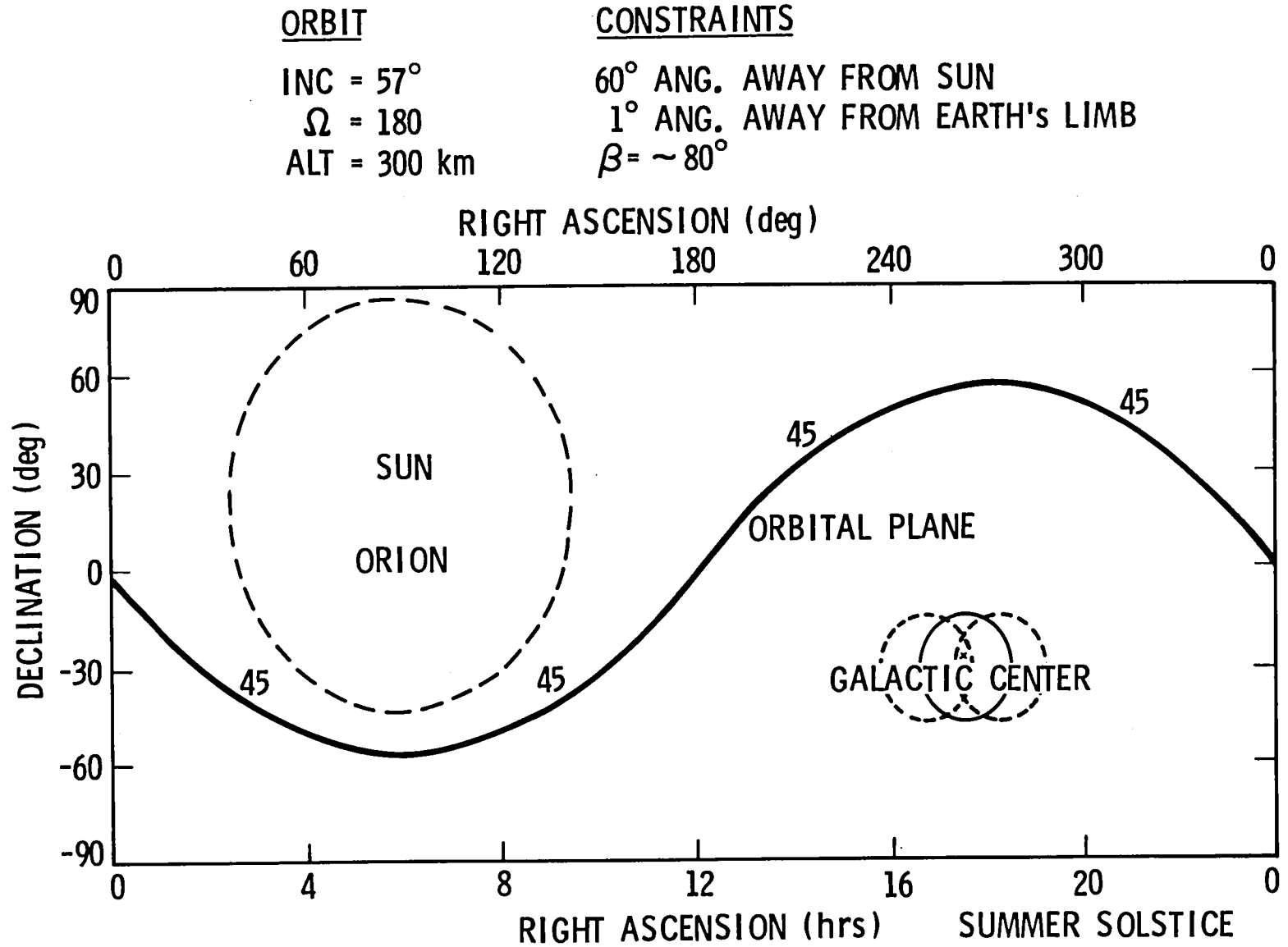
Figure II-8.— Effects of inclination and orbit on viewing constraints.
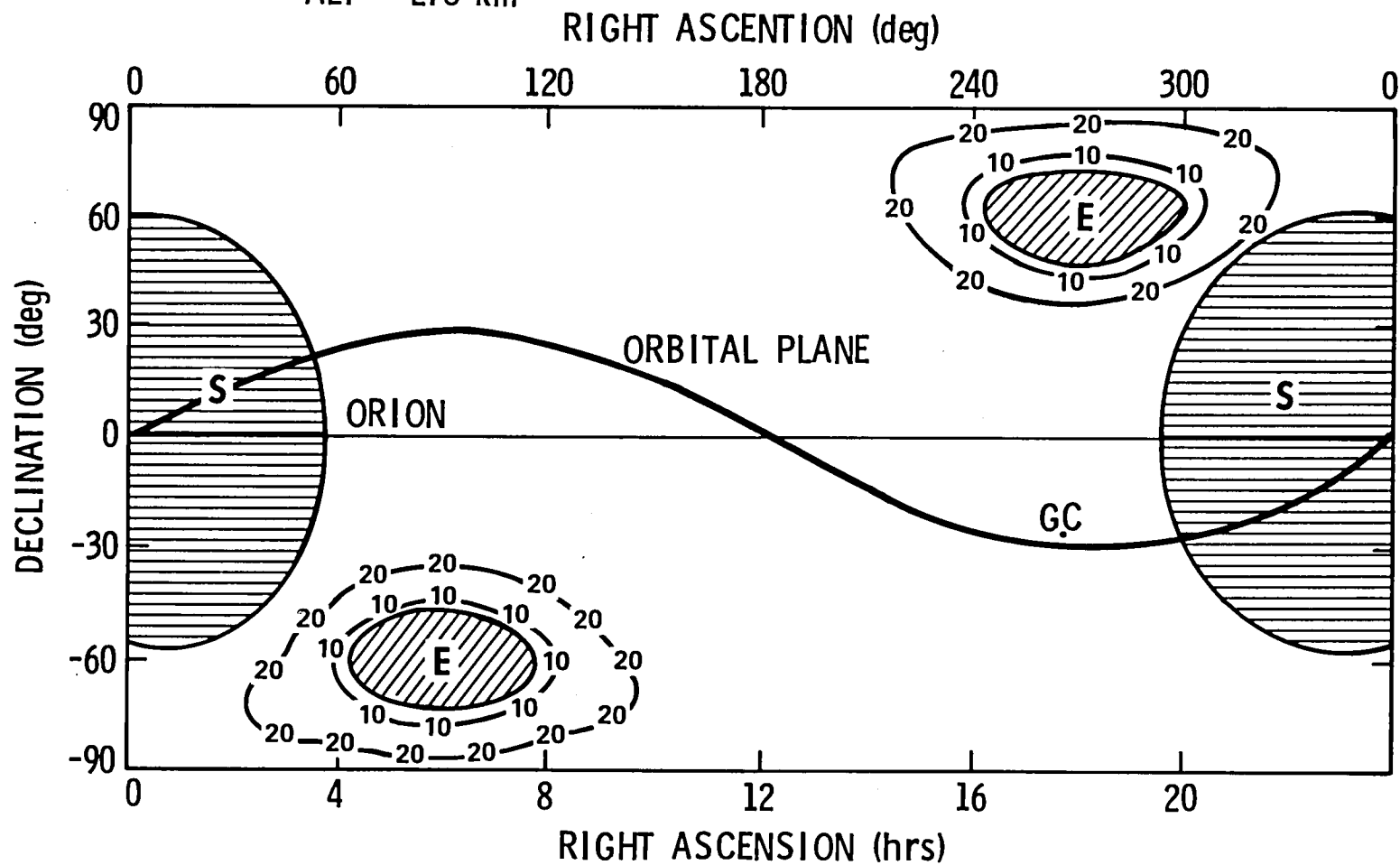
Figure II-9.— Effects of inclination and orbit on viewing constraints.

SUN
60° FROM
℄
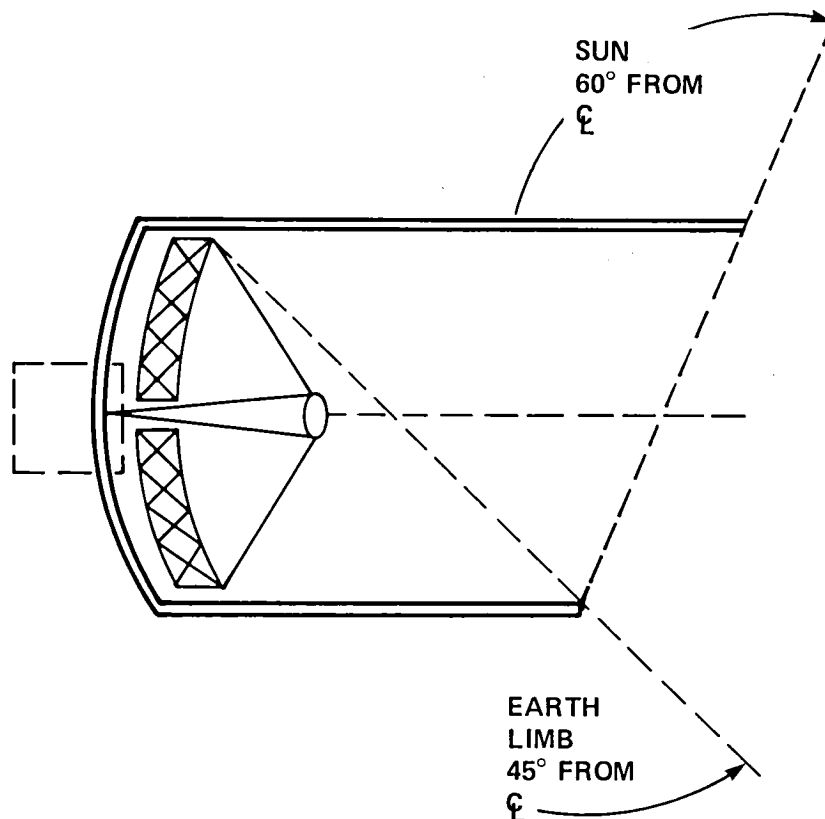
EARTH
LIMB
45° FROM
℄

FOCAL LENGTH AT CASSEGRAIN FOCAL PLANE = 500 m

COOLED OPTICS IN INSTRUMENT PACKAGE PROVIDES DESIRED
IMAGE SIZE ON DETECTOR FOCAL PLANE

ATTITUDE CONTROL SHOULD PREVENT:

(a) SUNLIGHT ILLUMINATING INTERIOR OF SHADE TUBE
(b) EARTHLIGHT ILLUMINATING PRIMARY REFLECTOR

(OTHERWISE A LID MAY BECOME NECESSARY)

Figure II-10.— LDR representative sunshade concept.

f. *Thermal control technology*— Thermal control to meet the requirements of 150 K cooling for the primary reflector and 125 K cooling for the secondary mirror was thought by this panel to be a potential technology driver for LDR. Because the area of thermal control was not specifically covered by any of the other technology panels, it is addressed in the Systems and Missions Panel section of this report.

g. *Power considerations*— Power systems was another critical discipline that was not addressed by any specific panel. At this time, power needs appear particularly demanding and disturbing in their potential systems impact.

Total continuous power needs call for about 10 kW, a majority of which would run the closed-cycle refrigerators. This capacity entails about 100 m^2 of solar panel and a total power subsystem mass of about 4000 kg. Because this is considerably more than the allocated mass, one must hope for considerable technological growth here or accept a different concept and perhaps reduced mission capability. Stored

cryogens would also reduce the power requirement, but at the expense of replacing them at regular intervals.

7. Development Plan

A schedule for the development of LDR, determined by the Systems and Missions Panel, is shown in figure II-11. The schedule was predicated up through LDR flight hardware development (Phase C/D) in FY89. Detailed funding requirements were not established at Asilomar. However, it was estimated by the Systems and Missions Panel that multiple hundreds of thousands of dollars are required in FY83 and FY84, increasing to multiple millions of dollars per year for the major LDR technology thrust in FY85–89, for a total preproject technology cost of tens of millions of dollars. It was felt that such a schedule could be met only with risk and that the schedule should be updated annually, based upon the success of the technology program. It was thought highly probable that, besides a very good ground demonstration and a sophisticated systems simulation, a zero-g "proof of concept" may also be required to demonstrate the LDR method of deployment.

The following is a discussion of the major elements of the LDR development program shown in figure II-11. A major recommendation of the Workshop was the continuing participation by the science community in the LDR development. A continuing science involvement will permit a science review of systems definition studies and technology developments, and updating and refinement of the science requirements, as needed. In addition, science participation was desired to define a preliminary set of instruments to guide the telescope design and instrument technology (detectors/receivers, cryo, and cryo optics) development.
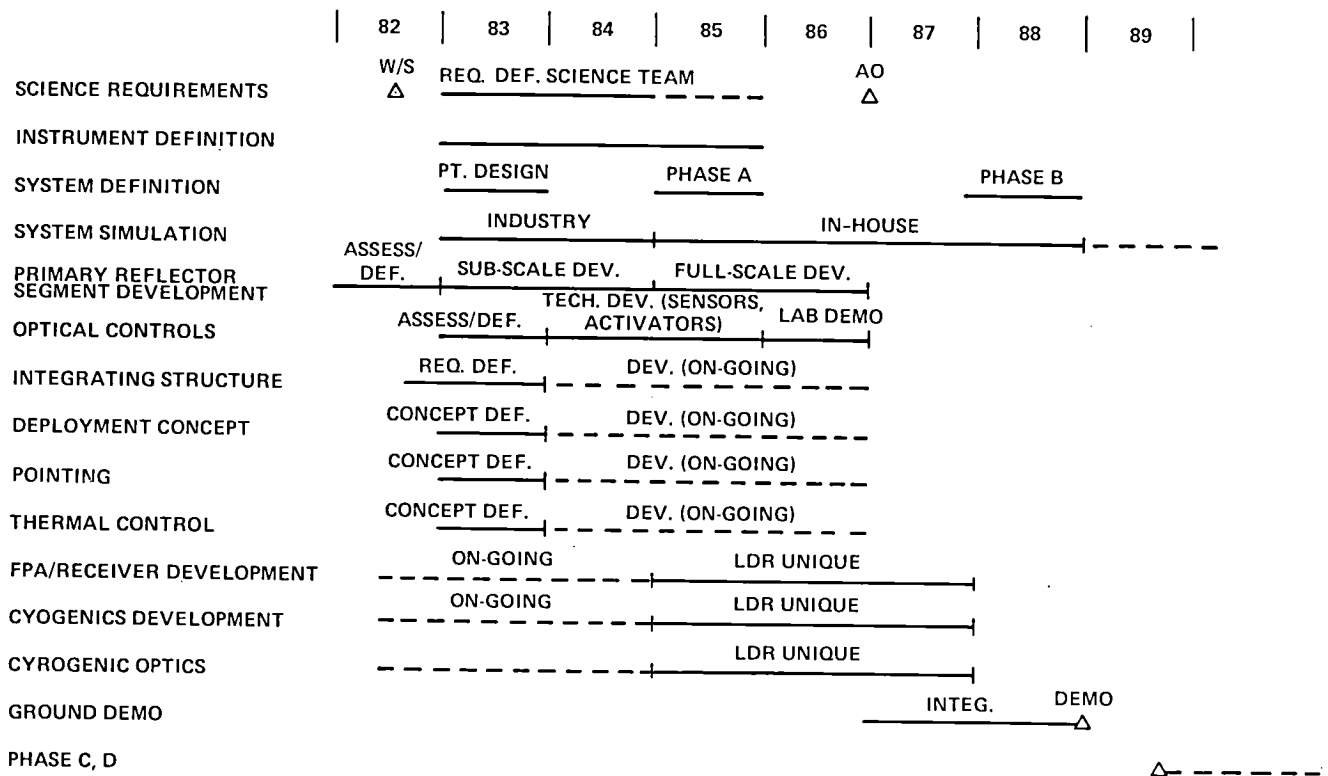

Figure II-11.– LDR development plan.

To guide the technology development programs from a top-down systems standpoint, an immediate (FY83) point design study was highly recommended by the Systems and Missions Panel. As part of this study, major systems level trade-offs and analyses (orbit, mass, viewing, method of thermal control, diffraction-limit versus light-bucket-performance optical configuration, autonomous versus human-assisted deployment, location of chopper, etc.) should be conducted to arrive at a design point.

A Phase A (Requirements/Conceptual Design) study was recommended in parallel with the start of the major technology developmental effort in FY85. A Phase B (Detailed Design) study was recommended in conjunction with the ground technology demonstration. Parallel competitive efforts were recommended for both the Phase A and Phase B studies.

The most pressing element of the LDR technology program, as assessed by the Systems and Missions Panel, are the primary reflector segments. Here, stringent surface-smoothness (1-μm-rms) requirements combined with the requirement for extremely lightweight (aerial density $\leqslant 20$ kg/m^2) and low-thermal-expansivity materials that are also affordable place LDR well beyond the present state of the art.

If the flight project is to begin in FY89, segment technology development should proceed in FY83, beginning with subscale sizes (i.e., <1 m) of the most promising materials and followed by full-scale development of these materials. The segment development should address both materials and low-cost (i.e., replicated) manufacturing methods.

Recommendations from a segment study being conducted by PE (see Introduction of this report) will form the basis for the segment development program. Aside from the thin glassy ceramics being recommended by PE, developments in computer-controlled, machined, lightweighted glass blanks at Itek, development of Pyrex mirrors at the University of Arizona, and development of composite honeycomb sandwiches at JPL are also under consideration.

The next most pressing elements of the LDR technology program are optical controls and instrument technology. In the area of optical controls, a technology assessment leading to a LDR concept definition should be conducted in FY83. During FY84 and FY85, components of the optical control subsystem (figure sensor, actuators, etc.) should be developed and then demonstrated as a subsystem in the laboratory in FY86. The emphasis of this development should be on low cost and space qualification.

In the area of instrument technology, LDR has three driving requirements: size (instrument volumes of ~ 4 m^3), long-wavelength operation (requiring array and receiver technology that does not presently exist at wavelengths >200 μm, and long-life (1 to 3 yr) cooling. Ongoing NASA detector/receiver, cryogenic (both open and closed cycle), and cryogenic-optics developments should be augmented in FY83 and FY84, with specific development of LDR to begin in FY85.

In the technology areas of integrating structures, pointing, and thermal control, it was assessed that while LDR has requirements that press the state of the art, these requirements are not unique, and therefore ongoing efforts in NASA and the Department of Defense (DOD) should provide the required technologies by FY89. However, this assessment requires further verification, and studies of LDR requirements compared with structures, pointing, and thermal control technology were strongly recommended for FY83. The development of an LDR deployment concept in conjunction with the system point design study in FY83 was also highly recommended.

To ensure the integration of the various critical technologies for LDR, a systems simulation capability and a realistic ground demonstration were considered to be absolute necessities. The systems simulation must realistically model LDR structurally, thermally, and optically. The recommendation was to make use of simulations available in industry until an in-house capability can be developed. The ground demonstration

would integrate the segment, optical controls, and structural technologies into a multiple-segment proof of concept. To ensure the validity of this demonstration, it should be conducted in a vacuum chamber under realistic thermal conditions.

8. Topics for Future Study

During the deliberations of the Systems and Missions Panel, a number of areas were identified as needing further study, analysis, and definition. The following is a list of these recommended topics for future study.

a. Define the thermal-system weight penalty associated with the equatorial orbit that can be used to compensate for the diminished weight necessary to launch a spacecraft into a solar-synchronous orbit. The benefit of diminished weight is simplification in viewing schedules; that is, there is no need to avoid the Earth and Sun on each orbit to find the most interesting sky.

b. Quantify the advantages and disadvantages of off-axis optics.

c. Quantify the effects of Sun exclusion angle on Sun/Earth shade weight and inertial problems.

d. Derive a matrix for user needs as a function of λ. Identify cross couplings that can be drivers, evaluate their worth if systems are pushed too far, and identify which experiment needs dimensions for capture area or resolution.

e. Review the general experiences of chopping (chopping for other reasons may shed light on vibration problems, even if the motivation was different).

f. Simplify the instrument (for purposes of fitting into one Shuttle, achieving a polar orbit, living with much reduced cost, etc.) by increasing the λ limit, decreasing size, and decreasing sensitivity (by increasing T). The laws for reducing these should be established to facilitate optimization under any changed constraints.

g. Describe the system and operational consequences of using a slot asymmetrical beam for high-resolution searches and perform the science trade of reduced-aperture area with resolution.

h. Refine irregularities in model statistics for light-bucket analysis. Are there variations associated with different types of segment construction and/or active alignment methods? How does the requirement for active focused area (detector coverage) change with λ and irregularity statistics?

i. Examine concepts of an evolutionary LDR. These need to be performed for a small aperture growing to a much larger size.

j. Study the impact of a space platform or a manned orbital facility (i.e., space station) on the schedule, concept technology, and erection and deployment of LDR. This study is highly desirable because the projected schedule of a manned orbital facility coincides with the planned development of LDR.

C. OPTICS PANEL

1. Chairman's Overview

The first main concern of the Optics Panel was how a primary reflector could be made to meet the desired goals. There is no proven technology that can meet the required weight, thermal and mechanical stability, and surface figure requirements. Because the surface is so large, cost and production time are serious considerations. The second main concern of this panel was that serious consideration be given to non-circular apertures, interferometric options, and off-axis geometry.

2. Primary Reflector Construction

There was a consensus among the Panel that a reflector made of some form of lightweight glass segments was the most viable approach. To some extent this consensus reflects the expertise of the Panel members, but it also reflects the direction that this technology is being driven by military needs for reflectors to operate at shorter IR wavelengths.

A review was made of methods to fabricate lightweight segments of very-low-expansion glass by frit-bonding (e.g., Corning Co., Kodak Co.) and then machining, followed by acid etching (Itek Corp). Industry is tooling up to make segments of 4 m diam, and machines are being developed for rapid computer-controlled polishing and precision grinding of off-axis segments to $\sim$1 μm rms. It appears that this technology for making high-quality segments for an $\sim$100-m^2 primary reflector will be practical and available relatively soon. However, the ability to make primary reflector segments of $\sim$1000 m^2 is uncertain. The segments have to be much lighter and flimsier (for a single or even double Shuttle launch), and the cost and production schedule to make and figure the huge area could easily grow out of hand.

This Panel reviewed other technologies that might lend themselves more easily to the large area and somewhat reduced tolerances of the LDR. Most of the alternatives involve materials that are not so thermally forgiving as the structured ultra low expansion (ULE) segments. Their practicality will depend upon the thermal environment — the operating temperature and its temporal and spatial variations. For this reason the Panel identified the study of the sunshade, orbit, and thermal design as a good alternative to reflector technology.

Alternative glasses that should be considered for a reasonably benign temperature environment are borosilicate and the Cervit-Zerodur families. The latter, partially devitrified glasses, can be slumped into curved sheets, but because they are thin their figure is dependent on minimizing front-to-back temperature gradients, even though the coefficient of thermal expansion (c.t.e.) is very low. Borosilicate can be fabricated into deep, lightweight structures more easily than the refractory ULE segments, but it also needs low thermal gradients because of its larger c.t.e.

This Panel was uncertain about the value of graphite epoxy and other composites for LDR segments, considering the goal of diffraction — limited operation at 30 μm. Because of the inhomogeneity in c.t.e., it seems likely that segments using graphite epoxy would have to be tested at the operating temperature. There was also concern about the long-term stability of the material; for example, its sensitivity to humidity. Nevertheless, the possibility of simple replication of very light, rigid, finished segments from precision masters, as is being tried by Dornier and the University of Arizona, remains tantalizing. Hard numbers on current performance are needed to see whether this is worth pursuing further. If LDR favors a larger-area, less-precise mirror, then this approach could be very competitive, as could all-aluminum honeycomb segments. Aluminum is homogeneous, but its very high c.t.e. (10 times that of borosilicate) would seem to rule

it out for use at 30 μm. There are still further exotic technologies to be considered, such as that of stretched membranes. A careful, unbiased general review would be valuable.

The area of segment figuring was felt to be almost as problematical as that of developing a good substrate. Leighton has demonstrated a capability to measure an assembled dish to an accuracy approaching LDR's goal (1 μm). Methods of figuring based on this type of axisymmetric turning, and on smaller numerically controlled fine-grind and polishing machines need to be evaluated.

Included in the discussions were the methods available to sense mirror figure and wavefront error, and to make the needed corrections. Although the principles for doing this are reasonably well understood, practical devices need to be demonstrated and questions of cost, weight, and control complexity are critical. For example, it is much easier to make light, 1/2-m segments with the correct shape and adequate stiffness than it is to make 2 m segments, but the number of sensors and correcting actuators goes up by 16. This trade-off can be addressed only if some specific concepts are worked out in detail. The problem becomes that of getting the reflector initially into alignment (more difficult) and maintaining alignment during operation (less difficult).

The method to be used for wavefront sensing has a critical effect on segment specifications. For example, if the wavefront is to be studied with visible or near-IR point sources using Hartman (or Shack) methods or interferometry, then smooth, shiny segments are required.

3. Optical Configurations

The area of optical configurations needs immediate attention in the form of optical designs. Like radio telescopes, reflectors that operate at the diffraction limit are often not simply made as round dishes, but their collecting area is spread out in some way to improve spatial resolution. Therefore, rather than make the LDR the biggest round dish affordable, it may be preferable to organize it, for example, as two dishes to be used as an interferometer, with one dish going up first; or as an elongated aperture, 8 by 30 m instead of a circular aperture 15 m in diameter. Obviously, packaging and deployment is radically affected by the reflector geometry, so the options need to be explored soon. The major uncertainty identified by this Panel was the image quality that can be recovered from elongated apertures. It is well known that images with a resolution corresponding to the longest dimension obtainable can be recovered from a set of exposures at different orientations, but the trade-off in signal/noise for point objects and diffuse fields needs to be clarified. Other uncertain factors are the demand for detector stability during a set of exposures, and feeds for beams that are not round.

Another optical configuration choice that must be explored early on is whether to use an on-axis or off-axis optical system. Off-axis systems are mechanically more demanding, but they offer an improved diffraction pattern, lower thermal background, and absence of standing waves at the longer wavelengths. Elongated apertures can be made off-axis relatively easily. Optical design and optimization is needed to explore the diffraction-limited fields that can be obtained with these different options. Off-axis or elongated apertures tend to make the telescopes longer, and correcting schemes with more than one secondary mirror should be explored to keep the physical size down and the field size up. A formal systematic study of design options is recommended.

D. SENSING AND CONTROL PANEL REPORT

1. Chairman's Overview

Sensing and Control will constitute a major subsystem of the LDR and will be critical to its success. The subsystem must perform the following functions:

a. Provide slewing and pointing control of the entire telescope to sub-arcsec accuracy: 0.06 arcsec (absolute), 0.03 arcsec jitter.

b. Provide active alignment, figure, and vibration control of a very large (~20-m) optical system to tolerances of 1 μm.

c. Make the initial alignment of the optical system following deployment and periodically verify and adjust system alignment and optical performance during use.

The three major subsystems of the LDR control system needed to achieve these functions are telescope pointing, figure sensing and control, and telescope calibration and wavefront control. Figure II-12 shows a representative control approach and the interrelationship among these subsystems.

Although listed separately for purposes of discussion, these functions/subsystems are interrelated and are also closely connected to other parts of the system. This close interaction will require that development in all of these areas go forward simultaneously, and because of technical uncertainties, the work to meet these challenges should be undertaken as soon as possible.

It is particularly important that sensor, actuator, and control analysis and synthesis technologies be developed well in advance of any decision on the final LDR configuration. There are many critical system trade-offs (such as the size of primary reflector segments versus the number of actuators required) that can be made only if the sensing and control system technology is well understood.

There are a number of sensing and control techniques of potential application to LDR. Many of these have been demonstrated in the laboratory, a few have been used in flight programs, but none has been applied to a system of the size and complexity of LDR. The state of the art with respect to the various major functions of the sensing and control system is summarized below.

2. Sensing and Control Technology Needs and Status

a. *Telescope pointing—* Although the requirements for pointing and tracking LDR will be numerically less demanding than those of ST, which will precede it in space, the size and flexibility of LDR will make the pointing task the most demanding yet to be faced.

Part of the necessary pointing technology for LDR will be provided by the high-precision, attitude-control techniques of the Shuttle IR Telescope Facility (SIRTF) and ST. Specifically, attitude will be sensed by a combination of inertial-reference units and star trackers. The required star trackers are likely to have significantly larger optical apertures than those used in other systems in order to achieve offset pointing from faint guide stars. Advanced solid-state star trackers and very-low-drift gyros are needed to meet the 0.06 arcsec accuracy and 0.03 arcsec jitter requirements.

PRIMARY FIGURE
CONTROLLER

SECONDARY
CONTROLLER

PRIMARY FIGURE
SENSOR

ATTITUDE CONTROL
WHEELS AND THRUSTERS

FOCAL PLANE
FAST
STEERING MIRROR

IR LOS

IRU

STAR TRACKER

VISIBLE LOS
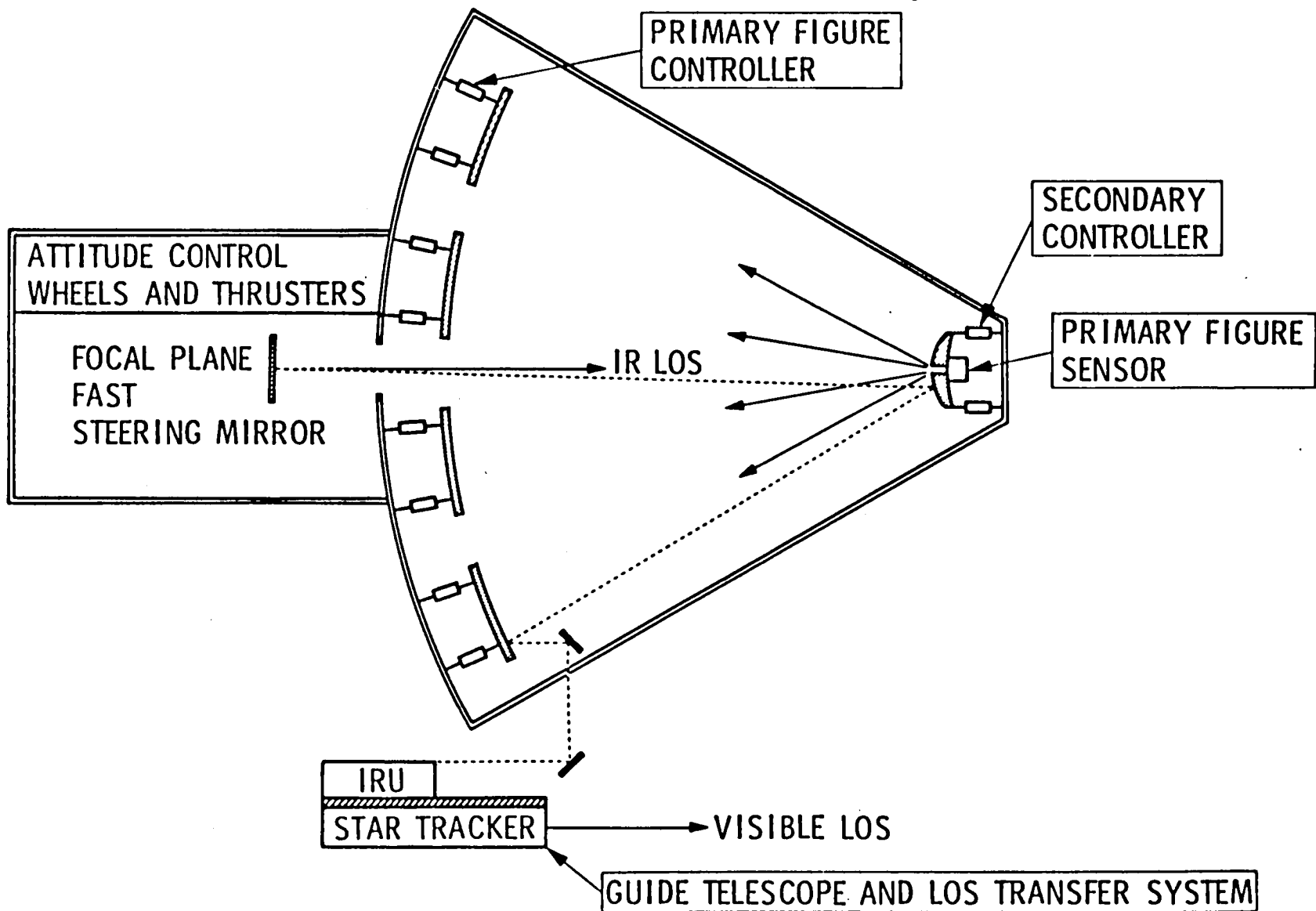
GUIDE TELESCOPE AND LOS TRANSFER SYSTEM

Figure II-12.— LDR representative control approach.

Other aspects of the system are much less developed and understood. The attitude information, having been sensed, must be transferred to the main telescope. Since the main instrument is very flexible, this transfer involves the systems used to sense and control the figure of the primary reflector and the position and orientation of the secondary mirror. Although there is some knowledge of how to make attitude transfers for optical systems consisting of rigid elements, making such transfers in systems with nonrigid elements will require the development of significant new technology for a suitable integrated opto-mechanical measurement and transfer system.

Stabilization of the entire LDR spacecraft to the very low jitter levels needed for successful data taking will require nonimpulsive momentum transfer, using large reaction wheels (these wheels must be large to control the large telescope and meet slewing requirements). Long life and ultraquiet operation may best be satisfied by magnetic bearing wheels.

b. *Figure sensing and control—* This function requires the use of sensors and actuators to accurately measure and control the position and orientation of the segments of the primary reflector and other optical elements of the system, and the control algorithms to process the sensor information and issue the appropriate actuator commands. Although this area has progressed significantly in recent years, LDR will require considerable technology development to achieve (1) a space-qualifiable system capable of sensing the large number of points required by LDR; (2) reliable figure actuators which can be made in large numbers (200–500) at reasonable cost; (3) control algorithms (and processing capabilities) to handle the data from many points simultaneously; and (4) precise LDR dynamic models and the technology to update them in flight.

There are two general approaches to the sensing of segment position. One is global in which the locations are measured from a central location by triangulation, trilateralization, interferometry, or similar techniques. The other is the local or edge-sensing technique in which the position of a segment with respect to its neighbors is measured by sensing the relative position of their edges. These techniques exist in the laboratory in simple form. This extension to a space-qualifiable system capable of handling the large number of points needed by LDR will require considerable technological development.

The control algorithms needed for the large number of degrees of freedom encountered in the figure-control task will be a significant extension beyond anything done to date, and a substantial increase in space-qualified computing capacity will be required. The need for very accurate LDR dynamic models will require on-board system identification and adaptive control technology development in order to update the models in flight and carry out the necessary control system corrections. autonomously.

c. *Telescope calibration and wavefront control—* At present, there is a very limited technology base to draw upon for the initial alignment of the optical system and for the periodic verification of system alignment and optical performance. The consensus among technologists indicates that this should be done by pointing the instrument at a bright astronomical object and sensing the wavefront within the instrument. Although this is a common technique at wavelengths in or close to the visible, its extension to the wavelengths of LDR will require extensive development. Important system tradeoffs will be involved in this area. For example, the tradeoff between the precision with which the system deploys and the ability of the sensing and control system to handle the initial misalignment. In a similar way there is another tradeoff between the cost of providing high surface quality on the segments, thus allowing calibration of the telescope at shorter wavelengths using existing interferometry techniques, versus the cost of developing wavefront sensing at longer wavelengths.

d. *Attitude-figure-wavefront sensing and control integration—* Another significant technology issue is the incorporation of the attitude, figure, and wavefront sensing control functions into the required overall telescope pointing and stabilization function. Technology development is necessary in this area covering a

wide range of technology needs. These needs range from basic principles to demonstration of the concept consisting, as a minimum, of (1) development of extensive analytical simulation tools that integrate control, structure, and electromagnetic models; and (2) laboratory-scaled proof of concept to demonstrate functional capability, and correlation of actual and predicted performance to validate analysis and simulation tools.

3. LDR Control Technology Development Plan

The LDR Control Technology Development Plan shown in figure II-13 is designed to carry out advances in the control system technology required for control of large deployable reflector systems. The specific control systems that this technology enables are: (a) shape determination and control to accuracies of 1 μm, (b) attitude and pointing control of large flexible systems to 0.05 arcsec, and (c) active vibration and shape control for minimizing effects of on-board disturbances. The plan is structured as an integrated series of tasks of modeling, analysis, design, and performance evaluation by means of computer simulation and hardware demonstration. These tasks are to

a. Establish control requirements consistent with system configuration and mission definition developments.

b. Provide conceptual definition of pointing, figure and vibration control systems including actuator/ sensor mechanizations and algorithms for shape determination.

c. Develop analytical models for selected control concepts and incorporate in control dynamics; obtain performance estimates for pointing error, rms surface error, instantaneous primary segment misalignment, slewing dynamics, etc.

d. Establish sensor actuator implementation requirements and develop hardware technology for precise figure and vibration control; develop wavefront sensing technology for determining corrections to the primary reflector to produce the desired wavefront.

e. Develop integrated figure control system for real-time operations and compatibility with the environment.

f. Demonstrate capability to maintain precise figure control in the presence of thermal and dynamic disturbances; verify control systems performance by means of computer simulation.

g. Develop sensor and actuator concepts to brassboard level.

h. Ground-demonstrate functional capability by means of scaled proof-of-concept demonstrations.

E. STRUCTURES AND MATERIALS PANEL REPORT

1. Overview and Summary

a. *Overview*— The Structures and Materials Panel technology assessment with respect to the science requirements was based on a generic class of structural concepts. This class of concepts utilizes an array of rigid, precision, doubly curved, reflector segments that are supported by a stiff truss structure. This generic concept lends itself to active surface control by the addition of actuators between the reflector elements and

FY 84	FY 85	FY 86	FY 87	FY 88

LDR CONTROL SYSTEM SYSTHESIS & TECHNOLOGY TRADES

Conceptual Designs   Mechanization Concepts   Preferred Mechanization
   · Circular   Comparision criteria   Sensor & Actuator Requirements
   · Slot   Control/Structure Optimization   Evaluation of Sensors & Actuator
                   Design Trades   Candidates

CONTROL TECHNOLOGY DEVELOPMENT & PERFORMANCE EVALUATION

Control Law Development   Computer Model Development
   Figure Sensing & Control   Parametric Analyses
   Distributed Control   Control Performance Evaluation
   System Identification/Adaptive Control   Integrated Control/Structure/Optics performance Evaluation

SENSOR TECHNOLOGY DEVELOPMENT

LDR Calibration Wavefront Sensor   Secondary Alignment Sensor
Primary Figure Sensor   Line-of-Sight Sensor/Transfer System

ACTUATOR TECHNOLOGY DEVELOPMENT

Primary Figure Actuators   Distributed Attitude and Vibration Control Actuators
Momentum Compensated Secondary Chopping Actuator

CONTROL SYSTEM TECHNOLOGY DEMONSTRATION

Definition   Build   Closed Loop Demo
Scale   Dynamic Models   Correlation with Analytical Tools
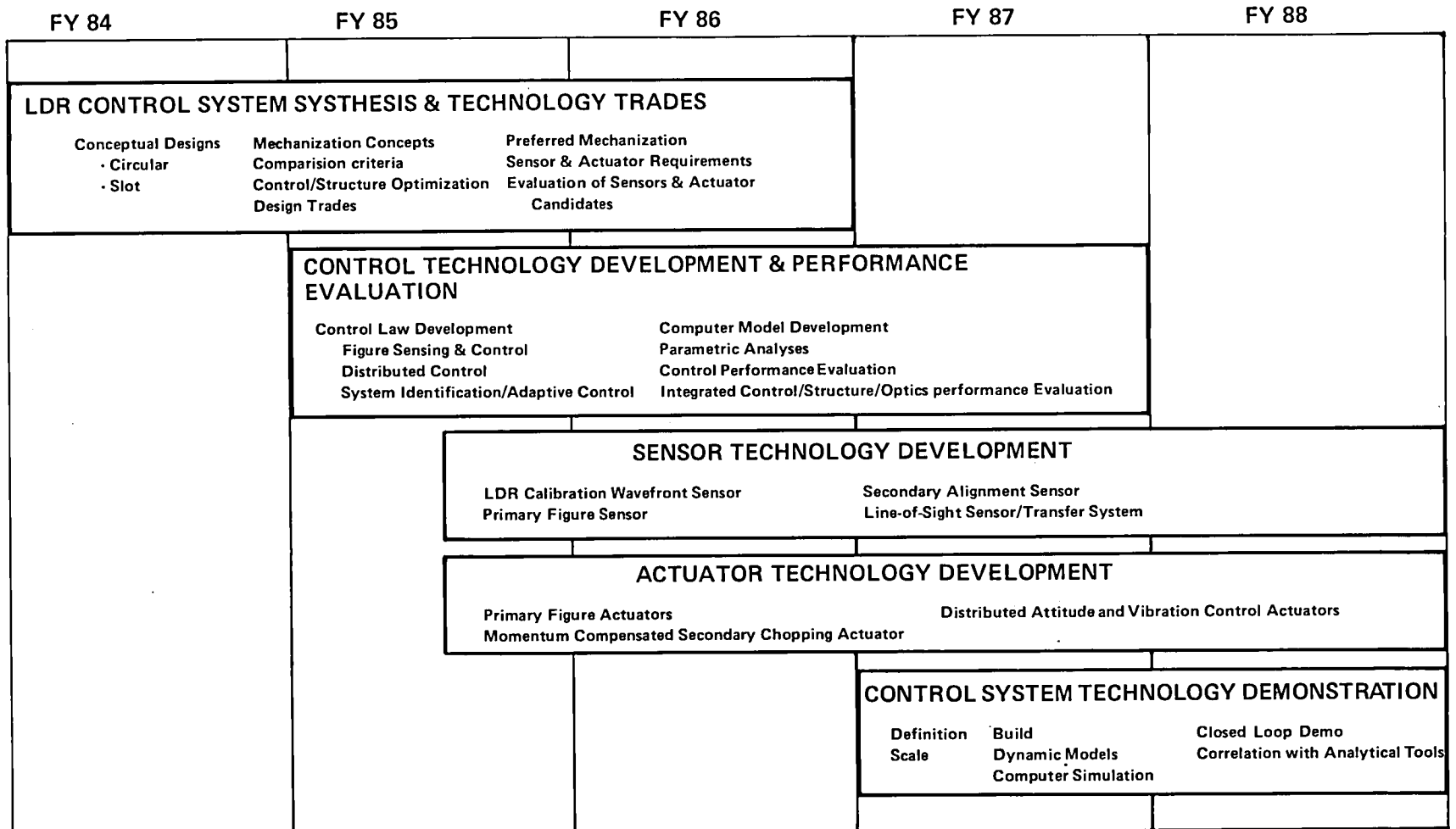   Computer Simulation

Figure II-13.— LDR Control Technology Development Plan.

support structure and to a variety of antenna configurations, with circular or rectangular apertures with on- or off-axis feeds.

Critical technology identification and characterizations were developed by means of a work breakdown structure (table II-3) that contained the specific disciplines needed to accommodate the development of LDR. Results of the LDR technology assessment worksheets provided the technology assessments, task descriptions, timelines, and estimates of resources.

The highest risk structures and materials technology identified was the provision for the highly accurate reflector segments. Technologies with moderate risk included structure deployment/erectable concepts, and structural simulation and validation techniques. The need for low-cost, lightweight, high-surface-tolerance segments is clearly the technological driver for LDR from a structural/materials point of view. Ranges of performance were established for the reflector segments with the limits defined as high probability of success on one end and the best that could be expected at the other. For example, segment weight goes from 10 to 20 kg/m^2, surface precision from 1 to 5 μm rms for segments from 1 to 2 m in size. The higher-precision segment requirements can probably be satisfied only by monolithic material technology whereas the other end of the range might be accommodated by advanced structural composite materials technology.

Structural concepts for space deployment or assembly are required for the primary reflector and its thermal shade. The thermal shade whose design is driven by the orbit, desired operating temperature of the reflecting surfaces, and telescope geometry, is a larger structure than the primary reflector itself. The challenge of developing an attractive combination of the two major elements is great. Limits of potential performance must be established for specific concepts to accommodate the trades needed to determine the range of usefulness of deployment versus assembly and single versus multiple Shuttle flights. The Panel suggests that one Shuttle flight might accommodate a deployable LDR up to 15 m in diameter with an overall surface tolerance of 5 μm rms with reasonably high probabability.

Current analytical tools appear to be marginally adequate for structural simulation of LDR concepts. However technology for interactive analytical performance prediction and the refined materials characterizations needed for such analysis need significant improvement.

b. *Summary*— The LDR reflector concept for a 30-m diam priamry reflector, in a 28° orbit, using 0.5-μm rms segments has significant implications regarding the number of Shuttle flights, the approach for building the structure, the feasibility of manufacturing such high-tolerance segments, and the possible need for an active thermal shade. Current technology is not expected to accommodate a 30-m LDR in a single Shuttle flight, even with moderate relaxation of segment surface requirements. The structural approach for accommodating a 30-m diam LDR will probably be different than that for a 15-m structure. On-orbit assembly becomes more attractive as larger structures are considered. The desired surface tolerance for the reflector segments is so demanding that the use of advanced structural composite materials is probably prohibited, and monolithic glass technology may have to be considered. The 28° orbit is so much more severe than the baseline polar orbit (Beta 90°) that baffles, orbit slews, and/or active shading techniques may be required.

TABLE II-3.— STRUCTURES AND MATERIALS PANEL WORK BREAKDOWN STRUCTURE

I. Structural concepts
   Deployable
   Modular
   Erectable
   Hybrid

II. Structural characterization
   Backup truss for primary reflector
   Reflector segments
   Thermal shade

III. Reflector segment concepts and materials
   Sandwich
   Build-up
   Monolithic
   Membrane

IV. Thermal shade support structure
   Structural support
   Materials

V. Advanced Concepts

The overall viewpoint is that the 30-m-diam (or even 20-m-diam) LDR reflector poses technology difficulties in the area of deployment/erectable schemes and overall subsystem weight. The state of the art will improve as will the capability as the technology programs defined by the assessment worksheets are carried out. It must be emphasized, however, that the needs exceed current capabilities by orders of magnitude in several areas such as the segments. The technology program therefore must be monitored and modified along with the science program.

2. Introduction

The purpose of the Workshop was to review and evaluate the preliminary scientific rationale, generic design concepts, and results of ongoing technology assessment and development for the LDR and to establish realistic technology needs. The Workshop provided a forum for the scientific and technical community to provide inputs and constructive criticism at an early stage in the LDR planning. Results of the Workshop are expected to (a) further define the scientific objectives for a large IR-submm telescope, (b) identify the technical requirements and difficulties imposed by the scientific objectives, and (c) recommend the specific technology developments to accommodate the LDR.

a. *Objectives—* The purpose of the Structures and Materials Panel was to identify the critical technologies and define the specific development tasks needed to accommodate the LDR as defined by the science requirements, resulting from the Workshop by assessing technological requirements, forecasting technology growth, prioritizing needs, identifying options, assessing risk, estimating rough cost, and formulating a technology development plan.

b. *Participants—* The participants of the Structures and Materials Panel represent experts in the subject field from NASA, industry, and the academic community. The individuals and their organizations is given in appendix D.

c. *Tutorial presentations—* Technical presentations were made at the beginning of each panel session by Workshop participants to familiarize panel members with specific technologies and their applicability to LDR.

3. Panel Report

a. *LDR baseline configuration—* The Structures and Materials Panel technology assessment with respect to the science requirements was based on a generic class of structural concepts. The generic concept selected is based on using rigid segmented reflector elements that are kinematically supported, through actuators, by a backup structure. A review of the state of the art for deployable antenna technology indicated that the potential value of current mesh and passive precision surface concepts did not satisfy LDR requirements. On the other hand, concepts for optical applications, which are usually very expensive, more than met the needs of LDR. However, a simplified version of some of the concepts intended for optical wavelengths appears to offer real promise for LDR. The technology options considered for the mechanical configuration include (1) a number of different materials and configurations for the reflector elements, (2) the structural configuration and materials to be used for the truss structure, (3) passive versus active segments, (4) the sunshade configuration and deployment schemes, and (5) the configuration and materials for the secondary support structure.

Active control of the individual panels by actuators was selected as part of the baseline concept. A passive system was considered; however, this approach is not expected to accommodate LDR requirements because of (1) the initial alignment of the panels is dependent on the dimensional repeatability tolerance of

the truss structure, which is not expected to meet LDR surface tolerance requirements; (2) the static support of the panels is a function of the thermal distortion of the truss, which could be significant with respect to requirements and the long-term dimensional stability of the materials used for the truss; and (3) the dynamic stability of support for the panels, which is influenced by the control used for attitude and pointing.

(1) Reflector panels. The LDR mechanical configuration can utilize proven ULE mirror technology or a more cost-effective alternate approach. Since one of the objectives of the Workshop was to assess feasibility for the development of low-cost panels, conventional structural materials such as graphite epoxy, graphite/ magnesium, carbon carbon, graphite glass, and others were considered for application.

(2) Reflector support truss. A truss, whether self-deployable or space-erectable, has the capability of providing a relatively stiff and thermally stable backup structure. Truss-type structures lend themselves to deployable techniques, and a unique deployment scheme for LDR was developed by Astro Research Corporation. This deployable concept has the potential for accommodating LDR in the size range up to 15 m in diameter. Larger LDR structures may have to depend on space-erectable techniques, which may not be sufficiently mature to accommodate LDR by the early 1990s.

(3) Secondary reflector support structure. The secondary support structure originates at three discreet points on the outer edge of the truss and terminates in a support cage for the secondary reflector. The three legs provide a stable support while minimizing the complexity. This basic configuration precludes blockage between the primary and secondary reflectors while providing a relatively stiff structure. The width of each of the three legs of the secondary support structure needs to be minimized to reduce blockage from the primary reflector. Actuators are positioned between the subreflector and its support to correct for defocus and decenter errors. The subreflector support cage can also serve as the reference platform for the star-tracker system.

(4) Focal plane support structure. The optical-reference-plane support structure contains the receiving electronics and must maintain alignment with respect to the secondary reflector. By necessity, this structure will be located along the telescope axis behind the primary reflector to avoid blockage. This structure also interfaces the telescope with the spacecraft. The structure will have to be kinematically attached to the primary truss structure and spacecraft so distortions of the primary reflector and spacecraft interface structure will not be introduced into the optical reference plane. Additionally, this structure will be stable for its three-point support configuration. Theoretically, the structure could be a truss, frame, monocoque, or frame and shear panel configuration. However, many functional considerations, such as surfaces for heat rejection, functional component geometry, reflector deployment schemes, micrometeorite protection and others, will strongly influence the selection and configuration of the structure.

(5) Sunshade subsystem. Evaluation of the LDR concept with respect to thermal distortion of the reflector elements indicates the need for controlling the thermal gradients. Preliminary analysis has shown that multilayer blankets behind the reflector will significantly reduce the gradients through the panels, although some type of sunshade is required to reduce the gradients across the panels so they receive a more uniform flux. No specific concepts have been identified for a deployable sunshade at this time. One important mechanical requirement is that the truss provides the support for the shade structure to avoid introducing unnecessary loading to the panels.

4. Critical Technologies

a. *Reflector panels*— Several different panel concepts have been considered for the manufacture of reflector panels for existing telescopes. These include: (1) honeycomb construction (Al face sheet adhesively bonded to Al honeycomb, and quartz faceplate frit-bonded to a quartz honeycomb); (2) lightweight

monolithic glass mirrors fabricated by selectively removing material from a solid slab of glass leaving a thin face sheet supported by integral stiffeners, (3) slip-casting of glass (ULE) into egg-crate forms, bonding on faceplates and slump-forming over a precision mold to achieve required shape; and (4) membrane technology wherein a relatively thin face sheet is shaped to desired curvature by magnetic or electrostatic forces. The 2.4-m-diam primary mirror used on the ST is very high quality, but has a high areal density (180 kg/m^2). Similar quality mirrors have been fabricated with a much lower areal density (25 kg/m^2), but have had a small diameter (24 in.). (Unfortunately, as diameter increases, so does weight per unit area.)

The technical challenge is to make large-diameter mirror segments (up to 4 m which are lightweight (10–20 kg/m^2), have a surface quality at 150–200 K of 3- to 5-μm rms, and are durable enough to survive launch loads and handling required to deploy or assemble in space. A substantial research and development effort will be required to achieve these goals. Advances in processing and fabrication are likely to occur slowly and at considerable cost. Characterization of candidate materials for final selection and panel design will involve verification tests to establish mechanical and dynamic performance and thermal-vacuum tests to establish surface smoothness over the expected service temperature range. Significant technology advancements are expected to occur in ongoing DOD programs, and LDR can benefit from these efforts. However, a NASA-funded program should be initiated to investigate promising approaches such as composite material panels for specific LDR requirements that are not being actively investigated in DOD programs. NASA-funded technology development on reflector panel materials and designs would be expected to assure the availability of high-quality reflector panels capable of meeting LDR requirements by 1989.

b. *Deployable/erectable concepts—* Structural concepts for space deployment or assembly are required for the primary collector and its thermal shield.

A deployment scheme was developed by John Hedgepeth of Astro Research Corporation specifically for the LDR class of telescopes. The deployment approach is based on breaking up the truss structure into a number of separate deployable tetrahedral cells. Each of these individually deployable truss elements is attached to a single reflector element. These modular elements (i.e., truss and reflector element) are hinged together and stored and supported in a canister-type structure that contains the hinging, extension, and latching mechanisms to accommodate the automated deployment of the reflector portion of the telescope.

The thermal shield, whose design is driven by the orbit, desired operating temperature of the reflecting surfaces, and telescope geometry, is a larger structure than the reflector itself. The challenge of an attractive combination of the two major elements is great. Innovative concepts are needed for a deployable LDR sunshade. Such a new sunshade deployment concept would probably utilize the best features of numerous existing deployable concepts.

Limits of potential performance must be established for specific concepts to accommodate the trades needed to determine the range of usefulness of deployment versus assembly and single versus multiple Shuttle flights. Current concensus suggests that one Shuttle flight might accommodate a deployable LDR about 15 m in diameter with an overall surface tolerance of 5-m rms with reasonably high probability. This assumes that the panel support structure will be highly compactible. Larger-diameter LDR likely will require an erectable structure, extravehicular activity (EVA), and some assembly support equipment (using more cargo bay volume).

As the diameter moves toward 20 m, and as the thermal shielding is better understood (shield becomes more complex), at least two Shuttle launches may be required. Also, it is felt that the panels will have to be well buffered against Shuttle ascent dynamics because of their fragility. Because of their size, considerable cargo bay volume could be required. The sensors planned will also be large and thus the spacecraft could take up considerable Shuttle bay volume. Finally, it must be recognized that the forward 80 in. of the cargo bay will be taken up by EVA and a payload deployment or berthing fixtures, and that more than a few inches

must be left between each separate item that is stowed in the cargo bay to leave room for extraction. Consequently, it is concluded that two launches will most likely be required if a 20-m configuration is sought. This will, as a side benefit, provide relief to the weight restrictions imposed on the panel developers.

c. *Thermal implications of a 28° orbit and 150 K primary—* The 28° inclination combined with a desire for a 150 K primary greatly complicates the thermal design. In 28° inclination orbits, the orbit plane/sun incidence angle (*B*) varies from 0° to 50°. The worst-case thermal design occurs at *B* = 0°. Here the environment is characterized by intense Earth albedo while on the sunlit side of the orbit followed by a relatively cool environment as the telescope passes through Earth occultation.

The principal concern is how to achieve the 150 K. The orbit temperature variations are of lesser concern since segments with large time constants relative to the environment can probably be achieved with proper surface coatings (e.g., silver) and multilayer insulation (MLI) on the panel backside. Two basic approaches (fig. II-14) should be considered for the thermal shield design: an open-aperture shield combined with orbit slews or a shutter aperture shield (similar to the one used with the ST).
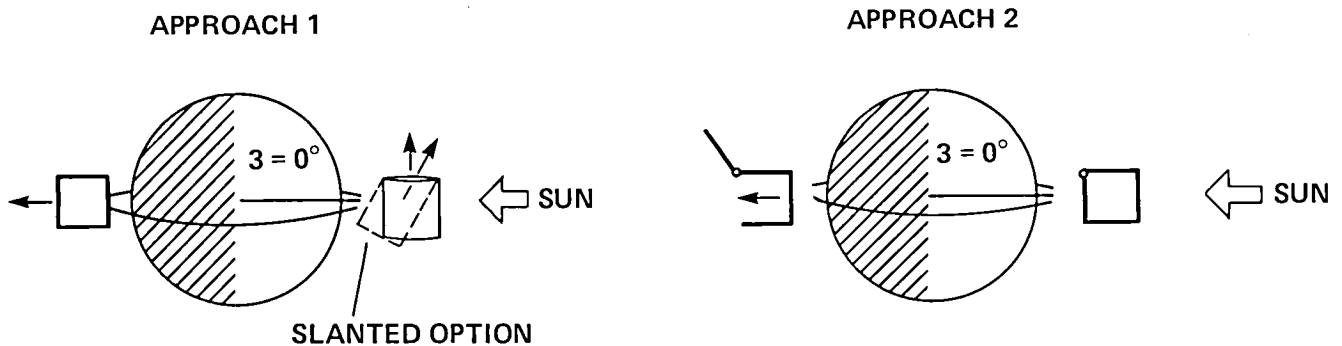
Figure II-14.— Thermal shield design.

An initial (back of envelope) analysis indicates that an open-aperture shield slewed to minimize solar, albedo, and Earth IR entering the aperture could probably be designed to meet 180 to 200 K. It is possible that 150 K can be reached with clever baffling techniques, but this has to be quantified by analysis. In any case, the slewing requirement places a stiff penalty on attitude control.

In the second approach, the telescope would be held solar-inertial with the aperture shutter opened only on the shaded side of orbit. The cover and the sunshade walls would be constructed with MLI to minimize inner to outer surface heat leak. This approach can achieve cooler temperatures that are primarily dependent on the effective emissivity of the MLI. Low-inclination orbits may also result in additional thermal distortions due to larger temperature gradients across the reflector.

d. *Structural simulation and validation techniques—* Current analytical tools appear to be adequate for structural simulation of LDR concepts. However, technology for interactive discipline performance prediction and the refined materials characterizations needed for such analysis needs significant improvement. For example, the technology for performance evaluation involving thermal/structural/control is inadequate to support the trades needed for the efficient and effective technology development for LDR.

Structural/thermal analysis in support of the LDR technology effort should include design optimization of reflector segments, backup truss, and sunshade. Telescope performance needs to be predicted using updated versions of the finite element and thermal models. Additional input/output utility programs need to be developed to automatically interface the thermal, structural, controls, and optical point-spread function models.

5. Technology Development Approach

The basic development approach should be a combination of analysis and hardware model development and testing. The analytical models would characterize the potential performance of the particular subsystem, the developmental hardware models would demonstrate basic concepts at the component and scale-model level, and the breadboard and prototype hardware would validate predictions and manufacturing capability. These same analytical and developmental hardware models would be used for interactive discipline testing such as structure/control/optical. The level of hardware development would depend upon the level of maturity of the specific technologies involved such as the segments selected; the deployment schemes selected for the support truss, secondary reflector, and sunshade; and the material selected for the secondary reflector.

Analytic performance prediction should account for the static, dynamic, and thermal behavior of the LDR. The telescope structural analysis needs to consider dimensional distortions due to mechanical loading, temperature variation, moisture desorption, microcracking, and long-term degradation. Parametric analyses should be conducted to determine the influence of material properties such as stiffness modulus, thermal diffusivity, and coefficient of thermal expansion. Realistic anisotropic properties should be used in these models. The segment optimization needs to consider configuration factors such as the ratio of diameter to depth, the mass distribution between the face sheets and core, and composite fiber orientations.

Static and dynamic structural analysis of the backup truss should consider parameters such as truss aspect ratio, strut elements sizing and material composition, and joint configurations. The models must represent realistic internal damping characteristics. Methods of attaching the sunshade to the backup structure need to be evaluated to minimize induced vibrations on the reflector elements.

The telescope thermal analysis should examine performance at various orbits and orientations. Parametric analysis should be conducted to size the sunshade, to determine multilayer insulation needs and surface thermo-optical properties, and to define thermally imposed attitude constraints. Various sunshade design details need to be evaluated, including baffling techniques, multilayer insulation walls, aperture shutter, and radiator cut-outs. Thermo-optical coatings on the reflector panels should be evaluated to enhance fin effectiveness and increase the time constant relative to the radiation environment.

F. SCIENCE INSTRUMENTS PANEL REPORT

1. Introduction

None of the candidate instruments discussed at the Workshop can be built at this time, but it is reasonable to expect that with sustained developmental progress and breakthroughs in some areas, high-performance imaging and spectroscopic instruments will fly on LDR. The necessary technology work falls into the general categories of heterodyne detection, direct detection, and refrigeration. Specific tasks are unique to NASA astronomical requirements; no significant technological progress relevant to LDR needs should be expected from outside the Agency. A list of technical topics discussed by the panel is included in table II-4.

2. Development Needs

Heterodyne systems for the submm are poorly developed. For the wavelength range near 1 mm, laboratory demonstrations with available components and a few astronomical observations have been carried out.

TABLE II-4.– TECHNICAL TOPICS – SCIENCE INSTRUMENTS PANEL

Heterodyne detection	Direct detection	Instrument technology
Local oscillators (including power and frequency stability requirements) Mixers IF amplifiers Back-end electronics Calibration techniques Radiation effects EMI susceptibility Signal processing	Discrete photon detectors Discrete thermal detectors Arrays (photon and thermal) Cryogenic electronics Radiation effects Calibration techniques	IR filters and beamsplitters Instrument and detector cooling Cryogenic mechanisms Cryogenic optics Signal processing Multiple-instrument accommodations

For wavelengths less than ~400 μm, little more than ideas exist. A well-supported and coordinated technology program to improve the performance of local oscillators, mixers, and frequency multipliers should be set up now, so that level of maturity can be achieved by the beginning of LDR construction. Because there is no previous space project experience for heterodyne systems at these wavelengths and there is negligible military interest, a serious effort by NASA is required. In most cases, the technology is not well enough understood to make definitive specific recommendations. For local oscillators, recent carcinotron developments are promising. This technology should be improved and extended to shorter wavelengths. New solid-state local oscillator concepts with higher output power should also be pursued, since this approach is far more compact and spaceworthy than tube technology. To varying degrees, each of the Schottky, bulk, and superconductor-insulator-superconductor (SIS) mixers have been demonstrated at or near 1 mm, but sensitivity and spectral coverage are limited. It is recommended that all of these ideas, in addition to innovative new approaches, be developed in parallel in the near-term, until clear choices emerge. Improved multipliers would allow established local oscillators to be shifted to otherwise inaccessible wavelengths. It may be that a program concentrating on SIS mixers, solid-state local oscillators, and frequency multipliers would provide the best ultimate performance throughout the 100- to 1000-μm range.

The LDR instrument concepts involving direct detectors emphasized multielement arrays. This area has at least a preliminary technological base at shorter wavelengths. Throughout the far-IR, it is expected that the imaging instruments will be background-limited. Some aspects of the problem should have been addressed by SIRTF before the LDR flight. The unique aspects of LDR, however, involve the emphasis on longer wavelengths, the large numbers of array elements, the need for low focal-plane power dissipation, and the large detector, filter, and instrument dimensions required. Significant technological developments will be required to produce space-qualified extrinsic Ge photoconductor and bolometer arrays for wavelengths greater than 30 μm. Work on a (~100 by 100) Ge:Ga array and a (~10 by 10) bolometer array was given the highest priority. Continuing advances in low-temperature, low-frequency cryogenic electronics should go hand in hand with detector advances.

It appears that LDR will require cryogenic cooling in the instruments which exceeds the state of the art. The need to absorb approximately 1 W at 2 K for a 3-yr period indicates a closed-cycle refrigerator which has significantly longer life, higher reliability, and lower temperature than exists at present. This power level would be reduced by allowing sections of the instruments to run at higher temperatures (~20 K), and by minimizing or filtering the instruments' entrance apertures. A suggested development plan in this area was to develop a low-temperature stage which would couple with higher-temperature, military-sponsored cooler technology. Primarily for reasons of mass and volume, a stored-cryogen system was judged to be impractical. In addition, improved 0.1 and 0.3 K cooling stages will be required if optimum bolometer performance is to be achieved.

The Panel recommended immediate support in all of these areas. Parallel approaches in a well-coordinated program will be required. This is especially true in the heterodyne area, in which the performance of components is tightly coupled (e.g., through mixer and local oscillator power requirements). For direct detectors, it is essential that significant technical progress be made under the SIRTF project. It was emphasized that ground-based and airborne observational experience with advanced instrumentation is an important part of technology development. It should be noted that an active LDR development program would also benefit ongoing and planned orbital, airborne, and ground-based IR/submm astronomy programs. A mix of industrial, academic, and government expertise should be brought to bear, and, since we have at least a decade before LDR flies, promising speculative ideas should be supported.

3. Instrument Complement

The Panel conceived seven instruments which seemed to satisfy most of the requests of the science panels. As was stated above, each would require some level of development, ranging from moderate to major. A heterodyne package to cover three spectral ranges at very high spectral resolution, with common back-end electronics, is included. One- and two-dimensional arrays of photon detectors and bolometers were envisioned in lower-resolution imaging instruments, and in dispersive and transform spectrometers. In the direct-detector instruments, the large size and throughput of LDR and the desire for reasonably high resolution imply large instrument dimensions; it was estimated that a volume of 4 m^3 and significant cooling loads would be required for the instrument package. A careful analysis of sensitivity and resolution requirements would be needed before the proper choice between heterodyne and direct detector systems for the 10^4 to 10^5 range of spectral resolutions could be made.

4. System Implications

It appeared that background subtraction in multielement arrays, which might eliminate the need for spatial chopping, was difficult, except for special cases with level signal-to-noise ratio. Device temporal instabilities and 1/f noise will not allow correction to the 10^{-6} level.

As was mentioned above, large instrument dimensions are anticipated. This implies many cubic meters of Shuttle bay volume, significant power to run the refrigerator (6 kW estimated), and significant cooling loads. The idea of a window or windows at the focal surface to protect the instruments from cryo-contamination was discussed? this would involve development for wide spectral coverage and cooling considerations.

It seemed that dynamic disturbances from the cryogenic refrigerator or interferometer instrument concept would be minor. However, the proposed equatorial orbit could introduce thermal and system instabilities that would rule out extended integration times.

The following three tables were based in the Panel's final presentation.

In table II-5, the development tasks are listed in decreasing order of priority. While all this work was felt to be important, the tasks which were judged essential are marked with asterisks in the table. The phrase "heterodyne systems" encompasses local oscillator, mixer, and frequency multiplier components. Item D-4 includes a variety of important topics, including cryogenic electronics and multiplexers, IR filters and beam-splitters with larger dimensions and improved long-wavelength performance, cryogenic optics and mechanisms, arrays for wavelengths less than 30 μm, and improved long-wavelength photon detectors for both heterodyne and direct detection.

Table II-6 shows a possible instrument complement. For all wavelengths greater than 30 μm with modest ($<10^3$) resolutions, it was anticipated that background-limited performance could be achieved. At higher resolutions and for 1- to 4-μm range, detector or preamplifier noise would be limiting. The heterodyne instruments are listed in order of increasing difficulty.

Concerns about the present LDR representative system configuration from an instrument perspective are listed in table II-7, with the primary problem areas marked with asterisks. Note that about 6 kW of thermal power, and not necessarily electrical power, would be required to run the refrigerator.

TABLE II-5.— INSTRUMENTS PANEL TECHNOLOGY DEVELOPMENT TASKS

Refrigeration
R-1*   Long-life, high-power, 2K refrigerator
R-2   0.1 and 0.3K cooling stages

Heterodyne
H-1*   Heterodyne systems for 300–1000 μm
H-2*   Heterodyne systems for 100–300 μm
H-3   500 μm heterodyne arrays

Direct detectors
D-1   Large (100 × 100) 30–120 μm arrays
D-2*   Large (10 × 10) 120–1000 μm arrays
D-3   120–200 μm arrays
D-4   Supporting technology for instruments

TABLE II-6.— INSTRUMENT COMPLEMENT IDEAS

Instrument	Spectral coverage	Comments
1. 100 × 100 Ge:Ga imager	30–120 μm	Filter wheel $\sim 10^{-16}$ W/$\sqrt{Hz}$ NEP
2. 1 × 100 Ge:Ga spectrometer	30–120 m	• 3 gratings/3 Fabry-Perots, or lamellar • $\sim 10^{-16}$ W/$\sqrt{Hz}$ NEP • Large dimensions with $\lambda/\lambda\Delta = 10^5$ • Single detector option
3. 40 × 40 stressed Ge:Ga imager	100–200 μm	• $\sim 10^{-16}$ W/$\sqrt{Hz}$ NEP
4. 10 × 10 bolometer imager	200–1000 μm	• $\sim 10^{-16}$ W/$\sqrt{Hz}$ NEP • A backup for the 100–200 μm range
5. 10 × 10 Fourier transform spectrometer	$\sim$10–1000 μm	• 1 m travel, folded optics • Large pixels for 40 arcsec coverage • Bolometer array • Heterodyne instead? • $\sim$1 m^3 estimated volume
6. Heterodyne package	110–652 μm	• $\sim$500 W required for carcinotron(s) • Common back-end • $\sim$2 m^3 estimated volume
a. 522–652 μm		• NH$_3$, CO, H$_2$O, C, . . . • 5 times quantum noise limit
b. 361–455 μm		CO, NH, . . .
c. 110–157 μm		Narrow band for selected lines: CII? HD?
7. 40 × 40 Si:In imager or $\sim$2 × 100 spectrometer	1–4 μm	• $\sim$3/4 mm pixels (large) • 2 gratings/2 arrays • $\sim$5 × 10^{-17} W/$\sqrt{Hz}$ NEP

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TABLE II-7.— COMMENTS ON PRESENT LDR REPRESENTATIVE SYSTEM CONFIGURATION

Characteristic	Comment
1. 1.5 kW allowed for instruments*	Estimate ~6 kW, without communication electronics needs
2. Instruments' volume*	One-half of Shuttle bay?
3. Modularity of instruments	Probably harder than Space Telescope
4. Date rate	About Space Telescope rate
5. 3 arcmin FOV, 20 m diameter	Large but plausable dimensions for instrument components
6. Equitorial orbit	Stability problems? FTS would like 20-min integration times
7. Disturbing torques	Should be minor • Estimate 10^{-3} to 10^{-2} N-m from cooler • ~10 kg moving 1/2 m in 20 min for FTS

III. CONCLUSIONS

A. HIGHLIGHTS OF LDR SCIENCE

Viewed in the broadest sense, the scientific rationale for LDR imposes two crucial instrumental requirements: angular resolution approaching 1 arcsec in the 100-μm wavelength region and high-resolving-power spectroscopy with good sensitivity. This reflects the historical experience in the optical and radio wavelength bands in which imaging and spectroscopic capabilities brought a new dimension to our understanding of the universe. These two themes recur throughout the range of scientific problems discussed at this workshop.

LDR, with angular resolution of 1 arcsec, will bring into much sharper focus our view of the universe at IR wavelengths. This resolution will allow us to resolve and study in detail a number of objects ranging from distant galaxies to spiral arms in distant galaxies, to giant molecular clouds (GMC) in nearby galaxies, to the collapsing precursors of protostars in our own galaxy, and, perhaps, to planetary systems around nearby stars and to the bands and the Great Red Spot on Jupiter.

The second major theme for LDR will be sensitive observations of spectral lines. The region from 1 to 1000 μm is crowded with spectral lines of important molecules, atoms, and ions. These lines can be used to probe the physical, chemical, and dynamical conditions in objects as diverse as giant molecular clouds in external galaxies and comets within our own solar system. The critical role for LDR in this area arises from its large collecting area, which allows the detection of very weak lines in small ($\lesssim$1 arcsec) sources, and from its ability to accommodate the complex instrumentation required for spectroscopic observations.

LDR is essential for investigating a wide range of scientific problems detailed in Volume II of this report. The two areas in which LDR will have the greatest effect, as anticipated by the Astronomy Survey Committee, are in studies of the formation of stars and planetary systems and in studies of the structure of the early universe.

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The major conclusions of the Asilomar Science Workshop concerning the telescope requirements derived from scientific rationale are summarized as follows. It was agreed that, since much of the astronomy anticipated is spectroscopic, the telescope need not be at temperatures less than 150 to 200 K. Such temperatures are achievable by passive cooling and a thermal shield. The angular resolution required to provide a major step in our understanding of star formation is about 1 arcsec. For 100 μm, characteristic of emission from star forming regions, this implies a telescope of approximately 20-m diameter.

The reflecting surface should be sufficiently accurate to provide diffraction-limited performance to about 30 to 50 μm. As a secondary goal, it may be desirable to have the capability for making observations in a light-bucket mode in the 1- to 4-μm range, with a blur circle of about 1 to 2 arcsec. Such capability would give LDR unprecedented power in detecting distant galaxies, determining the overall structure of the universe, and predicting its ultimate fate.

B. GENERAL DESCRIPTION OF LDR

One goal of the Asilomar conference was to begin to define the physical parameters of LDR which would be required to achieve the currently anticipated astronomical objectives. As currently conceived, LDR is an approximately 20-m-diameter reflecting telescope deployed in space with a single Shuttle launch. Presently, we envision a free-flying observatory. However, it may be attached to a proposed Space Platform, and it may eventually involve several Shuttle launches and include multiple components. It will be operated as a major national observatory with a lifetime of 10 or more years. Revisits may occur more frequently to replenish cryogens and change instruments.

The physical configuration of LDR is not yet certain, and the project poses many intriguing technical challenges. There are some obvious factors to take into account. The weight and volume constraints of the Shuttle (particularly to polar orbits), the demands of the space environment, and the projected status of technology available for LDR limit the range of options available. Preliminary technical studies have defined the following general characteristics which any design for LDR must have:

1. Because of the limited size of the Shuttle bay, which is 4-m wide, a larger LDR cannot be carried into orbit as a unit. Instead, the reflector surface may have to be built from smaller mirror segments, less than 4 m in diameter. These segments and their associated backup truss must be deployed or assembled in space to form the finished telescope. One alternative to this might be a 4- by 18-m rectangular reflector.

2. The segments themselves must be of low areal density (mass/m^2 of reflector) because of the limited carrying capability of the Shuttle. For a 20-m-diam LDR, the maximum allowable areal density of the reflecting surface is about 22 kg/m^2. This is considerably lower than the areal density of conventional optical telescopes (for comparison, the ST mirror has an areal density of approximately 180 kg/m^2), although glass segments of areal density $\ll$100 kg/m^2 have been fabricated. By contrast, precision high-frequency radio telescopes now operating at submm wavelengths longward of approximately 300 μm have areal densities as low as 20 kg/m^2. A lightweight mirror segment capable of meeting the LDR requirement of a 30-μm diffraction limit has not yet been built, and finding a suitable segment material is a major technological challenge to the project.

3. Both the expected imprecision of the deployment process and the response of the segmented surface to the varying thermal and mechanical disturbances during its orbit require that the relative positions of the segments be controlled; some form of "active optics" will be required to maintain acceptable image quality. This requires a means of sensing the positions of the segments (or the quality of the image) and a means of

moving the segments to achieve the desired figure. It is not anticipated, however, that the figure of each individual panel will have to be controlled.

4. LDR should be thermally stable to minimize corrections to the surface figure and to prevent degraded performance in the sensitive IR detectors. For these reasons, LDR must be provided with a thermal shield to protect the surface from direct sunlight; limits on how closely the line of sight can approach the Sun will also be necessary.

In summary, LDR is conceived as a telescope with a segmented, actively controlled primary reflector which is fabricated of extremely lightweight materials. A thermal shade will be required for thermal protection of the system. The telescope will possibly be carried into space in a single Shuttle launch and be deployed or assembled space before being placed in its final orbit. Atmospheric drag on the large surface area will require an orbital altitude of ~700 km instead of the normal ~300 km operating limit of the Shuttle, so that an additional propulsion unit will be part of the package.

These preliminary considerations were combined with the astronomical technical considerations at the workshop to produce a set of performance requirements and representative system parameters. These appear in table III-1; an artist's conception of what such a telescope might look like is shown in figure I-1.

TABLE III-1.– LDR SYSTEM PARAMETERS AND PERFORMANCE REQUIREMENTS

Parameters	Requirements
Diameter	20 m primary, 1 m secondary
Field of view	$\geqslant$3 arcmin
F/Ratio	System F/10, primary F/0.5
Shortest wavelength of diffraction-limited performance	30-50 μm (aperture efficiency $>$ 30% at 30 μm)
Light-bucket blur circle[a]	2.0 arcsec (at 1-4 μm)
Optics temperature	Primary $\leqslant$200 K ($\pm$1 K uniformity), secondary $\lesssim$125 K ($\pm$1 K uniformity)
Emissivity (system)	0.05
Absolute pointing	0.05 arcsec
Jitter	0.02 arcsec – within 1 min after slew
Slew	$\gtrsim$50°/min
Scan	1° × 1° – linear scan at 1°/min
Track	0.2°/hr (for comets $\gtrsim$25° from Sun)
Orbit requirements[b]	750 km altitude
Chopping	Yes, 2 Hz, 1 arcmin (reactionless)
Sidelobes	Low near sidelobes
Other	Limited cross polarization
Thermal shade L/D	1
Sky exclusion	$\gtrsim$90° Sun from Sun, $\gtrsim$45° from Earth
Cryo system	Various temperatures in the range 0.1 K to 50 K, 1.5 kW total power required
Lifetime	$>$10 yr, approximately 3 yr revisit
Deployment mode	Person(s) assisted (if necessary)
Mass	27,000 kg total (one shuttle)
Weight of instruments	3000 kg (including cryogen)

[a]The tolerances (e.g., rms surface accuracy) needed to achieve a value of 2 arcsec for the light-bucket mode are more severe than the tolerances associated with a diffraction limit of 50 μm. This requirement will be studied further.

[b]Polar orbit desirable but may require multiple shuttle flights. Particle radiation may cause consideration of a lower orbit.

Because the main scientific payoff from LDR will result from observations at high spectral and spatial resolving power, emphasis will be placed on instruments to achieve good resolution. For the highest spectral resolution, coherent detection with heterodyne techniques similar to those of radio astronomy can be used at submm wavelengths. Spectral resolving power ($R = \nu/\delta\nu = \lambda/\delta\lambda$, where ν is the frequency, $\delta\nu$ or $\delta\lambda$ is the resolution, and λ is the wavelength) in excess of 10^6 can be achieved with these techniques, at least to wavelengths as short as 100 to 200 μm. For shorter wavelengths and/or lower spectral resolving power (perhaps in the range $R = 10$ to $R = 10^4$–10^5), spectrometers of various types — grating instruments and Fabry-Perot and Michelson interferometers — will probably be used. The detectors to be used with these spectrometers would include both IR-sensitive, photoconductive devices and bolometers, the latter being used at the longer wavelengths ($\gtrsim 200$ μm). Both single- and multielement (array) detectors will be used with the spectrometers.

Broadband photometric and mapping observations can be carried out with a variety of instruments based on detectors similar to those described above. We can anticipate, however, that in the LDR era monolithic IR arrays will be in wide use. An array can be incorporated with a suitable optical system into an IR camera which will provide images at IR wavelengths and utilize the spatial resolving power of LDR.

A range of filters permitting observations of narrow spectral features will be incorporated into such a camera; additionally, the camera could be used in tandem with a spectrometer for true spectral imaging. Polarizers could be added to the system so that polarization measurements could be made. For certain types of specialized measurements (e.g., high-time resolution studies), a single detector optimized for a particular purpose may be preferable to an array. We can anticipate that most instruments will require some form of cooling to temperatures from 0.1 to 50 K for satisfactory operation, so that cryogenic systems will accompany the telescope and instruments into space.

C. COMPARISON OF LDR WITH OTHER TELESCOPES

1. Current and Future Infrared and Submillimeter Telescopes

A 20-m-diameter LDR would provide approximately 20 times better spatial resolution and 400 times more collecting area than the 1-m class airborne and balloon-borne telescopes now in use at wavelengths between 30 and 600 μm. The increased aperture leads to a dramatic jump in scientific capability and makes possible the exciting and important investigations described herein.

At some wavelengths between 300 μm and 1 mm, it is sometimes possible, though difficult, to observe from mountaintop sites; large ($\gtrsim 10$ m) ground-based telescopes for this purpose will certainly come into use before LDR is launched. Like the airborne and balloon-borne telescopes, these ground-based telescopes will be important scientific and technical precursors of LDR; however, the atmospheric windows in the 300-μm to 1-mm range are narrow and variable. For most purposes, the total freedom from atmospheric effects should make LDR much more powerful than a comparably sized ground-based telescope, which, in any case, could not operate in the LDR primary range of 30 to 300 μm. Similarly, if LDR can be used in the light-bucket mode at $\lambda \lesssim 4$ μm, LDR will be much more sensitive in the near-IR than even the 10- to 20-m diameter New Technology Telescopes projected for the next generation. This is a result of lower LDR temperature and the absence of atmospheric attenuation and emission.

LDR will also complement other space telescopes planned for IR observations over the coming decade. Comparison of LDR with the Cosmic Background Experiment (COBE), the Infrared Astronomical Satellite (IRAS), and the Space Infrared Telescope Facility (SIRTF) — each cryogenically cooled and, therefore, very sensitive — is particularly instructive. COBE is designed explicitly to study the diffuse cosmic background radiation. Its three instruments span the wavelength range from 1 μm to 1 cm. The highest angular

resolution achievable from COBE will be 1°; its findings will thus be complemented by the higher angular resolution provided by LDR. These fine-scale measurements are crucial for investigating small-scale signals from the galaxy-formation epoch. IRAS (size ~0.6 m) has surveyed the sky at IR wavelengths to very low flux levels and catalogued tens of thousands of previously unknown sources, many of which will be seen primarily with a spatial resolution of approximately 100 arcsec at 60 and 120 μm, wavelengths where LDR will be very powerful. IRAS has no spectroscopic capabilities for wavelengths longer than about 30 μm. Because of its much larger aperture and spectroscopic capabilities, LDR will be sensitive enough to study many IRAS sources in great detail and will give us our first information on the sizes and structures of the sources on scales $\lesssim$30 arcsec. SIRTF (size ~1 m) will be an observatory-class facility with interchangeable focal-plane instruments. It is designed to operate from 1.8 to 700 μm, and its very cold ($\lesssim$7 K) optics will make it 100 to 1000 times more sensitive than presently existing IR instrumentation from 5 to 200 μm. SIRTF will therefore open many new fields for study and exploration in the IR. LDR is designed to be especially effective in the submm ($\lambda \lesssim 200$ μm), where telescope cooling is not so important, and possibly also at 1 to 4 μm, short of its own emission peak. The spatial resolution of LDR will be greater than that of SIRTF. LDR will also be more sensitive for many spectroscopic observations because the temperature of the optics matters little at high spectral-resolving power.

The scientific complementarity of LDR, SIRTF, and other facilities is shown in figure III-1, in which spectral resolving power is plotted versus wavelength. The characteristic spectral resolution and wavelength used to study a number of key scientific problems are shown, as is the domain in which each telescope system can be used most advantageously. Although the demarcation is not sharp and distinct, it is shown that LDR will certainly be the instrument of choice for high-spectral-resolution observations at wavelengths $\gg$30 m and for most measurements at wavelengths between 200 μm and 1 mm, whereas SIRTF will be used most effectively for low to moderate spectral resolution at wavelengths from –3 to 200 μm. Large ground-based telescopes can be used for high-spectral-resolution work at wavelengths shortward of 30 μm and may achieve higher sensitivity than SIRTF for most measurements at wavelengths <3 μm. If a light-bucket mode is implemented, LDR may also be very powerful for selected problems at wavelengths of <30 μm. An important dimension not displayed in the figure is that of spatial resolution and FOV. At any wavelength in which it is diffraction-limited, LDR will achieve substantially higher spatial resolution than SIRTF. On the other hand, for observations of spatially extended objects SIRTF's cryogenic optics give it advantages over LDR beyond those shown in figure IV-1.

At wavelengths longer than 100 μm, large, ground-based, millimeter-wavelength telescopes such as the 30-m IRAM (Institut de Radio Astronomie Millimetrique) telescope will excel, although atmospheric transparency makes the exact boundary here uncertain. The ST will have unexcelled capabilities for observations from 1 μm shortward to the ultraviolet.

2. Facilities for Use at Other Wavelengths

LDR, as the first major facility for far-IR and submm wavelengths, is comparable in magnitude and scientific importance to current and planned major facilities being developed for use in other spectral bands. Scientifically, LDR complements ST, AXAF, and large gound-based radio and optical telescopes.

LDR will provide far-IR images of galaxies with angular resolution comparable to that obtained in visual photographs from the ground. Similarly, LDR will explore regions of star formation mapped with comparable angular resolution in lines of CO and NH_3 by advanced millimeter-wave interferometers and by the Very Large Array (VLA) radio telescope, LDR studies these regions at the wavelengths in which they emit most of their energy and will therefore have many magnitudes more sensitivity than the millimeter instruments — enough to detect advanced stages of star formation and the formation of planetary systems.

TYPICAL SCIENCE OBJECTIVES
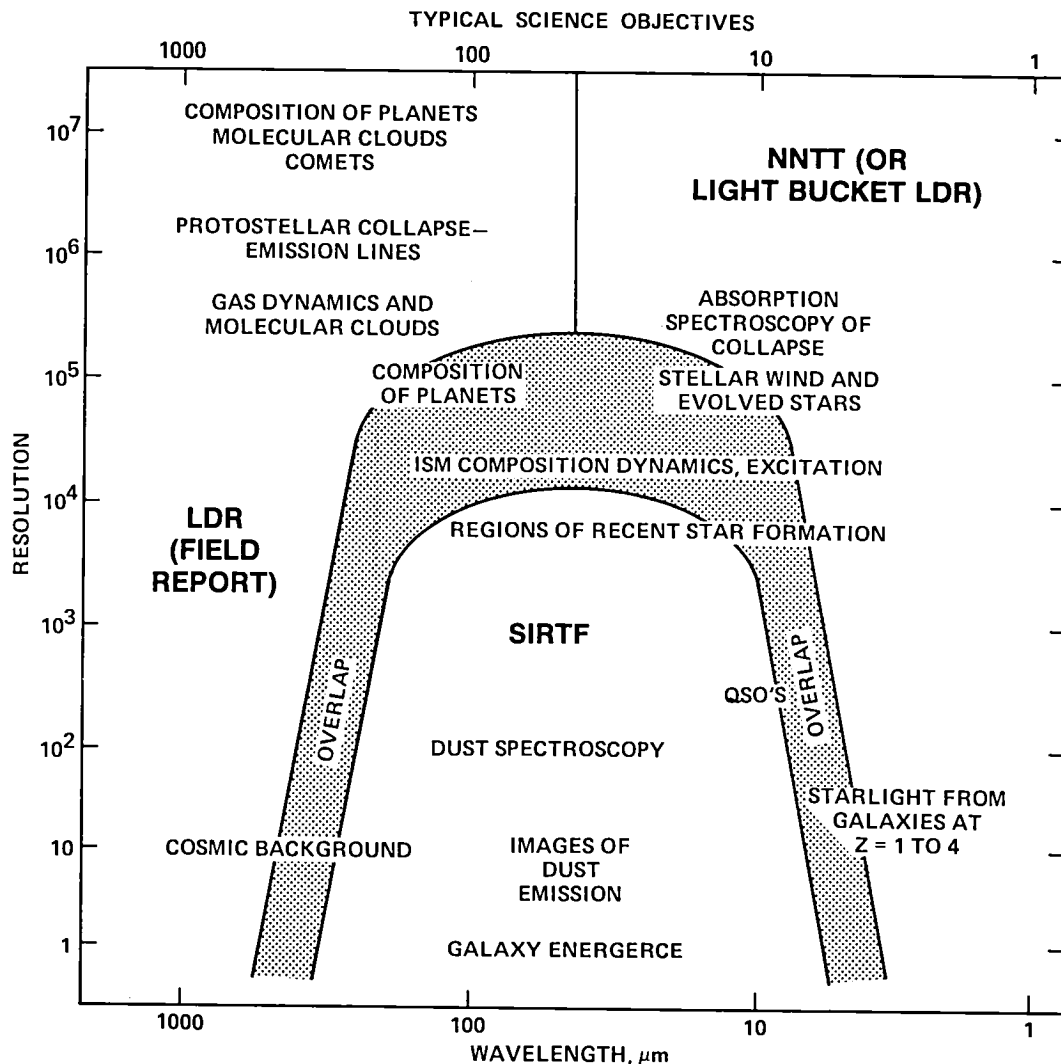
Figure III-1.— Complementarity of LDR, SIRTF, and other facilities.

As a mature observatory, LDR will not just complement telescopes that operate at neighboring wavelengths. For instance, LDR studies of the Sunyaev-Zeldovich effect in clusters of galaxies will be combined with X-ray observations from AXAF to determine Hubble's constant.

Facilities like LDR, ST, AXAF, and the VLA bring immense increases in capability to their respective disciplines. The recent history of astrophysical exploration shows that such leaps in instrumental capability lead to the solution of pressing astrophysical problems and to the discovery of entirely new phenomena.

LDR will bring major advances in performance for high spatial and spectral resolution work across almost three decades of wavelength from 2 to 1000 μm. Together, these advanced facilities will attack astrophysical problems across the entire frontier. LDR, with its unique capabilities for studying cosmology and star formation, will play a crucial role in these investigations and will become one of our major resources for astronomical research for decades.

D. CLOSING TECHNICAL REMARKS

In general, it was found that some areas of LDR are within the state of the art and others will be achieved in the near-term by NASA or military-sponsored developments. However, there are many unique areas in all the major technology disciplines that will have to be specifically funded for LDR. If the guideline for an LDR phase C/D start in the late 1980s is to be met, an intensive LDR technology program of 3- to 5-yr duration must be started soon and will require millions to tens of millions of dollars of funding per year. The feasibility of a late 1980s LDR phase C/D start would be dependent on the success of such an intensive LDR technology program.

It was the concensus of the Workshop Technology participants that there was moderate to high risk in such a technology program providing a sound basis for a late 1980s LDR phase C/D start and an absolute certainty that such dates could not be made without significant technology effort being funded in the next several years. Again, it should be emphasized that the Workshop Technology Panels achieved only a first step in defining the technology issues. The many recommendations of the Technology Panels all require further investigation.

The existing LDR technology development plan (updated Nov. 1981) needs to be updated again based upon these recommendations. Further systems definition studies and mission/telescope/technology tradeoffs are required, such as orbit versus weight versus sunshade/thermal control, and light bucket versus diffraction-limit. A Phase A study in the near-term is essential for providing guidance for an LDR technology program.

Finally, workshops such as this one, on an annual basis, would be extremely useful to reexamine technology versus performance requirements in a technology field that is rapidly evolving.

APPENDIX A

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APPENDIX B

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APPENDIX C

GLOSSARY

angular resolution

The minimum angular separation of two point sources that the telescope could resolve; the angular size of the blurred image of a point source.

carcinotron

A backward wave oscillator that is a source of approximately monochromatic radiation.

light-bucket blur circle

The angular size of the blurred image of a point source observed in the light-bucket regime. Usually defined so that, for example, 50% of the light falls into this angular cone.

light-bucket operation regime

The regime in which the angular resolution or the light-bucket blur circle depends not on the diameter of the mirror, but on the quality of the mirror surface, alignment of the mirror, etc. (also referred to as the geometric optics regime).

spatial resolution

The same as angular resolution, but translated to a length and therefore dependent on the distance of the source or sources from the telescope; for example, 1-arcsec angular resolution means 92 million miles spatial resolution at a distance of 3 ℓ.y., but 184 million miles spatial resolution at a distance of 6 ℓ.y.

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16. Abstract

The Science and Technology Workshop on the Large Deployable Reflector (LDR) convened on June 21–25, 1982, to discuss a large ambient-temperature, far-infrared/submillimeter telescope in space. This is the third volume of the proceedings of the Workshop. This volume contains the results of the five Technology Panels at the Workshop: Optics, materials, and structures, sensing and control, science instruments, and systems and missions.

The goal of the Technology Panels was to review the science objectives developed by the Science Panels and to develop telescope requirements that would enable the science objectives to be met. The Technology Panels then would assess the technology requirements against the projected state of the art at the beginning of the LDR development. Any shortfalls in technology were noted as areas in which NASA would have to augment the generic technology research to produce the technology required to implement LDR. This volume lists the telescope requirements, the estimated technology levels, and the areas in which the generic technology work will have to be augmented.

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