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ADVANCED PASSIVE COMMUNICATION SATELLITE SYSTEMS COMPARISON STUDIES

April 1969

VOLUME II - TECHNICAL DISCUSSION

Contract No. NAS5-10295

Prepared by

GOODYEAR AEROSPACE CORPORATION
Akron, Ohio

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GODDARD SPACE FLIGHT CENTER
Greenbelt, Maryland

CODE IDENT NO. 25500

GOODYEAR AEROSPACE CORPORATION

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FINAL REPORT

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FOREWORD

This report was prepared by prime contractor Goodyear Aerospace Corporation and subcontractor Stanford Research Institute under NASA Contract NAS-5-10295.

The work was administrated by Goddard Space Flight Center. Mr. W. Nyberg, Code 733, was the NASA Technical Officer throughout the program.

This report covers work that was started November 1966 and completed August 1968. J. Roth was the Goodyear Aerospace Project Engineer with B. R. Stack of Stanford Research Institute serving as Project Engineer on the subcontract.

The work reported hwerein is the result of a cooperative effort by a number of persons from Goodyear Aerospace Corporation and Stanford Research Institute. Volumes I and II were prepared by:

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The appendixes, (Volume III), were written by the following GAC and SRI personnel.

APPENDIX

A. Marketos, J.D., Raff, B.W.; Goodyear Aerospace Corporation; "Saddle Reflector Design and Preliminary Structural Analysis."

B. Roth, J., Ray, R.D., Telew, W.; Goodyear Aerospace Corporation; "Saddle Gain and Reflection Characteristics."

C. Schneider, L.,Nedelk, J.; Goodyear Aerospace Corporation; "Position Keeping, Attitude Control, and Fuel Requirements for Large Area-to-Mass Ratio Satellites."

D. Stack, B.R.; Stanford Research Institute; "Study of the Capabilities of Parabolic Antenna Systems with Large Equivalent Apertures."

E. McNaul, J.P.; Stanford Research Institute; "Alternate Antenna Designs."

F. Stack, B.R.; Stanford Research Institute, " An Approximate Expression for the Cost-Gain Relationship in Large Parabolic Antennas."

G. McNaul, J.P.; Stanford Research Institute, "Problems of Radome Use for Very Large Antennas."

H. Baum, Elmer, Clemens, Jules R.; Stanford Research Institute, "A Survey of Very High Power Microwave Transmitter."

I. Ray, R.D., Goodyear Aerospace Corporation; Stack, B.R., Stanford Research Institute; "Derivation of Expression for the System Gain of a Double-Hop Passive Satellite System."

J. McNaul, J.P.; Stanford Research Institute; "Potential Active Satellite Improvement Areas."

K. Stack, B.R.; Stanford Research Institute; "Criteria for Comparison of Performance of Active and Passive Communication Satellite Systems."

L. Stack, B.R.; Stanford Research Institute; "Space Segment Establishment and Maintenance Analysis."

M. Stack, B.R., Stanford Research Institute; "Determination of Channel Capacity of an Active Satellite."

N. Stack, B.R., Stanford Research Institute; "Approximate Cost of Large Ground Based Repeater Station."

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INTRODUCTION

In 1963, the Rand Corporation completed a generalized study of passive communication satellites (Ref. 1). Based upon their conclusions and recommendations, considerable government and industry investigation have been performed in the areas associated with passive communication satellites. However, these prior efforts, which dealt primarily with passive reflectors in low altitude orbits, did not reflect the recent advances in passive satellite technology and did not include sufficient comparative cost analysis. In that sense, previous studies did not provide sufficient data to permit a realistic comparison with corresponding active satellites. The purpose of this Advanced Passive Communication Satellite Systems Comparison Study Program was to review the recent advances and to combine these new technologies to establish for the 1970 time period, a state-of-the-art, feasible, advanced passive communication satellite system for synchronous orbit. This system was then compared against an appropriate advanced active communication satellite system.

The results presented in this report represent the most up-to-date analysis of the comparative effectiveness of active and passive satellite systems. They are considered unique in connection with the study of systems utilizing passive reflectors in stationary orbit since no previous studies of such systems have been performed.

The following section headings comprise the major areas of investigation during the study and provide the main body of this report:

1. TECHNOLOGY BASE

   This section is a summary of each of the major components which comprise an active and/or passive communication satellite system. These areas contain state-of-the-art and projected near-future capabilities along with their associated costs.

2. ECONOMIC AND TECHNICAL COMPARISONS OF ACTIVE AND PASSIVE COMMUNICATION SATELLITE SYSTEMS

   From the technology base, components are selected to fabricate a future passive and active communication satellite system. These advanced systems are compared on a technical and economic basis for two representative applications:

   a. A point-to-point system for two-way voice communications

   b. A one-way television broadcast system

3. TECHNICAL CONSIDERATIONS OF ACTIVE AND PASSIVE COMMUNICATION SATELLITE SYSTEMS

In addition to the economics of comparable systems, which is the prime concern of Item 2 above, other factors may determine the utility of any communication satellite system. This section considers some of these operational problems such as coverage areas, interference to other facilities, and the utilization of the already overcrowded spectrum.

4. ANALYSIS OF THE RELATIVE PERFORMANCE OF A PASSIVE COMMUNICATION SATELLITE SYSTEM AT FREQUENCIES OTHER THAN X-BAND

This section considers the merits of operating passive satellite systems at frequencies as low as 2 GHz and up to 100 GHz.

5. CONCLUSIONS

Conclusions based on this study are delineated. The conclusions, although based upon specific comparison, are extended in this section to the general case of active vs passive satellites. This section provides recommendations as to future investigations, development, and possible implementations of passive communication satellite systems.

6. APPENDICES

The appendices provide, in detail, some of the more significant areas which comprised the basic framework of this study.

TECHNOLOGY BASE

General

This section is a summary of the major constituents that are required to define and establish a satellite, either active or passive, communication system. Each of the following areas contains state-of-the-art and projected near future capabilities along with the associated costs (where applicable):

(1) Passive Satellites

(2) Active Satellites

(3) Large Aperture Antenna Systems

(4) High Power Microwave Transmitters

(5) Launch Vehicle Capabilities

Passive Satellites

Types of Passive Satellites.- Reflectors of various designs were considered for use as passive satellites. To facilitate the comparison, these general concepts were categorized into two groups. The first, summarized in Table I, consists of those potential satellites whose reflection characteristics are such that no satellite stabilization or orientation is required. Table II delineates the general classes of passive reflectors whose application as communication satellites requires some type of attitude control.

The specular sphere, which has been employed as a passive communication satellite, is the simplest of the non-stabilized types. The remainder of the non-stabilized reflectors in Table I all strive to achieve a higher gain-to-weight ratio than that obtainable with the sphere by virtue of tradeoffs toward frequency, angle or time sensitivity .

The reflectors of Table II tend to yield a higher gain but at the expense of additional complexity and the requirement for continuous attitude control. The attitude control requirement, whether accomplished actively or passively, reduces the payload weight which can be applied solely for increased cross section. If an active attitude control system is employed the satellite's useful lifetime will most likely be limited to the lifetime of the attitude control system itself.

Of particular interest among the stabilized passive satellites are the spherical cap and saddle reflector. The spherical cap or lenticular satellite is derived from a segment of a spherical surface. This concept has received extensive consideration in the past since it literally discards that section of the sphere not required for the reflection to take place, thus greatly increasing the effective cross section to weight ratio.

The saddle reflector is a new concept. It's name is derived from its physical shape. The saddle is a portion of the surface of a hyperboloid of one sheet and has reflecting properties quite similar to those of the spherical cap.

One unique property of the above two concepts is that the beam into which they scatter the incident energy is independent of the capture area they present to the incident energy. Stated in another way, the satellite gain and beam coverage area are independent.

The additional concepts of Table II are all capable of achieving extremely large gain to weight ratios. However, unlike the spherical cap and saddle reflectors, these reflectors all have a gain-beamwidth dependence. Therefore, the large gains achievable with these reflectors necessarily result in very narrow beams which in turn demands highly accurate stabilization and would restrict the applications of these type reflectors to point-to-point services.

Passive Communication Satellite Selection.- On the basis of gain-to-weight ratio considerations, non-stabilized reflectors are not competitive with the

Table I. Non-Stabilized Passive Satellites

1.	Specular
	Spheres
	Advanced Spherical Reflectors
	Lens Reflectors on a Sphere
2.	Non-Specular
	Diffuse Reflectors
3.	Volume Scatterers
	Dipole Reflector Clouds
	Dipole Reflector Belts

Table II. Stabilized Passive Satellites

1.	Curved Surfaces	
	Spherical Cap	
	Saddle Reflector	----Selected Concept
2.	Flat Surfaces	
	Flat Plate	
	Flat Plate Statistical Surfaces	
	Corner Reflector	
	Reflectors on Flat Surfaces	
3.	Collimating	
	Shorted Feed Parabolic	
	Shorted Feed Spherical	
	Arrays	

stabilized types. That is, even with the addition of a weight allowance for attitude control, the stabilized reflectors appear to offer an order of magnitude or more improvement in the gain-to-weight ratio achievable with a sphere. This factor is illustrated in Figure 1, which is a plot of gain vs weight (gain referenced to 8 GHz) for several reflectors, including the sphere.

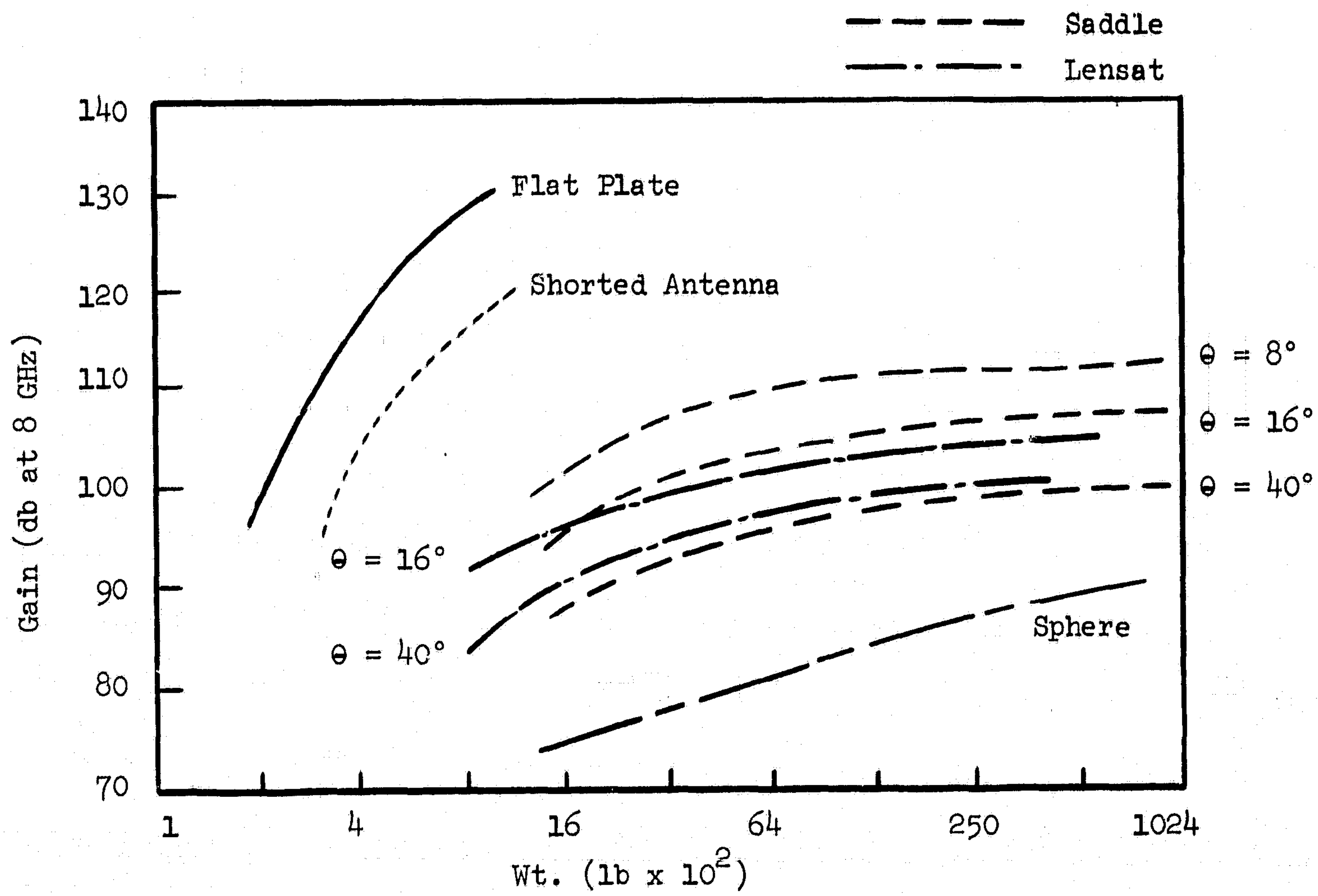


Figure 1. Weight Vs Gain for Various Reflectors

It should be noted that spheres of the size associated with Figure 1 are probably not practicable to build, even if they were competitive on a gain-to-weight basis.

It is also apparent from Figure 1 that the reflectors whose gain and beamwidth parameters are related, offer extremely high gain-to-weight ratios. This is illustrated by the included plots for the flat plate and for the shorted parabolic antenna, which confine the series of plots on the upper end.

However, associated with the high gains for these two plots is an extremely narrow beamwidth, resulting in relatively small ground coverage and a requirement for rather accurate attitude control. For example, with reference to the flat plate plot, the aperture size range between 10 feet and 60 feet with corresponding beamwidth of 0.75 to 0.125 degree respectively.

It is a factor inherent with stabilized reflectors that the direction of the main beam of the reflected energy is fixed by the direction of the incident field relative to some attitude vector of the satellite. That is, the direction of the beam from a given ground station, reflected by the satellite, cannot be controlled once the satellite is positioned and pointed.

However, a desirable feature of a communication satellite system is the capability to receive signals at a number of ground stations when transmitting from any particular site and vice versa. To achieve this flexibility, in view of the limitation defined above, it is essential that some control be exercised over the width of the beam of energy reflected from the satellite. That is, a wider beam is required.

While the beam can be varied for any of the stabilized reflectors, it has been noted that, for other than the curved surface reflectors, variations in the beamwidth result in corresponding changes in the radar cross section or gain. Furthermore, the beamwidth for the curved surface reflectors is independent of frequency, but directly related to the frequency for the other reflectors.

The above factors greatly affect the utility of the passive satellite in a system application and form the background for selection of the curved surface reflectors.

Gain vs weight plots for the lenticular satellite and the saddle reflector are included in Figure 1. Plots are included for a representative range of beam angles, emphasizing this flexibility aspect.

It can be noted that the saddle and lenticular satellite gain/weight characteristics are fairly compatible over the range plotted. However, the saddle reflector has been chosen for the comparative analysis of this study because its structural characteristics permit a tensioned reflecting surface with extremely good tolerances and inherently greater load bearing capability than the lenticular satellite.

Saddle Description.-As mentioned, the saddle reflector (Figure 2) is derived from a portion of the surface of a hyperboloid of one sheet. In its orbital configuration such a reflector can be obtained utilizing a structural approach wherein the entire reflecting surface is always in tension. The basic elements of the approach are illustrated in Figure 3.

Here, the reflecting surface has basically an octagonal planform with catenaries to distribute the load from structural member attachment points. The surface is tensioned by eight bowed structural members jointed at the hub. The bowed structural members are each comprised of a series of telescoping triangular trusses, deployed by drive members located in the hub.

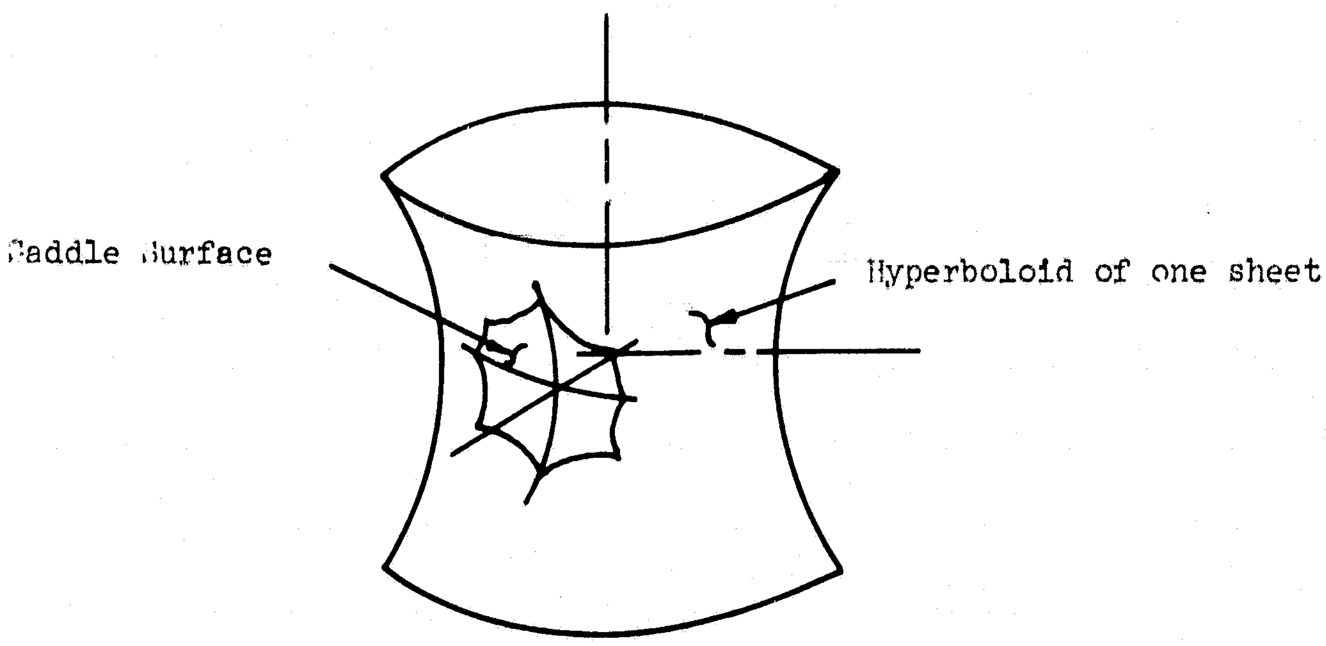


Figure 2. Saddle Reflector Derived From Hyperboloid of One Sheet

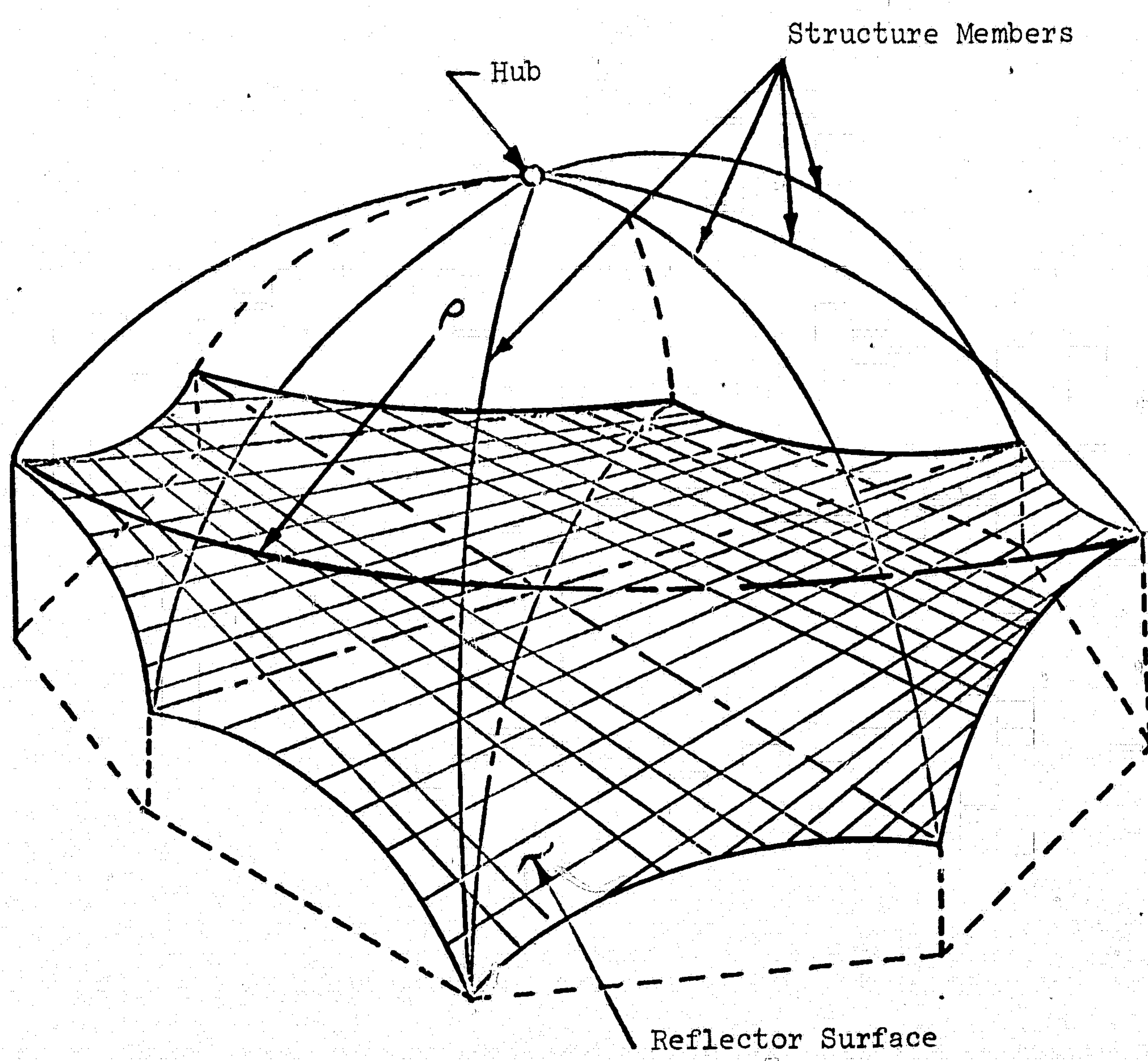


Figure 3. Saddle Reflector and Structure Geometry

A detailed description of the saddle shape, the telescoping booms, deployment mechanisms, deployment sequence and packaged configuration is given in Appendix A.

Saddle Gain.- The gain (Reference Appendix B) of the saddle reflector is defined by the radar cross section referenced to an isotrope.

$$G_s = \left(\frac{2\pi\rho}{\lambda}\right)^2$$

where

ρ = radius of curvature of satellite

λ = wavelength

The angle θ to which the reflected energy is confined is referred to as satellite beamwidth and is similar to the antenna beamwidth of active satellites. The relationship between the passive satellite diameter, D, and its beamwidth and gain is

$$G_s = \left[\frac{4\pi D}{\lambda\theta}\right]^2$$

It should be noted that the beamwidth does not uniquely define the reflector gain as is the case in parabolic antennas.

Figure 4 is a plot of the saddle reflector gain as a function of diameter and beamwidth.

Weight Budget.- Because of the cost gap which exists between Titan IIIC + Burner II and the Saturn V launch vehicle, a 325-foot diameter saddle reflector, whose weight and launch volume are commensurate with the maximum payload capability of the Titan IIIC + Burner II, is the largest reflector utilized in the study.

The weight budget for a 325-foot saddle reflector and associated subsystems is as follows: (Assumed lifetime - 5 years)

	lb
Reflector	
Structural members	1070
Hub and deployment actuators	310
Membrane (1/2 mil aluminized Kapton)	400
TOTAL	1780
TT&C System	50
Propulsion System	640
Power System	330
Control System	65
TOTAL	2865 lbs

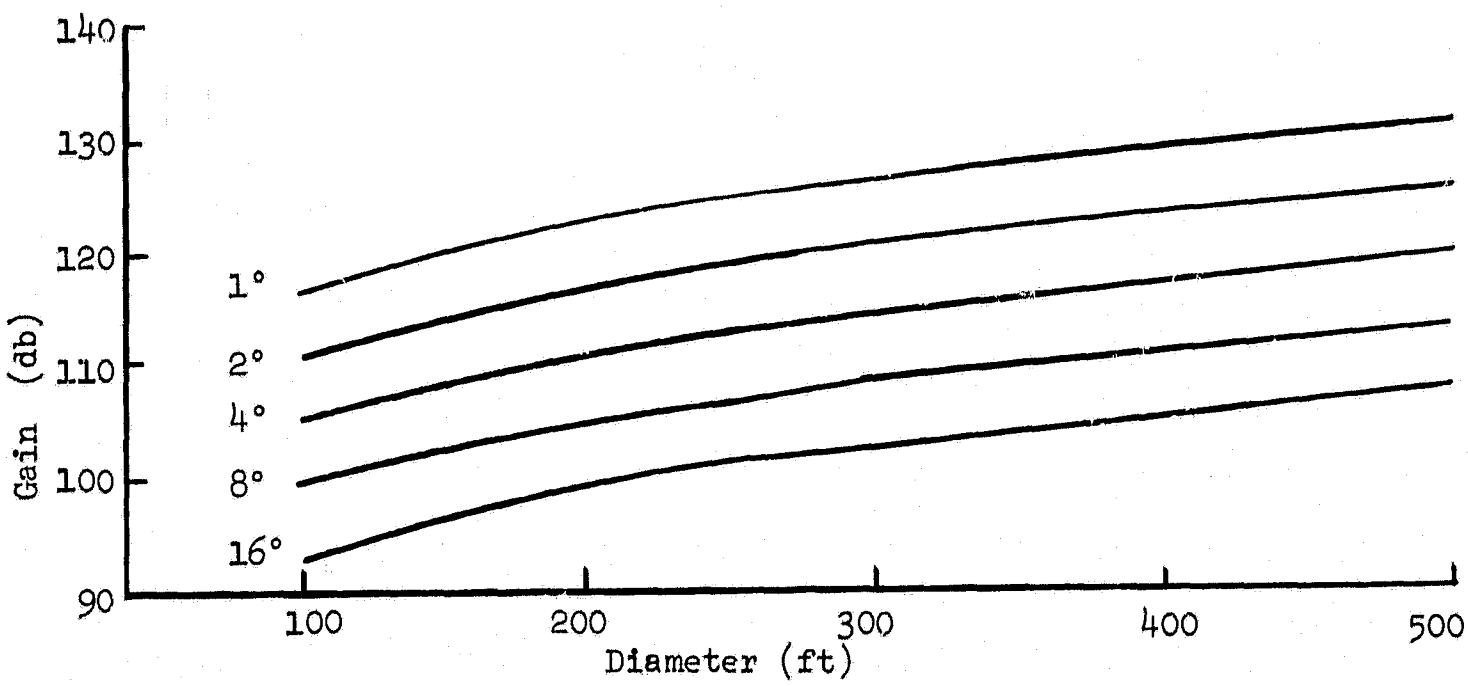


Figure 4. Saddle Satellite Gain

Included in the weight budget are the reflector; supporting booms, solar cell arrays; a rigid hub containing electronic equipment and deployment mechanisms; and a propulsion system for station keeping (Appendix C).

Parametric weights, as a function of equivalent reflector diameter, were generated for the saddle satellite, in a manner similar to the preceding. Two assumptions were made concerning the packaging diameter available for the structural members.

The first was that the packaging diameter is a function of reflector equivalent diameter with packaging diameter assumed as follows:

Packaging Diameter (ft)	Reflector Equivalent Diameter (ft)
3	100
6	400
12	1600

The weights for this analysis are shown by the upper curve of Figure 5. The second assumption was that the packaging diameter is a constant 20 feet

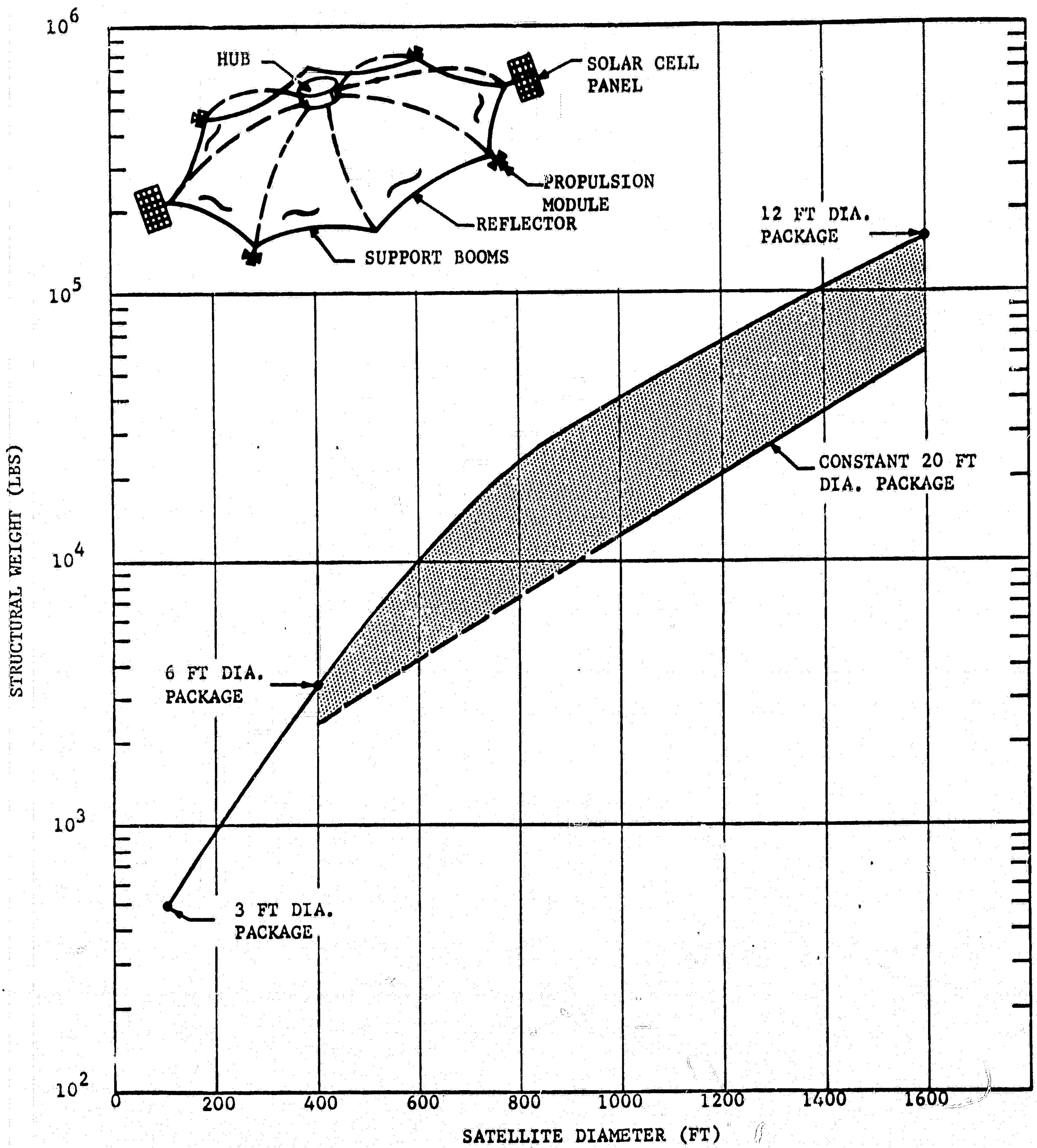


Figure 5 - Reflector Parametric Weight

which would be compatible with the Saturn V launch vehicle. While a limitation was placed on the diameter utilized in the analysis, this program was run for diameters from 10C to 1600 feet. The results are indicated by the lower curve on Figure 5. This curve was then extrapolated to smaller diameters (reflector diameters as shown by the dotted line.

Satellite RDT&E Costs.- The saddle satellite RDT&E costs have been estimated on the basis of consideration of the following major cost elements:

(1)	Engineering design and test costs	C_A
(2)	Tooling costs	C_B
(3)	Development test model costs	C_C
(4)	Flight test unit costs	C_D
(5)	Facilities costs	C_E
(6)	Ground support equipment costs	C_F
(7)	Management costs	C_G
(8)	Documentation costs	C_H

The above major elements combine in the following manner to yield total RDT&E costs.

$$\text{RTD\&E cost} = C_A + C_B + C_C + C_D + C_E + C_F + C_G + C_H$$

For the passive reflector under consideration, each of the terms in the above expression can be expressed directly as a function of satellite diameter (D), with the exception of C_G and C_H.

That is,

$$C_A = 1300D^{1.4}$$

$$C_B = 13.2D^{1.4} + 4.45 \times 10^4$$

$$C_C = (460D^{1.4} + 1.15 \times 10^6)\ N'$$

$$C_D = (400D^{1.4} + 1.35 \times 10^6)\ N$$

$$C_E = 4.71\ (D + 30)^2 = 4.71D^2 + 282.6D + 4240$$

$$C_F = 80D^{1.4} + 0.27 \times 10^6$$

where

N' = number of equivalent* development units

N = number of delivered units.

It should be noted that while the flight test unit cost includes provisions for launch support costs, the booster costs have not been included.

C_G and C_H are expressed as simple percentages of the first six terms in RDT&E cost expression described above. That is,

$$C_G = 0.06 \left[C_A + C_B + C_C + C_D + C_E + C_F \right]$$

$$= 0.2826D^2 + \left[83.59 + 27.6N' + 24N \right] D^{1.4} + 16.96D + \left[0.0191 + 0.069N' + 0.081N \right] \times 10^6$$

$$C_H = 0.05 \left[C_A + C_B + C_C + C_D + C_E + C_F \right]$$

$$= 0.2355D^2 + \left[69.7 + 23N' + 20N \right] D^{1.4} + 14.13D + \left[0.0159 + 0.0575N + 0.0675N \right] \times 10^6$$

The final expression for RDT&E cost can then be written as

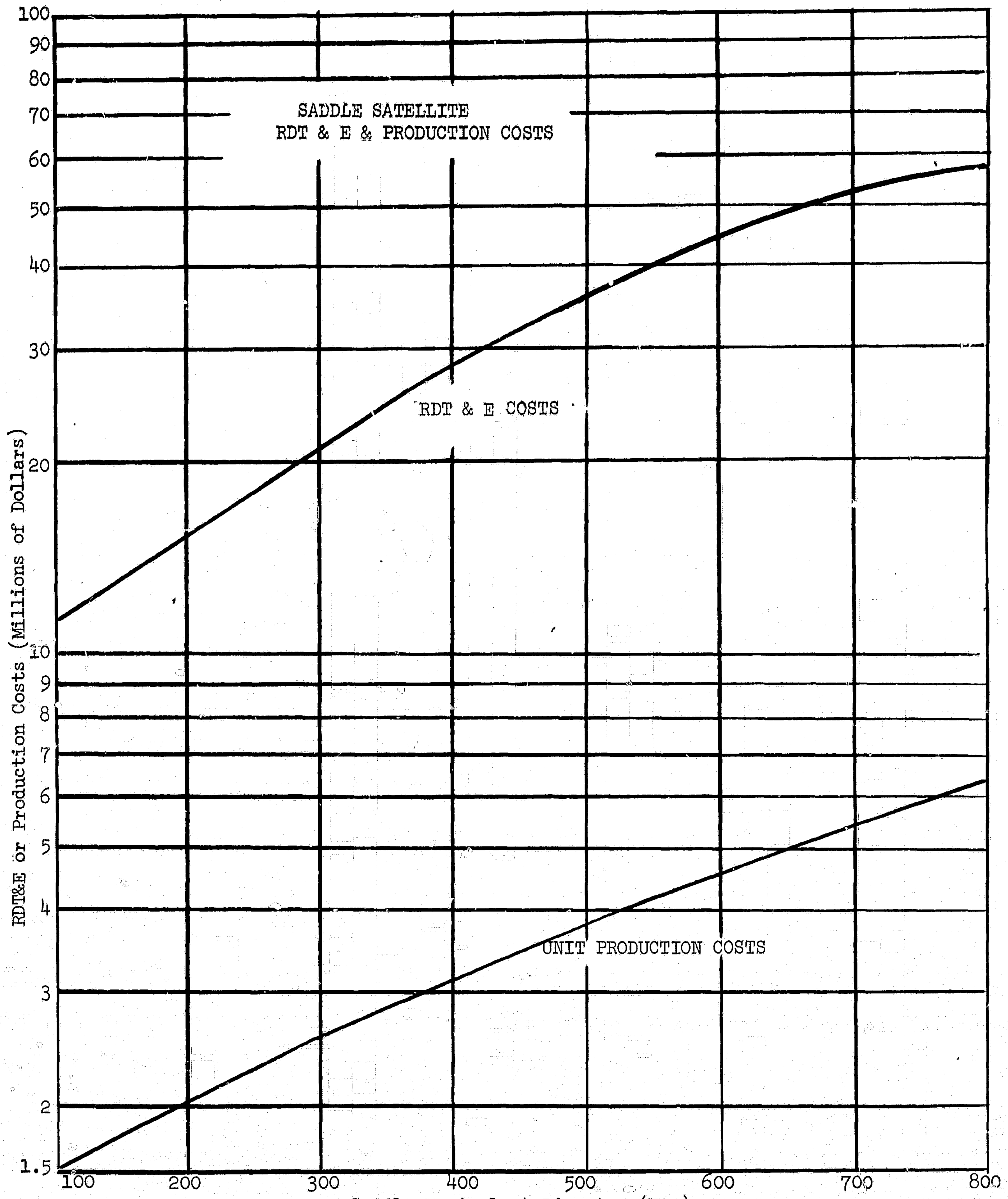
$$\text{RTD\&E cost} = 5.23D^2 + \left[1546.5 + 511N' + 444N \right] D^{1.4} + 314D + \left[0.354 + 1.277N' + 1.50N \right] \times 10^6.$$

The RTD&E costs are plotted in Figure 6 as a function of saddle aperture diameter with the assumption that three equivalent development units will be fabricated ($N' = 3$) and that two flight test units will be delivered ($N = 2$).

For the 325-foot reflector the RTD&E costs are \$22.01 M. The \$22 million is distributed as follows among its 8 previously defined major cost elements;

C_A	\$ 4.27 M
C_B	0.09
C_C	9.04

*The term equivalent applies to non-assembled portions or subsystems of a unit which when assembled would comprise a complete unit.


SADDLE SATELLITE
RDT & E & PRODUCTION COSTS
RDT & E COSTS
UNIT PRODUCTION COSTS
RDT&E or Production Costs (Millions of Dollars)
100
90
80
70
60
50
40
30
20
10
9
8
7
6
5
4
3
2
1.5
100
200
300
400
500
600
700
800
Saddle Equivalent Diameter (Ft.)
Figure 6.

C_D	\$ 5.32
C_E	0.59
C_F	0.54
C_G	1.17
C_H	0.99
TOTAL	\$22.01 M

Satellite Production Costs.- The unit satellite production costs have been related in terms of the saddle aperture diameter as follows:

$$C_1 = 400D^{1.4} + 1.35 \times 10^6$$

Utilizing the above expression, the per unit development test model costs are equal to 1.15C, while per unit flight test costs are equal to $1.0C_1$, and ground support equipment costs are equal to $0.20C_1$.

The expression for unit production costs is plotted in Figure 6 as a function of satellite diameter D. Unit cost for the 325-foot reflector is \$2.66 M.

The above expression for unit production costs has been used extensively throughout this study in trade-off analyses and systems comparisons. It has been noted that some variation in the expression occurs due for example to considerations of lifetime. However, such variations are small and within the "noise" of the estimate.

As an example, the unit production costs quoted above for the 325-foot diameter unit break down as follows for the subsystems:

Structure	\$ 1.068 M
TT&C	0.300
Power Supply	0.700
Attitude Control	0.026
Propulsion	0.320
Total	\$ 2.414 M

with the remainder of the cost being associated with integration, flight acceptance testing, quality assurance and so forth.

Active Satellites

General.- For the immediate future, the capacity of active communications satellites will be limited by the amount of power they can radiate toward the earth. This so-called "down-link" limitation is largely due to the economic cost of orbiting high power transmitters in space, with their attendant large and heavy spacecraft structures and solar power supplies. However, the ability to orbit large steerable antennas (preferably with multiple beams) will ease this transmitter power problem and permit a much higher ERP through the passive antenna gain. At this point satellite capacity will probably become limited more by repeater instantaneous bandwidth than power.

The Present Status.- The basic spin-stabilized communication satellite design, so successfully demonstrated with Syncom in 1963, has now evolved through several design modifications to become the standard commercial communication satellite (Intelsat III) for use during the 1968-72 time period. Major design changes evolving during the transition from Syncom through Early Bird (Intelsat I) and Intelsat II, to Intelsat III include larger size, higher power amplifiers, and higher gain antennas. The pertinent parameters of these satellites are shown in Table III. As may be seen, both the power level of the final amplifier and the gain of the antenna have been increasing over the five-year period. With increased satellite size, higher RF powers can be supported by the increased solar panel area available and with increased confidence in satellite attitude stabilization and attitude measurement, higher gain antennas may be used. For global communication systems, antenna beamwidth is limited to earth coverage plus some overlap for satellite attitude errors. Intelsat I has demonstrated the ability to "squint" the antenna off axis and limit the beam to less than earth coverage in a north-south direction. Up through Intelsat II all transmit beams had been donut shaped because of the spin stabilization of the vehicle. However, on Intelsat III a mechanically despun antenna will permit essentially earth coverage beamwidth.

The Future Satellites and Their Costs.- Three prime areas for future satellite communication improvement exist: (1) satellite transponder design, (2) satellite transmitter power output device, and (3) satellite antenna gain. The critical items for down-link performance are shown in Figure 7. Actually, of course, the total system performance must be looked at for an optimized solution since down-link performance reflects back on up-link performance in terms of many of the same type of parameters shown in Figure 7; e.g., the satellite ERP and the satellite front end noise temperature are inversely proportional given a fixed allowable up-link noise contribution.

The above selection of critical areas depends on several assumptions: (1) frequency allocations will be such that available bandwidth will be no limitation, (2) the ability to economically produce d.c. power up to several kilowatts will exist, and (3) the cost and technical capability of producing ERP on the ground will be such that despite improved down-link performance, the up-link will not become limiting.

Table III. Evaluation of Standard Commercial Communication Satellite

Parameter	SYNCOM	INTELSAT I (Early Bird)	INTELSAT II	INTELSAT III
SIZE				
Solar array diameter	72 cm	72 cm	142 cm	141 cm
Solar array length	40 cm	59 cm	67 cm	104 cm
WEIGHT				
At launch	66.5 kg	68 kg	175 kg	269 kg
Postapogee motor fire	35.4 kg	38.5 kg	87 kg	136 kg
COMMUNICATIONS				
Repeater	Two redundant, selectable, frequency translation repeaters, with bandwidths of a single 5 MC or 2 each 0.5 MC channel respectively	Two independent frequency translation repeaters, each with 25 MHz bandwidth	Two redundant repeaters, each with 126 MHz bandwidth	Two indpendent repeaters, each with 225 MHz bandwidth
Power amplifier	Two 2-watt TWT's, one operating and one spare	Two 6-watt TWT's, one operating and one spare	Four 6-watt TWT's, one, two, three, or four operating at one time	Two 10-watt TWT's, one in each band
Antenna	Receiver, omni; transmit, coaxial slot array; 25° beam-centered at equator	Receiver, omni; transmit, collinear slot array; 11° beam-centered at +7° aspect angle	Receiver, omni; transmit, multiple-element biconical horn; 12° beam-centered at equator	
EIRP	9 dBW	10 dBW/repeater	14 dBW	22 dBW/repeater

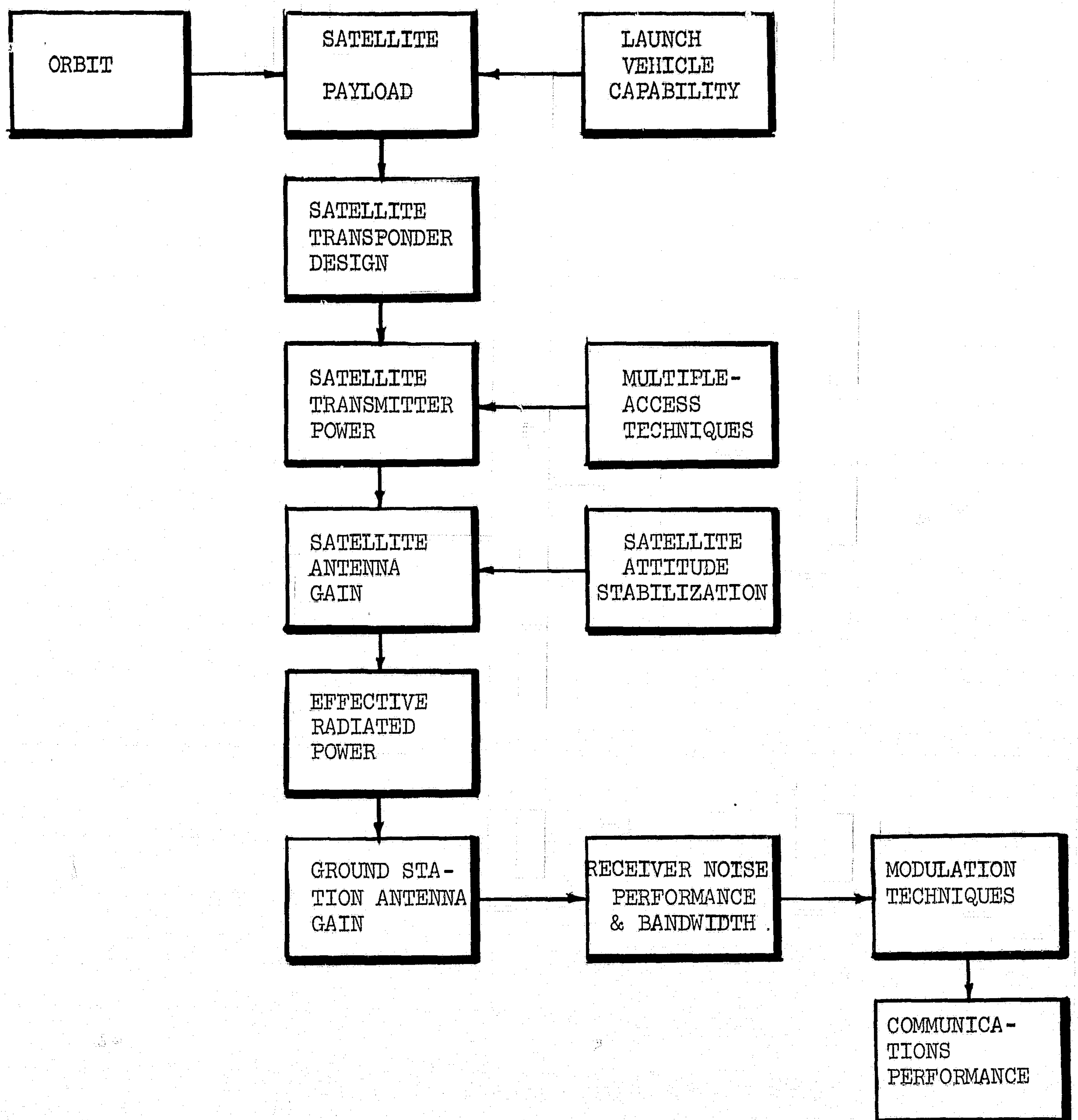
Table III. Evaluation of Standard Commerical Communication Satellite

(Continued)

Parameter	SYNCOM	INTELSAT I (Early Bird)	INTELSAT II	INTELSAT III
FREQUENCIES				
Up-link	7361, 7363 MHz	6301 ± 13 MHz, 6390 ± 13 MHz	6345 ± 63 MHz	Repeater I 5930 to 6155 MHz
Down-link	1815, 1814 MHz	4081 ± 13 MHz, 4161 ± 13 MHz	4120 ± 63 MHz	3705 to 3930 MHz
				Repeater II 6195 to 6420 MHz
				3970 to 4195 MHz

SOURCE: Intelsat I, II, and III data from Robert C. Barthle and Robert D. Briskman, "Trend in Design of Communications Satellites Earth Stations." Microwave Journal, 10, (October, 1967) p. 28.

Syncom data from Syncom Engineering Report, NASA Goddard Space Flight Center, Greenbelt, Md., NASA TR R-233; March 1966.



SOURCE: Stanford Research Institute

Figure 7. Satellite Down-Link Communication Performance

The state-of-the-art in the generation of DC power (and as a result of RF power) in space with solar cell technology is advancing at a rapid pace. Discussions with manufacturers indicate that approximately 35 watts of RF power at X band can be considered as state-of-the-art with flight qualified components.

The estimates of future capability of active satellite to generate RF power vary rather widely with manufacturers. The following values are based on data obtained from Comsat Corporation (Ref. 2) and represent the best estimate available at this time.

r_s = Specific power (watts/lb) = 9 w/lb 1972 technology
18 w/lb 1975 technology

p = DC to RF conversion efficiency at 8 GHz = 0.25

m = Functional allocation of payload to power supply = 0.35

n = Fraction of DC power allocated to spacecraft electronics and batteries = 0.5

W_T = Spacecraft payload

Therefore, the RF power can be estimated from $P_{rf} = mpr_s W_T (1 - n)$, and using the above figures with r_s based on 1972 technology, $P_{RF} = 0.4 W_T$; thus, for satellites with different weights the RF power can be estimated as follows. The cost of R&D associated with the development of these satellites and the estimated satellite unit cost based on Comsat Corporation estimates are also shown.

Payload wgt.(lbs)	DC power kw	RF Power Watts	RF Power dB	Cost of R & D ($M)	Unit cost of Satellite
1000	3.2	400	26	27.4	5.1
2000	6.4	800	29	35.0	9.0
3000	9.6	1200	31	42.0	11.5

The total cost of R&D includes the development of new designs required to produce high RF powers, the development of new antennas with very narrow beamwidth and flight qualification tests.

In case of the lower power satellite SAT-1 which represents the existing state-of-the-art, the principal R&D costs required are those associated with development of narrow beam antennas.

Because of the wide divergence of views between various manufacturers concerning the R&D costs of developing antennas with 1 and 2 degree beamwidth, and meeting the associated pointing accuracy and stabilization requirements a compromise figure of $10 million has been adopted.

For 4 and 8 degrees (at 8_{GHz}) it is assumed that only minor modifications are required. In case of high power satellites these costs are absorbed in the total R&D costs estimated by Comsat Corporation and are listed in the previous table. These costs do not include a flight test which is considered necessary before any new designs may become flight qualified. Accordingly, the total cost of the R&D program can be presented by the following equation

$$C_T = C_{RD} + NC_S + 1.1C_L \tag{1}$$

where

C_T = total R&D program cost

C_{RD} = R&D cost

C_S = flight satellite unit cost

C_L = cost of launch

N = number of flight qualified satellites required

It is assumed that boosters required to lift various payloads into stationary orbit and their respective cost are as follows:

Payload Wt.	Booster	Launch Cost
1000	Atlas-Agena : BII	$ 8.4 Million
2000	Titan IIIC	$15.9 Million
3000	Titan IIIC + BII	$18.1 Million

It is also assumed that two flight qualified satellites are manufactured as part of the R&D program. Thus, N = 2 in Eq. (1).

The ERP which can be produced by these satellites can be calculated from the formula

$$ERP = \text{RF power} + \text{antenna gain}$$

$$\text{Antenna gain} = \frac{1}{1 - \cos(\theta/2)}$$

where θ = half power beamwidth in degrees

It is also assumed that approximately 3 dB loss is incurred as a result problems associated with stabilization pointing accuracy, antenna despinning, etc.

Accordingly, the ERP capability of these satellites can be calculated from the above relationships.

The pertinent data including costs is summarized in Table IV. There are listed four types of satellites representative of existing and future state-of-the-art, which are designated as follows:

Low-power	SAT-1	represents existing state-of-the-art and is assumed to have a payload weight of 1000 lbs.
High-power	SAT-2) SAT-3) SAT-4)	represent future state-of-the-art in high power satellites and their payload weight is assumed to be 1000, 2000, and 3000 lbs respectively.

Large Aperture Parabolic Antenna Systems

Little practical experience is available in the area of large size communication antennas. Because of the improvements in the efficiency of active satellites, the design trend appears to be toward reducing the size of such antenna systems rather than towards increasing them. However, for passive satellite systems large antennas are sometimes desirable and even mandatory. Some information is available in the field of radio astronomy on large antennas. It must, however, be applied to communication systems with some discretion.

The objective of this part of the study was to estimate the maximum gain that can be achieved with a single parabolic dish ground antenna (Appendix D). Multiplate, arrays, and other types of antennas capable of large equivalent apertures are considered in Appendix E.

Recent progress in microwave technology and digital information processing has already resulted in noticeable advances in the state of the art of large size antenna systems and has laid the foundations for further improvements. Of particular usefulness was the application of computer aided analytical techniques to the design of large antenna structures. Additionally, improvements in illumination and spillover efficiencies such as hyperbola subreflectors and "dielguide" techniques for Cassegrain systems indicate substantial increases in the overall efficiency of large parabolic antenna systems.

Table IV. Active Satellite Characteristics

Beam-width Degrees	Satell. ERP (DBW)	Satellite Wt. (lb.)	Booster required	C_{LS} Launch cost ($M) +	C_s Satellite unit cost ($M) =	C_x Cost per Launch	Total Cost/ Launch ($1.1C_x$)	R&D Costs to develop ($M) Power Capabil.	Antenna & Stabiliz.	Flight Test Costs ($M) 2 flt. Satell.	Launch 1.1 C1	Total R&D
1°	56	1000	Atlas/Agena+ BII	8.4	4.5	12.9	14.1	-	10	9	9.2	28.2
	67	1000	Atlas/Agena+ BII	8.4	6.0	14.4	15.8	27	10	12	9.2	58.2
	70	2000	Titan IIIC	15.9	10.0	25.9	28.5	35	10	20	17.5	82.5
	72	3000	Titan IIIC + BII	18.1	12.0	30.1	33.1	45	10	24	20	99.0
2°	50	1000	Atlas/Agena + BII	8.4	4.0	12.0	13.2	-	10	8	9.2	27.2
	61	1000	Atlas/Agena + BII	8.4	5.5	13.9	15.3	27	10	11	9.2	57.2
	64	2000	Titan IIIC	15.9	9.5	24.5	27.0	35	10	19	17.5	81.5
	66	3000	Titan IIIC + BII	18.1	12.0	30.1	33.1	45	10	24	20	99.0
4°	44	1000	Atlas/Agena + BII	8.4	3.5	11.9	13.1	-	2.	0	0	2.0
	55	1000	Atlas/Agena + BII	8.4	5.0	13.4	14.7	27.	0	10	9.2	46.2
	58	2000	Titan IIIC	15.9	9.0	24.9	27.4	35.	0	18	17.5	70.5
	60	3000	Titan IIIC + BII	18.1	12.0	30.1	33.1	45.	0	24	20	89.0
8°	38	1000	Atlas/Agena + BII	8.4	3.0	11.4	12.5	--	0.5	0	0	0.5
	49	1000	Atlas/Agena + BII	8.4	5.0	13.4	14.7	27.	0	10	9.2	46.2
	52	2000	Titan IIIC	15.9	9.0	24.9	27.4	35.	0	18	17.5	70.5
	54	3000	Titan IIIC + BII	18.1	12.0	30.1	33.1	45.	0	24	20	89.0
16°	32	1000	Atlas/Agena + BII	8.4	3.0	11.4	12.5	--	0	0	0	0
	41	1000	Atlas/Agena + BII	8.4	5.0	13.4	14.7	27.	0	10	9.2	46.2
	46	2000	Titan IIIC	15.9	9.0	24.9	27.4	35.	0	18	17.5	70.5
	48	3000	Titan IIIC + BII	18.1	12.0	30.1	33.1	45.	0	24	20	89.0

The gain of an ideal parabolic reflector is given by

$$G = \frac{4 \pi A}{\lambda^2} \qquad (2)$$

where A = reflecting area

λ = wavelength

In practice this gain is reduced by some overall antenna aperture efficiency, η_T. Thus for a circular aperture, equation (2) becomes

$$G = \eta_T \left(\frac{\pi D}{\lambda}\right)^2 \qquad (3)$$

η_T is a composite of several factors and can be written as

$$\eta_T = \eta_1 \; \eta_2 \; \eta_3 \; \eta_4 \; \eta_5 \qquad (4)$$

where η_1 = degradation due to random phase errors resulting from surface errors

η_2 = illumination efficiency

η_3 = illumination spillover efficiency

η_4 = power reflection coefficient

η_5 = fractional power absorption due to resistive losses

Ruze (Reference 3) has shown that the relationship between the loss of gain and the surface deviation can be expressed by

$$\frac{G}{G_o} = \exp. - (\bar{\delta}^2) + \frac{1}{\eta} \left(\frac{2\,C}{D}\right)^2 \exp - (\bar{\delta}^2) \sum_{\eta=1}^{\infty} \frac{\bar{\delta}^{2} \cdot \eta}{\eta \cdot \eta^{1}} \qquad (5)$$

where G/G_o = reduction in axial gain relative to a no-error gain

D = antenna diameter

C = radius of area where phase values are completely correlated

$\bar{\delta}^2$ = phase front variance produced by rms surface error, d

For reasonable tolerances, and small correlation regions the second term of equation (5) may be neglected. Thus

$$\frac{G}{G_o} = \exp - (\bar{\delta}^2) = \exp - \left[\frac{4 \pi d}{\lambda}\right]^2 \qquad (6)$$

and from equations (3) and (4),

$$G = \eta_x \left[\frac{\pi D}{\lambda}\right]^2 \exp - \left[\frac{4 \pi d}{\lambda}\right]^2 \qquad (7)$$

where $\eta_x = \eta_2 \ \eta_3 \ \eta_4 \ \eta_5$

d = effective reflector tolerance (rms deviation value from best fit paraboloid)

Figure 8 shows the deviation in gain for some surface roughness from that of the ideal paraboloid as a function of frequency.

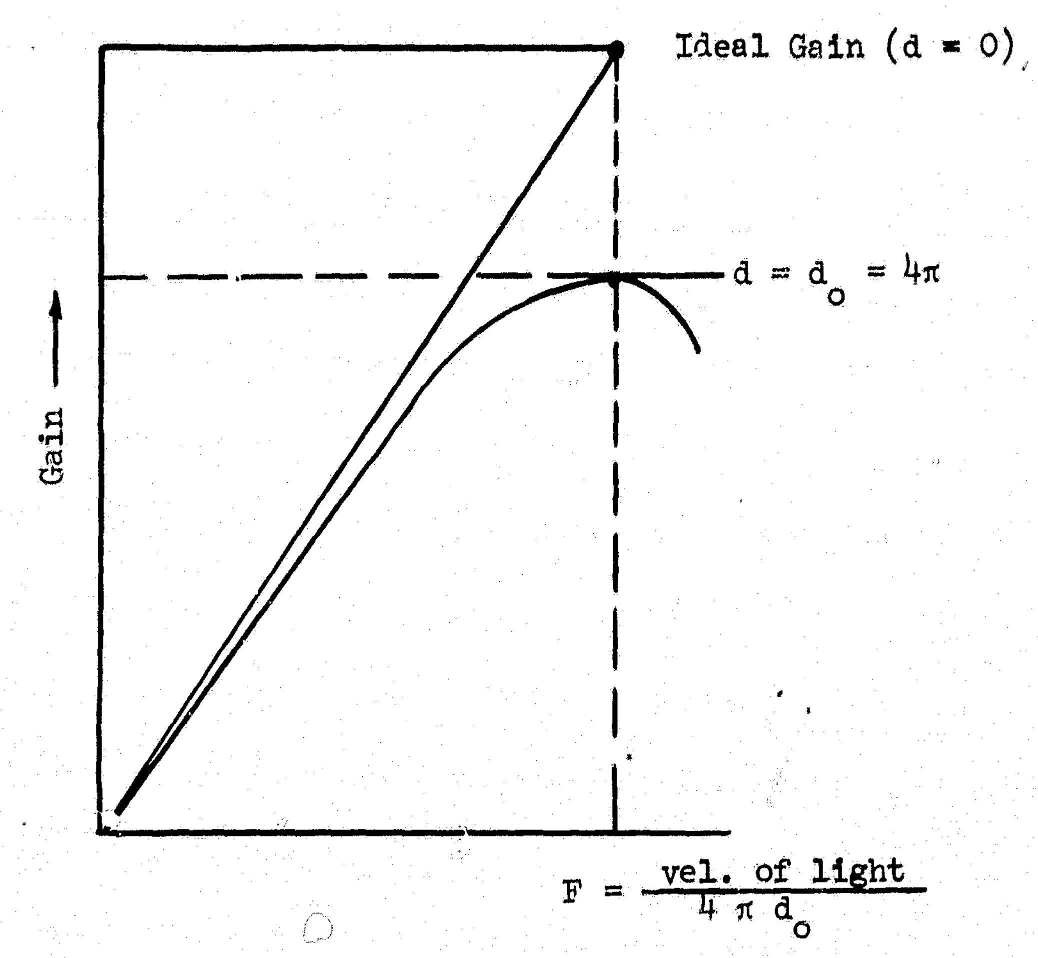
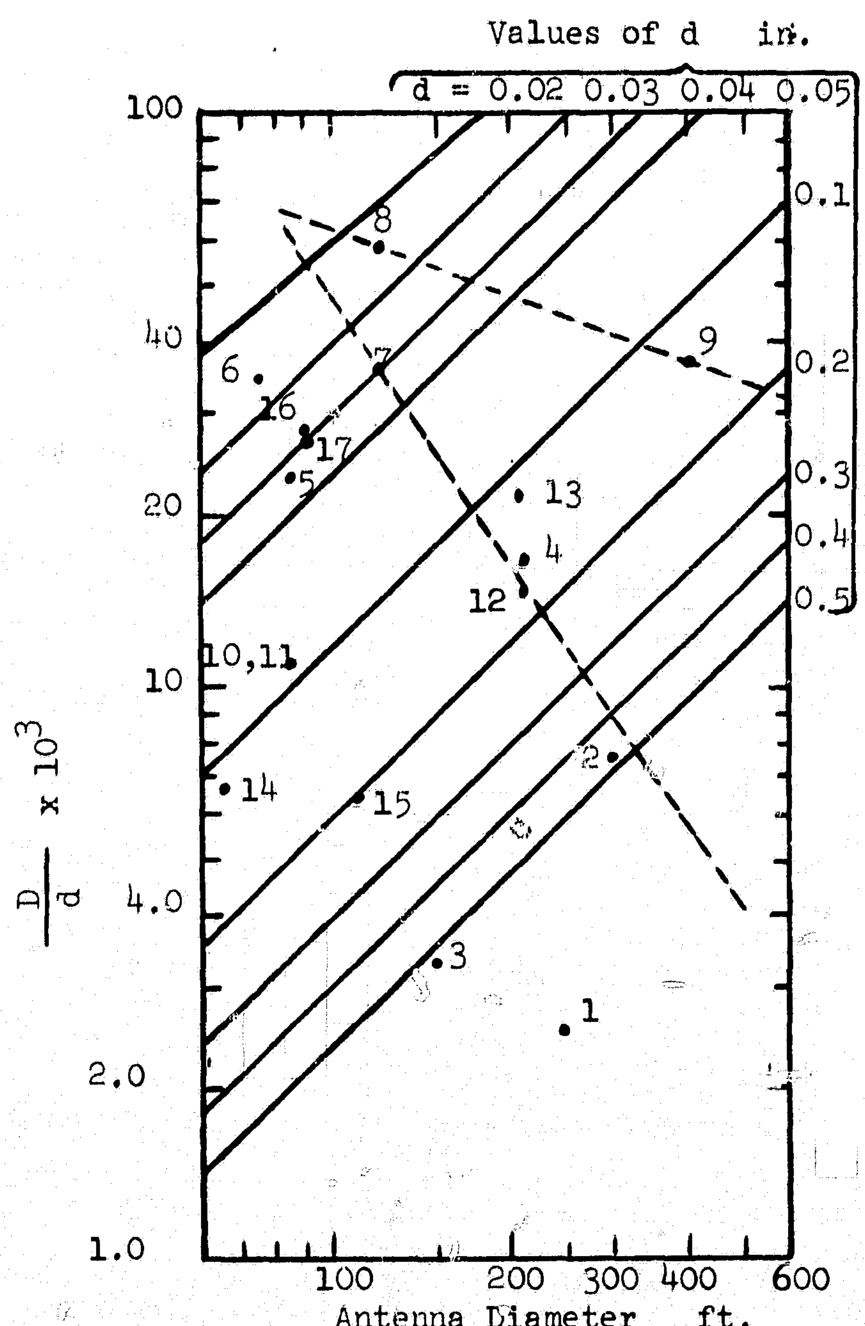


Figure 8, Gain Deviation from Ideal Paraboloid Due to Surface Irregularities

Recent improvements in antenna designs as described in Appendix D indicate potential increases over those previously assumed. Based upon these advancements a figure of 0.6 for η_x will be used as a state-of-the-art figure.

In order to estimate the practical limits on surface tolerances, the values of "manufacturing precision" parameter D/d for existing antennas are plotted in Figure 9. Using these values it is possible to determine a quantity q called "manufacturing precision per foot of antenna diameter".

$$q = \frac{d}{12\, D^2} \tag{8}$$



Radio Astronomy Antennas

1. Jodrell Bank
2. Greenbank
3. Stanford
4. Parkes-Csiro
5. Michigan
6. Lebedev
7. Haystack
8. Haystack (In radome)
9. Camroc (In radome)

Communication Antennas

10. GPO Goonhilly
11. JPL, Goldstone (85 ft.)
12. JPL, Goldstone (210 ft.)
13. JPL, Goldstone (210 in radome proposed)
14. KDD, Japan
15. Radio Research Lab., Jap
16. Deutche Bundespost, Raisting
17. Philco, Italy

Figure 9. Manufacturing Precision of Existing and Proposed Antennas

Based upon a 100-foot antenna with a 0.04 inch rms surface tolerance and a 210 foot reflector with an rms tolerance of 0.17 inches a value of ;

$$q = 3.3 \times 10^{-7}$$

where d is in inches

D is in feet .

Discussions with manufacturers and analysis of antenna design possibilities for a 400-foot antenna included the CAMROC (Reference 4) report indicate that these values are reasonable for exposed antennas. From equation (7) and the value for q the following results

$$G = \eta_x \left(\frac{\pi D}{\lambda}\right)^2 \exp. - \left[\frac{4\pi}{\lambda} \cdot \frac{4 D^2}{10^6} \cdot \frac{1}{12}\right]^2 \qquad (9)$$

where λ and D are both in feet.

Under the above assumptions for η_x = 0.6 the optimum performance for various frequencies are given in Table V. and gain versus antenna diameter is plotted in Figure 10.

Table V. Optimum Antenna Performance Under Practical Conditions

Frequency Gc	Approximate Maximum Gain dB Obtainable in Practice with Surface Toler. = $4D^2 10^{-6}$	Approximate Antenna Diameter D ft
1	58	400
2	60.9	288
3	62.6	238
4	63.9	200
5	64.8	180
6	65.6	163
7	66.3	150
8	66.9	144
9	67.3	136
10	67.8	130

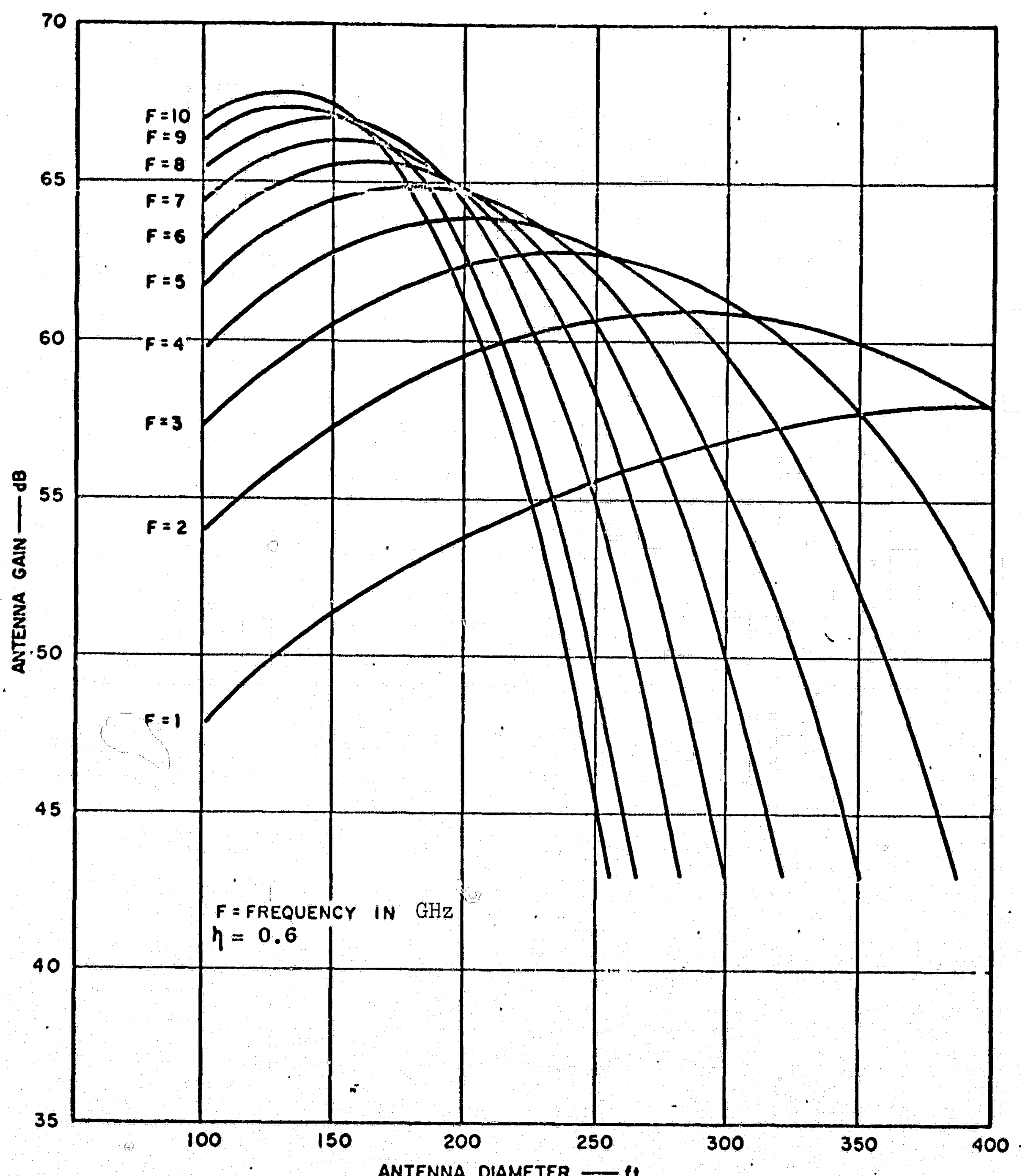


Figure 10. Antenna Gain vs Diameter
(RMS Surface = $4D^2/10^6$)

The cost of such antennas has normally been expressed in terms of the antenna diameter according to the formula

$$\text{Cost} = nD^p \tag{10}$$

where D is the antenna diameter in feet and n and p are constants. The weakness of this formula is quite apparent.

The use of equation (10), although it yields the cost, does not impart any knowledge as to the exact gain of the antenna. Without such knowledge, equation (10) conveys little information except in an "intuitive sense," which is often misleading.

As a result, an attempt has been made to develop an expression (Appendix F) for the cost of large parabolic antennas that would answer the following question:

> "What is the minimum cost of G(dB) of gain at an operating frequency of F(GHz), and what is the best antenna diameter and the required rms reflector surface tolerance under these conditions?"

To answer this question the following approach has been developed.

Since the gain of an antenna depends on its diameter (D) and on the rms surface tolerance (d), as shown in equation (7), the cost of this gain is a function of the cost of D and the cost of d. The least total cost will be obtained for a specific set of values of D and d which must be determined by minimization of the cost equation. In order to accomplish such minimization, d must be expressed in terms of D (or vice-versa). Thus the following steps are necessary:

Step 1: Express the rms surface tolerance as a function of the antenna diameter:

$$d = f(D). \tag{11}$$

This is a subjective decision based on available data and knowledge of manufacturing techniques. The value of the rms surface tolerance obtained in this manner is called "basic tolerance corresponding to the diameter D."

From the preceding value of q (3.3×10^{-7})

$$d \approx \frac{4\,D^2}{10^6} \tag{12}$$

with both D and d in feet. Any other tolerance d_1 will then be expressed as a fraction (a) of d; i.e.,

$$a = \frac{d_1}{d} \qquad (13)$$

or

$$d_1 = ad$$

Substituting into equation (11), the following is obtained

$$d_1 = af(D) \qquad (14a)$$

or

$$d_1 = a\ (4D^2/10^6) \qquad (14b)$$

Step 2: Express gain in terms of D and d_1.

Using equation (7) for antenna gain G, in general

$$G = X(D)\ y(d_1) \qquad (15)$$

Substituting equation (14a) into equation (15)

$$G = X(D)\ y(af(D)) \qquad (16a)$$

or specifically

$$G = \eta_x \left[\frac{\pi D}{\lambda}\right]^2 \exp - \left[\frac{4\pi}{\lambda} \cdot a \cdot \frac{4D^2}{10^6}\right]^2 \qquad (16b)$$

Step 3: Determine fractional increase in antenna cost "b" associated with fractional change of basic tolerance d (represented by a):

$$b = k(a) \qquad (17)$$

or

$$a = k_1(b) \qquad (18)$$

This cost relationship can be determined from available data and constitutes a subjective input. For this study it was concluded that over a restricted range of variation an inverse relationship would be used

$$b = 1/a \tag{19}$$

Substituting equation (18) into equation (16a),

$$G = X(D)y \left[k_1 (b), f(D) \right] . \tag{20 a}$$

or specifically,

$$G = \eta \times \left[\frac{\pi D}{\lambda} \right]^2 \exp - \left[\frac{4 \pi}{\lambda} \cdot \frac{1}{b} \cdot \frac{4D^2}{10^6} \right] \tag{20b}$$

Equation (11) can now be solved for b, yielding

$$b = N(D,G), \tag{21a}$$

or

$$b = \frac{K_1 D^2}{\left[2 \ln \left[K_2 D \right] - \ln G \right]^{1/2}} \tag{21b}$$

where

$$K_1 = \frac{16 \pi F \times 10^9}{12C \times 10^6} \quad \text{and } K_2 = \frac{\sqrt{\eta} \pi F \times 10^9}{C} \quad \text{(F in GHz)}$$

Thus, the fractional increase in antenna cost (b) associated with a change in the basic rms surface tolerance of the antenna can be expressed as a function of antenna diameter and the gain that will be produced.

Step 4: Determine the cost of the basic antenna with diameter D and associated tolerance d defined by equation (8):

$$C_B = M(D) \tag{22}$$

This cost equation is the one that is normally quoted as "the cost of an antenna with diameter D and is sometimes represented by equation (10). The exact relationship used for this study was

$$C = 28.8D^{2.42} \tag{23}$$

Step 5: Obtain the formula for the cost of an antenna with any diameter D and any tolerance d_1. This relation can be obtained by combining equations (21) and (22):

$$C_T = M(D) \times b = 28.8D^{2.42} \cdot b \tag{24}$$

$$= M(D)\ N(D,G). = 28.8D^{2.42} \frac{K_1 D^2}{2\left[\ln K_2 D - \ln G\right]^{1/2}} \tag{25}$$

Step 6: Minimize the total cost. Equation (24) represents the total cost of an antenna with arbitrary rms surface tolerance and diameter. It is of interest to minimize this cost for any required gain G. This can be accomplished by setting G at the required value, differentiating equation (25) with respect to D, and equating the result to zero. This will yield the value of D_{opt} that satisfies the minimum cost condition:

$$\frac{dC_T}{dD} = 0 = \frac{d(M(D))}{dD} N(D,G) + M(D) \frac{d\ N(D,G)}{dG} . \tag{26}$$

Since G is a constant we can solve equation (26) for D, obtaining D_{opt} as a function of given gain G. We can now use this value of D_{opt} in equation (21) to find the corresponding value b_{opt} of b. The total minimum cost of the antenna is found from equation (24) using values of D_{opt} and b_{opt}. For this study the total minimum cost is

$$C_{MIN} = (28.8)(4.42)(D^{4.42}) \cdot (K_1) \tag{27}$$

This is plotted in Figure 11.

Step 7: Determine the value of rms surface tolerance d_1 required to produce gain G with antenna diameter D_{opt} for minimum cost condition. Substituting the value of b_{opt} found above into equation (18), we find "a", which is then used together with D_{opt} in equation (14) to find the rms tolerance d_{opt}.

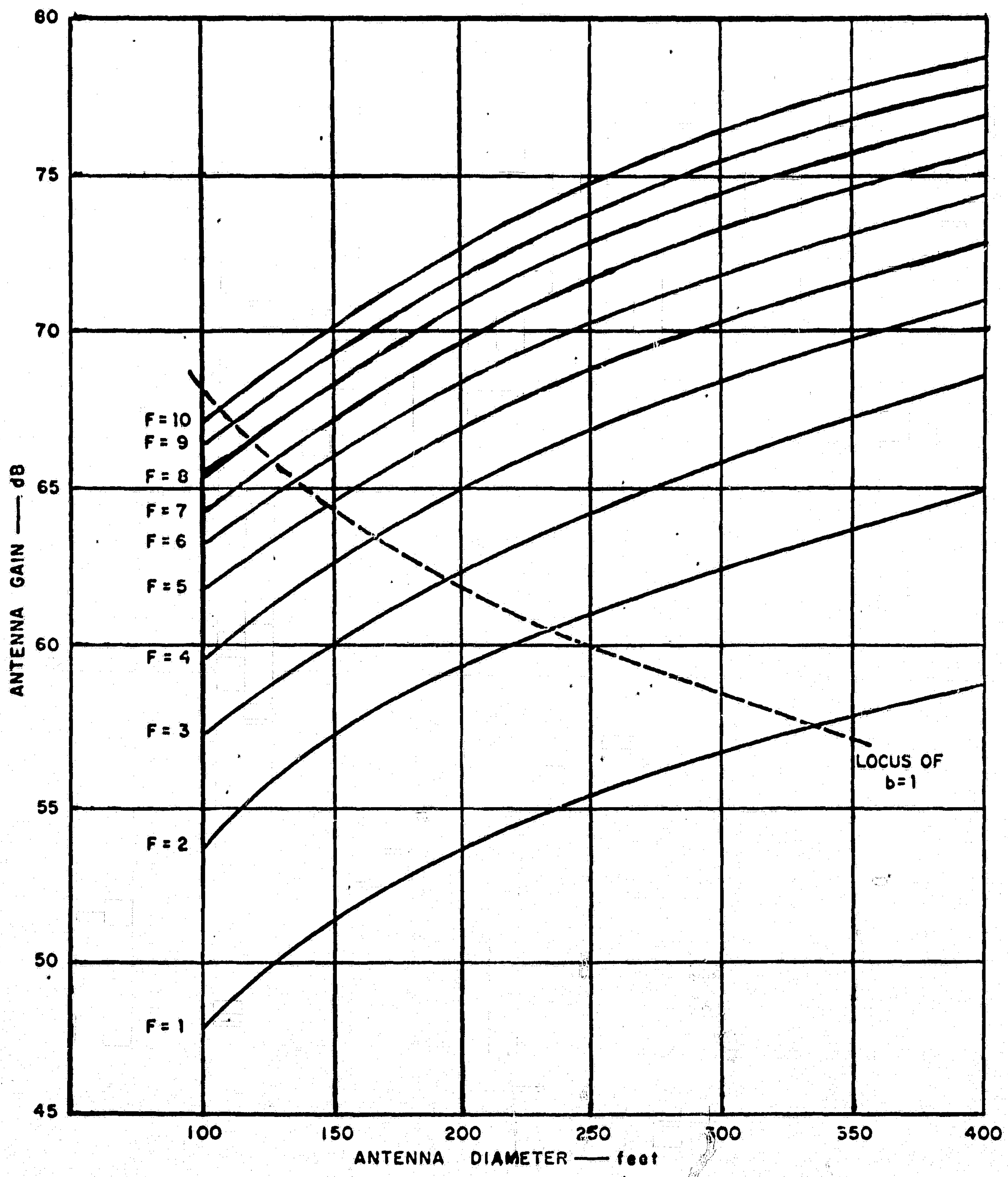


Figure 11. Minimum Cost Relationship Between Antenna Gain and Diameter (rms surface deviation = $4D^2/b \times 10^6$ = constant)

The procedure of the last two steps can be summarized as follows:

(A) $\frac{dC_T}{dD} = 0$ yields the value of D for minimum cost $D = D_{opt}$.

(B) Using D_{opt}, compute:

b_{opt} from equation (21) for given G

C_{MIN} from equation (24), using D_{opt} and b_{opt}

d_{opt} from equations (18) and (14).

For a required value of gain G, the minimum cost C_{MIN} is thus obtained and plotted in Figure 12.

The costs considered above do not take into account antennas operating with radomes. Radomes may reduce the overall ground station costs by reducing the cost of the antenna (Appendix G).

The development of all these equations and figures is described in Appendix F. The assumptions on which they are based are discussed in some detail in order that the reader may get a clear conception of all the factors affecting the accuracy of the final result.

High Power Microwave Transmitters

Since the capacity of a communication link employing a passive satellite is directly proportional to the transmitter power, a high transmitter power is desirable.

The ability to produce high power at microwave frequencies depends primarily on the type of power amplifier employed. Klystrons, traveling wavetubes, and crossfield amplifiers are used to generate high power in the microwave band. The klystron amplifier has the highest power handling capability with a reasonable efficiency. It has been estimated that an average power up to 30 megwatts might be achieved from a single tube if sufficient funds were provided for its development. The bandwidth of the klystron amplifier becomes its limiting parameter. Tunable bandwidths are generally large but operating bandwidths are nominally on the order of one percent. As the absolute power capability is decreased bandwidths up to about 5 percent become available. The traveling wave tube (TWT) provides the greatest bandwidth capability with 20 to 25 percent being readily achievable, but maximum power and efficiency are the limitations on TWTs. Cross-field amplifiers fall midway between klystrons and TWTs in terms of power. One advantage of cross-field amplifiers is that their power efficiency can be as high as 80 percent. Table VI is a comparison of these major characteristics. Some successful attempts have been made in paralleling

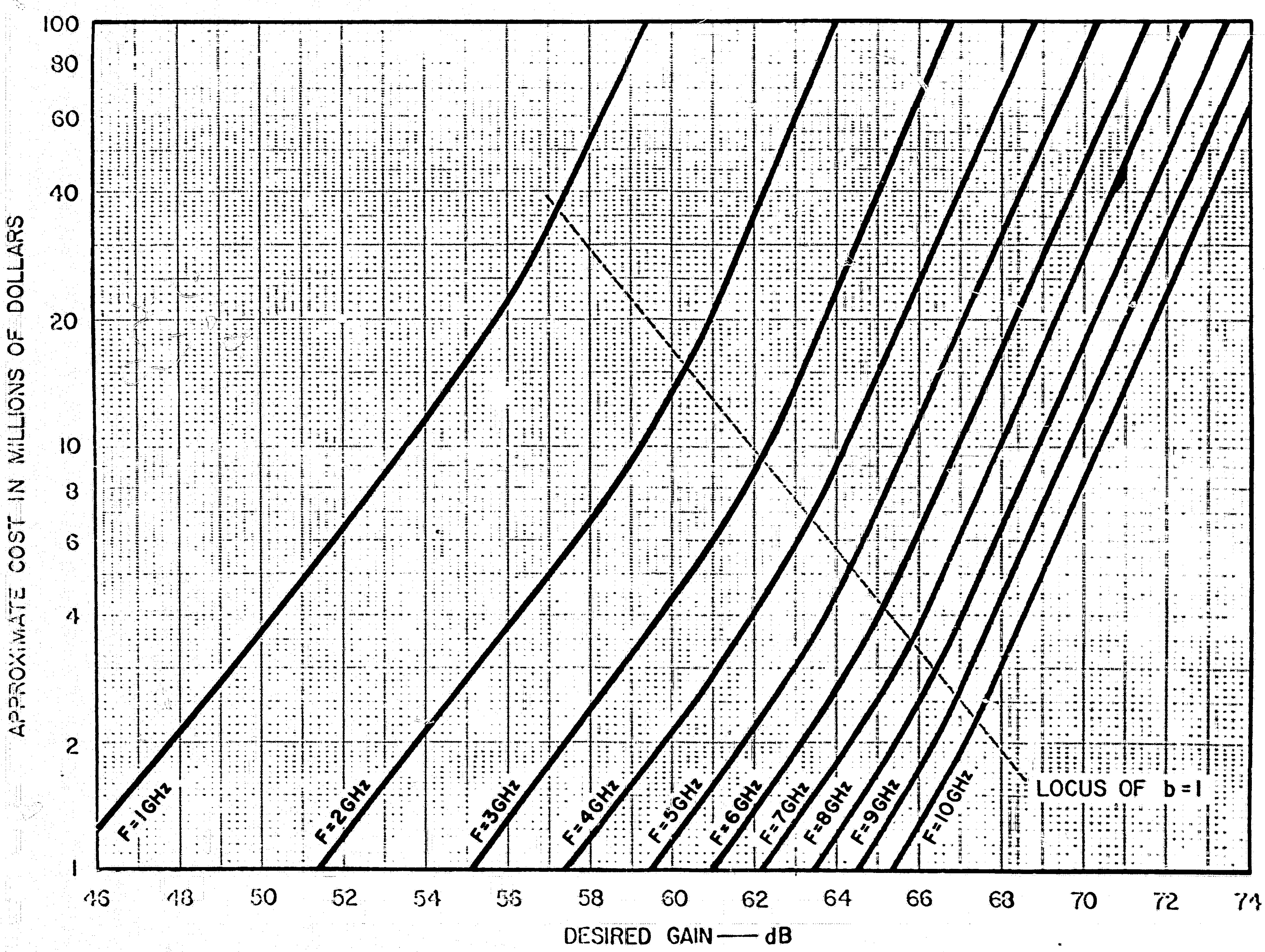


Figure 12. Minimum Cost of Gain for Large Parabolic Antennas

Table VI. Comparison of Microwave Transmitters

Parameters	Klystron	TWT	Cross-Field Amplifier
Available Power - KW	1000	10	375
Estimated Maximum Power - KW	30,000	30	375
Bandwidth	0.5% - 5%	20-30%	10%
Efficiency	60%	47%	80%

two or more tubes to achieve higher powers. It is possible to achieve output phase coherence by applying phase correction between the inputs to the power tubes and a common driver; however, modulation bandwidth can be severely reduced unless the output tubes are closely matched.

Appendix H provides a summary of available tubes capable of 100 kw or more. In addition in that appendix is a more inclusive list showing the commercially produced tubes having outputs in excess of 20 kw with operation frequencies between 1 and 10 GHz.

In the frequency range of 1 to 10 GHz, absolute output power is more or less independent of operating frequency. Costs, however, increases exponentially with increased power. Figure 13 shows some representative cost points for various output powers. From this curve a best fit equation for the cost for transmitter power amplifiers can be given by:

$$\text{Cost} = 25\ P^{0.63}$$

where P is in watts.

The cost of the output power amplifier is only one of the many expensive items in a transmitter. Other basic items comprising a typical transmitter procurement are:

(1) D.C. power supply

(2) magnet

(3) heat exchanger

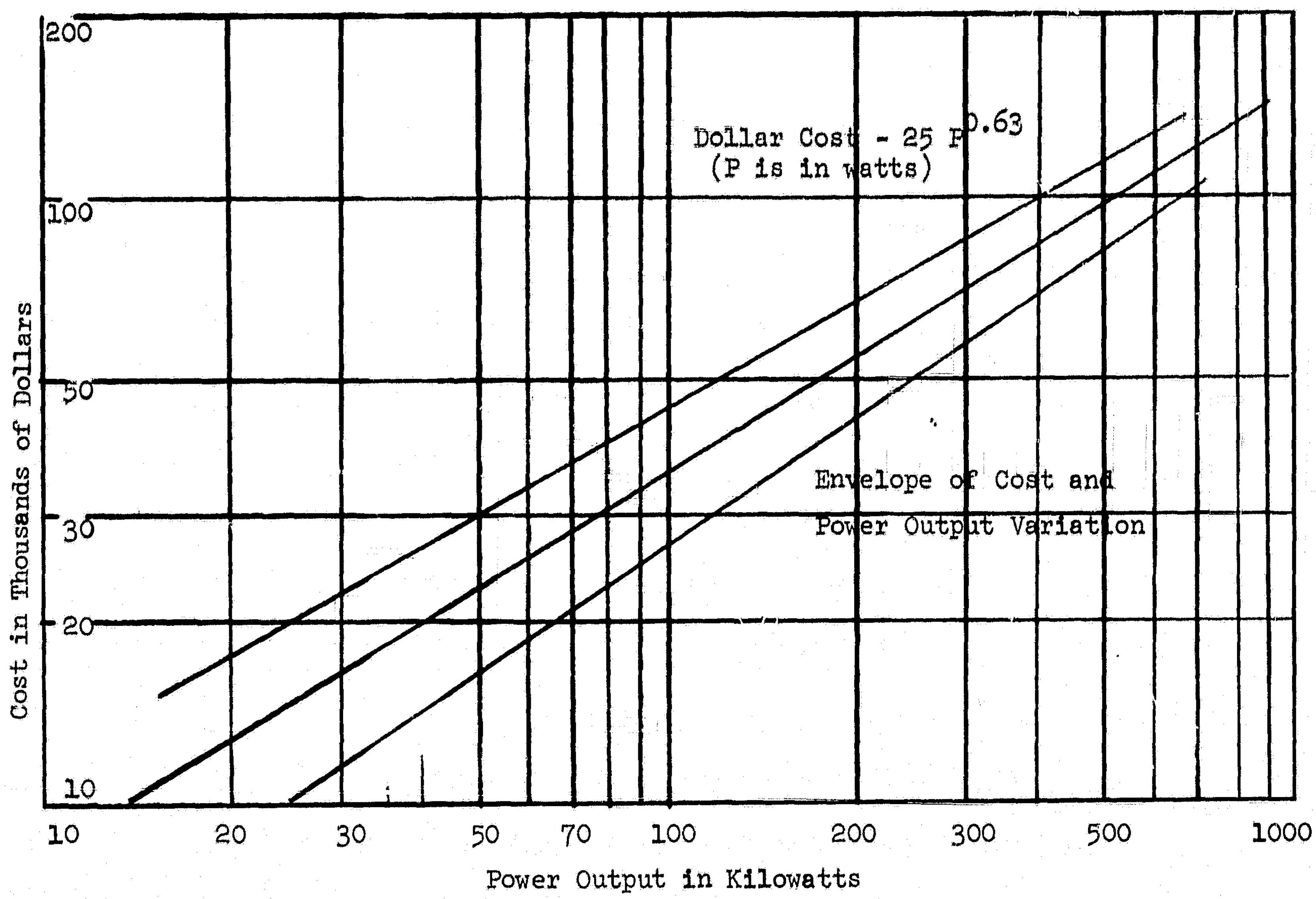


Figure 13. Variation of Frequency and Cost with Power Output for Klystron Power Amplifiers

(4) dummy load

(5) exciter

(6) racks and other structural elements

(7) instruction manuals, sketches and manufacturing drawings

(8) remote control panel

(9) assembly and integration costs.

Based upon Appendix H, the major elements and their assumed cost relationships are shown in Table VII.

Table VII. Transmitter Costs

Major Transmitter Elements	Cost Equation
Power Amplifier	$C = 25P^{0.63}$
Magnet, Heat Exchanger, Dummy Load and associated waveguide parts	$C = 25P^{0.63}$
Exciter, Remote Control Panel, Racks and other structural members	$C = 25P^{0.63}$
Instruction Manuals, Sketches and Manufacturing Drawings	$C = 25P^{0.63}$
D.C. Power Supply	$C = 25P^{0.63}$

If several power tubes are used in parallel the total transmitter cost would then be given as:

$$\text{Cost} = 75\,(m + k)\left(\frac{P}{k}\right)^{0.63} + 50\,P^{0.63}$$

where P = total delivered power in watts

k = number of operating power tubes

m = number of standby power tubes

On the basis of the data presented in Appendix H, the following limiting characteristics were assumed in this study for a high power transmitter in the 1970 time period:

Operating frequency	8 GHz
Modulation bandwidth	300 MHz
Rated output power	625 kw
Operating output power	500 kw
Signal to distortion ratio	16 db
Tube mean time to failure at 90% C.L.	20,400 hours 2.3 years of continuous operation
M.T.T.F. of transmitter (except power tube) at 90% C.L.	4,400 hours (5 years)
Prime power required	1.5 megwatts

Launch Vehicle Capabilities

The launch vehicle study was directed toward an evaluation of the capabilities of existing boosters , boosters presently under development and a projection of these capabilities forward to the 1970 time period, the objective being the selection of a minimum cost launch vehicle for satellite injection.

The flight path chosen for a payload and the payload weight determine what capabilities are required of a launch vehicle. The United States has developed a family of launch vehicles which are compatible with the variety of space missions now foreseen. Justification for such a development is, in part, economical for it allows selection of a minimum cost launch vehicle consistent with the orbital and payload requirements of a particular mission.

The capability of the current launch vehicle family capable of synchronous injection and examined in the study is given in Table VIII. The passive and active satellites utilized in the study align themselves in the weight range of 1000 to 3000 pounds. An examination of the characteristics in Table VIII and consideration of the payload volume, availabilities, etc. of these boosters led to standardization of three launch vehicles for the study. These are the Atlas/Agena + Burner II (BII), the Titan IIIC, and the Titan IIIC + BII with approximate payload weights of 1000, 2000, and 3000 pounds respectively. While it is not expected that the Atlas Agena will be available for launchings in the 1970 time period, it is used since it is believed to be representative, from a cost and weight standpoint, of boosters which will become available to fill its gap. A brief description of the various pertinent launch vehicles is given in the following paragraphs.

Thor/Delta.- Since its evolution, the Delta has undergone several modifications. The various models have been used successfully in the Echo, Telstar, Relay and Syncom communication satellite programs and a new Delta (Model M) will launch the first Intelsat III or British Skynet series of communication satellites.

The Delta is a three-stage launch vehicle for medium weight satellites. Included among the upgraded versions are the Thrust-Augmented Delta (TAD). The TAD first-stage was a modified version of the Thor launch vehicle with strap-on solid propellant motors for thrust augmentation. The second-stage was an improved stage from the Vanguard and Thor ABLE programs. Radio guidance in the second stage provided velocity and attitude control. The Thrust-Augmented Delta also adapted the Scout developed X-258 to replace the Vanguard third stage used on earlier vehicles. The newer Delta, TAD, increased the capacity of the second stage by adapting and extending the propellant tanks from the Able-Star stage. It also adapted the USAF developed FW-4 solid propellant motor to replace the X-258 third-stage capability. Payload capability of this improved Delta is illustrated in Figure 14.

The current version of Delta (Model M) incorporates the USAF Long Tank Thor first stage, the improved Delta second stage and a solid propellant third stage adapted from the Surveyor spacecraft retro-motor.

Table VIII. Synchronous Launch Vehicle Capability and Costs

Launch Vehicle	Payload To Synchronous (lb)	Estimated Costs (Meg $)
Delta	210 to 290	3.7
Atlas (SLV-3A) & Agena D with Apogee Motor	500 1100	8.0 8.4
Atlas (SLV-3A) & Improved Agena With Apogee Motor	850 1340	8.0 8.4
Atlas (SLV-3C) & Agena D with Apogee Motor	- 900	- 8.4
Atlas (SLV-3C) & Improved Agena with Apogee Motor	250 1100	8.0 8.4
Atlas/Centaur + Burner II	1850	14.2
Titan IIIC	2050	15.9
Titan IIIC + Burner II	3000	18.1
Saturn V	47000	203.0

NOTE: Some variation in weight and cost as a function of source was noted and some judgment was therefore exercised in the above listing.

The Long Tank Thor uses liquid oxygen and thrust augmentation is provided by three solid motors. The vehicle has a synchronous transfer capability of 785 pounds.

Now being proposed to NASA is an uprated Delta. The uprated Delta uses the present first and third stages and fairing integrated with a new hydrogen/oxygen second stage. Uprated Delta increases the synchronous transfer capability to 2000 pounds and could fill the gap left by the Atlas/Agena phase-out.

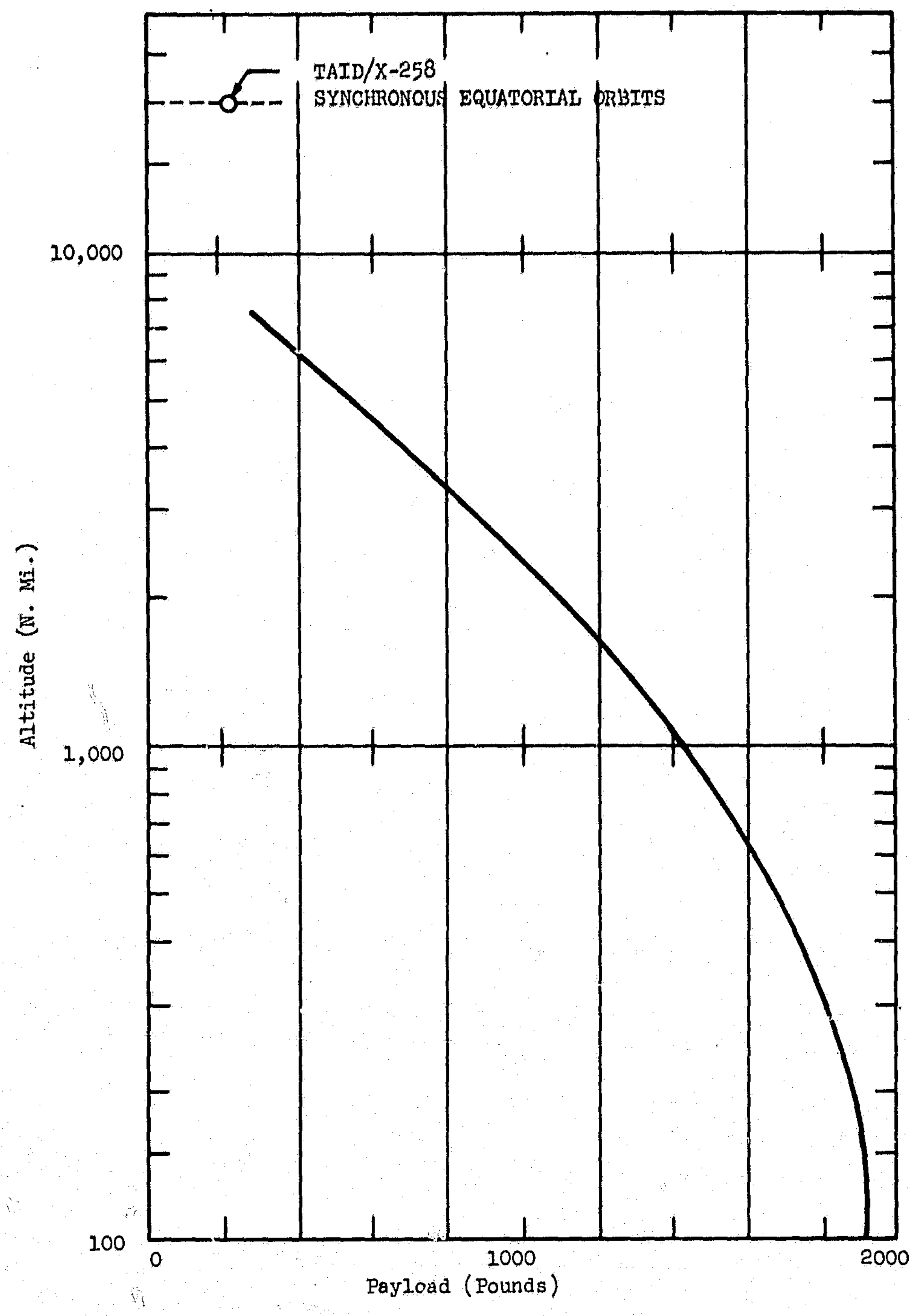


Figure 14. Thrust Augmented Improved Delta Payload Capabilities

Atlas/Agena.- Atlas/Agena is a two-stage all-liquid propellant vehicle capable of orbiting relatively heavy earth satellites and placing into escape trajectories, lunar probers and interplanetary and planetary exploration spacecraft. The first stage is an Atlas vehicle. There are several versions of the Atlas booster which can accept the Agena upper-stage. The Atlas includes the SLV-3A and SLV-3C. The SLV-3A is 117 inches longer than the SLV-3 and has increased capability. While it is four feet shorter, the SLV-3C has the same maximum thrust as the SLV-3A.

The upper-stage Agena is a liquid fueled, single engine vehicle with multiple re-start capabilities. When used as a launch vehicle, the Agena (after separation) also becomes a satellite with its own stabilization and control system, power supply and re-entry capability.

An improved Agena is currently under development. Virtually identical to the Agena D is external configuration, the improved Agena utilizes a different propellant which will permit pad holders of up to one month. This improved Agena also offers restart capabilities.

Figure 15 shows the payload capabilities of the Atlas/Agena D. The Atlas/Agena may also use as an upper stage the Burner II. This is a solid

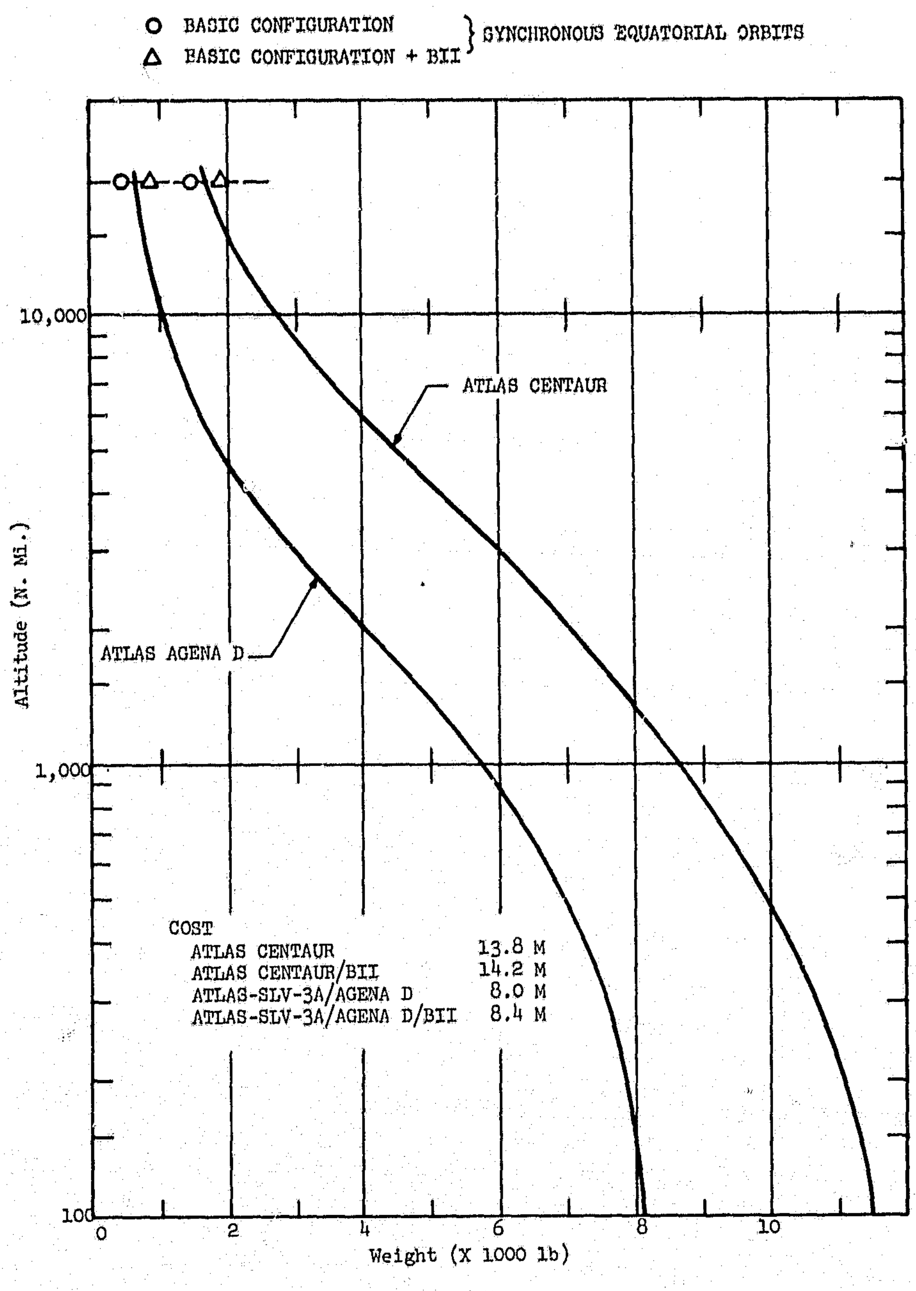


Figure 15. Atlas/Agena D Payload Capabilities

fueled single engine vehicle which can be adapted to a variety of boosters for precise orbit insertion and maneuverability of payloads in space. Originally developed for use with the Thor booster, the Burner II must be modified for payloads weighing more than 200 pounds and/or flying on other boosters. The design modifications are available. Burner II, which weighs about 300 pounds at burnout, becomes attractive when the spacecraft cannot be made to include an apogee kick motor for a loss of useful payload weight less than 300 pounds. It is also attractive where three-axis attitude control is favored over spin stabilization for the transfer orbit coast.

Atlas/Centaur.- The Atlas/Centaur is a two-stage liquid-fueled vehicle. Standing 100 feet high and weighing 300,000 pounds, this is the most advanced of the Atlas based series of launch vehicles. It develops a thrust of more than 300,000 pounds and can fly unmanned lunar and planetary spacecraft beyond the capabilities of the Atlas/Agena launch vehicles.

Centaur is a flight-proven high energy upper stage powered by two liquid oxygen engines. It develops 30,000 pounds of thrust and has a single restart capability. The weight which the Atlas/Centaur can place into orbit is shown in Figure 15.

The Burner II is also readily adapted to use the Centaur vehicle. Mating of the Burner II with the Atlas/Centaur would provide a launch vehicle that could be used for certain types of radio and TV broadcast satellites.

Titan IIIC.- The Titan family provides a capability greater than any other existing system with the exception of Saturn. Its boosters use solid and liquid stages and strap-on motors. The basic building block of the booster family is the Titan IIIA which uses a Titan II core and maneuverable transtage. The Titan IIIC, currently the most powerful in the Titan family develops 2.5 million pounds of thrust. It employs two five-segment 120-inch strap-on motors as stage zero, the two core stages of the Titan IIIA and the transtage upper stage. Guidance and other services for the entire Titan booster are packaged in the transtage which is capable of synchronous orbit injection using inertial memory. Figure 16 shows the Titan III standard aerodynamic fairing and figure 17, payload capabilities of the vehicle. Figure 17 also shows the payload capabilities of a Titan IIIC/Centaur. Such a combination is under study for orbiting large communication satellites.

The Burner II can also be adapted for use with the Titan IIIC. This allows an additional 900 pounds to be launched into synchronous orbit.

Saturn IB/Centaur.- Saturn IB is a two-stage launch vehicle designed to perform large payload, manned and unmanned space flights. The three-stage Saturn IB/Centaur is an advance version which will be capable of placing 9800 pounds into synchronous orbit. The three-stage vehicle weighs, less payload, about 1,282,000 pounds at launch.

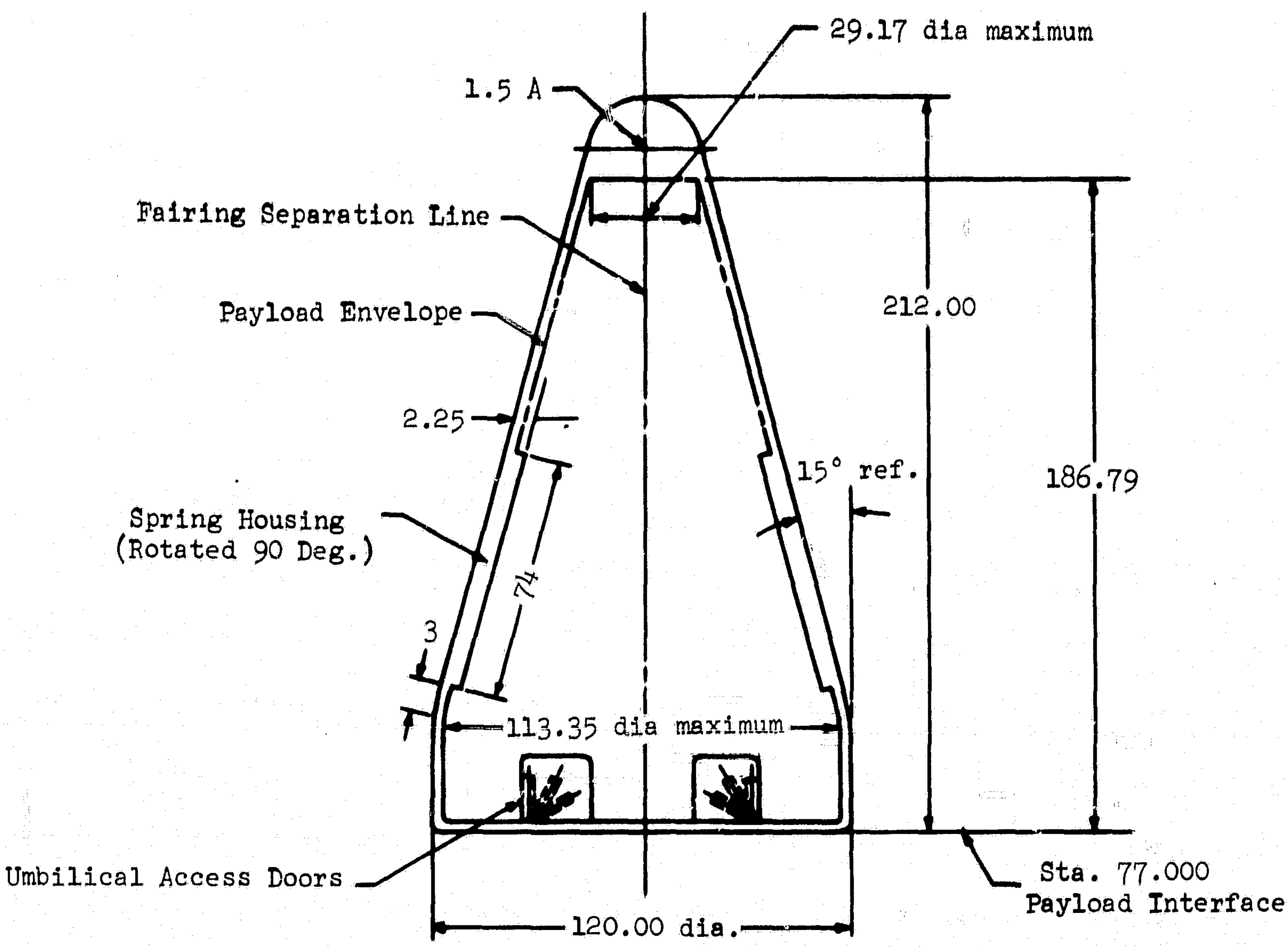


Figure 16. Standard Aerodynamic Fairing (Titan III-C)

The first stage of the Saturn IB/Centaur is an S-IB developed and qualified on the Redstone, Jupiter and Saturn I vehicles. The second stage is an S-IVB above which is housed the guidance, control and flight instrumentation systems. Centaur has its own guidance and control system which controls the stage after its separation from the S-IVB.

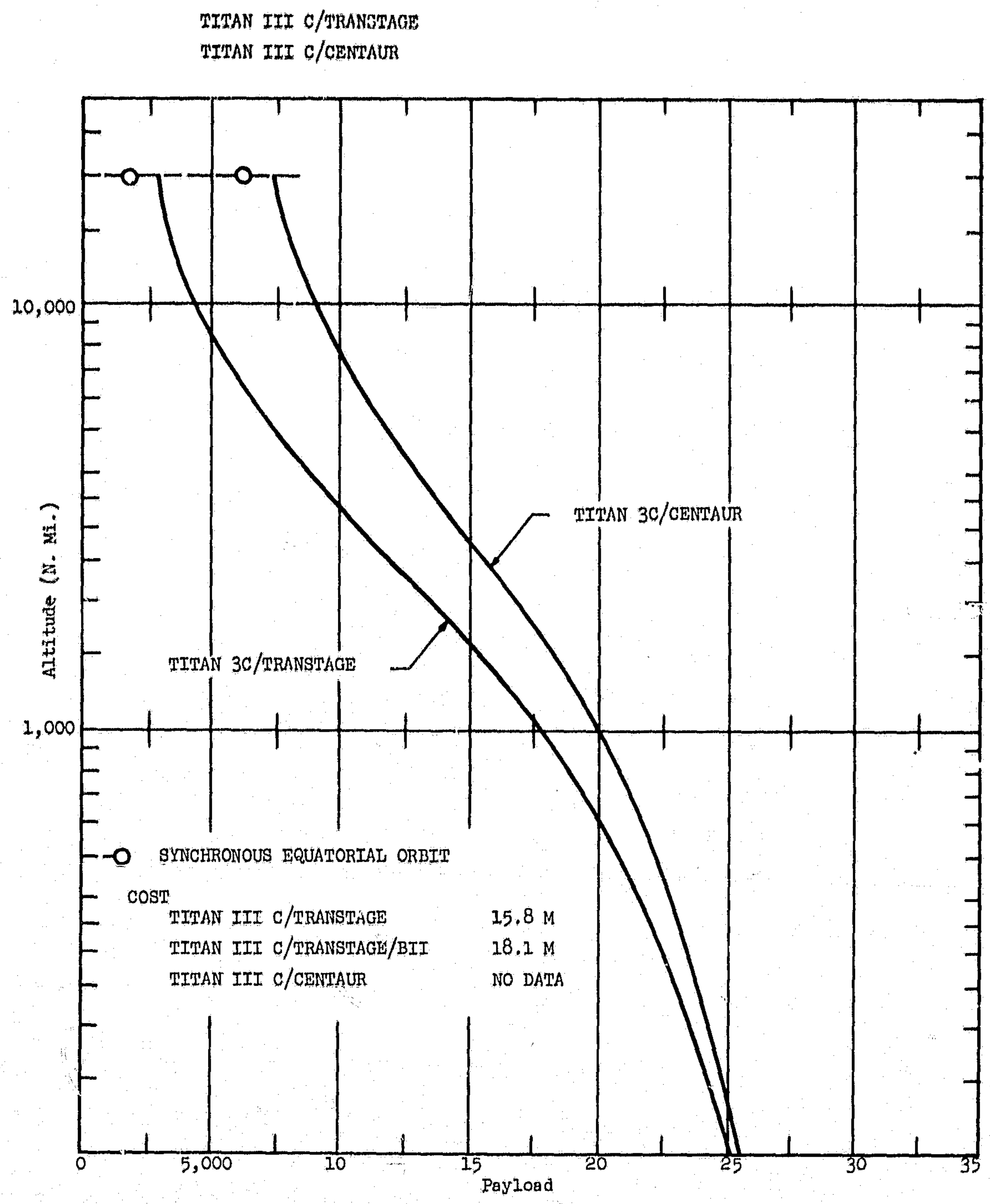


Figure 17. Titan III-C Payload Capability

The payload capabilities of the Saturn IB/Centaur is shown in Figure 18.

Saturn V.- Saturn V is a three-stage launch vehicle employing the S I-C first stage, the S II second stage and S-IV B third stage. The instrumentation

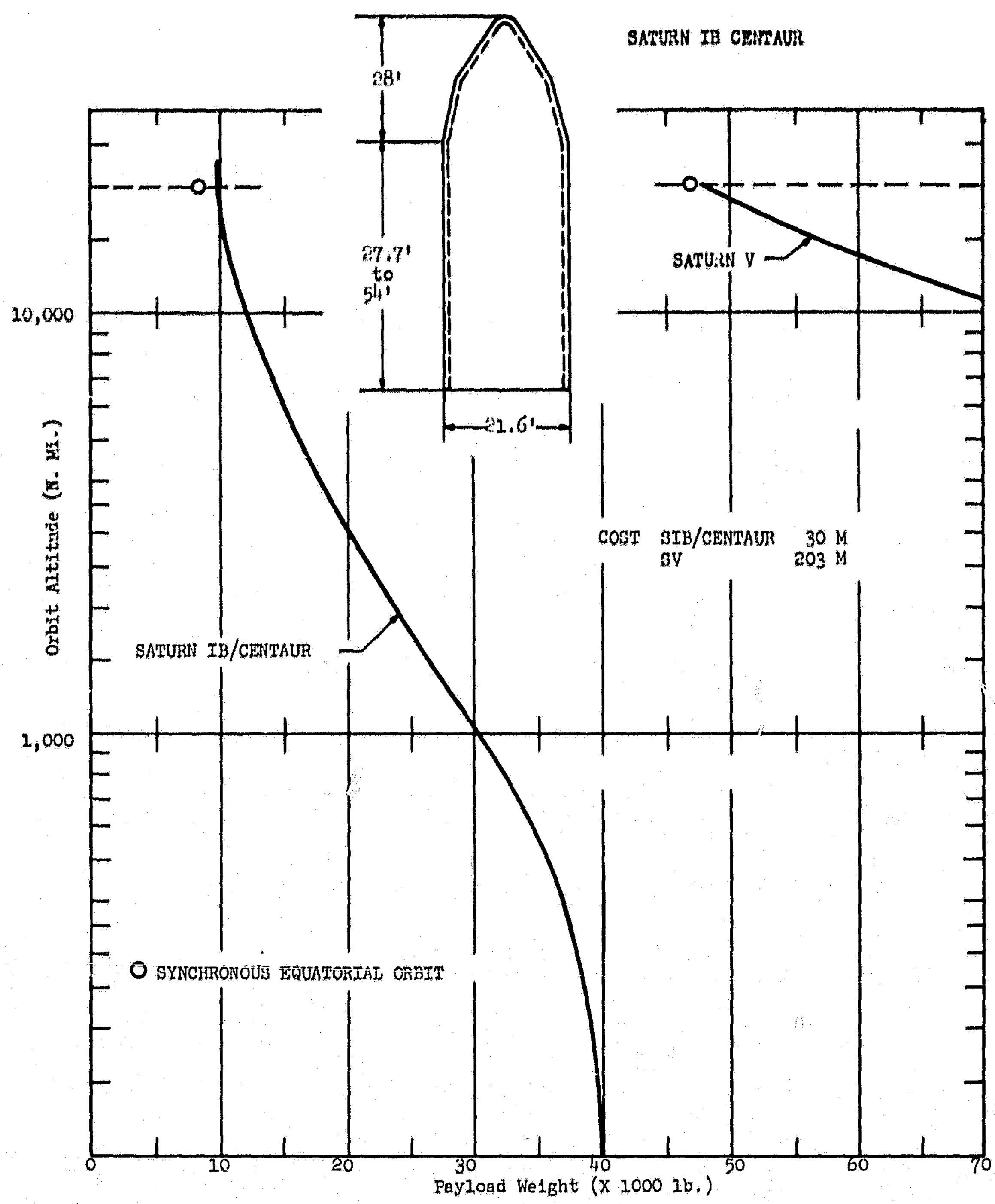


Figure 18. Saturn IB/Centaur Payload Capabilities

unit is basically the same on both Saturn IB and Saturn V vehicles. Saturn V stands 363 feet high and produces 7.5 million pounds of thrust. It has the capability of placing over 142 tons into a low earth orbit or 47,000 pounds into synchronous orbit.

Synchronous Payload Cost.- Figure 19 is a plot of the cost of weight into synchronous orbit. Cost of some of the launch vehicles are plotted and extrapolations made in order to determine approximate cost required to launch a particular payload into synchronous orbit. Some variance in cost and payload capability was experienced in conducting the survey. However, as can be seen in the figure, these are small and can be approximated by a single line.

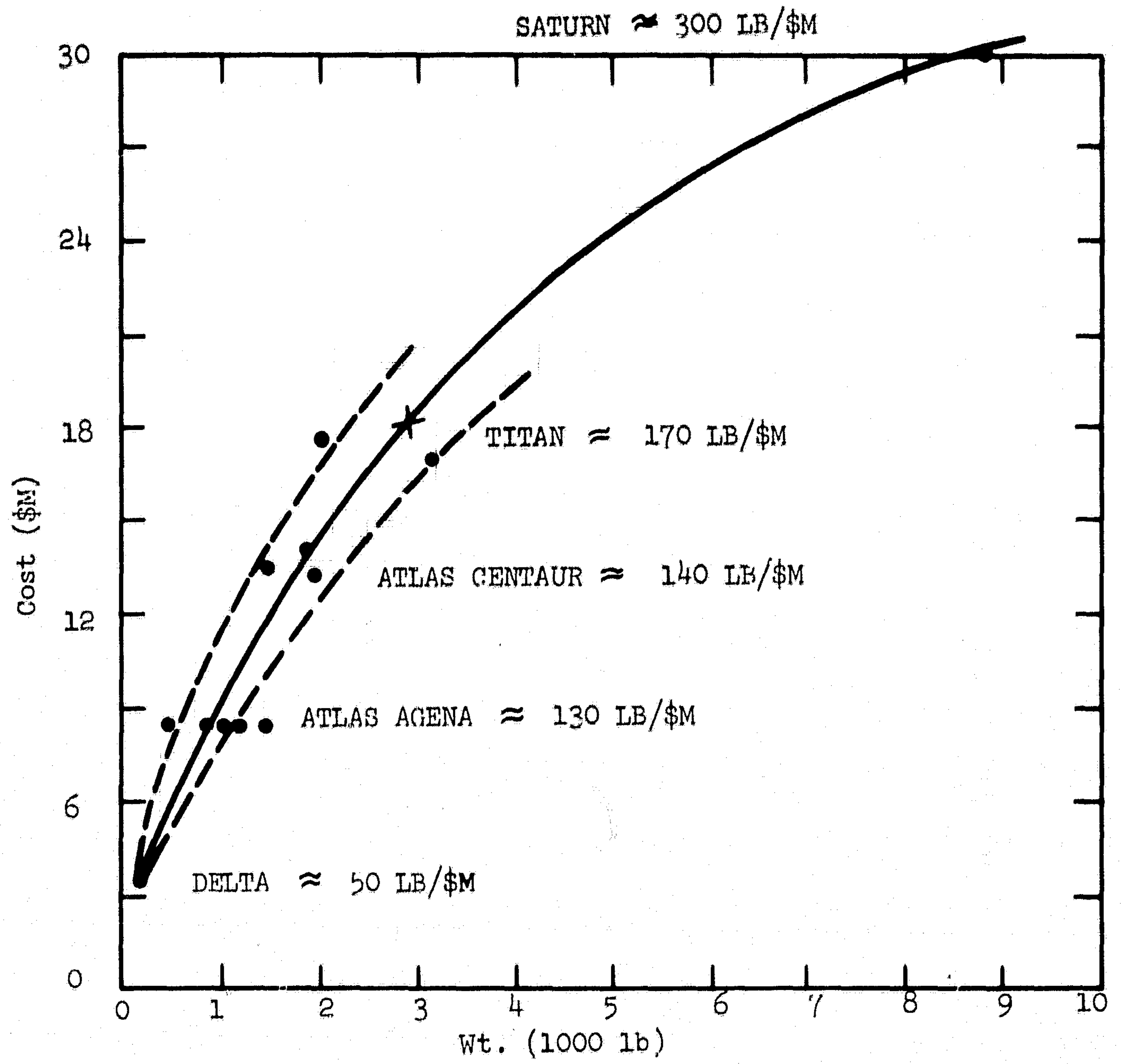


Figure 19. Cost of Weight for Synchronous Orbit

Advanced Vehicles. - In the past, new launch vehicle requirements have been satisfied by operating vehicles, adding strap-on motors, combining new stages, developing velocity packages and kick stages and, when required, by new vehicles such as Saturn V for the Apollo program. Such a procedure provides cost effectiveness and reliability and is expected to continue. Currently under development is the Titan IIIM with first launchings expected in late 1968. This vehicle replaces the Titan IIIC five-segment motors by seven-segment motors. It is designed to launch 3,200 pounds into synchronous orbit with 3.2 million pounds of thrust. Additional improvements in the Titan IIIC are envisioned in the Titan IIIF. The

IIIF takes advantage of the seven-segment motors used in the Titan IIIM and core modification. It employs a second-stage restart or an increase of 12,000 pounds in the transtage propellant to increase high attitude capability.

An additional improvement in the Atlas is the Atlas SLV 3X. This booster would increase the thrust of the SLV-3 but retain the present sustained thrust.

As previously mentioned, a study is under way for mating the Titan IIIC and the Centaur. Mating of the Titan family with the Burner II is also planned. Burner II is an attempt at developing a new upper-stage. In addition to its adaptability to the Titan IIIC, Atlas/Centaur and the Atlas/Agena vehicles, it can be used as the second stage of the Atlas and the third stage of the Thor/Delta. Other new upper stages have been proposed to satisfy the requirements of high velocity missions. These include a "High Energy Kick Stage" whose use of fluorine as an oxidizer makes it a vehicle truly representative of advanced technology.

Other vehicles and new combinations have been proposed for filling existing gaps, such as that of the Saturn booster, and for creating increased cost effectiveness. The development of these vehicles will depend in large measure upon their utilization.

ECONOMIC AND TECHNICAL COMPARISONS OF ACTIVE AND PASSIVE COMMUNICATION SATELLITE SYSTEMS

General

Guidelines.- This section analyzes the conditions under which a system utilizing passive satellites may prove to be more advantageous than a system where active satellites are employed.

In any system comparison, two primary factors are of importance:

(1) Technical performance

(2) Cost effectiveness

If one system offers unique technical advantages which the other cannot offer, and if these technical advantages are required because of operational considerations, no true effectiveness comparison is possible since no choice exists. However, if both systems are capable of similar technical and operational performance, then the comparison of the total costs of establishing and operating these systems yields a criterion for the determination of their relative effectiveness.

The comparison of active and passive satellite systems must, therefore, be based on the evaluation of the following characteristics of each type of system under study.

(1) Unique operational properties

(2) Technical limitations

(3) Costs

The unique features of passive reflector systems which cannot be provided with active systems are of particular interest. These features may be important in many cases and may therefore dictate the choice of the orbiting element. The usefulness of these unique properties will normally depend on the mission to be accomplished. In some cases, however, these properties may also become important when future growth of the system or its operation in changing environment is contemplated. These aspects of the problem will be considered later in the report when specific system configurations selected for analysis are discussed.

Basic Comparison Criteria.- In order to preserve as much generality in the study as is possible, the following guidelines for the comparison have been adopted:

(1) The systems to be compared will be those designed to carry conventional communication traffic such as voice, data, and television.

(2) The technical effectiveness of the systems will be compared on the basis of the total number of communication channels that can be provided by each system with a single satellite in orbit; the channels in both systems meeting the same performance requirements.

(3) The required channel performance will be specified in terms of the signal-to-noise ratio at the output of the user receiving station.

(4) The primary comparison criterion will be the total relative cost of establishing and operating each of the systems under study when the total required number of channels in each system is the same, and when channels in both systems meet the same performance specifications.

(5) Since only a relative cost comparison is required, the cost of user stations, which is identical in both systems, does not have to be included in the cost analysis.

Comparative Analysis of Point-to-Point Voice Communication System

In this section passive and active communication satellite systems which provide two-way voice communications from point-to-point are compared. For the passive system case a ground based repeater and reflector in synchronous orbit is assumed to provide the required system gain for operation between the smaller user terminals. Active satellites with hard limiting repeaters comprise the active system.

Comparison Criteria. - The systems are compared as to their technical effectiveness in terms of the total number of channels each can support. The primary comparison criteria, however, is the cost per channel of the specified service as a function of the total number of channels provided by each system.

Limitations on the Scope of the Study.- The authorized scope of the program did not permit the analysis of all the pertinent factors and has necessitated certain limitations on the system parameters which can be listed as follows:

(1) The study is limited to systems employing frequency modulation and utilizing frequency division multiplex (FDM) method of multiple access

(2) Operating frequencies are 8 GHz uplink and 7.25 GHz down link

(3) All user terminal stations in the system are of one type. This implies that the effective radiated power (ERP) of all user transmitters is the same and that all user receivers in the system have the same fm threshold and the same sensitivity (G/T). As explained later in the text, five different types of user stations have been considered in the analysis.

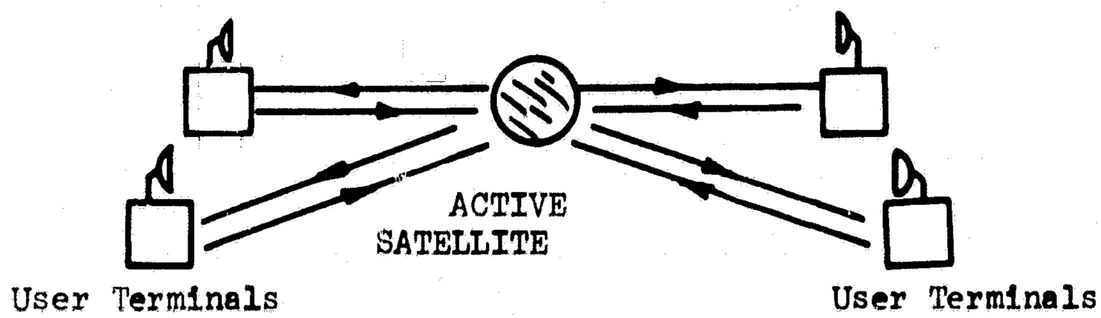
(4) The methods of system traffic control are not considered in the analysis of cost-effectiveness. This approach was taken since the state-of-the-art in the area of system traffic control techniques for active satellite systems with many accesses is in its infancy and could not be reasonably included within the scope of this study. Accordingly, the analysis does not include the loss of system capacity and additional costs which would be associated with such traffic control subsystem.

All these restrictions are discussed more fully in the pertinent sections of this report.

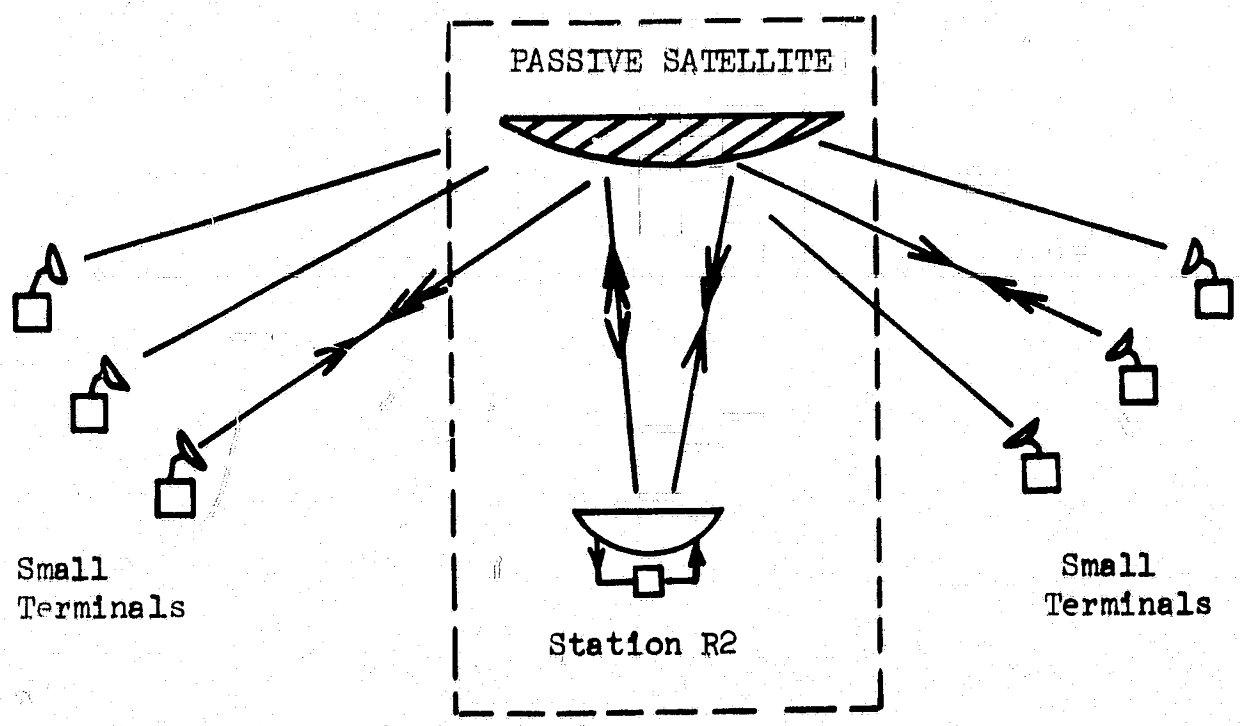
System Configurations.- Two system configurations were selected, one for the active and one for the passive satellite systems as shown in Figure 20. These two configurations were designated as Systems A1 and B1.

System A1: System A1 is a frequency division multiplex multiple access system utilizing active satellites in stationary orbit, providing two-way voice communication between small ground terminals.

System B1: System B1 is a frequency division multiplex multiple access system utilizing a passive relfector in synchronous orbit and a ground based repeater station (designated R2) and providing two-way communications between user terminals. This system will be referred to as a "double-hop passive system" because it requires twice the transmission path needed for active systems. (It can be shown by basic calculations that repeater R2 is required to provide the necessary system gain, when transmitting terminals have low ERPs.) (see Appendix I)



System A1



System B1

Figure 20. System A1 and B1 - Double-hop Passive System

Several assumptions must be made regarding the repeater station R2. These assumptions are made in order to limit the scope of the study and do not represent any inherent limitations or requirements on the system. They are as follows:

(1) Only one parabolic dish antenna is used for both receiving and transmitting functions.

It would be possible to have different antennas--for example, an array for receiving and a parabolic dish for transmitting. However, the technical and cost analysis of these alternatives was beyond the scope of this study. (See Appendix E for discussion of various antenna systems.)

(2) The ground station R2 acts as a simple frequency translating repeater having a linear transfer characteristic.

The assumption is justifiable by the fact that since only a ground-based installation is considered, linearity of the repeater can be effectively obtained by standard techniques, which although more costly are quite feasible.

Technical Characteristics of Subsystems.- This section describes the technical characteristics of the various subsystems which are pertinent to the study. The major subsystems are:

(1) The user's ground terminal stations

(2) The active satellite

(3) The passive satellite

(4) The ground based repeater (R2) associated with the passive satellite System B1.

Terminal Stations: Five types of ground terminal stations will be considered in this study designated ST-1, ST-2, ST-3, ST-4, and ST-5. These station's characteristics were selected to cover the entire range of applications--from small mobile terminals (with 6-foot antennas) (ST-1) to large stations exceeding the capabilities of presently used comsat-type terminals (with 100-foot antenna) (ST-5). All of these stations have either been built or are entirely within the state-of-the-art. Their basic characteristics are shown in Table IX.

The Active Satellite: Four types of active satellites have been considered in this study. Their characteristics (Table X) in terms of antenna beamwidth and ERP cover the entire range beginning with the existing state-of-the-art, which is represented by SAT-1, and extending to the performance which might

Table IX. Characteristics of Terminal Stations

Parameter	Units	ST-1	ST-2	ST-3	ST-4	ST-5
Antenna Diameter	ft.	6	15	30	60	100
Antenna Gain (8 GHz)	dB	41	49	55	61	65
Transmitter Power	watts	1000	5K	10K	10K	100K
Transmitter Power	dBW	30	37	40	40	50
Receiver Noise Temp.	°K	315	100	100	64	64
Receiver Noise Temp.	dB°	25	20	20	18	18
G/T	dB	16	29	35	43	47
$(ERP)_1$	dBW	71	86	95	101	115

Table X. Active Satellite Parameters

Designation →		SAT-1	SAT-2	SAT-3	SAT-4
Useful weight	lbs	1000	1000	2000	3000
Receiver noise figure	dB	5	5	5	5
Receiver bandwidth	GHz	0.5	0.5	0.5	0.5
Receiving antenna gain	dB	19	19	19	19
Transmitter power	dB	15	26	29	31
Transmitter RF Power	Watts	35	400	800	1200
Misc. Losses	dB	3	3	3	3
G/T	dB	-12	-12	-12	-12
ERP with 16° Beamwidth	dBW	32	43	46	48
8		38	49	52	54
4		44	55	58	60
2		50	61	64	66
1		56	67	70	72
Booster required		Atlas/Agena		Titan IIIC	Titan IIIC & BII

become available in 1975 time period or later (SAT-4). It is assumed that an earth coverage receiving antenna is used in all cases and the satellite receiver has a noise figure of 5 and a total bandwidth of 500 MHz. The transmitter power capabilities are based on Comsat Corporation estimates and a loss of approximately 3 dB is assumed to be associated with the problems of antenna despinning and system stabilization and pointing accuracy. The various features of these satellites are discussed in more detail in Appendix J.

The Passive Satellite Characteristics: The passive reflectors which are assumed in this study are of the "saddle" type (see Appendices A and B). Two sizes are considered having a diameter of 325 feet and 150 feet, corresponding to the maximum weight which can be lifted by a Titan IIIC and BII and an Atlas/ Agena and BII booster respectively. The "gain" of these passive structures has previously been defined as:

$$G = \left[\frac{4 \pi D}{\lambda \theta}\right]^2$$

The gains of the passive satellites used in the study along with their required boosters are shown in Table XI.

Table XI. Characteristics of Passive Reflectors

Designation →		A	B
Diameter →	ft	325	150
Gain with 1° beamwidth at 7.25 GHz	dB	124.7	118
2		118.7	112
4		112.7	106
8		106.7	100
16		100.7	94
Booster required		Titan IIIC & BII	Atlas/Agena + BII

The Ground Based Repeater (R2):

<u>Antenna Gain</u>

The technical limitations on the size and gain of large ground antennas are discussed in Appendices D, E and G. The costs associated with the gain of such antennas have been calculated in Appendix F. Based on these considerations (see Table 5 in Appendix F), the following antenna parameters have been selected for use in the study as representing a compromise between reasonable cost and antenna gain.

Antenna gain = 69 dB (at 8 GHz)

Antenna diameter = 159 ft

Antenna rms surface tolerance = 0.057 inch

Antenna cost = 11.2 million dollars

Only a single parabolic dish was considered. Other antenna configurations such as arrays and multiplate systems are discussed in general terms in Appendix E but the scope of the program precluded their more detailed evaluation.

Effective Radiated Power

The maximum rf power capability of ground based transmitters is analyzed in the preceding main section and Appendix H. It is concluded that a practical operating limit is reached utilizing two high power klystrons, each rated at 625 kw and operating them in parallel at 500 kw to achieve a reasonable signal to distortion ratio. Thus, total output of 60 dBW is assumed which is degraded by 1 dB to account for miscellaneous losses before the signal is radiated, resulting in a total RF power delivered to the antenna of 59 dBW. When combined with antenna gain of 69 dB, a total ERP of 128 dBW is obtained.

As mentioned previously, ground based station R2 is a simple frequency changing linear repeater. Sufficient degree of linearity is obtained by operating the output tubes below their rated values as discussed in Appendix H.

Bandwidth

The total operating bandwidth of the repeater is constrained by the bandwidth of the power tubes and the front end. As discussed in Appendix H, for operation with two power tubes in parallel, and a single wide band preamplifier,, a bandwidth of 500 MHz can be achieved at X band. This is primarily the result of preamplifier bandwidth limitations which are discussed more fully in Appendix J.

Noise Temperature

An overall noise temperature of 50°K is assumed for the receiver in the ground repeater station R2. Since the attainment of such temperature is well within the state-of-the-art, the assumption requires no further analysis.

Summary

The important characteristics of the ground repeater station R2 derived from studies reported in Appendices D, F, G, H, and J are summarized in Table XII.

Table XII. Characteristics of Ground Based Repeater R2

Antenna gain	69 dB
Transmitter power	59 dBW
Losses in transmitter	1 dB
Receiver noise temp	50° K
ERP	128 dBW
Receiver G/T	52 dB
Total bandwidth	500 MHz

Performance Requirements: Appendix K analyzed in detail the signal-to-noise ratio requirements for voice service at the output of user's receiver and relates them to the input of frequency modulation receiver utilizing threshold extension demodulator (FMFB).

If the modulation index of 2.5 is assumed, the operational performance parameters for voice transmission listed in Table XIII can be calculated from the data provided in Appendix K.

Table XIII. Operational Performance Requirements for Voice Transmission

Output voice bandwidth	b = 4 KHz
Output SNR	SNR_{out} = 24 dB
Modulation index	m = 2.5
RF bandwidth - B	B = 30 KHz
Receiver threshold in Bandwidth B	T = 7.1 dB
Input Carrier-to-noise density ratio	C/N_o = R = 51 dB-Hz
These values will be used throughout the study.	

Selection of the Cost Model: Various cost models for the total system cost have been considered for use in this study. They ranged from the model used by DCA in the ADCSP studies to the model used by Comsat Corporation in their study of domestic satellite TV distribution systems.

The ADCSP system model is based on the calculation of the present value of the total system costs stated for the year during which full operational capability is achieved for the first time. The sum of the total R&D and establishment costs is annualized and adjusted upward using a given compound interest rate to reflect the amount of time required between program initiation and the commencement of system operations. The annual replenishment costs for 10 years of system operation are discounted to the present value at the year of commencement of system operation.

As a result the model represents the present value of all costs incurred in the establishment and operation of the system, referred to the starting date of operations.

The communication satellite model, on the other hand, annualizes all R&D and system establishment costs over the economic life of the system. Space segment maintenance costs are also annualized over the mean life of satellites. The level annual costs are calculated to return a given percentage on investment after taxes, when discounted to present value. As a result this model yields the present value of the system costs spread over the life of the system.

Having examined the relative advantages and disadvantages of these approaches, a simple model has been selected which is based on the premise that all initial investments will be converted to level annual costs calculated to return 8 percent on investment over the life of the system when discounted to present values and all yearly maintenance costs will be written off during the year in which they are incurred. The total system cost will therefore be expressed in terms of level annual costs over the life of the system. For comparison purposes between the passive and active systems, the model is completely adequate since the interest was in comparative results rather than absolute ones.

Thus, the model of the total annual system cost* can be expressed as follows:

$$C_{TOT} = n \left\{ \left[\left(C_{RDS} + C_{ES} \right) + \left(C_{RDG} + C_{EG} \right) \right] \left[\frac{i}{1-(1+i)^{-n}} \right] + \left[C_{MG} + C_{MS} \right] \right\} \quad (28)$$

C_{RDS} = Cost of initial R&D for orbiting subsystem

C_{RDG} = Cost of initial R&D for ground subsystem (Repeater R2 in the passive case)

C_{ES} = Cost of establishment of orbiting subsystem

C_{EG} = Cost of establishment of ground subsystem (Repeater R2 in the passive case)

n = Number of years to recover capital expenditures (can correspond to system operating life)

*It is assumed that the system has no salvage value at the end of n years of operation.

i = Annual rate of return on invested capital (interest rate)

C_{MG} = Annual cost of operation and maintenance of the ground segment

C_{MS} = Annual cost of replenishment of the space segment.

The establishment cost of the space segment is equal to

$$C_{ES} = N_E \left[C_{LS} + k_E C_S\right] \qquad (29)$$

where N_E = number of launches needed to establish the space segment

C_{LS} = total cost of booster and launch services

k_E = number of satellites per booster

C_S = cost of individual satellite

The annual cost of replenishment of the space segment is equal to

$$C_{MS} = N_M \left[C_{LS} + k_M C_S\right] \qquad (30)$$

N_M = number of launches needed per year to replenish the space segment

C_{LS} = cost of booster and launch services

k_M = number of satellites per booster

C_S = cost of individual satellite

Thus, the total level annual cost is represented by the following equation.

$$C_{T/A} = \left\{\left[\left(C_{RDG} + C_{EG}\right) + \left(C_{RDS} + N_E\left(C_{LS} + k_E C_S\right)\right)\right]\left[\frac{i}{1-(1+i)^{-n}}\right] + \left[C_{MG} + N_M\left(C_{LS} + k_M C_S\right)\right]\right\} \qquad (31)$$

Alternatively, equation (29) can be written to separate the costs of the ground and space segments

$$C_{T/A} = C_{TAG} + C_{TAS}$$

$$C_{T/A} = \left[\left(C_{RDG} + C_{EG}\right) \left(\frac{i}{1-(1+i)^{-n}}\right) + C_{MG} \right] +$$

$$\left[\left\{ C_{RDS} + N_E \left(C_{LS} + K_E C_S \right) \right\} \left(\frac{i}{1-(1+i)^{-n}} \right) + N_M \left(C_{LS} + k_M C_S \right) \right] \quad (32)$$

The first squared bracket represents the level annual cost of the ground segment (C_{TAG})

The second squared bracket represents the level annual cost of the space segment (C_{TAS})

This cost model will now be applied to the computation of level annual costs of:

(1) Active satellite system A1

(2) Passive satellite, "double-hop" system B1

Cost Effectiveness Analysis:

General Approach

In this section the comparative cost-effectiveness of the active satellite system A1 and of the passive system B1 will be analyzed. The comparison will be based upon the determination of the maximum system capacity in terms of accesses and in terms of the corresponding cost per access.

This study is not concerned with the problems of system loading or utilization factor. A fully loaded system is considered which represents the worst operating condition from power consumption and intermodulation point of view.

The full system load implies that there exists substantially more ground stations than can be accommodated at any one time so that when traffic statistics are taken into account the system can be expected to be filled to capacity at all times.

Since it is assumed that the transportable user ground stations in the two systems are identical in technical performance and cost, it is not necessary to include them in the cost analysis. The study can be reduced, therefore, to the comparison of the relative cost of the active satellite in the case of system A1, and of the passive reflector in orbit and an associated ground-based repeater B2 (shown enclosed by dotted lines in Figure 20) in the case of system B1.

The comparison approach will therefore consist in determining the total annual cost of both systems (excluding user's terminals) when such systems operate with the same user terminal equipment. Since both systems meet identical performance requirements, the relative comparison of the costs will yield an indication of their relative effectiveness.

The above approach is taken to render the final results more meaningful by considering relative rather than absolute costs. The determination of accurate total absolute costs would entail an effort outside of resources of this project. On the other hand, relative comparisons can be made with more confidence since errors of similar nature tend to cancel.

The analysis will be accomplished as follows:

(1) Determination of total level annual cost of

(a) Active satellite system (A1)

(b) Passive satellite - double hop system (B1)

(2) Determination of total access capacity of

(a) Active system A1

(b) Passive system B1

(3) Determination of costs per access

(4) Comparison and conclusions

Determination of total level annual system cost of the active satellite system (A1)

The cost model developed can be applied to the case of active satellites as follows:

$$C_{T/A} = \left[C_{RD} + N_E\left(C_{LS}+k_E C_S\right)\right]\left[\frac{i}{1-(1+i)^{-n}}\right] + N_M\left(C_{LS} + k_M C_S\right) \qquad (33)$$

C_{RD} = Cost of satellite R&D

N_E = Number of launches required to establish one satellite in orbit for 90 percent confidence limit.

C_{LS} = Launch cost = Cost of booster plus launch services

k_E = Number of satellites per launch. (k_E = 1 for the case)

C_S = Unit production cost of satellite

$\frac{i}{1-(1+i)^{-n}}$ = Factor for converting investment to level annual cost. It is assumped that the return on investment of approximately 8 percent (i = 0.08) over the period of 10 years (n = 10) which corresponds to the life of the system. For these conditions the factor equals approximately 0.15.

N_M = Number of launches per year required to restore one satellite that has failed in orbit. From Table 10 of Appendix L $N_M = 0.22$.

k_M = 1 = Number of satellites per launch

(1) Cost of Satellite R&D

Four types of active satellites whose characteristics are listed in Table X can be used. The estimates of their R&D costs have been based on several sources.

Satellite No. 1 is a low-power satellite of 1000-pound weight and represents the state-of-the-art of technology. Its R&D costs have been estimated in Appendix J.

Comsat Corporation, in its study, "Satellite Broadcasting," issued in July 1967, has estimated the R&D costs associated with the development of high-power satellites. Using this data R&D costs for satellites designated as Nos. 2, 3, and 4 in Table X have been estimated. These estimates, together with the raw DC power which the satellite would produce are shown in Table XIV below.

Table XIV. R&D Cost of Active Satellites

Sat.	Weight	DC Power kw	R&D Cost $M	Cost of one satellite
SAT-2	1000 lb	3.2	27.0	5.0
SAT-3	2000 lb	6.4	35.0	9.0
SAT-4	3000 lb	9.6	45.0	12.0
	4000 lb	12.8	50.0	14.2

The R&D cost shown does not include the delivery of flight qualified hardware and does not include a flight test. It covers primarily the development of satellites capable of producing high power with solar cell technology. When large antennas with narrow beamwidths are required additional R&D is required. In order to estimate additional costs necessary to develop stabilization techniques and associated hardware which would result in pointing accuracies necessary for operation with 1 degree and 2 degree beamwidth from space, various space antenna manufacturers were consulted. Because of a wide difference of opinion on the subject of R&D costs for this item, a compromise figure of $10 million was adopted. This R&D cost is added to all satellites when a 1 degree or 2 degree beamwidth is required.

It was also felt that a flight test would be required to prove the new designs, in addition to basic R&D costs. It was assumed that the test would be necessary for all satellites that have not been flown before. This includes all high-power satellites and the low-power satellite (SAT-1) with very narrow beamwidth (1 degree and 2 degree). No test is needed for low power satellites with 4 degree, 8 degree, or 16 degree beamwidth because the existing state-of-the-art is sufficient in these cases.

The flight test program was assumed to consist of the construction of two flight qualified satellites and one launch. The cost of launch was multiplied by a factor of 1.1 corresponding to the number of launches required to attain a 90 percent confidence level of orbiting the satellite with Launch Success Probability (LSP) of 0.9. (See Table 4 of Appendix L). The unit cost of satellites and the cost of launch are discussed in the succeeding paragraphs. The total R&D costs are summarized in Table XV.

(2) Number of Launches (N_E)

In this case the orbiting subsystem consists of one satellite in orbit. Thus one satellite is launched per booster. The number of launches required to establish one satellite in orbit with 90 percent confidence when the launch success probability is 0.9 and satellite deployment probability is 0.99 has been calculated in Appendix L. Table 4 in that appendix shows that for mean satellite life of 5 years, 1.1 launches are required to establish the system. Thus N_E = 1.1 in this case.

(3) Cost of Launch (C_L)

The cost of boosters and related launch services has been provided in the previous main section and is based on data obtained from NASA and major booster manufacturers. Following values are used, based on geo-synchronous orbit (Table XVI).

Table XV.

ACTIVE SATELLITE R&D COSTS ($Million)

Beam-width Degrees	Satell. ERP (DBW)	Satellite Wt. (lb.)	Booster required	C_{LS} Launch cost ($M) +	C_s Satellite unit cost ($M) =	C_x Cost per Launch	Total Cost/ Launch ($1.1C_x$)	R&D Costs to develop ($M): Power Capabil.	R&D Costs to develop ($M): Antenna & Stabiliz.	Flight Test Costs ($M): 2 flt. Satell.	Flight Test Costs ($M): Launch 1.1 Cl	Total R&D
1^o	56	1000	Atlas/Agena+ BII	8.4	4.5	12.9	14.1	-	10	9	9.2	28.2
	67	1000	Atlas/Agena+ BII	8.4	6.0	14.4	15.8	27	10	12	9.2	58.2
	70	2000	Titan IIIC	15.9	10.0	25.9	28.5	35	10	20	17.5	82.5
	72	3000	Titan IIIC + BII	18.1	12.0	30.1	33.1	45	10	24	20	99.0
2^o	50	1000	Atlas/Agena + BII	8.4	4.0	12.0	13.2	-	10	8	9.2	27.2
	61	1000	Atlas/Agena + BII	8.4	5.5	13.9	15.3	27	10	11	9.2	57.2
	64	2000	Titan IIIC	15.9	9.5	24.5	27.0	35	10	19	17.5	81.5
	66	3000	Titan IIIC + BII	18.1	12.0	30.1	33.1	45	10	24	20	99.0
4^o	44	1000	Atlas/Agena + BII	8.4	3.5	11.9	13.1	-	2.	0	0	2.0
	55	1000	Atlas/Agena + BII	8.4	5.0	13.4	14.7	27.	0	10	9.2	46.2
	58	2000	Titan IIIC	15.9	9.0	24.9	27.4	35.	0	18	17.5	70.5
	60	3000	Titan IIIC + BII	18.1	12.0	30.1	33.1	45.	0	24	20	89.0
8^o	38	1000	Atlas/Agena + BII	8.4	3.0	11.4	12.5	--	0.5	0	0	0.5
	49	1000	Atlas/Agena + BII	8.4	5.0	13.4	14.7	27.	0	10	9.2	46.2
	52	2000	Titan IIIC	15.9	9.0	24.9	27.4	35.	0	18	17.5	70.5
	54	3000	Titan IIIC + BII	18.1	12.0	30.1	33.1	45.	0	24	20	89.0
16^o	32	1000	Atlas/Agena + BII	8.4	3.0	11.4	12.5	--	0	0	0	0
	41	1000	Atlas/Agena + BII	8.4	5.0	13.4	14.7	27.	0	10	9.2	46.2
	46	2000	Titan IIIC	15.9	9.0	24.9	27.4	35.	0	18	17.5	70.5
	48	3000	Titan IIIC + BII	18.1	12.0	30.1	33.1	45.	0	24	20	89.0

Table XVI. Cost of Launch

Boster	Max. Useful Payload (lb.)	Cost of Launch ($M)
Atlas/Agena + Burner II	1000	8.4
Titan IIIC	2000	15.9
Titan IIIC + Burner II	3000	18.1

(4) Cost of Satellite (C_S)

The unit cost of low power satellites (SAT-1) was estimated from data provided by manufacturers (see Appendix J). The unit costs of high power satellites (SAT-2, 3, 4) are based on projections made by Comsat Corporation in its study entitled "Broadcast Satellites," July 1967 . (This subject is discussed more extensively in Appendix J.)

The projected cost of high power satellites estimated by Comsat Corporation was modified as follows to allow for improved antennas: $0.5 million was added for 2° and $1 million for 1° beamwidth satellites. The figures of satellite unit costs used in our study are listed in Table XVII.

Table XVII. Unit Cost of Active Satellites ($M)

	Beamwidth →	1°	2°	4°	8°	16°
SAT-1	Low Power	4.5	4.0	3.5	3.0	3.0
SAT-2	Hi Power	6.0	5.5	5.0	5.0	5.0
SAT-3	Hi Power	10.0	9.5	9.0	9.0	9.0
SAT-4	Hi Power	13.0	12.5	12.0	12.0	12.0

(5) Conversion to Level Annual Cost (γ)

It is assumed that a capital investment recovery period of ten years (corresponding to system life) is to be used and a return on investment of 8 percent per annum is desired when discounted to present value

Thus $i = 0.08$

$n = 10$

and $$\gamma = \frac{i}{1-(1+i)^{-n}} \approx 0.15$$

Thus the level annual cost of 0.15 for ten years at 8 percent per annum is required for each $1 of investment.

(6) Number of Replenishment Launches (N_M)

The number of annual launches required to maintain one satellite in orbit with 90% confidence for L.S.P. = 90% is shown in Table XVII of Appendix L. For this report (satellite mean life of five years) it equals 0.22 launches. Again, one satellite is launched per booster ($k_M = 1$).

(7) Total Annual Cost of an Active Satellite System

Using the cost factors just developed and substituting them into the cost model (Equation 33) the total level annual cost of the active satellite system has been computed. The calculation assumes the following:

1) System lifetime - 10 years

2) Satellite mean time to failure - 5 years

3) Launch success probability - 0.9

4) Satellite deployment probability after successful launch - 0.99

5) Satellite R&D cost as shown in Table XV

6) Satellite production cost shown in Table XVII

7) Booster cost as shown in Table XVI

8) Interest rate - 8%.

The results of the calculations are shown in Table XVIII as a function of the beamwidth for each of the four satellites.

(8) The Total Access Capacity of Active Satellites With a Hard Limiting Transponder

The access capacity of the active satellites will be calculated on the assumption that frequency modulation is used and that the satellite transponder is hard limiting. It will also be assumed that the peak to average ratio of modulating speech wave at the ground transmitter is 6 dB. (See the discussion of these factors in Appendix M).

Table XVIII. Total Level Annual Cost of Active Satellite Systems

SAT-1 (Low power)	1°	\$9.2 Million	SAT-3	1°	\$22.4 Million
	2°	8.8		2°	22.0
	4°	7.5		4°	20.2
	8°	4.5		8°	20.2
	16°	4.4		16°	20.2
SAT-2	1°	\$14.3 Million	SAT-4	1°	\$26.8 Million
	2°	14.0		2°	26.6
	4°	12.0		4°	26.4
	8°	12.0		8°	26.4
	16°	12.0		16°	26.4

The total number of accesses that can be supported by the four types of satellites listed in Table X can be calculated from Equation 42 developed in Appendix M which is reproduced below.

$$p = \frac{P_T}{B} \cdot \frac{G_3}{T_3} \cdot \frac{1}{kL_D\beta} \left[\frac{\frac{1}{(SNR)_{IN}} - \frac{1}{SIR} + 1.26 \frac{M}{P_1}}{1 + a\left(\frac{1}{SIR} + 1.26 \frac{M}{P_1}\right)} \right] \quad (34)$$

where

p = total number of accesses

P_T = total satellite ERP (from Table X)

B = rf signal bandwidth per access (from Table XIII)

W = total transponder bandwidth

SIR = signal to intermodulation power ratio in any bandwidth B in which both the signal and intermodulation noise are uniformly spread

a = bandwidth wastage factor $\frac{W}{pB}$

$(SNR)_{IN}$ = required signal-to-noise ratio at the input to the receiver (equal to receiver threshold)

$$\left.\begin{aligned} M &= \frac{T_2}{G_{2R}} \cdot kL_u^2 \\ P_1 &= \frac{ERP_1}{B} \end{aligned}\right\} \frac{P_1}{M} = \text{uplink SNR}$$

ERP_1 = effective radiated power of the ground transmitters

$\frac{G_3}{T_3}$ = is the sensitivity (gain-to-system noise temperature) of the receiving ground station (from Table X)

$\frac{G_{2R}}{T_2}$ = is the sensitivity of the satellite receiver (from Table X)

L_D = the net down-link loss (between antennas)

L_u = the net up-link loss (between antennas)

α = represents miscellaneous up-link losses

β = represents miscellaneous down-link losses

k = Boltzman's constant.

Equation 34 can be rewritten as follows:

$$p = (\text{constant}) \cdot \frac{\frac{X}{SNR} - 1}{X + a} \qquad (35)$$

where

$$X = \frac{1}{\frac{1}{SIR} + 1.26 \frac{M}{P_1}} \qquad (36)$$

is the signal-to-noise ratio at the output of the satellite.

Inspection of equation 36 indicates that the up-link signal-to-noise ratio $\left(\frac{P_1}{M}\right)$ must be sufficiently larger than the SIR to have a negligible effect on X. This, in fact, is the case for all situations.

To the first approximation, therefore, we could assume that X = SIR. The relation between bandwidth wastage factor "a" and the SIR was calculated in Appendix 6. It was shown that for $a = 1$, $X = 9$ dB, and for $a \rightarrow \infty$, $X \rightarrow 16$ dB.

If the value of the square bracket in equation 35 is plotted against "a", it will exhibit a very flat peak yielding a maximum at the value of a = 3.665. This corresponds to the maximum number of accesses. The required bandwidth per access at the transponder corresponds in this case to

$$A = Ba$$

$$A = 30{,}000 \times 3.665$$

$$= 109.5 \text{ kHz}$$

The value of the constant in equation 35 which is equal to

$\left(\frac{P_T}{B} \; \frac{G_3}{T_3} \; \frac{1}{k_3 L_D \beta}\right)$ establishes the absolute maximum on

the number of accesses which can be obtained disregarding bandwith limitations. These were calculated for all combinations of the four satellites and five user stations (defined in Tables IX and X) and are shown in Table XIX. Since each channel requires an RF bandwidth of 109.6 KHz, it is obvious that the total required bandwidth would be unreasonable in most cases, particularly with high power satellites.

We have originally assumed, however, that the rf transponder bandwidth in the satellite will be restricted to 500 MHz. (See Appendix J for discussion.) This establishes a limit on the number of accesses which can be handled by the system, as expressed by the equation

$$p = \frac{500 \times 10^6}{a \cdot B} \qquad (37)$$

where B is the required rf bandwidth

The two limitations discussed above are shown graphically in Figure 21 below, for the case where the system becomes bandwidth limited at some point.

The value of p at the point of intersection of the two curves, yields the largest number of accesses. A computer program was developed to find the point of intersection and the results of the computations are shown in Table XX, which lists the values of a, the required access bandwidth = (aB) and the maximum number of accesses under a total bandwidth limitation of 500 MHz, for all combinations of satellites and user terminals.

Table XIX

MAXIMUM NUMBER OF CHANNELS IN ACTIVE SYSTEMS
DISREGARDING BANDWIDTH LIMITATIONS
(a = 3.665 m = 2.25 B = 109.6 KHz)

User Station	Beamwidth (degrees)	Sat 1	Sat 2	Sat 3	Sat 4	No. of Ch. Limited by b'width
		Effective Radiated Power dBW				
		56	67	70	72	
ST-1	1°	10,476	131,901	263,802	$418\text{x}10^3$	4562
	2°	2,631	33,132	66,264	$105\text{x}10^3$	4562
	4°	661	8,322	16,644	26,400	4562
	8°	166	2,090	4,180	6,640	4562
	16°	41	525	1,050	1,662	4562
ST-2	1,2	41,643	524,286	1,048,572	$1.66\text{x}10^6$	4562
	4	13,222	106,480	332,960	$.514\text{x}10^6$	4562
	8	3,321	41,817	123,634	$196\text{x}10^3$	4562
	16	834	10,503	21,006	32,250	4562
ST-3	1,2,4	41,643	524,286	1,048,572	$1.66\text{x}10^6$	4562
	8	13,322	166,480	323,960	$.514\text{x}10^6$	4562
	16	3,321	41,817	123,634	$196\text{x}10^3$	4562
ST-4	1,2,4,8	41,643	524,286	1,048,572	$1.66\text{x}10^6$	4562
	16	20,957	263,855	527.710	$.835\text{x}10^6$	4562
ST-5	All	41,643	524,286	1,048,572	$1.66\text{x}10^6$	4562

p = No. of accesses

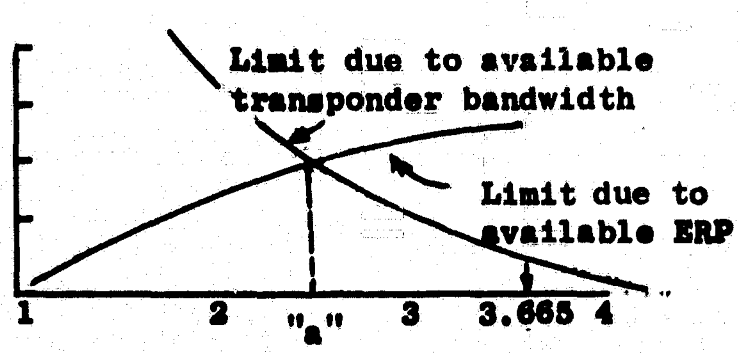


Figure 21. Limits on the number of accesses

(9) Annual Cost per Access

In Table XVII, the total annual system cost has been determined. In Table XIX, the maximum number of access has been calculated. The ratio of corresponding quantities in these two tables yields the annual cost per access.

(10) Summary of Results

All pertinent cost data and access capacity data for the 100 possible configurations of the active satellite system utilizing one satellite in orbit (4 possible satellites, 5 beamwidths, and 5 ground stations) are summarized in Table XXI, which is self-explanatory. The results are interpreted and discussed in the "Conclusions" section of this report.

TABLE XX.
MAXIMUM NUMBER OF ACCESSES
ACTIVE SATELLITES
(Bandwidth Limited to 500 MHz)

		SATELLITE 1			SATELLITE 2			SATELLITE 3			SATELLITE 4		
User Terminal	Beamwidth (Degrees)	a	Access B'width A = KHz	No. of accesses in 500 mc Bandwidth	a	A	No. of accesses	a	A	No. of accesses	a	A	No. of accesses
ST-1	1	2.082	62.2	8033	1.489	44.5	11228	1.476	44.1	11326	1.476	44.1	11326
	2	3.665	109.6	2631*	1.605	48.0	104.7	1.528	45.7	10944	1.502	44.9	11132
	4	3.665	109.6	661*	2.326	69.6	7188	1.798	53.8	9299	1.657	49.5	10094
	8	3.665	109.6	166*	3.665	109.6	2090*	3.665	109.6	4171*	2.674	79.9	6254
	16	3.665	109.6	41*	3.665	109.6	525*	3.665	109.6	1047*	3.665	109.6	1660*
ST-2	1	1.476	44.1	11326	1.464	43.8	11426	1.464	43.8	11426	1.464	43.8	11426
	2	1.554	46.5	10763	1.464	43.8	11426	1.464	43.8	11426	1.464	43.8	11426
	4	1.914	57.2	8736	1.489	44.5	11228	1.476	44.1	11326	1.464	43.8	11426
	8	3.665	109.6	3321*	1.579	47.2	10587	1.515	45.3	11037	1.489	44.5	11228
	16	3.665	109.6	834*	2.082	62.2	8033	1.721	51.5	9716	1.605	48.0	10417
ST-3	1	1.464	43.8	11426	1.464	43.8	11426	1.464	43.8	11426	1.464	43.8	11426
	2	1.467	44.1	11326	1.464	43.8	11426	1.464	43.8	11426	1.464	43.8	11426
	4	1.554	46.5	10763	1.464	43.8	11426	1.464	43.8	11426	1.464	43.8	11426
	8	1.914	57.2	8736	1.489	44.5	11228	1.476	44.1	11326	1.464	43.8	11426
	16	3.665	109.6	3321*	1.579	47.2	10587	1.515	45.3	11037	1.489	44.5	11228
ST-4	1	1.464	43.8	11426	1.464	43.8	11426	1.464	43.8	11426	1.464	43.8	11426
	2	1.464	43.8	11426	1.464	43.8	11426	1.464	43.8	11426	1.464	43.8	11426
	4	1.476	44.1	11326	1.464	43.8	11426	1.464	43.8	11426	1.464	43.8	11426
	8	1.515	45.3	11037	1.464	43.8	11426	1.464	43.8	11426	1.464	43.8	11426
	16	1.721	51.5	9716	1.476	44.1	11326	1.464	43.8	11426	1.464	43.8	11426
ST-5	1	1.464	43.8	11426	1.464	43.8	11426	1.464	43.8	11426	1.464	43.8	11426
	2	1.464	43.8	11426	1.464	43.8	11426	1.464	43.8	11426	1.464	43.8	11426
	4	1.464	43.8	11426	1.464	43.8	11426	1.464	43.8	11426	1.454	43.8	11426
	8	1.476	44.1	11326	1.454	43.8	11426	1.464	43.8	11426	1.464	43.8	11426
	16	1.554	46.5	10763	1.464	43.8	11426	1.464	43.8	11426	1.464	43.8	11426

*Indicates that the system is power limited.

FM mod index — m = 2.25
RF bandwidth — A = 30.a KHz
SNR (Threshold) — T = 7.1 dB

Table XX

(All Values in

		SAT-1 (Low Power - 1000)					SAT-2 (		
Beamwidth Degrees		1°	2°	4°	8°	16°	1°	2°	
Satellite Unit Cost	C_S	4.5	4.0	3.5	3.0	3.0	6.0	5.5	
Booster and Launch Cost	C_{LS}	8.4	8.4	8.4	8.4	8.4	8.4	8.4	
Cost per Launch	$C_S + C_{LS}$	12.9	12.4	11.9	11.4	11.4	14.4	13.9	1
Number of Launches	N_M	1.1							
Total Launch Cost (C_{TL})	$N_M(C_S+C_{LS})$	14.3	13.6	13.0	12.5	12.5	15.8	15.2	1
R & D Cost	C_{RD}	28.2	27.2	2.0	0.5	0	58.2	57.2	4
Total Establishment Cost	C_{TE}	42.5	40.8	15.0	13.0	12.5	74.0	73.4	6
Level Annual Costs									
Total Launch Cost	$0.15\ C_{TL}$	2.1	2.0	1.9	1.9	1.9	2.4	2.3	
OP. + Maintn. (0.22 Launches/yr)		2.8	2.7	2.6	2.5	2.5	3.2	3.1	
Total Level Annual Satellite Cost		4.9	4.7	4.5	4.4	4.4	5.6	5.4	
Annual R & D	$0.15\ C_{RD}$	4.2	4.1	3.0	0.1	0	8.7	8.6	
Total Level Annual System Cost	$C_{T/A}$	9.2	8.8	7.5	4.5	4.4	14.3	14.0	1
Maximum Number of Accesses									
User terminal ST-1		8033	2631	661	166	41	11228	10417	
User terminal ST-2		11326	10763	8736	3321	834	11426	11426	1
User terminal ST-3		11426	11326	10763	8736	3321	11426	11426	1
User terminal ST-4		11426	11426	11326	11037	9716	11426	11426	1
User terminal ST-5		11426	11426	11426	11326	10763	11426	11426	1
Annual Cost per Access (Dollars)									
User terminal ST-1		1145	3344	11346	27110	107317	1273	1343	
User terminal ST-2		812	817	858	1355	5275	1251	1225	
User terminal ST-3		805	776	696	515	1324	1251	1225	
User terminal ST-4		805	770	662	407	452	1251	1225	
User terminal ST-5		805	770	656	397	408	1251	1225	
Total Level Annual System Cost									
System with one satellite		9.2	8.8	7.5	4.5	4.4	14.3	14.0	1
System with two satellites		14.1	13.5	12.0	8.9	8.8	19.9	19.4	1
System with three satellites		19.0	18.2	16.5	13.4	13.2	25.5	24.8	2

FOLDOUT FRAME 1

e XXI. Summary of Pertinent Cost Factors
Active Satellite System
in Millions of Dollars Unless Otherwise Stated)

T-2 ([illegible]000 lb)				SAT-3 (2000 lb)					SAT-4 (3000 lb)				
°	4°	8°	16°	1°	2°	4°	8°	16°	1°	2°	4°	8°	16°
5	5.0	5.0	5.0	10	9.5	9.0	9.0	9.0	13	12.5	12.0	12.0	12.0
4	8.4	8.4	8.4	15.9	15.9	15.9	15.9	15.9	18.1	18.1	18.1	18.1	18.1
9	13.4	13.4	13.4	25.9	25.4	24.9	24.9	24.9	31.1	30.6	30.1	30.1	30.1
2	14.7	14.7	14.7	28.5	27.9	27.3	27.3	27.3	34.2	33.6	33.1	33.1	33.1
2	46.2	46.2	46.2	82.5	81.5	70.5	70.5	70.5	99	99	89	89	89
4	60.9	60.9	60.9	111.0	109.4	97.8	97.8	97.8	133.2	132.6	132.1	132.1	132.1
3	2.2	2.2	2.2	4.3	4.2	4.1	4.1	4.1	5.1	5.0	4.9	4.9	4.9
1	2.9	2.9	2.9	5.7	5.6	5.5	5.5	5.5	6.8	6.7	6.6	6.6	6.6
4	5.1	5.1	5.1	10.0	9.8	9.6	9.6	9.6	11.9	11.7	11.5	11.5	11.5
6	6.9	6.9	6.9	12.4	12.2	10.6	10.6	10.6	14.9	14.9	13.4	13.4	13.4
0	12.0	12.0	12.0	22.4	22.0	20.2	20.2	20.2	26.8	26.6	24.9	24.9	24.9
17	7188	2090	525	11326	10944	9299	4171	1047	11326	11132	10094	6254	1660
26	11228	10587	8033	11426	11426	11326	11037	9716	11426	11426	11426	11228	10417
26	11426	11228	10587	11426	11426	11426	11326	11037	11426	11426	11426	11426	11228
26	11426	11426	11326	11426	11426	11426	11426	11426	11426	11426	11426	11426	11426
26	11426	11426	11426	11426	11426	11426	11426	11426	11426	11426	11426	11426	11426
43	1669	5882	22857	1977	2010	2172	4842	19293	2366	2389	2490	3970	15000
25	1068	1133	1493	1960	1925	1783	1830	2079	2345	2328	2180	2218	2390
25	1050	1068	1133	1960	1925	1767	1783	1830	2345	2328	2180	2180	2218
25	1050	1050	1059	1960	1925	1767	1767	1767	2345	2328	2180	2180	2180
25	1050	1050	1050	1960	1925	1767	1767	1767	2345	2328	2180	2180	2180
0	12.0	12.0	12.0	22.4	22.0	20.2	20.2	20.2	26.8	26.6	24.9	24.9	24.9
4	17.1	17.1	17.1	32.4	31.8	29.8	29.8	29.8	38.7	38.3	36.4	36.4	36.4
8	22.2	22.2	22.2	42.4	41.6	39.4	39.4	39.4	50.6	50.0	47.9	47.9	47.9

FOLDOUT FRAME 2

Determination of the Level Annual Cost of a Double-Hop Passive System B2

The computation of costs of the passive system utilizes the same cost model as that used for active systems. In this case, however, the costs of the ground based repeater station (R2) have to be included in addition to the cost of the passive satellite in orbit. The cost elements associated with the ground repeater subsystem are identified by subscript G. The cost elements associated with the satellite by subscript S.

Two passive satellite sizes are considered initially, each representing the largest satellite that can be boosted with the specified booster.

Satellite A - 325 ft. diameter - Atlas/Agena + BII

Satellite B - 150 ft diameter - Titan IIIC + BII

(1) R&D Required - Satellites

Cost data developed previously in this report indicate the following R&D costs associated with the development of passive reflectors:

325 ft Satellite (type A) - 5 yr life - R&D cost $22.01 million

150 ft Satellite (type B) - 5 yr life - R&D cost $13.3 million

These costs are based on an R&D program which involves the development of three R&D satellites, construction of two flight test models, and associated miscellaneous expenses. To this should be added a flight test consisting of one launch. Table 4 of Appendix L shows that 1.1 launches are required to attain 90 percent confidence level of placing one satellite in orbit (launch success probability = 0.9). Thus, the following launch costs must be added to the R&D program:

Satellite A-(Titan IIIC + BII booster) - (1.1x18.1) = $19.9 million

Satellite B-(Atlas/Agena + booster) (1.1x8.4) = $9.24 million

As a result, the total R&D costs including flight test are as follows:

Satellite A - $41.92 million

Satellite B - $22.5 million

(2) Unit Cost of Passive Satellites

Data developed previously indicate the following unit production costs of passive reflectors:

Satellite A (325 ft) $2.66 million

Satellite B (150 ft) $1.8 million

(3) Number of Launches Required and Number of Satellites per Launch

The same figures are used as for the case of active system. (Confidence level 90 percent - L.S P. = 0.9)

Number of launches required to establish one satellite in orbit

$$N_E = 1.1$$

Number of launches to replenish

$$N_M = 0.22 \text{ per year}$$

In both cases one satellite is launched at a time

$$k_E = k_M = 1$$

These costs are the same for any desired satellite beamwidth.

(4) R&D Required - Ground Repeater (R2)

The total R&D costs of the ground based repeater are estimated at $1 million. Three quarters of this cost is also entirely associated with the development of the high power transmitter subsystem. It includes the development of a 630 megawatt klystron with 300 MHz bandwidth at X-band (estimated at $350,000), development of high power plumbing and dual feedhorn (estimated at $300,000) and the integration and test of the overall subsystem ($100,000). The remaining $250,000 is allocated to necessary modification of antenna systems to handle the high power.

(5) Investment Cost - Ground Repeater

The approximate cost formula for the ground repeater was developed in Appendix N, equation 5.

$$C_{EG} = C_A + n\left(\frac{1.8}{T^{0.9}}\right) + 0.63\left(1 + \frac{D}{100}\right) + \left(\frac{D}{100}\right)^{1.25} + 1.1 + \left[75\,(m + k)\left(\frac{P}{k}\right)^{0.63} + 50P^{0.63}\right] 10^{-6} \qquad (37)$$

C_A = cost of the antenna = $11.2 million

D = antenna diameter = 159 ft

T = the noise temperature of the parametric preamplifiers has been chosen as 50° K.

n	=	Number of preamplifiers (It is assumed that four units are purchased originally to provide redundancy and hot standby.)
k	=	The number of operating high power klystrons in the transmitter was assumed to be 2.
m	=	Total no. of standby power tubes. It is assumed that a hot standby is provided for each operating tube. Thus m = k.
P	=	The total transmitter power (assumed to be 1000 KW). (See Appendix H).

Thus, for the case under consideration the values of these constants are as follows:

C_A = \$11.2 million

n = 4

T = 50

D = 159

m = 2

k = 2

p = 10^6

Under these conditions, the investment cost of the ground station, calculated from the above formula, is

C_T = \$17.23 million

(6) Operational and Maintenance Costs for Ground Repeater

The formula for calculation of O&M costs has been developed in Appendix N (equation 6). Using this formula and the cost data developed above, the annual O&M cost becomes:

$$C_{MG} = 0.05C_A + 0.05 \left(\frac{D}{100}\right)^{1.25} + 0.25 \left(\frac{1.8n}{T^{0.9}}\right) + 0.2 \left[\frac{1.8n}{T^{0.9}} + 0.63 \left(1 + \frac{D}{100}\right) + \frac{75\,(m+k)}{10^6} \left(\frac{P}{K}\right)^{0.63} + \frac{50}{10^6} P^{0.63}\right] \quad (38)$$

C_{MG} = \$1.327 million

(7) Calculation of Level Annual Cost of Double Hop Passive System B1

The cost model previously selected may now be applied to calculate the total level annual cost of the double-hop passive system:

$$C_{T/A} = \left[\left(C_{RDG} + C_{EG} \right) + \left(C_{RDS} + N_E \left(C_{LS} + k_E C_S \right) \right) \right] \frac{1}{1-(1+i)^{-n}}$$

$$+ \left[C_{MG} + N_M \left(C_{LS} + k_M C_S \right) \right]$$

In the preceding paragraphs, we have established the cost components of the model as follows:

1) Cost of passive satellite R&D

C_{RDS} = Satellite A \$41.92 million

Satellite B \$22.5 million

2) Cost of ground repeater R&D

C_{RDG} = \$1 million

3) Ground Repeater investment cost

C_{EG} = \$17.23 million

4) Number of launches to establish

N_E = 1.1

5) Number of launches to replenish

N_M = 0.22 per year

6) Cost of launch

C_{LS} = \$18.1 million for Satellite A

= \$8.4 million for Satellite B

7) Number of satellites per launch

$k_E = k_M = 1$

8) Satellite unit cost

$$C_S = 2.66 \text{ million for Satellite A}$$

$$= 1.8 \text{ million for Satellite B}$$

9) Conversion to level annual cost

$$\frac{i}{1-(1+i)^{-n}} = 0.15$$ (Assumes 8% return on investment (i - 0.08) over a 10-year recovery period (n = 10))

10) Annual cost of O&M for ground repeater

$$C_{MG} = \$1.31 \text{ million}$$

Substituting these constants into our cost model, we obtain the total level annual cost of the System for Satellite A.

$$C_{T/A} = \left[(1+17.23) + 41.92 + 1.1(18.1+2.66)\right]0.15$$
$$+ 1.31 + 0.22(18.1+2.66)$$
$$= (2.7 + 1.3) + 9.71 + 4.56)$$
$$= 4.01 + 14.28$$
$$= \$18.29 \text{ million}$$

The annual cost of ground repeater $C_{TAG} = \$4.01$ million

The annual cost of the satellite in orbit $C_{TAS} = \$14.28$ million

For Satellite B (150 ft)

$$C_{T/A} = (1+17.23) + 22.5 + 1.1(8.4+1.8) \;\; 0.15 + 1.31$$
$$+ 0.22(8.4 + 1.8)$$
$$= 4.01 + (5.06+2.24)$$
$$= 4.01 + 7.3$$
$$= \$11.31 \text{ million}$$

These costs pertain to satellites of 325 ft and 150 ft diameter. In a double hop passive satellite system, however, the total system gain can be provided either by the antenna in the ground repeater R2 or by the satellite in orbit. As a result, in cases where surplus gain exists, it may be possible to select these gains in such a manner as to minimize the cost of the system.

Consider the following expressions

$$Z = G_{2R} \cdot G_{S1}$$

or $$Z_{dB} = (G_{2R})_{dB} + (G_{S1})_{dB}$$

where

G_{2R} is the gain of the receiving antenna in the ground repeater

G_{S1} is the gain of the passive satellite in orbit

The maximum gain of the antenna was considered in Appendices D and F, and it was decided to use the value of 69 dB as the best compromise between the cost and the performance.

Thus

$$G_{2R} = 69 dB$$

The maximum gain of passive satellites with diameters of 325 feet and 150 feet was calculated in Table XXII as follows.

Table XXII. Gain Limits of the Passive Reflector (G_{S1}) dB at 7.25 GHz

Beamwidth (Degrees)	Satellite Size	
	A (325 ft.)	B (150 ft.)
1	124.7 dB	118 dB
2	118.7 dB	112 dB
4	112.7 dB	106 dB
8	106.7 dB	100 dB
16	100.7 dB	94 dB

Thus, the product of the antenna and satellite gains (the sum of the dB values) represents the maximum available value of Z and is as follows (Table XXIII):

Table XXIII. Maximum Available Value of Z(dB)
$Z = G_{2R} \cdot G_{S1}$

Beamwidth (degrees)	Satellite Size A (325 ft.)	Satellite Size B (150 ft.)
1	193.7	187
2	187.7	181
4	181.7	175
8	175.7	159
16	169.7	163

Wherever the available gain Z exceeds the gain that is required to meet the system performance requirements, it will be possible to reduce the values of the antenna gain (G_{2R}) and satellite gain (G_{2S}) in a manner which will result in cost minimization. It is therefore necessary to determine first, what gain is required by the system.

The equation which will be used is that developed in Appendix I.

$$Z = G_{S1} \cdot G_{2R} = R \left\{ \frac{1}{2} \left[a_2 + \frac{a_1}{P_A} \right] + \sqrt{\frac{1}{2} \left[a_2 + \frac{a_1}{P_A} \right] + \left[\frac{a_1 a_2 B}{R P_A} \right]} \right\} \qquad (39)$$

where

G_{S1} = Gain of the passive reflector

G_{2R} = Gain of the ground antenna

R = Signal to noise density ratio at the user's receiver = C/No

a_2, a_1 are constants associated with system parameters

P_A = Ground transmitter power per access

B = Required RF bandwidth per access

This equation indicates that the required system gain depends on the power per access P_A available in the ground transmitter. Since the objective is to have as many accesses as possible, the factors must be investigated which impose a limit on this quantity. It is obvious that either the total available power of the ground transmitter or the total available bandwidth constitutes such a limit. These limitations were discussed in Appendix H and it was concluded that the ground repeater F2 bandwidth is limited to 500 MHz and the maximum transmitter power is limited to 59 dBW.

Accordingly,

$$W = 500 \times 10^6 \text{ Hz} \quad (40)$$

$$P_{TOT} = 59\text{dBW} = 10^{5.9} \text{ watts} = 794.3 \text{ KWatts} \quad (41)$$

It is known from Table XIII, that the rf bandwidth per access is approximately

$$B \approx 30{,}000 \text{ Hz} \quad (42)$$

Thus, in a bandwidth limited case the total number of accesses is obtained by dividing equation (40) by equation (42)

$$p \approx \frac{500 \times 10^6}{30{,}000} \approx 16{,}722^* \quad (43)$$

If the total available power (equation (41)) is divided by the total number of accesses, the power per access available in a bandwidth limited system is obtained.

$$P_A \approx \frac{794.3 \times 10^3}{16{,}722} \approx 47.7 \text{ watts} = 16.8 \text{ dB} \quad (44)$$

If this value of P_A is now substituted into equation (39), the values of system gain Z required when the system operates with different user stations (described in Table IX) is obtained. These values are shown in Table XXIV.

*This number is obtained, rather than 16,667, since B is not exactly 30,000.

Table XXIV. Required Values of System Gain Z dB for Various User Stations Given P_A = 47.7 Watts

User Station	Z dB
ST-1	195
ST-2	182
ST-3	176
ST-4	168
ST-5	164

The required values of system gain Z shown in Table XXIV can now be compared to the maximum available values of Z shown in Table XXIII. The comparison reveals the particular cases where surplus gain is available and is summarized in Table XXV, for the case of passive satellite (A). The sign (+) indicates that surplus gain is available; the sign (-) denotes gain deficiency.

Table XXV. Summary of System Gain Availability in Bandwidth Limited Passive Satellite Systems

Beamwidth (degrees)	ST-1 (6 ft.)	ST-2 (15 ft.)	ST-3 (30 ft.)	ST-4 (60 ft.)	ST-5 (100 ft.)
1	(-)	(+)	(+)	(+)	(+)
2	(-)	(+)	(+)	(+)	(+)
4	(-)	(-)	(+)	(+)	(+)
8	(-)	(-)	(-)	(+)	(+)
16	(-)	(-)	(-)	(+)	(+)

(8) System Cost Minimization

In cases of bandwidth limited operation designated by plus signs in Table XXV, there exists a surplus of system gain (which is defined as the product of the gains of the antenna and of the passive satellite). Accordingly, we can select the values of these two gains in a way which will minimize the total system cost.

In order to accomplish this, a computer program was developed which performed the cost minimization as follows: For a specified value of Z (listed in Table XXIV), the required gain of the passive satellite (G_{S1}) was first calculated for varying values of ground antenna gain (G_{2R}) using the expression

$$(G_{S1})_{dB} = Z_{dB} - (G_{2R})_{dB} \tag{45}$$

The diameter of the passive satellite corresponding to the required gain G_{S1} was then determined using the following formula

$$D_S = \sqrt{G_{S1}} \left(\frac{\theta \lambda}{4\pi} \right) \tag{46}$$

where

θ = beamwidth in radians

λ = operating wavelength

Using D_S the cost components of the passive system was calculated from formulae developed previously.

Cost of satellite $C_S = 400\, D_S^{1.4} + 1.35\, 10^6$

Cost of R&D = $C_{RDS} = 5.32 D_S^2 + 3971 D_S^{1.4} + (3.4+8.35\text{x}10^6)\, D_S$
$+ 1.1\, C_{LS}$

Cost of launch = $C_{LS} = (C_L + C_S)$ = cost of booster + cost of satellite.

From these data, the total annual cost of the space segment can be computed using the cost model previously described (equation 32).

In a similar way, since the gain of the ground antenna is known (equation 45) the antenna cost and the antenna diameter can be found from formulae developed in Appendix F.

For this case (8GHz)

$$\text{Antenna Cost} = C_{ANT} = G_{2R}^{A} \cdot \frac{10^{(7.311-5.622A)}}{8^{(1.21+A)}}$$

$$A = \begin{matrix} 1.21 \text{ for } G < 65.25 \text{ dB} \\ 2.21 \text{ for } G > 65.25 \text{ dB} \end{matrix} \qquad (47)$$

$$D_G = \left[\frac{C \text{ ant}}{28.8 \text{ k } 4.42} \right]^{1/4.42} \qquad \text{for } G > 65.25\text{dB} \qquad (48)$$

or

$$D_G = \left[\frac{C_{ANT}}{28.8} \right]^{1/2.42} \qquad \text{for } G < 65.25 \text{ dB} \qquad (49)$$

where k is a constant

$$k = \frac{4\pi}{3c} \times 10^3$$

$$c = \text{speed of light in ft/sec.}$$

Using the value of antenna diameter, the investment cost of the ground station and the annual maintenance cost can be computed using equations (37) and (38). The total level annual cost of the ground segment can then be determined from the cost model (equation 32).

The sum of the annual cost of the ground station and of the satellite represents the total annual cost of the system.

To minimize the total cost, several sets of values of annual cost of both the ground and space segments are computed by varying the ground antenna gain. The gains which yield the lowest total cost are then selected and other pertinent cost items are automatically yielded by formulae (46) through (49). Note that trade-offs are performed on the basis of total annual costs which include operation and maintenance cost yielding thereby a time cost optimization.

The results of computer calculations for the cases of five different types of user terminals and five different beamwidths are shown in Table XXVI, which indicates the optimum division of total system gain between the ground antenna G_{2R} and the satellite G_{S1}, the corresponding diameters and associated cost items.

As indicated previously, cost minimization applies only to bandwidth limited cases. For power limited cases, denoted by an asterisk in Table XXVI, the costs have been calculated and are included in the table.

(9) Maximum Number of Accesses in a Passive Satellite System

It was shown (equation 43) that for bandwidth limited systems, designated by a plus sign in Table XXV, the maximum number of accesses is 16,722. When the system becomes power limited (as indicated by a minus sign in Table XXV) the 16,722 channels, which is the limit established by available bandwidth, cannot be obtained because the system gain required when that many channels are used (Table XXIV) exceeds the gain that is available (Table XXIII).* In order to find the maximum number of accesses that can be accommodated in those cases (power limited system), Equation (39) is rewritten as follows:

$$P_A = \frac{R(a_1 Z + a_1 a_2 B)}{Z(Z - Ra_2)} \quad (50)$$

The required values of Z (from Table XXIV) is now substituted into equation (50) and the corresponding power per access P_A calculated. The total number of accesses is obtained by dividing the total available power P_{TOT} (equation 41) by these values of P_A. These calculations were performed and are summarized in Table XXVII which shows the total number of accesses for both types of passive satellites. The asterisk denotes the cases where the number of channels is limited by bandwidth availability and is equal to 16,722.

(10) Determination of Annual Cost per Access for Passive Satellite Systems

The total annual costs have been determined as well as the maximum number of accesses that can be obtained for various system configurations. The ratio of those two quantities represents the annual cost per access. These and all other pertinent data are summarized in Table XXVI. The results are interpreted and discussed in the "Conclusions" section of this report.

Expansion of System Capacity

It is now assumed that in all cases previously discussed, it is desirable to augment the system capability by doubling and then tripling the total number of accesses available with a single system.

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*It must be understood that the requirement for system gain Z is established by the requirements of the signal to noise ratio on the first hop of the system. The amount of transmitter power available per channel establishes the relationship between the SNR of the first hop and the overall SNR requirement. When $P_A \rightarrow \infty$ the SNR of the first hop approaches the total SNR. See Appendix I for development of the pertinent relationships.

Table XXVI.

User Station	Beamwidth (degrees)		Gains: G_{2R} DB	Gains: G_{S1} DB	Diameter: D_{2R} FT	Diameter: D_{S1} FT	Investment Costs ($M): Passive Satellite R&D	Investment Costs ($M): Passive Satellite	Investment Costs ($M): Grou Ante
ST-1	1	*	69	124.7	159	325	41.920	2,664	11.1
(6 ft.	2	*	69	118.7	159				
ant.)	4	*	69	112.7					
	8	*	69	106.7					
	16	*	69	100.7					
ST-2	1		65	117	89	137	21.670	1.745	1.
(15 ft.	2	*	69	118.7	159	325	22.010	2.660	11.
ant.)	4	*	69	112.7					
	8	*	69	106.7					
	16	*	69	100.7					
ST-3	1		62	114	63	97	20.097	1.593	.
(30 ft.	2		65	111	89	137	21.672	1.745	1.
ant.)	4	*	69	112.7	159	325	22.010	2.660	11.
	8	*	69	106.7	159	325			
	16	*	69	100.7	159	325			
ST-4	1		58	110	40	61	18.911	1.478	.
(60 ft.	2		61	107	56	87	19.735	1.558	.
ant.)	4		64	104	80	123	21.080	1.688	1.
	8		65	103	89	219	36.138	2.110	1.
	16		68	100	141	311	41.151	2.586	6.
ST-5	1		57	107	35	43	18.406	1.428	.
(100 ft.	2		60	104	50	61	18.911	1.478	.
ant.)	4		62	102	63	97	20.107	1.594	.
	8		65	99	89	138	21.690	1.747	1.
	16		66	98	112	246	37.525	2.242	2.

* Asterisk denotes power limited systems

FOLDOUT FRAME 1

…I. Passive Satellite System Cost Parameters
(Millions of Dollars)

…s ($M)		Level Annual Costs ($M)				
Ground Antenna	Ground Station	Ground Repeater (A_p)	Passive Satellite (F_p)	Total	Number of Accesses (P_p)	Annual Cost/ Access
11.138	18.233	4.011	14.278	18.289	11,464	1,595
			14.278	18.289	2,725	6,711
			14.278	18.289	536	34,121
			14.278	18.289	8	2,286,125
			14.278	18.289	-	
1.541	7.290	1.767	7.125	8.892	16,722	531
11.138	18.233	4.011	14.278	18.289	16,722	1,093
				18.289	14,564	1,255
				18.289	3,560	5,137
				18.289	798	22,918
.668	5.943	1.474	6.832	8.306	16,722	497
1.541	7.290	1.767	7.125	8.892	16,722	532
11.138	18.233	4.011	14.278	18.289	16,722	1,093
				18.289	14,629	1,250
				18.289	3,625	5,045
.219	5.098	1.284	6.611	7.895	16,722	472
.506	5.662	1.412	6.764	8.176	16,722	489
1.167	6.736	1.648	7.015	8.662	16,722	518
1.541	7.290	1.767	13.145	14.912	16,722	892
6.695	13.442	3.041	14.075	17.116	16,722	1,024
.165	4.974	1.255	6.517	7.772	16,722	465
.382	5.434	1.361	6.611	7.971	16,722	477
.688	5.944	1.474	6.834	8.308	16,722	497
1.541	7.290	1.767	7.128	8.895	16,722	532
2.419	8.596	2.048	13.402	15.450	16,722	924

FOLDOUT FRAME 2

Table XXVII. Number of Accesses in Passive Systems

Beamwidth (Degrees)	Using Satellite A (325 ft.)				
	ST-1	ST-2	ST-3	ST-4	ST-5
1	11,464	*	*	*	*
2	2,725	*	*	*	*
4	536	14,564	*	*	*
8	8	3,560	14,629	*	*
16	-	798	3,625	*	*

Beamwidth (Degrees)	Using Satellite B (150 ft.)				
	ST-1	ST-2	ST-3	ST-4	ST-5
1	2,289	*	*	*	*
2	428	12,376	*	*	*
4	-	3,010	12,442	*	*
8	-	660	3,076	*	*
16	-	79	723	4,875	12,497

*Number of accesses is limited by bandwidth and equals 16,722

This could represent a situation where, because of the growth of traffic, additional capacity is required, or, when new and independent systems are being established. If the original condition, that active satellite and ground repeaters associated with passive satellite systems are both individually limited to a bandwidth of 500 MHz is retained, the cost effectiveness of such augmented systems can be determined in the following way:

(1) Active Satellite Systems

In the active case, additional satellites must be launched, which is equivalent to establishing new and independent systems. It is assumed that no new R&D is required.

To compute the total annual cost of systems with two or three satellites, added to the cost of the original system (first satellite) shown in Table XXI (Line 20), is the annual cost of extra satellites in orbit. Since it is assumed that no additional R&D expenses are incurred the additional cost per satellite is as shown in line 16 of Table XXI. It can be seen that, depending on the type of satellite and the beamwidth desired, the annual cost of adding one satellite to the system varies from $4.4 million (for a low power satellite (SAT-1) with 16° beamwidth) to $11.9 million (for SAT-4 with 1° beamwidth).

Thus, the total annual cost of a system with two or three satellites is obtained by adding this figure to the cost of the system with one satellite. This is shown in line 36 of Table XXI. Similarly, for three satellites the total annual cost is shown in line 37 of Table XXI.

Since the number of accesses doubles with two satellites in orbit and triples with three, the annual cost per access is then calculated by dividing the total annual cost of a system consisting of two or three satellites in orbit by the appropriate number of accesses. In this way the original R&D cost is shared by all three systems.

The annual costs per access for the cases of one, two and three satellites in orbit are tabulated in Table XXVIII.

(2) Passive Satellite Systems

In systems utilizing passive reflectors in orbit the bandwidth and power limitations apply to the ground repeater station R2. It is assumed that the satellite itself is capable of operation over a wide frequency range and can reflect any amount of power.

Accordingly, in order to augment the access capacity of the system, additional ground repeaters must be added. The annual cost of the ground repeaters has already been calculated and is shown in Table XXVI. It includes an annual R&D expense of $0.11 million which was originally added to adapt the station to high power operation. It is assumed that the same expense is applicable to all repeater stations regardless of the number of them. Accordingly, the cost of adding one additional ground repeater to the system varies from $4.01 million when the system operates with small user terminals (ST-1) to $1.26 million when large user stations (ST-5) are used and the required ground coverage corresponds to a beamwidth of 1°. The number of accesses doubles when the second repeater station is added and triples with the third.

Variations of Annual Cost per Acc

(Annual Costs

User Station	Number of systems → / Type of system	1°					2°				
		1	2	3	∞		1	2	3	∞	
ST-1	Passive	1595	972	765	349		6711	4091	3218	1465	
(6 ft.	SAT-1	1145	877	788	609		3344	2565	2305	1786	
antenna)	2	1273	866	757	498		1343	931	793	518	
	3	1977	1430	1247	883		2010	1452	1267	895	
	4	2366	1708	1489	1050		2389	1720	1497	1051	
	Passive	531	318	247	106		1093	669	528	239	
ST-2	SAT-1	812	622	559	432		817	627	563	436	
(15 ft.	2	1251	870	743	490		1225	848	723	471	
antenna)	3	1960	1417	1236	872		1925	1391	1213	855	
	4	2345	1693	1476	1041		2328	1676	1458	1021	
ST-3	Passive	497	292	224	88		532	318	247	106	
(30 ft.	SAT-1	805	617	559	428		776	595	535	414	
antenna)	2	1251	870	743	490		1225	848	723	472	
	3	1960	1417	1236	875		1925	1391	1213	851	
	4	2345	1693	1476	1041		2328	1678	1458	1023	
ST-4	Passive	472	274	208	77		489	286	219	85	
(60 ft.	SAT-1	805	617	554	428		770	590	530	411	
antenna)	2	1251	870	743	490		1251	848	723	472	
	3	1960	1417	1236	875		1960	1391	1213	857	
	4	2345	1693	1476	1041		2328	1676	1458	1023	
ST-5	Passive	465	269	204	75		477	279	213	82	
(100 ft.	SAT-1	805	617	554	428		770	590	530	411	
antenna)	2	1251	870	774	490		1225	848	743	472	
	3	1960	1417	1236	875		1925	1391	1236	857	
	4	2345	1693	1476	1041		2328	1693	1476	1023	

FOLDOUT FRAME 1

Table XXVIII

ccess with System Capacity Augmentation

ts per Access in $)

4°					8°					16°			
1	2	3	∞		1	2	3	∞		1	2	3	∞
34121	20802	16361	7450		2286125	1393750	1096250	501000		--	--	--	--
11346	9077	8320	6807		27110	26807	26907	26506		107317	107317	107317	107317
1669	1189	1029	2500		5882	4191	3627	2500		22857	16285	14095	9714
2172	1602	1412	2301		4842	3572	3148	2301		19293	14231	12543	9169
2490	1800	1595	1838		3970	2910	2540	1831		15000	10920	2600	6927
1255	768	606	275		5137	3144	2480	1122		22918	14028	11065	5020
858	686	629	515		1355	1339	1344	1324		5275	5275	5275	5275
1068	761	659	453		1133	807	698	481		1493	1064	921	613
1783	1315	1159	845		1830	1350	1189	870		2079	1533	1351	988
2180	1590	1394	1002		2218	1648	1419	1045		2390	1741	1524	1128
1093	666	524	239		1250	762	599	273		5045	3075	2419	1105
696	557	511	418		515	509	511	503		1324	1324	1324	1324
1050	748	647	446		1068	761	659	454		807	698	481	481
1767	1304	1149	840		1783	1315	1159	847		1830	1189	869	869
2180	1590	1394	1006		2180	15190	1394	1006		2218	1648	1419	1024
518	308	238	98		892	497	367	106		1024	602	462	182
662	529	485	397		407	403	404	398		452	452	452	452
1225	748	647	446		1050	748	647	446		1059	754	653	450
1925	1304	1149	840		1767	1304	1149	840		1767	1304	1149	840
2180	1590	1394	1006		2180	1590	1394	1006		2180	1590	1394	1006
497	292	224	88		532	318	247	106		924	523	389	125
656	525	481	393		397	392	394	388		408	408	408	408
1050	748	647	446		1050	748	647	446		1050	748	647	446
1767	1304	1149	840		1767	1304	1149	840		1767	1304	1149	840
2180	1590	1394	1006		2180	1590	1394	1006		2180	1590	1394	1006

FOLDOUT FRAME

The annual costs per access of such augmented systems are shown in Table XXVIII.

To illustrate these cases Figure 22 shows the plots of the annual cost per access versus the number of accesses for a satellite system operating with small user stations ST-1 (6 ft. antennas) and for the ground coverage corresponding to the satellite beamwidth of 4°. The graph shows annual costs corresponding to systems with up to three satellites in orbit for three different kinds of active satellites (SAT-1, SAT-2, SAT-3) and a passive system with up to three ground repeaters.

Discontinuities in the curves occur when total access capacity of the original system is reached and another satellite (or ground repeater) is added. At this point the cost of the system was increased by adding a second satellite, but the same number of accesses are used as before. Thus cost per channel increases. As the additional channels which are now available are utilized, the cost per channel decreases until the total capacity is utilized and the third satellite (or ground repeater) is required.

It can be observed from these graphs that as the system capacity is increased the annual cost per access decreases. It is of interest to derive a limiting condition for this process.

Consider the equation

$$\text{Annual cost per access} = \frac{(C_{RD} + C_F) + nA}{np} \qquad (51)$$

where

C_{RD} represents the annual cost of original R&D (applicable to R&D of active satellites only)

C_F represents the annual cost of that portion of the system which remains unaffected when the system is augmented (i.e., cost of passive reflector in orbit for passive systems)

A represents the annual cost of augmenting the system capacity by an amount equal to the capacity of the original system

n number of augmentations

p number of accesses in the original system

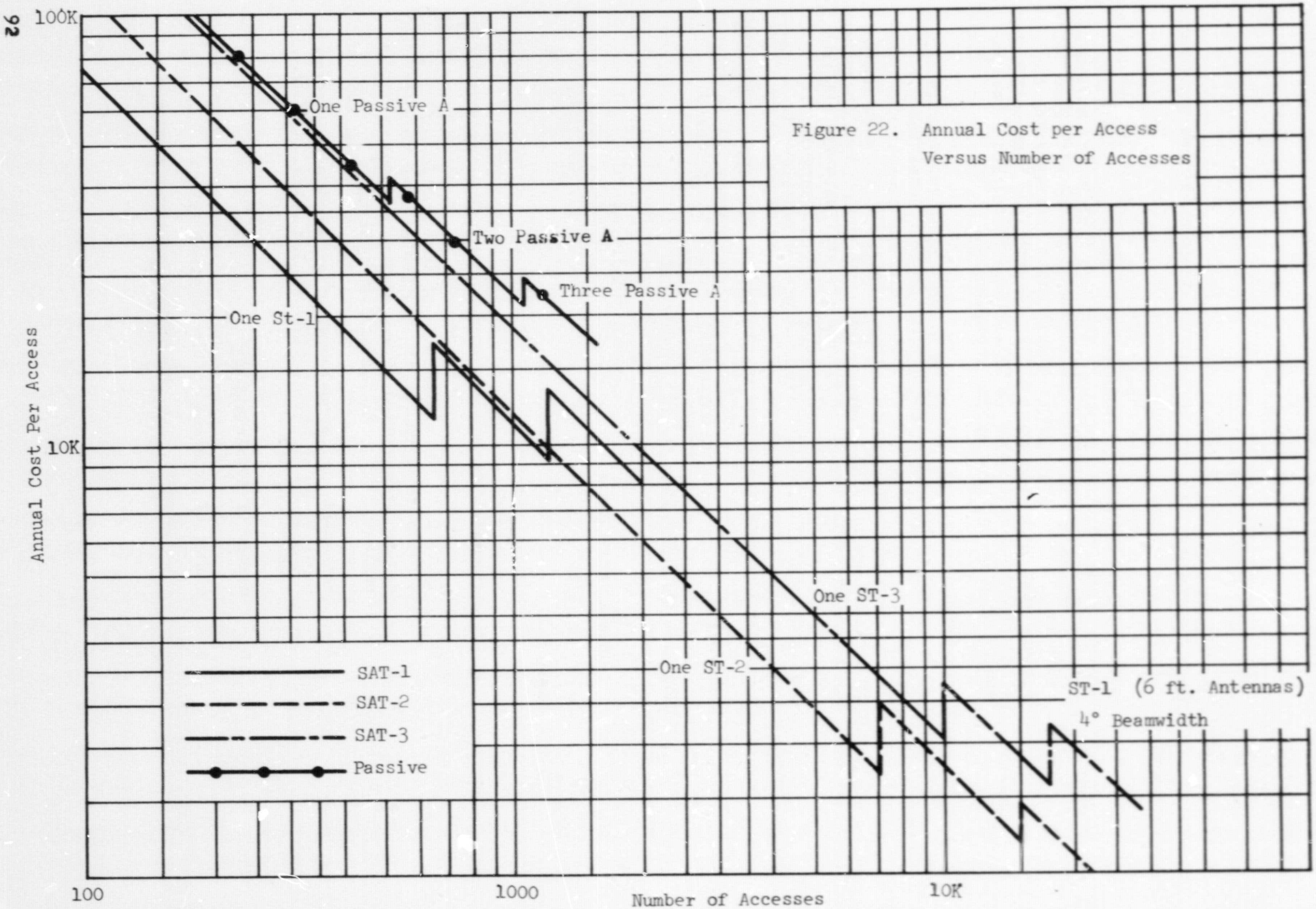


Figure 22. Annual Cost per Access Versus Number of Accesses

When the system is expanded without limit, n becomes very large and the savings realized from sharing the R&D costs in active systems, or sharing one passive reflector in passive systems, becomes negligible. The annual system cost per access then approaches the cost of system augmentation divided by the maximum number of accesses per system. Since both of these quantities are known, the annual cost per access of hypothetical systems of infinite capacity can be computed. Such a value would represent a lower limit on annual cost per access.

Thus, as $n \rightarrow \infty$ equation (52) approaches the following value:

$$\text{Annual cost per access} \longrightarrow \frac{A}{p} \qquad (52)$$

The values of $\frac{A}{p}$ have been calculated for the 125 different system configurations and are shown in Table XXIX. They indicate that as the system capacity is expanded the passive system will become more economical in all cases except the following:

(a) Operating with user stations equipped with 6-foot antennas (ST-1) with ground coverage corresponding to beamwidth of larger than 2°

(b) Operating with 15-foot stations (ST-2) and beamwidth larger than 8°

(c) Operating with 30-foot stations (ST-3) and beamwidth larger than 16°.

To indicate the variations of annual cost per access as the system capacity is increased, Table XXVIII was compiled summarizing all previously derived cost data.

The table is arranged to show how the annual cost per access decreases when the system capacity is expanded by a factor of 1 (original system), 2, 3 and ∞.

It is possible from observing the results for each column to find the least expensive system at any stage of system expansion. To make it more apparent, the same information is presented in Figure 22 in a graphical form. The data is arranged in the form of a matrix showing any desired system configuration (i.e., user terminal and satellite beamwidth).

For each configuration graphs are drawn indicating the relative ranking in terms of annual cost per access of the various satellite systems as the system capacity is expanded to infinity. In this

Table XXIX.

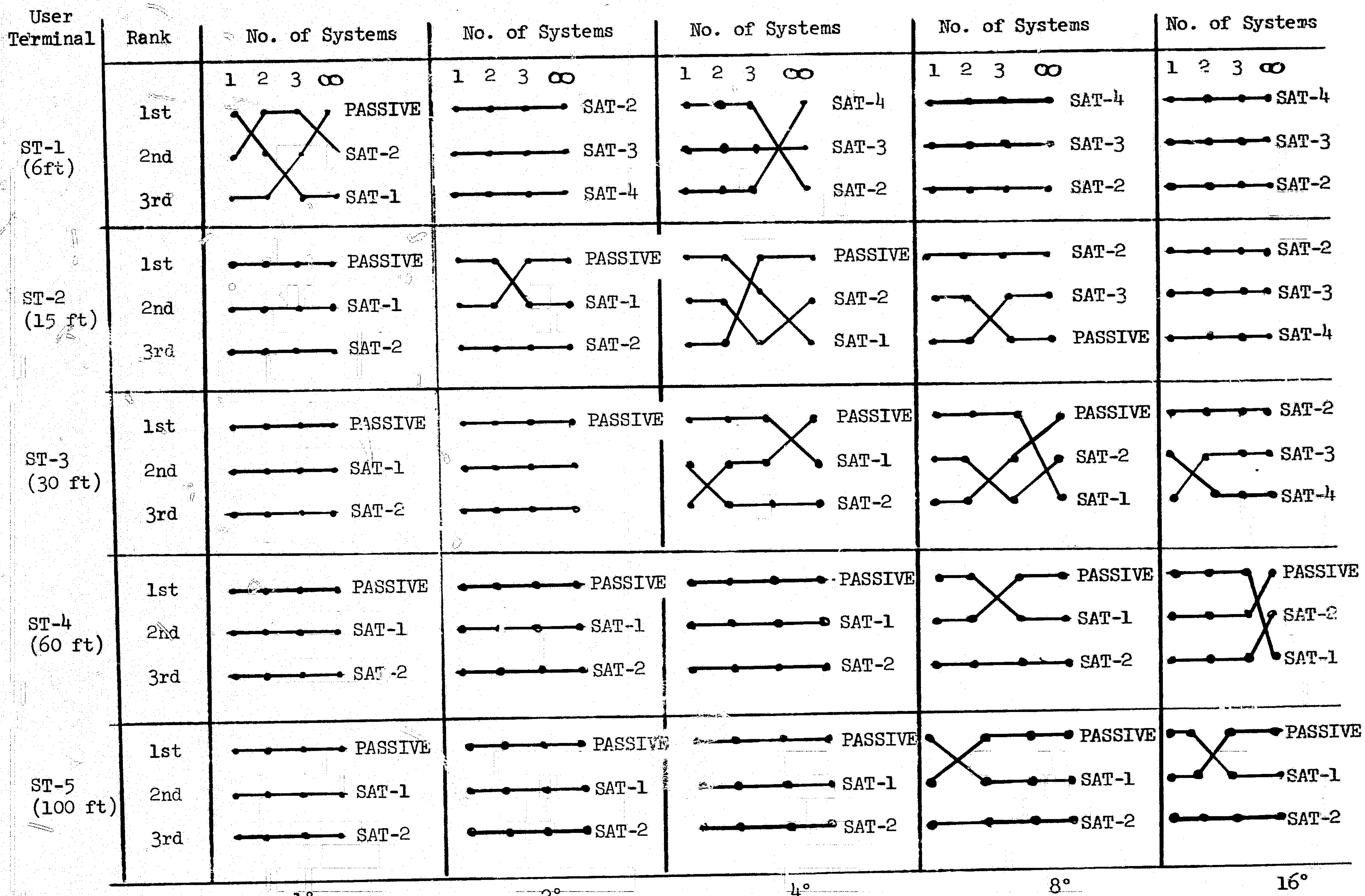
HYPOTHETICAL MINIMUM ANNUAL COST PER ACCESS
FOR SYSTEMS WITH INFINITE ACCESS CAPACITY

User Station	TYPE OF SYSTEM / Beamwidth (degrees)	Passive	SAT-1	SAT-2	SAT-3	SAT-4	Least Expensive System
ST-1 (6 ft ant)	1	349	609	498	882	1,050	Passive
	2	1,465	1,786	512	895	1,050	SAT-2
	4	7,450	6,807	709	1,032	1,140	SAT-4
	8	501,000	26,506	2,500	2,301	1,838	SAT-4
	16	-	107,317	9,714	9,169	6,927	SAT-1
ST-2 (15 ft ant)	1	106	432	490	875	1,041	Passive
	2	239	436	472	857	1,023	"
	4	275	515	454	847	1,006	"
	8	1,122	1,324	481	869	1,024	SAT-2
	16	5,020	5,275	634	988	1,103	SAT-2
ST-3 (30 ft ant)	1	88	428	490	875	1,041	Passive
	2	106	414	472	857	1,023	"
	4	239	418	446	840	1,006	"
	8	273	503	454	847	1,006	"
	16	1,105	1,324	481	869	1,024	SAT-2
ST-4 (60 ft ant)	1	77	428	490	875	1,041	Passive
	2	85	411	472	857	1,023	"
	4	98	397	446	840	1,006	"
	8	106	398	446	840	1,006	"
	16	182	452	450	840	1,006	"
ST-5 (100 ft ant)	1	75	428	489	875	1,041	Passive
	2	82	411	472	857	1,023	"
	4	88	393	446	840	1,006	"
	8	106	388	446	840	1,006	"
	16	125	408	446	840	1,006	"

manner it is easy to find the least expensive system for any type of operating environment and system size.

Figure 23 indicates that passive systems may become more economical than any of the active systems as the system capacity is expanded.

Figure 23. Relative Ranking of Satellite Systems
(Cost per Access)



NOTE: Number of Accesses per system is that shown in Table XXI (Lines 23-27)

In order to estimate at what point the annual cost per access of passive system becomes smaller than the corresponding cost of an active system, the following approximate formula can be applied.

$$\frac{F_p + m\,A_p}{m\,P_p} = \frac{F_A + n\,A_A}{n\,P_A} \qquad (53)$$

where

F_p = annual cost of the fixed portion of passive system (annual cost of passive satellite in orbit)

F_A = annual cost of fixed portion of active system (annual cost of initial R&D of satellites)

A_p = annual cost of augmentation of passive satellite system (annual cost of ground repeater)

A_A = annual cost of augmentation of active system (annual cost of satellite in orbit)

m = number of passive systems (i.e., number of ground repeaters)

n = number of active systems (i.e., number of satellites in orbit)

P_p = number of accesses per one passive system

P_A = number of accesses per one active system

Equation (53) represents the case when the annual cost per access of both passive and active systems is equal.

If it is required that

$$m\,P_p = n\,P_A \qquad (54)$$

$$m = n\,\frac{P_A}{P_p} \qquad (55)$$

the equation will represent the situation where the annual cost per access of both systems is equal for the same number of accesses. Graphically, this is represented by the intersection of two curves (one for active systems and one for passive), each of which represents the locus of the minimum annual cost per access (i.e., annual cost per access when the system is fully loaded) as the number of systems is increased. This is shown in Figure 24.

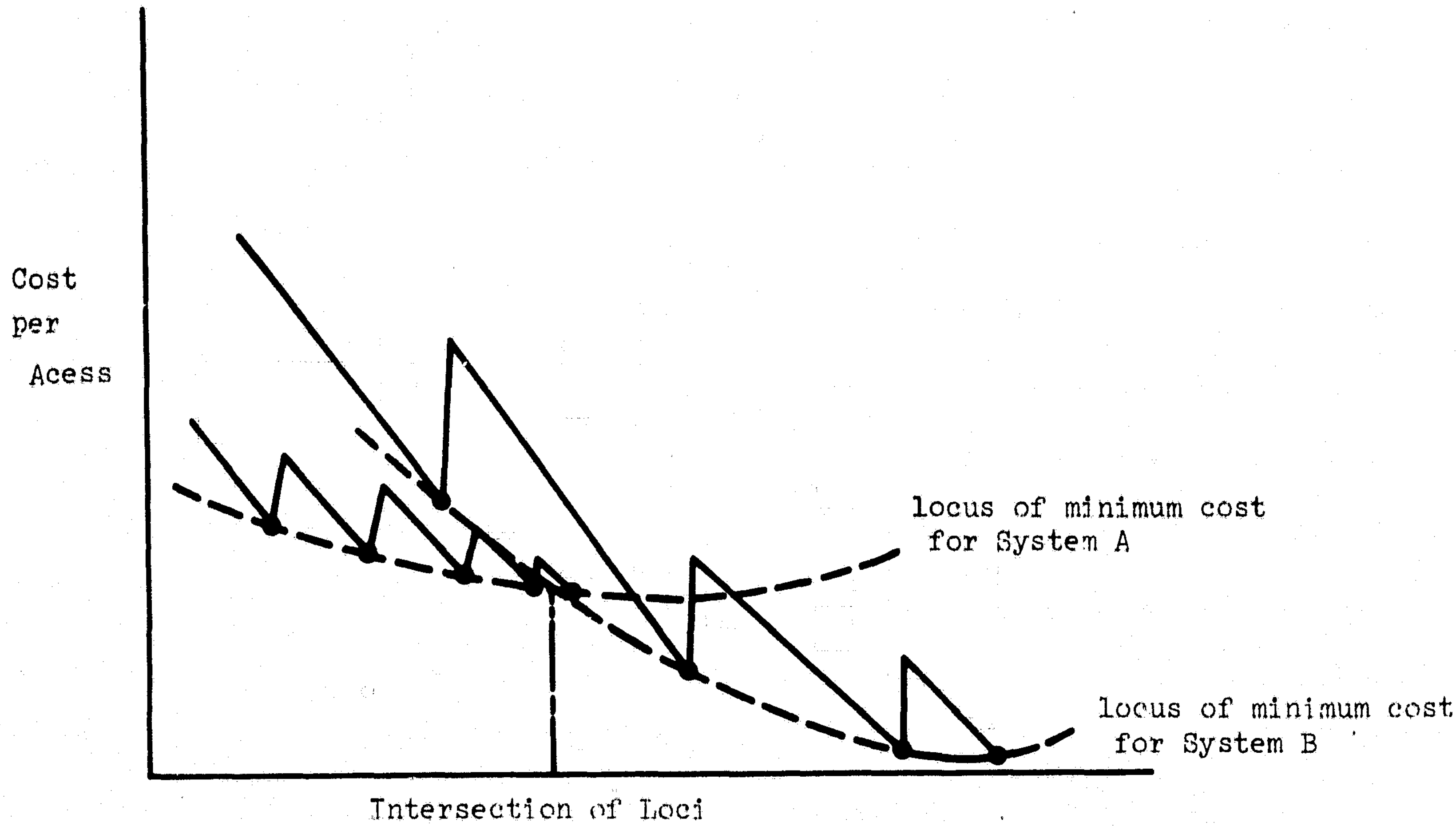


Figure 24. Loci of Minimum Cost Points

Equation (53) can be rewritten using equations (54) and (55).

$$F_p + n \left(\frac{P_A}{P_p}\right) A_p = F_A + n A_A$$

and solving for n

$$n = \frac{F_p - F_A}{A_A - \left(\frac{P_A}{P_p}\right) A_p} \quad (56)$$

Since the values of F_p are given in Table XXVI

A_p are given in Table XXVI

P_p are given in Table XXVI

F_A are given on line 13 in Table XXI

A_A are given on line 29 in Table XXI

P_A are given on line 39-42 in Table XXI

the value of n can be computed from equation (56).

Since n represents the number of systems, it must be an integer. The next higher integral value was chosen for n and was multiplied by the corresponding number P_A to obtain the approximate number of accesses for which the passive system becomes less costly (on the annual cost per access basis) than the active system. These calculations were performed and the results are shown in Table XXX.

Table XXX summarizes the comparative cost effectiveness study of passive and active satellite systems. It indicates that passive satellite systems are competitive costwise with active systems in a large number of cases of interest.

Comparative Analysis of One-Way Television Broadcast Service

General.- This portion of the report covers the comparison of the passive and active satellite systems utilized for one-way distribution of television signals. In the passive system case, it is assumed that the ground-based transmitter is similar to that used in repeater R2 in the preceding analysis of voice communication systems. The technical limitations listed in Table XII, therefore, are applicable in this case.

In the case of the active system it is assumed that each active satellite can accommodate up to 12 transponders to handle 12 individual TV channels. Since this implies only one TV channel per transponder, no intermodulation distortion is present. The characteristics of the satellites are those listed in Table X.

Comparison Criterion.- A television distribution system, which is considered in this section, consists of a transmitter, a satellite in orbit and a number of receive-only stations.

The satellite may be either active or passive, and an attempt is made to compare the relative cost effectiveness of these systems.

In order to calculate the total system cost, the cost of the receiving stations must be known, which may vary depending on the sensitivity (G/T) of

Table XXX.

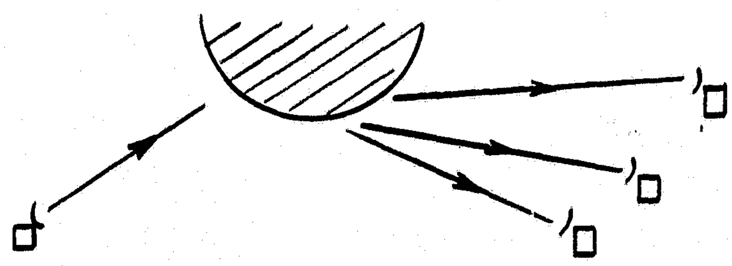
APPROXIMATE NUMBER OF CHANNELS AT WHICH A PASSIVE SATELLITE SYSTEM BECOMES MORE ECONOMICAL (AN ANNUAL COST PER ACCESS BASIS) THAN AN ACTIVE SATELLITE SYSTEM

User Station	Ground coverage (beamwidth) (degrees)	Approximate no. of channels at which the pass. sat. sys. becomes more economical	Type of satellite required	Repeater Antenna D (ft.)	G dB	Number of stations required
ST-1 (6 ft ant.)	1° (city)	45,000	A-325 ft.	159	69	4
	2 (state)	Act. systems are always cheaper	SAT 2			
	4 (time zone)		SAT 4			
	8 (U. S.)		SAT 4			
	16 (1/3 earth)		SAT 4			
ST-2 (15 ft. ant.)	1	Pass. sat. always cheaper	B-137 ft.	89	65	1
	2	50,000	A-325 ft.	159	69	3
	4	50,000	A-325 ft.	159	69	3
	8	Act. sat. are always cheaper	SAT 2			
	16		SAT 2			
ST-3 (30 ft. ant.)	1	Pass. sat. always cheaper	B-97	63	62	1
	2		B-137	89	65	1
	4	67,000	A-325	159	69	4
	8	120,000	A-325	159	69	9
	16	Act. sat. always cheaper	Sat 2			
ST-4 (60 ft. ant.)	1	Passive satellite always cheaper	B-61 ft.	40	58	1
	2		B-87 ft.	56	61	1
	4		B-123 ft.	80	64	1
	8	50,000	A-219 ft.	89	65	3
	16	65,000	A-311 ft.	141	68	4
ST-5 (100 ft. ant.)	1	Passive sat. always cheaper.	B-43 ft.	35	57	1
	2		B-61 ft.	50	60	1
	4		B-97 ft.	63	62	1
	8	22,500	B-138 ft.	89	65	2
	16	46,500	A-246 ft.	112	66	3

these stations. Since these costs were not available, the comparison between the passive and active systems was accomplished by assuming that in both cases the same number of ground receivers with the same (G/T) are used. Since this assumption means that the total costs of the ground receivers will be the same in all cases, they do not have to be included inthis comparison. Accordingly, it is sufficient to calculate the annual costs of the satellite and the transmitter for both the passive and active systems and compare them.

Because of the fact that with a large number of ground receiver, their cost may be higher than the cost of satellites it is desirable to keep the (G/T) of receiving stations as low as possible. It is assumed, therefore, that values of (G/T) of 42 dB or smaller will be considered.

Capacity of a Passive Satellite Distribution System.- The system configuration assumed for the purposes of this study is shown below and consists of a single transmitter, a passive reflector in orbit, and a set of ground receivers which are all identical.



From Table 6 of Appendix K the following performance and operating parameters have been defined for a TV channel transmitted by frequency modulation at 8 GHz with FM feedback receivers at the ground terminal.

$S/No = 88.2$ dB

m = deviation ratio = 3

B_{RF} = Carson's rule rf bandwidth = 32 MHz

The effective radiated power which must be transmitted by the transmitting stations can be computed from

$$ERP = (S/No)\, L_1\, L_2\, \alpha\, k\, \frac{T_3}{G_3} \cdot \frac{1}{G_s} \qquad (57)$$

where

L_1 and L_2 are the uplink and downlink free space losses at 8 GHz (201.6 dB for satellite in synchronous orbit)

α represents miscellaneous losses and is assumed to be 3 dB

k is the Boltzman's constant (-228.6 dB)

$\frac{G_3}{T_3}$ is the sensitivity of the receiving terminal

G_s is the gain of the passive satellite.

Substituting the constants

$$(ERP_1)\ dB = 88.2 + (2x201.6) + 3 - 228.6 - \left(\frac{G_3}{T_3}\right) dB - (G_S)\ dB$$

$$(ERP_1)\ dB = 265.8\ dB - \left(\frac{G_3}{T_3}\right) dB - (G_S)\ dB \qquad (58)$$

or

$$P_{T_{dB}} + G_{2R\ dB} - 265.8\ dB + (G_S)\ dB = -\left(\frac{G_3}{T_3}\right) dB$$

where

P_T is the total power of the transmitter

G_{2R} is the gain of the transmitter antenna

The maximum value of P_T of 59 dBW was established in Appendix H. Therefore, the value of system gain Z can be calculated.

$$Z\ dB = G_{2R}\ dB + G_S\ dB = 206.8\ dB - \left(\frac{G_3}{T_3}\right) dB \qquad (59)$$

$$Z\ dB = 206.8\ dB - \left(\frac{G_3}{T_3}\right) dB \qquad (60)$$

or

$$\frac{G}{T} = 206.8\ dB - Z\ dB \qquad (61)$$

From Equation (60), the required values of Z for any given (G/T) can be calculated. Knowing the value of Z the values of G_{2R} and G_S can be selected so as to minimize the overall cost of the system.

The minimization is accomplished using the same approach as that described previously in this report in connection with the voice communication system. The results are tabulated in Table XXXI and plotted in Figure 25, which show the annual cost of the passive system consisting of one satellite and one transmitter as a function of (G/T) of the receivers.

The limits of the passive system capability when the ground antenna gain is 69 dB can be derived using Table XXII, which shows the maximum gain of the satellite. The sum of these two numbers (in dB) represents the system gain Z which is then substituted into Equation (61). The calculations yield values shown in Table XXXII. The annual cost of a passive system required to produce these results have been previously calculated to be $18.3 million.

Table XXXII. Minimum Receiver (G/T) Required With Passive Satellite TV Distribution System

Beamwidth (Degrees)	Minimum (G/T) dB
1	13
2	19
4	25
8	31
16	37

<u>Capacity of an Active Satellite Distribution System.</u>- The active system configuration consists of a transmitter, an active satellite in orbit and identical ground receivers.

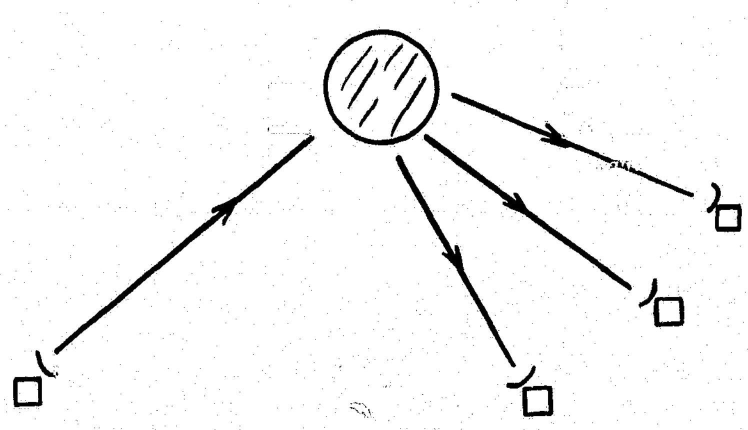


Table XXXI

MINIMUM COST OF PASSIVE SATELLITE TV I

Beamwidth = 1°

Rcvr. G/T	System Gain Z		Anten. Gain	Pass. Sat. Gain	Anten. Dia.	Satel. Dia.	ANNUAL COST Ground Trans.	Satel. in or.	Total Cost		Anten. Gain	Pass. Sat. Gain	An
dB	dB		dB	dB	Ft.	Ft.	$M	$M	$M		dB	dB	
13	194		69	125	159	325	4,010	14,286	18,296				
17	190		66	124	112	298	2,048	13,934	15,982		*		
19	188		66	122	112	237	2,048	13,318	15,366		69	119	
20	187		69	118	159	149	4,010	7,126	11,227		68	119	
23	184		66	118	112	149	2,040	7,216	9.264		66	118	
25	182		65	117	89	137	1,767	7,125	8,892		64	118	
26	181		64	117	80	133	1,647	7,089	8,736		69	112	
29	178		62	116	63	133	1,474	7,091	8,565		66	112	
31	176		62	114	63	97	1,474	6,852	8,306		65	111	
32	175		62	113	63	87	1,474	6,764	8,238		64	111	
35	172		60	112	50	81	1,360	6,730	8,090		63	109	
37	170		60	110	40	61	1,360	6,611	7,971		63	107	
39	168		58	110	40	61	1,284	6,611	7.815		61	107	
43	164		57	107	35	43	1,255	6,517	7,772		60	104	

Beamwidth = 8°

Rcvr. G/T	System Gain Z		Anten. Gain	Pass. Sat. Gain	Anten. Dia.	Satel. Dia.	Ground Trans.	Satel. in or.	Total Cost		Anten. Gain	Pass. Sat. Gain	An
31	176		69	107	159	325	4,010	14,286	18,296				
32	175		69	106	159	300	4,010	13,956	17,967				
35	172		66	106	112	300	2,048	13,957	16,005		*		
37	170		65	104	89	246	2,048	13,402	15,450		69	101	
39	168		65	103	89	219	1,767	13,145	14,912		68	100	
42	165		66	99	112	142	2,048	8,158	9,206		66	99	
43	164		65	99	89	138	1,767	7,128	8,895		66	98	
44	162		64	98	80	129	1,648	7,062	8,709		69	93	

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XXI

TE TV DISTRIBUTION SYSTEM

Beamwidth = 2°

Pass. Sat. Gain dB	Anten. Dia. Ft.	Satel. Dia. Ft.	ANNUAL COST Ground Trans. $M	Satel. in or. $M	Total Cost $M
119	159	325	4,010	14,286	18,296
119	141	325	3,041	14,286	17,327
118	112	298	2,048	13,943	15,990
118	80	298	1,647	13,943	15,590
112	159	149	4,010	7.218	11,229
112	112	149	2,048	7,219	9,267
111	89	137	1,767	7,125	8,892
111	80	133	1,647	7,091	8,739
109	71	105	1,551	6,891	8,442
107	71	87	1,551	6,764	8,316
107	56	87	1,412	6,764	8,176
104	50	61	1,361	6,611	7,971

Beamwidth = 16°

Pass. Sat. Gain dB	Anten. Dia. Ft.	Satel. Dia. Ft.	ANNUAL COST Ground Trans. $M	Satel. in or. $M	Total Cost $M
101	159	325	4,010	14,286	18,296
100	141	311	3,041	14,075	17,116
99	112	284	2,048	13,784	15,834
98	112	246	2,048	13,402	15,450
93	159	145	4,010	7,187	11,197

Beamwidth = 4°

Anten. Gain dB	Pass. Sat. Gain dB	Anten. Dia. Ft.	Satel. Dia. Ft.	ANNUAL COST Ground Trans. $M	Satel. in or. $M	Total Cost $M
*						
69	113	159	325	4,010	14,286	18,296
68	112	141	299	3,041	13,943	16,984
66	112	112	299	2,048	13,943	15,997
64	112	80	309	1,647	14,055	15,702
65	110	89	237	1,767	13,318	15,086
67	105	126	133	2,434	7,094	9,528
65	105	89	133	1,767	7,094	8,861
64	104	80	123	1,648	7,015	8,662
62	102	63	97	1,474	6,834	8,308

Foldout Frame 2

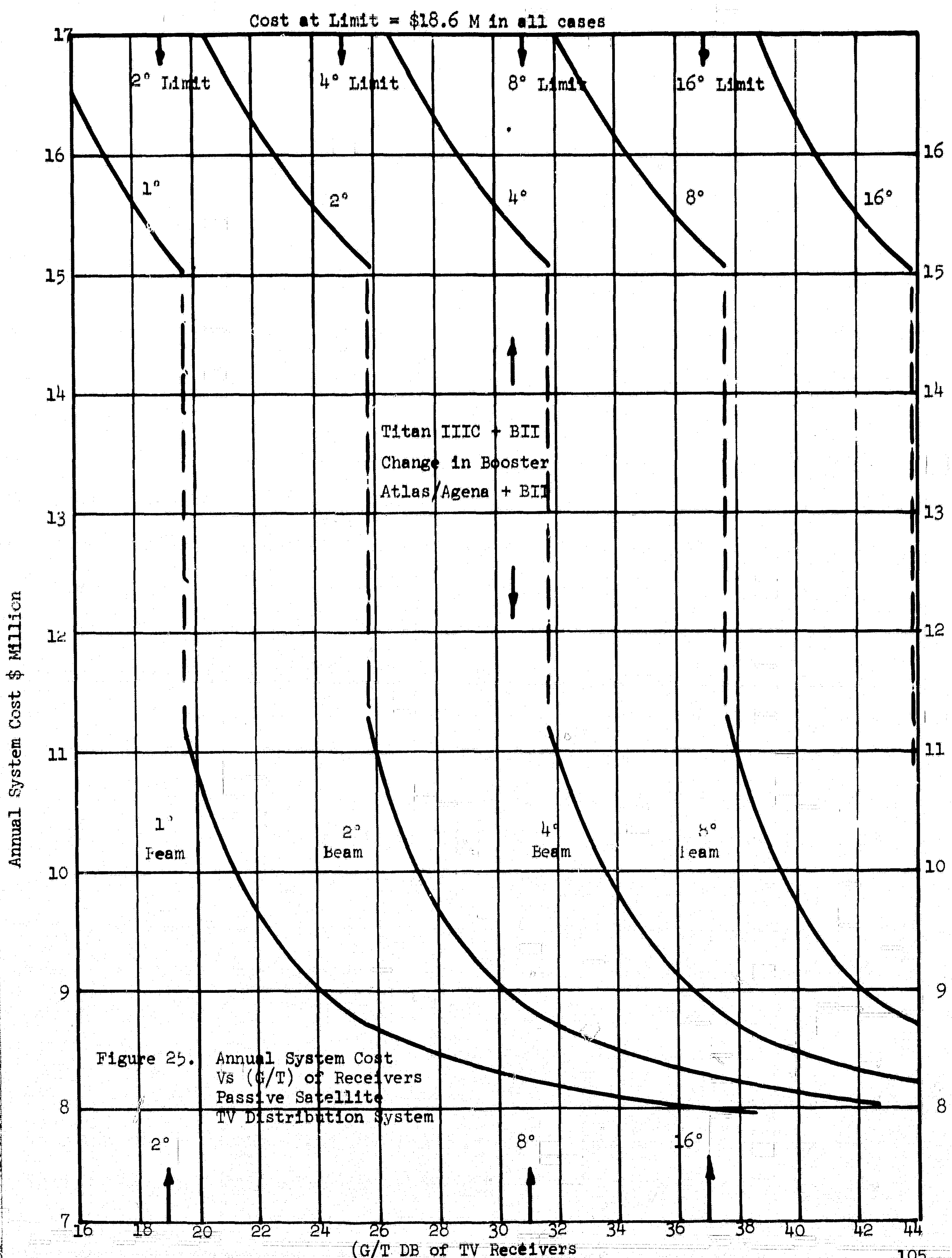


Figure 25. Annual System Cost Vs (G/T) of Receivers Passive Satellite TV Distribution System

The required ERP from the satellite is

$$ERP = (S/No)\ L_1 \alpha k\ \frac{T_3}{G_3}$$

where the symbols are the same as those in the preceding section. For comparative purposes it is assumed that the frequency of operation is the same as in the passive case, i.e., 8 GHz.

$$(ERP)dB = 88.2 + 201.6 + 3 - 228.6 - \left(\frac{G}{T}\right) dB$$

$$(ERP)dB = 64.2\ dB - \left(\frac{G}{T}\right) dB \qquad (62)$$

Using Equation (62) the required satellite ERP for various values of (G/T) of the receivers can be calculated. The relation between the annual cost of the satellite in orbit and its ERP can be obtained from consideration of Tables X and XVIII. The annual cost of a ground transmitter must be added to the cost of the satellite.

Assuming that the uplink SNR should be at least 10 dB larger than that for the downlink, and that the (G/T) of the satellite is -12dB (See Table X) the required ERP of the ground transmitter can be calculated using Equation (62).

$$ERP = 64.2 + 12 = 76.2\ dB$$

Such an ERP can be produced by an installation using a 15-foot antenna (approximate gain at 8GHz = 49 dB) and a 1 kw power transmitter (30 dBW). The annual cost of such an installation is very small compared to the annual cost of the satellite in orbit and will not, therefore, be considered. The annual cost of the system having ERP as calculated from Equation (62) as a function of the G/T of receivers is shown in Table XXXIII.

Comparisons of Table XXXIII with Table XXXII indicate that in every case the receiver (G/T) required for operation with active satellites is below the best value obtainable with passive systems when one TV channel is broadcasted.

<u>Systems Which Provide more than One TV Channel.</u>- The approach taken to compare the annual costs of passive and active systems when more than one TV channel is used is as follows:

The minimum annual cost of a passive system operating with one TV channel has already been computed and is shown in Table XXXI. Using these results, an estimate is made of the minimum cost to increase the channel capacity to 2, 4, 8 and 12 channels respectively at any given value of (G/T) of the ground receiver.

Table XXXIII.

ANNUAL COST OF ACTIVE SYSTEMS FOR TV DISTRIBUTION AS A FUNCTION OF (G/T) OF THE RECEIVERS (ONE TV CHANNEL)

Beamwidth	Satellite	Approx. Receiver (G/T)	Satellite ERP (dBW)	Annual Cost ($M)
1°	SAT-1	8	56	9.2
	2	-3	67	14.3
	3	-6	70	22.4
	4	-8	72	26.8
2°	SAT-1	14	50	8.8
	2	3	61	14.0
	3	0	64	22.0
	4	-2	66	26.6
4°	SAT-1	20	44	7.5
	2	9	55	12.0
	3	6	58	20.2
	4	4	60	26.4
8°	SAT-1	26	38	4.5
	2	15	49	12.0
	3	12	52	20.0
	4	10	54	26.4
16°	SAT-1	32	32	4.0
	2	21	43	12.0
	3	18	46	20.2
	4	16	48	26.4

The cost minimization procedure is similar to that used for the case of one ground transmitter. In this manner we develop an approximate annual cost for a system which provides several TV channels and operates with ground receiving stations of various (G/T)'s.

In a similar manner, the least cost of an active system can be estimated. Here, however, is a choice of providing different kinds of satellites to achieve operation with required (G/T) of ground terminals. One set of selections of satellites is shown in Table XXXIV with the corresponding costs and (G/T)'s.

Using data derived from Tables XXXI, XXXIV and additional computations, Figures 26, 27 and 28, were prepared which show total annual cost of TV distribution systems providing 1, 2, 4, 8, and 12 channels and with ground coverage corresponding to a beamwidth of 1°, 4° and 8°.

Table XXIV.

ACTIVE SYSTEM ARRANGEMENTS
FOR TV DISTRIBUTION

Beamwidth	No. of TV Channels	System	Required G/T (dB)	Annual Cost ($ M)	Cost/Channel
1^{o}	1	One SAT-1	8	9.2	9.2
	2	One SAT-2	0	14.3	7.15
	4	One SAT-2	3	14.3	3.57
	8	One SAT-2	6	14.3	1.79
	12	One SAT-2	8	14.3	1.19
2^{o}	1	One SAT-1	14	8.8	8.8
	2	One SAT-2	6	14.0	7.0
	4	One SAT-2	9	14.0	3.5
	8	One SAT-2	12	14.0	1.75
	12	One SAT-2	14	14.0	1.17
4^{o}	1	One SAT-1	20	7.5	7.5
	2	One SAT-2	12	12.0	6.0
	4	One SAT-2	15	12.0	3.0
	8	One SAT-2	18	12.0	1.5
	12	One SAT-2	20	12.0	1.0
8^{o}	1	One SAT-1	26	4.5	4.5
	2	One SAT-1	29	4.5	2.25
	4	One SAT-2	21	12.0	3.0
	8	One SAT-2	24	12.0	1.5
	12	One SAT-2	26	12.0	1.0
16^{o}	1	One SAT-1	32	4.0	4.0
	2	One SAT-1	35	4.0	2.0
	4	One SAT-1	38	4.0	1.0
	8	One SAT-2	30	12.0	1.5
	12	One SAT-2	32	12.0	1.0

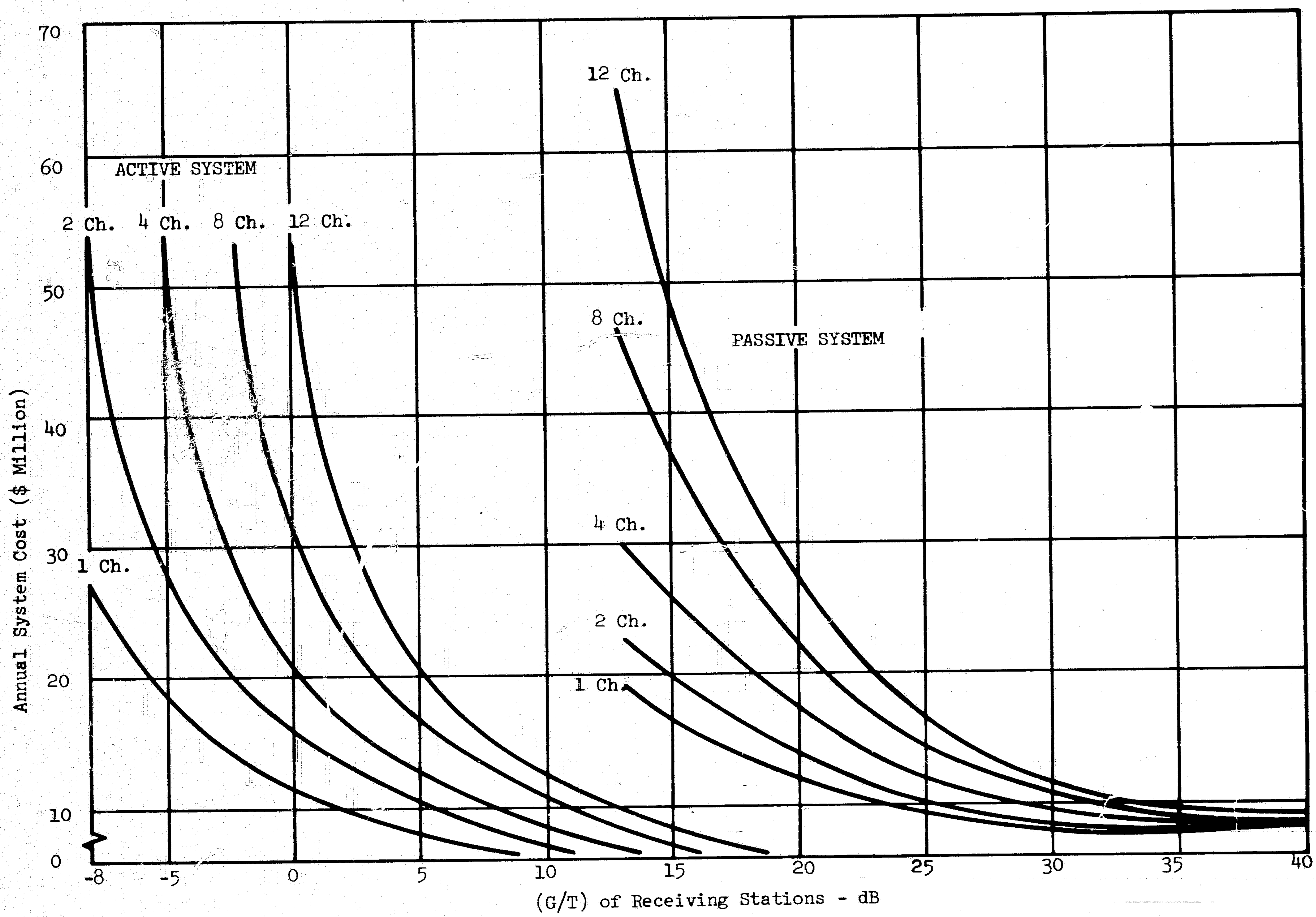


Figure 26. Minimum Annual System Cost for 1, 2, 4, 8, 12 TV Channels
1° Beamwidth

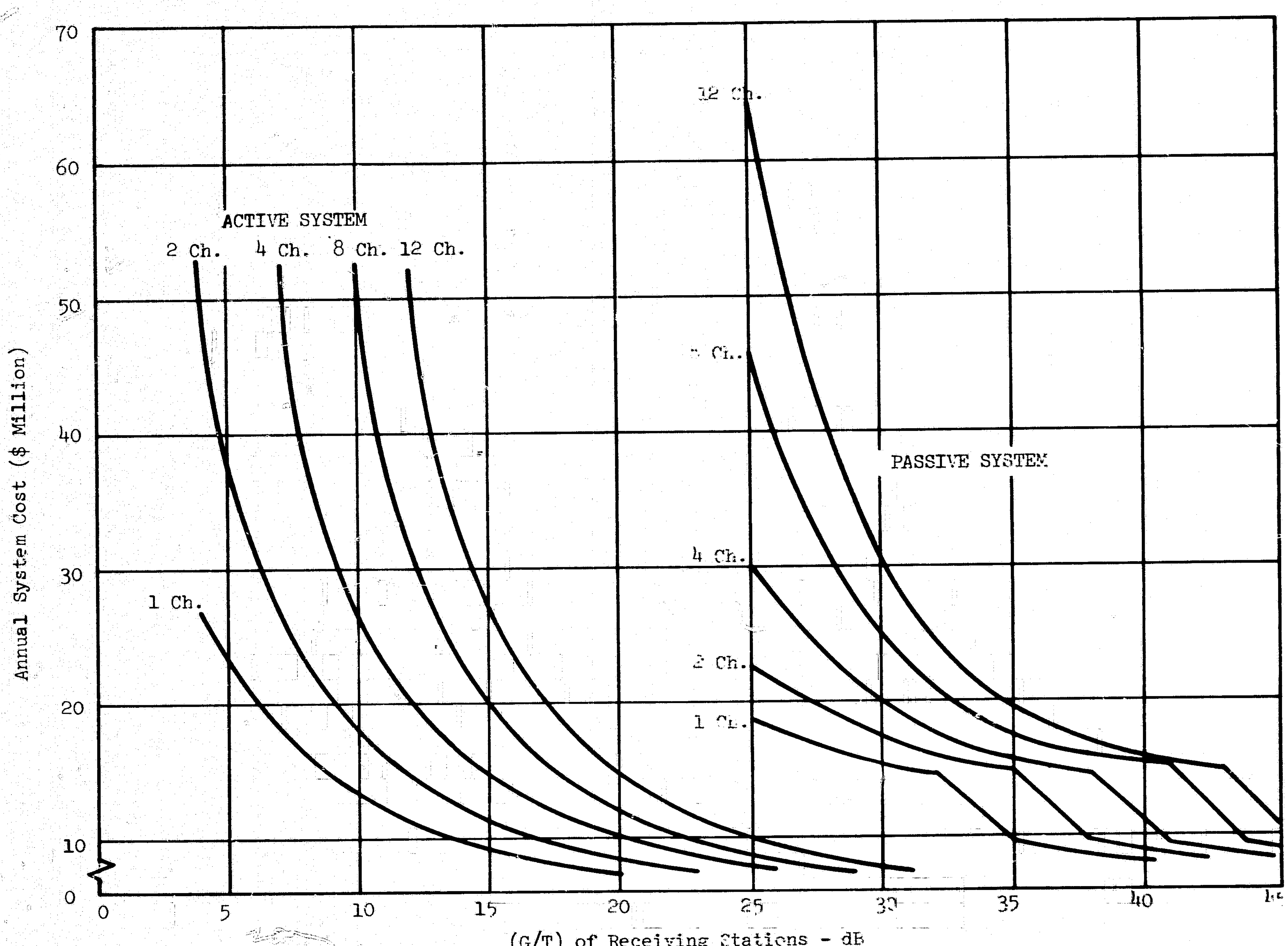


Figure 27. Minimum Annual System Cost for 1. 2. 4. 8, 12 TV Channels
4° Beamwidth

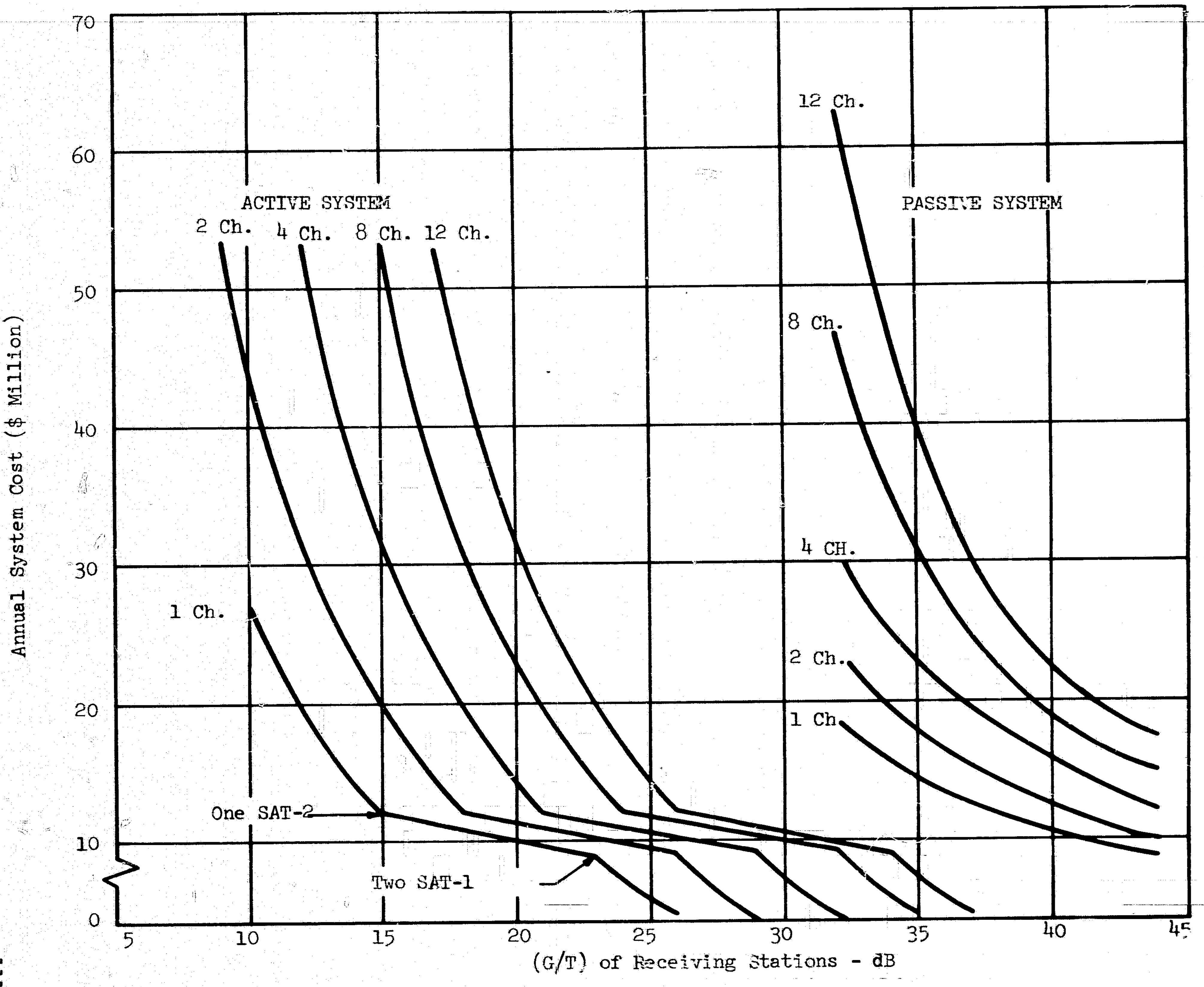


Figure 28. Minimum Annual System Cost for 1, 2, 4, 8, 12 TV Channels
8° Beamwidth

It can be seen from these graphs that the total annual system cost of active systems is always smaller for any given (G/T) than that of a passive system which provides comparative service to the same ground stations. Figures 26, 27, and 28 are approximate only and should not be used for accurate determination of absolute system costs. They indicate the annual cost of transmitter and satellite, but do not include the cost of the ground receivers.

Discussion of Results

Point-to-Point Communication System.- The results of this work are summarized in Figure 23 and Table XXX. Figure 23 indicates that in a great majority of cases the passive systems are either always less expensive (on the basis of annual cost per access) or become less expensive as the number of accesses is increased. This result may be explained as follows:

The total cost per access is obtained by dividing the total system cost by the number of accesses. Active satellites, because of higher ERP (compared to the maximum possible reflected power of a passive system) would normally have a larger channel capacity. However, because of intermodulation produced by hard limiting satellite transponder, a certain amount of radiated power represents the unwanted intermodulation power. To reduce intermodulation, the bandwidth of each access must be widened. Since the total transponder bandwidth is fixed at 500 MHz, such widening implies fewer accesses. Thus, there are two limitations on the total number of accesses - one due to available ERP, and one due to available bandwidth. As a result, an optimization procedure described earlier in this report must be employed to maximize the number of accesses. The results shown in Tables XX and XXVI indicate the maximum number of accesses for all cases under consideration. It can be seen that when systems become bandwidth limited, the limiting number of accesses that can be handled by a passive system is greater than that of an active system. This is due to the fact that a wider bandwidth per access is required in active systems to keep intermodulation distortion within prescribed limits.

It was considered that an active system consists of a single satellite in orbit, while a passive system consists of a passive satellite in orbit and a ground repeater. When the required number of accesses exceeds the capacity of such systems, it can be doubled by orbiting another active satellite (in case of an active system) or by adding another ground repeater (in case of passive systems). This process can be repeated if still more capacity is desired. The costs of such additions are shown in line 16 of Table XXI for active systems and in Table XXVI for passive systems. It can be seen that the highest annual cost of the ground repeater is \$4.0 million while the cost of orbiting a satellite varies from \$4.0 to \$26.8 million.

Thus, in most cases it costs more to double the capacity of the active system than it does to double the capacity of a passive system. Since the capacity of one passive system was in most cases larger than that of an active system, the process of further increasing the number of accesses causes the annual cost per access of passive systems to decrease at a faster rate than the corresponding decrease in the annual cost of the active systems. After a sufficiently high number of accesses is reached the passive systems annual cost per access becomes lower than that of the active systems. The number of accesses at which this situation occurs has been estimated and is shown in Table XXX.

The results also show that on the annual cost per access basis, active systems are always less expensive when high satellite ERP is required per access. This is particularly true when operating with small user terminals (SAT-1). The reason is that because of our limitation on the ERP of the ground repeater, the maximum total power which is reflected towards earth by the passive satellite in synchronous orbit is always lower than that of active satellites. Table XXXV shows the differences.

Table XXXV. Ratio of ERP from Active Satellites to Maximum Reflected Power of Passive Systems (dB)

Active Satellite	dB Above Passive
SAT-1	5 dB
SAT-2	16 dB
SAT-3	19 dB
SAT-4	20 dB

Thus, a larger number of accesses can always be obtained with active systems.

Since the above discussion applied to system costs only, it is also necessary to consider the operational factors which affect the choice between the active and passive systems. These factors are discussed in the next main section heading of this report. The importance of these factors to the mission being planned may be decisive in the selection of the systems.

The general conclusion that can be drawn from the results on point-to-point communication systems is therefore that passive satellite systems may become competitive with active systems on the annual cost-per-access basis in many situations and should not, therefore, be disregarded in the planning of such systems.

TV Distribution.-In all cases studied, it is always possible to provide an active satellite TV distribution system at an annual cost smaller than the comparative cost of a passive system. In the proper context, the cost comparison methods used in the preceding analyses were exactly the same. In both cases, data relating level annual system cost was developed as a function of ground terminal G/T with traffic level and ground coverage as parameters. Therefore the least costly system for a given set of parameters could be determined.

The only differences in the two missions were the total communication traffic considered and the intermodulation problem present in the active satellite voice mission. These factors are responsible for the apparent conflicting results as stated above.

OPERATIONAL CONSIDERATIONS OF PASSIVE AND ACTIVE SATELLITE SYSTEMS

General

In the previous section of this report passive and active satellite systems were examined from the point of view of their total channel capacity and annual costs. It was concluded that in many cases passive satellite systems become cost competitive with active satellite systems when a sufficiently large number of channels is acquired.

In this section, brief consideration is given to the main operational problems associated with large communication systems utilizing satellites. The topics discussed are:

(1) Areas of Coverage

(2) Technical Performance
 - Signal suppression and intermodulation
 - Jamming
 - Operational flexibility
 - Propagation time delay

(3) Interference and Spectrum Utilization
 - Transmitter power
 - Scatter
 - Interference with other sciences
 - Safety
 - Modulation
 - Multiplexing
 - Operating frequencies

(4) Traffic Control

Coverage Areas

The coverage area and location of the rf energy on the earth from an active satellite in synchronous orbit is determined primarily by the satellite's antenna beamwidth and its attitude control. In contrast, the beam location of a passive satellite in synchronous orbit is determined not only by the beam pattern of the satellite and its attitude control but also by the location of the transmitting station.

Each type of satellite considered previously needs to be examined to determine its particular reflecting properties. Once these are known, the associated reflection geometries can be determined. The following paragraphs will be concerned with that class of reflectors on which the most emphasis was placed in this report; the specular reflectors whose reflection characteristics are defined entirely by Snell's law.

(1) $\sin \gamma_t = \sin \gamma_i$

where

γ_t = angle of reflection referred to the surface normal

γ_i = angle of incidence referred to the surface normal

Assuming the satellite is in an equatorial synchronous orbit, the location of the center of the reflected beam can be given by:

(2) $\sin(\lambda_R) = C_3 \left[-C_1 \left(\frac{R_o+h}{R_o}\right) \pm \sqrt{(C_1^2 - 1)\left(\frac{R_o+h}{R_o}\right) + 1} \right]$

(3) $\sin(\beta_R) = \frac{C_2}{C_3} \tan \lambda_R$ if $C_3 \neq 0$, or

(4) $\cos(\beta_R) = C_2^{\ 2} k \pm C_1 \sqrt{1 - C_2^{\ 2} k}$ if $C_3 = 0$

where

λ_R = latitude of receiver (+ if north, - if south)

β_R = angular displacement (longitude) of receiver relative to satellite longitude (+ if east, - if west)

and

$$C_1 = (1/K_1) \left[A_1 (2\theta_{33}^{\ 2} - 1) - A_2 (2\theta_{31}\theta_{33}) + A_3 (2\theta_{32}\theta_{33}) \right]$$

$$C_2 = (1/K_1) \left[-A_1 (2\theta_{31}\theta_{33}) + A_2 (2\theta_{31}^2 - 1) - A_3 (2\theta_{31}\theta_{32}) \right]$$

$$C_3 = (1/K_1) \left[A_1 (2\theta_{32}\theta_{33}) - A_2 (2\theta_{31}\theta_{32}) + A_3 (2\theta_{32}^{\ 2} - 1) \right]$$

where

$$K_1 = R_o \sqrt{1 + k^2 - 2k \cos \lambda_T \cos \beta_T}$$

$$A_1 = R_o (\cos \lambda_T \cos \beta_T - k)$$

$$A_2 = R_o (\cos \lambda_T \sin \beta_T)$$

$$A_3 = R_o \sin \lambda_T$$

and

$$\theta_{11} = \cos\theta$$

$$\theta_{12} = 0$$

$$\theta_{13} = -\sin\theta$$

$$\theta_{21} = \sin\theta\sin\phi$$

$$\theta_{22} = \cos\theta\sin\phi$$

$$\theta_{31} = \sin\theta\cos\phi$$

$$\theta_{32} = -\sin\phi$$

$$\theta_{33} = \cos\theta\cos\phi$$

where

λ_T = latitude of transmitter (+ if north, - if south)

β_T = longitude of transmitter relative to satellite longitude (+ if east, - if west)

$$k = \frac{R_o + h}{R_o}$$

h = satellite altitude

R_o = earth radius

θ = pitch of satellite relative to satellite earth-center line (+ moves surface normal eastward)

ϕ = roll of satellite relative to satellite earth-center line (+ moves surface normal northward).

Note that when the radicals of equation (2) or (4) are negative, the center of the reflected beam exceeds the earth's subtended angle as seen from the satellite. Note also the existence of two solutions to these equations. One solution is the position of the beam center on the front face of the earth (the desired solution). The other represents this point projected on through to the back of the earth.

From the above equation, it is obvious that, to an advantage or disadvantage, each transmitter location reflecting off a passive satellite with a particular orientation has its own discrete coverage area location and no other in which a designated receiver can be located. The active satellite can, however, redirect a wave into any location dependent only on antenna orientation regardless of the transmitter direction. As a corollary of course, the active satellite is limited to relay into only one area at any given time while the passive satellite can simultaneously relay traffic into many different areas. The result is a difference in the number of satellites required to support a system strictly on the basis of geometry.

From a standpoint of the number of satellites required, the worst case for the passive satellite is represented by the situation in which a satellite of beamwidth Θ, is required to provide communication between any two points in an area of intercept angle from synchronous orbit corresponding to ϕ. In a single hop passive system the number of satellites necessary is

$$n = \left(\frac{2\phi}{\Theta}\right)^2 \tag{63}$$

while the number of single beam active satellites required is

$$m = \left(\frac{\phi}{\Theta}\right)^2 \qquad \Theta \geq \phi \tag{64}$$

The multiple beam type active satellite would require $\frac{x}{y}$ satellites assuming x ground stations and y beams if the uplink beam is $\geq \phi$. For large m and realistic values of n, the multiple beam type may require more satellites than either the single-beam active or passive.

Considering again equations (63) and (64), it is seen that, for equivalent beamwidths, four times as many passive satellites are required than active satellites to provide communications between any two points within a given area. If the same number of satellites are desired, the beamwidth of the passive must be twice that of the active satellite.

The above is necessarily true only for a single hop passive system. If a double hop system (master terminal concept) is used, each system would require the same number of satellites; i.e.,

$$n = m = \left(\frac{\phi}{\Theta}\right)^2$$

By using a combination of single and double hops, most, or in some instances, all stations within the prescribed area could communicate with each other via a passive system having a beamwidth equivalent to that of an active satellite.

Figure 29 illustrates this point, which represents a matrix of 12 major cities in the U.S.A. With a passive "saddle" satellite having a 4° beamwidth

ROLL = 5.5
PITCH = 0
SAT LONG = 97°

RECEIVERS

	Los Angeles	San Francisco	New York	Detroit	Atlanta	Houston	Denver	Miami	Minneapolis St. Paul	Dallas	Kansas City	Chicago
Los Angeles	0	0	X	X	X	0	0	X		0	0	X
San Francisco	0	0	X	X	X	0	0	X		0	0	X
New York	X	X	0	0	0			0				
Detroit	X	X	0	0	0	0	X	0	0	X	0	0
Atlanta	X	X	0	0	0	0	X	0	0	0	0	0
Houston	0	0		0	0	X	X	0	X	X	X	X
Denver	0	0		X	X	X	0	X	X	X	X	X
Miami	X	X	0	0	0	0	X	0	0	0	0	0
Minneapolis St. Paul				0	0	X	X	0	0	X	X	0
Dallas	0	0		X	0	X	X	0	X	X	X	X
Kansas City	0	0		0	0	X	X	0	X	X	X	X
Chicago	X	X		0	0	X	X	0	0	X	X	0

Figure 29

Communication Links Within the United States Which Could be Established via a Single Passive Reflector in Stationary Orbit (4° Beamwidth)

X = Direct connection
0 = Double-hop connection

located in stationary orbit at 95° W longitude over the equator and pointed towards a point 95° W longitude and 37° N latitude, a communication capability can be established as shown in the figure. The first column denotes transmitting stations. Sign "X" in a row of the matrix indicates that a receiver identified on the top of each column (1st row) can be reached. Single "X" indicates that direct (one hop) contact is possible. A circle (O) indicates that a double-hop connection can be established. For example, transmission between Los Angeles and San Francisco can be established by first reaching Detroit, and then retransmitting the signal to San Francisco.

Figure 29 indicates that with a single 4° passive satellite, communications between New York and Dallas could not be established even with two hops. However, using two passive reflectors and creating essentially two systems with one common point for retransmission, communications throughout the U.S. could be provided.

The total number of telephone communication channels which would be required by 1980 among the 12 cities shown in the figure has been estimated by the Bell System at 236,000. The analysis of cost effectiveness of passive and active systems previously presented has shown that when 4° beamwidth is desired, the passive systems become more economical when more than 67,000 channels are used (with ground transmitter stations equipped with 30-foot antennas). It would appear, therefore, that, on the basis of the analysis in the previous section, passive communications networks across the U.S. could be economically competitive with an active system if operational aspects of the problem were satisfactorily solved.

Technical Performance

General.- Active satellites equipped with hard limiters and operating in non-linear portions of the output tube characteristics are subject to all the disadvantages resulting when several independent signals are simultaneously passed through a non-linear device. Passive satellites, on the other hand, can be considered linear reflectors over a wide range of frequencies. As such they do not suffer from these drawbacks. From a standpoint of technical performance, this presents passive satellites several unique advantages which cannot be duplicated by active systems.

Signal Suppression and Intermodulation.- The amount of output power available to the different signals transmitted through a non-linear transponder is of great importance in the design of satellite systems. It has been shown that when input signals do not have equal amplitudes, signal suppression of weak signals can occur. This is particularly evident when a small number of signals are present. For example, the signal-to-signal ratio between the input and output when one signal is strong and one is weak indicates that the weak signal can be suppressed by a theoretical maximum of 6 dB. On the other hand, when there are two equally strong and one weak signal, the weaker signal is enhanced at high SNR's.

However, when a large number of signals are present and all have equal amplitudes, the loss in output signal power is restricted to slightly more than 1 dB. Accordingly, some method of power control is desirable with non-linear systems to insure that the many carriers at the output to the satellites are roughly equal in power.

The presence of many signals in the non-linear transponder results in interference through the production of crossproducts. In Appendix M this problem has been discussed in more detail and has shown that the resulting signal-to-interference ratio (SIR) has a direct effect upon the access capacity of the system.

In summary, it may be stated that active satellite systems equipped with non-linear transponders are subject to signal suppression and intermodulation product generation and generally require some input signal power control.

None of this is required by passive reflectors which ideally would provide no loss to signals during the process of reflection. Since non-linearities do not exist, no intermodulation products or crosstalk between accesses is generated and signals of any magnitude can be accommodated. As a result, no input signal power control is required and earth transmitters can be substituted at will with complete freedom as to their ERP.

Jamming.- The linearity of a passive system also prevents the possibility of it being disabled by intentional or non-intentional jamming.

In active satellites the total output power from the satellite is fixed. Accordingly, a strong jamming signal could disable the system by effectively "capturing" all the useful power of the transmitter. This is not possible with a passive reflector where no limitation on the total reflected power exists. Thus, passive systems exhibit a performance under jamming conditions which is substantially superior to that of hard limiting active systems.

Operational Flexibility.- Another major advantage of passive systems is the flexibility in system design permitted by the fact that ideally no limitations exist on either the operating frequency that can be used or on the power which is reflected by the passive satellite in orbit.

This means that once the reflector is put in orbit, earth stations can be changed, new systems operating at other frequencies can be added, etc. The possibility of simultaneously operating several systems means that the cost of the satellite can be shared between them and that, in emergencies, no delays associated with orbiting of new satellites are incurred. Earth transmitters can be added at will, permitting rapid and unscheduled system expansion.

Such flexibility is not possible with active satellites. Limited total power capability imposes a constraint upon the maximum number of earth transmitters which can simultaneously use the system. Restriction on total satellite bandwidth (arising from the bandpass characteristics of power tubes, preamplifiers and antennas) imposes a limit on the bandwidth of individual accesses (in FDM systems). Once the satellite is orbited and the system operates at full load no further accesses can be added, nor can other systems operating on different frequencies be accommodated.

In addition, some flexibility in earth station ERP is lost due to the advisability of regulating the signal power of each carrier at the input to the satellite.

Propagation Time Delay.- An additional technical consideration is that of propagation time delay. When satellites are used to establish communication links, the time delay associated with the speed of signal propagation becomes appreciable. With satellites located in stationary orbit, a time delay of up to 0.3 seconds can occur for one way propagation. If the signal is reflected at the receiver, it returns to the origin in the form of an echo with a delay of up to 0.6 seconds. When a double-hop system is used, the echo would be delayed up to 1.2 seconds. The two major considerations, therefore, are:

(1) Echo

(2) One-way time delay.

The problem of echo due to satellite links has received a great deal of attention. Despite serious misgivings voiced by many people in the early days of satellites, all present problems appear to have been satisfactorily solved by the use of improved echo suppressors. It should be remembered that echoes occur primarily at the points where four-wire to two-wire conversion occurs in the circuit. If separate transmit and receive circuits are used throughout the system up to and including a four-wire telephone set the problem vanishes. Although such solution is not very feasible commercially, it could be used in some special applications.

The situation can also be improved by the use of push-to-talk arrangement whereby the telephone receiver is not operative during transmission. The effects of echo in double-hop circuits can be handled in a similar manner.

These various possibilities require further study. It appears, however, that double-hop systems can provide an operation which would be quite acceptable under most conditions, especially when interconnection with established terrestrial systems is not contemplated.

The one-way time delay (as differentiated from the echo) has the psychological effect of rendering an exchange of ideas more difficult because of the delay in receiving a reply. This annoyance problem can be alleviated by push-to-talk operation and is also reduced as the user becomes more familiar with the system.

In general the effects of echo and delay in double-hop systems must receive a more thorough consideration before their impact upon the development of such systems can be evaluated. In special cases, however, particularly with push-to talk method of operation, satisfactory results can most probably be obtained.

Interference and Spectrum Utilization

General.- The problem of the compatibility of satellites and efficient spectrum utilization has recently received considerable attention. Specifically, when considering communication satellites, a look at Table XXXVI indicates that below 10 GHz only 100 MHz of bandwidth is available for exclusive communication satellite use. The remaining 2700 MHz of bandwidth allocated for communication satellites must be shared with existing terrestrial services.

Table XXXVI. Comsat Frequency Assignments (1963)

3400-4200 MHz	Satellite to Earth	Shared
4400-4700 MHz	Satellite to Earth	Shared
5725-5850 MHz	Earth to Satellite	Shared in most regions
5850-5925 MHz	Earth to Satellite	Shared in most regions
5925-6425 MHz	Earth to Satellite	Shared in most regions
7250-7300 MHz	Satellite to Earth	Exclusive
7300-7750 MHz	Satellite to Earth	Shared
7900-7975 MHz	Earth to Satellite	Shared
7975-8025 MHz	Earth to Satellite	Exclusive
8025-8400 MHz	Earth to Satellite	Shared

Total Allocated Bandwidth

Exclusive	100 MHz
Shared	2700 MHz
	2800 MHz

Transmitter Power.- The term spectrum utilization is concerned, in part, with the problem of interference control in the frequency sharing environment. Except for very special applications, earth stations operating in a passive communication satellite system are required to transmit much larger ERP's than the equivalent station of an active system. Possible exceptions occur when the desired satellite ground coverage area is very small. The higher ERP required results because the passive systems "up-link gain" (intercept area) is generally not sufficient to overcome the advantage the active satellite accrues through the amplification process at the satellite. The implication is that the active satellite can more efficiently utilize the available spectrum.

A higher ERP does not, however, necessarily result in more interference to neighboring facilities. If the same diameter earth transmitting antenna is employed, in an interference comparison between active and passive communication satellite systems, then the passive system must obtain the required higher ERP by transmitting higher power which could result in higher interference levels to surrounding systems. If, however, the passive system utilizes a larger antenna to achieve at least a portion of the ERP differential, then, assuming the interference results from the antenna sidelobes as opposed to the main lobe, the resulting interference (on a comparative basis) is determined by the relative sidelobe levels in addition to the relative transmitted power.

Use of the master terminal concept discussed previously provides another method through which the problems associated with the transmitted ERP of a passive system can be alleviated. While such terminals require even larger ERP's, by virtue of the reflection characteristics of passive satellites, the interference problem can be minimized by proper location of the large master terminal, e.g., a domestic USA system might locate the master terminal in South America where the problem of direct interference would be virtually nonexistent. However, there are other difficulties associated with operation in unimproved areas including that of supplying prime power which can amount to several megawatts.

Unique spectrum allocation is another solution to the problem. This would alleviate direct interference with other systems but would not prevent possible interference with the passive systems own receivers. Even with a unique spectrum allocation, interference arises as a result of spurious radiation at harmonic frequencies caused by non-linearities in the transmitter.

In any case, substantial shielding of the transmitter site would be required to attenuate unwanted radiation to more acceptable limits. Such shielding requirements may restrict the freedom of site selection and impose restriction on the minimum elevation angle of the antenna. It may, in addition, increase the cost of the installation because of shielding itself and because of the desirability of locating the antenna in remote areas.

CCIR Recommendations. - The high ERP required of the transmitting terminals in a passive system must also be viewed relative to the tabulated CCIR recommendations. The ERP of the largest terminal considered herein is 129 dbw over 500 MHz in the main beam of the antenna. If proper siting, shielding and antenna design for low sidelobes are given due consideration, interference to terrestrial systems in the shared frequency bands should be negligible, even for the high ERP's considered.

The high active satellite ERP's utilized in the cost comparison are, for many cases, in excess of existing CCIR recomendations on spectral density from space of -130 dbw per square meter in the shared frequency bands. This recommendation, however, has since been determined to be stringent and a proposed change would make it $(-152 + \theta/15)$ dbw/m^2/4kHz.

Scatter. - Precipitation scatter or other forms of scatter constitute potential interference sources which have not been analyzed in this study but are presently being considered by other researchers (Reference 4). Concern has been expressed regarding the possible magnitude of this problem and further study would be necessary to evaluate its importance with respect to passive system operation, particularly from the point of view of its effects upon the system's own receivers.

Interference with Other Sciences.- Large passive communication satellites of the type considered in this report can potentially interfere with other sciences such as astronomy-optical, radio, and radar. It is easily calculated that a 325-foot diameter saddle satellite with a radius of curvature near 11,000 feet in synchronous orbit can have an apparent magnitude of -4.9. This is slightly brighter than the planet Jupiter at its brightest. For radio astronomy, some occulting would surely occur but this could be advantageous as well as harmful.

Safety.- The high power operation of passive system transmitters also represents a possible safety problem. In addition to the safety of the personnel operating the transmitting station, the extremely high density of radiated power may present hazards to aircraft or other space vehicles flying through main beam of the antenna. This problem also has not been sufficiently analyzed and additional study is required to assess its importance.

Modulation.- In addition to the external problem of interference, the efficient spectrum utilization of any system is also dependent upon its internal engineering techniques. For example, from an internal spectrum view point it is desirable to employ a modulation technique which requires the minimum bandwidth to transmit a particular amount of information. However, minimum bandwidth is generally incompatible with the external spectrum utilization problem of interference which dictates minimum power. The best trade must, therefore, be made.

Multiplexing.- Considering multiplexing techniques, if FDM (frequency division multiplexing) is used, active satellites which make use of hard-limiting receivers need to space the signals widely in frequency and control the level of each signal to prevent harmful inter-modulation and cross-modulation productions. Spectrum-wise this is very wasteful and an undesirable restriction. Passive satellites, on the other hand, permit many signals to be closely spaced in frequency and with little constraint on power.

Operating Frequencies.- Assuming both the active and passive communication satellite systems employ the same type modulation and multiplexing, yet another "internal" difference exists between the two systems which determines the amount of spectrum required for a particular channel of information. In an active communication satellite system all stations of a given network transmit in one frequency band and receive in another; the translation being accomplished at the satellite as required due to the lack of good diplexing techniques. In contrast, the passive satellite being only a reflector does not effect a frequency translation. If the master terminal concept is not used in the passive system it can be shown that the active system requires up to twice the frequency range as the equivalent passive system for the same circuit capacity. If the master terminal is used, the two systems are identical.

Traffic Control

Any communications system serving a large number of users requires some method by which connections between users can be established and supervisory circuit control can be exercised. The switching function which has to be performed normally requires an amount of equipment proportional to the size of the system, and the switching installation, because of its size and prime power consumption, is one of the most essential parts of the system. When active satellites are used to provide transmission links directly between the two users, the problem of how to switch the connections to permit each station to communicate with every other station becomes a serious one. As yet, no completely acceptable solutions have been found, although suggestions have been made to locate the switching equipment in the satellite. Apart from the obvious difficulty resulting from impossibility of maintenance, such an approach would preempt a major portion of satellite power and weight, thereby reducing the overall system capacity. Any solution along those lines has not been attempted as yet and must be considered outside the immediate state-of-the-art.

When a double-hop passive system is used, a ground based repeater station is required (see Figure 20). All switching and supervisory equipment can be located at this station, thus providing a complete traffic routing and control capability. Since the switching equipment is located on the ground and the reflectors provide only a passive communication link, this system approaches most closely the conventional terrestrial telephone network capability, with which we are all familiar.

The conclusion that must be drawn, therefore, is that, since no tested and generally accepted technique exists of providing traffic control and switching function in orbit, communication systems utilizing active satellites must resort to other techniques as yet unknown, or to a double-hop system arrangement similar to that of a passive system shown in Figure 20. Thus, for the traffic control point of view a double-hop system may be required even in active satellite systems. If such is the case, the passive satellite system will provide twice the capacity in the total bandwidth as compared to an active system. This is due to the fact that in a passive system different frequency bands are used for each hop, whereas in two-hop active systems, each hop requires one-half of both bands. This is shown in Figure 30.

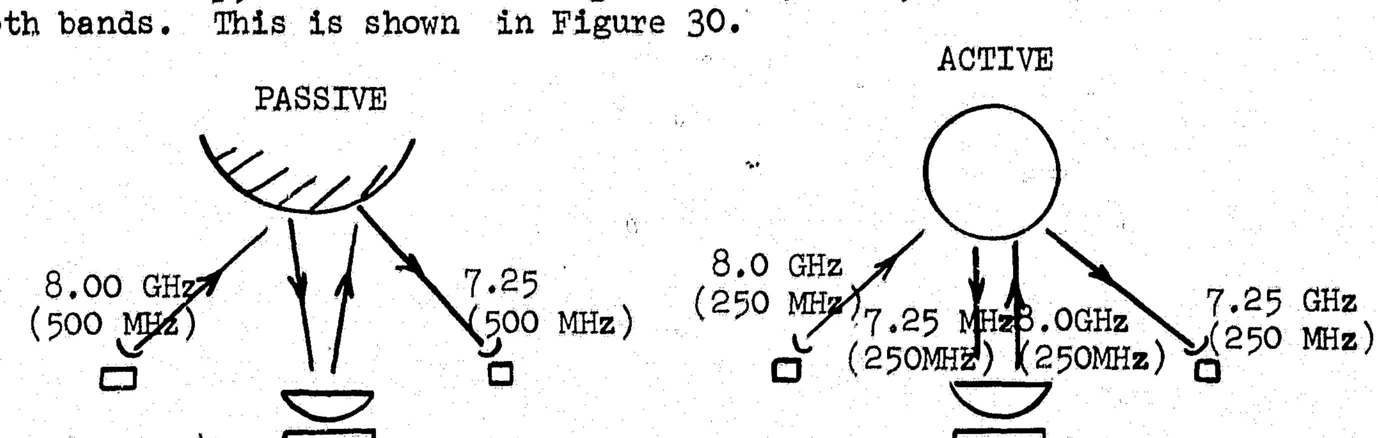


Figure 30. Comparison of Double-hop Systems

The traffic control requirement described above constitutes one of the major unsolved problems in the development of satellite systems with capabilities comparable to terrestrial switched telephone systems. If a two-hop satellite system is required to achieve such capability, passive satellite systems become particularly attractive.

Summary of Operational Considerations

Considerations resulting from operational differences between active and passive satellites have been summarized. Since the differences result in pros and cons for both systems, it is difficult to derive a single conclusion based on the summary and any conclusion warrants considerable discourse.

Most of the negative indicators resulting from the analysis can be bypassed in system design, or other considerations for either the passive or active system while still maintaining the basic conclusions resulting from the cost analysis.

Perhaps one of the most serious problems considered relates to possible interference effects of the passive system high ERP transmit terminal operating in the shared microwave bands. These large ERP terminals would require careful antenna design, judicious siting, as well as other forms of shielding. However, on a comparative basis, active satellites may suffer similar problems under presently existing CCIR regulations.

Therefore, either system would require careful design to meet these regulations, based on technical evolutions, or system modifications such as a switch to higher uncluttered and unshared spectrum. It has been noted that the number of satellites required to support any given mission or missions as a function of only geometric considerations can be different for active or passive systems. However, the factor cannot, in general, be construed as a problem for either passive or active systems and must be evaluated for specific requirements. The important point is that geometry must be considered in other than general comparisons between active and passive systems, since the number of required satellites greatly affects system cost considerations.

ANALYSIS OF THE RELATIVE PERFORMANCE OF A PASSIVE SATELLITE SYSTEM AT FREQUENCIES OTHER THAN X BAND

General

The analysis to this point has been related primarily to a base frequency near 8 GHz and little consideration has been given to the spectrum on either side. In this section, consideration is given to the frequency varying parameters affecting the signal-to-noise ratio at the input of a passive satellite receiving station to determine if, from a capacity standpoint, other operating frequencies are more advantageous. The analysis includes the frequency range from 1 to 100 GHz, but particular emphasis is placed on the spectrum above 10 GHz because of the advantages offered in antenna gain and reduced interference.

Initially, a technology base will be established for an earth-to-space link operating in the band between 10 GHz and 100 GHz. The theory of attenuation due to the absorption, scattering and refraction processes is briefly summarized for the purpose of determining the losses which result from atmospheric gases, precipitation and clouds. State-of-the-art technology in pertinent millimeter wave components is also reviewed. In addition, the various antenna types which may be used for satellite communications and the limitations on these antennas is considered. Emphasis is placed on physically large parabolic reflectors since these have been used for radio astronomy and give rise to gain which, hitherto, did not seem possible at the lower microwave frequencies. This factor makes them particularly attractive as ground based terminals for passive communication satellites.

Propagation Parameters

When propagating through the atmosphere at millimeter wavelengths, in addition to the free space losses encountered, an attenuation is experienced as a result primarily of atmospheric gases, precipitation and clouds. The degree of attenuation resulting from these mechanisms varies as a function of frequency with the longer wavelengths also being subjected, but to a lesser extent. Oxygen and water vapor, the principal atmospheric gases contributing to the attenuation, absorb microwave energy while liquid water, in the form of rain and clouds, attenuate through both absorption and scattering.

Oxygen and water vapor are the prime attenuators of an electromagnetic wave propagating through a clear atmosphere. The attenuation at some wavelengths is so extreme that the atmosphere is made opaque to radio waves. Molecules of oxygen have permanent magnetic dipole moments and those of water vapor have electric dipole moments. As a result of these moments there is a large number of energy transitions that produce maximum values of absorption at millimeter frequencies. Below 100 GHz, water vapor has a single resonance which occurs at a frequency of about 22 GHz while a cluster of oxygen lines exist at 60 GHz. The shape of the water vapor resonance curve is a function of atmospheric temperature, pressure and the partial pressure of water vapor. Oxygen resonance lines are a function of atmospheric temperature and pressure.

The peak absorption bands are shown in Figure 31 which is typical of curves depicting the total atmospheric attenuation resulting from atmospheric gases. In the plot a standard atmosphere was assumed. As can be seen low absorption bands or windows exist slightly above 30 GHz and 90 GHz. It is these windows which are of interest in the implementation of earth to space links. The regions of high loss are of significance where propagation through the atmosphere is not required, such as in satellite to satellite communications. The value of using these bands for transmission outside of the earth's atmosphere

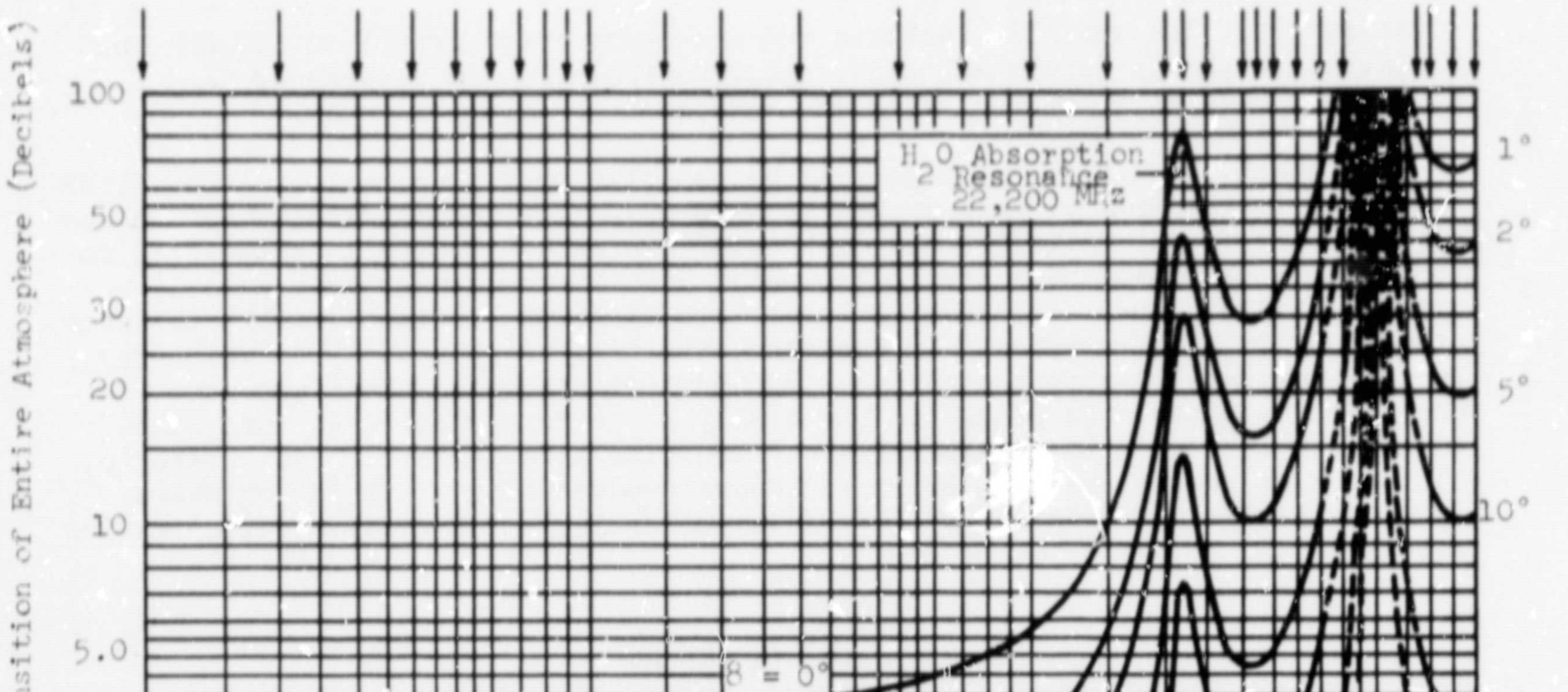


Figure 31. Radar attenuation for traversal of entire troposphere at various elevation angles, applicable for targets outside the troposphere. Does not include ionospheric loss, which may be significant below 500 MHz in daytime. Arrows at top margin indicate frequencies at which calculations were made.

STANDARD ATMOPSHERE

Source: L. V. Blake, "Tropospheric Absorption and Noise Temperature for a Standard Atmosphere," Digest of The IEEE PTGAP 1963 International Symposium.

stems partially from the private links which can be established. Secure links are possible, particularly in the 60 GHz region, because the high attenuation assures against reception on the ground.

The degree of attenuation experienced is dependent upon the elevation angle. Since at lower elevation angles, more of the atmosphere is traversed, the attenuation experienced is considerably greater than that experienced by an electromagnetic wave passing vertically through the atmosphere. This fact, in addition to an increase in problems associated with characteristics such as refraction, and apparent sky temperature limits the minimum useful elevation angle.

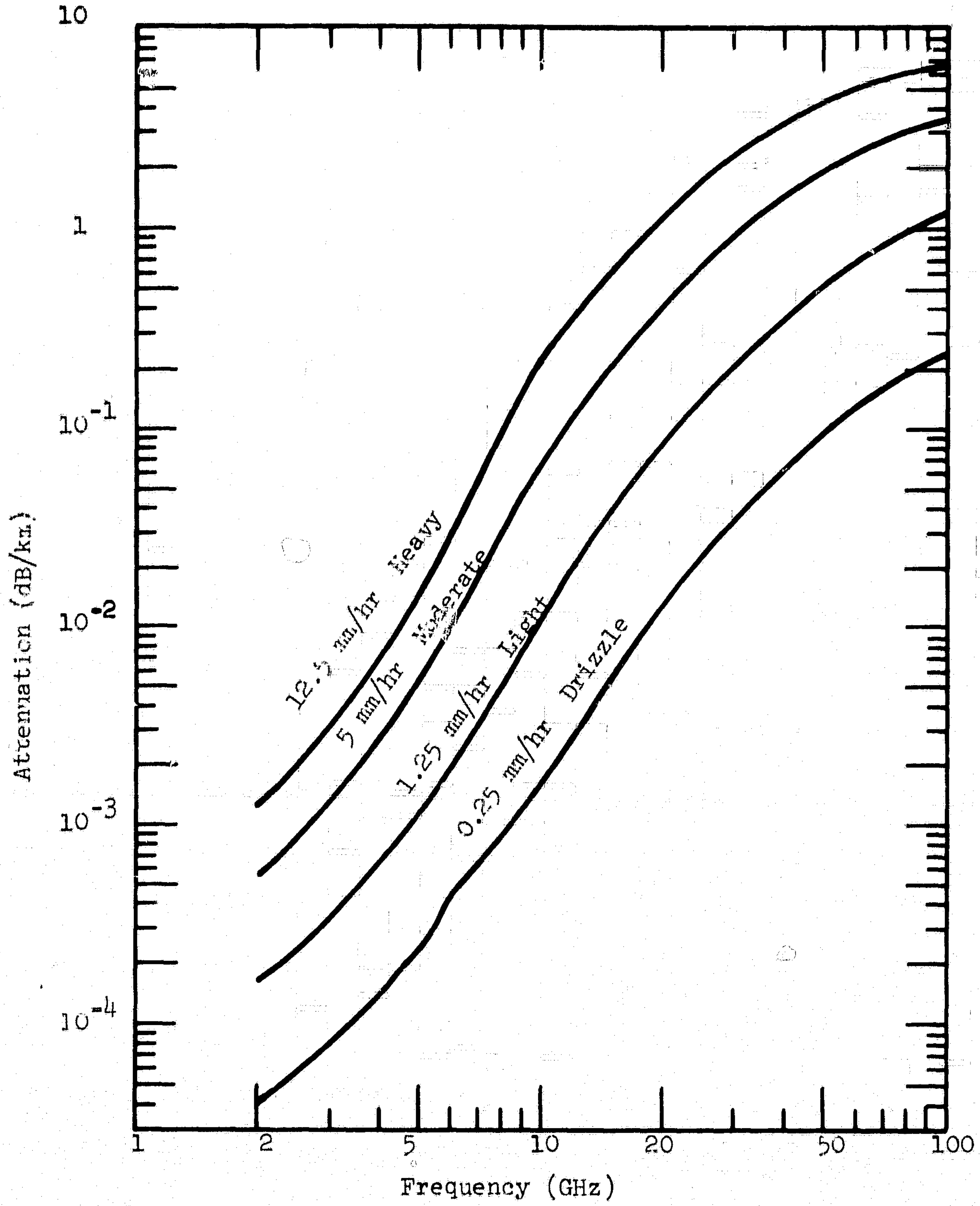
Precipitation and clouds are atmospheric constituents which can add to the attenuation of a clear environment. At millimeter frequencies, the losses caused by these constituents are higher because of the increased particle size with respect to a wavelength. Attenuation due to both absorption and scattering has been expressed in equation form by Mie, 1908 (Reference 6). However, if droplets of condensed water in the form of rain, fog, clouds, etc. are very small compared to a wavelength, the Rayleigh approximation may be used. For the frequency range of interest, droplet size is such that the latter can be used to characterize the attenuation due to all but rain, where the Mie scattering solution is required.

To fully assess the attenuation associated with rain, the rate of rainfall must be considered. Attenuation constants as a function of frequency for various rainfall rates are plotted in Figure 32. At 35 GHz in a heavy rain a 3 db/km loss is incurred and approximately a 1 db/km loss is experienced in a moderate rain. The effect of such losses on communication and the necessity for providing sufficient compensation has been demonstrated at lower frequencies on presently operating satellites. However, the inclusion of such a margin must reflect the location in which the system operates to prevent waste of power. To give an indication of rainfall rates, Figure 33 is included. This is a plot of time distribution of rates for certain typical climate areas. Also included is the time distribution of attenuation for these areas.

Attenuation due to ice particles (hail) or dry snow tend to be relatively low when compared to rain of equal water content. However wet snow can be a much stronger attenuator than water droplets of the same volume.

The nature of attenuation in clouds and fog is similar to that of rain with droplet size generally being less than that of rain. Loss is primarily due to absorption of microwave energy rather than scattering because of the small cross section of the particles. Water content is generally characterized by visibility. Plotted in Figure 34 is the attenuation, as a function of frequency, for heavy and light fog.

In the above paragraphs the attenuation due to atmospheric gases, various forms of precipitation and fog has been presented by typical plots. The difficulty in trying to relate these values to the total attenuation through



Ref: Medhurst, "Rainfall Attenuation of Centimeter Waves: Comparison of Theory and Measurement," PGAP-13, July 1965.

Figure 32. Rainfall Attenuation - Temp 20 deg Kelvin

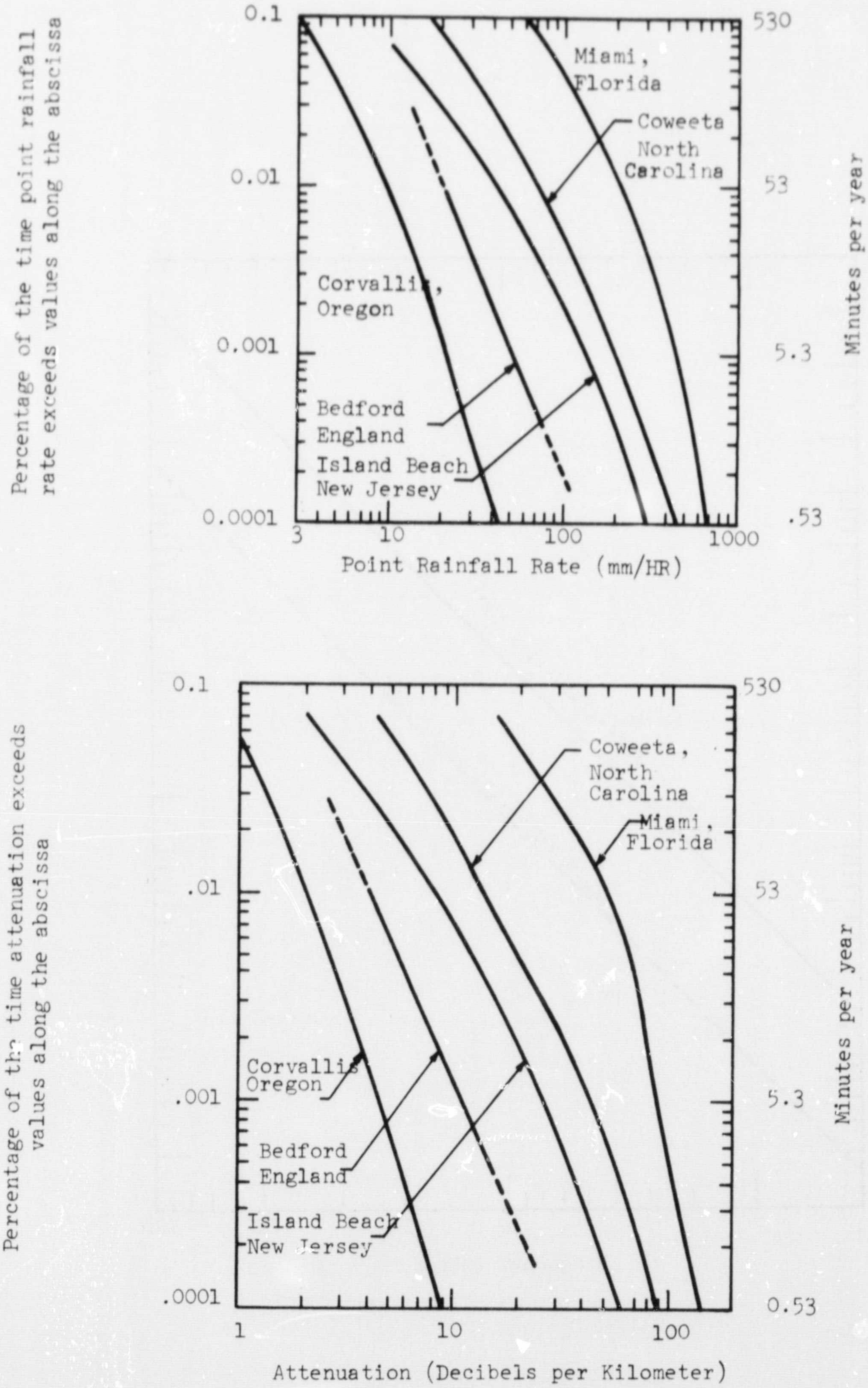


Figure 33. Rainfall and Its Attenuation at 30 GHz

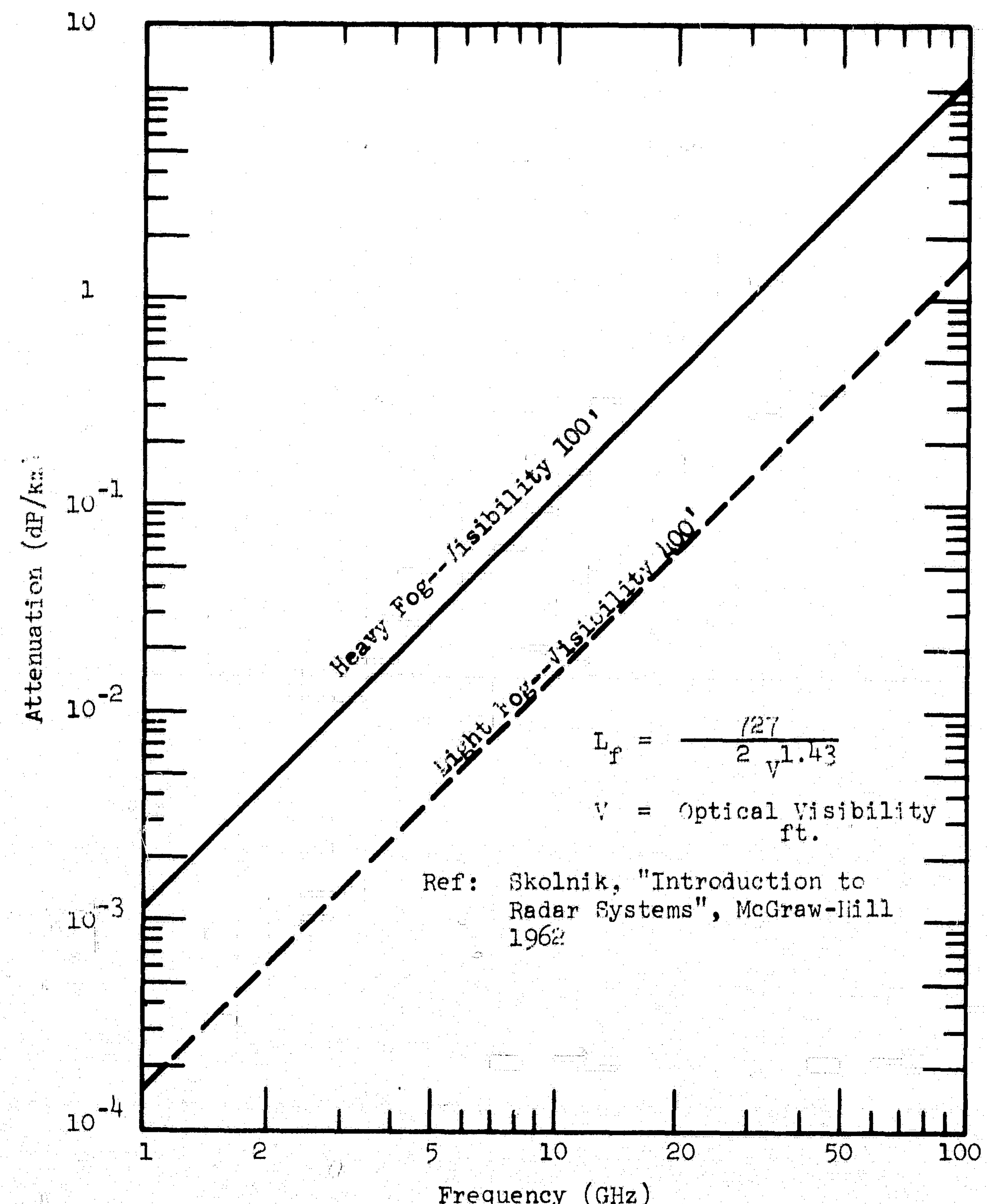


Figure 34. Fog Attenuation - Temp 18 deg Kelvin

the atmosphere lies in the selection of a model to represent the atmosphere. Models vary between geographical areas and in fact an appropriate model for one location may differ from day to day due to the variability of the weather and extremes in the weather. These variations result in signal fading which presents limitations on a millimeter system.

Another important characteristic of millimeter wave propagation which causes fluctuations in signal strength is that of refraction. Refraction is a bending of an electromagnetic wave upon passing from one medium to another caused by a resulting change in velocity. The index of refraction due to the earth atmosphere is given for microwave frequencies by the equation

$$(\eta - 1)\, 10^6 = 77.6 \frac{P}{T} + 3.73 \times 10^5 \frac{P_{WV}}{T^2}$$

where

η = index of refraction

N = $(\eta - 1)\, 10^6$ = refractive modulus

P = air pressure (millibars)

T = temperature (°K)

P_{WV} = partial pressure of water vapor (millibars)

For the standard atmosphere η decreases with height. A wave passing from a lower to an upper layer is bent away from the zenith. Because of this, the apparent position of a source outside the lower atmosphere appears at a slightly greater elevation angle than the true angle. For high elevation angles this difference is negligible but for low angles it must be compensated for. This can be accomplished by changing the antenna angle. A plot of the correction necessary for various elevation angles is given in Figure 35.

System Noise Temperature

The performance of a satellite communication system is dependent upon the noise temperature of the system. Two factors contribute to system noise; (1) space and environmental noise and (2) losses from the antenna input terminals to the output of the receiver. System noise temperature may be expressed as

$$T_i = T_a + T_o\,(\overline{NF} - 1)$$

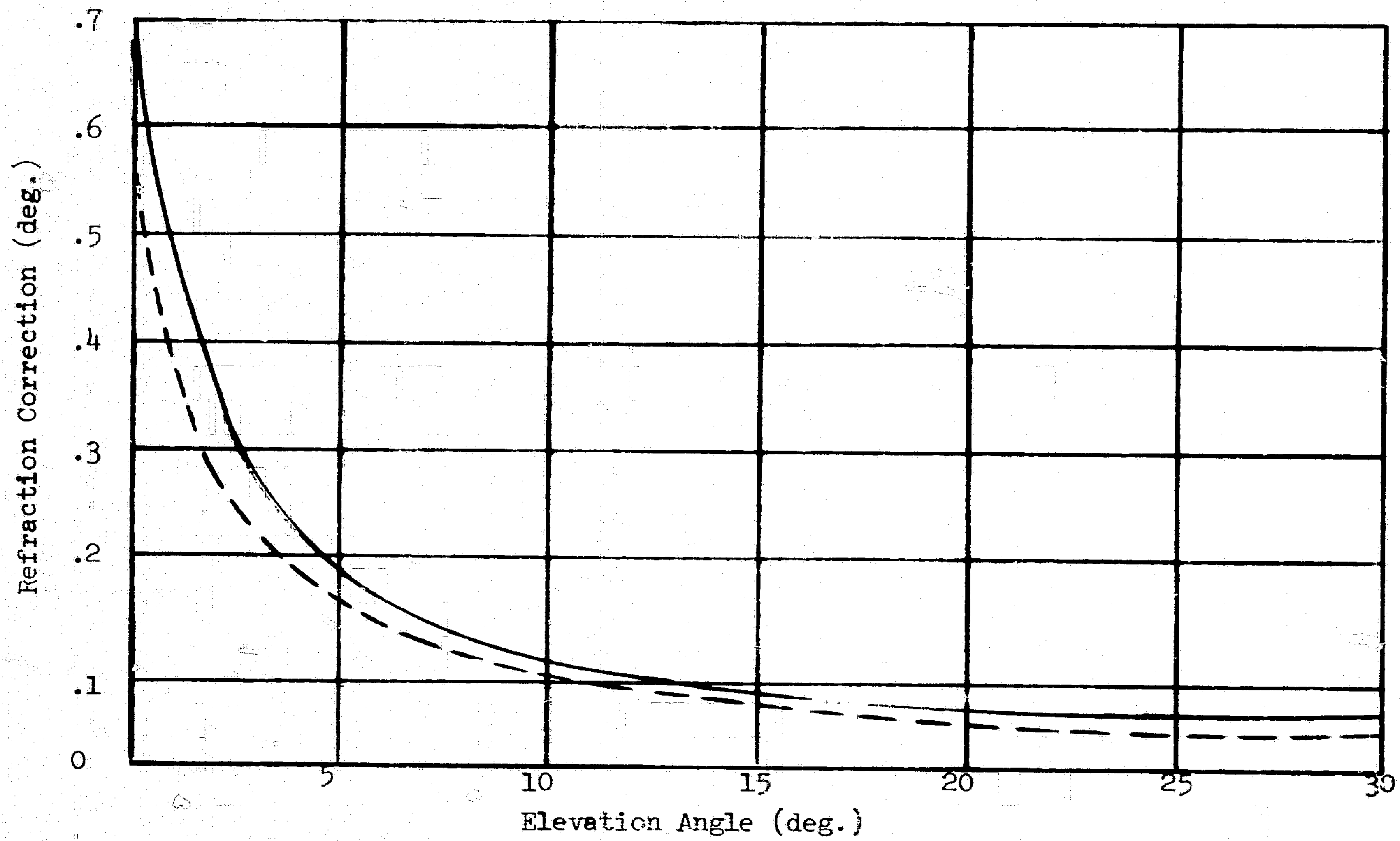


Figure 35. Refraction Correction Vs Elevation Angle

Altshuler, Edward W., "Earth to Space Communications at Millimeter Wavelengths" AFCRL-65-566, Aug. 1965, Physical Science RES. Papers, No. 125

where

T_a = effective antenna noise temperature

T_o = 290° K (reference temperature)

$\overline{NF}$ = receiver noise figure

The effective antenna noise temperature generally represents cosmic noise, solar noise, atmospheric noise and ground noise. Cosmic radiation, which accounts for most of the effective antenna noise temperature below 1 GHz, is negligible at millimeter frequencies and solar noise is not a problem unless the receiving antenna is pointed directly at the sun or moon. The primary contributors to T_a at the frequencies of interest are the atmosphere constituents which, in addition to being attenuators of microwave energy, are emitters of electromagnetic energy. This emission by atmospheric gases and precipitation is referred to as sky noise.

The total noise received from the above sources, in addition to being frequency dependent, is a function of the antenna pointing angle, antenna beam pattern and variations in the sources themselves. Hence, T_a may be determined only in a statistical manner. Further, without knowledge of the specific antenna pattern, typical side and main beam lobes must be assumed. Much of this work was done by Blake (Reference 7) and it is through his analysis that the effective antenna noise temperature was determined. Figure 36 indicates T_a as a function of frequency for main beam elevation angles of 10 and 30 degrees. The plot indicates the effective noise temperature in a clear atmosphere and how this noise temperature is influenced by rain and fog.*

System noise temperature is also a function of the receiver noise figure. Figure 37 shows the noise figure of a crystal mixer and uncooled parametric amplifier that might be used in satellite communication. Since data above the frequency band presently used in most satellite communication systems is scarce, the noise figure for uncooled parametric amplifiers above 10 GHz has been projected from other data. Noise temperatures lower than that shown are realizable with cooled paramps and masers but only at considerably more expense both in the initial purchase and operation and maintenance. Further, current bandwidth capabilities of masers and parametric amplifiers are less than 500 MHz in the frequency range up to 40 GHz. However, since ultimately communication satellite earth stations will require receivers with 500 MHz or more of bandwidth, it is felt that such a paramp as well as masers, will be developed.

Transmitter Power

A major factor in the successful implementation of a passive satellite system is the ground terminal ERP. Two elements contribute: antenna gain and

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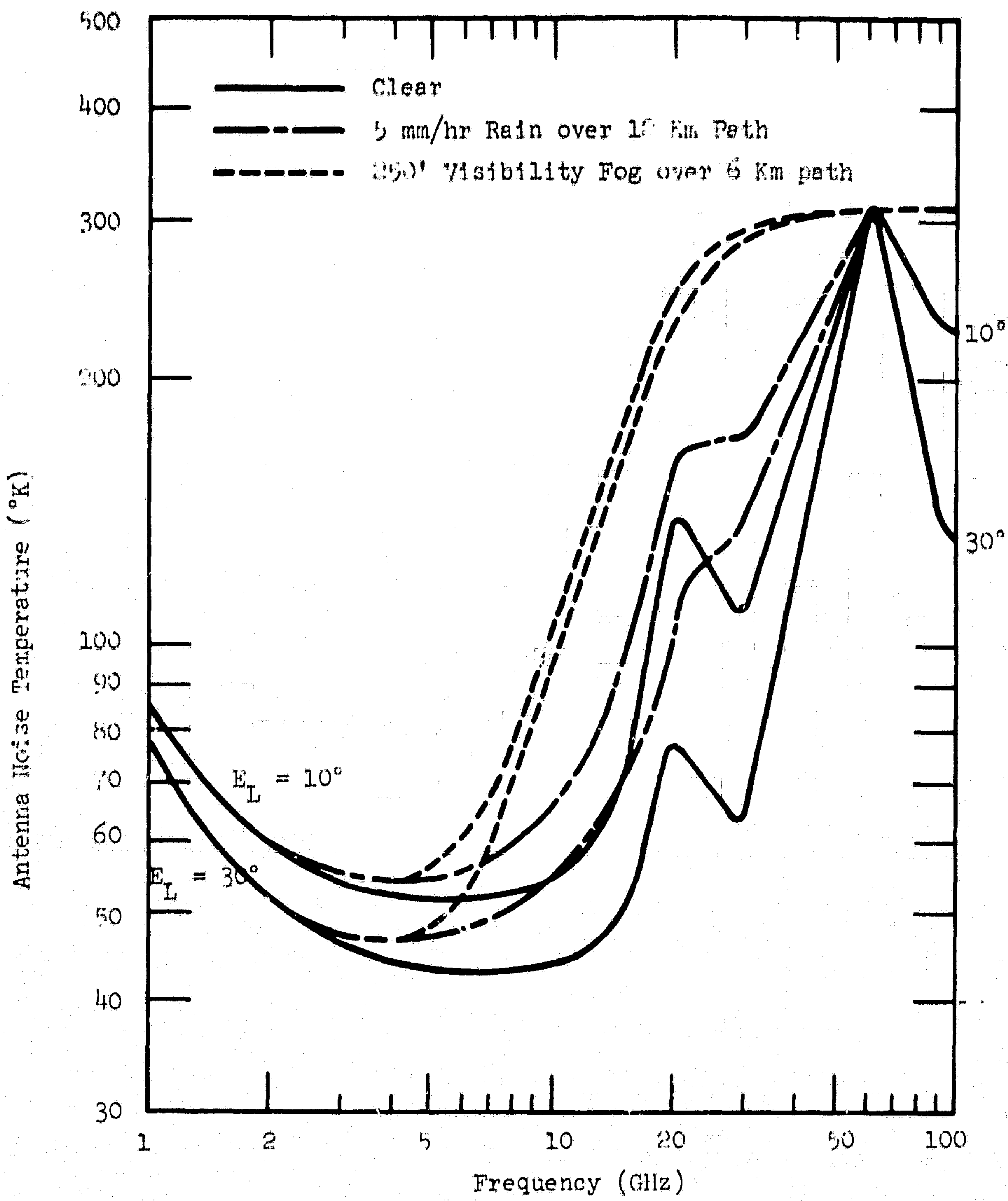
*5 mm/hr of rain over a 12 km propagation path and 250' visibility for over a 6 km propagation path were assumed.



Ref: **Blake**, "Antenna & Receiving-System Noise Temperature Calculation," NRL Rpt. 5668, September 1961.

Hogg, "The Effective Noise Temperature of the Sky," Microwave Journal, March 1960.

Figure 36. Effective Noise Temperature

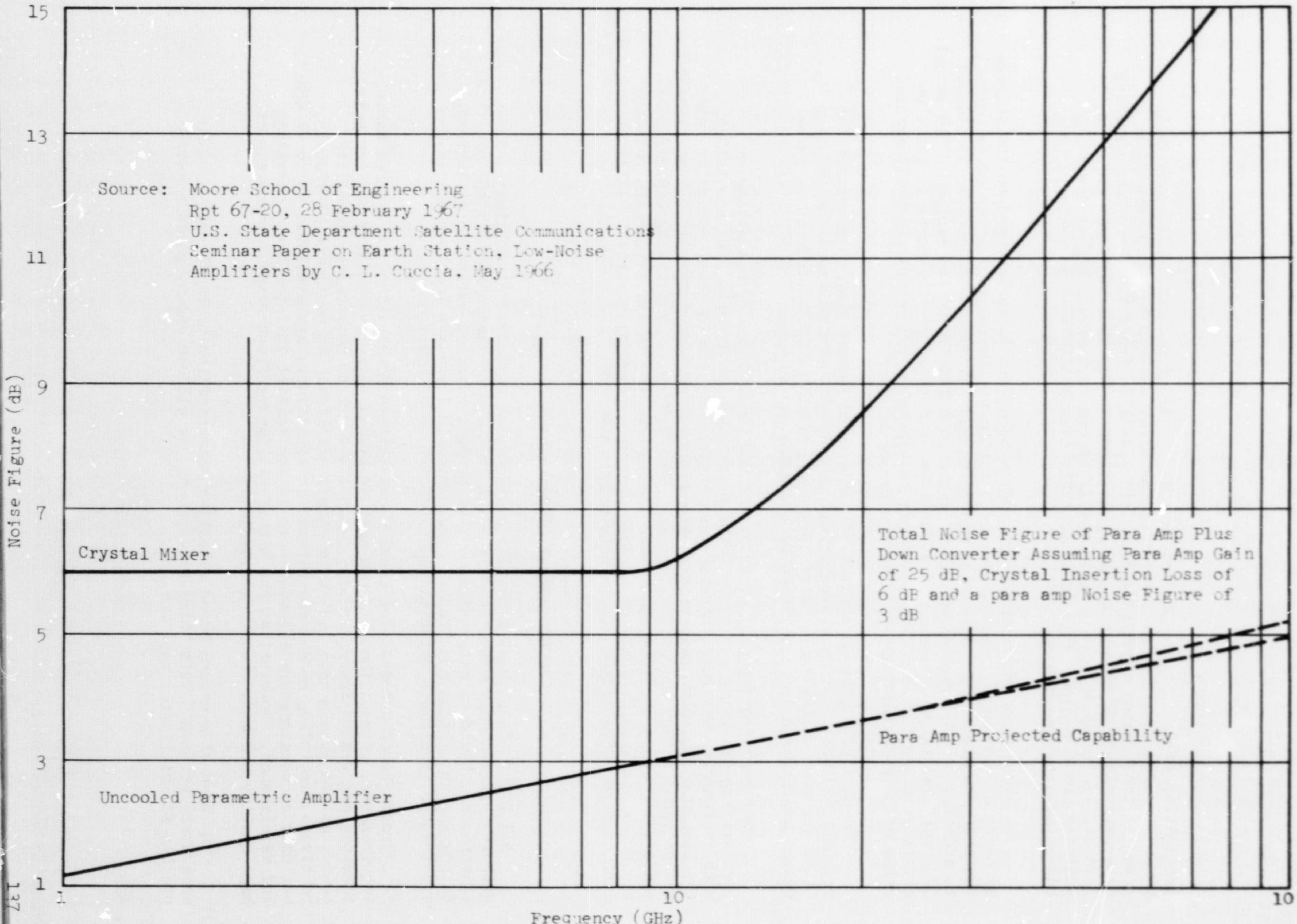


Figure 37. Noise Figure of Typical Satellite Communication Receivers

transmitter power. Figure 38 indicates the state-of-the-art average available power for electron tubes at various frequencies. As can be noted, available power at frequencies above 8 GHz drops off rapidly. These tubes are now operating at an efficiency of 35 percent, which is close to the ultimate limit of 40 to 45 percent. To increase power substantially beyond that shown, higher operating voltages are required. This would probably make possible an increase in power output by a factor of five.

The power from the transmitter tube or tubes has to be conveyed to the antenna by means of waveguide. Hence, when considering available transmitter power output, the power handling capacity of the waveguide and its components must be considered in addition to the transmitter tube. Shown in Figure 38 is the maximum "Theoretical CW Power" rating of waveguide as a function of frequency. The curve is based on a voltage breakdown of 15 kilovolts per centimeter which is the generally assumed value of 30 kv/cm modified by a safety factor of two.

The plot of Figure 38 applies to pulse power rather than cw power for two reasons; (1) breakdown is a statistical phenomenon and the longer the RF power is on the more chance there is of breakdown, and (2) high average on cw power causes heating and the likelihood of breakdown is enhanced.

Power handling capacity of waveguide may be improved by evacuating or pressurizing the waveguide or by using over-moded waveguides. For the latter both rectangular waveguide several wavelengths long and circular waveguide using the low loss TE_{01} mode have been proposed and tested experimentally but at present are not used in any operational system. The difficulty is avoiding higher-order modes which cause spurious resonances increasing the insertion loss and reducing the power handling capacity at certain sharply defined frequencies. It is also difficult to build components in over-moded waveguides.

Ground-Based Millimeter Wave Antennas

All types of antennas presently known may be exploited at millimeter frequencies but the microwave trend is being followed in that virtually all practical antennas are based on geometrical optics design, commonly parabolic reflectors, Cassegrainian systems and lenses. The choice is largely a function of the application, available material and precision of manufacture.

Ground-based antennas for passive satellite communications have three basic requirements. First, the antennas must be highly directive to give maximum performance and reduce interference. Secondly, a ground antenna for satellite communication should have low noise characteristics. As mentioned previously, receivers, including masers and parametric amplifiers, are available up to 40 GHz but only at considerable expense, both in the initial investment and operation and maintenance. However, at the higher millimeter frequencies, components of high quality are less readily available.

The beam of a ground based satellite communication terminal must also be accurately pointed. This third requirement, as will be shown, poses a severe problem for millimeter wave antennas.

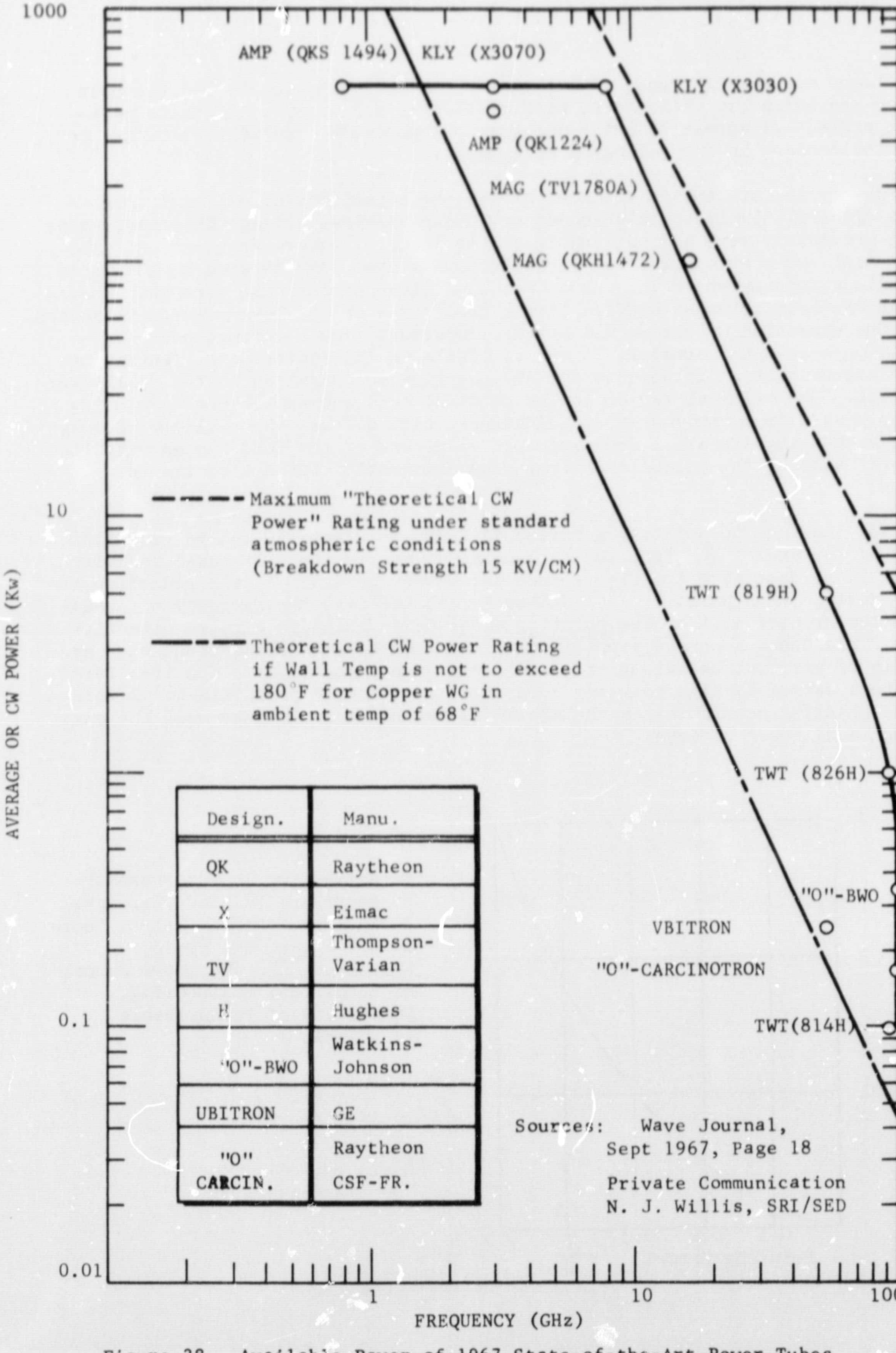
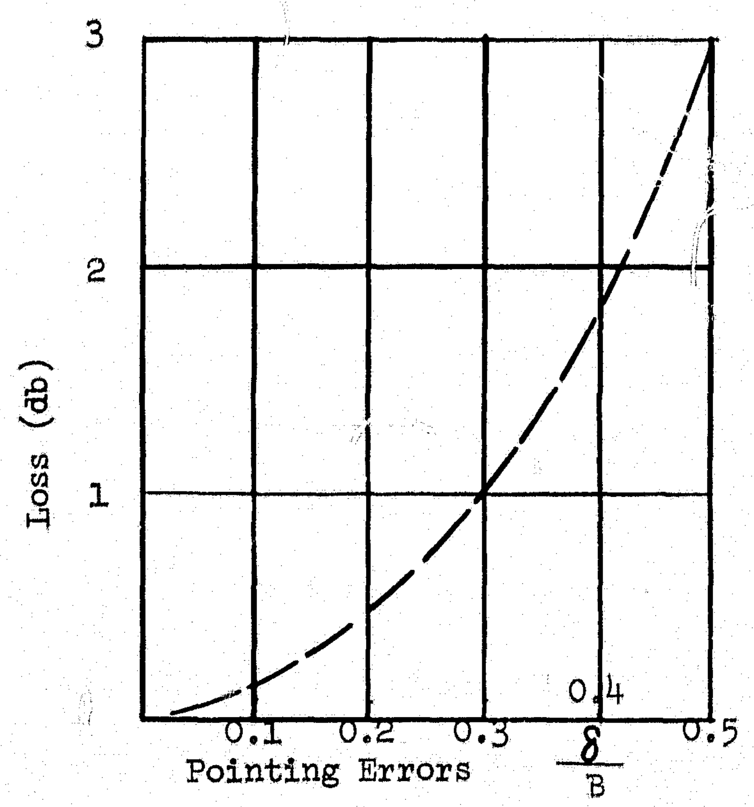


Figure 38, Available Power of 1967 State-of-the-Art Power Tubes

There are several types of antennas potentially applicable but the most common are parabolic reflectors, horn reflectors and arrays. Of these parabolic reflectors appear to offer the greatest potential and will therefore be of prime concern in the following paragraphs.

Use of the millimeter spectrum offers the capability of extremely high gains with relatively small antennas or, using physically large antennas, gains which previously were not obtainable at the lower microwave frequencies. The gains achievable with parabolic reflectors have been demonstrated in the field of radio astronomy where they have been used with considerable success. The design of these antennas differs little from those of the lower microwave region. With the exception of errors which cause departure from a uniform phase distribution across the aperture, there is little in the factors contributing to inefficiency that would suggest any disadvantage to operating in the millimeter spectrum. One critical factor is the pointing accuracy achievable. Pointing errors result from environmental conditions which distort the reflector surface thereby changing its axis, from improper alignment of the feed system with the best fit axis of the parabola or from wind and gravity effects on the feed system.

The loss due to pointing accuracy is shown in Figure 39 and is given in terms of the angle δ from the antenna boresight to the half-power beamwidth, B. It is evident from the figure that the lower the desired gain reduction the lower must be the ratio δ/B. Stated in another way, the narrower the beamwidth the greater must be the pointing accuracy to maintain a given directivity loss. This poses a severe problem for millimeter wave antennas since they are capable of narrower beamwidths for apertures of reasonable size and therefore must have extremely high pointing accuracies to maximize performance. Errors due to pointing accuracies can be minimized as frequency is increased but only through additional expense.



"Investigation In and Research of Aerospace Related Microwave Technology," Final Report, Moore School Report No. 67-20, February 1967, The Moore School of Electrical Engineering, University of Pennsylvania PP 379-413

Figure 39. Point Error Loss

Another constraint imposed on peak gain at millimeter frequencies is that due to surface defects. For a given reflector, gain increases as a function of the frequency squared at the lower frequencies. However, at higher frequencies, gain deteriorates as the tolerance effects begin to predominate and limits the upper frequency at which the antenna is usable. Maximum gain of an aperture as a function of surface tolerance occurs when $\lambda_m = 4\pi\epsilon$, where a tolerance loss of 4.3 db with respect to a perfect reflect, is incurred (Ref. 8). At this frequency gain is given by

$$G_m = \frac{\eta}{43} \left(\frac{D}{\epsilon}\right)^2$$

Here η represents all losses except those due to ϵ, the effective reflector surface tolerance.

It is evident that the frequency range over which the antenna can operate and the maximum gain possible can be improved by increasing the surface precision. While technology is capable of very precise tolerances the big obstacle is cost. A tradeoff between performance and cost is usually made. By the Rayleigh criterion, parabolic surface errors of less than $\lambda/32$ are desired and generally achieved (Ref. 9). For Cassegrainian systems, tolerances must be divided between the reflector and the subreflector and is usually done proportionally. (Ref. 9)

To realize the surface tolerance given by the Rayleigh criterion, or any λ/a, requires more rigid manufacturing techniques at millimeter wave frequencies than does a similar tolerance at lower frequencies. Manufacturing techniques have, however, been devised which make possible the necessary precision. Machined aluminum castings appear to be the best of the present state of the art. Tolerances can also be achieved by metal spinning, die casting or stamping and by liquid spinning techniques. The choice is primarily a function of cost, volume and reflector size. (Ref. 9)

Commonly parabolic reflectors are circular with either a focal point feed or Cassegrainian feed system. At millimeter frequencies, the tradeoffs between the two are the same as at the lower microwave frequencies. The focal point feed has a cost advantage in that the Cassegrain system requires at least one additional piece of equipment, the subdish. Additional costs must be entailed for the more stringent tolerance and fabrication requirements and for careful integration of the paraboloid, feed and subdish, which is necessary in a Cassegrainian feed or suffer the consequences of poor performance. Those latter factors influence phase errors which result in peak gain reduction.

On the other hand, a dual reflector eliminates losses which are inherent in long transmission lines of focal point reflectors. These losses can be of significance in large antennas and/or in antennas operating at high frequencies. In addition, the mechanical stability of the Cassegrainian feed system which results when the feed is located near the vertex of the parabola, permits accurate pointing of the antenna. Because of their narrow beamwidths, this is important to millimeter wave antennas. In general, the pointing accuracy of the Cassegrainian system is better than the single reflector antenna since the feed system associated with the latter is usually heavier.

Gregorian antenna systems may also be used as ground based satellite communication terminals. Many of the advantages and disadvantages of the Cassegrainian system will be evident in the Gregorian system. However, the mechanical problems of accurate support of the subreflector is more severe on the Gregorian system.

The above discussion tends to indicate that parabolic reflectors are feasible for ground terminals in a passive system at millimeter wavelengths. Structural limitations ultimately impose limitations on electrical performance as higher operating frequencies are used. Where the limit is reached depends largely on the finances available per dB increase in gain.

Parabolic reflectors are presently being employed at millimeter frequencies, particularly in the field of radio astronomy. Typical of these are the ones listed in Table XXXVII. For each antenna there is included the surface accuracy, pointing accuracy and the maximum operating frequency.

Each of these facilities could be used in a passive satellite system but their degree of usefulness would depend on orbital parameters. For example, because of slow drive and slew rate capabilities, not all facilities are capable of tracking a low orbit target. However, these same terminals could be of value for higher orbit satellites.

Another type of antenna which could be utilized throughout the region of interest is the horn. Manufacturing precision is no problem and with proper tapers and exact flare angles, all types of illumination may be produced. Horns are free of the shadowing and spillover losses which are problems with parabolic reflectors. The horn at Andover, Maine had an efficiency of 77 percent. However, as is evident by this structure and its associated equipment, horns for the desired purpose are complex and costly.

Array antennas can, in principal, be designed and constructed for any portion of the frequency and have been proposed for satellite communications at lower microwave frequencies. (Reference 10) They are attractive for the following reasons:

(1) Their capability to generate many beams simultaneously enables them to handle many satellites.

(2) Their almost instantaneous handover capability.

(3) Their design flexibility in adjusting sidelobe levels.

(4) Their growth potential in that additional links may be introduced by adding modular signal processing networks to a common array.

Table XXXVII. Typical Parabolic Reflectors Employed at mm Frequencies

Facility	Location	Type of Antenna	Antenna Dia (ft)	Gain at 35 GHz (db)	Surface Tolerance (in. rms)	Maximum Frequency (GHz)	Pointing Accuracy (Minutes)	Beamwidth at 35 GHz (minutes)	$\frac{\delta}{B}$	Types of Mount
U. of Texas	Austin, Texas	Feed at Focus	16	62.5	0.002	472	0.6	7.5	.08	Equatorial
Aerospace	El Segundo, Calif	Cassegrain	15	62	0.0018	525	0.33	7.8	.04	Equatorial
Lincoln Lab	Lexington, Mass.	Modified Cassegrain	28	67.4	0.008	120	5	4.4	1.1	AZ-EL
Haystack	Tungsboro, Mass.	Cassegrain	120	77	0.025	38	0.3	1.0	.3	AZ-EL
AFCRL	Waltham, Mass.	Cassegrain	29	67.5	0.007	135	0.9	4.3	.2	AZ-EL
North American	Columbus, Ohio	Cassegrain	30	67.5	0.012	80	0.33	3.9	.08	AZ-EL
GSFC	Greenbelt, Md.	Cassegrain	15	-	-	-	3	7.8	.39	AZ-EL
NARO	Kitt Peak, Ariz.	Cassegrain	36	69.5	0.004	240	-	3.3	-	AZ-EL
NRL	Maryland Pt., Md.	Cassegrain	85	--	0.045	21	-	-	-	Equatorial
DRTE	Ottawa, Canada	Cassegrain	30	65	0.022	43	0.6	-	-	AZ-EL
Sylvania	Buffalo, N. Y. (Transportable)	Cassegrain	12	61	0.003	315	-	-	-	AZ-EL
USNEL Stiff Cliff	San Diego, Calif.	Feed at Focus	60		0.025	38	-	-	-	AZ-EL

However, no arrays have as yet been manufactured which have the high gain capability required by earth-based satellite communication terminals.

Arrays of horns and reflectors are more promising than those of individual radiators such as dipoles or slots. Arrays using horns have been exploited at about 70 GHz (Ref. 10). In one system each horn has a block of ferrites in its aperture and its beam may be electronically shifted. Ferrite phase shifters are also used in the feed line to each horn radiator. The success of such a system for the millimeter spectrum will depend on the development of ferrites or other phase shifting materials.

Relative Performance

The evaluation of a passive system operating at frequencies other than X band, will be accomplished on the basis of maximum capacity per terminal. To this end, transmitter power and receiver noise temperatures which are state-of-the-art and maximize signal-to-noise ratio, are used. The antenna utilized at the base frequency for the transmit and receive station in the system is the 159-foot reflector. From the standpoint of performance and cost this is the optimum antenna for this frequency. The previous paragraphs show parabolic reflectors are also quite feasible for higher frequencies and as such will be used herein. To determine optimum gains of these antennas for the 10 to 100 GHz range, size and surface tolerance are varied in a manner similar to that used in selecting the base antenna. However, to provide a more meaningful evaluation, the optimization is achieved at a fixed cost of $11.2 million as determined by the referenced antenna.

The signal-to-noise ratio at the input of an IF amplifier of a receiving station in a passive satellite system may be defined as:

$$\frac{S}{N} = \frac{P_t G_t G_r \lambda^2 \sigma}{(4\pi)^3 R_t k T_i B L_T R_r} \qquad (65)$$

where

P_t = Transmiter Power (Watts)

G_t = Gain of the transmitting antenna

G_r = Gain of the receiving antenna

λ = Wavelength

σ = Satellite cross-sectional area $\approx \pi r^2$, r = radius of curvature of satellite

R_t = Range from the transmitter to the satellite (meters)

R_r = Range from the receiver to the satellite (meters)

k = Boltzman's Constant - 1.38×10^{-23} Joules/°K

T_i = System Noise Temperature

B = Receiver effective noise bandwidth (r/2)

L_T = System Loss

Rewriting Equation (65)

$$\frac{S}{N} = \frac{\sigma}{R_t^2 \; R_r^2} \; f(\lambda)$$

where:

$$f(\lambda) = \frac{P_t G_t G_r \; \lambda^2}{64 \; \pi^2 \; kT_i \; GL_T} \qquad (66)$$

are the quantities which are frequency variant. To provide a comparison between the link capacity at the base frequency and that of other frequencies, each of these must be examined and their net effect on the signal-to-noise ratio determined.

For previous calculations at the base frequency, a 159-foot parabolic reflector was chosen as the ground terminal. Surface tolerance of the antenna was ±0.057 inches and, by methods explained previously, its cost was $11.2 million. Plotted in Figure 40 is the gain of this antenna as a function of frequency. The dashed-line is representative of gain as given by:

$$G = 0.54 \left(\frac{\pi D}{\lambda}\right)^2 e^{-\left(\frac{4\pi d}{\lambda}\right)^2} = 5.5 \; f^2 \; D^2 \; e^{-1.132 \; f^2 \; d^2} \qquad (67)$$

where

D = diameter of the antenna (feet)

f = frequency (GHz)

d = tolerance (inches)

and the solid line, the gain of a perfect parabolic reflector (i.e. $d = 0$). While the referenced antenna could be used efficiently at lower frequencies, to consider its use above 16 GHz would be pointless because of the rapid deterioration in gain as the tolerance effects begin to predominate. The

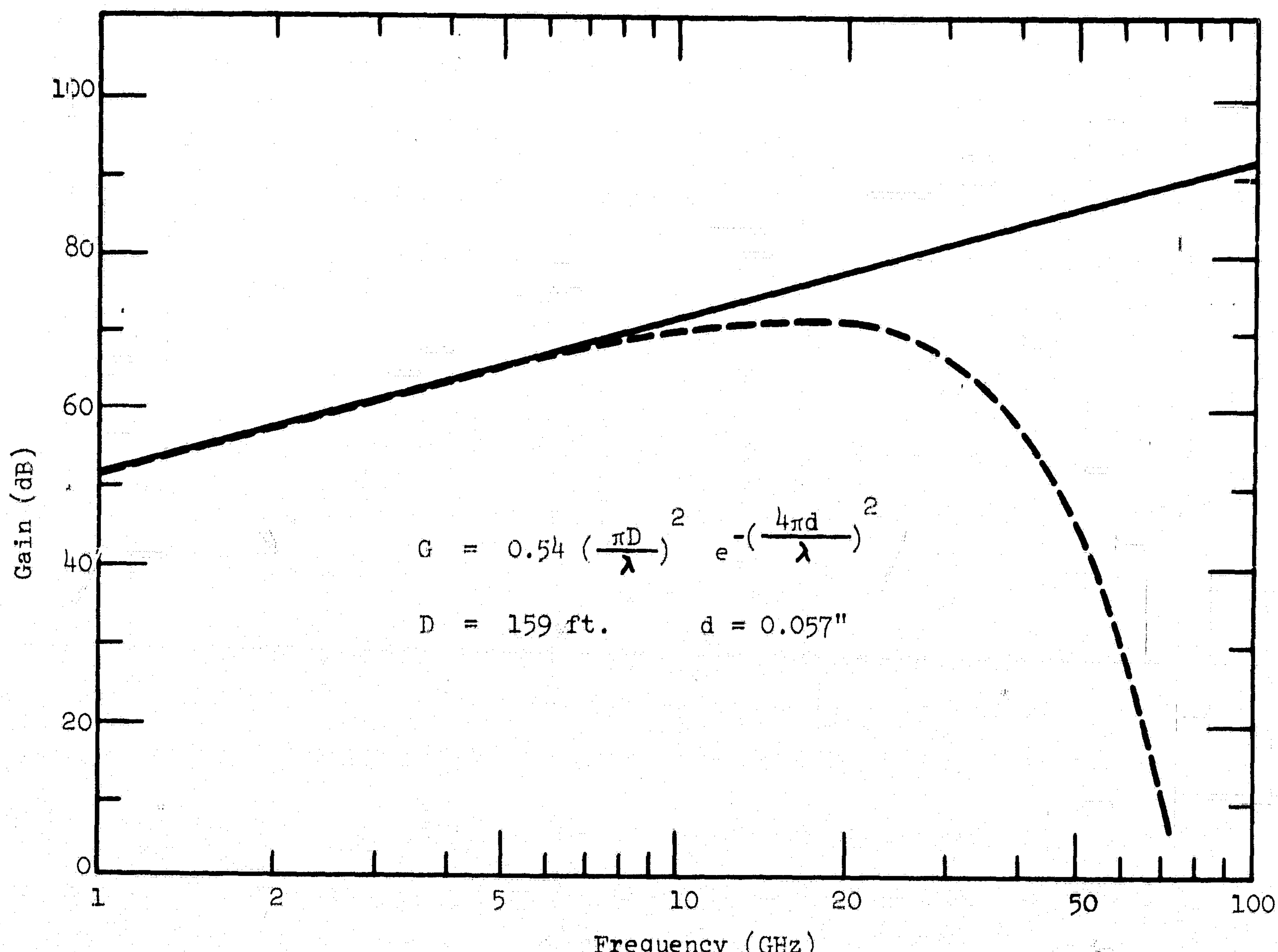


Figure 40. Antenna Gain for Parabolic Reflector of Dia. 159 Ft., Tol. 0.057"

frequency range over which the antenna is usable could, of course, be increased by increasing surface precision. This, however, would require additional cost and to demonstrate a true improvement in the signal-to-noise ratio, if in fact such an improvement is possible, antenna performance must be improved without increasing cost. As will be shown, this can be accomplished by decreasing the antenna diameter and tolerance in the proper ratio to obtain optimum gain as frequency is varied.

From previous consideration, the basic antenna tolerance and diameter are related by the equation*

$$d = 4 D^2 \times 10^{-6} \qquad (68)$$

Where tolerances are given by equation (68), the relationship between cost and diameter is **

$$C = 28.8 D^{2.42} \quad \text{(For antennas with diameters near 100 foot or larger)} \qquad (69)$$

Decreasing the antenna diameter, therefore, improves surface tolerance and decreases cost but at the expense of gain. By departing from the basic tolerance, gain can however, be improved. Any such departure will affect the cost as follows:

If d_1 is the actual antenna tolerance and is related to equation (68) by the expression:

$$d_1 = \frac{1}{b} d = \frac{1}{b} (4 D^2 \times 10^{-6}) \qquad (70)$$

then the total cost becomes

$$C_{d_1} = Cb = 28.8D^{2.42} \times b$$

Holding the $11.2 million cost of the referenced antenna constant, the relationship between antenna diameter and the tolerance factor, b, for optimum gain, is found by differentiating equation (67) w.r.t. antenna diameter and setting the result equal to zero. The resulting equation has been found in Appendix F to be:

$$b = 8.94 \times 10^{-6} D^2 F_{GHz}$$

*Antennas considered are without radomes
**Includes structure and the drives and control

Knowing b and D, the optimum gain as a function of frequency may be found and is plotted in Figure 41. As may be noted, additional gain over the referenced antenna can be realized at all frequencies with the increase being more marked at frequencies above 8 GHz.

The gain versus frequency relationship plotted in Figure 41 will be used in determining signal-to-noise ratios. The other frequency varying factors involved in equation (66) were discussed in some detail in previous paragraphs. In general, while substantial increases in antenna gain can be realized in the millimeter range, losses encountered through the atmosphere are greater, system noise temperature is higher and available transmitter power is less. Below 8 GHz, losses are less than that encountered at the base frequency but so, also, is antenna gain. The net effect of $f(\lambda)$ is indicated in Tables XXXVIII and XXXIX and plotted in Figure 42. Values were determined from equation (66) using maximum available transmitter powers and minimum receiver noise temperatures previously obtained. The following additional assumptions were made:

(1) The receiver bandwidth was 500 MHz

(2) Parametric amplifiers in the 2 to 100 GHz frequency band exist with bandwidth of 500 MHz and gain of 25 db. The crystal detector has a nominal insertion loss of 6 db. The post amplifier has a nominal noise figure of 3 db.

(3) The transmitter and receiver operate at approximately 30° elevation angle.

(4) For comparison in a rain environment, the rain rate is 5 mm/hr and falls over 12 km of the propagation path.

(5) For comparison in a fog environment, the fog limits to 250 feet over 6 km of the propagation path.

(6) The transmission line network from the transmitter tube(s) to antenna is designed to handle the power produced by the transmitter tube(s).

Using the values of $f(\lambda)$ and knowing the slant ranges to the satellite (R_t, R_r) and r, the value of the S/N ratio may be obtained from equation (65) for the assumptions listed above.

From a standpoint of capacity, the above tables indicate that 8 GHz is the optimum operating frequencies. With specific reference to the millimeter spectrum, the additional antenna gain is more than overcome by the increase in receiver and external noise, the increase in atmospheric losses and the decrease in available transmitter power. It must be emphasized, however, that this conclusion results only from a consideration of maximum capacity per terminal. The spectrum up to 10 GHz is slowly becoming overcrowded and it seems reasonable to assume that the time will come when millimeter wave frequencies will be used for space communications and data links to reduce spectrum crowding. This

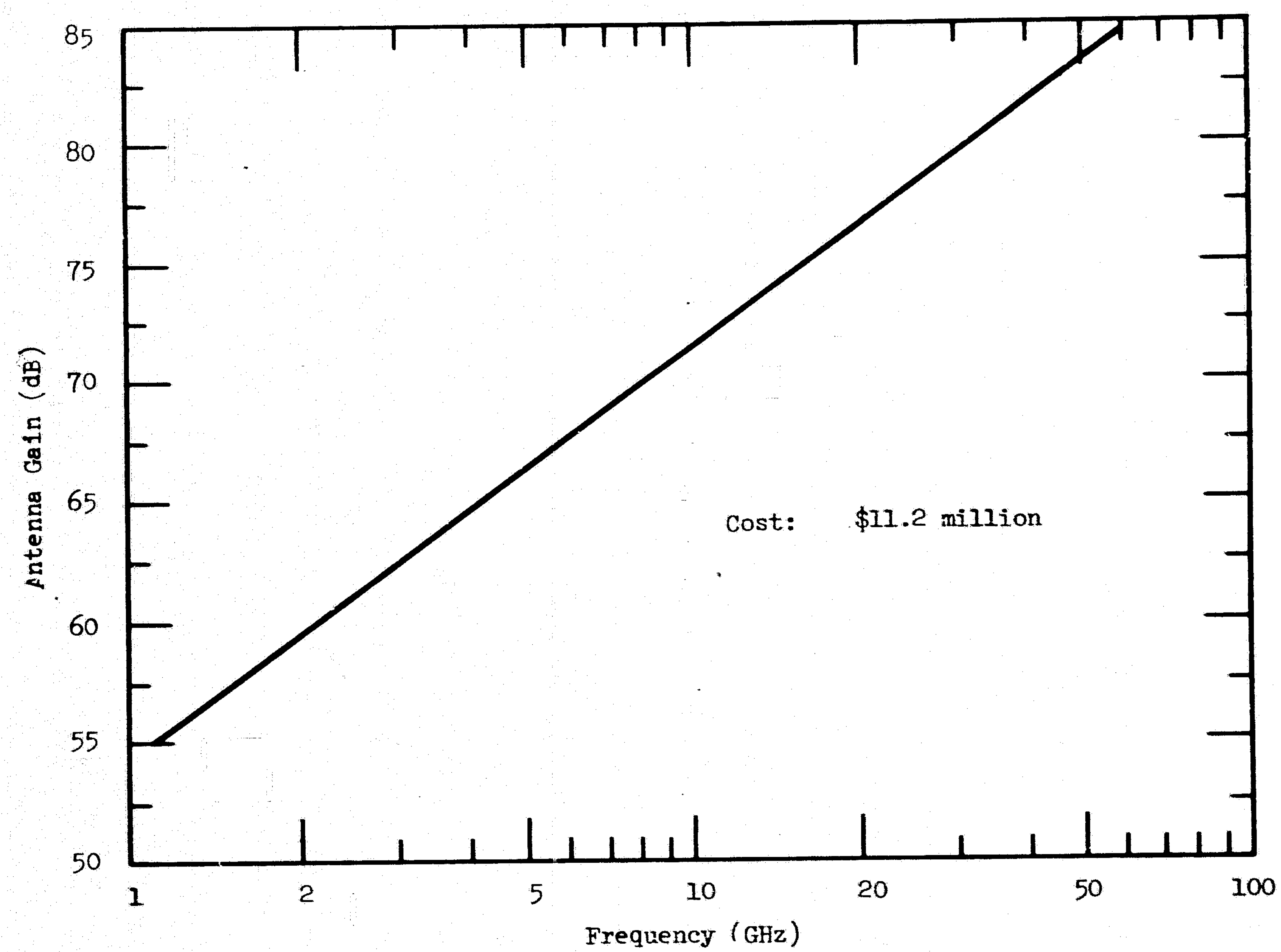


Figure 41. Optimum Antenna Gain for Constant Cost

Freq (GHz)	f(λ) - (dB)		
	Clear	Rain	Fog
2	249.3	249.3	249.3
5	251.8	251.7	251.7
8 (Ref)	254.1	253.6	253.6
10	252.7	251.7	251.9
15	250.0	247.0	248.5
20	243.5	239.9	243.3
30	243.6	231.7	240.4
40	239.4	222.1	235.5
80	229.6	190.6	217.4
100	223.2	178.2	204.3

Table XXXVIII S/N Ratio Factor, f(λ)

Freq (GHz)	$\frac{f(\lambda)}{f(3.75\ cm)}$ - (numeric)		
	Clear	Rain	Fog
2	4.8	4.3	4.3
5	2.3	1.9	1.9
8	0	0	0
10	1.4	1.9	1.7
15	4.1	6.6	5.1
20	10.6	13.7	10.3
30	10.5	11.9	13.2
40	14.7	31.5	18.1
80	24.5	63.0	36.2
100	30.9	75.4	49.3

Table XXXIX Normalized Factor f(λ)/f(3.75 cm) in Decibels.

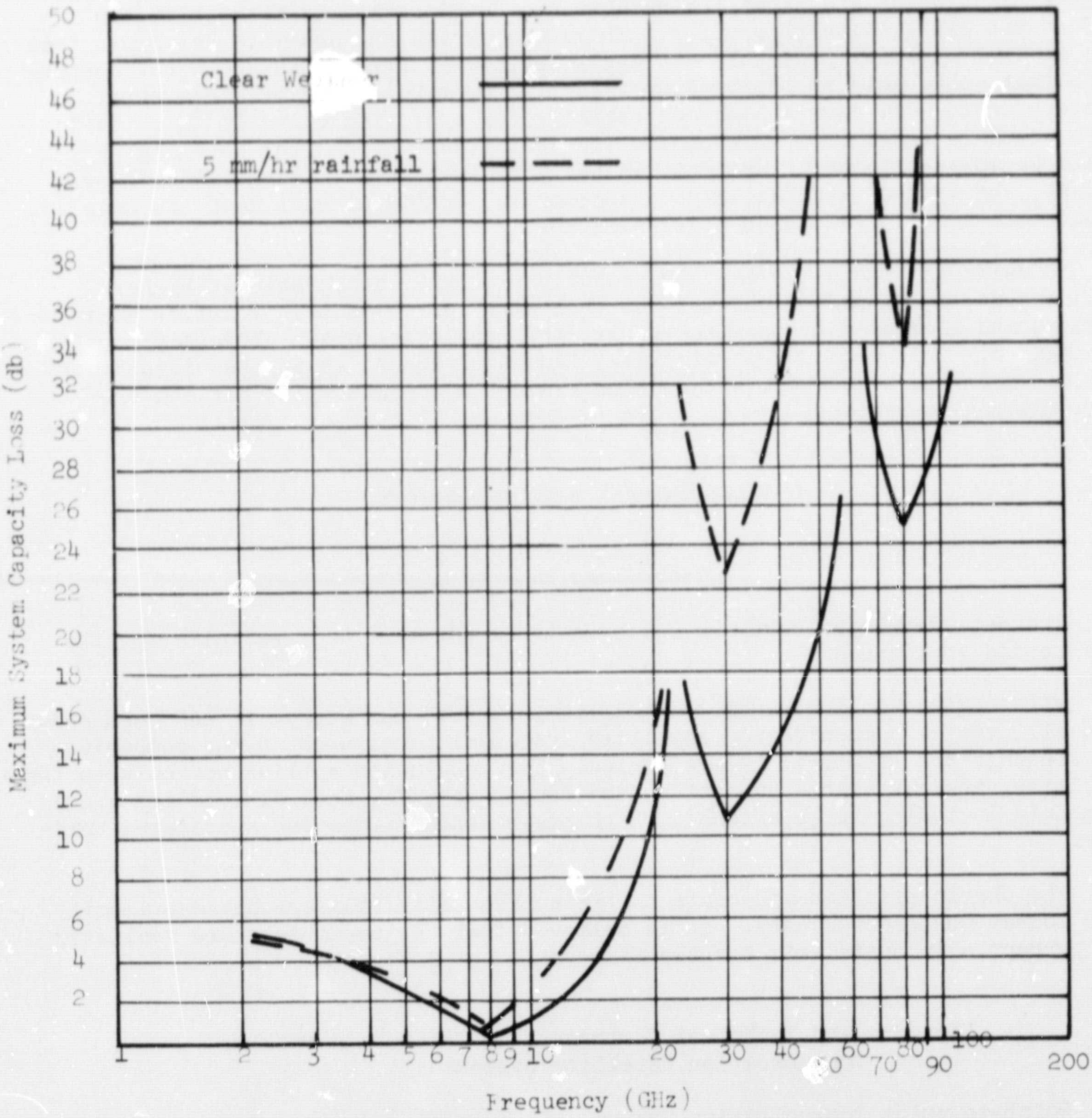


Figure 42. Normalized Maximum System Capacity vs Frequency (Normalized to operation at 8 GHz in Clear Weather)

advantage of reduced spectrum crowding is a consequence of the fact that the band above 10 GHz is largely unused. The problems of interference which are causing increasing concern in the sharing environment of the lower microwave bands could, therefore, be reduced. In addition to freedom from interference, higher frequencies are promising because of the wide bandwidth capabilities and secure links which they offer. Therefore, while the analysis has shown that the maximum capacity presently achievable at higher frequencies does not compete with that achievable at the base frequency, proper weighting of these other factors could well show a high desirability for operation above 10 GHz. It is also possible that, from an economic standpoint, use of shorter wavelengths would be more efficient. While it is not anticipated that this will be proven a fact, the lack of availability on antenna and component cost data has made impossible a full evaluation of this factor.

Considering again the maximum capacity presently achievable at higher frequencies, it should be pointed out that with improvement in receiver noise figures and increased transmitter power, the conclusion drawn above might well be negated. This would be particularly true at frequencies in the vicinity of 30 GHz where the atmosphere attenuation reaches a minimum value between the high absorption regions.

CONCLUSIONS AND RECOMMENDATIONS

Technology Base

The data developed here are believed to be accurate and realistic for the time period considered.

With regards to the passive satellite inputs to the study, it has been shown that all passive communication satellite system elements used in the comparison are feasible for the early 1970's period. The conclusion applies not only to the satellite, its associated subsystems and launch vehicle, but, also to the ground terminals including large antennas, high power transmitters and associated hardware.

The characteristics and costs of the active satellites are based primarily upon Comsat Corporation data. It is believed that the parameters are realistic and perhaps even optimistic for the time period of interest.

Economic and Technical Comparison of Active and Passive Communication Satellite Systems

Point-to-point Communication System.- In a great majority of cases passive systems are either always less expensive (on the basis of annual cost per access) or become less expensive as the number of accesses is increased. This conclusion may be explained as follows:

The total cost per access is obtained by dividing the total system cost by the number of accesses. Active satellites, because of higher ERP (compared to the maximum possible reflected power of a passive system) would normally have a larger channel capacity. However, because of intermodulation produced by hard limiting satellite transponder, a certain amount of radiated power represents the unwanted intermodulation power. To reduce intermodulation, the bandwidth of each access must be widened. Since the total transponder bandwidth is fixed at 500 MHz, such widening implies fewer accesses. Thus, there are two limitations on the total number of accesses - one due to available ERP and one due to available bandwidth. As a result, an optimization procedure described earlier in this report must be employed to maximize the number of accesses. The results indicate that when systems become bandwidth limited, the limiting number of accesses that can be handled by a passive system is greater than that of an active system. This is due to the fact that a wider bandwidth per access is required in active systems to keep intermodulation distortion within prescribed limits.

An active system includes a single satellite in orbit, while a passive system includes a passive satellite in orbit and a ground repeater. When the required number of accesses exceeds the capacity of such systems, it can be doubled by orbiting another active satellite (in case of an active system) or by adding another ground repeater (in case of passive systems. This process can be repeated if still more capacity is desired.

In most cases it costs more to double the capacity of the active system than it does to double the capacity of a passive system. Since the capacity of one passive system was in most cases larger than that of an active system, the process of further increasing the number of accesses causes the annual cost per access of passive systems to decrease at a faster rate than the corresponding decrease in the annual cost of the active systems. After a sufficiently high number of accesses is reached the passive systems annual cost per access becomes lower than that of the active systems. The number of accesses at which this situation occurs has been estimated and is shown in Table XL.

To illustrate the above for a particular example, consider Figure 43. This case compares satellite systems with 4 degree beamwidths operating between user terminals of the 15-foot diameter variety (ST-2). It can be observed from this figure that after augmentations, corresponding to about 50,000 accesses, the passive satellite system becomes more economical on a cost-per-access basis than any of the active satellite systems considered.

A similar figure can be drawn for any of the cases listed in Table XL.

The results in Table XL also show that on the annual cost-per-access basis, active systems are always less expensive when high satellite ERP is required per access. The reason is that because of the limitation on the ERP of the ground repeater, the maximum total power which is reflected towards earth by the passive satellite is synchronous orbit is always lower than that of active satellites. Table XLI shows the differences.

Table XLI

APPROXIMATE NUMBER OF CHANNELS AT WHICH A PASSIVE SATELLITE SYSTEM BECOMES MORE ECONOMICAL (AN ANNUAL COST PER ACCESS) THAN AN ACTIVE SATELLITE

User Station	Ground coverage (beamwidth) (degrees)	Approximate no. of channels at which the pass. sat. sys. becomes more economical	Type of satellite required	Repeater Antenna D (ft.)	G dB	Number of stations required
ST-1 (6 ft ant.)	1^{o}(city)	45,000	A-325 ft.	159	69	4
	2 (state)	Act. systems are always cheaper	SAT 2			
	4 (time zone)		SAT 4			
	8 (U. S.)		SAT 4			
	16 (1/3 earth)		SAT 4			
ST-2 (15 ft. ant.)	1	Pass. sat. always cheaper	B-137 ft.	89	65	1
	2	50,000	A-325 ft.	159	69	3
	4	50,000	A-325 ft.	159	69	3
	8	Act. sat. are always cheaper	SAT 2			
	16		SAT 2			
ST-3 (30 ft. ant.)	1	Pass. sat. always cheaper	B-97	63	62	1
	2		B-137	89	65	1
	4	67,000	A-325	159	69	4
	8	120,000	A-325	159	69	9
	16	Act. sat. always cheaper	Sat 2			
ST-4 (60 ft. ant.)	1	Passive satellite always cheaper	B-61 ft.	40	58	1
	2		B-87 ft.	56	61	1
	4		B-123 ft.	80	64	1
	8	50,000	A-219 ft.	89	65	3
	16	65,000	A-311 ft.	141	68	4
ST-5 (100 ft. ant.)	1	Passive sat. always cheaper.	B-43 ft.	35	57	1
	2		B-61 ft.	50	60	1
	4		B-97 ft.	63	62	1
	8	22,500	B-138 ft.	89	65	2
	16	46,500	A-246 ft.	112	66	3

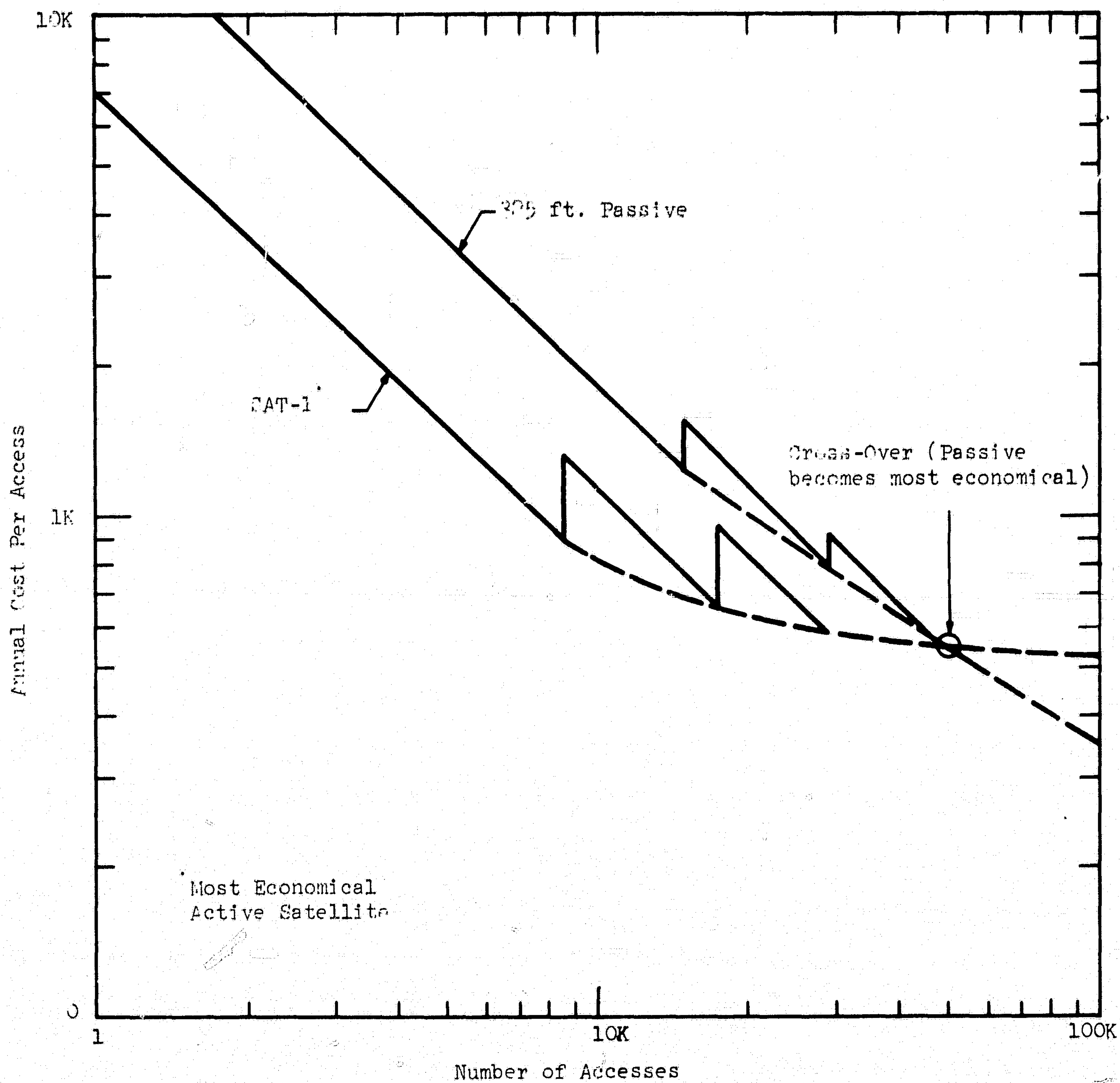


Figure 43. Point-to-Point Voice Communication
4° Beamwidth 15 Ft ST-2

Table XLI. Ratio of ERP from Active Satellites to Maximum Reflected Power of Passive Systems (dB)

Active Satellite	dB Above Passive
SAT-1	5
SAT-2	16
SAT-3	19
SAT-4	20

Thus, in this case, a larger number of accesses can always be obtained with active systems.

In general, however, it can be concluded from the results of the comparison on point-to-point communications systems that passive satellite systems may become competitive with active systems on the annual cost-per-access basis in certain situations.

It should be pointed out that the above comparison was based on a passive system employing a large central relay terminal. When large user terminals and narrow beamwidth satellites are considered the relay terminal is not required. This type of system would become cost competitive at fewer accesses and would avoid the potential problems of time delay and echo associated with the double hop. It is conceivable, however, that a relay terminal could still be desirable from the viewpoint of coverage area due to the reflection geometry considerations associated with the passive satellite.

TV Broadcast System. - In all cases studied, it is always possible to provide an active satellite TV-distribution system at an annual cost smaller than the comparative cost of a passive system provided that there is no limitation (due to international regulations) on the total power which can be radiated from space. This results for two reasons:

(1) The active satellite uses one transponder per TV channel and thus there are no intermodulation problems

(2) The maximum communication capacity considered is small (relative to the voice mission considered) and requires only a single active satellite.

General. - In general it can be seen that the larger the total communication traffic, whether it be voice, TV, TTY, etc., or any combination of these, using the satellite system (passive or active) the more attractive on an economic basis the passive system becomes.

Operational Considerations of Active and Passive Communication Satellite Systems

The operational differences between active and passive satellite systems can generally be grouped under the following categories:

(1) System Flexibility

(2) Traffic Control

(3) Interference

(4) Spectrum Utilization

(5) Coverage Areas

(6) Time Delay

(7) Jamming

System Flexibility. - Once designed, the active satellite is constrained to operate with a particular type of communication traffic. It cannot accommodate a large change in frequency, modulation, power level, etc. Additionally, it must operate with all user terminals of approximately the same size, since large signal levels can completely mask smaller signals.

To the contrary, the passive satellite is not constrained by the type of traffic, its amount, its power level, its frequency, etc. The passive satellite itself can accommodate many frequencies from various size user terminals, employing a variety of modulation techniques. The system or systems can be changed or added virtually at will since the satellite itself offers no constraint.

Traffic Control. - One type of passive system considered herein employs a repeater station located on the ground. This repeater station provides inherent capability for switching to control and route traffic. For the active satellite to duplicate this it must most probably assume a similar relay or control station, since the art of switching many circuits in space is not yet feasible.

Interference. - Since the large repeater station considered, transmitted in most cases very high power levels, it would be necessary for the passive system to judiciously site and shield this station to avoid interference to terrestrial services. The active systems considered have this problem to a much less extent.

However, on the downlink, the active system considered, in general, radiates a much higher ERP. In fact ERP considered in this study for the active satellite exceeds in most cases, the present CCIR recommendations. The passive satellites reflect a lower ERP and do not violate the CCIR recommendations.

Spectrum Utilization. - Because of the intereference problem, the spectrum utilization of the passive system is believed to be the worst. However, if a double hop system were not considered the passive system can utilize any allocated bandwidth more than twice as effectively, on a number of circuit basis, when compared to the active satellite system. This results because of the hard-limiting characteristic of the active satellite and because it requires a frequency translation for any complete circuit.

Coverage Areas. - The passive satellite is a Snell's law reflector. Therefore, the direction of any reflected wave is determined by the satellite orientation and the location of the ground transmitter. The active satellite can, however, redirect a wave into any location, dependent only on the downlink antenna orientation regardless of the direction to the ground transmitter. As a corollary of course, the active satellite is limited to relay into only one area at any given time, while the passive satellite can simultaneously relay traffic into many different areas. The result is a difference in the number of satellites required to support a system strictly on the basis of geometry.

Time Delay. - When the passive system employs a double hop with repeater station, the problems of signal and echo time delay become nearly twice as bad as the equivalent active satellite system.

Jamming. - Since the passive system is linear and any jamming signal must undergo twice the space loss normally considered, it requires much larger power levels over large bandwidths to effectively jam a passive satellite system than to jam an active system. Additionally, due to the reflection characteristics of the passive satellite, the "jammer" must be properly located with respect to the satellite; as opposed to the active system where the jammer's location is generally not important.

Analysis of the Relative Performance of a Passive Satellite System Operating at Frequencies above X-Band

It has been shown that from a standpoint of capacity, 8 GHz is the optimum operating frequency. With specific reference to the millimeter spectrum, the additional antenna gain is more than overcome by the increase in receiver and external noise, the increase in atmospheric losses and the decrease in available transmitter power. It must be emphasized, however, that this conclusion results only from a consideration of maximum capacity per terminal. The spectrum up to 10 GHz is slowly becoming overcrowded and it seems reasonable to assume that the time will come when millimeter wave frequencies will be used for space communications and data links to reduce spectrum crowding. This advantage of reduced spectrum crowding is a consequence of the fact that the band above 10 GHz is largely unused. The problems of interference which are causing increasing concern in the sharing environment of the lower microwave bands could, therefore, be reduced. In addition to freedom from interference, higher frequencies are promising because of the wide bandwidth capabilities and secure links which they offer. Therefore, while the analysis has shown that the maximum capacity presently achievable at higher frequencies does not compete with that achievable at the base frequency, proper weighting of these other factors could well show a high desirability for operation above 10 GHz. It is also possible that, from an economic standpoint, use of shorter wavelengths would be more efficient. While it is not anticipated that this will be proven a fact, the lack of availability on antenna and component cost data has made impossible a full evaluation of this factor.

Considering again the maximum capacity presently achievable at higher frequencies, it should be pointed out that the improvement in receiver noise figures and increased transmitter power, the conclusion drawn above might well be negated. This would be particularly true at frequencies in the vicinity of 30 GHz where the atmosphere attenuation reaches a minimum value between the high absorption regions.

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