NASA CR-135227

VOLUME I

TECHNICAL REPORT

(NASA-CR-135227) MILLIMETER WAVE SATELLITE CONCEPTS, VOLUME 1 (Georgia Inst. of Tech.) HC A11/MF A01 CSCL 22B

N78-15144

Unclas

G3/15 01847

MILLIMETER WAVE SATELLITE CONCEPTS

by

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NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

ENGINEERING EXPERIMENT STATION
GEORGIA INSTITUTE OF TECHNOLOGY

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
NASA Lewis Research Center
Contract NAS 3–20110

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1 Report No. NASA CR-135227	2 Government Accession No.	3 Recipient's Catalog No
4. Title and Subtitle MILLIMETER WAVE SATELLITE CONCEPTS		5 Report Date September 1977
		6 Performing Organization Code EES/SED/STB
7 Author(s) N. B. Hilsen, L. D. Holland, R. E. Thomas, R. W. Wallace, J. G. Gallagher		8 Performing Organization Report No. GT-A1855
		10. Work Unit No
9. Performing Organization Name and Address Engineering Experiment Station Georgia Institute of Technology Atlanta, Georgia 30332		11. Contract or Grant No. NAS3-20110
		13 Type of Report and Period Covered Contractor Report
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D. C. 20546		14. Sponsoring Agency Code

15 Supplementary Notes

Project Manager, Grady Stevens, Space Flight Systems Study Office,
Nasa Lewis Research Center,
Cleveland, Ohio

16 Abstract

This research program addressed the identification of technologies necessary for development of millimeter spectrum communication satellites from a system point of view. The objectives of the program were (a) development of methodology based on the technical requirements of potential services that might be assigned to millimeter wave bands for identifying the viable and appropriate technologies for future NASA millimeter research and development programs, and (b) testing of this methodology with selected user applications and services. The scope of the program included the entire communications network, both ground and space subsystems. The report includes (1) cost, weight, and performance models for the subsystems, (2) conceptual design for point-to-point and broadcast communications satellites, (3) analytic relationships between subsystem parameters and an overall link performance, (4) baseline conceptual systems, (5) sensitivity studies, (6) model adjustment analyses, (7) identification of critical technologies and their risks, (8) brief R&D program scenarios for the technologies judged to be moderate or extensive risks. Identification of technologies for millimeter satellite communication systems, and assessment of the relative risks of these technologies, have been accomplished through subsystem modeling and link optimization for both point-to-point and broadcast applications.

17. Key Words (Suggested by Author(s))	18 Distribution Statement
Satellite, Communications, Cost Model, Performance Model, Weight Model, Optimization, Millimeter, Technologies, Broadcast, Point-to-Point, Risk Assessment	Unclassified - unlimited

19. Security Classif. (of this report)	20 Security Classif. (of this page)	21. No. of Pages	22 Price*
Unclassified	Unclassified		

* For sale by the National Technical Information Service, Springfield, Virginia 22161

NASA-C-168 (Rev 10-75)

NASA CR-135227

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FOREWORD

The "Millimeter Wave Satellite Concepts" project under Contract NAS3-20110 was conducted by the Engineering Experiment Station (EES) at Georgia Tech. The program was administered under Georgia Tech Project A-1855 by the Systems Technology Branch of the Systems Engineering Division.

This report describes the work performed during the period June 1976 through June 1977. The program was managed by the NASA/Lewis Research Center Space Flight Systems Study Office. The NASA Program Manager was Mr. Grady Stevens.

The Georgia Tech Project Director was Dr. Neil B. Hilsen, Head of the Systems Technology Branch, with Mr. Larry D. Holland serving as Associate Project Director. The project was conducted under the general supervision of Mr. Robert P. Zimmer, Chief of the Systems Engineering Division. In addition to the project director and associate project director, the project team was comprised of the key personnel from the EES listed below along with their principal area of contribution.

R. E. Thomas	Systems Integration/Switching Technology
R. W. Wallace	Communication Systems/Applications
J. G. Gallagher	Millimeter/Optical Systems

SUMMARY

This research program addressed the identification of technologies necessary for development of millimeter spectrum communication satellites from a system point of view. The objectives of the program were (a) development of methodology based on the technical requirements of potential services that might be assigned to millimeter wave bands for identifying the viable and appropriate technologies for future NASA millimeter research and development programs, and (b) testing of this methodology with selected user applications and services. The scope of the program included the entire communications network, both ground and space subsystems. The report includes (1) cost, weight, and performance models for the subsystems, (2) conceptual design for point-to-point and broadcast communications satellites, (3) analytic relationships between subsystem parameters and an overall link performance, (4) baseline conceptual systems, (5) sensitivity studies, (6) model adjustment analyses, (7) identification of critical technologies and their risks, (8) brief R&D program scenarios for the technologies judged to be moderate or extensive risks. Subsystem models are applicable over a frequency range from about 18 GHz to 80 GHz, but the primary emphasis in the study has been for 40 and 50 GHz.

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SECTION 1
INTRODUCTION

Satellites have been used over the past decade for a variety of purposes ranging from scientific experiments such as measurement of the atmospheric characteristics to applications which provide improved services to society such as weather prediction, crop forecasting, and communications. The application satellites which have probably been of greatest commercial value have been the communication satellites which provide instantaneous international video communications, and have spawned a sizeable industry in so doing. Previous NASA studies [1] [2] have indicated that there will be a significant increase in both the applications and volume of satellite communications in the 1980 - 2000 time frame. Associated with an increase in demand is the potential problem of spectral crowding; obviously, some form of achieving higher capacity is necessary. One means of obtaining spectrum relief is to expand the communications services upward to the millimeter wave region of the spectrum. The larger bandwidths available at these frequencies will provide capabilities for higher data rates, and the possibility of extremely narrow beams can lead to very high reuse of the frequency assignments. The wide bandwidths available may permit a more reasonable number of picture phone channels than could be handled by current satellite, for example.

Up to now, United States industry has enjoyed a unique capability which has led to marketing of U.S. satellite technology abroad. Recently this position has eroded somewhat, especially in the area of ground terminals, due to increased competition from European and Japanese industry. Introduction of proven U.S. millimeter technology would enhance our nation's industrial position. Hence, there exists a need to investigate the technology associated with use of the millimeter spectral region for satellite communications.

Recent NASA-Lewis study programs relevant to expansion of satellite communications include a recent Georgia Tech study entitled, "Cost-Benefit of Space Communications Technologies" [1] which developed methodologies that would provide guidelines to NASA for undertaking R&D programs and a National Scientific Laboratory study entitled, "40 and 80 GHz Technology Assessment" [2] which has emphasized determination of user-service and technology trends of millimeter wave communications technology. The next logical step in the development of this technology is identification of cost effective R&D paths which take into account both performance and weight constraints consistent with a practical communications satellite system.

1.1 Objectives and Scope

With the potential millimeter services partially identified by previous studies, the objectives of this program have been to identify the technologies necessary to satisfy those services and to assess the relative risks of these technologies. Specifically, the objectives of this program were to (a) develop a methodology based on the technical requirements of potential services that might be assigned to millimeter wave bands for identifying viable and appropriate technologies for future NASA millimeter research and development program, and (b) to test this methodology with selected user application and services.

This program objective is a subset of, and totally consistent with, an overall NASA objective of developing system concepts and plans leading to applications of bands allocated to millimeter communications satellites, and identifying necessary technologies for making the millimeter bands technically and economically competitive. An additional objective of the overall NASA program has been to provide input for the WARC as the need arises.

The scope of this program is such as to include the entire communications network; i.e., ground station and satellite support as well as communication subsystems. The final product includes (1) cost, weight, and performance models for the subsystems, (2) conceptual designs for point-to-point and broadcast communications satellite, (3) an optimization methodology for design tradeoff studies, (4) baseline conceptual systems, (5) sensitivity studies, (6) model uncertainty analyses, (7) identification of critical technologies and their estimated risks, and (8) brief R&D program scenarios for those technologies judged to be of moderate and extensive risk. Subsystem models which are frequency dependent are presented for frequencies ranging from about 18 GHz to 80 GHz, but the primary emphasis in the conceptual application is at 40 and 50 GHz, with supplemental results presented for 18 and 30 GHz.

1.2 Approach

The program objectives have been met by an approach which utilizes an appropriate level of detail in the subsystem models utilized and in the numerical optimization procedure used for tradeoff analyses. After a review of the pertinent literature, the applicable subsystem models available from SAMSO [3] and Hughes [4] were selected as the basis for the subsystem model library. Models for the remaining subsystems were established from published specifications and from contact with personnel in the space communications industry. The overall communications link equation (received carrier to noise ratio) was written in terms of the independent performance parameters in the subsystem models. The total satellite system weight was expressed in terms of the same independent variables. Lower and upper bounds on the performance variables of all subsystem models were established, and a computerized random-search optimization procedure was adapted for selection of the minimal cost (total space and ground elements) system.

The optimization procedure was utilized to establish baseline design of the point-to-point application and of the broadcast application. The combination of assumed rain attenuation statistics and satellite weight constraint resulted in reduction of the broadcast application link reliability from the initial goal of 99.5% to 96.5%. Sensitivity analyses were performed for each of the baseline systems, and model uncertainty impacts were evaluated by reoptimizing the systems for given percentage increases in the cost and/or weight model of interest. The resulting impact was then expressed as a likely dollar uncertainty, and was used as a basis to rank the relative risks of the technologies required for the development and application of millimeter wave communication satellite systems.

1.3 Overview

Section 2 presents a brief review of the basic concepts of communication satellite systems and indicates the influence of subsystem parameters and atmospheric attenuation due to precipitation upon the performance of the communication link. The methodology used in this study is described in Section 3, and the subsystem cost and weight models are described in Section 4. Conceptual designs of the point-to-point and the broadcast applications are presented in Section 5, and the application of the methodology and subsystem models to these two concepts are presented in Section 6 and Section 7, respectively. Section 8 relates the technology to an estimated dollar impact for the two applications and presents the technology risk assessment and the suggested technology R&D scenarios. The conclusions and recommendations from this study are presented in Section 9. Appendices have been used for that material which, though informative and pertinent to the study, is not required for an understanding of the basic methodology and results.

SECTION 2
COMMUNICATION SATELLITE SYSTEMS

Communication satellite systems are similar to terrestrial microwave communication links in that either system consists of transmitting stations, one or more repeater stations, and receiving stations. Communication satellites to date have primarily served as "repeaters in the sky" for receiving communication signals from the ground, amplifying them, and transmitting them to another ground station. Examples of communication satellites of this type include the series of international communication satellites (INTELSAT I, II, III, IV, and IV-A), the first generation domestic communication satellites built by Hughes (ANIK and WESTAR), and the second generation domestic communications satellites built by RCA (SATCOM and ANIK II). Experimental communications satellites have included the Application Technology Satellite (ATS) series culminated by the currently active ATS-6, and the Communication Technology Satellite (CTS). The ATS-6 satellite possesses a large parabolic reflector antenna capable of projecting a high flux density signal upon a relatively inexpensive ground station, and has been used for experimental remote service applications. The CTS operates in a higher frequency band than ATS and employees a high power transmitter (200 watt TWT).

Future communication satellites will possess the capability to separate preaddressed messages and separately transmit them to various desired destinations. This mode might be referred to as "switchboard in the sky." Currently, transmission of a message between widespread parts of the world by satellite often requires a two-hop path (transmitter to satellite to intermediate ground station to second satellite to final destination); future systems will allow a direct transmission between satellites to alleviate this time delay. While the current application of communication satellites is primarily for point-to-point communication between a small number of relatively sophisticated ground stations tied into terrestrial communications systems, future applications might also include a broadcast mode where many small inexpensive ground stations would be able to communicate via a larger more powerful communication satellite. Applications of such a system might include direct wide-band data or video links (for teleconferencing) between

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corporation locations using rooftop antennas. The wide-bandwidth and narrow beam potential of the millimeter wave frequency band offers advantages for such broadcast applications, but the difficulties associated with high attenuation of the signal, by atmospheric weather conditions, must be overcome.

2.1 REQUIRED SUBSYSTEMS

A satellite communication system requires both ground and satellite subsystems; the satellite subsystems can be further divided into the communications link and housekeeping subsystems specifically associated with the satellite. The functions of the subsystems may be understood by tracing the complete routing of a communication message from its initial arrival at the transmitting ground station to its final departure from the receiving ground station. The information signal arriving at the originated ground station will be processed by a high speed modem, a TV head-in, or a voice multiplexor (depending upon the type of information), and by a signal processor to prepare it for transmittal. The information is then amplified by a high power transmitter, carried to the antenna feed by wave guide or coaxial cable, and transmitted from the antenna to the communication satellite. An antenna pointing and control subsystem directs the antenna toward the satellite. The antenna may be protected from the environment by a radome.

The attenuated transmitted signal, together with electromagnetic noise, is picked up by the satellite receiving antenna and is amplified by a low noise receiver. After the signal is amplified, it may be processed through a series of switches and filters to select the proper destination path. The information signal is then further amplified by the satellite transmitter and, after antenna beam switching, transmitted by the satellite's antenna beam.

A portion of the signal power transmitted by the satellite is collected by the receiving ground station antenna and amplified by its low-power receiver. The resulting signal is a combination of the original information signal from the transmitting ground station, and the system noise generated by the electronic equipment and picked up by the two receiving antennas.

Performance of the link is determined primarily by the ratio of the information signal received to the total system noise. After reception of the signal at the receiving ground station, the separate information channels are developed by signal processing, and the related information is distributed by modem, head-ins, and telephone line interconnection. Other subsystems which may exist at the ground station include bulk data storage for (1) interfacing between ground equipment and the space communications link and for (2) use with time division multiple access data links. Also, if there is a diversity station associated with the main station, there will be a diversity land line connecting the two stations.

Non-communication subsystems on-board the satellite include the attitude control system, station keeping system, electrical power supply system, and the structure and thermal control system. The attitude control system maintains the satellite orientation in space; the station keeping system maintains the satellite position in space. The electrical power supply system provides electrical power for the communication and other subsystems (usually by conversion of solar energy to electricity using solar cells). The structure and thermal control subsystem consists of the frame, covering and temperature control system of the spacecraft.

2.1.1 Ground Subsystem

The land line interface provides the connection between ground station and the "outside world." The primary technical features of its high speed modem, television head-in, and voice multiplex equipment are allowable data rate, number of video channels, and number of voice signals. For purposes of this project, the land line interface subsystems have been modeled as cost items; i.e., they are not considered to influence the performance of the communications link. The primary performance measure of the ground signal processing equipment include bandwidth, or data rate. This system, like the land line interface, is treated as a cost item which does not degrade the link performance.

The primary performance measure of the ground transmitter are its output power level and its RF bandwidth. The power level is a significant factor in determining the total link performance measure, the received carrier to noise ratio (C/N). The primary performance factor of the ground antenna is its signal gain (a function of antenna diameter and operating frequency).

The performance of the ground antenna is further influenced by the accuracy of the ground antenna pointing and control system and the attenuation introduced by any radome used to protect the ground antenna from the environment. Any error in the pointing of the ground antenna, or any attenuation of the signal passing through the radome reduces the power received at the satellite.

The receiving chain at the ground station has the opposite sequence from the transmitting chain and substitutes the receiver for the transmitter. The same antenna, and similar signal processing and interfacing equipment, is used within the receiving chain. Primary technical features of the ground receiver are its bandwidth and its noise characteristics. The amount of noise introduced by the receiver is usually expressed in terms of its equivalent noise temperature, or its noise figure. Additional costs for each ground station must be allocated for real estate and for housing the equipment.

A primary limiting factor of the use of millimeter wave bands for satellite communications is the large attenuation associated with propagation through rainfall. As a result of this and of the limited geographical extent of a given rain cell, significant reduction in the transmitted power levels necessary to exceed probably atmospheric attenuation can be achieved by using ground stations in pair or triplet figurations. Normal separation between these diversity ground stations is about ten miles. The cost and weight models developed within this research program include a model for the cost of the diversity land line which links the cooperating ground stations with full RF bandwidth.

2.1.2 Satellite Subsystems

The satellite subsystems consist of those used for communications and those associated with providing a platform and power for the communications equipment. The satellite subsystems associated with communications include the receiving and transmitting antennas, the receiver, the space signal processing, and the satellite transmitter. The primary feature of the satellite antennas are their gains which, like the ground antennas, depend upon the diameter of the antenna and the operating frequency. The satellite receiver, like its ground station conterpart, has bandwidth and noise equivalent temperature as its characteristic parameters. The space signal processing subsystem configuration is highly dependent upon the multiplex scheme being utilized and upon the number of channels being separately processed onboard. Its primary impact within the models used in this program, however, is its weight and cost; degradation of the communication signal quality is assumed negligible with respect to other subsystems. The satellite transmitter is characterized by its output power level and RF bandwidth; transmitter weight is also a key factor.

The attitude control system is characterized by the allowable error in satellite orientation, the mass of the satellite, and the mass of the attitude control system itself. The station keeping subsystem is primarily characterized by its error in holding the satellite at the desired orbital position and by mass quantitites similar to those for the attitude control system. The satellite electrical power supply system is characterized by the quantity of electric power it can provide to the other subsystems. The structure and thermal control system primarily affects the satellite weight and cost. All satellite subsystems influence the total satellite cost through (1) their subsystem cost and (2) launch vehicle cost, which increases with overall satellite weight.

2.2 INFLUENCE OF SUBSYSTEMS UPON COMMUNICATION LINK PERFORMANCE

The figure of merit for a space communications systems is considered to be the ratio of the carrier power to the noise power (C/N) at the receiving ground station. The value of received C/N depends upon each of the link terms given in Table 2.1. However, certain terms, such as the ground transmitter power and ground antenna gain, are of more importance in the link performance than are other terms such as the ground antenna pointing and control. Those terms considered most significant have been marked in the table as fundamental, and those less significant listed as secondary. The equations which relate the link performance to the individual subsystems will first be presented with only the fundamental terms (to improve visibility), secondary terms will then be added in subsection 2.2.3. (A complete derivation of the link equation is given in Appendix A.) Subsection 2.3 will then relate the effect of attenuation due to rain to the overall link reliability and to the presence or absence of ground station diversity.

TABLE 2.1

TERMS OF LINK EQUATION

Term (System)	Fundamental	Secondary
1. Ground Transmitter	x	
2. Ground Station Misc. Losses		x
3. Ground Antenna	x	
4. Ground Antenna Pointing & Control		x
5. Radome Attenuation		x
6. Space Loss (Divergence)	x	
7. Rainfall Attenuation (Uplink)	x	
8. Attitude Control and Station Keeping		x
9. Satellite Receiving Antenna	x	
10. Satellite Receiver (with Noise)	x	
11. Satellite Transmitter	x	
12. Satellite Misc. Losses		x
13. Attitude Control and Station Keeping		x
14. Satellite Transmitting Antenna	x	
15. Space Loss (Downlink)	x	
16. Rainfall Attenuation	x	
17. Radome Attenuation		x
18. Ground Antenna Pointing & Control		x
19. Ground Antenna	x	
20. Ground Receiver (with Noise)	x	

2.2.1 Fundamental Terms of the Link Equation

The communications link equation (C/N) is developed below for those subsystems which are indicated as fundamental in Table 2.1. Definitions of symbols are given in Table 2.2.

2.2.1.1 Transmitting Ground Station

A commonly used figure of merit for the transmitting portion of a ground station is its Effective Isotropic Radiated Power (EIRP), which is the power which would have to be transmitted through an omni-directional antenna in order to achieve the same power density in space along the center of the beam of the actual antenna. The EIRP is the product of the ground transmitter power, P_{GT}, and the antenna gain, G. The gain of the ground station antenna is given by

$$G = (68.0)\ (F_{UL})^2\ (D_{GA})^2 \tag{2.1}$$

where F_{UL} is the uplink frequency in Gigahertz and D_{GA} is the diameter of the ground station antenna in meters. The EIRP of the ground station is given by Equation 2.2.

$$EIRP \triangleq P_{GT} \cdot G = P_{GT} \cdot (68.0)\ (F_{UL})^2\ (D_{GA})^2 \tag{2.2}$$

2.2.1.2 Satellite Subsystems

The performance of the communications uplink is indicated by the ratio of the received carrier power to the received noise power (Appendix A).

$$\frac{C_{RS}}{N_{RS}} = \left\{ \frac{(1.9582 \times 10^{-15})\ P_{GT}\ (F_{UL})^2\ (D_{GA})^2\ (10)^{-(L_{RUL}/10)}\ (D_{SRA})^2}{k\ B[T_{SA} + T_{STD}\ (F_{SR} - 1)]} \right\} \tag{2.3}$$

TABLE 2.2

DEFINITION OF SYMBOLS

Uplink Frequency, GHz	F_{UL}
Downlink Frequency, GHz	F_{DL}
Ground Antenna Diameter, m	D_{GA}
Satellite Receiving Antenna Diameter, m	D_{SRA}
Satellite Transmitting Antenna Diameter, m	D_{STA}
Ground Transmitter Power, watts	P_{GT}
Satellite Transmitter Power, watts	P_{ST}
Boltzmann's Constant (1.38×10^{-23})	k
Information Bandwidth, Hertz	B
Standard Noise Temperature (290°K)	T_{STD}
Satellite Antenna Noise Temperature	T_{SA}
Ground Antenna Noise Temperature	T_{GA}
Satellite Receiver Noise Figure	F_{SR}
Ground Receiver Noise Figure	F_{GR}
Carrier Power Received at Satellite	C_{RS}
Equivalent Noise Power Received at Satellite	N_{RS}
Carrier Power Received at Ground	C_{RG}
Equivalent Noise Power Received at Ground	N_{RG}
Uplink Radome (Water Layer) Attenuation (dB)	L_{RDOMU}
Downlink Radome Attenuation (dB)	L_{RDOMD}
Uplink Rainfall Attenuation (dB)	L_{RUL}
Downlink Rainfall Attenuation (dB)	L_{RDL}
Ground Antenna Misalignment (degrees)	E_{GA}
Satellite Attitude Control Error (degrees)	E_{SAC}
Satellite Misc. Power Losses	L_{SM}
Ground Misc. Power Losses	L_{GM}
Total Uplink Secondary Losses	L_{UL}
Total Downlink Secondary Losses	L_{DL}

2.2.1.3 Receiving Ground Station

The primary figure of merit of the receiving ground station is the ratio of the antenna gain to the system noise equivalent temperature, with the ratio usually being expressed in dB. As shown in the development in Appendix A, the figure of merit represents that portion of the receiving ground station's contribution to the received carrier to noise ratio. The carrier to noise ratio of the resultant received signal is (Appendix A)

$$C/N = \frac{C_{RG}}{N_{RG}} = \left\{ \frac{C_{RG}}{k\ B[T_{GA} + T_{STD}\ (F_{GR}-1)] \ +\ C_{RG}/[C_{RS}/N_{RS}]} \right\} \tag{2.4}$$

where

$$C_{RG} = \left\{ (1.9582\text{x}10^{-15}) \cdot \frac{P_{TS}\ (F_{DL})^2\ (D_{STA})^2\ (D_{GA})^2}{1 + 1/[C_{RS}/N_{RS}]} \cdot (10)^{-(L_{RDL}/10)} \right\} \tag{2.5}$$

2.2.2 Secondary Terms of the Link Equation

The link equation's secondary terms account for (1) miscellaneous power losses between the transmitter and transmitting antenna at the ground station and at the satellite; (2) mis-alignment of antenna beams resulting from errors in ground antenna pointing control systems; and in satellite station-keeping; (3) satellite attitude control; and (4) attenuation of the electromagnetic wave passing through a (wet) ground station radome. The secondary effect will be grouped into three attenuation terms which modify the link performance as specified in Equation 2.4: (1) an attenuation factor for the uplink carrier power received, (2) a similar attenuation factor for the downlink carrier and noise power received, and (3) an attenuation factor for the ground station antennas noise temperature.

The miscellaneous losses at either the ground station or the satellite include such effects as attenuation of the transmitted power within the waveguide or co-ax connecting the transmitter to the antenna feed, polarization losses due to rotational mis-alignment between the transmitting and receiving antennas, sometimes the degradation of transmitter power level, and any other loss terms not explicitly accounted for in the fundamental or secondary terms. Antenna mis-alignment (azimuth and elevation) gain reductions are often included in the miscellaneous losses, but are treated separately as secondary terms in this analyses. The miscellaneous losses are assumed expressed in dB, with L_{GM} representing ground station miscellaneous losses and L_{SM} representing satellite miscellaneous losses.

2.2.3 Resultant Communication Link Equations

The overall effect of both the fundamental and the secondary terms in the communication link equation are summarized by the following (Appendix A):

$$C/N = \left\{ \frac{C_{RG}}{k\ B[T_{GA} \cdot (10)^{-(L_{RDOMD}/10)} + T_{STD}\ (F_{GR}-1)] + C_{RG}/[C_{RS}/N_{RS}]} \right\} \tag{2.6}$$

where

$$C_{RG} = \left\{ (1.9582 \times 10^{-15}) \cdot \frac{P_{TS}\ (F_{DL})^2\ (D_{STA})^2\ (D_{GA})^2 \cdot 10^{-(L_{DL}/10)}}{1 + 1/[C_{RS}/N_{RS}]} \cdot (10)^{-(L_{RDL}/10)} \right\} \tag{2.7}$$

and

$$[C_{RS}/N_{RS}] = \left\{ \frac{(1.9582 \times 10^{-15})\ P_{GT}\ (F_{UL})^2\ (D_{GA})^2\ (D_{SRA})^2 \cdot 10^{-(L_{UL}/10)}}{k\ B[T_{SA} + T_{STD}\ (F_{SR} - 1)]} \cdot 10^{-(L_{RUL}/10)} \right\} \tag{2.8}$$

and

$$L_{UL} = [L_{GM} + L_{RDOMU} + 0.29\ F_{UL}\ (D_{GA}\ E_{GA} + D_{SRA}\ E_{SAC})] \tag{2.9}$$

and

$$L_{DL} = [L_{SM} + L_{RDOMD} + 0.29\ F_{DL}\ (D_{GA}\ E_{GA} + D_{STA}\ E_{SAC})] \tag{2.10}$$

The computer program SCOR (Satellite Cost Optimization Routine) contains an implementation of Equations 2.6 through 2.10 for evaluation of communication satellite link performance, C/N, as a function of subsystem design parameters. SCOR also contains models for the cost of ground and space subsystems as a function of these design parameters; weight models are also included for the space components. SCOR accepts a specified value of C/N and a weight upper limit for the satellite, and produces a design which meets (if possible) the two specifications while minimizing the overall communication systems cost.

2.3 INFLUENCE OF WEATHER UPON COMMUNICATION LINK RELIABILITY

2.3.1 Atmospheric Attenuation Statistics

One of the primary disadvantages of application of the millimeter frequencies for satellite communication systems is the large attenuation encountered during propagation through precipitation. Both the uplink and downlink equations of subsection 2.2 contain terms (L_{RUL} and L_{RDL}, respectively) representing the power margin which must be included to assure adequate transmission through the varying weather conditions for at least some specified percentage (reliability) of the time. One-way link reliability is usually described by a plot such as that given in Figure 2.2 showing estimates of one-way link attenuation (power margin required) as a function of the percentage time in which the actual rain induces attenuation will not exceed the ordinate value. These estimates were arrived at through smoothing and frequency extrapolation of radiometer data at 19 and 38 GHz [2,6]. For lack of a more precise set of attenuation statistics, these estimates were used to determine required power margins. In view of the uncertainty in such estimates, it is appropriate to evaluate the impact of possible errors. This has been done, in a qualitative fashion, and the results are given in Section 6.

2.3.2 Effect upon the Link Equation

The successful operation of a satellite communications link requires both a successful uplink transmission and a successful downlink transmission. The spacing between the two earth stations utilizing the satellite will be large enough that the assumption of independent local weather conditions should be valid. The probability of the successful communications link can then be expressed as a product of the probabilities of a successful uplink and a successful downlink.

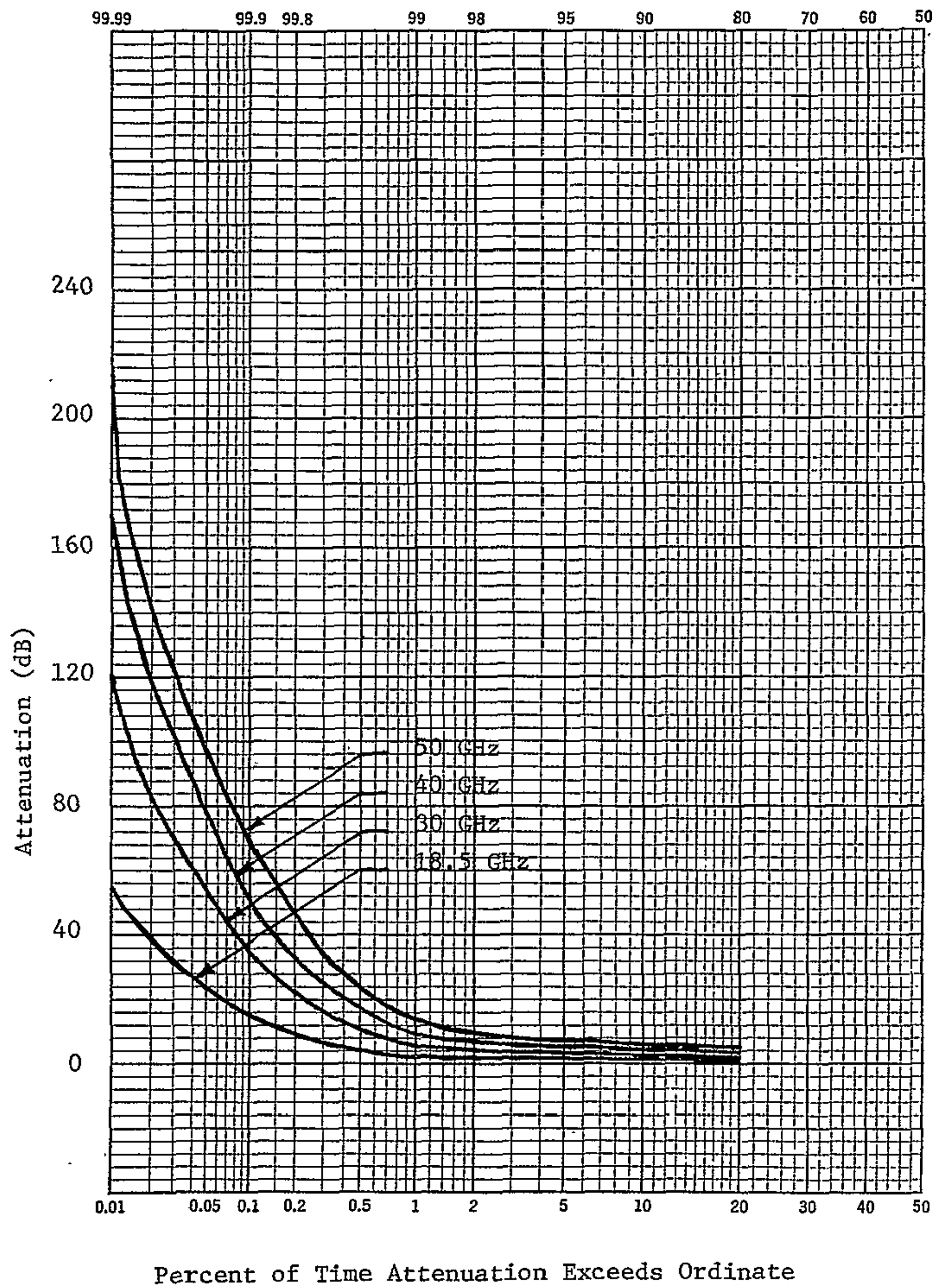

Figure 2.1. Rain Attenuation, No Diversity

Table 2.3 Rain Attenuation

A. No Diversity

Outage(%)	18.5 GHz	Attenuation 30 GHz	40 GHz	50 GHz
0.01	54.4*	121.0*	171.0**	214.0**
0.05	22.9	52.5*	75.9**	97.0**
0.10	14.9	34.7*	50.8**	65.6**
0.50	4.5	10.7	16.3	21.6
1.00	2.2	5.5	8.5	11.5

B. Two-Station Diversity

Outage(%)	18.5 GHz	30 GHz	40 GHz	50 GHz
0.01	9.6	21.2	31.2	40.4
0.05	5.5	11.7	17.3	22.6
0.10	4.2	8.8	13.0	17.1
0.50	2.3	4.2	6.0	7.8
1.00	1.7	2.9	4.0	5.2

C. Three-Station Diversity

Outage(%)	18.5 GHz	30 GHz	40 GHz	50 GHz
0.01	3.6	9.7	14.4	18.8
0.05	3.1	6.1	8.9	11.7
0.10	2.6	4.9	7.1	9.2
0.50	1.7	2.8	3.8	4.9
1.00	1.4	2.1	2.8	3.5

* Smoothing procedure used departs significantly from actual data in this range.

** Extrapolation likely in error due to deviation of smoothed trends.

$$P_L = P_{UL} \cdot P_{DL} \tag{2.11}$$

The apportionment of the overall link reliability between the uplink and the downlink can be established from several different approaches. Once the designer establishes his selection of, say, the uplink reliability, the downlink reliability requirement is determined from Equation 2.11. One might arbitrarily require that the uplink and downlink reliabilities (and thus their design margins) be the same; that is,

$$P_{DL} = P_{UL} = P_L \tag{2.12}$$

However, this would be most cost effective only if the incremental cost of ground transmitter power were equivalent to the incremental cost of the satellite transmitter RF power. A more logical choice might well be to put the burden upon the ground transmitter due to its lower cost and available sources of raw power. As a practical matter, this would be implemented by letting the probability of failure of the uplink be no greater than 1/10 of the probability of failure of the downlink. Alternately, the designer may choose to optimize his link design over all possible combinations of uplink and downlink reliabilities which satisfy the overall link reliability constraint. The approach utilized in this study, and implemented in SCOR has been the latter one; i.e., SCOR apportions the overall link reliability between the uplink and the downlink such as to minimize the overall system cost. The resulting uplink and downlink rainfall attenuations become L_{RUL} and L_{RDL}, respectively, in the link equations.

2.3.3 Ground Station Diversity

Previous studies [2] have indicated that ground station separation of 10 miles or greater is adequate to assure virtually independent precipitation statistics. As a result, many designs proposed for millimeter wave satellite communications systems utilize the concept of multiple ground stations at each site (site diversity). A diversity ground station would be located about 10 miles away from the main ground station but connected to the main station by a terrestrial communication link capable of real time transmission of the full bandwidth signal. The diversity station would contain only the RF equipment and would not have the signal processing and ground interface equipment located at the main ground stations. The diversity ground stations can either have receive-only capabilities or may have both transmit and receive capabilities. The effect of the use of diversity ground stations upon the link reliability expressions of the previous subsection is to decrease the power margin required to achieve a given uplink or downlink reliability. Economic advantages result when the cost of the ground diversity station is less than the increase in cost of the main ground station and satellite equipment which would be required for the higher precipitation attenuation power margin. Since the diversity and main ground stations are assumed to be separated adequately for independent heavy, rainstorm activity, the probability of excessive attenuation of the one-way space link is [6] given by:

$$(1 - P_{UL})_{DIV.} = P(\text{rain}) \cdot (1-P_{UL})^N; \qquad N\text{=site diversity} \tag{2.13}$$

where P(rain) is the probability of occurence of rain (obtained from weather bureau) and $(1-P_{UL})$ the conditional probability of attenuation exceeding the link margin [2]. As an example which indicates the effect of the use of ground diversity, consider a one-way link with a required reliability of three nines (i.e., 99.9%) at 40 GHz. Entering Figure 2.1, at 0.1% outage (99.9% reliability), it is found that ~ 51 db of power margin would be required with single station diversity. With two-station diversity, the individual station reliability need not be this high since traffic can be routed to the station experiencing the least attenuation. The two-station reliability is obtained thusly (assuming P(rain) = 0.05)

$$(1 - .999) = (0.05)\ (1-P_{UL})^2$$

$$R_{DIV} = 1 - .05\ (1-P_{UL}) = 0.993 \tag{2.14}$$

The use of the one-way link per-station reliability of 0.993 in Figure 2.1 results in the desired reliability with a required power margin of only 13* dB. Table 2.3 summarizes the results of such a calculation for up to three station diversity. For a satellite design which is already approaching a weight or power limit, the large savings in power through multiple-station diversity can make the difference between success or failure in system design.

*Usual engineering practice is to add 1 dB to the ideal margin to account for some dependence between sites [2].

The ground and space subsystems of Section 2.1 interact through the link equation of Section 2.2 with the atmospheric attenuation and ground station diversity effects described above to produce the resultant space communication system. The following section describes the methodology which is later applied to this communication system.

SECTION 3

ANALYSIS METHODOLOGY

The analysis methodology utilizes a level of detail consistent with the overall objectives of the study. The subsystem models and the communication link optimization procedure are used in identifying viable and appropriate technologies for future NASA millimeter research and development programs. The sequence of development and application of the methodology has been as follows: (1) development of models for cost (also for weight of spacecraft subsystems) as a function of primary performance variables for each subsystem; (2) development of the overall link carrier-to-noise ratio equation in terms of the primary performance variables of the subsystems; (3) development of optimization methodology (computerized) for minimization of total system cost, subject to overall link performance and satellite weight constraints; (4) generation of conceptual designs for point-to-point and broadcast communication satellites utilizing the millimeter wave frequencies; (5) optimization of each of the two conceptual systems utilizing the subsystem models and the optimization technique developed earlier; (6) performance of sensitivity and model adjustment analyses for the baseline conceptual designs; and (7) selection of critical technologies and performance of a risk assessment for each. The inter-relationships between the cost models, weight models, link equation, and weight budget during system optimization is demonstrated in Figure 3.1. The following subsections describe these elements of the analyses methodology in more detail.

3.1 Subsystem Model Requirements

The ground and space subsystems and their categorizations are indicated in Figure 3.2. The cost model for each subsystem (and the weight models for the spacecraft subsystems) must be developed in terms of the subsystem performance parameters which appear in the communication link equation derived in Section II. Table 3.1 gives the primary and secondary parameters for each subsystem model. The primary parameter appears in the link equation explicitly, and the secondary parameters are dependent upon the application.

The individual subsystem models are applicable over a specified range of the performance parameters, and the models are continuous (though not necessarily differentiable) over the allowable range of the performance

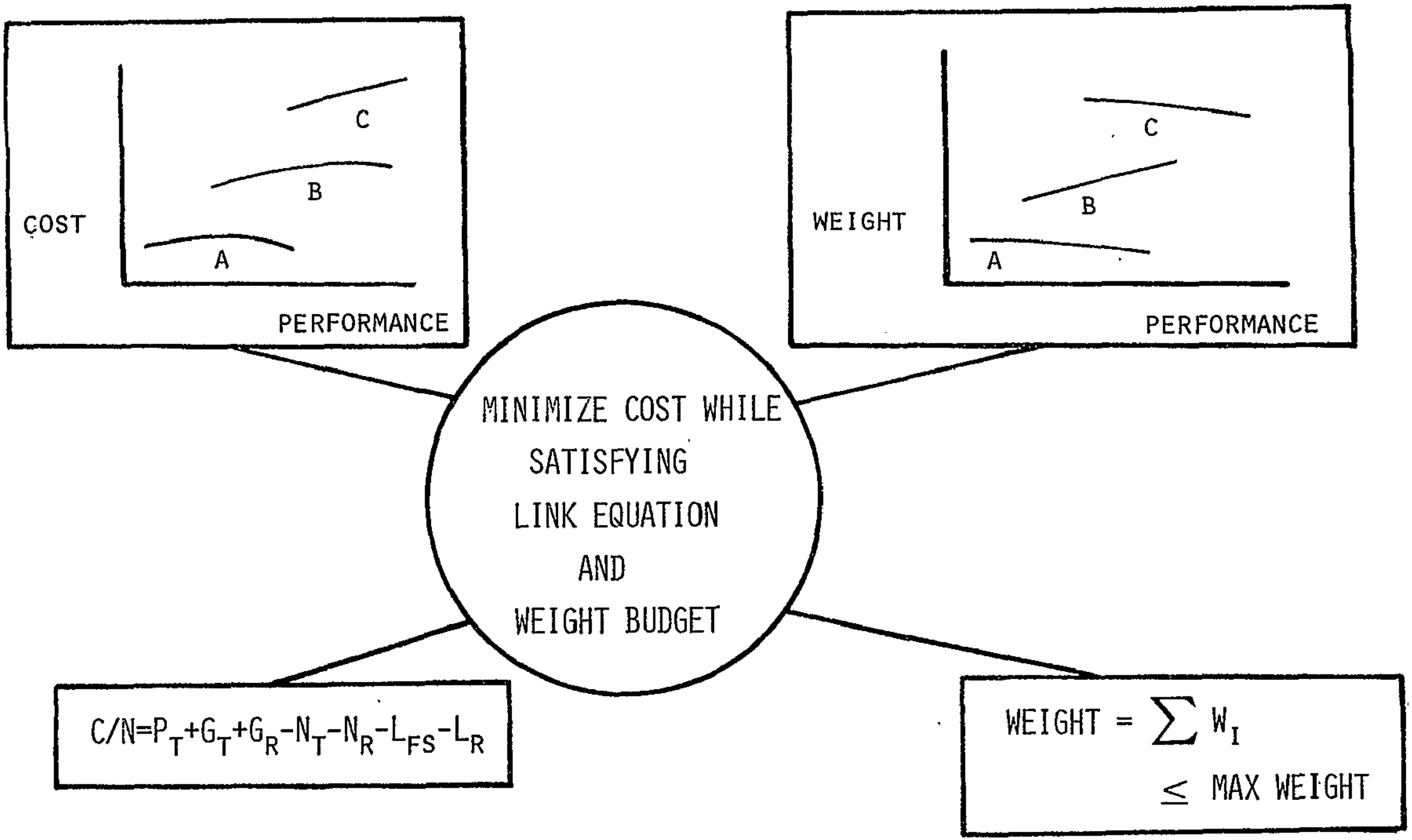

Figure 3.1. Analysis Technique

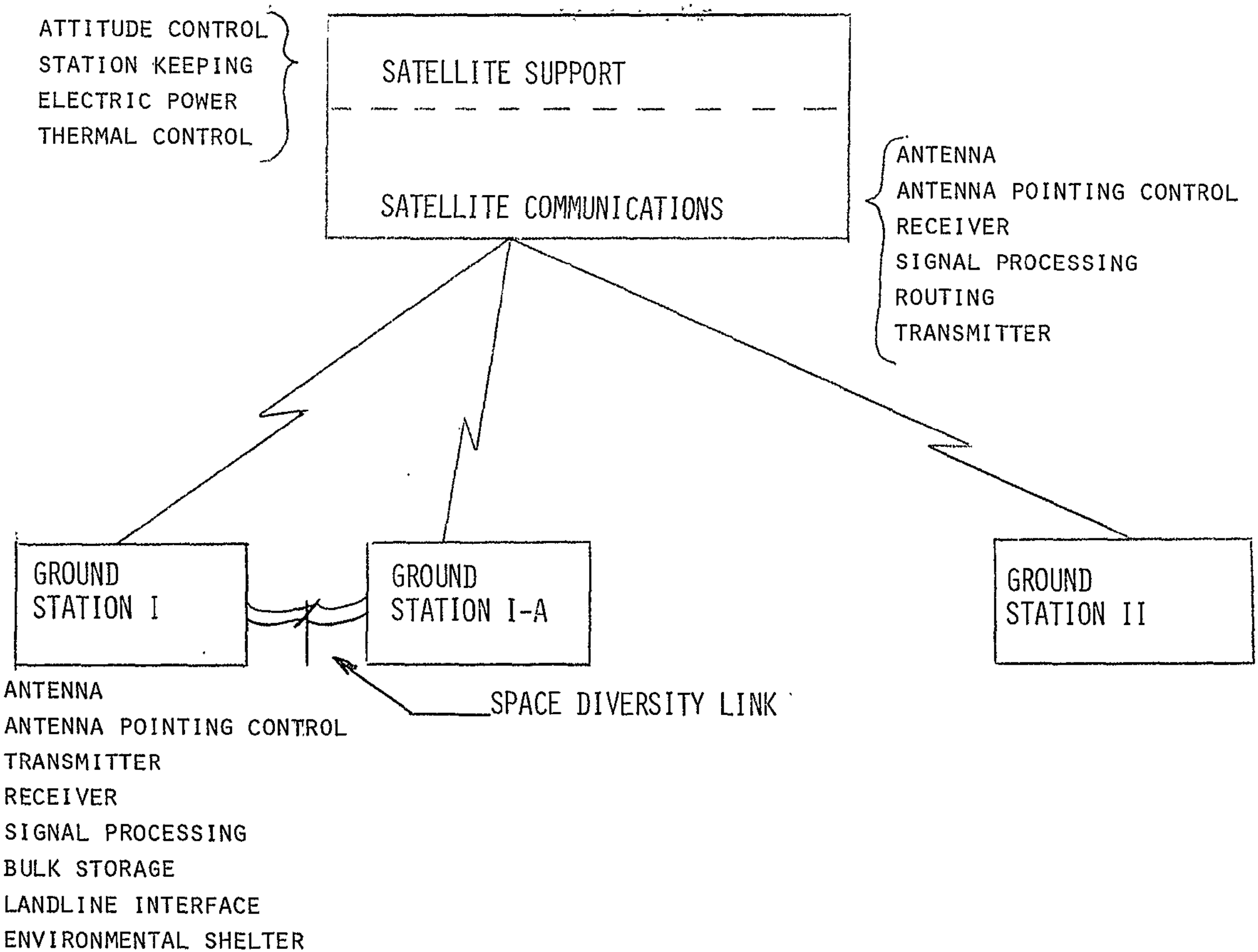

Figure 3.2. Ground and Satellite Subsystem Categories

TABLE 3.1

SUBSYSTEM MODEL PARAMETERS

SUBSYSTEM	PRIMARY PARAMETER	OTHER PARAMETERS
Ground Systems		
Antenna	Diameter	
Antenna Pointing Control	Pointing Tolerance	
Transmitter	Power (RF)	
Receiver	Noise Figure	Bandwidth
Signal Processing	No. of Channels	Multiplex type
Bulk Storage	Rate, Capacity	
Landline Interface	Rate	Type
Space Diversity Link	Length	Bandwidth
Spacecraft Systems		
Antenna	Diameter	
Receiver	Noise Figure	Bandwidth
Signal Processing	No. of Channels	Multiplex Type
Transmitter	Power (RF)	Bandwidth
Attitude Control	Tolerance	Spacecraft Mass
Station Keeping	Tolerance	Spacecraft Mass
Electric Power	Power (DC)	

parameter. Certain of the models (e.g., the station keeping subsystem weight model) both influence and depend upon the total weight of the spacecraft; application of these models involves an iteration technique. Also, many of the cost models are based upon SAMSO cost estimates relationships (CER) which model the subsystem costs as functions of the subsystem weights, where the subsystem weight is modeled as another function of the performance parameters. In general, the accuracy of the cost and weight models is consistent with the objective of this program. Extremely accurate models, such as would be required in the design phase of a communications system, would involve considerably more development effort than appropriate for this program. The resultant cost and weight models are documented in Section IV of this report.

3.2 Link Optimization

The methodology for optimization of the communication link must select all subsystem performance parameters in such a way that the overall link carrier-to-noise ratio requirement, and the satellite weight constraint are satisfied, and the total system cost is minimized. The link performance constraint is an equality constraint while the satellite weight constraint is an inequality constraint. The performance index (cost) and both constraints involve non-linear functions. For each optimization, minimum and maximum limits will exist for each of the performance parameters.

Optimization methodologies generally available for computer implementation include linear programming, non-linear programming, exhaustive radome search routines, and gradient search algorithms. Although linear programming methods can be applied to piece-wise linear approximations of non-linear functions, they are limited to convex functions. The non-linear programming package available at EES utilized penalty functions of the form VH(X) to attempt forced satisfaction of constraints and equalities. Experience with this non-linear programming method early in this project indicated that it would not be satisfactory for this optimization problem, since constraints were repeatedly violated. A random search algorithm which uses a computerized random number generator to select trial points over the parameter intervals has been developed and used for most of the optimizations performed during the program. The algorithm reduces the parameter interval in successive optimizations until the density of random points selected is quite high in the final optimization step. This methodology has proven to be effective and efficient. However, for applications in which the optimal solution lies on the weight boundary, the random search algorithm does require a significant increase in computer time. As a result, an interactive man-in-the-loop gradient search algorithm has also been developed as an option to the random search procedure. Use of this option (from a remote computer terminal) has significantly decreased the computer time for establishing the cost-optimal conceptual design of the satellite broadcast analysis of Application II. The resulting computer program is called SCOR, an acronym for Satellite Cost Optimization Routine.

3.3 Sensitivity and Model Adjustment Analyses

Application of the cost minimization routine SCOR to a satellite communication system conceptual design yields optimal values for each of the subsystem performance parameters. A question of how critical a specific parameter might be is usually resolved by performing a sensitivity analysis with respect to the optimal parameters.

3.3.1 Sensitivity Analysis

Such an analysis indicates, for each of the parameters, the change in total system cost as a function of a small change in a parameter value. A normalized form of sensitivity, called elasticity, is frequently used to provide a numerical measure associated with the qualitative terms "low" and "high" sensitivity. Elasticity is the ratio of the incremental change in the system variable (e.g. cost) divided by the nominal system variable to the incremental change in the parameter (e.g. performance) divided by the nominal value of the parameter.

In applications of SCOR, the elasticities of the total system cost, satellite weight, and link carrier-to-noise ratio have been calculated and tabulated for each computer analysis. The calculations are open-loop in that incremental changes are calculated without reoptimization, but presentation of elasticity of cost, weight, and link figure-of-merit allow direct determination of the effects upon performance.

3.3.2 Model Adjustment Analysis

The effect of variations in the cost and weight models utilized for the subsystems has been evaluated by a model adjustment analysis. In this analysis, each cost or weight model was increased (decreased) significantly, while holding all other models constant, and repeating the total optimization procedure. Results of the reoptimizations which are of interest include the impact on total system cost, and the manner in which subsystem performance parameters are changed as a result of the model adjustment. The analysis is then used to establish which subsystems and related technologies are critical; that is, which technologies are responsible for the greatest impact in the overall system cost, or equivalently, in the feasibility of the conceptual design.

3.4 Critical Technology Selection and R&D Risk Assessment

The model adjustment analysis establishes the system cost impact resulting from large changes in the subsystem cost and weight models. This information, when combined with estimates of the likelihood of occurrence of these model changes, provides a measure of criticality of the subsystem and its associated technologies. Once the set of technologies which are critical to millimeter space communication system have been identified, it is desirable to estimate the risks associated with advancement of each technology. The primary measure of risk which has been used is the time required for conducting an R&D program to adequately reduce both the uncertainty and the base value of the cost and weight characteristics of the technology.

3.4.1 Critical Technologies

Identification of technologies which are critical to the implementation of millimeter space communication systems requires three additional steps of action: (1) identification of uncertainty levels with each subsystem; (2) estimation and ranking of subsystem uncertainty impacts; and (3) relation of subsystem impact to the specific technologies.

Initial qualitative estimates of the subsystem model uncertainties are assigned quantized likelihoods (10%, 30%, 50%, 70%, or 90%). The likelihood number may be viewed as an approximate probability that the model adjustment utilized in the model adjustment analyses will actually occur. The product of this likelihood number and the increase in total system cost resulting from that subsystem model adjustment will be a measure of the resulting system impact. The subsystems are then ranked according to the estimated system impact of uncertainty. The technologies associated with the subsystems having the higher estimated system impact will then be isolated for risk assessment.

3.4.2 Risk Assessment

The estimated risk (R&D time requirement) is estimated for each of the technologies associated with the subsystems with high ranking estimated system cost impact. The risk of these technologies is then categorized as being short-term (2-4 years), long-term (5-10 years), or unknown term (requiring an invention). The estimated risk results from judgement of professionals knowledgable of the state-of-the-art for the specific technology. R&D program scenarios are then briefly outlined for those technologies categorized as short-term or long-term risks.

In summary, the overall analysis methodology utilizes: cost and weight vs. performance models for the subsystems, optimization of the overall communication link system, sensitivity and model adjustment analyses around the baseline (optimal) designs, and selection and assessment of critical technologies and their estimated R&D time requirements. The subsystem models are presented in the following section.

SECTION 4
SUBSYSTEM MODELS

4.1 Summary of the Subsystem Models

Parametric cost models have been formulated for each of the subsystems included in the satellite/ground station configurations. In most cases there is one major parameter affecting the cost while several minor parameters are used to specify features of the configuration. A summary of the cost models and their independent parameters is given in Table 4.1.

Parametric weight models have been formulated for each of the satellite subsystems. These models normally have the same independent variables as the corresponding cost models. In cases where total satellite weight is the independent variable for a subsystem weight model an iterative technique is used for computations. A summary of the weight models is given in Table 4.2.

In many cases the effect of a subsystem on communication performance is directly related to the subsystem independent parameters. In other cases a parametric model is provided for a value such as gain or attentuation. These models are presented in this section with the associated cost and weight models. The total communication link performance is described in Section 2.

4.2 Ground Subsystem Models

The ground antenna is considered to include dish, mount, and feeds for 1 GHz operation. A single dish is used for both receive and transmit functions. Two ground antenna models are used in the analysis. For the point-to-point application a free-standing dish and mount are used. For the broadcast case a dish for roof-top mounting is modelled. Cost and gain are given for these models as a function of antenna diameter and operating frequency.

Antennas for the point-to-point application are used in limited quantity, thus a substantial portion of the estimated research and development cost is included in the cost model.

Antennas for the broadcast application are used in large quantities thus reducing the research and development allocation and reducing production costs. Frequency is not included in this model since analysis was performed for a single band.

A radome may be provided for weather protection of the ground antenna subsystem. Both self-supporting and inflatable types have been considered with the least expensive type chosen for a particular antenna size. Cost and

Table 4.1 Subsystem Cost Models

Subsystem	Independent Variables
Ground Antenna	Dish diameter Transmitter frequency
Radome	Radome diameter
Ground pointing and control	Pointing error Dish diameter
Ground transmitter	Transmitter power Transmitter frequency
Ground receiver	Receiver noise figure Receiver frequency
Ground signal processing	Baseband channel bandwidth
Bulk data storage	Data rate Storage volume
Landline interface	Data rate Number of television headins Number of voice multiplexors
Diversity link	Diversity range
Satellite antenna	Antenna diameter Operating frequency Number of feeds
Satellite transmitter	Transmitter power Operating frequency
Satellite receiver	Noise figure Operating frequency
Satellite signal processing	Number of channels Number of subchannels per channel
Attitude control system	Attitude control system weight
Station keeping system	Station keeping system weight
Structure and thermal control	Structure and thermal control weight
Satellite power supply	Prime power required

Table 4.2 Subsystem Weight Models

Subsystem	Independent Variables
Satellite antenna	Antenna diameter Operating frequency Number of feeds
Satellite transmitter	Transmitter power Operating frequency
Satellite signal processing	Number of channels Number of subchannels per channel
Attitude control system	Attitude control error Satellite weight
Station keeping system	Station keeping accuracy Satellite weight
Structure and thermal control	Satellite weight
Satellite power supply	Prime power required

the attenuation effects of water on the radome are modelled versus radome diameter frequency and rainfall rate. The radome diameter is assumed to be 1.5 times the antenna diameter.

The most significant portion of the attenuation due to the radome is from rainfall causing a sheet of water. The attenuation from the radome material is relatively minor. A complete derivation of the attenuation equation is given in Appendix B.

The <u>pointing and control subsystem</u> includes the antenna pointing mechanism and the associated automatic pointing system. The purpose of the subsystem is to track a synchronous satellite which may have a long term drift of up to $\pm 0.5°$. Cost of the subsystem is modelled as a function of antenna size and required pointing accuracy.

The cost model was established by considering several types of antenna support systems. Current vendor prices were used to give the plot in Figure 4.1. Price is given as a function of antenna diameter for a) simple support structure without automatic control, b) simple structure with auto-track system, c) quality pedestal with step-track and d) quality pedestal with full monopulse pointing control.

Each of these control systems has a characteristic accuracy. This data was used to derive a model with pointing error as a parameter. Linear extrapolation is used for pointing accuracies less than 0.05°. As for the ground antennas, pointing and control systems were found to be less expensive for the roof mounted dishes in broadcast application. The model for these costs is given separately from that for point-to-point systems.

The <u>ground transmitter model</u> gives transmitter cost as a function of the ground transmitter power. The cost of the oscillator was modelled as a constant with the total cost being a function of the 50-51 GHz high power amplifier. The same model applies to both the point-to-point and the broadcast applications. Frequency dependence is not included in the broadcast case since only a single set of frequencies was used in the analysis.

The ground transmitter consists of a master oscillator and a high power amplifier (HPA) at 50-51 GHz. A capability for transmitting a signal with a 1 GHz bandwidth is required. The output of the high power amplifier is fed to the ground antenna for transmission to the satellite.

It is assumed that the state-of-the-art for the 50-51 GHz oscillator is advanced sufficiently to allow the cost for oscillator to be considered as an additive constant. The cost is then assumed to be a function of the power

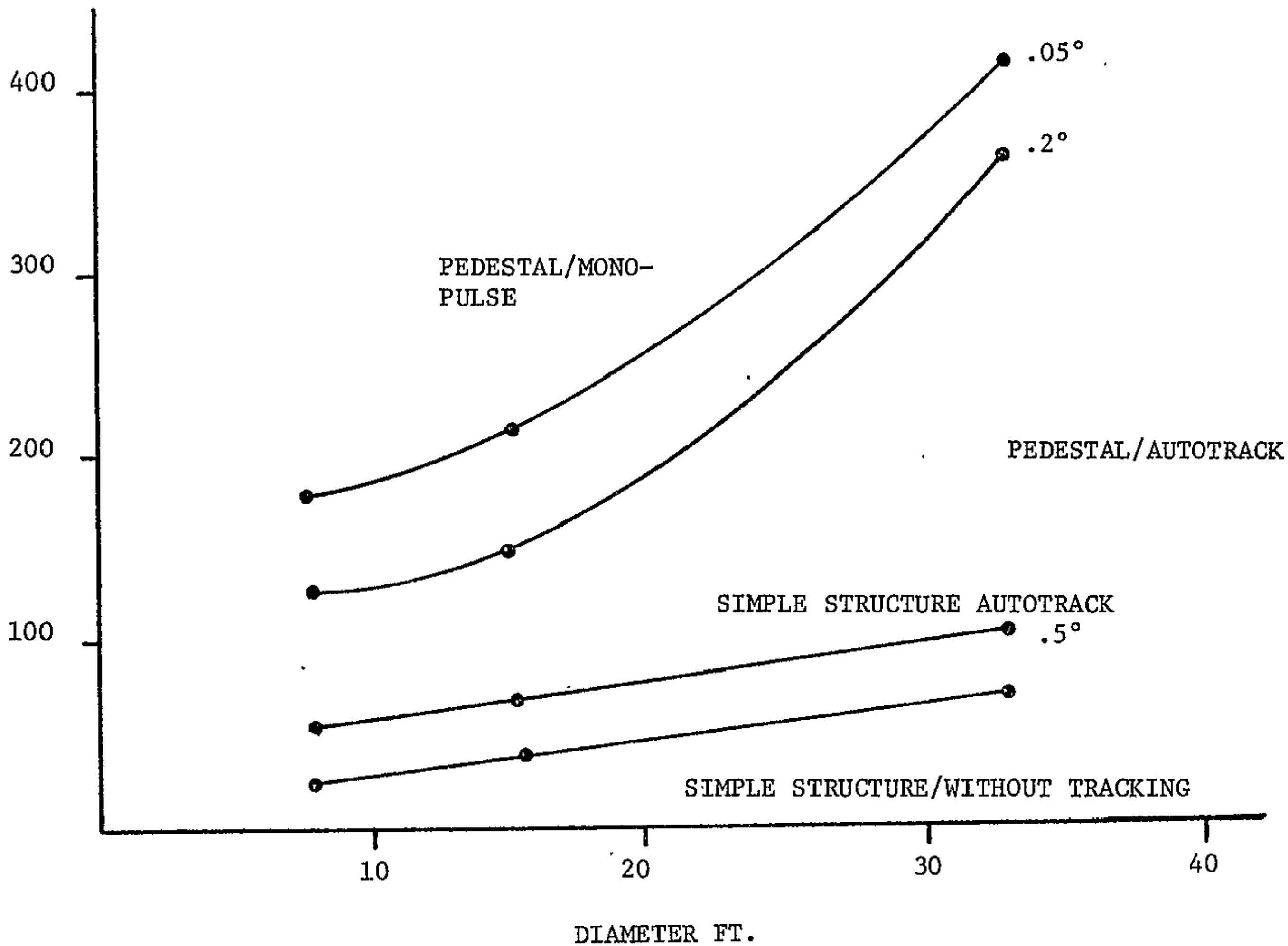

Figure 4.1. GROUND ANTENNA POINTING CONTROL SYSTEM DATA

capability of the high power amplifier. The HPA cost model is obtained by extrapolation from the cost at lower frequencies (5-6 GHz) by multiplying by the frequency ratio with a small addition to account for bandwidth. The bandwidth of the transmitter is assumed to be 1 GHz.

The ground receiver model gives receiver cost as a function of the noise figure of the millimeter wave low noise amplifier (LNA). The cost of the mixer, local oscillator and IF amplifier were modelled as a constant additive constant since these components are currently available. The same model applies to both point-to-point and the broadcast applications. Frequency dependence is not included in the broadcast case since only a single set of frequencies was used in the analysis.

The ground receiver receives the signal from the satellite (40-41 GHz), amplifies in a low noise amplifier (LNA), down-converts the signal to 5-6 GHz, and amplifies this IF signal. The equipment for this subsystem consists of a 40-41 GHz low-noise amplifier (LNA), followed by a Schottky barrier mixer with a 35 GHz solid state local oscillator and a 5-6 GHz IF amplifier. A 1 GHz bandwidth is required for the applications.

All costs for this model are expressed in 1976 dollars. It is assumed that the state-of-the-art for mixers, Gunn oscillators with sufficient stability to serve as LO's and 5-6 GHz IF LNA's is sufficiently advanced to allow the cost of these units to be lumped as an additive constant. No models exist for the 40-41 GHz LNA. It was assumed from a comparison with lower frequency LNA's that, for high noise figure (noise temperature), the cost is directly proportional to frequency whereas part of the cost for low noise figure amplifiers is related to cryogenic apparatus which has been developed independent of the operating amplifier. For amplifiers below 35 GHz, costs are reduced by 20% over those for 40-41 GHz devices, and a further 20% reduction is assumed for amplifiers below 25 GHz.

The ground signal processing subsystem serves to interface between the 1 GHz bandwidth signal at the receiver and transmitter IF stages and the multiple baseband channels at the landline interface. Two techniques are considered for this subsystem. The frequency-division multiple access subsystem requires that baseband channels be demodulated from different carrier frequency bands. A block diagram is shown in Figure 4.2. The time-division multiple access subsystem requires that samples of baseband signals be interleaved in time and that buffering and reassembly of the messages be used. A block diagram is given in Figure 4.3.

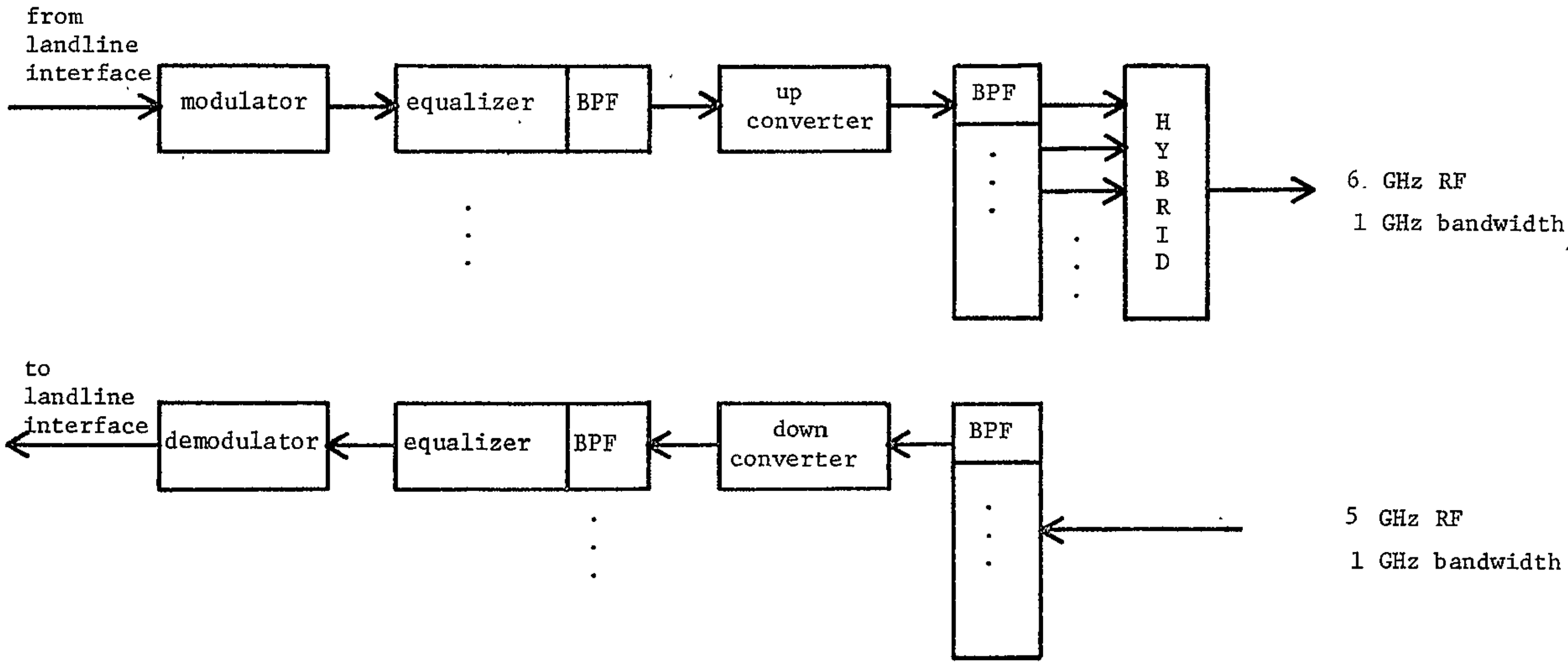

Figure 4.2 FDMA Ground Signal Processing Subsystem Diagram

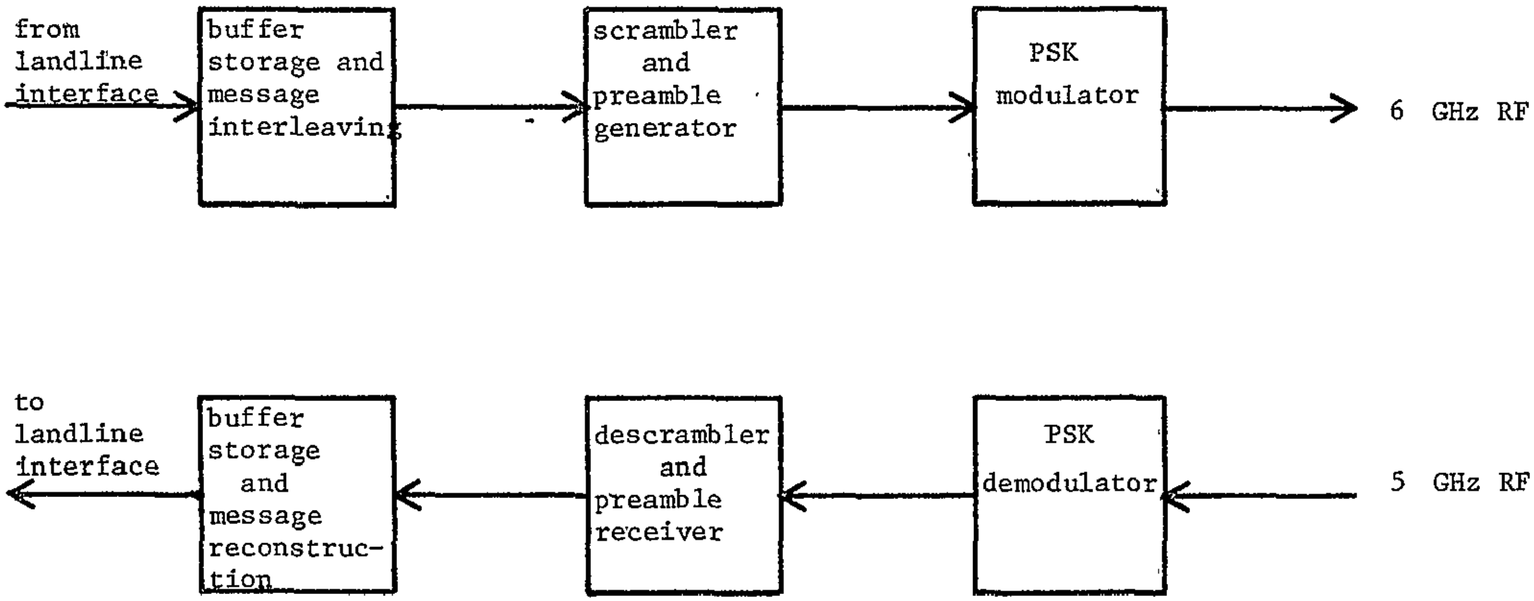

Figure 4.3 TDMA Ground Signal Processing Subsystem Diagram

Bulk data storage is included in ground station configurations to allow store and forward switching in packet switching applications and to provide for delayed transmission of program material after peak load periods. The cost model was derived from costs of existing digital memory systems and has parameters, data rate and data volume. Linear relationships were assumed in cases where parallel equipment was used.

The landline interface is provided in the ground system for connection to various types of common carrier lines. Included are high-speed modem for digital data service, television headin for standard television transmission and multiplexed voice interface for standard telephone interconnect. Costs for each type interface was derived from currently available equipment prices. It is assumed that any combination of these components is allowable.

The diversity land line model gives the cost of using a land link to connect the two sites in a spatial diversity configuration. The link can be a one-way transmission when only one transmitter and two receivers are used, or a two-way transmission when two transmitters and two receivers are used. Several transmission schemes capable of high data rates can be considered as potential land lines.

The diversity land link provides the transmission capability between the two diversity sites, which are assumed to be 10 miles apart. Schemes considered included line-of-sight microwave, laser propagation, guided millimeter waves and fiber optics. The line-of-sight microwave system, with a fiber optics system a close second, was chosen as the appropriate subsystem.

Based on JPL projections, the line-of-sight microwave land link has been employed. The initial assumptions were that the total cost including installation costs was 300 K per mile. Further projections and consideration of relative costs reduced the assumed cost. The diversity distance is assumed to be 10 miles for most applications.

Buildings and the associated real estate serve to house the communication and power equipment and the antenna system for a ground station. Costs are estimated for two types of installations: the main site and the diversity site. Though costs for the buildings and land are highly dependent on location an average is chosen for modelling purposes.

4.3 Satellite Subsystem Models

This model characterizes the cost, weight and performance of communication antennas for space application. Included in the model are reflector and feeds for a multi-feed, multi-beam antenna. For all applications considered separate receive and transmit antennas were used.

Extensions to this model should include multi-beam lens antennas and phased arrays. Applications requiring these antennas are currently modelled with the reflector antenna model.

The space transmitter model gives the transmitter cost, weight and efficiency as a function of transmitter power. The cost of the transmitter is modelled as a constant for the IF amplifier, local oscillator at 35 GHz and the up-converter/40 GHz filter. The same model applies to both the point-to-point and the broadcast applications. Frequency dependence is not included in the broadcast case since only a single set of frequencies was used in the analysis.

The space transmitter consists of a 5-6 GHz IF, which receives its input from the satellite-borne switching system. The amplified signal is up-converted tp 40-41 GHz frequency range, filtered to provide only a 40-51 GHz signal to the HPA and transmitter to the transmit antenna. The system consists of the 5-6 GHz IF, a 35 GHz IF, an up-converter, bandpass filter (40-41 GHz) and a 50-41 GHz HPA.

It is assumed that the IF, up-converter, 35 GHz LO and band-pass filter are available with capabilities for use in space-qualified applications. A constant cost is used for each of these. The HPA cost is obtained by extrapolating lower lower frequency curves in comparison with individual units currently available at lower frequencies and at 40-51 GHz. The weight models and efficiency models are taken from Hughes reports.

The space receiver model gives the cost as a function of the 50-51 GHz noise temperature. The cost for mixer, LO and IF amplifier are given as an additive constant. The same model applies to both the point-to-point and the broadcast applications. Frequency dependence is not included in the broadcast case since only a single set of frequencies was used in the analysis.

The space receiver consists of a 50-51 GHz LNA, a Schottky barrier mixer, solid state LO, a filter before the IF, and an IF amplifier. This subsystem receives the up-link signal at 40-51 GHz, amplifies in LNA, down-converts to 5-6 GHz and amplifies at this IF. This signal is then presented to switching system. The cost does not include additional filters, and switches after the IF amplifier.

The model is based upon curves extrapolated from lower frequencies for LNA's with a factor added for space qualified units. The model further assumes that the current state-of-the-art provides mixers, LO's and IF amplifiers suitable for operation. The weight is assumed as a constant factor.

The <u>space signal processing</u> is used to switch the subchannels of the incoming beams to the outgoing beams according to traffic requirements. Subsystems for both frequency-division multiple access and time-division multiple access systems are modelled. In the FDMA case subchannel signals are separated using bandpass filters and switched based only on traffic volume between the various terminals. A block diagram is given in Figure 4.4. In the TDMA case subchannel signals are separated by switching in a synchronized time frame. A block diagram is given in Figure 4.5. The switching hardware requirements for the TDMA case are considerably less than those for the FDMA case.

The <u>attitude control system</u> maintains the satellite orientation by sensing its current attitude, computing any necessary change in attitude, and applying the appropriate torque to the satellite. The functions are implemented with (1) attitude sensors (horizon sensors, star trackers, beacon trackers, inertial units, etc.), (2) control electronics (analog or digital circuitry), and (3) actuators (thrusters or momentum wheels).

Cost and weight models are derived which depend on attitude control tolerance and satellite weight. The dependence of the weight model on total satellite weight requries that an iterative computation be performed in the analysis procedure.

The attitude control system weight is the sum of the sensor and electronics weight, W_{se}, and the actuator weight, W_a. The sensor and electronic weight depends upon the attitude tolerance while the actuator weight depends upon disturbance torque level and therefore upon the size of the satellite. The weight model assumes that (1) a nominal attitude control system has 80% of its weight in the actuators, and that (2) the sensor and electronics weight varies with attitude tolerance according to $W_{se} \propto \sqrt{1/B}$.

The model coefficients are based upon a nominal satellite whose attitude control system weight is 3% of the satellite weight for an attitude tolerance of 0.1° in pitch and roll and is 0.3° in yaw.

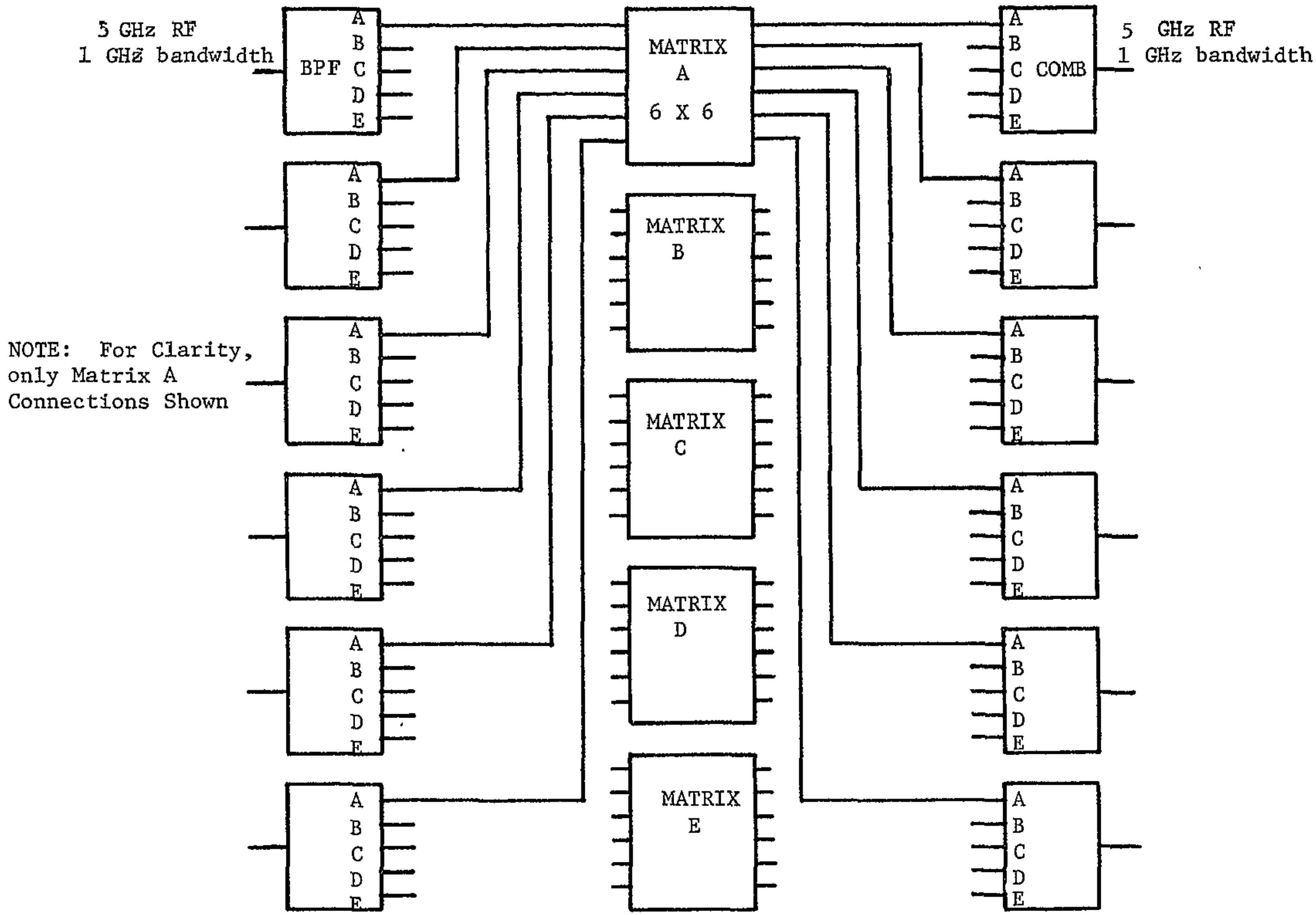

Figure 4.4 FDMA Space Signal Processing Subsystem

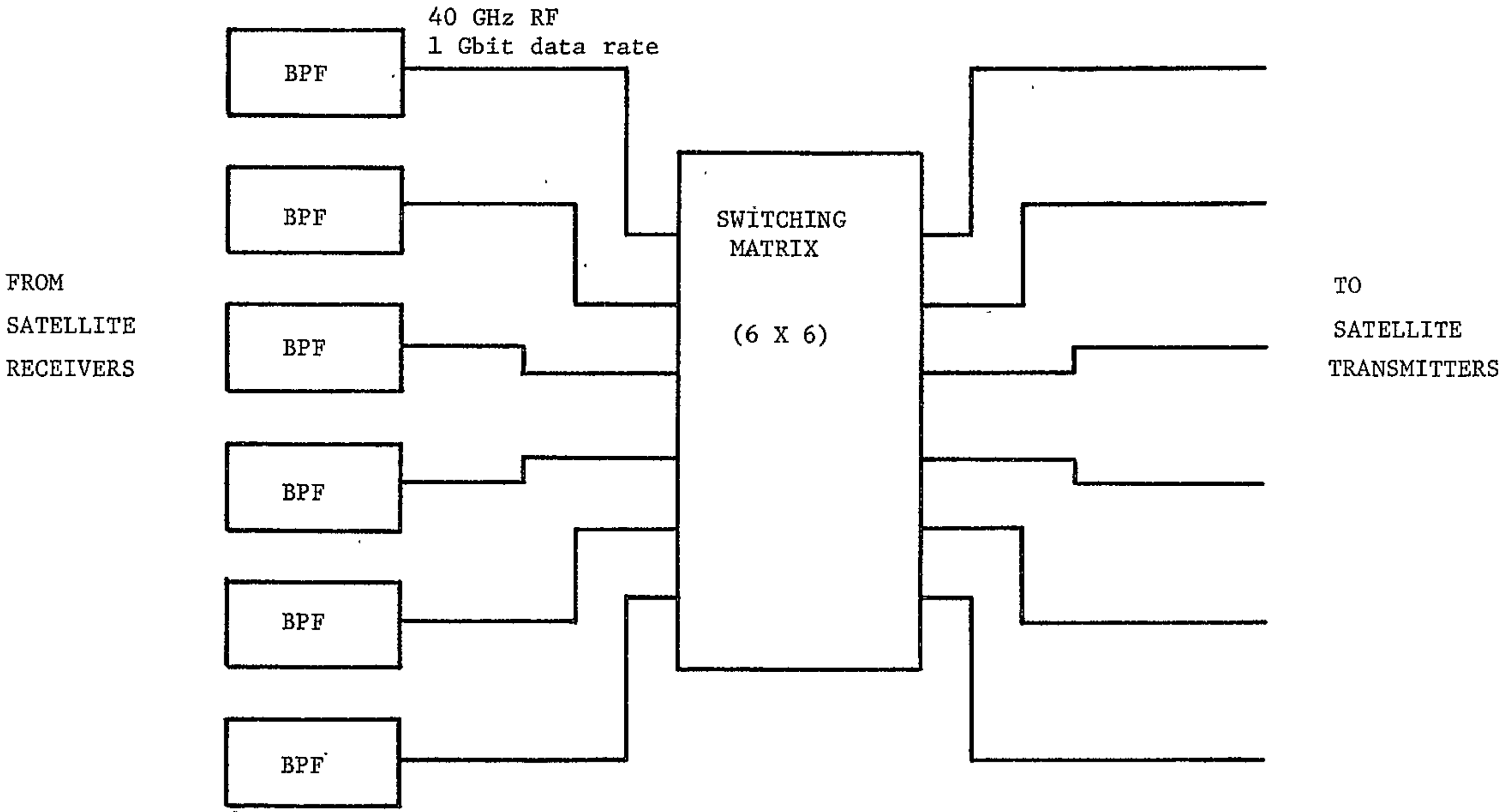

Figure 4.5 TDMA Space Signal Processing Subsystem

The station keeping system is provided to maintain the position of the communication satellite in synchronous orbit. Two technologies were considered for this system: one requiring hydrazine propellant for positioning and another using an ion engine. The ion engine system was used in the analysis due to its large advantage in weight.

The structure provides the support and mounting surfaces for all subsystem equipment and bears the majority of spacecraft dynamic stress loads. It includes struts, substrates, antenna supports, experimental booms, solar panel supports, mechanical despin equipment and interstage. Thermal control maintains the temperature of the platform and equipment within allowable limits. It consists of paint, insulation, lower assemblies, temperature sensors and heat pipes. The structure and thermal control are included in the same model since for unmanned spacecraft the thermal control is considered to be an integral part of the structure. Better model estimates may be made by considering these components together.

The power supply generates, regulates, stores and distributes electrical power to all satellite subsystems. It includes solar panels, regulators, convertors, batteries and wiring harnesses. Models are given for power supply cost and weight as a function of power supplied. A further model is given which relates power supplied to communication payload.

The transmitter power is assumed to be the most significant factor in prime power requirements. For transmitter powers below 500 watts a 50% increment in prime power is allocated for other systems. For each watt over 500 a 10% addition is made for other systems.

Tables 4.3, 4.4, and 4.5 present the cost and weight model equations described above. Appendix C contains further details on these models.

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TABLE 4.3 GROUND COST MODELS*

Cost Model	Equation	Parameters
Ground Antenna Point-to-Point Case	$C_1 = 250.99 + 9.8057\ D^{1.7852}$ $C_2 = 260.01 + 6.544\ D^{2.1164}$ $C = C_2$ for $F \geq 30$ $C = (1-a)\ C_1 + aC_2$ for $18 \leq F < 30$ where $a = (F-18)/12$	Dish diameter, D(m) Range: 1-10 Transmitter frequency, F (GHz) Range: 18-60
Ground Antenna Broadcast Case	$C = 1.95\ D^2 + 5$	Dish diameter, D (m) Range: 1-10
Radome	$C = 16.9 - 1.982\ D + 0.258\ D^2$	Radome diameter, D (m) Range: 3.9 - 15
Ground Pointing and Control Point-to-Case	$C = a + b\ E$ $E < E_o$ $= C_o$ $E \geq E_o$ where a, b, E_o and C_o depend on D. D a b E_o C_o 2.4 190 -280 .59 25 4.5 225 -325 .58 37 10.0 490 -780 .54 70	Dish diameter, D (m) Range: 1-10 Pointing error, E (degrees) Range: 0.02-1.0
Ground Pointing and Control Broadcast Case	$C_B = 0.1 \cdot C_{PP}$	C_{PP} = point-to-point ground pointing and control cost
Ground Transmitter	$C = a\ (29.5 + 0.084\ P)\ (0.000632\ BW + 0.368)$ where $a = 1.0$ $30 < F \leq 60$ $= 0.8$ $20 < F \leq 30$ $= 0.64$ $18 < F \leq 20$	Transmitter power, P (W) Range: 0-1500 Transmitter frequency, F (GHz) Range: 18-60 Transmitter bandwidth, Range 0-1000 BW/MHz
Ground Receiver	$C = a\ (C_{LNA}\ (NF) + C_{mixer} + C_{LO} + C_{IF})$ $= a\ (C_{LNA}\ (NF) + 6.66)\ (0.000632\ BW + 0.368)$ where $a = 1.0$ $60 \geq F > 30$ $= 0.8$ $30 \geq F > 20$ $= 0.64$ $20 \geq F \geq 18$ and $C_{LNA}\ (NF) = 30.00$ $4.0 \geq NF \geq 1.95$ $= 106.72 - 39.34\ NF$ $1.95 > NF \geq 1.34$ $= 164.35 - 82.35\ NF$ $1.34 > NF \geq 1.17$ $= 502.57 - 371.43\ NF$ $1.17 > NF \geq 1.03$ $= 120.00$ $1.03 > NF \geq 1.0$	LNA noise figure, NF (linear) Range: 1-4 Receiver frequency, F (GHz) Range: 18-60 Receiver bandwidth, BW (MHz) Range: 0-1000
Ground Signal Processing FDMA	downlink subsystem $C_o = 10\ \frac{B_o}{BW}\ (18 + 36\ \log \frac{BW}{B_o})$ $100 \leq BW \leq 316$ $= 10\ \frac{B_o}{BW}\ (-1 + 74\ \log \frac{BW}{B_o})$ $316 \leq BW \leq 1000$ uplink subsystem $C_u = 10\ \frac{B_o}{BW}\ (16 + 36\ \log \frac{BW}{B_o})$ $100 \leq BW \leq 316$ $= 10\ \frac{B_o}{BW}\ (-5 + 78\ \log \frac{BW}{B_o})$ $316 \leq BW \leq 1000$ WHERE B_o = 100 MHz	Baseband channel bandwidth, BW (MHz)
Ground Signal Processing TDMA	Subsystem Cost = $2834 K	
Bulk Data Storage	$C = 2.5\ R + 0.125\ V + 50$	Data rate, R (Mbit/sec) Range: 100-1000 Data volume, V (Mbit) Range: 1000-6000
Landline Interface	Highspeed modem cost, $C_1 = 40 + 4R$ Television headin cost, $C_2 = 10 + 30N$ Multiplexed voice interface cost, $C_3 = 10 + 25N$	Two-way data rate, R (Mbs) Number of 6 MHz television channels, N. Number of 6 MHz baseband MHX voice channels, M.
Diversity Landline	$C = 100.7\ L$ for first one-way link $= 40.3\ L$ for return one-way link	Diversity distance, L (mi) Range: 0-10
Building and Real Estate	Main site building and land - \$100 K (1976) Diversity site building and land - \$50 K (1976)	

*Refer to Appendix for details

TABLE 4.4 SATELLITE COST MODELS*

Cost Model	Equation	Parameters
Satellite Antenna	$C = (0.8 + 0.2N)\ (61.924 + 82.716\ D^{2.2464})$ $F = 18$ $= (0.8 + 0.2N)\ (61.924 + 145.34\ D^{2})$ $30 \le F \le 60$ interpolate between these expressions for $18 < F < 30$	Antenna diameter, D (M) Range: 1-5 Operating frequency, F (GHz) Range: 18-60 Number of feeds, N. Range: 1-10
Satellite Transmitter	$C = a\ [C_{HPA}\ (P) + C_{UC} + C_{LO} + C_{IF} + C_{F})$ $= a\ (0.53\ P + 37)$ where $a = 1.0$ $30 < F \le 60$ $a = 0.8$ $20 < F \le 30$ $a = 0.64$ $18 \le F < 20$	HPA Power, P (w) Range: 0-1500 Operating frequency, F (GHz) Range: 18-60
Satellite Receiver	$C = a\ (C_{LNA}\ (NF) + C_{MIXER} + C_{LO} + C_{IF} + C_{F})$ $= a\ (\frac{8.966}{NF-1} + 108 + 49)$ where a is as above	LNA noise figure, NF (linear) Range: 1-4 Operating frequency, F (GHz) Range: 18-60
Satellite Signal Processing FDMA	$C = (M)\ (2N)\ (0.65M + 0.1)$ (Switches) $+ (N)\ (M)\ (2.15 - 0.15M)$ (Filters) $+ (N)\ (0.5M - 0.5)$ (Combiner)	Number of channels, N. Range: 1-6 Number of subchannels per channel, M. Range: 1-5
Satellite Signal Processing TDMA	$C = (2N)\ (1.3\ N + 0.2)$ (Switches) $+ (N)\ (1.85)$ (Filters)	Number of channels, N. Range: 1-15
Attitude Control System	$C = 103\ W_{ACS}^{0.5194} + 17.19\ W_{ACS}^{0.8569}$	Attitude control system weight, W_{ACS} (lb)
Station Keeping System	$C = 72\ (W_{SKS})^{0.52} + 9.5\ (W_{SKS})^{0.86}$	Station keeping system weight, W_{SKS} (lb)
Structure and Thermal Control	$C = 131.55 + 33.3\ W_{STC}^{0.54} + 9.99\ W_{STC}^{0.72}$	Structure and thermal control weight, W_{STC} (lb)
Satellite Power Supply	$C = 3.1258 + 2.6804\ P^{0.69486}$	Power supplied, P (W) Range: 0-8000

*Refer to Appendix for details.

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TABLE 4.5 SATELLITE WEIGHT MODELS*

Weight Model	Equation	Parameters
Satellite Antenna	$W = 0.165 + 8.0877\ D^{2.012} + N$ $F = 18$ $= 8.9125\ D^2 + N$ $30 \leq F \leq 60$ interpolate between these expressions for $18 \leq F \leq 30$	Antenna diameter, D (M) Range: 1-5 Operating frequency, F (GHz) Range: 18-60 Number of feeds, N. Range: 1-10
Satellite Transmitter	$W = b\ [9.93 + 0.939\ P^{0.187} + 10\ (BW-100)/900]$ where $b = 1.0$ $30 < F \leq 60$ $= 1.1$ $20 < F \leq 30$ $= 1.21$ $18 \leq F \leq 20$	Transmitter power, P (w) Range: 0-1500 Operating frequency, F (GHz) Range: 18-60 Transmitter bandwidth, BW (MHz) Range: 100-1000
Satellite Receiver	$W = 10$ $30 < F \leq 60$ $= 11$ $20 < F \leq 30$ $= 12.1$ $18 \leq F \leq 20$	Operating frequency, F (GHz) Range: 18-60
Satellite Signal Processing FDMA	$W = (M)\ (2N)\ (0.16\ M + 0.08)$ (Switches) $+ (N)\ (M)\ (0.5)$ (Filters) $+ (N)\ (0.3\ M - 0.3)/0.4536$ (Combiners)	Number of channels, N. Range: 1-6 Number of subchannels, M. Range: 1-5
Satellite Signal Processing TDMA	$W = (2N)\ (0.16\ N + 0.08)$ (Switches) $+ (N)\ (0.5)/0.4536$ (Filters)	Number of channels, N. Range: 1-15
Attitude Control System	$W_{ACS} = W_{SAT}\ (0.024 + .0019/\sqrt{B}$	Attitude control tolerance, B (deg) Satellite weight, W_{SAT} (lb)
Station Keeping System	$W_{SKS} = W_{SAT}\ [0.12 - 0.03 \log (10E)]$	Station keeping accuracy, E (deg) Satellite weight, W_{SAT} (lb)
Structure and Thermal Control	$W_{STC} = (W_{SAT} - 200)/3.762$	Satellite weight, W_{SAT} (lb) Range: 500-10,000
Satellite Power Supply	$W = 1 + 0.2P$	Power supplied, P (W) Range: 0-8000

*Refer to Appendix for details.

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SECTION 5
COMMUNICATION SATELLITE APPLICATIONS

5.1 Basic Considerations of User Applications

During the program considerable effort was devoted to the development of user applications. The purpose of developing user applications was to provide a realistic background for the development of subsystem models and to demonstrate the use of the SCOR model in evaluating proposed satellite communication systems. Based on the applications that were developed, minimum cost systems were determined based on maintaining desired system constraints, sensitivities of system costs to subsystem cost variations were evaluated, and critical technologies were determined.

5.1.1 Application Selection

There are many potential applications of millimeter wave communications satellites in both the public and private sector. This study used two basic systems which could be adopted for a variety of specific end users. For convenience the two basic systems have been designated point to point and broadcast. The point to point system is considered to provide broadband connections among a relatively small number of earth terminals whereas the broadcast system provides narrowband communications among a relatively large number of earth terminals. There are a number of similarities in the applications which will be discussed in the next paragraph.

5.1.2 Common Elements

Both of the applications were based on a number of common assumptions. Due to the anticipated pointing accuracy requirements, a body-stabilized satellite was assumed. To maintain reasonable earth station tracking requirements, the satellites were assumed to be in a geo-stationary orbit (about 35,000 km) positioned over the middle of the continental United States. An available RF bandwidth of one GHz was assumed for both applications on this uplink and downlink. The uplink frequency was considered to be in the 50 GHz band while the downlink was considered to be 40 GHz. In an auxiliary study to application I, termed application IA, the uplink frequency was selected to be 30 GHz with a downlink frequency of 18 GHz while all the other parameters were the same as in application I.

5.1.3 Level of detail modelled

The level of detail selected in modelling the system required careful consideration. If the models were too superficial, the validity of the results

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would be questionable and of little value. However, excessive modelling detail would require an inordinate amount of processing which to be valid would have to be performed over an extensively detailed data base resulting in excessive program costs. The level of detail chosen represents a compromise which provides sufficient detail for realistic model development at a reasonable program cost. Based on these considerations, the space and ground subsystem models of Table 5.1 were developed and used in constructing the various system configurations. The two user applications were based on the subsystems in Table 5.1. These applications are described in more detail in the following paragraphs.

5.2 Application I: Point-to-Point

In Application I simultaneous point-to-point transmissions among a number of ground terminals is considered. The baseline system is assumed to provide wideband communications among the following metropolitan areas:

New York	Atlanta	San Juan
Denver	Los Angeles	Honolulu

As a variation of Application I, the impact of varying the number of ground stations from 2 to 10 was calculated with results which will be described later. The geographical coverage of the baseline system is shown in Figure 5.1. Decreasing or increasing the number of ground stations will add to or eliminate the indicated ground stations. The Application I system block diagram is shown in Figure 5.2. Although a single satellite antenna is indicated, the system could be implemented with either a single antenna with a diplexer or separate transmit and receive antennas. Each ground station is considered to be identical with the capability of full duplex high speed data, broadcast quality television, or multiplex voice. The satellite has a separate beam for each earth station allowing each of the stations to use the full one GHz RF bandwidth. With sufficient transmit power, this bandwidth is capable of providing one of the services indicated in Table 5.2 or a lower capacity mix of all the services at each ground terminal. Four possible implementations of application number one are listed below.

- System A - frequency division multiplex, no onboard switching.
- System B - frequency division multiplex, onboard switching.
- System C - time division multiplex, no onboard switching.
- System D - time division multiplex, onboard switching.

Table 5.1. Space and Ground Subsystems

SPACE	
Communications	Support
o antenna	o attitude control
o transmitter	o station keeping
o receiver	o structure and thermal control
o signal processing	o satellite power
GROUND	
o antenna	o radome
o transmitter	o pointing and control
o receiver	o diversity land line transmit
o signal processing	o diversity land line receive
o bulk data storage	o ground station building
o high speed modem	o diversity station building
o television head in	
o voice multiplex	

Table 5.2. Capacity of Application I Services

Service	Bandwidth/Channel	Channels/1GHz BW
Telephone Grade Voice	30 KHz	30,000
Broadcast Quality TV	36 MHz	27
Picturephone R	6 MHz	165
DATA	Rate Dependent	1-1.5 Gbps

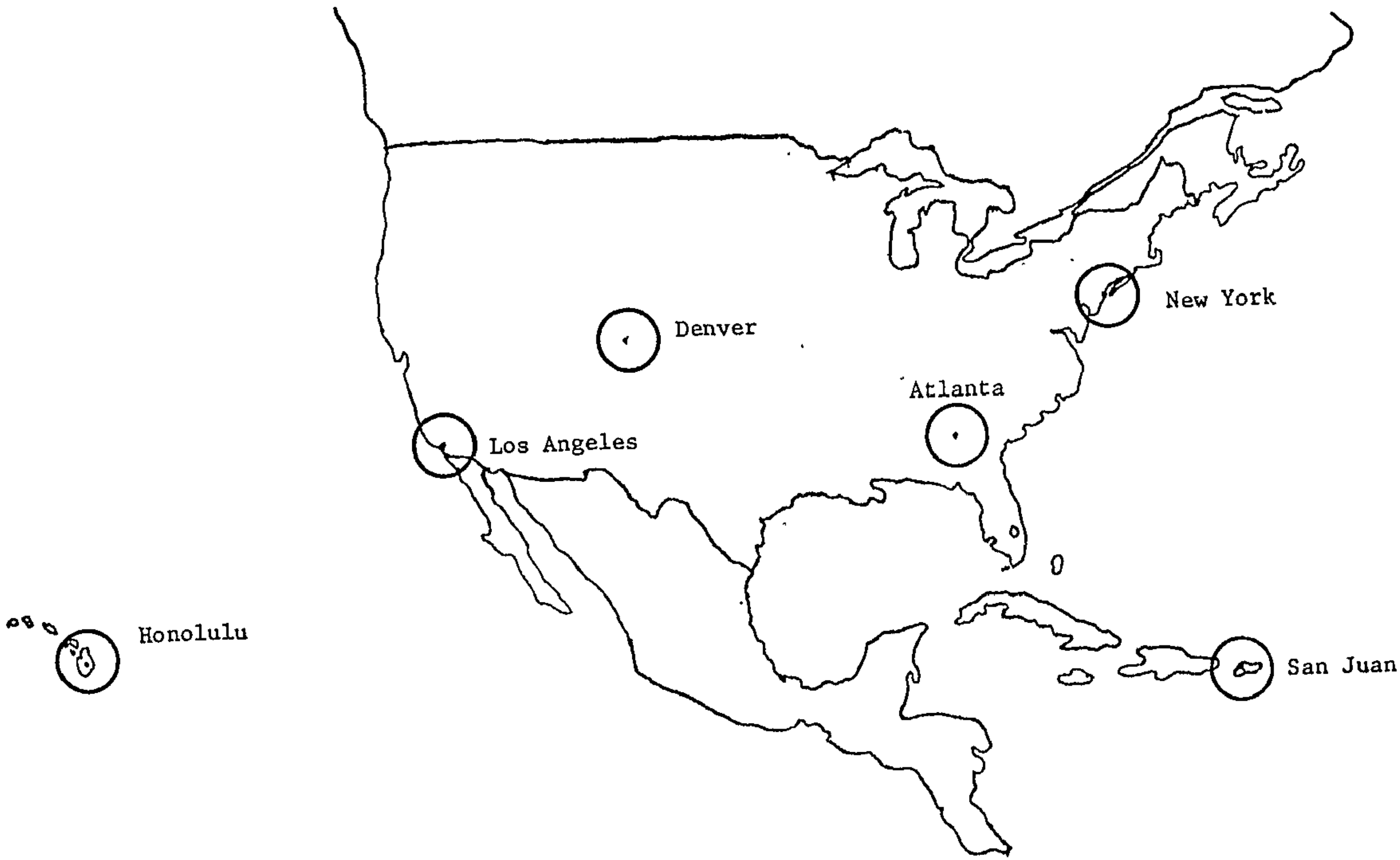

Figure 5.1. Application I Coverage Area

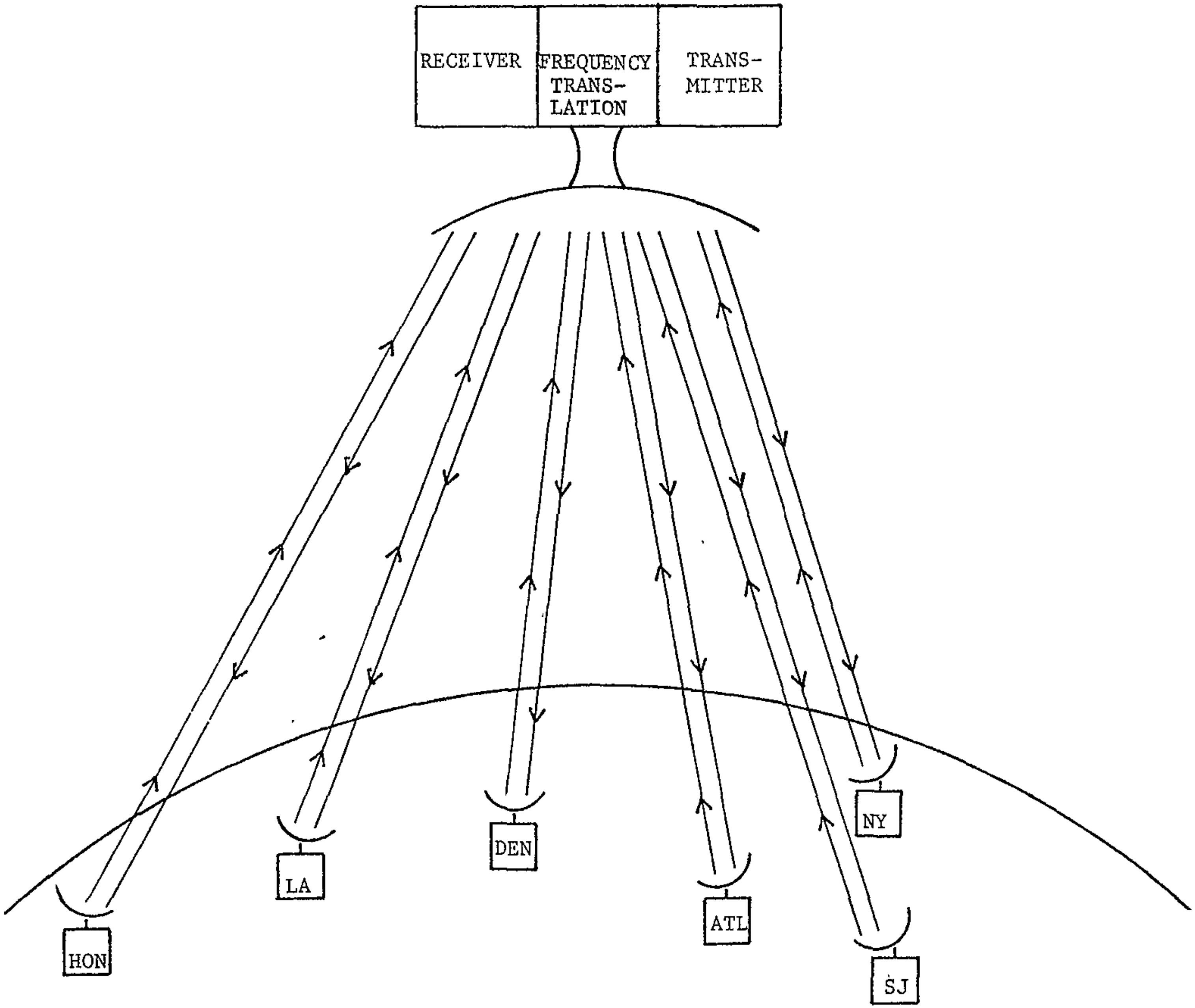

Figure 5.2. Application I System Block Diagram

With the frequency division multiplex systems, each ground station's one GHz bandwidth is divided into frequency channels for connection with each of the other ground stations while in the time division multiplex system, the full bandwidth is used for transmission between two ground stations at a given time with connection between all station pairs provided on a time dependent basis. A hybrid multiplexing system which could be considered is frequency/time division multiplex in which the RF bandwidth is divided into a number of frequency channels, each of which has a TDM signal applied to it.

Demand assignment of the channels will not be considered since this requirement primarily impacts the control circuitry and not the millimeter wave communication circuits. The four previously listed systems are briefly discussed in the succeeding paragraphs followed by a discussion of the selected approaches for the Application I system.

5.2.1 System A: FDM - No Onboard Switching

In this configuration, a frequency plan would be developed which would allow the distribution of data through the satellite on a channelized basis. As an example, consider dividing the one GHz bandwidth into five equal channels of 200 MHz each as follows:

	Baseband	Uplink	Downlink
Channel A	0-200 MHz	50.0-50.2 GHz	40.0-40.2 GHz
Channel B	200-400 MHz	50.2-50.4 GHz	40.2-40.4 GHz
Channel C	400-600 MHz	50.4-50.6 GHz	40.4-40.6 GHz
Channel D	600-800 MHz	50.6-50.8 GHz	40.6-40.8 GHz
Channel E	800-1000 MHz	50.8-51.0 GHz	40.8-41.0 GHz

These channels could then be allocated to the ground terminals as follows.

	To					
From	NY	SJ	ATL	DEN	LA	HON
New York	--	A	B	C	D	E
San Juan	E	--	A	B	C	D
Atlanta	D	E	--	A	B	C
Denver	C	D	E	--	A	B
Los Angeles	B	C	D	E	--	A
Honolulu	A	B	C	D	E	--

A simplified block diagram of a satellite configuration to provide this arrangement is shown in Figure 5.3.

The signals are received and amplified in the 50-51 GHz band and band pass filtered to remove any out of band contents. The signals are then mixed with the first local oscillator 42 GHz signal to produce the 8-9 GHz intermediate frequency (IF) signal. Each IF signal is then split into five distinct frequency bands by the channelizing filters A through E. These signals are amplified and connected to the proper output multiplexers as indicated in Figure 5.3. The output of each of the multiplexers is then mixed with the second LO signal to produce the 40-41 GHz signal which is amplified and routed to the downlink antenna associated with the multiplexer. Although separate receive and transmit antenna are shown, a single antenna could be used with the inclusion of diplexers at the antenna to separate the 40 GHz and 50 GHz signals.

An alternate approach which might be used if 200 MHz bandwidth filters exist at 40 GHz would be to convert directly to the 40-41 GHz downlink following the initial 50 GHz amplifier. The channelizing, amplification and multiplexing would be performed at 40 GHz and then would be amplified for transmission.

A more efficient use of the bandwidth could be made by determining the traffic statistics of each link and dividing the channels into unequal bandwidths. The heavy traffic links could then be assigned to wider bandwidth (and thus higher data rate) channels with lighter traffic links assigned to narrower bandwidth channels.

5.2.2 System B: FDM - Onboard Switching

This system would be similar to system A with the flexibility of onboard switching added. The frequency band at each ground terminal could be divided into five equal bandwidths as before with the connections between particular ground terminals made through an onboard switch. This capability would allow bandwidth between particular ground terminals to be reallocated as required by traffic. This reallocation would occur on both long term and short term bases. Long term changes could be those occurring over a period of months due to basic shifts in traffic while short term changes would be those occurring over a period of hours due to daily variations in traffic. For example, early in the day, Denver to New York traffic would be higher than Denver to Los Angeles traffic whereas later in the day the reverse would be true.

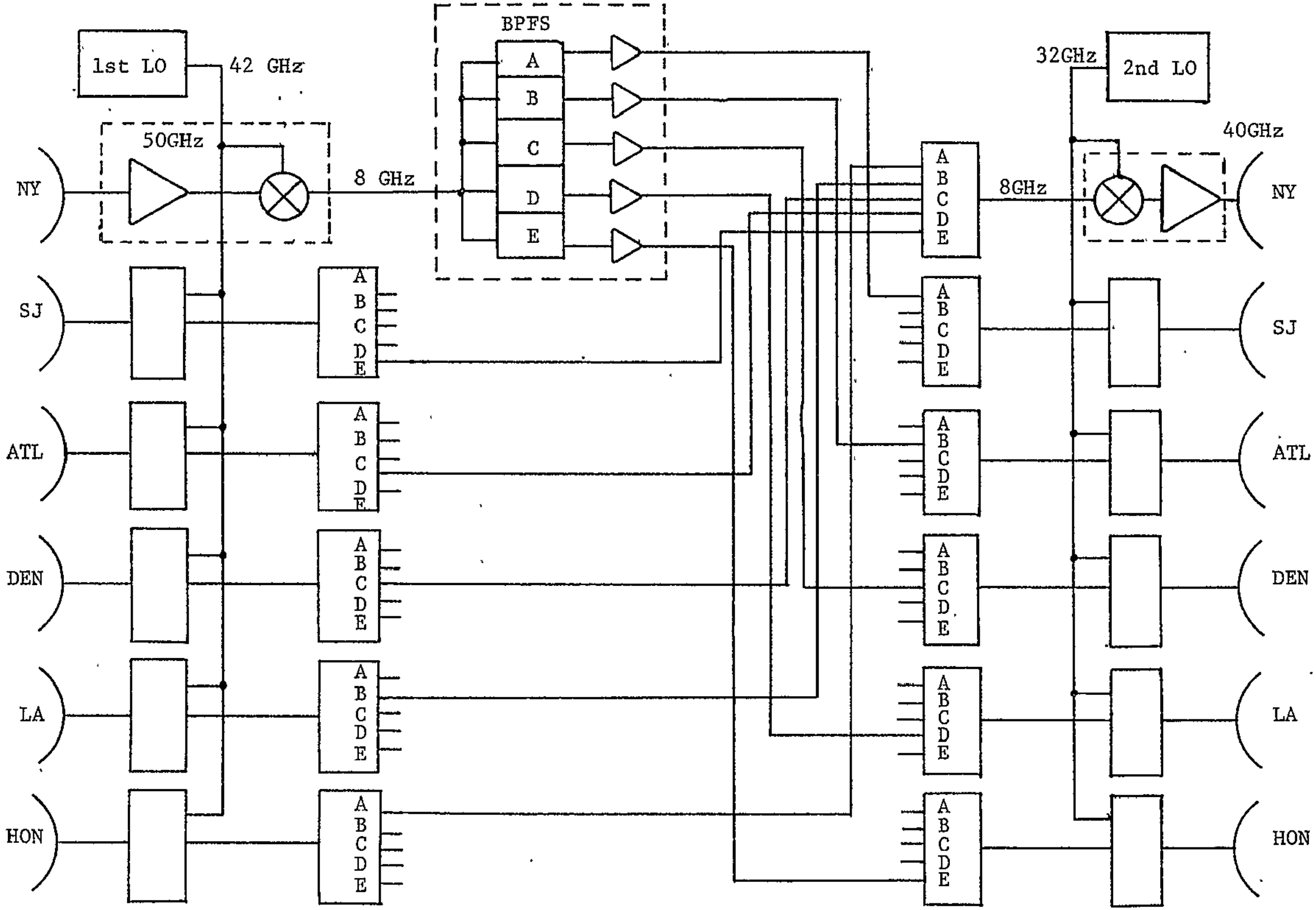

Figure 5.3. Satellite Block Diagram - FDM
No Onboard Switching

Figure 5.4 is a simplified block diagram of System B. The receivers and the input multiplexers would be the same as in System A. However, the signals from the input multiplexers would be routed to five 6 X 6 switch matrices, one for each channel. Under direction of a matrix controller, which is controlled from the ground, the channels from a given ground terminal are switched to the selected ground terminal for that channel.

The flexibility of this system is achieved at the cost of more complex satellite equipment (the switching matrices) and additional ground control equipment.

The same arguments for converting to 40 GHz for on board signal processing as in System A would apply to System B.

5.2.3 System C: TDM - No Onboard Switching

In a time division multiplex system with no onboard switching, the advantage of a multibeam system is diminished since the signals from each uplink are processed at the same frequency. This results from the requirement that only one ground terminal to ground terminal link may be connected at a given time to avoid interference. In a TDM system, simultaneous interconnection of multiple links is not possible without some form of onboard switching. The only advantage gained in a multibeam TDM system with no onboard switching is the increase in gain and decrease in noise due to limiting the signal energy to a smaller area that that included in a single complete coverage antenna.

Figure 5.5 is a simplified diagram of the System C satellite communication equipment. The signals from the uplink 50-51 GHz beams are combined after they have received the initial amplication. (Only one beam at a time will have a signal on it). The signal is then passed through a bandpass filter and mixed with the local oscillator signal to convert it to the downlink frequency of 40-41 GHz. This signal is then amplified and routed to the output multiplexer from which it is applied through bandpass filters and final amplifiers to the downlink antennas. Timing and synchronization equipment is required at each ground terminal to enable both signal transmission and signal reception at the proper time.

5.2.4 System D: Time Division Multiplex - Onboard Switching

This system uses the frequency spectrum much more efficiently than System C since all uplink and downlink beams may simultaneously carry traffic. This is true because the onboard switching arrangement allows the beam inter-connections to be completed without signal interference.

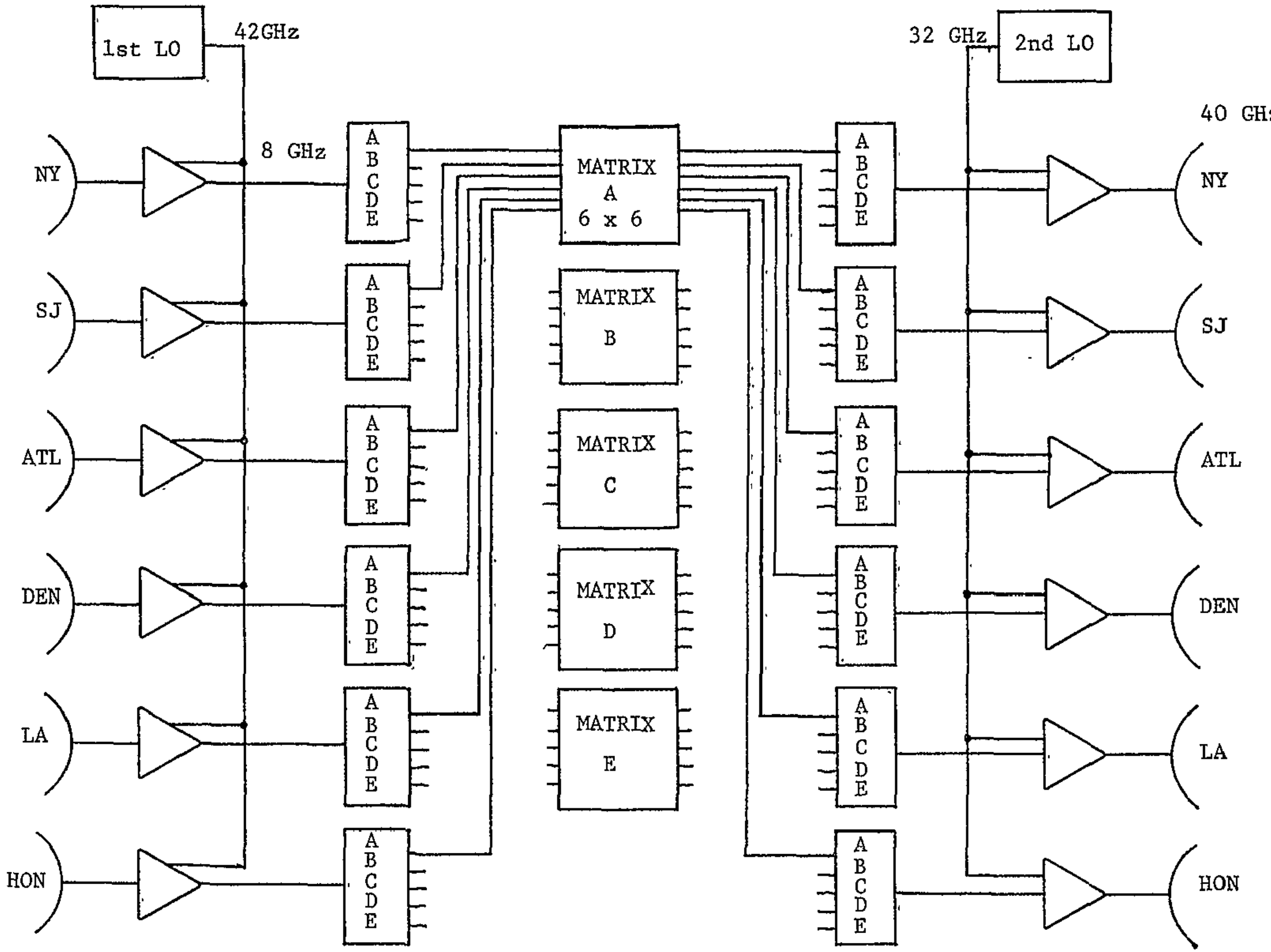

Figure 5.4. Satellite Block Diagram - FDM
Onboard Switching

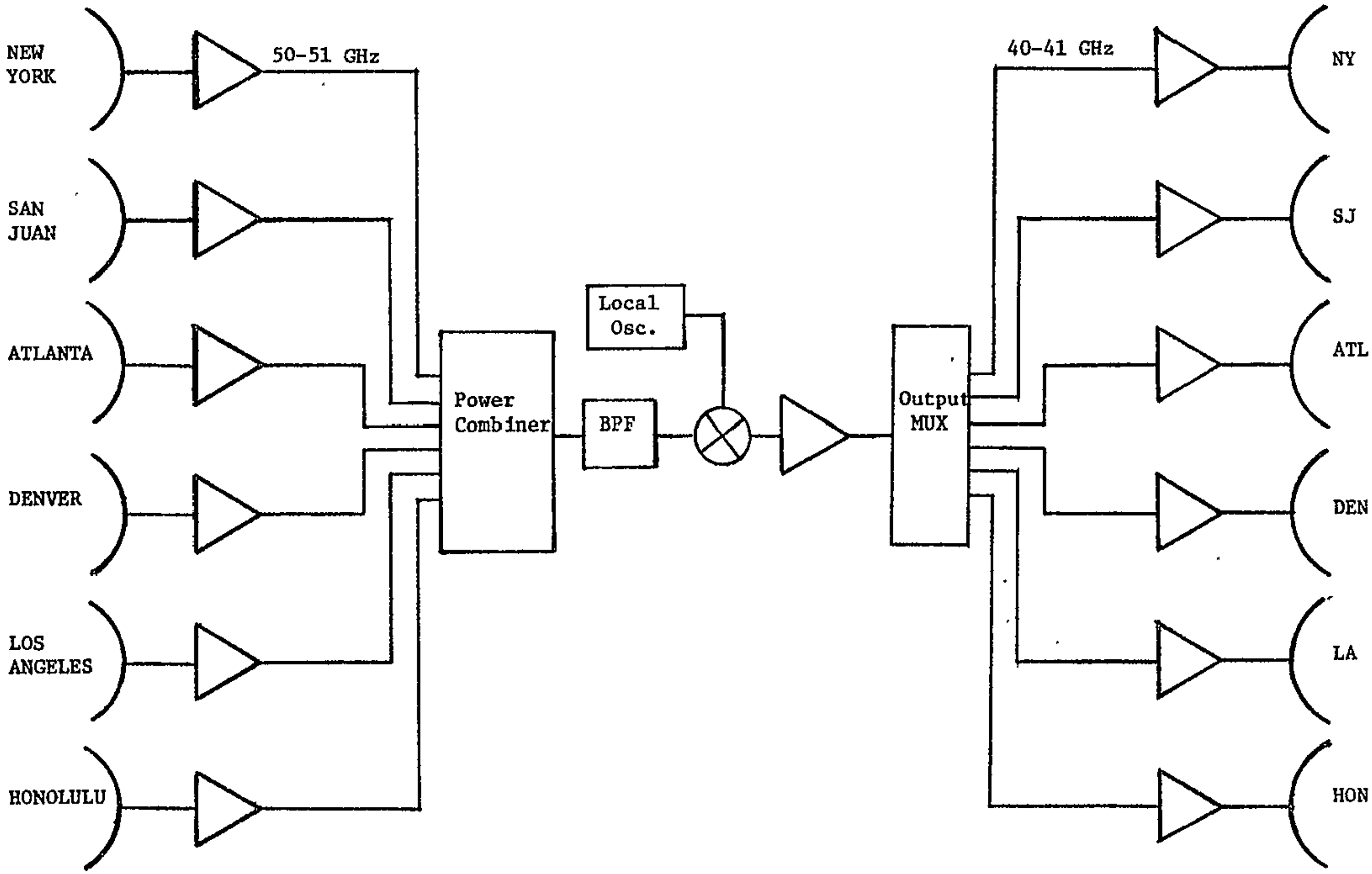

Figure 5.5. SATELLITE BLOCK DIAGRAM - TDM, No Onboard Switching

In this configuration, the beams are connected in a time dependent manner. During the time of connection, the full one GHz bandwidth is available between the connected terminals. For this application five time slots would be required to accomplish connections of all beams to each other. A typical multiplex plan is shown below.

	To				
From	T1	T2	T3	T4	T5
NY	SJ	ATL	DEN	LA	HON
SJ	NY	LA	HON	DEN	ATL
ATL	DEN	NY	LA	HON	SJ
DEN	ATL	HON	NY	SJ	LA
LA	HON	SJ	ATL	NY	DEN
HON	LA	DEN	SJ	ATL	NY

During T1, New York and San Juan would be connected, Atlanta and Denver would be connected, etc. The connections would be made in accordance with the table, repeating every five time slots. With a time slot of two milliseconds and a bit rate of one Gbps, two megabits of data would be transmitted in each direction between the connected terminals during each connection with a total throughput of 200 Mbps. The actual throughput data rate would be somewhat less than this due to the requirement for timing and synchronization and error coding bits.

Figure 5.6 is a block diagram of the satellite communications and configuration required to implement System D. After the beam signals have been received, amplified, and filtered at 50-51 GHz, they are routed to the mixers where they are downconverted to the 8 GHz IF. They are then connected to a 6 by 6 microwave switching matrix where they are sequentially switched to the downlink connections. On each downlink connection, the signals are converted to 40-41 GHz, and amplified for transmission to the ground terminals.

In the same manner as discussed for System A, the signals may be converted to the downlink frequency for onboard processing. This would be accomplished by replacing the indicated first local oscillator with a local oscillator which would effect a conversion to 40 GHz for onboard switching and amplification for transmission to the ground stations. A major component requirement for this implementation would be the existence of fast 40 GHz onboard switches which would be cost effective.

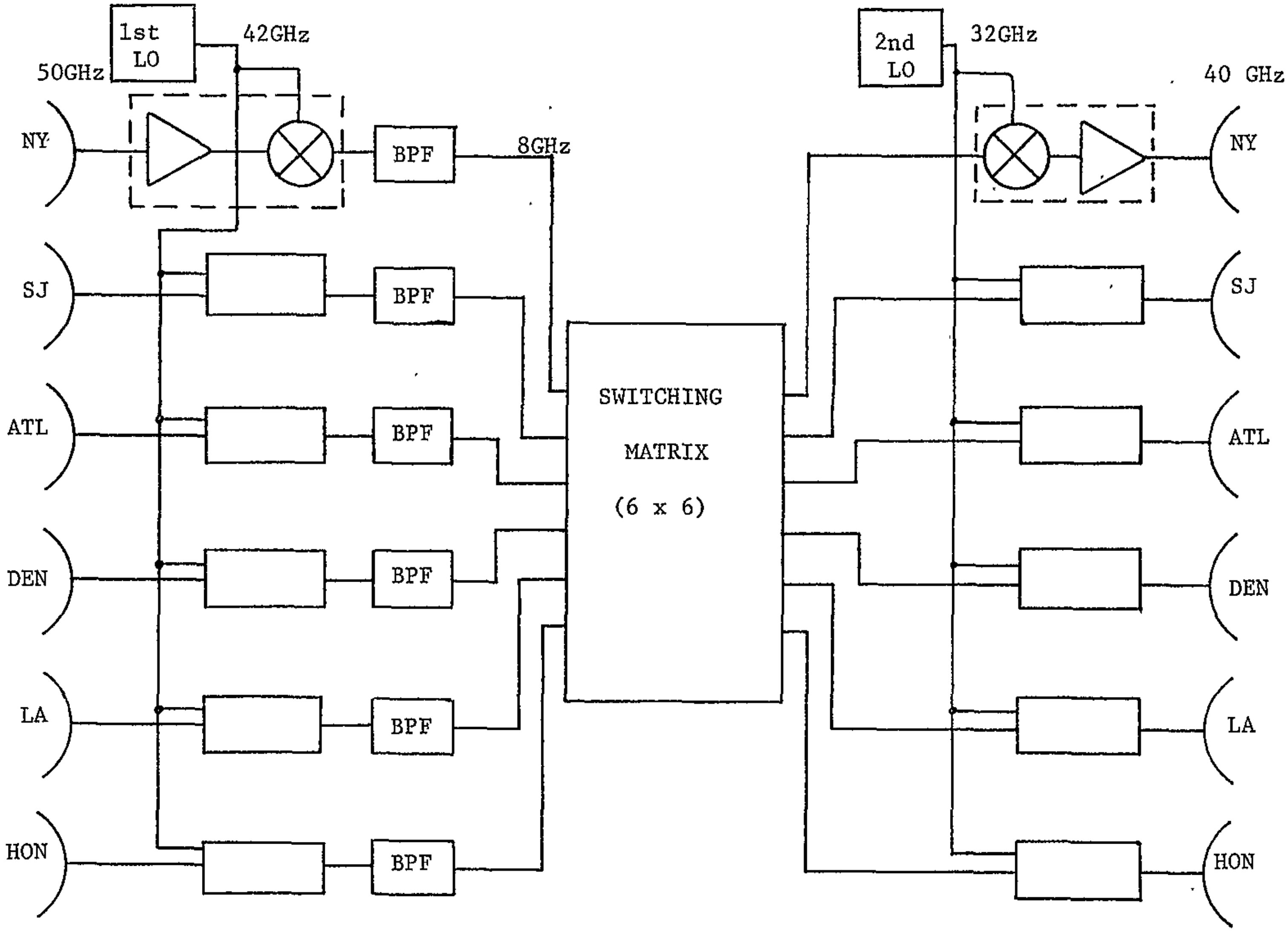

Figure 5.6. Satellite Block Diagram - TDM, Onboard Switching

A third alternative would be to demodulate the received signal and perform all onboard signal processing at baseband with remodulation for transmission. This has the advantage of significant signal to noise ratio improvement due to on-board digital regeneration.

After extensive consideration, it was decided to model both the FDM and the TDM systems for application I. The implementations selected are described in the following paragraphs.

5.2.5 Selected Implementation - FDM

The FDM system chosen for modeling was system B, FDM with on board switching. As described earlier, the system is based upon the ability of the satellite to interconnect a relatively small number of high capacity earth stations. Each of the earth stations is capable of receiving video, data, or multiplexed voice information from ground sources. For generality, let the number of earth stations be designated by N. Then each earth station will divide the one GHz bandwidth into N-1 contiguous frequency channels. Then, depending upon demand, each earth station could access each of the other earth stations on one or more of the N-1 channels.

A block diagram of the Application I FDM earth station is shown in figure 5.7. The earth station may be configured with varying degrees of transmit and receive diversity. Also configurations using and not using radomes may be constructed.

The basic earth station operation may be described as follows. Input data are received through a multiplexer and placed in a data buffer for the appropriate receiving earth station. A separate buffer is available for each earth station. Each buffer is then connected to the 50 GHz transmit frequency by the up converter. The appropriate output power is provided by the high power amplifier for transmission to the satellite. On the down link, the received signal is amplified by the low noise receiver and down converted to the IF frequency for further amplification. After demodulation the data are buffered and demultiplexed for transmission over the selected ground link.

The various earth station configurations may be used in determining optimum communication satellite systems. The results of the computer analyses for the Application I FDM configuration are reported in section 6.

5.2.6 Selected Implementations - TDM.

The TDM system selected was obviously System D since it allowed all uplink and downlink beams to simultaneously carry traffic. Each earth station would

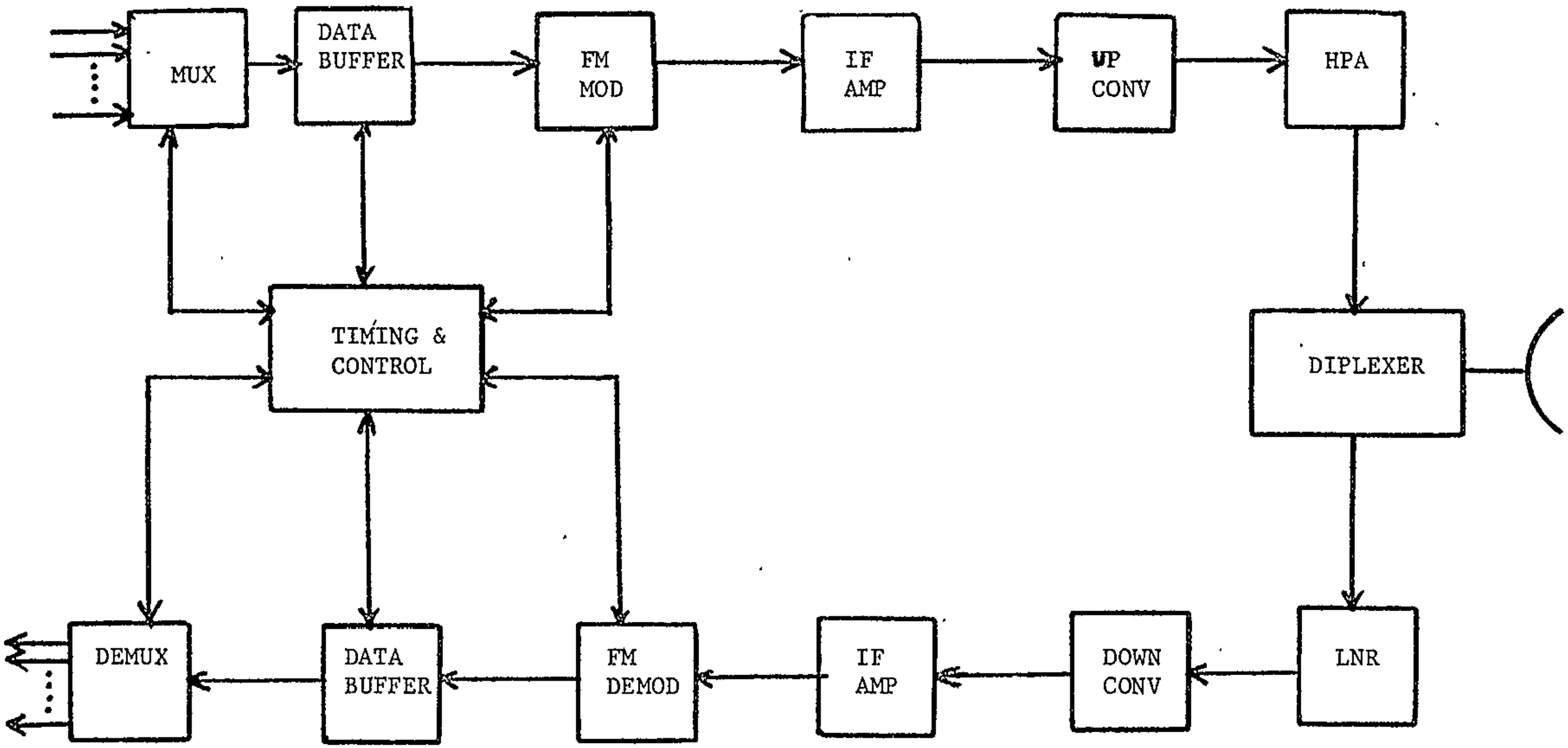

Figure 5.7. FDM EARTH STATION BLOCK DIAGRAM

have available the full one GHz RF bandwidth for its transmissions. Within this bandwidth a single carrier would be modulated with the baseband digital information for the other earth station. For effective control and coordination, the information would be organized into repeating frames which would include the required message bursts between the earth stations. For example, with a typical message burst consisting of 1,000 bits of data and with six earth stations in the network, an earth station would transmit 5,000 bits of data in each frame period. Further, if a one Gbps data rate is assumed, the effective average transfer rate between two earth stations would be 200 Mbps and the frame period would be five microseconds. A controller would be required to insure that more than one earth station would not attempt to transmit to the same earth station at the same time. Also, it should be noted that each earth station would require 1,000 bits of data storage for each other earth station or a total of 5,000 bits.

The earth station configuration used with the TDM application is shown in figure 5.8. The input data signals are received and placed in a buffer from which they are multiplexed through a scrambler for power density dispersion. The data are then combined with the signal from a preamble generator which adds synchronization and guard bits. From there the signal is applied to a phase shift key modulator and IF amplifier. This is followed by an up converter which converts the signal to the appropriate level for transmission to the satellite. The 40 GHz signal follows the inverse procedure. After amplification by the low noise receiver, it is down converted to the IF frequency where it is demodulated to the baseband data stream by the PSK demodulator. From there the preamble is stripped from the data, the signal is descrambled and routed to the appropriate output buffer by the multiplexer.

As with the FDM system, various configurations of diversity, radome, and reliability may be chosen during optimization. The application I TDM optimization results are included in section 6 .

5.2.7 Application IA

As a variation on Application I, Application IA was configured to provide results at the centimeter wave frequencies of 18 and 30 GHz. The FDM and TDM systems used for analysis in Application IA are identical to those in application I in every aspect other than frequency. The subsystem models were extended to the 18 and 30 GHz range for the analysis. In the systems, 30 GHz was used as the uplink frequency in place of 50 GHz and 18 GHz was used as the downlink frequency in place of 40 GHz. The Application IA results are also included in

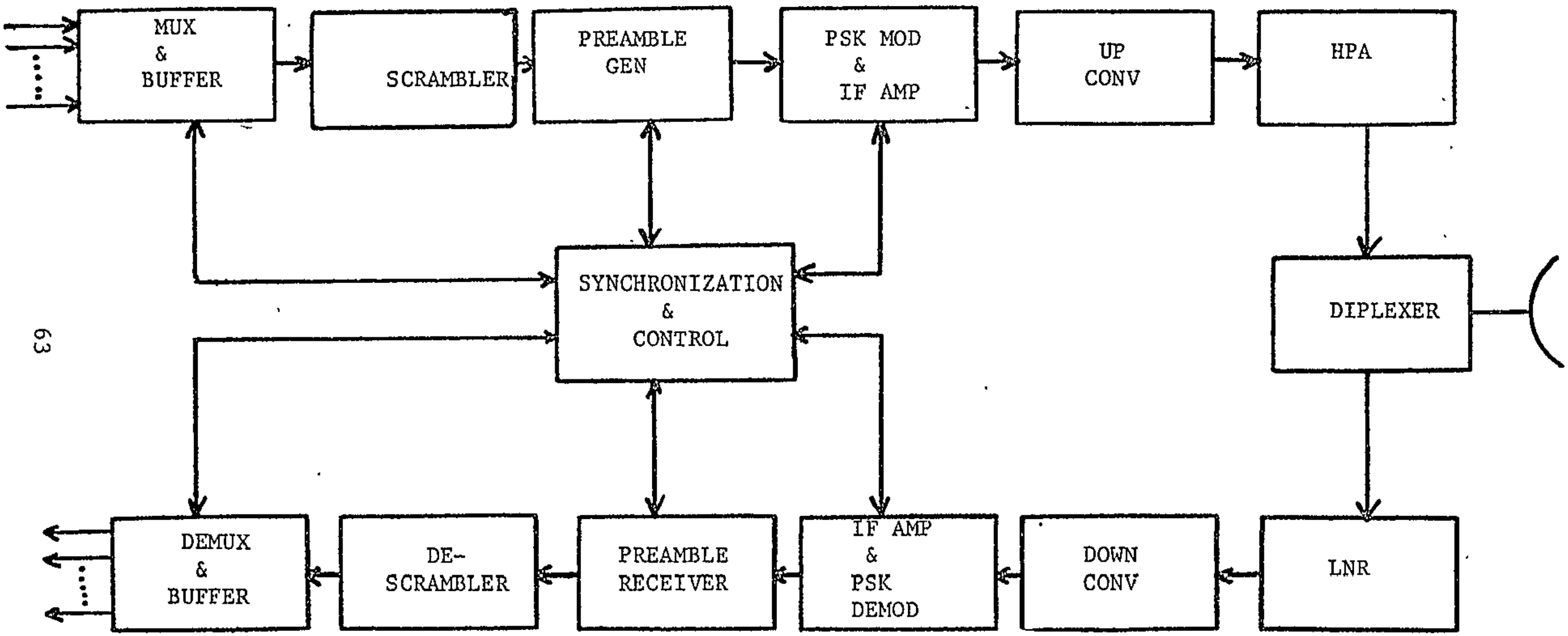

Figure 5.8. TDM EARTH STATION BLOCK DIAGRAM

section 6 .

5.3 Application II - Broadcast

5.3.1 System Description

This application considers the interconnection of a large number of earth stations throughout the United States. Total ground coverage is required although not simultaneously. In concept, however, an earth station located anywhere with the U.S. should be able to communicate with an earth station at any other point in the U.S. through this satellite. Each earth station must be capable of transmitting full bandwidth television or 1.544 Mbps data as a minimum.

The geographical coverage area of Application II is shown in Figure 5.9. This figure shows the number of beams required for the coverage which will vary depending upon power available, pointing capability, and simultaneous user requirements.

The area covered by a single beam is governed by the effective diameter of the satellite transmit antenna with a larger diameter antenna covering a smaller area. However, by concentrating the energy in a smaller area a larger antenna will have a higher effective gain. The selection of antenna size is governed by the amount of transmitter power available in conjunction with the downlink equation.

Figure 5.10 shows the basic system diagram. As shown in the figure, three earth stations are transmitting to three separate receiving earth stations while a number of other earth stations are neither transmitting nor receiving. This illustrates the feature of this application that allows a large number of widely separated users to be interconnected in a non-simultaneous manner.

5.3.2 Possible Implementations

Again, the methods of interconnecting a large number of users through a limited bandwidth satellite are considered to be either frequency division or time division multiplex.

With FDM, the frequency bandwidth would be divided into a number of channels, with each beam assigned portions of the spectrum. This simplifies beam isolation problems and at the same time permits simultaneous interconnection of earth stations. The number of earth stations that could be interconnected at a given time would be limited by the available spacecraft power and/or spectrum availability.

The time division multiplex implementation would allow the user of each beam to use the full allocated bandwidth for transmission of bursts to selected receiving earth stations. The system would be limited by the number of simultaneous downlink transmissions for which the satellite would be capable of providing

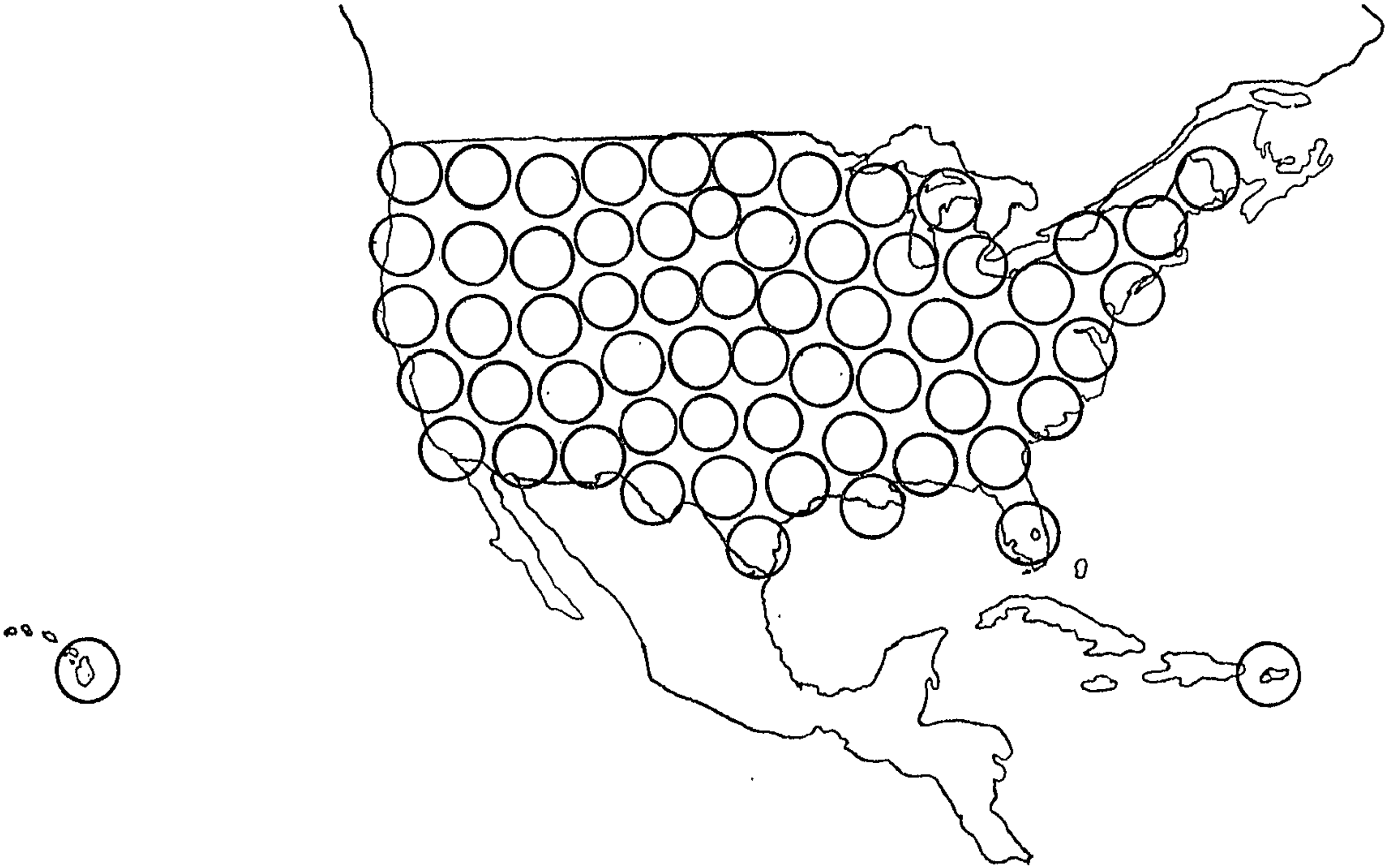

Figure 5.9. Millimeter Wave Satellite Application II
Coverage Area.

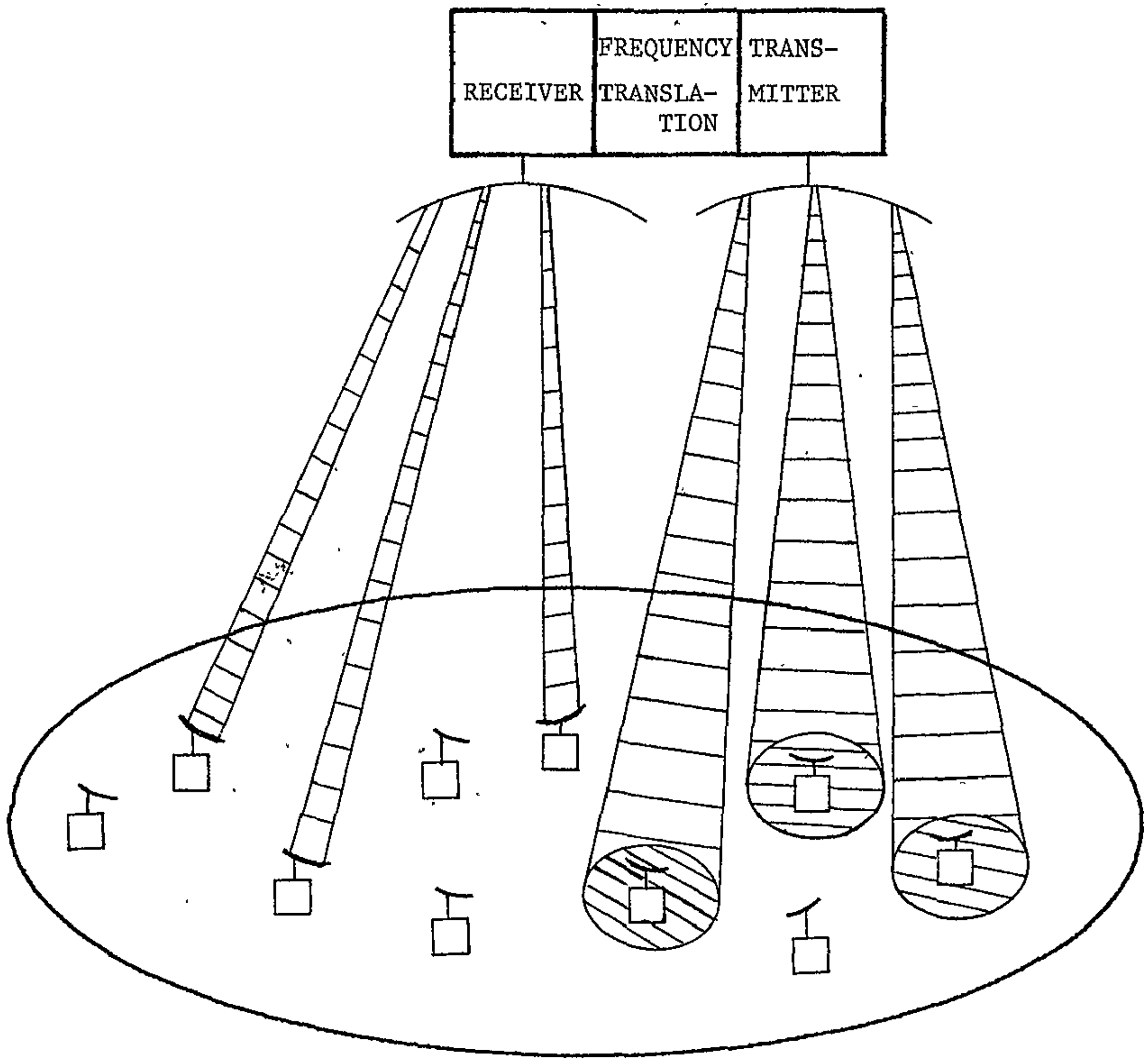

Figure 5.10. Application II System Diagram

power. A major drawback of TDM for this application, however, could be the synchronization and control equipment required by each earth terminal.

5.3.3 Selected Implementation - FDM.

An FDM implementation with beam switching was selected for Application II. A block diagram of the satellite is shown in Figure 5.11. As implemented, on-board switching is used extensively to interconnect both up and down link beams and satellite subchannels. The basic transmission unit in this configuration is the subchannel. Depending upon traffic, a transmitting earth station may send information through one or more subchannels of the satellite to a receiving earth station.

As shown in Figure 5.11, both antenna beam switching and subchannel switching are used extensively. In general, the satellite may have a total number of full bandwidth channels represented as NC (number of channels). Each of the NC channels is then frequency divided into NSC (number of subchannels) sub-channels by band pass filters. To gain the required earth coverage, a number of antenna feeds represented by NBC (number of beams per channel) may be connected to each of the channels.

The system may be best illustrated by considering the signal flow through the satellite. The signal from a transmitting earth station is included in one of the uplink beam coverage areas, for example, beam three of group one. This signal is connected by beam switch one to the 50 GHz receiver. Note that only one earth station in each group is permitted to transmit at any given time. From the receiver the signal is mixed with the 42 GHz first local oscillator signal to produce the 8 GHz intermediate frequency signal. This signal is separated into NSC subchannels by the band pass filter. Each subchannel is connected to an NC by NC matrix for routing to the desired transmitter. Note that each subchannel may be independently routed to any active transmitter. From the matrices, the subchannels are recombined into the NC channels by the combiners. A second local oscillator frequency of 32 GHz is mixed with the IF signal to produce the 40 GHz downlink signal. This signal is then amplified to the appropriate power level and routed through the beam switch to the selected downlink beam.

By selecting the number of beams, channels, and subchannels, system costs for the Application II implementation may be optimized using the same basic procedures as used with Application I. The results of the Application II analysis are given in Section 7.

Table 5.3 is a summary of basic data for the selected millimeter wave frequencies of 40 GHz, 43 GHz, 50 GHz, and 51 GHz. The data include wavelength,

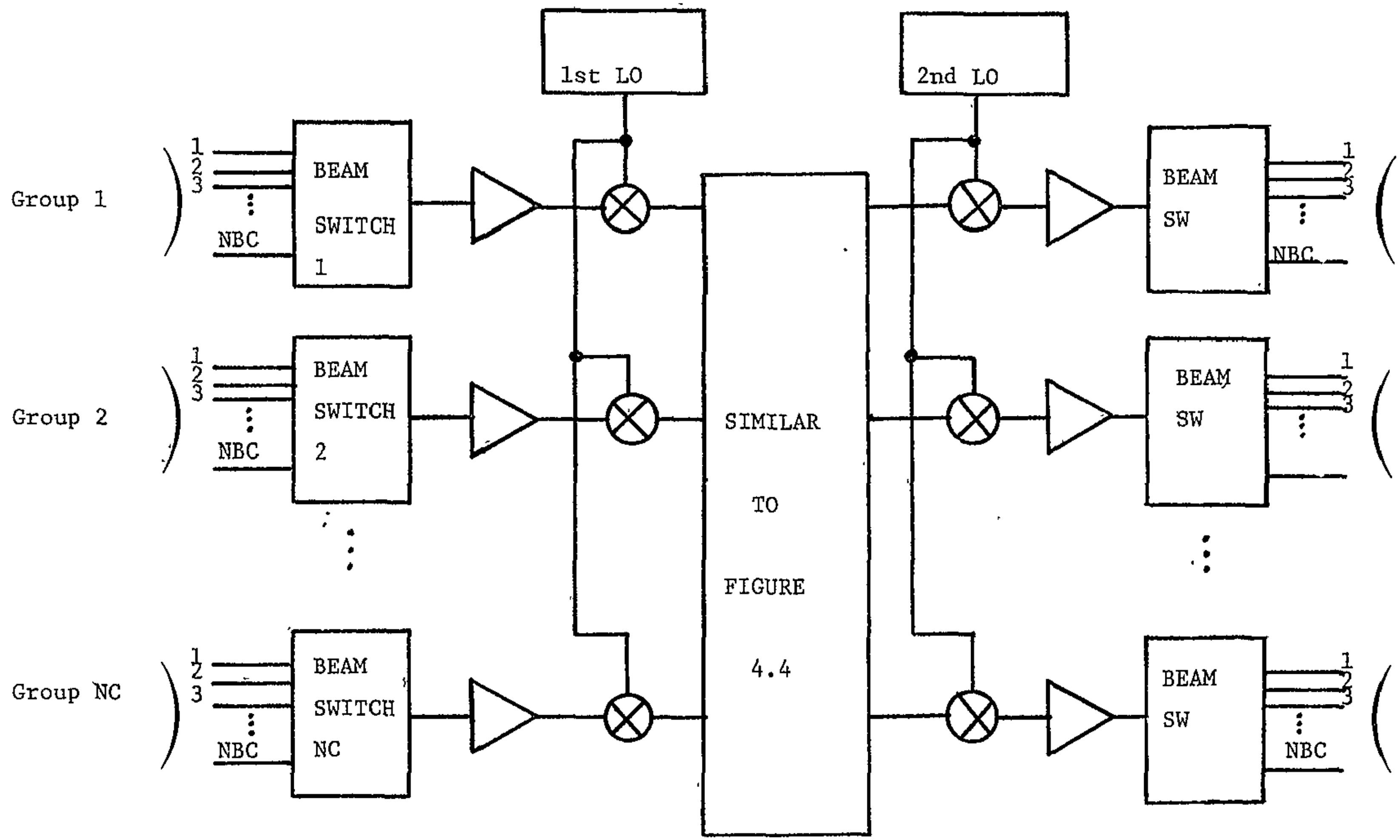

Figure 5.11. Application II Satellite Block Diagram

Table 5.3. Basic Data for Selected Frequencies

Frequency	20 GHz	30 GHz	40 GHz	50 GHz
Wavelength (mm)	15	10	7.5	6
Quarter Wavelength (mm)	3.75	2.5	1.88	1.5
Space Attenuation at Synch. Alt. (dB)	210.8	214.1	216.7	218.6
<u>ANTENNA DATA</u> (Parabolic dish, 55% eff.)				
Frequency	20 GHz	30 GHz	40 GHz	50 GHz
Diam - 0.5m				
Gain (dB)	37.8	41.3	43.8	45.8
3dB BW (deg)	2.2	1.5	1.1	0.88
diam of coverage (km)	1378	940	689	551
Diam - 1.0m				
Gain (dB)	43.8	47.3	49.9	51.8
3dB BW (deg)	1.1	0.74	0.54	0.44
diam of coverage (km)	689	464	338	276
Diam - 5m				
Gain (dB)	57.8	61.3	63.8	65.8
3dB BW (deg)	0,22	0.15	0.11	0.09
diam of coverage (km)	138	94	69	56
Diam - 10m				
Gain (dB)	63.8	67.3	69.9	71.8
3dB BW (deg)	0.11	0.07	0.05	0.04
diam of coverage (km)	69	46	31	25

Note: Beamwidth computed from values on Collins Radio "Space Systems Calculator" slide chart.

quarter wavelength, and the free space attenuation at geosynchronous altitude for the given frequencies. Antenna data are given for parabolic reflector antennas with diameters of 0.5 m, 1 m, 5 m, and 10 m, and the gain for each antenna is in decibels. The figures given do not include any reduction for surface tolerance. The 3 dB beamwidth in degrees is given along with the coverage diameter in kilometers at the synchronous distance.

SECTION 6

POINT-TO-POINT APPLICATION RESULTS

6.1 Point-to-Point Application Baseline System

6.1.1 System Description

A baseline conceptual system was developed for the point-to-point application from the considerations in Section 5.2 and from optimization analysis on the use of radomes and the choice of diversity type. The system uses six ground stations, each with single station diversity for both receive and transmit. No radomes are used. The satellite, with onboard switching, is depicted in Figure 4.5. For baseline analysis all signal processing is assumed to be by frequency-division multiplex.

As for all analyses performed to calculate system cost, the cost for the baseline system was minimized under carrier-to-noise and weight constraints by the computer program SCOR. A complete set of the parameters required for input to this minimization is given in Table 6.1. Included are system constraints, system configuration parameters, and various assumed constants. The lower portion of the table gives the assumed subsystem redundancies where the constant is a multiplier on the number of subsystems operating in the baseline system.

Several of the parameters require explanation.

Number of Channels - This is the number of beams from the ground to the satellite and from the satellite to the ground. This is equivalent to the number of satellite receivers and the number of satellite transmitters.

Number of Positions per Beam - For the broadcast application beam position switching is used. In this case, however, the channel beams are fixed.

Ground Transmitters per Link - This parameter along with the number of Ground Receivers per Link defines the diversity configuration of the ground stations.

Number of Subchannels per Channel - Each beam from the ground is divided into subchannels with either FDM or TDM techniques.

Diversity Link Receive Cost - This is the cost for one-way diversity channel of 1 GHz bandwidth.

Diversity Link Transmit Cost - This is the additional cost to provide a two-way diversity channel.

The results of the cost minimization are given in Figure 6.1. Shown first are the system variables adjusted in the cost minimization as well as their optimal value. These are self-explanatory except for "LOG{PR (FAIL DL)/PR(FAIL UL)}".

Table 6.1. Point-to-Point Application Baseline Parameters

Parameter	Value
Carrier/Noise Constraint Limit (DB)	15.00
Weight Constraint Limit (LBS)	5000
Downlink Frequency (GHZ)	40.50
Uplink Frequency (GHZ)	50.50
Satellite Channel Bandwidth (MHZ)	1000.
Number of Channels (Beams)	6
Number of Positions Per Beam	1
Reliability (Percent)	99.90
Rain Rate (MM/HR)	50.00
Number of TV Headins	12
Number of Voice Muxes	12
Digital Data Rate (MBS)	3.000
Bulk Data Rate (MBS)	200.0
Bulk Data Volume (MB)	1000.
Number of Ground Stations	6
Ground Transmitters Per Link	2
Ground Receivers Per Link	2
Number of Subchannels Per Channel	5
Ground Station Bandwidth (MHZ)	1000.
Diversity Link Receive Cost (K$/MI)	100.7
Diversity Link Transmit Cost (K$/MI)*	40.30
Diversity Link Range (MI)	9.940
Ground Station Building Cost (K$)	100.0
Diversity Station Building Cost (K$)	50.00
Uplink Misc. Losses (DB)	7.000
Downlink Misc. Losses (DB)	8.000
Atmosphere Temperature (K)	300.0
Ground Temperature (K)	290.0
FDM Communications	
No Radomes	

*Incremental cost of 2-way Diversity Link over 1-way Diversity Link.

Table 6.1. Point-to-Point Application Baseline Parameters (con.)

Subsystem	Redundancy
Ground Antenna	1.0
Radome	1.0
Ground Pointing and Control	1.0
Ground Transmitter	2.0
Ground Receiver	2.0
Ground Signal Processing	2.0
Bulk Data Storage	1.0
High Speed Modem	1.0
Television Headin	1.0
Voice Multiplex	1.0
Diversity Land Line Receive	1.0
Satellite Anenna	1.0
Satellite Transmitter	2.0
Satellite Receiver	2.0
Space Signal Processing (Switches)	1.5
Space Signal Processing (Filters)	1.5
Space Signal Processing (Misc)	1.5
Attitude Control System	1.0
Station Keeping System	1.0
Structure and Thermal Control	1.0
Satellite Power Supply	1.5
Diversity Land Line Transmit	1.0
Ground Station Building	1.0
Diversity Station Building	1.0
Satellite Beam Switching	1.5

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APPLICATION 1 BASELINE

TRIAL 13 SUCESSFUL SAMPLES 130 TOTAL SAMPLES 176

**** OPTIMAL VARIABLES

VARIABLE	MIN	MAX	OPT
GROUND XMIT POWER (WATTS)	983.1	1083.	932.3
GROUND ANTENNA DIAMETER (M)	5.179	5.241	5.227
GROUND REC NOISE FIGURE (LIN)	1.206	1.208	1.207
SATELLITE XMIT POWER (WATTS)	217.7	230.2	220.7
SATELLITE REC NOISE FIGURE (LIN)	1.204	1.207	1.207
SATELLITE ANTENNA SIZE (M)	2.623	2.642	2.627
GROUND ANT. POINTING ERROR (DEG)	.2020E-01	.2035E-01	.2024E-01
ATTITUDE CONTROL ERROR (DEG)	.1217E-01	.1717E-01	.1529E-01
STATION KEEPING ACCURACY	.1046E-01	.1421E-01	.1069E-01
LOG PR(FAIL DL)/PR(FAIL UL)	.4236E-01	.5486E-01	.4671E-01

*****GROUND SUBSYSTEMS

QUANTITY	SUBSYSTEM	COST(K$)	% OF TOTAL
12	GROUND ANTENNA	5721.560	10.9
0	RADOME	0.000	0.0
12	GROUND POINTING AND CONTROL	3027.068	5.8
24	GROUND TRANSMITTER	2614.286	5.0
24	GROUND RECEIVER	1720.189	3.3
12	GROUND SIGNAL PROCESSING	3340.450	6.4
6	BULK DATA STORAGE	4050.000	7.7
6	HIGH SPEED MODEM	312.000	.6
6	TELEVISION HEADIN	2220.000	4.2
6	VOICE MULTIPLEX	1860.000	3.5
6	DIVERSITY LAND LINE RECEIVE	6005.748	11.4
6	DIVERSTY LAND LINE TRANSMIT	2403.492	4.6
6	GROUND STATION BUILDING	600.000	1.1
6	DIVERSITY STATION BUILDING	300.000	.6
		34174.814	65.1

*****SPACE SUBSYSTEMS

QUANTITY	SUBSYSTEM	COST(K$)	% OF TOTAL	WEIGHT(LBS)	% OF TOTAL
2	SATELLITE ANTENNA	4260.741	8.1	135.0	4.4
12	SATELLITE TRANSMITTER	1847.884	3.5	270.1	8.7
12	SATELLITE RECEIVER	2404.292	4.6	120.0	3.9
90	SPACE SIGNAL PROCESSING (SWITCHES)	301.500	.6	174.6	5.6
45	SPACE SIGNAL PROCESSING (FILTERS)	63.000	.1	49.6	1.6
9	SPACE SIGNAL PROCESSING (COMBINERS)	18.000	.0	10.8	.3
1	ATTITUDE CONTROL SYSTEM	2299.096	4.4	121.7	3.9
1	STATION KEEPING SYSTEM	3598.722	6.9	460.1	14.9
1	STRUCTURE AND THERMAL CONTROL	2529.543	4.8	768.3	24.9
1	SATELLITE POWER SUPPLY	985.449	1.9	980.6	31.7
		18308.228	34.9	3090.9	

TOTAL COST (K$) 52483.042

***** SYSTEM PARAMETERS

CARRIER/NOISE(DB)	15.0
UPLINK RAIN ATTN (DB)	23.2
DOWNLINK RAIN ATTN (DB)	17.0
G/T (DB/K)	46.5
ERP (DB)	96.2

Figure 6.1. Point-to-Point Application
Optimum Baseline System

This parameter is used to allow optimization on the distribution of link reliability between up- and down-link. The name signifies

$$\log_{10} \left\{ \frac{\text{probability of failure on the downlink}}{\text{probability of failure on the uplink}} \right\} .$$

The variable has the range [-1,1] implying either probability may be 10 times the other. The remainder of the figure gives a cost and performance description of the system with the optimal parameters. Cost and weight are given by subsystem as well as total cost, total weight and system carrier-to-noise ratio.

6.1.2 Analysis for Baseline Configuration

Two analyses were performed prior to choosing the baseline system. Optimizations were performed for five types of diversity and both with and without radomes. Results of these analyses are given in Table 6.2. Equivalent runs were made at the 40-50 GHz frequencies and at 18-30 GHz for comparison purposes. In some cases no system was found which met the system carrier-to-noise constraint. No cost is given for these; maximum achievable C/N is given instead.

Examining system costs for the various diversities shows that the lowest cost system is realizable for single-station diversity where the diversity station contains both receiver and transmitter. This diversity type was thus chosen for the baseline. Comparison of the same system with and without radomes shows that total system cost is consistently more for the required performance with radomes. For this reason no radomes were included in the baseline configuration.

6.2 Sensitivity Analyses for the Optimum Baseline System

Two types of sensitivity analysis were performed to highlight features of the baseline system. In three cases a system parameter was varied and the cost reoptimized for each parameter value. In a fourth case each of the ten optimization variables was varied one per cent in turn and the effects on the system were recorded. In all of the plots giving the results of the analyses, cost is given as the portion of total system cost allotted to each ground terminal. That is, a portion of the satellite cost, excluding launch cost, is included in the terminal cost.

For all point-to-point application systems the optimum satelite weight was well below realistic weight constraints. For this reason no analysis of system cost versus weight constraint was performed.

Table 6.2. Point-to-Point Application

Diversity and Radome Analyses

Diversity # of Receivers	Diversity # of Transmitters	Radome	Total System Cost (K$)** 40-50 GHz 99.9 Reliability	40-50 GHz 99.99 Reliability	18-30 GHz 99.9 Reliability	18-30 GHz 99.99 Reliability
2	2	N	50931	*	43566	51149
		Y	57014		44981	
3	3	N	58902	65742	55067	57279
		Y	61770		56107	

*This configuration does not satisfy the 15 dB C/N constraints.
No configuration with fewer receivers or transmitter.

**These costs do not include launch cost.

6.2.1 Cost Versus Link Reliability

Cost was minimized under the baseline constraints for several link reliabilities. Figure 6.2 gives a plot with these results. Note that as reliability increases from 90% to 99.9%, the per terminal cost increases from \$6.9 million to \$8.5 million.

6.2.2 Cost Versus Number of Ground Stations - FDM and TDM

The number of ground stations was varied from 2 to 10 to examine the effect of this change on per terminal cost. This was done for both FDM and TDM signal processing to determine changes in the relative attractiveness of these two techniques. The results are plotted in Figure 6.3. The decrease in cost is due to the further dividing of satellite costs. The fact that the per terminal cost for TDM processing is significantly higher is due to the necessity of high data-rate buffer storage at each station.

6.2.3 Cost Versus Satellite Receiver Noise Temperature

To judge the sensitivity of the baseline cost to suboptimal values of satellite receive noise temperature this parameter was fixed at various values while the other nine optimization variables were adjusted to minimize cost. The results are plotted in Figure 6.4. Here the increment in per terminal cost is given for total noise at the satellite receiver (exclusive of ground temperature). Below 100°K, cost rises due to the increased cost of the more sensitive spacecraft receivers. Above 100°K, the cost again rises due to the increased cost of the required higher powered ground transmitter. With the assumed models it appears that a 100°K spacecraft receiver noise temperature would be appropriate for the 40/50 GHz point-point service; this should be achievable without cooling.

6.3 Point-to-Point Application at 18-30 GHz

6.3.1 System Performance

For comparison purposes, some analysis was done for the point-to-point application at 18-30 GHz. The optimum system cost for the 18/30 GHz system was \$7365K less than the optimal 40/50 GHz system cost. Further cost and performance comparisons may be found in Table 6.2. It is interesting to note that due to decreased attenuation at 18-30 GHz feasible solutions are found for diversity types not possible at 40-50 GHz. Even so, the dual-station receive and transmit diversity is still optimum.

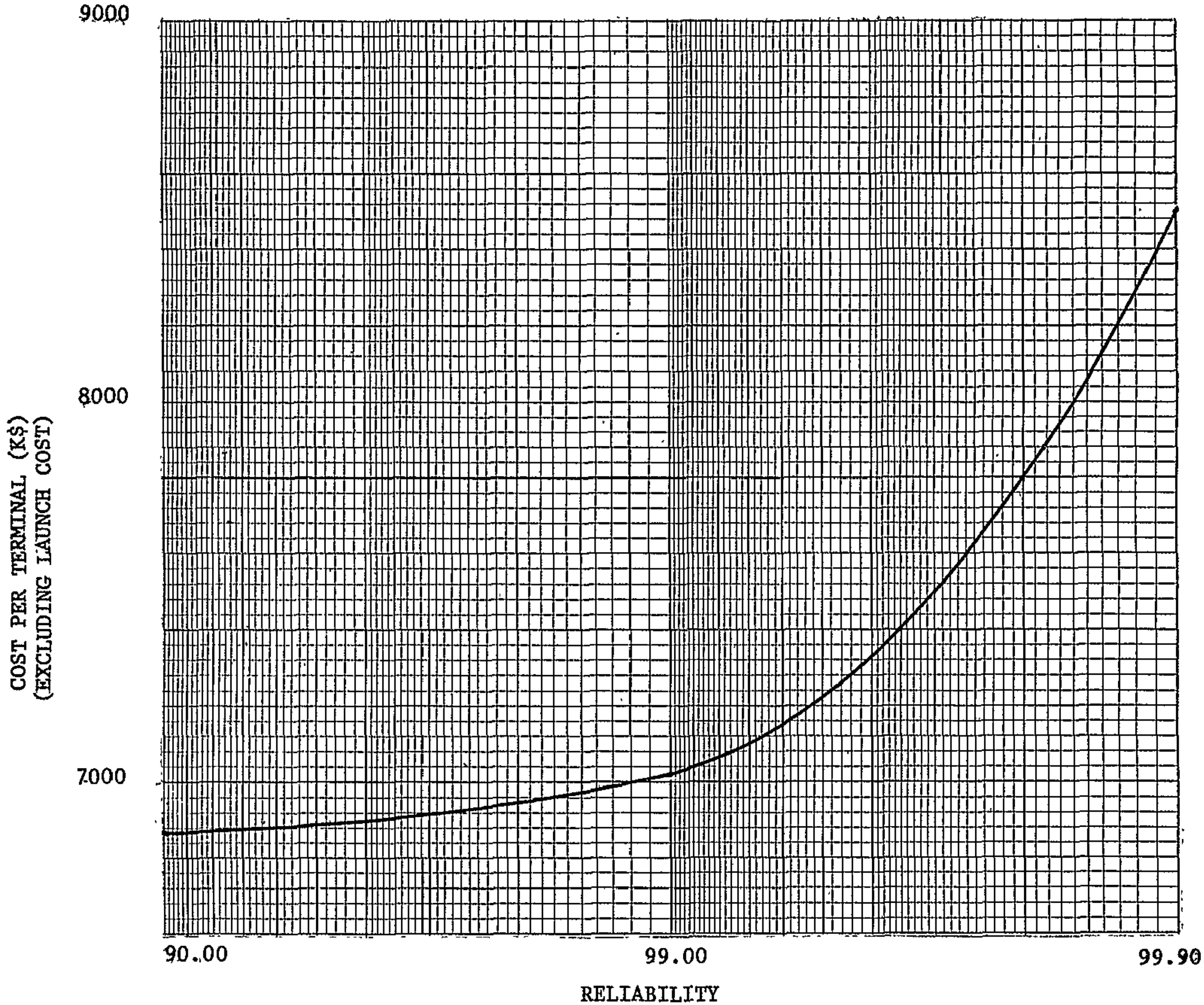

Figure 6.2. Cost per Terminal versus Link Reliability for Point-Point Service at 40/50 GHz.

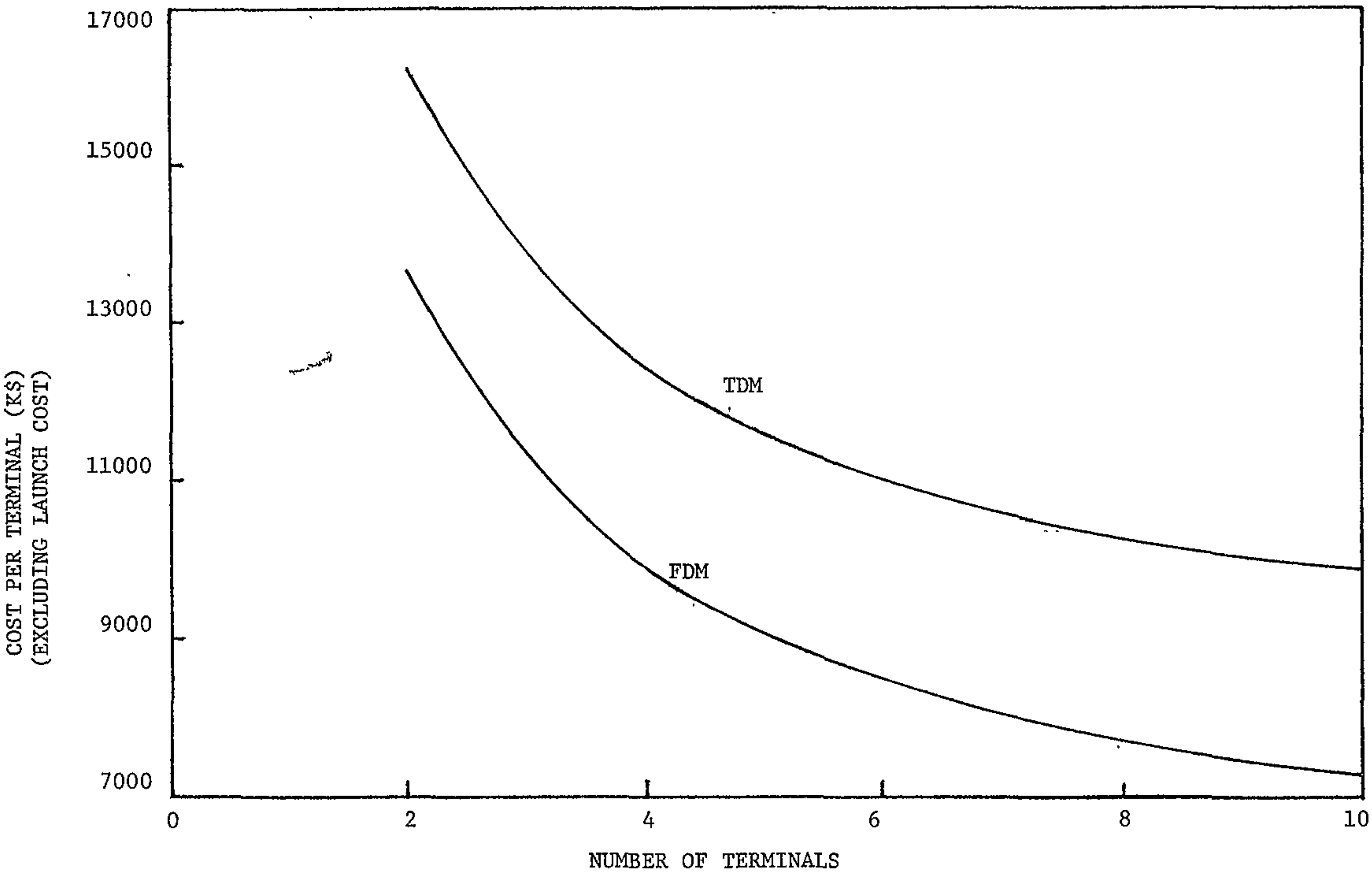

Figure 6.3. Cost per Terminal versus Number of Terminals - FDM and TDM Fixed Point-Point System at 40/50 GHz for 99.9% Reliability.

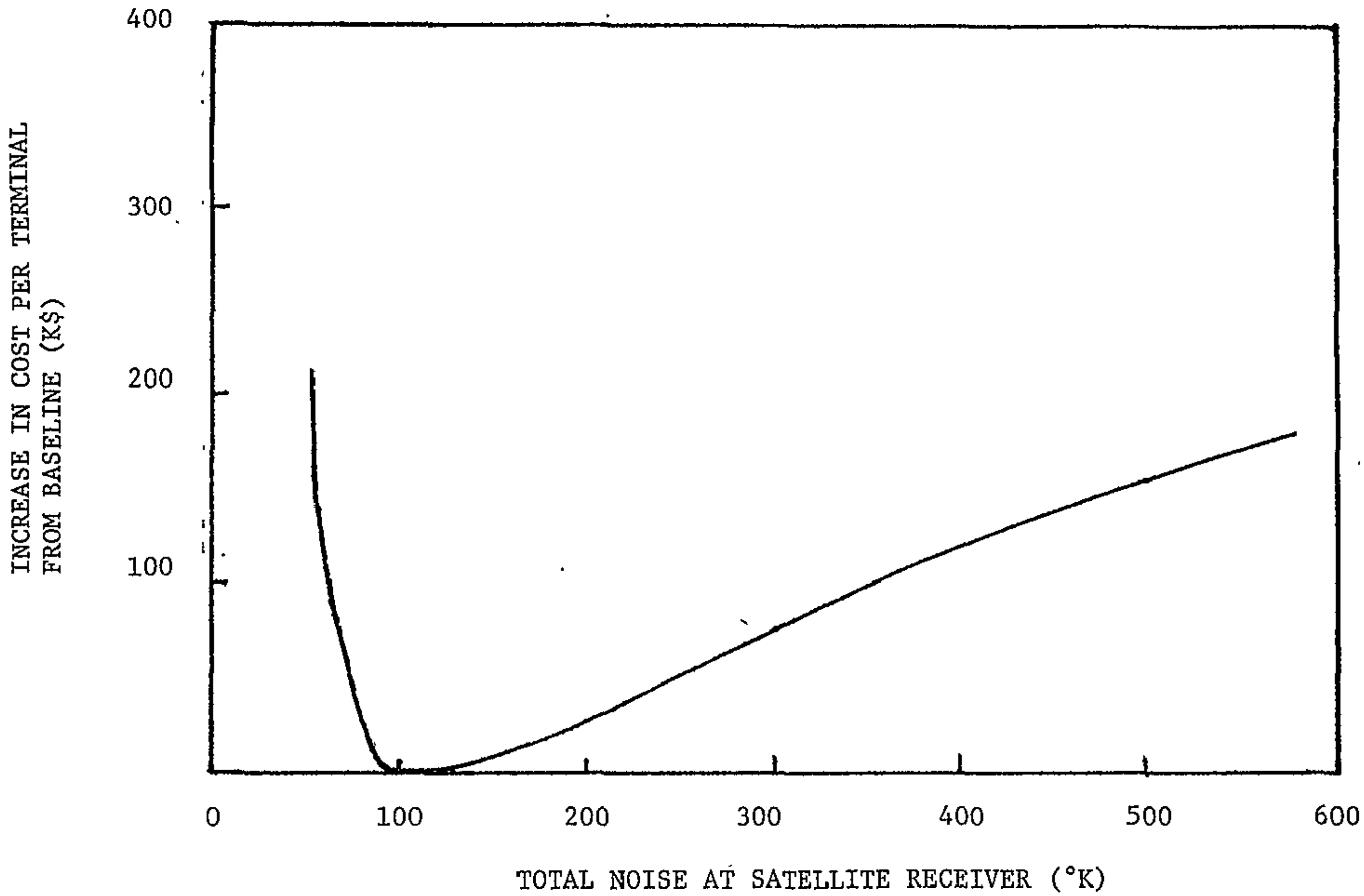

Figure 6.4. Increase in Cost per Terminal versus Satellite Receiver Noise

Table 6.3. Point Elasticities for Optimization Variables, Point-to-Point Application

Variable	POINT ELASTICITIES Cost Elasticity	Weight Elasticity	C/N Elasticity
Ground XMIT Power (watts)	.0324	0.0000	.0875
Ground Antenna Diameter (M)	.1845	0.0000	.5370
Ground Rec Noise Figure (Lin)	-.0474	0.0000	-.1969
Satellite XMIT Power (Watts	.0610	.3489	.2019
Satellite Rec Noise Figure (Lin)	-.0230	0.0000	-.0859
Satellite Antenna Size (M)	.1637	.1590	.5456
Ground Ant Pointing Error (Deg)	-.0002	0.0000	-.0073
Attitude Control Error (Deg)	-.0066	-.0138	-.0343
Station Keeping Accuracy	-.0062	-.0239	-.0356
Log PR (Fail DL)/PR (Fail UL)	0.0000	0.0000	.0019

6.3.2 Cost versus link reliability

Optimum per terminal cost for various link reliabilities was calculated for the 18-30 GHz case. A plot of these costs is given in Figure 6.5. This should be compared to Figure 6.2, a similar plot for the 40-50 GHz case. For these frequencies the system cost is much less sensitive to reliability since the link carrier-to-noise ratio is not on the borderline of acceptable performance.

6.3.3 Cost versus number of ground stations

Figure 6.6 gives cost per terminal for 2 to 10 ground stations. This plot may be compared to the FDM case of Figure 6.3.

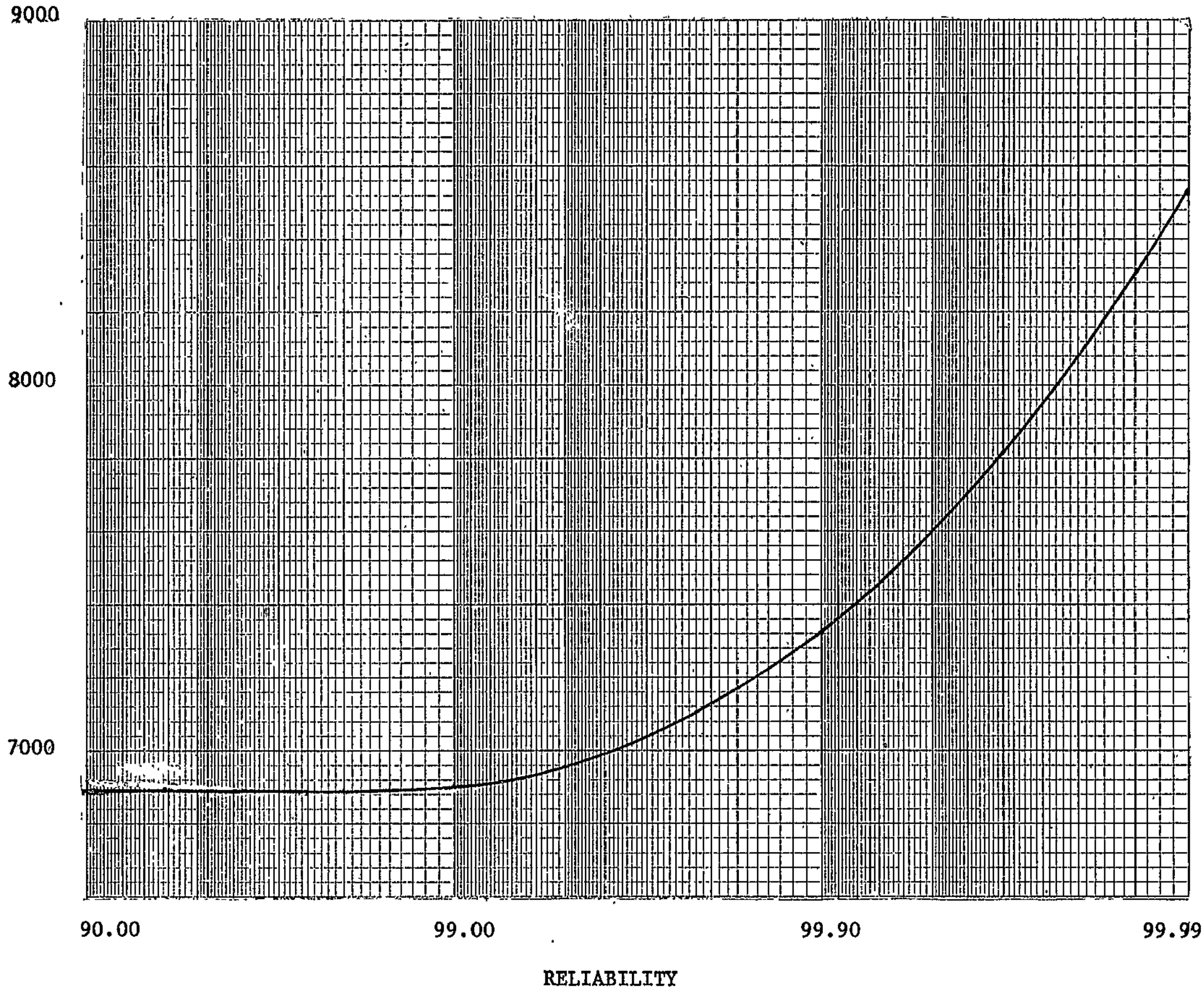

Figure 6.5. Cost per Terminal versus Link Reliability (18 - 30 GHz)

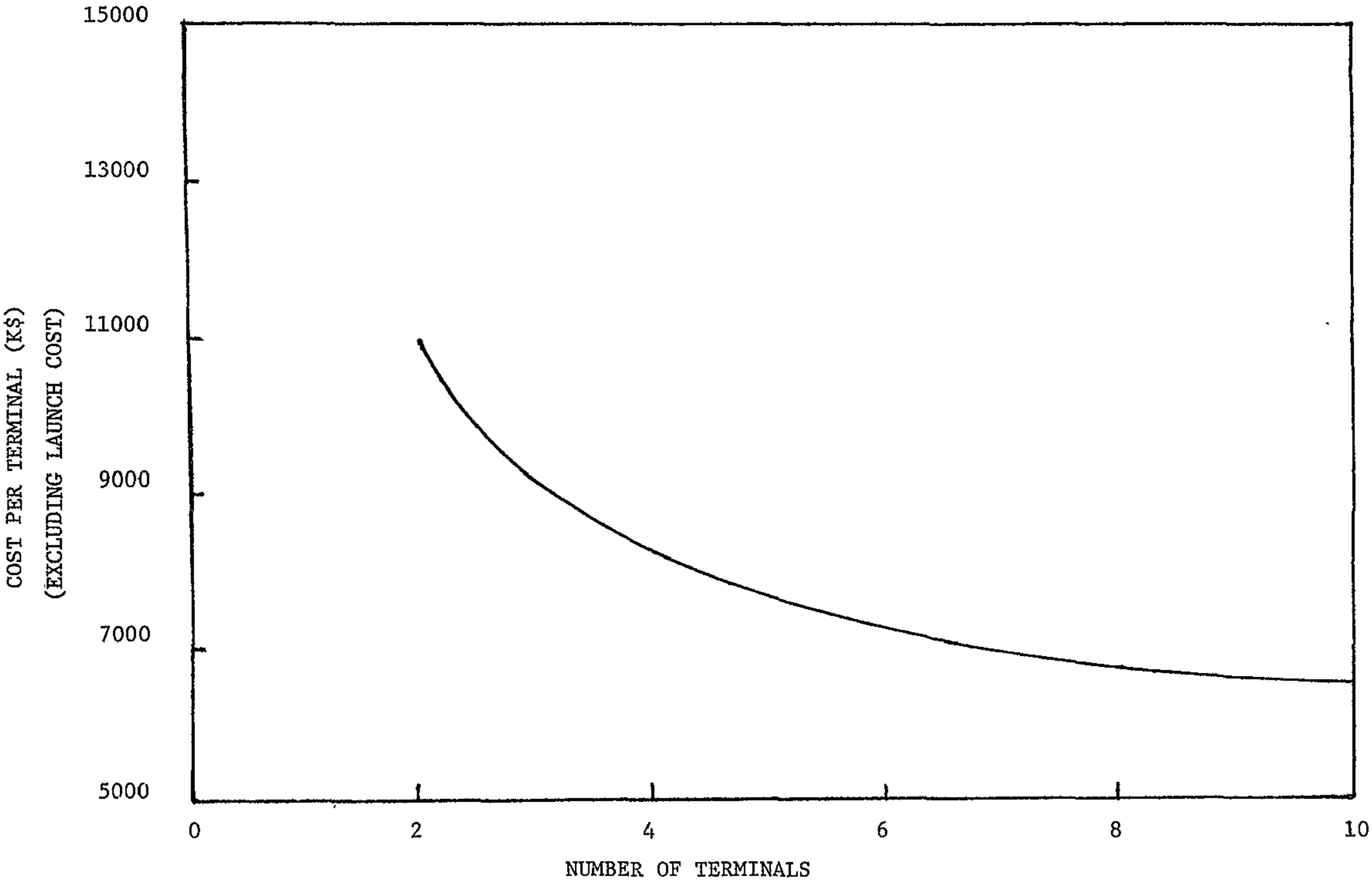

Figure 6.6. Cost per Terminal versus Number of Terminals - FDM, 18 - 30 GHz

SECTION 7

BROADCAST APPLICATION RESULTS

The objective of the initial broadcast application concept was to provide total U.S. coverage using adjacent spot beams with 99.5% reliability for wideband uses such as video distribution. Preliminary power calculations indicated that very large (heavy) satellites would be required for this concept, and a compromise baseline design with limited simultaneous beam utilization and with on-board switching was developed. This design provides up to 96.5% reliability (rain considerations only) with the assumed subsystem constraints (satellite weight, etc.); a baseline design with 95% reliability was used to facilitate the sensitivity analysis. Other system configurations such as multiple satellites or a very large satellite could possibly achieve the desired 99.5% reliability; this is a subject for future investigation.

The weight of the on-board switches is the limiting criteria in performance of the baseline system. The resulting "broadcast" link is estimated to be able to maintain its design value carrier-to-noise ratio (12dB) 95% of the time for the assumed rain attenuation statistics. Such a communication satellite system would not be commercially marketable in the sense of current communication satellites (e.g., video entertainment); however, there may well exist suitable applications such as high volume data transfer where the time of day for the data transfer is not critical. For example, the system being planned by Satellite Business Systems (SBS) is anticipated to accomplish data transfer using a satellite link with a bit error rate of 10^{-6} with 95% reliability [14].

7.1 Broadcast Application Baseline System

In order to achieve coverage of the entire continental United States, provisions were made for each of 6 channels to select from among 10 separate ground spot beams. To achieve the proper beam size, the satellite antenna diameter was fixed at 0.6 meter rather than used as an optimization variable. For the required coverage, 60 spots with diameter 450 KM are required. Once six receive beams and 6 transmit beams are selected, each beam carries 20 subchannels which are switched on-board the satellite. Any subchannel of a received beam may be transmitted on the corresponding subchannel of any transmitted beam. A block diagram of the satellite system is given in Figure 5.11. A complete tabulation of the baseline parameters is given in Table 7.1. A

Table 7.1. Broadcast Application Baseline Parameters

Parameter	Value
Carrier/Noise Constraint Limit (DB)	12.00
Weight Constraint Limit (LBS)	6500
Downlink Frequency (GHZ)	40.50
Uplink Frequency (GHZ)	50.50
Satellite Channel Bandwidth (MHZ)	1000.
Number of Channels (Beams)	6
Number of Positions Per Beam	10
Reliability (Percent)	95.00
Rain Rate (MM/HR)	50.00
Number of TV Headins	2
Number of Voice Muxes	0
Digital Data Rate (MBS)	0
Bulk Data Rate (MBS)	0
Bulk Data Volume (MB)	0
Number of Ground Stations	360
Ground Transmitters Per Link	1
Ground Receivers Per Link	1
Number of Subchannels Per Channel	20
Ground Station Bandwidth (MHZ)	100.0
Ground Station Building Cost (K$)	100.0
Uplink Misc. Losses (DB)	7.000
Downlink Misc. Losses (DB)	8.000
Atmosphere Temperature (K)	300.0
Ground Temperature (K)	290.0
FDM Communication	
No Radomes	

Table 7.1. Broadcast Application Baseline Parameters (cont.)

Subsystem	Redundancy
Ground Antenna	1.0
Ground Pointing and Control	1.0
Ground Transmitter	2.0
Ground Receiver	2.0
Ground Signal Processing	2.0
Bulk Data Storage	1.0
High Speed Modem	1.0
Television Headin	1.0
Voice Multiplex	1.0
Satellite Antenna	1.0
Satellite Transmitter	2.0
Satellite Receiver	2.0
Space Signal Processing (Switches)	1.5
Space Signal Processing (Filters)	1.5
Space Signal Processing (Misc)	1.5
Attitude Control System	1.0
Station Keeping System	1.0
Structure and Thermal Control	1.0
Satellite Power Supply	1.5
Ground Station Building	1.0
Satellite Beam Switching	1.5

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APPLICATION II BASELINE

TRIAL 10 SUCESSFUL SAMPLES 100 TOTAL SAMPLES 134

**** OPTIMAL VARIABLES

VARIABLE	MIN	MAX	OPT
GROUND XMIT POWER (WATTS)	60.94	112.5	83.27
GROUND ANTENNA DIAMETER (M)	2.974	3.115	3.034
GROUND REC NOISE FIGURE (LIN)	2.923	2.958	2.941
SATELLITE XMIT POWER (WATTS)	27.47	28.96	28.31
SATELLITE REC NOISE FIGURE (LIN)	3.072	3.166	3.103
SATELLITE ANTENNA SIZE (M)	1.233	1.329	1.263
GROUND ANT. POINTING ERROR (DEG)	.2183E-01	.2827E-01	.2593E-01
ATTITUDE CONTROL ERROR (DEG)	.2340E-01	.2650E-01	.2489E-01
STATION KEEPING ACCURACY	.2318E-01	.2436E-01	.2324E-01
LOG PR(FAIL DL)/PR(FAIL UL)	.6596E-01	.1285	.9334E-01

*****GROUND SUBSYSTEMS

QUANTITY	SUBSYSTEM	COST(K$)	% OF TOTAL
350	GROUND ANTENNA	8263.591	5.7
0	RADOME	0.000	0.0
350	GROUND POINTING AND CONTROL	6946.091	4.8
720	GROUND TRANSMITTER	11362.041	7.9
720	GROUND RECEIVER	11392.696	7.9
720	GROUND SIGNAL PROCESSING	17749.210	12.3
0	BULK DATA STORAGE	0.000	0.0
0	HIGH SPEED MODEM	0.000	0.0
350	TELEVISION HEADIN	25200.000	17.5
.0	VOICE MULTIPLEX	0.000	0.0
0	DIVERSITY LAND LINE RECEIVE	0.000	0.0
0	DIVERSTY LAND LINE TRANSMIT	0.000	0.0
350	GROUND STATION BUILDING	36000.000	25.0
.0	DIVERSITY STATION BUILDING	0.000	0.0
		----------	-------
		116913.589	81.1

*****SPACE SUBSYSTEMS

QUANTITY	SUBSYSTEM	COST(K$)	% OF TOTAL	WEIGHT(LBS)	% OF TOTAL
2	SATELLITE ANTENNA	7489.160	5.2	148.3	2.3
12	SATELLITE TRANSMITTER	624.083	.4	260.2	4.1
12	SATELLITE RECEIVER	552.000	.4	120.0	1.9
350	SPACE SIGNAL PROCESSING (SWITCHES)	4716.000	3.3	2603.2	41.1
160	SPACE SIGNAL PROCESSING (FILTERS)	180.000	.1	199.4	3.1
9	SPACE SIGNAL PROCESSING (COMBINERS)	85.500	.1	51.3	.8
1	ATTITUDE CONTROL SYSTEM	3534.015	2.5	228.4	3.6
1	STATION KEEPING SYSTEM	5685.214	3.9	880.7	13.9
1	STRUCTURE AND THERMAL CONTROL	3992.323	2.8	1630.9	25.7
1	SATELLITE POWER SUPPLY	344.418	.2	214.9	3.4
		----------	-------	--------	
		27202.734	18.9	6336.4	

TOTAL COST (K$) 144116.323

***** SYSTEM PARAMETERS

CARRIER/NOISE(DB)	12.0
UPLINK RAIN ATTN (DB)	.3
DOWNLINK RAIN ATTN (DB)	3.1
G/T (DB/K)	32.1
ERP (DB)	81.0

Figure 7.1. Broadcast Application Optimum Baseline System

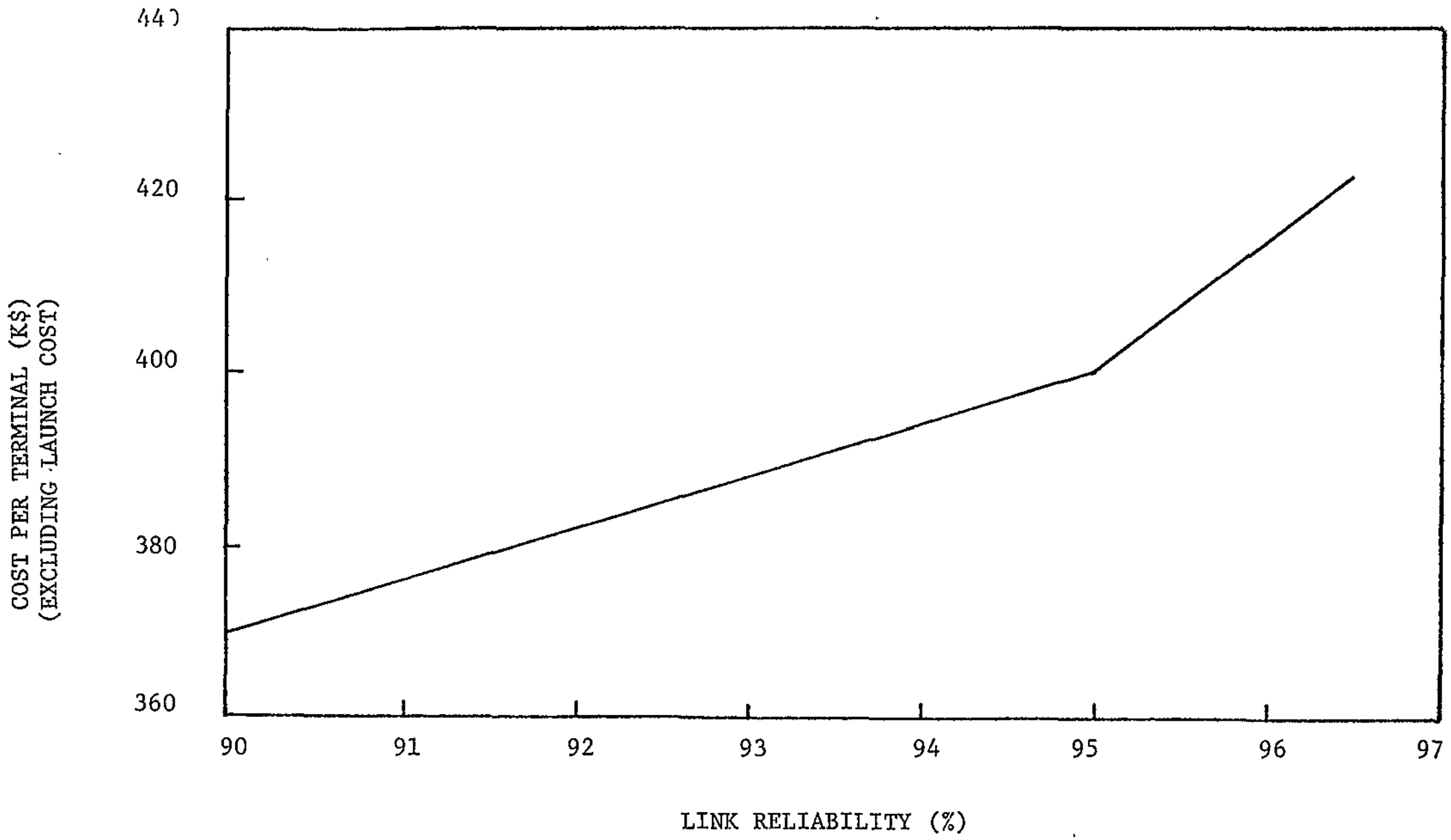

Figure 7.2. Cost per Terminal versus Link Reliability

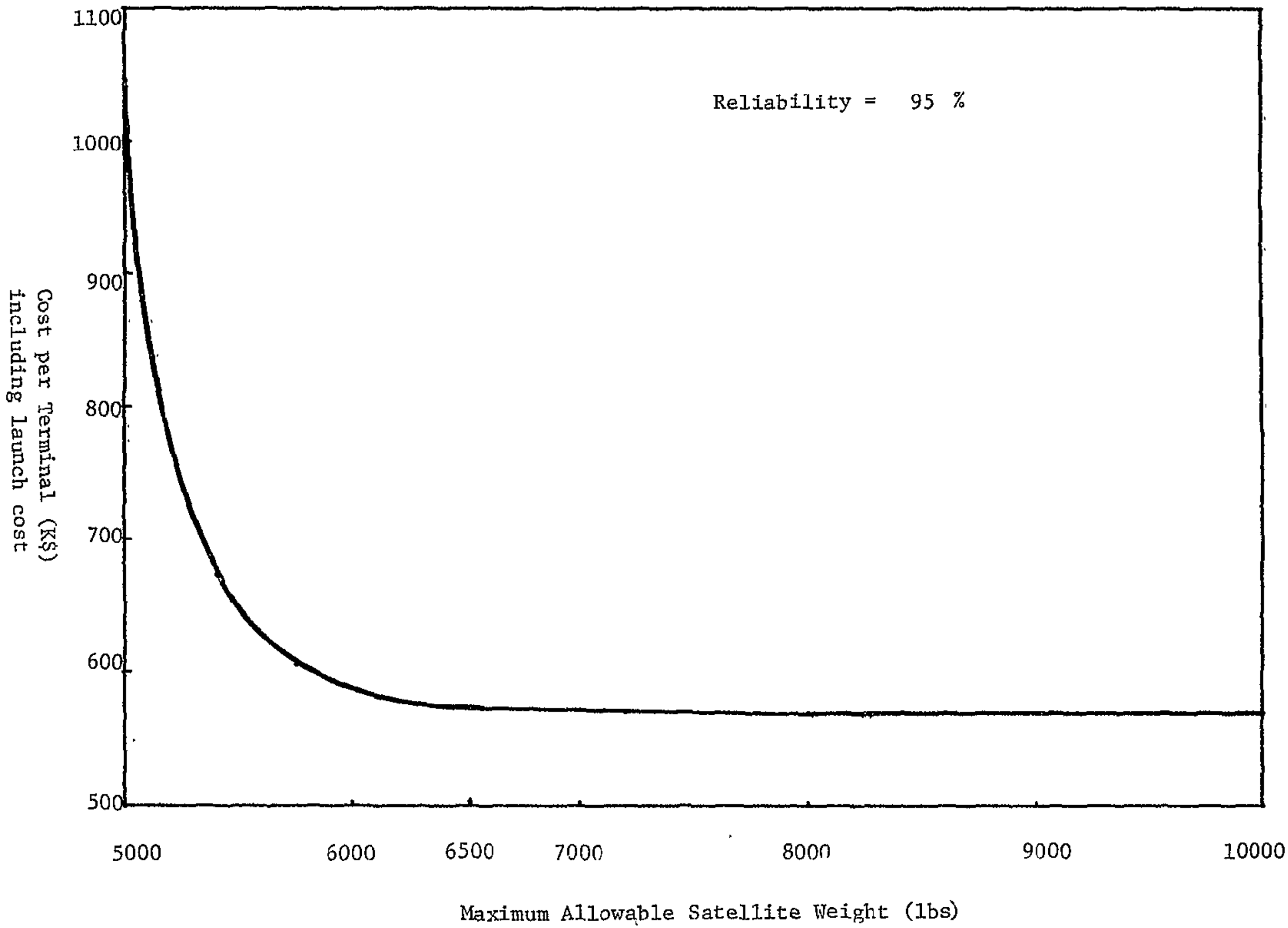

Figure 7.3. Cost Per Terminal Versus Satellite Weight Constraint
(For Application II Broadcast at 40/50 GHz)

listing of the baseline optimization run is given in Figure 7.1. Section 6.1.1 provides a description of some of the features of this information.

7.2 Baseline Analyses

7.2.1 Cost versus link reliability

Figure 7.2 gives a plot of the sensitivity of cost per ground terminal to changes in required system reliability. Reliabilities higher than 96.5% were not possible under the system constraints without the use of diversity stations. Note that there is approximately a 10% increase in cost per terminal as the reliability increases from 90% to 96.5%.

7.2.2 Cost versus satellite weight

Figure 7.3 gives a plot of the sensitivity of ground terminal cost to the maximum allowed satellite weight. Since launch weight has a significant impact on launch cost, a portion of estimated launch cost was added to the cost per terminal. A cost of $5000 per pound was assumed. It will be noticed that this cost is constant for weight constraints above 6500 pounds. The implication is that the optimum satellite weight is unconstrained above this limit. For larger weight constraints the optimum satellite weighs 6500 pounds.

7.2.3 Cost versus channel availability

In order to examine the cost per terminal for various numbers of ground terminals and for various communication capabilities, channel availability was defined as the ratio of the total number of channels to the number of ground terminals. Figure 7.4 gives cost per terminal versus availability for 120, 360 and 1080 ground stations. Since satellite weight varies considerably as utilization changes, launch costs are included in the cost per terminal as for the previous analysis. Utilizations greater than 0.22 were not possible for 1080 ground stations due to absolute launch weight limits.

The increase in cost per terminal is approximately linear with increases in utilization for all numbers of ground stations. The increase is due to the cost of additional switching components and the effects of increased satellite weight on satellite operational systems and launch weight.

For a constant utilization the cost may be studied for various numbers of terminals. For the increase to 360 from 120 ground stations the drop in per terminal cost is a result of the further division of satellite cost. For the increase to 1080 no similar drop is seen due to substantially increased launch cost for the heavier satellite.

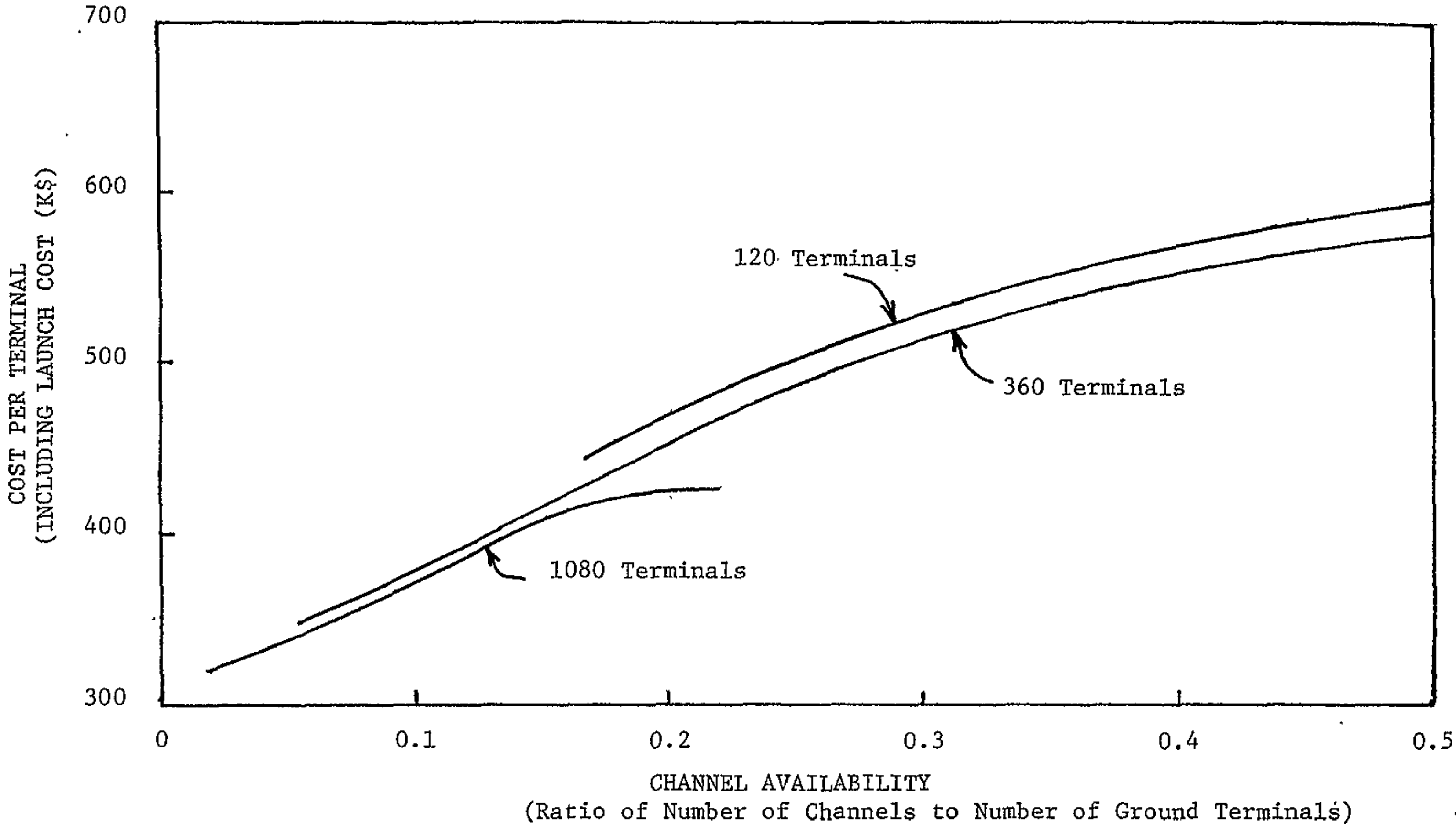

Figure 7.4. Cost per Terminal versus Channel Availability

SECTION 8

CRITICAL TECHNOLOGIES AND TECHNOLOGY RISK ASSESSMENT

Previous sections of this report contain the results of applying the subsystem models and optimization techniques to conceptual designs for point-to-point and broadcast communication systems. The sensitivity of the optimal designs to variations in performance parameter values have also been presented. The effects of subsystem model adjustments for the point-to-point and broadcast applications will be developed in this section and combined with estimates of the likelihood of occurrence of model changes for estimating subsystem model expected impacts.

Identification of technologies critical to implementation of millimeter space communications systems requires accomplishing the following four items: evaluation of system impacts of model adjustments (by re-optimization for each adjustment); (2) identification of likelihood of model adjustments for each subsystem; (3) estimation and ranking of expected system impacts; (4) relation of expected system impacts to the specific technologies. These steps will be applied to the point-to-point application and to the broadcast application. Results from the applications will then be combined to produce an overall listing of critical technologies for millimeter wave space communications systems.

8.1 Subsystem Model Adjustments

In order to judge the impact of changes in estimates for cost and weight models, each model has been increased by a fixed proportion (one at a time) and the system re-optimized. The subsystem models were then ranked by the resulting increase in system cost to allow further analysis of the most significant cases. If C(P) is a cost model with performance parameter P, the model $(1 + r) \cdot C(P)$ was substituted in the optimization, where $0 < r \leq 1$. In all cases where possible, $r = 1$ was used; this corresponds to an increase of 100% in the model of interest. In the case of some of the subsystem weight models, a 100% increase will not yield a system which meets the C/N and satellite weight constraints. In these cases a smaller r was chosen, and, in the presentation of cost impacts, the cost increases for these cases were extrapolated linearly for comparison.

Tables 8.1, 8.2, and 8.3 contain the model adjustment results for the 40/50 GHz point-to-point application, the 18/30 GHz point-to-point application, and the 40/50 GHz broadcast application, respectively. The subsystem with the largest cost impacts are of two types: the costly ground subsystems (diversity landline, landline interface, ground antenna, and bulk data storage) and the heavy satellite

Table 8.1. System Cost Impacts of Model Adjustments

APPLICATION I, POINT-TO-POINT, 40/50 GHz

	SUBSYSTEM MODEL	TYPE	NORMALIZED IMPACT[b] (S)
1.	Diversity Landline	Cost	.197
2.	Structure & Thermal Control	Weight	.115
3.	Landline Interface	Cost	.103
4.	Ground Antenna	Cost	.102
5.	Station Keeping System	Weight	.096
6.	Bulk Data Storage	Cost	.095
7.	Station Keeping System	Cost	.084
8.	Structure and Thermal Control	Cost	.058
9.	Satellite Receiver	Cost	.048
10.	Ground Signal Processing	Cost	.047
11.	Attitude Control System	Cost	.041
12.	Satellite Antenna	Cost	.038
13.	Attitude Control System	Weight	.036
14.	Ground Receiver	Cost	.025
15.	Ground Transmitter	Cost	.019
16.	Satellite Power Supply	Weight	.014
17.	Satellite Transmitter	Cost	.013
18.	Satellite Transmitter	Weight	.011
19.	Satellite Antenna	Weight	Less than .01
20.	Satellite Signal Processing	Cost	Less than .01
21.	Satellite Power Supply	Cost	Less than .01
22.	Ground Pointing and Control	Cost	Less than .01
23.	Satellite Receiver	Weight	Less than .01
24.	Satellite Signal Processing	Weight	Less than .01

(a) Baseline cost = \$44018 K\$ (excluding launch cost)

(b) $S = (\Delta C/C)/(P/100)$ where P is the percent adjustment in the subsystem cost or weight model.

Table 8.2. System Cost Impacts of Model Adjustments

APPLICATION IA, POINT-TO-POINT, 18/30 GHz

	SUBSYSTEM MODEL	TYPE	NORMALIZED IMPACT[b] (S)
1.	Diversity Landline	Cost	.205
2.	Landline Interface	Cost	.107
3.	Bulk Data Storage	Cost	.099
4.	Ground Signal Processing	Cost	.049
5.	Structure and Thermal Control	Weight	.045
6.	Ground Antenna	Cost	.037
7.	Station Keeping System	Weight	.035
8.	Station Keeping System	Cost	.027
9.	Structure and Thermal Control	Cost	.017
10.	Attitude Control System	Cost	.015
11.	Satellite Receiver	Cost	.013
12.	Satellite Antenna	Cost	.013
13.	Satellite Transmitter	Cost	.010
14.	Satellite Transmitter	Weight	Less than .01
15.	Satellite Antenna Weight	Weight	Less than .01
16.	Satellite Power Supply	Weight	Less than .01
17.	Ground Receiver	Cost	Less than .01
18.	Satellite Signal Processing	Cost	Less than .01
19.	Ground Transmitter	Cost	Less than .01
20.	Satellite Power Supply	Cost	Less than .01
21.	Ground Pointing and Control	Cost	Less than .01
22.	Satellite Receiver	Weight	Less than .01
23.	Satellite Signal Processing	Weight	Less than .01
24.	Attitude Control System	Weight	Less than .01

(a) Baseline cost = $42335 K$ (excluding launch cost)

(b) $S = (\Delta C/C)/(P/100)$ where P is the percent adjustment in the subsystem cost or weight model.

Table 8.3. System Cost Impacts of Model Adjustments
APPLICATION II, BROADCAST, 40/50 GHz

SUBSYSTEM MODEL	TYPE	NORMALIZED IMPACT[b] (S)
1. Structure and Thermal Control	Weight	.330
2. Station Keeping System	Weight	.219
3. Satellite Signal Processing	Weight	.189
4. Landline Interface	Cost	.141
5. Satellite Power Supply	Weight	.130
6. Ground Antenna	Cost	.124
7. Ground Transmitter	Cost	.101
8. Ground Signal Processing	Cost	.090
9. Ground Receiver	Cost	.087
10. Ground Pointing and Control	Cost	.072
11. Attitude Control System	Weight	.058
12. Satellite Transmitter	Weight	.048
13. Station Keeping System	Cost	.037
14. Satellite Antenna	Weight	.026
15. Structure and Thermal Control	Cost	.023
16. Satellite Receiver	Weight	.021
17. Attitude Control System	Cost	.021
18. Satellite Antenna	Cost	.017
19. Satellite Signal Processing	Cost	.011
20. Satellite Transmitter	Cost	.009
21. Satellite Power Supply	Cost	.005
22. Satellite Receiver	Cost	.005

(a) Baseline Cost = \$173,952 K\$ (excluding launch cost)
(b) $S = (\Delta C/C)/(P/100)$ where P is the percent adjustment in the subsystem cost or weight model.

subsystems (structure and thermal control, and station keeping systems). Inaccuracies in these subsystem models would cause the largest impacts in estimated total system cost and thus require more analysis in the modelling process. The ranking for the broadcast application is similar to those for the point-to-point applications except that the ground subsystems have increased in impact due to the significant increase in number of ground stations and due to the satellite design being at maximum weight.

8.2 Model Adjustment Likelihoods

Quantized estimates of subsystem uncertainties (10%, 30%, 50%, 70%, or 90%) have been developed for the subsystem models. The percent likelihood may be viewed as approximately the probability that the model adjustments in the previous subsection will actually occur. The product of (1) the likelihood and (2) the increase in total system cost resulting from the model adjustment will then be a measure of the resulting system impact. The adjustment likelihood estimates for the cost and weight models of the ground and space subsystems are given in Table 8.4. These values were established from consideration of both uncertainties in subsystem models and rate of change of the state-of-the-art of the associated technologies.

The relatively large likelihood associated with the ground antenna pointing control results from the necessity to extend the pointing tolerance downward for the decreased beamwidth of millimeter communication. The large uncertainty in the diversity land link is associated with technology developments in millimeter cables and fiber optics with 1 GHz bandwidths. In a similar fashion technology developments associated with multi-beam antennas are responsible for the relatively large uncertainty in the satellite antenna cost model. Further developments are anticipated in solid state satellite transmitters and wide band signal processing. The uncertainties associated with structure and thermal control are based on large variations in costs for existing systems. The adjustment likelihood values in Table 8.4 are used with the point-to-point and broadcast communication system in the following.

8.3 Expected System Impacts

The communication system cost impact due to uncertainty in the subsystem cost and weight model can be approximated as the product of the likelihood of the model adjustment and the cost impact of the model adjustment. The model adjustment likelihoods of Table 8.4 have been combined with the system cost increases for the subsystem model adjustment of Tables 8.1, 8.2, and 8.3 to produce the expected system impact given in Tables 8.5, 8.6, and 8.7. The subsystems are listed in

TABLE 8.4

ADJUSTMENT LIKELIHOOD

	Cost Model	Weight Model
I. Ground System		
Ground Antenna	10%	--
Ground Antenna Pointing and Control	50%	--
Radome	10%	--
Ground Transmitter	30%	--
Ground Receiver	30%	--
Ground Signal Processing	10%	--
Bulk Data	30%	--
Landline Interface	30%	--
Diversity Land Link	70%	--
II. Space Systems		
Satellite Antenna	50%	10%
Attitude Control System	30%	10%
Station Keeping	30%	10%
Satellite Transmitter	70%	30%
Satellite Receiver	30%	30%
Space Signal Processing	50%	50%
Structure and Thermal Control	50%	50%
Satellite Power Supply	10%	10%

Table 8.5. Expected System Impacts
Application I, Point-to-Point, 40/50 GHz

Subsystem Model	Type	Model Adjustment Likelihood	Expected Impact (%)
Diversity Landline	Cost	.7	13.7
Structure and Thermal Control	Weight	.5	5.8
Landline Interface	Cost	.3	3.1
Structure and Thermal Control	Cost	.5	2.9
Bulk Data Storage	Cost	.3	2.8
Station Keeping System	Cost	.3	2.5
Satellite Antenna	Cost	.5	1.9
Satellite Receiver	Cost	.3	1.4
Attitude Control System	Cost	.3	1.2
Ground Antenna	Cost	.1	1.0
Station Keeping System	Weight	.1	1.0
Satellite Transmitter	Cost	.7	0.9
Ground Receiver	Cost	.3	0.8
Ground Transmitter	Cost	.3	0.6
Ground Signal Processing	Cost	.1	0.5
Attitude Control System	Weight	.1	0.4
Satellite Transmitter	Weight	.3	0.3
Satellite Power Supply	Weight	.1	0.1

Table 8.6. Expected System Impacts
Application IA, Point-to-Point, 18/30 GHz

Subsystem Model	Type	Model Adjustment Likelihood	Expected Impact (%)
Diversity Landline	Cost	.7	14.4
Landline Interface	Cost	.3	3.2
Bulk Data Storage	Cost	.3	3.0
Structure and Thermal Control	Weight	.5	2.3
Structure and Thermal Control	Cost	.5	0.8
Station Keeping System	Cost	.3	0.8
Satellite Transmitter	Cost	.7	0.7
Satellite Antenna	Cost	.5	0.6
Ground Signal Processing	Cost	.1	0.5
Attitude Control System	Cost	.3	0.5
Satellite Receiver	Cost	.3	0.4
Ground Antenna	Cost	.1	0.4
Station Keeping System	Weight	.1	0.3

Table 8.7. Expected System Impacts
Application II, 40/50 GHz Broadcast

Subsystem Model	Type	Model Adjustment Likelihood	Expected Impact (%)
Structure and Thermal Control	Weight	.5	16.5
Satellite Signal Processing	Weight	.5	9.4
Landline Interface	Cost	.3	4.2
Ground Pointing and Control	Cost	.5	3.6
Ground Transmitter	Cost	.3	3.0
Ground Receiver	Cost	.3	2.5
Station Keeping System	Weight	.1	2.2
Satellite Transmitter	Weight	.3	1.4
Satellite Power Supply	Weight	.1	1.3
Ground Antenna	Cost	.1	1.2
Structure and Thermal Control	Cost	.5	1.1
Station Keeping System	Cost	.3	1.1
Ground Signal Processing	Cost	.1	0.9
Satellite Antenna	Cost	.5	0.9
Satellite Transmitter	Cost	.7	0.7
Satellite Receiver	Weight	.3	0.7
Attitude Control System	Cost	.3	0.6
Attitude Control System	Weight	.1	0.6
Satellite Signal Processing	Cost	.5	0.5
Satellite Antenna	Weight	.1	0.3
Satellite Receiver	Cost	.3	0.1
Satellite Power Supply	Cost	.1	0.05

Tables 8.5 through 8.7 in order of decreasing expected impact. Table 8.8 is a similar ranking of expected system impacts, but for a combination of applications I and II; i.e., for a point-to-point system with six ground stations and a broadcast application system, both operating in the 40/50 GHz allocated region. Note that the combined ranking is essentially the same as for the broadcast system itself.

8.4 Technology Risk Assessment

Estimates of the technology risk (i.e., the R & D time required for technology improvement) have been made for those subsystems ranked high with respect to system impacts in Tables 8.5 through 8.8. The technology risk has been categorized as being 2 to 4 years, 5 to 10 years, and invention required. The results of the technology risk assessment are given in Table 8.9.

8.5 R & D Program Scenarios

Those technologies categorized as having R & D time requirements between 2 and 4 years and 5 and 10 years from section 8.4 are considered briefly in the following where a sketch of the R & D program scenarios deemed necessary for risk removal is presented. The objective of these programs is to provide development for cost reduction and performance improvement of the technologies.

8.5.1 Propagation Studies

By far, the one item of greatest impact on the results of this study is the assummed propagation fade statistics. Consequently, a more refined engineering analysis of 40/50 GHz communications should await basic data from satellite experiments in the 40/50 GHz region. The scale of these data should be comparable with the work performed at lower frequencies. The propagation studies are more difficult at these wavelengths not only because of the increased clear air attenuation over that existing at lower frequencies but also because of the increased attenuation resulting from rain and cloud coverage. As a result of these factors, propagation of millimeter waves has exhibited severe fluctuation effects and has been difficult to characterize. The research required for millimeter wave propagation can be done in conjunction with other experimental work requiring geosynchronous satellites and allowing the additional payload of a group of millimeter wave beacons.

Among the phenomena which must be investigated at 40/50 GHz are the following:

1. Fluctuation effects in both amplitude and phase during clear atmosphere propagation.

2. Slant angle effects including refractive index variations for satellite-to-ground propagation.

Table 8.8. Expected System Impacts (Combined)
Point-to-Point & Broadcast, 40/50 GHz

Subsystem Model	Type	Model Adjustment Likelihood	Expected % Impact
Structure and Thermal Control	Weight	.5	15.9
Diversity Landline	Cost	.7	14.1
Satellite Signal Processing	Weight	.5	8.3
Landline Interface	Cost	.3	4.4
Ground Pointing and Control	Cost	.5	3.2
Ground Transmitter	Cost	.3	2.8
Ground Receiver	Cost	.3	2.5
Station Keeping System	Weight	.1	2.1
Structure and Thermal Control	Cost	.5	1.6
Station Keeping System	Cost	.3	1.5
Satellite Transmitter	Weight	.3	1.4
Ground Antenna	Cost	.1	1.3
Satellite Power Supply	Weight	.1	1.2
Satellite Antenna	Cost	.5	1.2
Ground Signal Processing	Cost	.1	0.9
Attitude Control System	Cost	.3	0.8
Satellite Transmitter	Cost	.7	0.8
Attitude Control System	Weight	.1	0.6
Satellite Receiver	Weight	.3	0.6
Satellite Signal Processing	Cost	.5	0.5
Satellite Receiver	Cost	.3	0.5
Satellite Antenna	Weight	.1	0.3
Satellite Power Supply	Cost	.1	0.0

Table 8.9

Technology Risk Assessment

Subsystem	Risk Category*
Structure & Thermal Control	A
Satellite Signal Processing	B
Landline Interface	A
Diversity Landline	A
Bulk Data Storage	C
Ground Pointing and Control	A
Station Keeping	A
Ground Transmitter	A
Satellite Antenna	A
Satellite Transmitter	B
Ground Receiver	A
Satellite Receiver	A

*Risk Category Definition:

A = 2 - 4 years
B = 5 -10 years
C = Invention Required

3. Fades during inclement weather, e.g. rain, snow, and storm cloud coverage.

4. Reliability improvement achievable through use of spatial diversity. All these effects should be evaluated with ground-based receivers at several key locations for an understanding of the over-all effects on a nationwide communication system. As a result of these studies the power requirements for space-to-earth millimeter communications during adverse weather conditions would be determined.

8.5.2 High Data Rate Diversity Line

In choosing the means of transmitting between two spatial diversity sites, several techniques have been considered. From the viewpoint of size and operation during inclement weather, the buried millimeter wave link and fiber optic system have the greatest potential. These two schemes also provide the greatest capability for high data rate transmittion. Substantial research and development efforts are already under way in both these areas and it is doubtful that additional effort would be called for. At this time, it would appear that the buried waveguide and optical fiber technologies will be competitive. However, because of its large contribution to the overall cost of the satellite communication system (Application I), the diversity link costs must be substantially reduced and/or the link operated with high traffic loads.

8.5.3 Bulk Data Storage

The attractive capability of millimeter wave communications to provide near 1 Gbit data rates is severely limited by the interface of the communication to the users. It is always necessary to provide buffer storage which operates at these high data rates. Currently solutions require high parallelism in digital equipment and correspondingly large costs. Several technologies have been suggested which may eventually accomodate these applications, but none is sufficiently developed to allow estimates of availability.

Since there is strong motive for the development of high data rate storage in the computer industry, it is likely that additional research sources will not speed the process. Rather, research should be limited to determining new advances in the area and judging their impact on the attractiveness of millimeter digital communications.

8.5.4 Space switching equipment

Switches for application in millimeter wave communications applications are currently available but are considered too bulky for the large capacity systems of interest. The development program for these components would be to provide reliable ferrite switches while taking advantage of the inherent small size of millimeter devices. Special attention should be given to the use of these switches in matrix arrangements with configurations adapted to satellite communication requirements.

This problem is primarily one of engineering design; most of the work is that of prototype construction and testing. Flight tests are required primarily for reliability and life-time analysis. After the switching capacity requirements are specified it is estimated that development can be completed in 2 years.

An alternate approach which has been considered during this program is the use of switching devices at the 50 GHz up-link frequency so that down-conversion to 40 GHz, and not to a low IF could be employed, for transmission. This approach could result in simplification of the entire space system, but, to achieve this operation, 50 GHz switches and amplifiers are needed in addition to efficient 50/40 GHz down-conversion. The 50 GHz switches, currently in the form of ferrite latching switches, must be lighter, more efficient and must provide sufficient isolation between channels. The distribution of the signals within the switching complex is also highly dependent upon the availability of good low loss circulators and band-pass filters at 50 GHz.

8.5.5 Receiver and Transmitter Development

Because of the severe propagation characteristics of millimeter waves improvements in system performance will depend heavily on the availability of high performance receivers and transmitters. In particular, the weight of the spacecraft transmitter is especially critical. With our assumed models, it appears these devices would account for a substantial portion of spacecraft weight. In some configurations the required satellite weight exceeded launch capabilities.

By our estimates a 2 lb. reduction in spacecraft weight can be realized for every 1 lb. reduction of transmitter weight. The 2:1 leverage occurs because of the reduced requirements for structure, attitude control and station keeping.

Our analyses indicates only a modest RF power requirement per device for Application I. However, the total RF power required is substantial requiring a significant weight penalty in the thermal control system. In Application II the RF power and attendent thermal control per transmitter was substantial and severely restricted satellite capacity.

Therefore, emphasis in the technology effort on spacecraft transmitters should be on lightweight devices, efficient operation, and modest to high power outputs.

Both the spacecraft and ground terminal receivers should have a relatively low noise performance. It appears appropriate to consider cryogenically cooled types for the ground terminals while uncooled types may suffice for the spacecraft.

In addition, it would be appropriate to pursue the following:

1. Continued mixer improvement in the area of cheaper, higher performance Schottky barrier materials. Improved mixer configurations and radiation coupling schemes will improve this situation. The utilization of subharmonoic mixing schemes offers the potential of lower noise characteristics than offered by fundamental mixing and the capability to employ lower frequency local oscillators which are inherently higher powered, more stable and cheaper. Lifetime is an important consideration for millimeter mixers. The characteristics of the mixer are equally important to good up-conversion from the IF to the 40 GHz down-link frequency.

2. The trends in lower cost, better performing solid state IF's must continue to higher frequencies to handle the high data rates projected for millimeter wave communications.

3. Improved L. O. solid state materials, e.g. In P, can contribute to lower noise, more efficient receivers.

4. With the requirements for high data rates, uniform wide-bandwidth amplifiers with efficient modulation of low noise, efficient oscillators will be needed for both ground and space subsystems.

8.5.6 Satellite antennas

Two areas of satellite antenna development are of interest in millimeter wave communication applications. One is to improve the tolerance of dish or lens fabrication. At millimeter wavelengths this allows significantly improved antenna gain. The second is further development of multibeam antenna techniques, an important adjunct to the switch capacity of a communication satellite. Each of these areas requires further engineering studies to improve construction techniques and to decide among alternative designs. Work is currently underway for both of these design efforts. Consequently, it is expected that 2 years is sufficient for adequate development after system requirements are defined.

SECTION 9

CONCLUSIONS AND RECOMMENDATIONS

Identification of technologies for millimeter satellite communication systems, and assessment of the relative risks of these technologies, have been accomplished through subsystem modeling and link optimization for both point-to-point and broadcast applications. The methodology developed for identifying viable and appropriate technologies for future NASA millimeter research and development programs is based upon the technical requirements of potential space communication services. Applicability of the methodology has been verified through its use with two conceptual communications systems. The subsystem cost and weight models are the appropriate level of detail for this study. Application of the methodology to the detailed design of a satellite system would require further model refinement.

One of the unknowns which will significantly influence the design and cost of a millimeter space communication system is the propagation statistics for the ground station locations. One of the primary results of the study relates the link reliability (percent of the time the link is operational) to assumed weather statistics and, in the case of the point-to-point service, an assumed ground station diversity.

For the point-to-point service redundant transmitting/receiving stations were located approximately ten miles from the normal ground station. Rain reliabilities of 90.0% to 99.9% were available with this configuration at varying system costs. As indicated in Figure 6.2, the ground station cost per terminal as a function of reliability (weather) varies between 8.5 and 9 million dollars as the reliability varies from 90% to 99.9%. This reliability improvement represents a cost increase of about 23%. Figure 6.5 indicates a cost increase of only 6% for the same range of reliabilities for an 18/30 GHz system. Primary difference between the two frequency range applications is propagation statistics.

As the number of ground terminals in the point-to-point communication system is varied from 2 to 10, the cost per ground terminal decreases about 38% for TDM and about 48% for FDM. FDM remained about 3 million dollars per ground terminal less expensive than TDM. Due to the difference in the TDM and FDM signal processing models this cost was constant for a given system configuration.

The broadcast concept initially considered provided continuous continental United States coverage through a large number of adjacent spot beams. However, preliminary power calculations indicated that excessive satellite weight would be required for this mode of operation. A compromise baseline design incorporating limited simultaneous beam utilization with on-board switching was then selected for analysis. The weight of the switches then became a limiting criteria in overall performance. The resulting "broadcast" link is estimated to be able to maintain its design value carrier-to-noise ratio (12dB) 95% of the time for the assumed rain attenuation statistics. Such a communication satellite system would not be commercially marketable in the sense of current communication satellites (e.g., video entertainment); however, there may well exist suitable applications such as high volume data transfer where the time of day for the data transfer is not critical (e.g., the system being planned by Satellite Business Systems (SBS) [15].

For the broadcast application, ground station diversity was not considered to be a viable option. As this concept developed the primary consideration became the launch capability. The system cost model indicated a need for a high power (and heavy) satellite with small inexpensive ground terminals to realize lowest costs. As shown in Figure 7.3 the cost per ground terminal decreases rapidly between 5000 and 6000 pound satellites and continues to decrease to a cost per terminal of 600,000 dollars where the allowable satellite weight reaches 6500 pounds. Further cost reductions are realized if the number of terminals is increased and low satellite utilization is assumed. In Figure 7.4 the minimum cost appears to be about 400,000 dollars per terminal, a relatively expensive service. The link reliability for the broadcast case cannot exceed 96.5% for a 6500 pound satellite (maximum weight) with the assumed statistics (a design value of 95% was used as baseline for the study). The reduced reliability for this service is a result of the need for a large number of switches, significant power requirements, and launch constraints.

Technology risks have been defined in Section 8 for those technologies deemed most critical to the cost of an overall millimeter communication system. The critical technologies include all receivers and transmitters, bulk data storage, diversity landline, satellite switching and satellite antennas. Brief R&D scenarios for these technologies have been given.

Recommendations as a result of this study include additional experiments and analysis of atmospheric propagation characteristics and the specific technology research scenarios of Section 8 intended to reduce the costs of subsystems. A recommendation for a continued model improvement is appropriate only to the extent that the methodology developed here for identification of appropriate technology be applied in the design of resulting satellites. It is also recommended that the methodology and models developed here be extended to other applications such as navigation satellites where maximum advantage can be taken of existing methodology and models.

Further investigation of satellite broadcast applications at millimeter frequencies is required. Such investigations should be directed toward increasing the link reliability by the use of multiple satellites and massive satellites to provide sufficient RF power to assure communications through moderate rainstorms. The commercial marketability of applicable services should also be investigated.

Other recommendations relative to implementation of advanced communication satellites would include additional research in on-board signal processing, direct modulation for receive/transmit at 50/40 GHz, data regeneration for use with digital transmission, investigation of additional methods of bulk data storage and methods for efficient use of space communication links with variable data rate users.

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APPENDICES

APPENDIX A

SPACE COMMUNICATION LINK EQUATION DERIVATION

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APPENDIX A. SPACE COMMUNICATION LINK EQUATION DERIVATION

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APPENDIX A

SPACE COMMUNICATION LINK EQUATION DERIVATIONS

The figure of merit for a space communications systems is considered to be the ratio of the carrier power to the noise power (C/N) at the receiving ground station. The value of received C/N depends upon each of the link terms given in Table 2.1. However, certain terms, such as the ground transmitter power and ground antenna gain, are of more importance in the link performance than are other terms such as the ground antenna pointing and control. Those terms considered most significant have been marked in the table as fundamental, and those less significant listed as secondary. The equations which relate the link performance to the individual subsystems will first be presented with only the fundamental terms (to improve visiability), secondary terms will then be added in subsection A.2.

A.1 Fundamental Terms of the Link Equation

The communications link equation (C/N) is developed below for those subsystems which are indicated as fundamental in Table 2.1. Definitions of symbols used in this Appendix are contained in Table A.1.

A.1.1 Transmitting Ground Station

A commonly used figure of merit for the transmitting portion of a ground station is its Effective Isotropic Radiated Power (EIRP), which is the power which would have to be transmitted through an omni-directional antenna in order to achieve the same power density in space along the center of the beam of the actual antenna. The EIRP is the product of the ground transmitter power, P_{GT}, and the antenna gain, G. The gain of the ground station antenna is given by

$$G = (68.0)\ (F_{UL})^2\ (D_{GA})^2 \qquad (A.1)$$

Table A.1

DEFINITION OF SYMBOLS

Uplink Frequency, GHz	F_{UL}
Downlink Frequency, GHz	F_{DL}
Ground Antenna Diameter, m	D_{GA}
Satellite Receiving Antenna Diameter, m	D_{SRA}
Satellite Transmitting Antenna Diameter, m	D_{STA}
Ground Transmitter Power, watts	P_{GT}
Satellite Transmitter Power, watts	P_{ST}
Boltzmann's Constant (1.38×10^{-23})	k
Information Bandwidth, Hertz	B
Standard Noise Temperature (290°K)	T_{STD}
Satellite Antenna Noise Temperature	T_{SA}
Ground Antenna Noise Temperature	T_{GA}
Satellite Receiver Noise Figure	F_{SR}
Ground Receiver Noise Figure	F_{GR}
Carrier Power Received at Satellite	C_{RS}
Equivalent Noise Power Received at Satellite	N_{RS}
Carrier Power Received at Ground	C_{RG}
Equivalent Noise Power Received at Ground	N_{RG}
Uplink Radome (Water Layer) Attenuation (dB)	L_{RDOMU}
Downlink Radome Attenuation (dB)	L_{RDOMD}
Uplink Rainfall Attenuation (dB)	L_{RUL}
Downlink Rainfall Attenuation (dB)	L_{RDL}
Ground Antenna Misalignment (degrees)	E_{GA}
Satellite Attitude Control Error (degrees)	E_{SAC}
Satellite Misc. Power Losses	L_{SM}
Ground Misc. Power Losses	L_{GM}
Total Uplink Secondary Losses	L_{UL}
Total Downlink Secondary Losses	L_{DL}

where F_{UL} is the uplink frequency in Gigahertz and D_{GA} is the diameter of the ground station antenna in meters. The EIRP of the ground station is given by Equation A.2.

$$EIRP \triangleq P_{GT} \cdot G = P_{GT} \cdot (68.0)\ (F_{UL})^2\ (D_{GA})^2 \tag{A.2}$$

The power density (watts per square meter) of the electromagnetic wave transmitted by the ground station decreases according to R^2 where R is the distance from the antenna. The product of the power density along the beam center and the surface area of a sphere of a radius R is equal to the EIRP, and the power density can be expressed as in Equation A.3, where R is expressed in meters.

$$P = \frac{EIRP}{4\pi R^2} = \frac{P_{GT} \cdot (68.0)\ (F_{UL})^2\ (D_{GA})^2}{4\ \pi (R)^2} \tag{A.3}$$

The separation distance, R, for a geosynchronous communications satellite link is essentially the altitude of the satellite (22,800 miles or $3.66852 \times 10^{+7}$ meters). The power density of the transmitted electromagnetic wave is further decreased by attenuation during rainfall; this is especially significant in the millimeter wave frequency band. The value to be used for the rainfall attenuation, L_{RUL} dB will be taken as that value which local statistical experiments indicate will not be exceeded by actual rainfall attenuation anymore than R_1% of the time, where R_1 is the desired reliability of the uplink. The corresponding rainfall attenuation scale factor is given in Equation A.4.

$$\text{RAINFALL ATTENUATION SCALE FACTOR} = 10^{-(L_{RUL}/10)} \tag{A.4}$$

A.1.2 Satellite Subsystems

The carrier signal which is amplified by the ground transmitter, directed by the ground antenna, attenuated by earth weather conditions, and diverged during its travel through space arrives at the communication satellites receiving antenna with a power density as described by

$$P_{SRA} = \frac{(10)^{-(L_{RUL}/10)} \cdot P_{GT} \cdot (68.0)\ (F_{UL})^2\ (D_{GA})^2}{4\ \pi(3 \cdot 66852 \times 10^7)^2} \quad \text{watts/m}^2$$

$$= (4.020856 \times 10^{-15})\ P_{GT}\ (F_{UL})^2\ (D_{GA})^2\ (10)^{-(L_{RUL}/10)} \qquad \text{(A.5)}$$

The carrier power level received by the satellite antenna is given by the product of the power density, p_{SRA}, and the effective apperature area, A_{es}, of the satellite's receiving antenna. The effective apperature area is proportional to the square of the wavelength of the uplink signal and to the gain of the receiving antenna, G_{SRA}:

$$A_{es} = \frac{\lambda^2\ G_{SRA}}{4\ \pi} = \frac{(3\text{x}10^8/F_{UL}\text{x}10^9)^2}{4\ \pi} \cdot (68.0)\ (F_{UL})^2\ (D_{SRA})^2$$

$$= (0.48701)\ (D_{SRA})^2 \qquad \text{(A.6)}$$

The resulting carrier power out of the satellite's receiving antenna is as given by Equation A.7 below, where D_{SRA} is the diameter of the satellite receiving antenna, in meters.

$$C_{RS} = P_{RS} = p_{SRA} \cdot A_{es}$$

$$= (4.02086\text{x}10^{-15})\ P_{GT}\ (F_{UL})^2\ (D_{GA})^2\ (10)^{-(L_{RUL}/10)} \cdot (0.48701) \cdot (D_{SRA})^2$$

$$= \left\{ (1.9582 \times 10^{-15})\ P_{GT}\ (F_{UL})^2\ (D_{GA})^2\ (10)^{-(L_{RUL}/10)}\ (D_{SRA})^2 \right\} \qquad (A.7)$$

The carrier signal received from the ground station by the satellite receiver is accompanied by noise picked up by the satellite antenna and noise generated by the satellite receiver. The equivalent noise power at the receiver input is the sum (uncorrelated noise sources) of the noise picked up by the satellite antenna and the noise introduced by the satellite low-noise amplifier in the receiver front end.

$$N_{RS} = N_{SA} + N_{SLNA} \qquad (A.8)$$

The antenna noise is given by the product of Boltzmann's constant ($k=1.38\text{x}10^{-23}$ joules/°K) and the equivalent noise temperature seen by the satellite antenna and the information bandwidth in Hertz.

$$N_{SA} = k\ T_{SA}\ B \qquad (A.9)$$

where T_{SA} is the equivalent noise temperature of the antenna (typically 300° K due to viewing the warm earth). In a similar fashion, the noise introduced by the receiver (reflected to its input terminal) can be written in terms of its equivalent noise temperature; however, it is common to express the equivalent receiver noise power in terms of the noise figure F_{SR}, as given in Equation A.10.

$$N_{SLNA} = k\ T_{STD}\ B\ (F_{SR} - 1) \tag{A.10}$$

The standard noise temperature, T_{STD}, in equation 2.10 is 290° Kelvin, and k and B are as earlier defined. The total equivalent noise power at the receiver input is

$$\begin{aligned} N_{RS} &= k\ T_{SA}\ B + k\ T_{STD}\ B\ (F_{SR} - 1) \\ &= k\ B\ [T_{SA} + T_{STD}\ (F_{SR} - 1)] \end{aligned} \tag{A.11}$$

When the antenna temperature is the same as the standard temperature, the satellite received noise expression simplifies to $N_{SA} \cdot F_{SR}$.

The performance of the communications uplink is indicated by the ratio of the received carrier power to the total noise power. Combining equations A.7 and A.11, the satellite's received carrier to noise ratio is written as equation A.12.

$$\frac{C_{RS}}{N_{RS}} = \left\{ \frac{(1.9582 \times 10^{-15})\ P_{GT}\ (F_{UL})^2\ (D_{GA})^2\ (10)^{-(L_{RUL}/10)}\ (D_{SRA})^2}{k\ B[T_{SA} + T_{STD}\ (F_{SR} - 1)]} \right\} \tag{A.12}$$

The independent parameters in the uplink which the system designer can vary are (1) the ground transmitter power, (2) the ground antenna diameter, (3) the satellite receiving antenna diameter, and (4) the noise figure of the satellite receiver. It is assumed that the assigned uplink frequency and bandwidth of the signal are fixed. The loss associated with propogation through weather conditions will be determined by the required realiability of the uplink. For purposes of this research program, it has been assumed that the processing of the signal in the satellite between the receiver output and the transmitter output does not influence the carrier to noise ratio; that is, it is assumed that the carried noise ratio at the transmitter output is the same as that out of the satellite receiver.

The primary parameter of the satellite transmitter is its output power, P_{TS}, which is the sum of the carrier power transmitted and the (uncorrelated) noise power transmitted.

$$P_{TS} = N_{TS} + C_{TS} \tag{A.13}$$

The assumption that satellite receiver output signal to noise ratio equals transmitter output signal to noise ratio results in a carrier power transmitted of

$$C_{TS} = \frac{P_{TS}}{1 + 1/(C_{RS}/N_{RS})} \tag{A.14}$$

and a noise power transmitted of

$$N_{TS} = \frac{P_{TS}}{1 + (C_{RS}/N_{RS})} \tag{A.15}$$

The EIRP for the satellite is the product of the satellite transmitter carrier power output and the gain of the satellite transmitting antenna, and is given by

$$(EIRP)_s = \frac{P_{TS}}{1 + 1/(C_{RS}/N_{RS})} \cdot (68.0)\ (F_{DL})^2\ (D_{STA})^2 \tag{A.16}$$

where F_{DL} is the downlink frequency in gigahertz, and D_{STA} is the diameter of the satellite transmitting antenna. In a manner analogous to that for the uplink, the information carrying electromagnetic wave transmitted by the satellite diverges such that the power density at the earth's surface would be

$$p_5 = \frac{(EIRP)_s}{4\ \pi\ R^2}\text{, where } R = 3.66852 \times 10^7 \text{ meters} \tag{A.17}$$

The signal is further attenuated by L_{RDL} dB such that the power density of the carrier at the ground station receiving antenna, p_{GRA}, is as given in Equation A.18. Note that Equation A.18 results from combination of Equations A.16 and A.17 with the downlink rainfall attenuation scale factor.

$$P_{GRA} = \frac{(EIRP)_s}{4\,\pi\,R^2} \cdot (10)^{-(L_{RDL}/10)}$$

$$= \left\{ \frac{P_{TS}}{1 + 1/(C_{RS}/N_{RS})} \cdot \frac{(68.0)\,(F_{DL})^2\,(D_{STA})^2}{(4\,\pi)\,(3\cdot 66852\text{x}10^7)^2} \cdot (10)^{-(L_{RDL}/10)} \right\}$$

$$= \left\{ (4.02085 \text{ x } 10^{-15}) \;\frac{P_{TS}\,(F_{DL})^2\,(D_{STA})^2}{1 + 1/(C_{RS}/N_{RS})} \cdot (10)^{-(L_{RDL}/10)} \right\} \qquad (A.18)$$

The fundamental parameters available to the systems engineer for design of the satellite communication subsystem include (1) the diameter (therefore gains) of the receiving and transmitting antenna, (2) the noise figure of the receiver, and (3) the output power level of the transmittor. Performance is also highly dependent upon the bandwidth of the communication channel and the RF frequency of the uplink and downlink. Secondary parameters such as the attitude control tolerance and the station keeping tolerance is discussed in Section 2.2.2.

A.1.3 Receiving Ground Station

The primary figure of merit of the receiving ground station is the ratio of the antenna gain to the system noise equivalent temperature, with the ratio usually being expressed in dB. This figure of merit represents that portion of the receiving ground station's contribution to the received carrier to noise ratio.

The carrier power received by the ground station antenna is determined from the power density at the ground receiving antenna, P_{GRA}, and the effective apperature area of the antenna, A_{eG}, in a manner analogous to that used for the satellite receiving antenna.

$$A_{eG} = \frac{\lambda^2 \cdot G_{GA}}{4\,\pi} = \frac{(3\text{x}10^8/F_{DL}\text{x}10^9)^2}{4\,\pi} \cdot (68.0)\,(F_{DL})^2\,(D_{GA})^2$$

$$= (0.48701)\,(D_{GA})^2 \qquad (A.19)$$

$$C_{RG} = p_{GRA} \cdot A_{eG}$$

$$= \left\{ (1.9582 \times 10^{-15}) \cdot \frac{P_{TS} (F_{DL})^2 (D_{STA})^2 (D_{GA})^2}{1 + 1/(C_{RS}/N_{RS})} \cdot (10)^{-(L_{RDL}/10)} \right\} \tag{A.20}$$

The noise power out of the ground receiver, and thus its equivalent input noise power, includes noise from three sources: (1) sky noise picked up by the ground antenna, (2) noise transmitted from the satellite, and (3) noise introduced by the ground receiver itself.

The equivalent noise power at the receiver input is

$$N_{RG} = N_{GA} + N_S + N_{GLNA} \tag{A.21}$$

where:

N_{GA} = Ground Antenna (background) Noise,

N_S = Noise Received from Satellite, and

N_{GLNA} = Equivalent Noise Introduced by Ground Receiver.

and the ground antenna noise power is

$$N_{GA} = k\, T_{GA}\, B \tag{A.22}$$

where T_{GA} is the ground antenna noise temperature (In the presence of precipitation this is typically 270° Kelvin for the millimeter bands). The portion of the noise power transmitted by the satellite, N_{TS}, could be determined by the same procedure utilized above for the carrier power received on the ground; however, it is simpler to use the fact that the same attenuation factors apply to both the noise power and the carrier power. Therefore, the noise power received from the satellite can be related to the ratio of the received to transmitted powers as follows.

$$N_S = N_{TS} \cdot \left(\frac{C_{RG}}{C_{TS}} \right) = \left(\frac{N_{TS}}{C_{TS}} \right) C_{RG}$$

$$= \left(\frac{N_{RS}}{C_{RS}} \right) \cdot \; C_{RG} = C_{RG} \Big/ (C_{RS} / N_{RS}) \tag{A.23}$$

The equivalent noise power introduced by the ground receiver is expressed in terms of the receiver noise figure, F_{ER}.

$$N_{GLNA} = \{k \; T_{STD} \; B \; (F_{GR} - 1)\} \tag{A.24}$$

The total equivalent noise power at the receiver input is then given by

$$N_{RG} = \; k \; B \; [T_{GA} + T_{STD} \; (F_{GR} - 1)] + C_{RG} / [C_{RS} / N_{RS}] \tag{A.25}$$

which reduces to

$$N_{RG} = k \; B \; T_{STD} \; F_{GR} = N_{GA} \; F_{GR} \tag{A.26}$$

For T_{GA} equal to T_{STD} (i.e., for antenna temperature equal standard temperature), the figure of merit of the entire communication link, C/N, can be rewritten by combining Equations A.20 and A.25 to yield the following summary equations (fundamental terms only).

$$C/N = \left\{ \frac{C_{RG}}{k\,B[T_{GA} \cdot (10)^{-(L_{RDOMD}/10)} + T_{STD}\,(F_{GR}-1)] + C_{RG}/[C_{RS}/N_{RS}]} \right\} \qquad (A.27)$$

where

$$C_{RG} = \left\{ (1.9582 \times 10^{-15}) \cdot \frac{P_{TS}\,(F_{DL})^2\,(D_{STA})^2\,(D_{GA})^2 \cdot 10^{-(L_{DL}/10)}}{1 + 1/[C_{RS}/N_{RS}]} \cdot (10)^{-(L_{RDL}/10)} \right\}$$

and

$$[C_{RS}/N_{RS}] = \left\{ \frac{(1.9582 \times 10^{-15}) \cdot P_{GT}\,(F_{UL})^2\,(D_{GA})^2\,(D_{SRA})^2}{k\,B\,[T_{SA} + T_{STD}\,(F_{SR} - 1)]} \cdot (10)^{-(L_{RUL}/10)} \right\}$$

Equation A.27 accounts for the subsystem terms listed as fundamental in Table 2.1. The following subsection provides the additional terms necessary to account for the secondary effects.

A.2 Secondary Terms of the Link Equation

The link equation's secondary terms account for (1) miscellaneous power losses between the transmitter and transmitting antenna at the ground station and at the satellite; (2) mis-alignment of antenna beams resulting from errors in ground antenna pointing control systems; and in satellite station-keeping; (3) satellite attitude control; and (4) attenuation of the electromagnetic wave passing through a (wet) ground station radome. The secondary effect will be grouped into three attenuation terms which modify the link performance as specified in Equation A.27: (1) an attenuation factor for the uplink carrier power received, (2) a similar attenuation factor for the downlink carrier and noise power received, and (3) an attenuation factor for the ground station antennas noise temperature.

The miscellaneous losses at either the ground station or the satellite include such effects as attenuation of the transmitted power within the wave-guide or co-ax connecting the transmitter to the antenna feed, polarization losses due to rotational mis-alignment between the transmitting and receiving antennas, sometimes the degradation of transmitter power level, and any other loss terms not explicitly accounted for in the fundamental or secondary terms. Antenna mis-alignment (azimuth and elevation) gain reductions are often included in the miscellaneous losses, but are treated separately as secondary terms in this analyses. The miscellaneous losses are assumed expressed in dB, with L_{GM} representing ground station miscellaneous losses and L_{SM} representing satellite miscellaneous losses. The corresponding scaler multiplication factors are

$$(10)^{-(L_{GM}/10)} \qquad \text{(A.28)}$$

and

$$(10)^{-(L_{SM}/10)} \qquad \text{(A.29)}$$

The effect of an error in pointing either a ground or satellite antenna is a reduction in that antenna's gain. The amount of the reduction in gain depends upon the geam shape (gain versus angle) of the antenna. For purposes of this study, the gain reduction has been modeled as being linear in dB; that is,

$$\Delta G_{db} = \frac{6E}{\Theta_{HP}} \tag{A.30}$$

where ΔG_{dB} is the antenna gain degradation in dB, Θ_{HP} is the half-power beamwidth of the antenna, and E is the error in antenna pointing. A good approximation for the half power beamwidth of ground station and satellite antenna is

$$\Theta_{HP} = \sqrt{\frac{30,000}{(68)\ (F)^2\ (D)^2}} = \left(\frac{21}{F\ D}\right) \text{ degrees} \tag{A.31}$$

where F is the frequency in gigahertz and D is the antenna diameter in meters. The corresponding gain reduction multiplication factor is given by

$$10^{-\left(\frac{\Delta G_{db}}{10}\right)} = 10^{-\left(\frac{6F\ D\ E}{21}\ /\ 10\right)} = 10^{-(0.029\ F\ D\ E)} \tag{A.32}$$

This expression for antenna gain degradation as a function of antenna beam center pointing error will be used to approximate antenna gain degradation for uplink and downlink transmission.

The effect of ground antenna pointing control error upon the uplink carrier power is given by the multiplicitive factor

$$10^{-(0.029\ F_{UL}\ D_{GA}\ \cdot\ E_{APC})} \tag{A.33}$$

in terms of the uplink frequency, the ground antenna diameter and the error of the antenna pointing control system. Similarly, the gain reduction associated with the downlink carrier power and satellite noise power is given by the factor

$$10^{-(0.029\ F_{DL}\ D_{GA}\ \cdot\ E_{APC})} \tag{A.34}$$

in terms of the downlink frequency, the ground antenna diameter, and the error in the antenna pointing control system.

The effect of satellite attitude control error upon the communication link is equivalent to an error in the pointing of the satellite's receiving and transmitting antennas. The multiplicitive attenuation factor for the uplink is

$$10^{-(0.029\ F_{UL}\ D_{SRA}\ \cdot\ E_{SAC})} \tag{A.35}$$

and the corresponding downlink factor is

$$10^{-(0.029\ F_{DL}\ D_{STA}\ \cdot\ E_{SAC})} \qquad (A.36)$$

where E_{SAC} is the satellite attitude control error, in degrees. The uplink factor affects only the carrier, while the downlink factor multiplies both the downlink carrier power and the downlink satellite noise power.

The effect of satellite station-keeping error upon the communications link is equivalent to an error in the pointing of the ground station antenna. The resulting uplink gain degradation is given by the multiplicitive factor

$$10^{-(0.029\ F_{UL}\ D_{GA}\ \cdot\ E_{SK})} \qquad (A.37)$$

where E_{SK} is the satellite station-keeping error in degrees. The corresponding downlink (carrier and satellite noise powers) gain reduction factor is given by

$$10^{-(0.029\ F_{DL}\ D_{GA}\ \cdot\ E_{SK})} \qquad (A.38)$$

Note that the gain degradation associated with ground station antenna pointing and control and with satellite staion-keeping errors can be eliminated by either an ideal ground antenna pointing system or an ideal satellite station-keeping system. In practice, ideal station keeping systems require excessive propellent and shorten satellite lifetime. The degradation factors associated with the ground antenna pointing and the satellite station keeping should be considered simultaneously. A single tolerance representing the upper bound on error of pointing of ground antenna at satellite, E_{GA}, which is a combination of the effects of an antenna and station keeping errors should be used.

$$10^{-(0.029\ F\ D_{GA}\ E_{GA})} \qquad (A.39)$$

Communications satellite ground stations sometimes incorporate radomes over the antennas for protection against rain, ice, snow, and wind. The primary effect of the radome upon the communication link performance is its attenuation of the electromagnetic wave passing through it; a secondary effect is decreased requirements on the ground antenna pointing and control system due to aleviation of wind torque. Radomes are designed for a minimum attenuation of the signal of interest, but recent studies [ ] have shown that a film of water on the radome due to rain introduces a significantly larger attenuation than does the same layer of water upon the antenna dish itself (for millimeter frequencies). The gain reduction factor for the uplink carrier power is given by

$$10^{-(L_{RDOMU}/10)} \qquad (A.40)$$

where L_{RDOMU} is the (wet) radome attenuation in dB for the uplink frequency. The corresponding attenuation factor for the downlink satellite carrier and noise powers is given by

$$10^{-(L_{RDOMD}/10)} \qquad (A.41)$$

where L_{RDOMD} is the downlink frequency attenuation of the radome in dB.

A.2.1. Summary of Secondary Term Effects

The uplink carrier power from the ground station received by the satellite as given by equation A.7 is reduced by the effects of the secondary terms by multiplication of the following composite factor. The noise power received by the satellite is not effected by these secondary terms.

$$\left\{\left(10^{-(L_{GM}/10)}\right)\cdot\left(10^{-(0.029\ F_{UL} D_{GA}\ E_{GA})}\right)\cdot\left(10^{-(L_{RDOMU}/10)}\right)\cdot\right.$$

$$\left.\left(10^{-(0.029\ F_{UL}\ D_{SRA}\ E_{SAC})}\right)\right\} \qquad \text{(A.42}$$

$$= \left\{10^{-(L_{UL}/10)}\right\}$$

where

$$L_{UL} = [L_{GM} + L_{RDOMU} + 0.29\ F_{UL}\ (D_{GA}\ E_{GA} + D_{SRA}\ E_{SAC})] \qquad \text{(A.43)}$$

The downlink carrier and noise powers from the satellite to the ground station as given by Equations A.20 and A.23 are reduced by the effects of the secondary terms by multiplication by another composite factor.

$$\left\{\left(10^{-(0.029\ F_{DL}\ D_{GA}\ E_{GA})}\right)\cdot\left(10^{-(L_{SM}/10)}\right)\cdot\left(10^{-(L_{RDOMD}/10)}\right)\cdot\right.$$

$$\left.\left(10^{-(0.029\ F_{DL}\ D_{STA}\ E_{SAC})}\right)\right\} \qquad \text{(A.44)}$$

$$= \left\{10^{-(L_{DL}/10)}\right\}$$

where:

$$L_{DL} = [L_{SM} + L_{RDOMD} + 0.29\ F_{DL}(D_{GA}\ E_{GA} + D_{STA}\ E_{SAC})] \cdot \qquad (A.25)$$

The atmospheric noise seen by the ground station receiving antenna is reduced by radome attenuation by multiplication of the following factor.

$$10^{-(L_{RDOMD}/10)} \qquad (A.46)$$

A.3 Resultant Communication Link Equations

The overall effect of both the fundamental and the secondary terms in the communication link equation are summarized by the following *:

$$C/N = \left\{ \frac{C_{RG}}{k\ B[T_{GA} \cdot (10)^{-(L_{RDOMD}/10)} + T_{STD}\ (F_{GR}-1)] + C_{RG}/[C_{RS}/N_{RS}]} \right\} \qquad (A.47)$$

where

$$C_{RG} = \left\{ (1.9582 \times 10^{-15}) \cdot \frac{P_{TS}\ (F_{DL})^2\ (D_{STA})^2\ (D_{GA})^2 \cdot 10^{-(L_{DL}/10)}}{1 + 1/[C_{RS}/N_{RS}]} \cdot (10)^{-(L_{RDL}/10)} \right\} \qquad (A.48)$$

*The L_{RDOMD} term in Eq. A.47 assumes equal attenuation of carrier and noise powers through the wet radome as in a lossless attenuator. Even with this optimistic estimate, the radome option does not compete with the non-radome option.

and

$$[C_{RS}/N_{RS}] = \left\{ \frac{(1.9582 \times 10^{-15})\ P_{GT}\ (F_{UL})^2\ (D_{GA})^2\ (D_{SRA})^2 \cdot 10^{-(L_{UL}/10)}}{k\ B\ [T_{SA} + T_{STD}\ (F_{SR} - 1)]} \cdot 10^{-(L_{RUL}/10)} \right\} \quad (A.49)$$

and

$$L_{UL} = [L_{GM} + L_{RDOMU} + 0.29\ F_{UL}\ (D_{GA}\ E_{GA} + D_{SRA}\ E_{SAC})] \quad (A.50)$$

and

$$L_{DL} = [L_{SM} + L_{RDOMD} + 0.29\ F_{DL}\ (D_{GA}\ E_{GA} + D_{STA}\ E_{SAC})] \quad (A.51)$$

The computer program SCOR (Satellite Cost Optimization Routine) contains an implementation of Equations A.47 through A.51 for evaluation of communication satellite link performance, C/N, as a function of subsystem design parameters. SCOR also contains models for the cost of ground and space subsystems as a function of these design parameters; weight models are also included for the space components. SCOR accepts a specified value of C/N and a weight upper limit for the satellite, and produces a design which meets (if possible) the two specifications while minimizing the overall communication systems cost.

A. 3.1 Frequently Used Approximations to the Link Equation

Certain approximations to the link equations are frequently made for hand calculations. The approximations result in un-coupling of the uplink and downlink equation so that the two halves of the system can be separately designed or evaluated. Such a decoupling is neither necessary or advantageous for a computerized analysis, but it is presented here as a reference for hand calculation and for showing the relationship between the equations implemented in SCOR and the link equation expression frequently seen in literature [ ]. If one assumes that the noise equivalent temperatures of the ground station and satellite antennas are equal to standard temperature and that the effect of the radome (if present) upon the ground satellite antennas' background noise is negligible, then Equation A.47 reduces to the following,

$$C/N = \frac{1}{\left(\dfrac{k\ T_{STD}\ B\ F_{GR}}{C_{RG}}\right) + \left(1/[C_{RS}/N_{RS}]\right)}$$

$$= \frac{1}{(1/[C/N]_{down}) + (1/[C/N]_{up})} \qquad (A.52)$$

and the uplink carrier to noise ratio given by Equation A.49 reduces to

$$[C_{RS}/N_{RS}] = \frac{(1.9582\text{x}10^{-15})\ P_{GT}\ (F_{UL})^2\ (D_{GA})^2\ (D_{SRA})^2}{k\ T_{STD}\ B\ F_{SR}} \cdot (10)^{-(L_{RUL}+L_{UP})/10} \qquad (A.53)$$

Assume that the uplink carrier to noise ratio is sufficiently large that

$$\left(\frac{P_{TS}}{1 + 1/[C_{RS}/N_{RS}]} \right) \simeq P_{TS} \tag{A.54}$$

is a valid approximation results in further simplification of Equation A.48.

$$C_{RG} = \left\{ (1.9582 \times 10^{-15}) \cdot P_{TS}\ (F_{DL})^2\ (D_{STA})^2\ (D_{GA})^2 \cdot (10)^{-(L_{RDL} + L_{DL})/10} \right\} \tag{A.55}$$

With these approximations, the uplink and downlink carrier to noise ratios appearing in Equation A.52 can be separately written.

$$[C/N]_{up} = \left\{ \frac{(1.9582 \times 10^{-15})\ P_{GT}\ (F_{UL})^2\ (D_{GA})^2\ (D_{SRA})^2 \cdot (10)^{-(L_{RUL}+L_{UP})/10}}{(k\ T_{STD}\ B\ F_{SR})} \right\} \tag{A.56}$$

and

$$[C/N]_{down} = \left\{ \frac{(1.9582 \times 10^{-15}) \; P_{TS} \; (F_{DL})^2 \; (D_{STA})^2 \; (D_{GA})^2 \cdot (10)^{-(L_{RDL}+L_{DL})/10}}{(k \; T_{STD} \; B \cdot F_{GR})} \right\} \qquad (A.57)$$

These last two expressions are often rewritten in dB to obtain an additive relationship. Frequently the antenna gain appears rather than the antenna diameter.

APPENDIX B

SIGNAL ATTENUATION INTRODUCED BY A RADOME

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Appendix B

Signal Attenuation Introduced by a Radome

The attenuation of centimeter and millimeter wave signals due to the radome will vary depending upon materials and construction techniques. A well-designed, self-supporting radome will produce the following signal attenuation:*

Freq.	Attenuation
10 GHz	0.5 dB
20 GHz	1.0 dB
30 GHz	1.3 dB
40 GHz	1.7 dB
50 GHz	2.0 dB

This attenuation may be approximated over the frequency range of 20 to 50 GHz by

$$L_R = 0.33\ (1 + 0.1f)$$

where:

L_R = loss due to the radome in dB

f = signal frequency in GHz

The above equation represents the attentuation due to a clean, dry radome. To evaluate the effects of using a radome for a communications system which must operate in various weather conditions, the effects of rainfall on the radome must be considered.

During rainfall, a layer of water will build up on the surface of the radome. The thickness of the water layer is a function of both the radome diameter and the rainfall rate.

Although it is difficult to formulate a realistic model for the thickness of the water layer on a practical radome, a model proposed by Gibble [5] predicts that the maximum thickness formed on a spherical radome in the absence of wind is given by:

---

* Private communication from H. Clark, ESSCO, Concord Mass., September, 1976.

$$d^3 = 3/2 \frac{\mu r R}{W},$$

where:

r = the radius of the radome

R = the rainfall rate

μ = the viscosity of water

W = the density of the water

Using metric values and substituting the values of water viscosity and density yields the following relation:

$$d = 0.035 \ (r\ R)^{1/3},$$

where:

d = thickness in millimeters

r = Radome radius in meters

R = Rainfall rate in mm/hr.

The equation may be expressed in terms of antenna diameter by assuming that the radome diameter is 1.5 times the antenna diameter and making the appropriate substitution. The resulting equation is:

$$d = 0.032 \ (DR),^{1/3}$$

where:

D = the antenna diameter.

This equation gives the thickness of the water layer on a radome as a function of rainfall rate and antenna diameter. The next requirement is to determine the signal attenuation at the frequencies of interest due to transmission though bulk water.

An article by Hogg and Chu [6] gives the attenuation by bulk water for frequencies ranging from 10 GHz to 1000 THz. The following values have been taken from Figure 2 in the referenced article.

Freq.	Attenuation (approx.)
20 GHz	10 dB/mm
30 GHz	15 dB/mm
40 GHz	20 dB/mm
50 GHz	25 dB/mm

To approximate the effects of rainfall on a radome at the frequencies of interest these values may be combined with the previous water thickness calculation, yielding:

$$L_w = 0.016 \ f \ (DR),^{1/3}$$

where:

L_w = attenuation in dB

f = frequency in GHz

D = antenna diameter in meters

R = rainfall rate in mm/hr.

Combining this attenuation due to the radome with the attenuation due to rainfall, the following relationship is derived:

$$L = L_R + L_w = 0.33 \ (1 + 0.1f) + 0.016 \ f \ (DR)^{0.33}$$

where:

L = total loss due to the radome in dB

f = signal frequency in GHz

D = antenna diameter in meters

R = rainfall rate in mm/hr.

APPENDIX C

SUBSYSTEM MODELS

APPENDIX C. SUBSYSTEM MODELS*

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* This appendix contains a detailed description of the models given in Tables 4.3 - 4.5.

APPENDIX C. SUBSYSTEM MODELS

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APPENDIX C. SUBSYSTEM MODELS

LIST OF FIGURES

GROUND ANTENNA

Ground Antenna Point-to-point case, cost model

- Dependent variable

  Cost, C (K $ 1976) Range: 261-1116

- Independent variables

  Dish diameter, D (m) Range: 1-10

  Transmitter frequency, F (GHz) Range: 18-60

- Equations

$$C_1 = 250.99 + 9.8057 \; D^{1.7852}$$

$$C_2 = 260.01 + 6.544 \; D^{2.1164}$$

$$C = C_2 \qquad \text{for } F \geq 30$$

$$C = (1-a)\, C_1 + aC_2 \qquad \text{for } 18 \leq F < 30$$

$$\text{where } a = (F-18)/12$$

- Source

  Technology Forecasting for Space Communications, Task 1 Report, Hughes Aircraft Company, November, 1974. [4]

Ground Antenna Broadcast case, cost model

- Dependent variable

  Cost, C (K $ 1976) Range: 2-200

- Independent variable

  Dish diameter, D (m) Range: 1-10

- Equation

$$C = 1.95\, D^2 + 5$$

- Source

  Andrew Corporation, General Catalog 29, 1976

Antenna gain model

- Dependent variable

  Gain, G (dB) Range: 43-74

- Independent variables

  Dish diameter, D (m) Range: 1-10

  Operating frequency, F (GHz) Range: 18-60

- Equation

$$G = 18.33 + 20 \log F + 20 \log D$$

- Source

  Georgia Tech Radar Short Course, text [11]

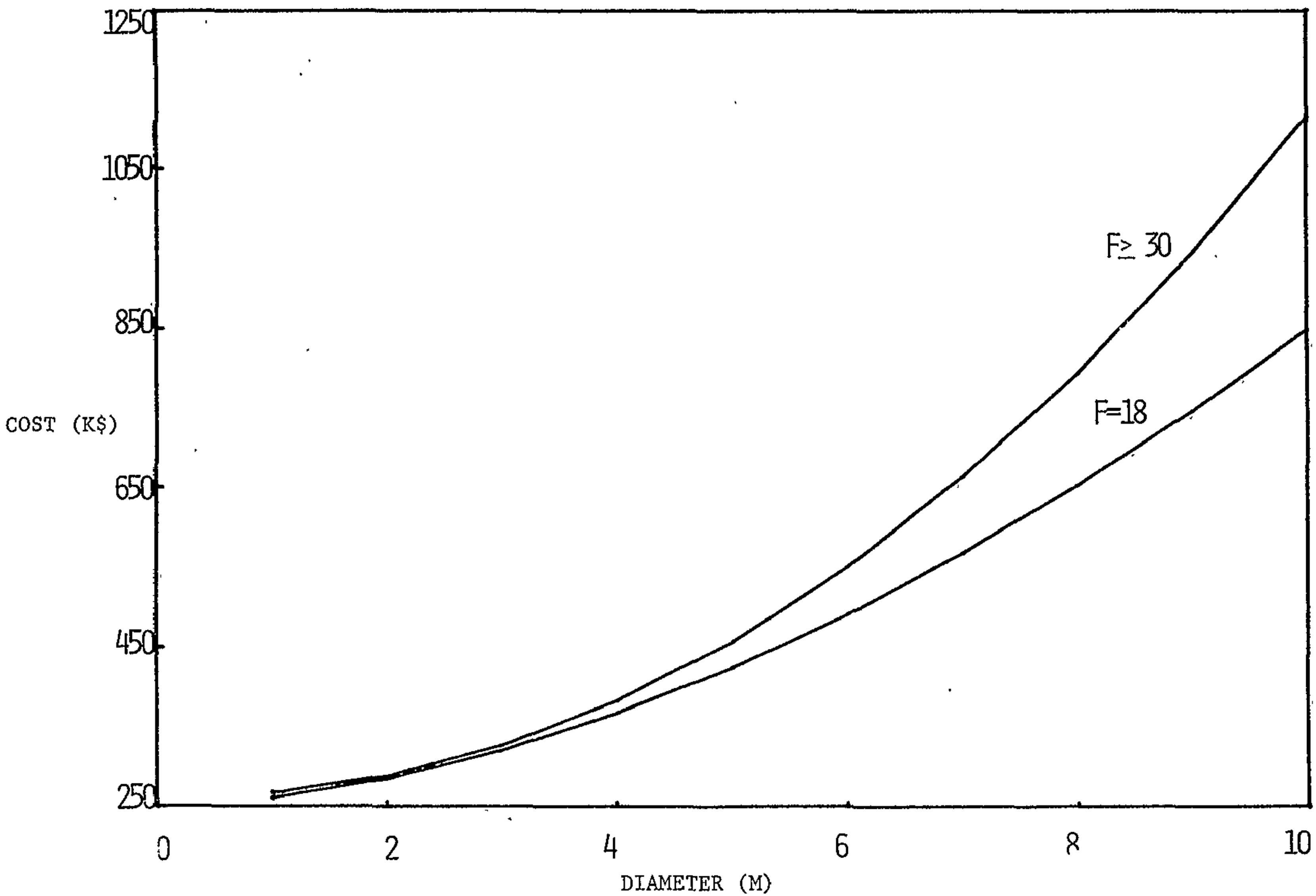

Figure C.1. Ground Antenna Subsystem Cost
(Point-to-Point Case)

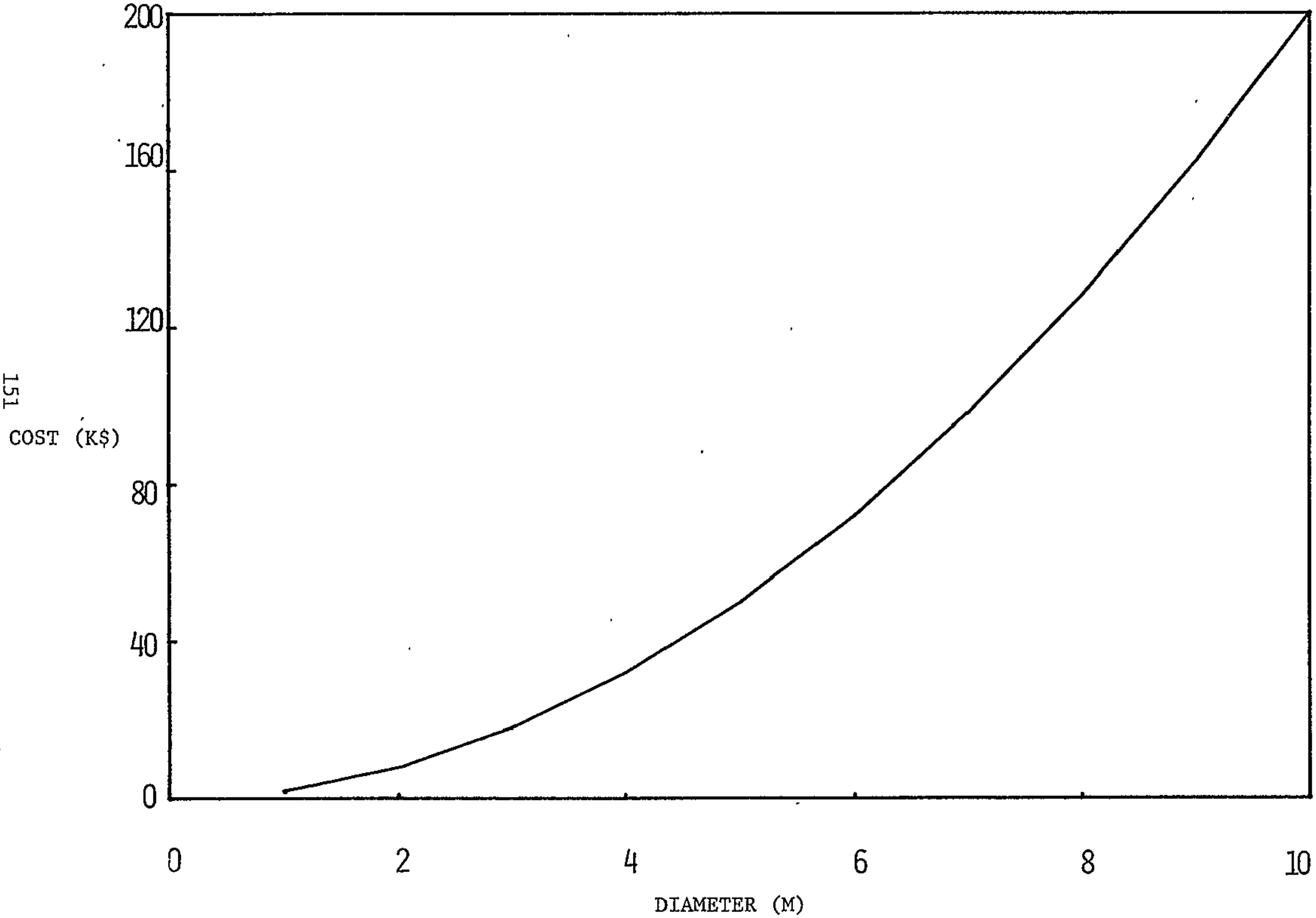

Figure C .2. Ground Antenna Subsystem Cost
(Broadcast Case)

RADOME

Radome Cost

- Dependent variable

  Cost, C (K $ 1976) Range: 13.1-45.3

- Independent variable

  Radome diameter, D (m) Range: 3.9-15

- Equation

  $C = 16.9 - 1.982\ D + 0.258\ D^2$

- Assumptions

  Costs are derived from current manufacturers' catalogs. It is assumed that no development cost is incurred to provide these radomes.

- Source

  ESSCO Corporation

Radome Attenuation

- Dependent variable

  Signal attenuation (one-way), A (dB) Range: 0-11

- Independent variables

  Signal frequency, F (GHz) Range: 20-60

  Radome diameter, D (m) Range: 3.9-15

  Rainfall rate, R (mm/hr) Range: 0-100

- Equation

  $A = 0.016 \cdot F \cdot (D \cdot R)^{1/3}$

- Assumptions

- Source

  D. C. Hogg and T. S. Chu, Proceedings of the IEEE, September 1975. [6]

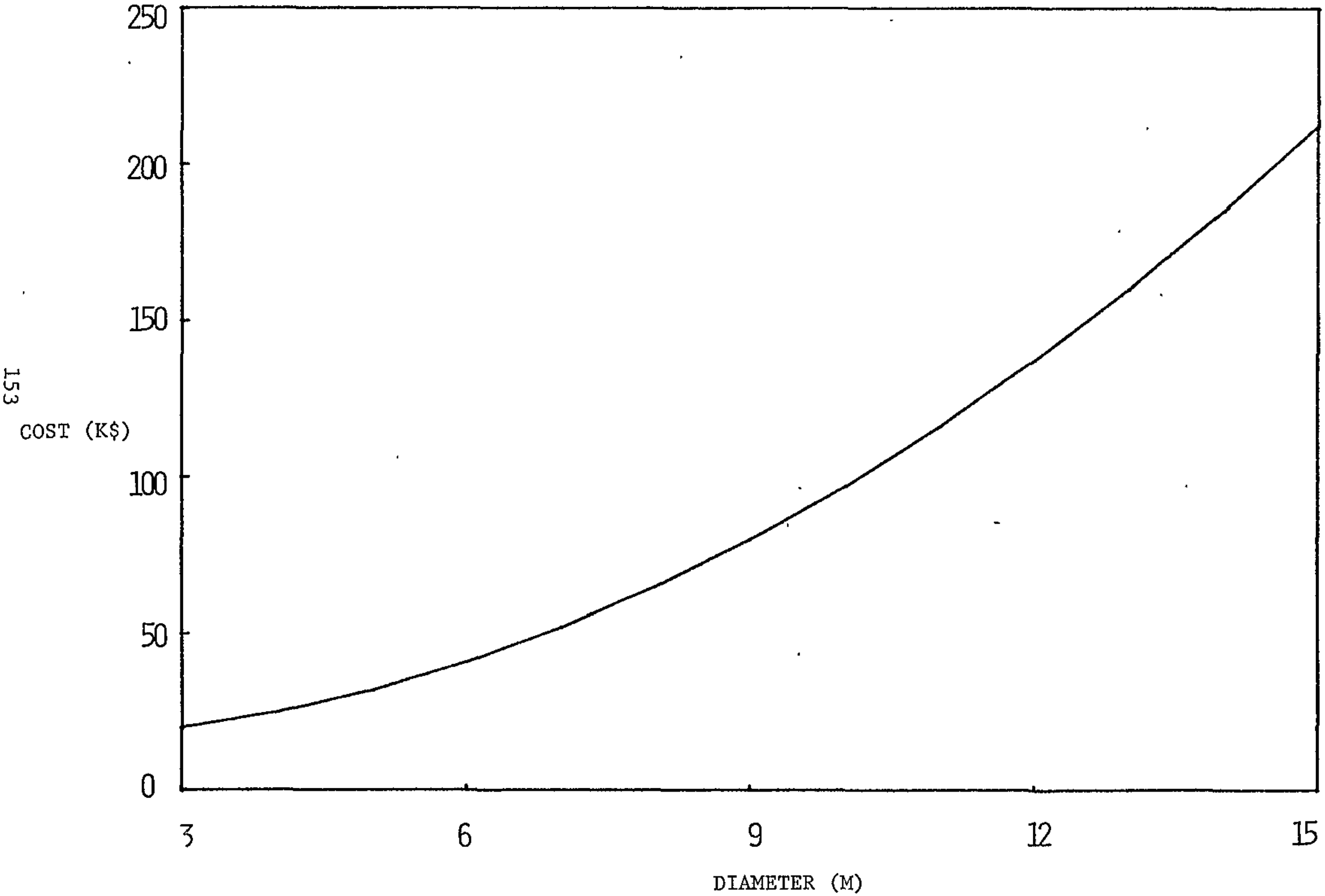

Figure C.3. Radome Cost

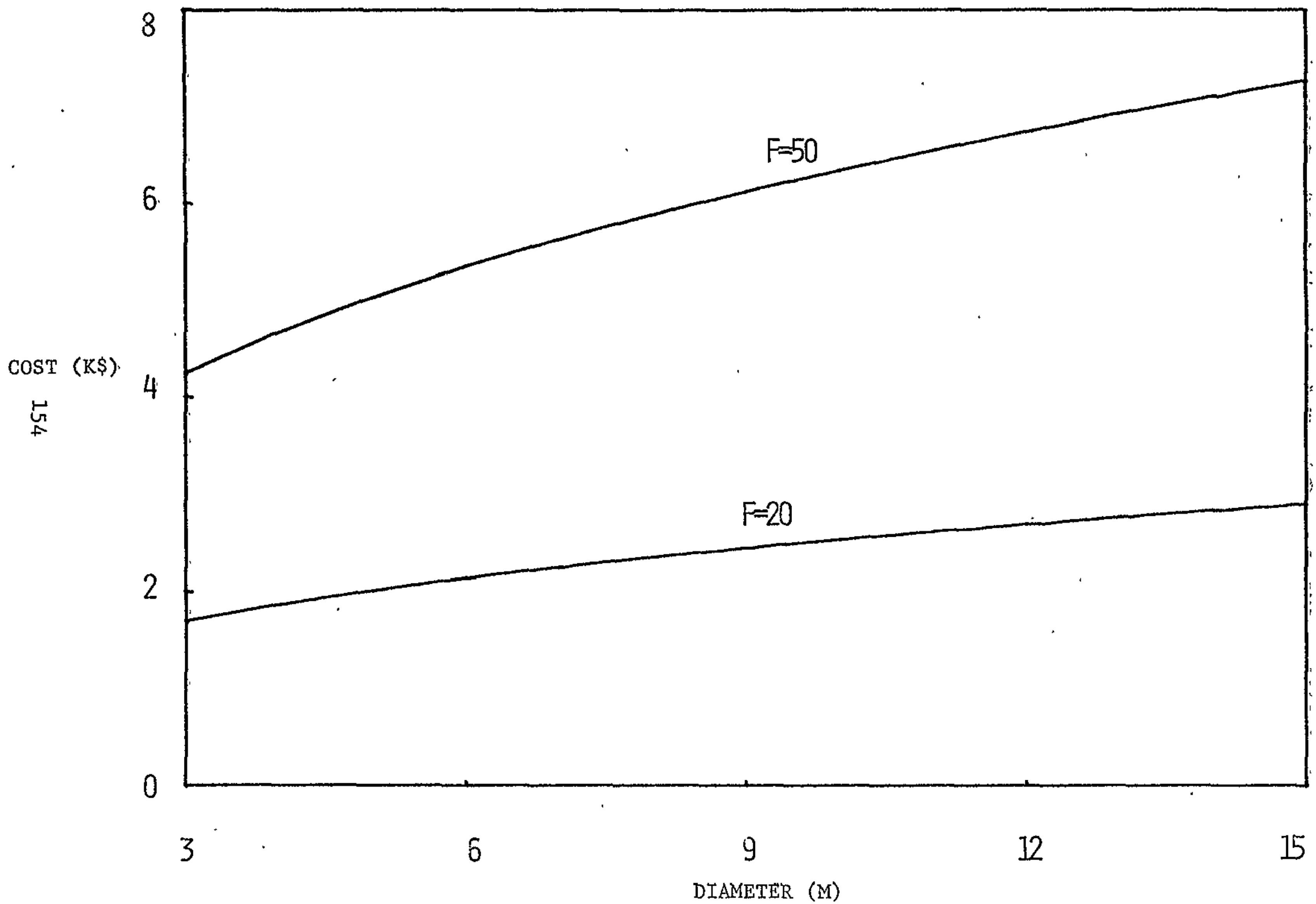

Figure C.4. Radome Attenuation

Pointing and Control Cost

- Dependent variable

  Cost, C (K $ 1976) Range: 25-475

- Independent variables

  Dish diameter, D (m) Range: 1-10

  Pointing error, E (degrees) Range: 0.02-1.0

- Equations

$$C = a + b\,E \qquad E < E_o$$

$$= C_o \qquad E \geq E_o$$

where a, b, E_o and C_o depend on D.

D	a	b	E_o	C_o
2.4	190	-280	.59	25
4.5	225	-325	.58	37
10.0	490	-780	.54	70

Linear interpolation or extrapolation is used for diameters not given in the table.

Source

Current vendor prices for systems in use at 6/4 and 14/11 GHz

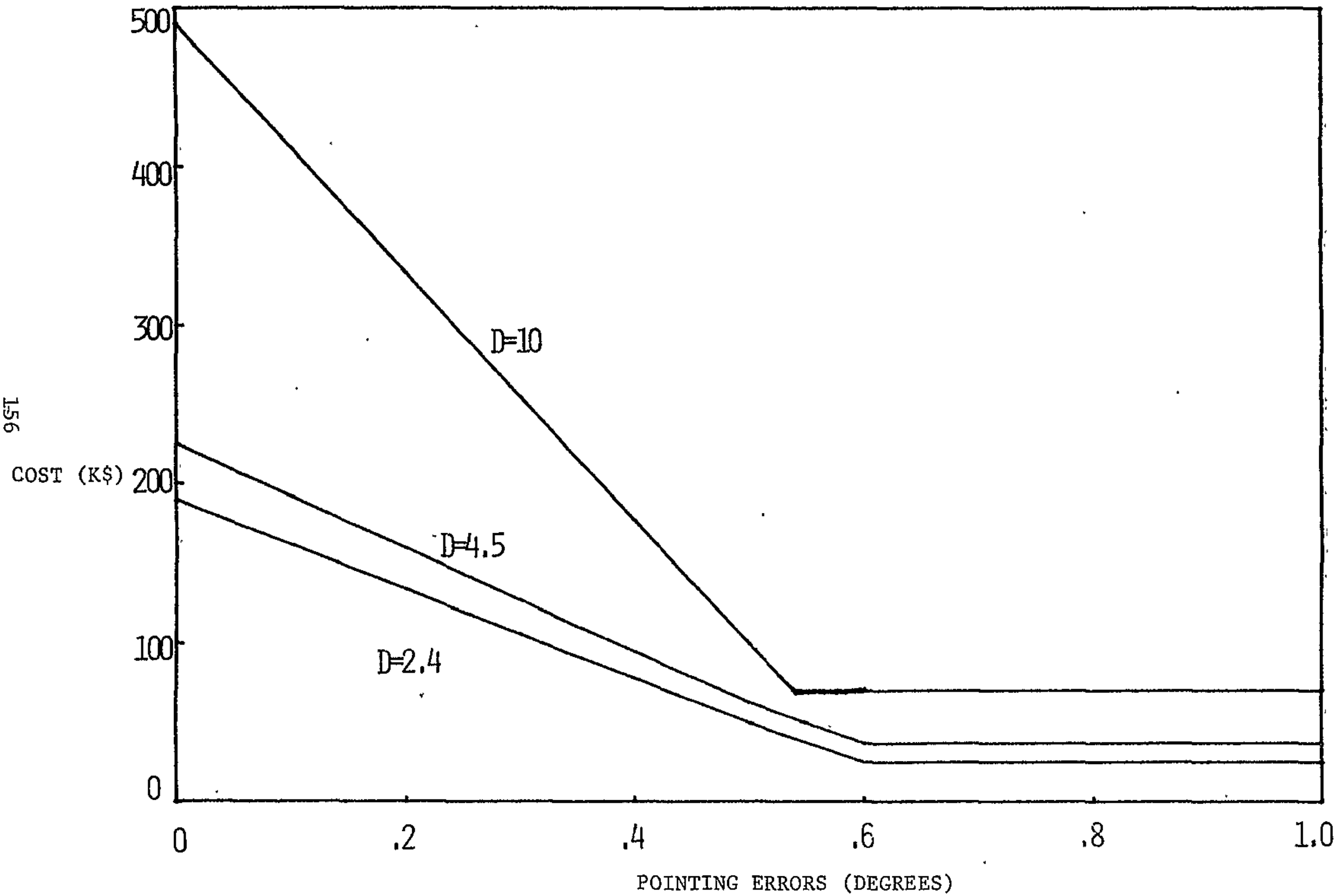

Figure C.5. Ground Antenna Pointing and Control Subsystem Cost

GROUND TRANSMITTER

Ground transmitter cost model

- Dependent variable

  C (K \$ 1976)   Range: 29-155

- Independent variables

  Transmitter power, P (W) Range: 0-1500

  Transmitter frequency, F (GHz) Range: 18-60

  Transmitter Bandwidth, BW (MHz) Range: 0-1000

- Equation

$$C = a\,(29.5 + 0.084P)\,(0.000632\,BW + 0.368)$$

$$\text{where } a = \begin{cases} 1.0 & 30 \leq F \leq 60 \\ 0.8 & 20 \leq F \leq 30 \\ 0.64 & 18 \leq F \leq 20 \end{cases}$$

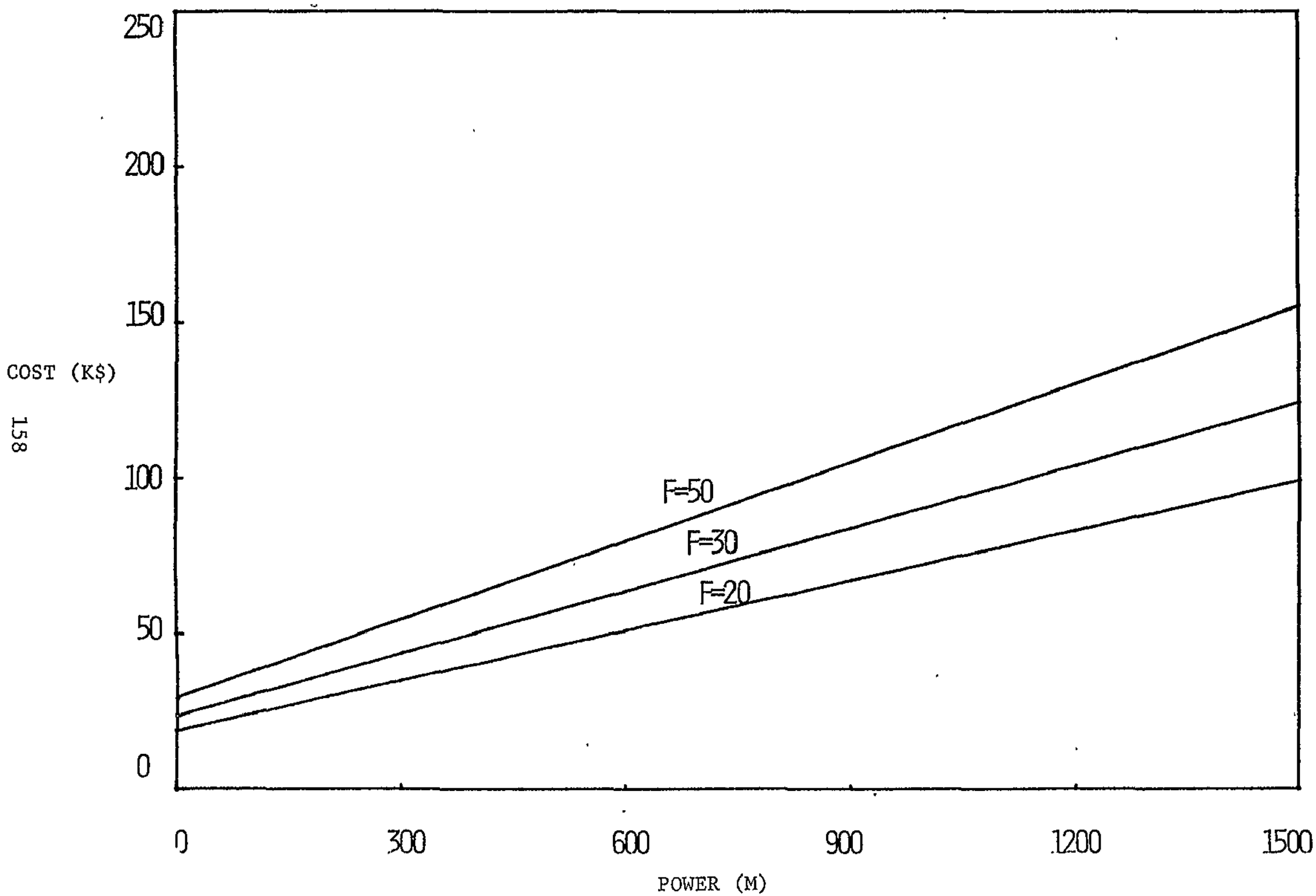

Figure C.6. Ground Transmitter Subsystem Cost

GROUND RECEIVER

Ground receiver cost model

- Dependent variable

    Cost, C (K $ 1976) Range: 40-127

- Independent variables

    LNA noise figure, NF (linear) Range: 1-4

    Receiver frequency, F (GHz) Range 18-60

    Receiver bandwidth, BW (MHz) Range: 0-100

- Equations

$$C = a\,(C_{LNA}(NR) + C_{mixer} + C_{LO} + C_{IF})\,(0.000632\ BW + 0.368)$$

$$= a\,(C_{LNA}\,(NF) + 6.66)\,(0.000632\ BW + 0.368)$$

where $a = 1.0 \qquad 60 \geq F > 30$

$= 0.8 \qquad 30 \geq F > 20$

$0.64 \qquad 20 \geq F \geq 18$

and $C_{LNA}(NF) = 30.00 \qquad 4.0 \geq NF \geq 1.95$

$= 106.72 - 39.34\ NF \qquad 1.95 > NF \geq 1.34$

$= 164.35 - 82.35\ NF \qquad 1.34 > NF \geq 1.17$

$= 502.57 - 371.43 NF \qquad 1.17 > NF \geq 1.03$

$= 120.00 \qquad 1.03 > NF \geq 1.0$

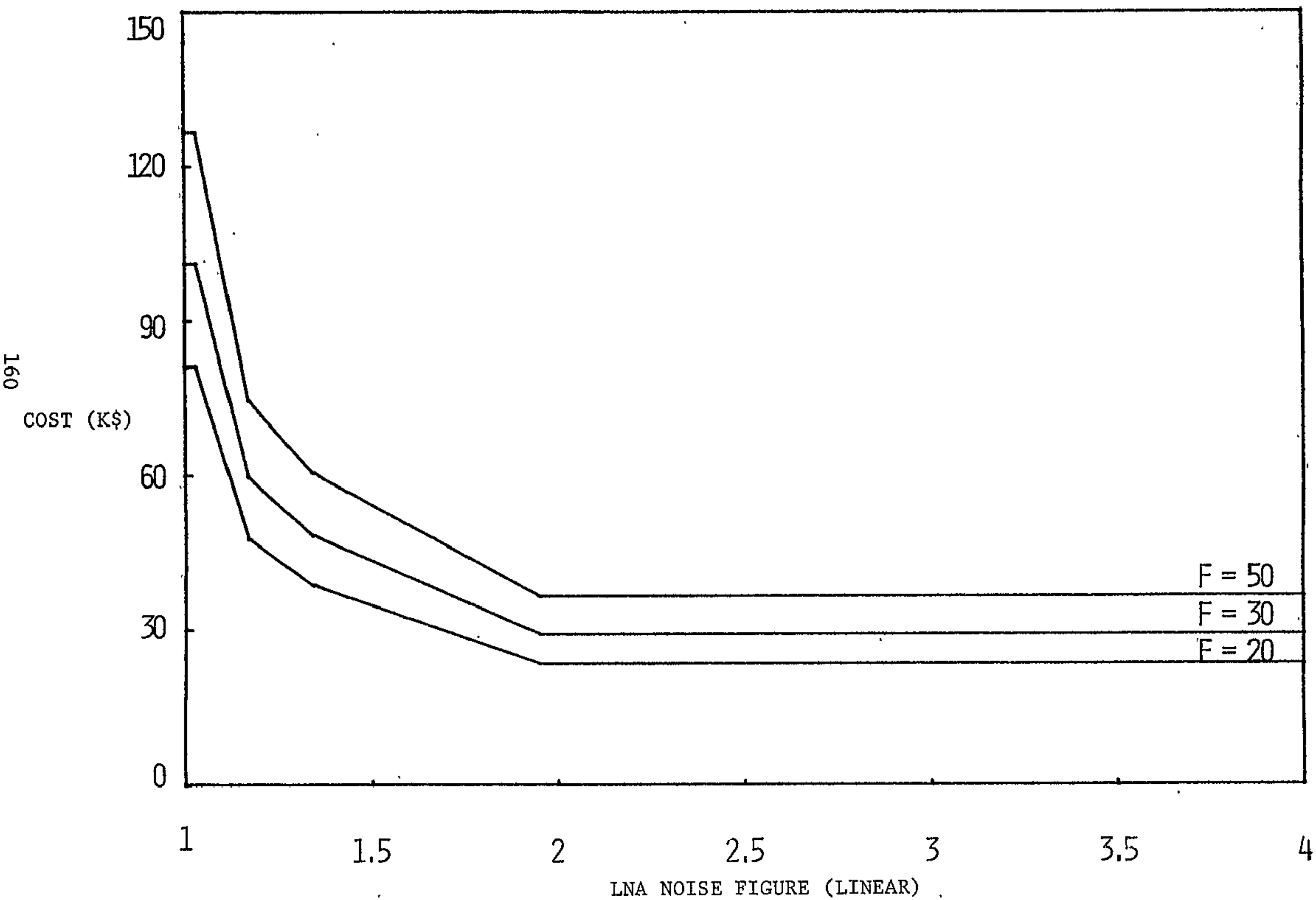

Figure C.7. Ground Receiver Subsystem Cost

FDMA GROUND SIGNAL PROCESSING

FDMA signal processing cost model

- Dependent variable

  Cost, C (K \$ 1976) Range: 73-180

- Independent variable

  Baseband channel bandwidth, BW (MHz) Range: 100-1000

- Equations

  downlink subsystem

$$C_o = 10^{\frac{B_o}{BW}} \left(18 + 36 \log \frac{BW}{B_o}\right) \qquad 100 \le BW \le 316$$

$$= 10^{\frac{B_o}{BW}} \left(-1 + 74 \log \frac{BW}{B_o}\right) \qquad 316 \le BW \le 1000$$

  uplink subsystem

$$C_u = 10^{\frac{B_o}{BW}} \left(16 \_ 36 \log \frac{BW}{B_o}\right) \qquad 100 \le BW \le 316$$

$$= 10^{\frac{B_o}{BW}} \left(-5 + 78 \log \frac{BW}{B_o}\right) \qquad 316 \le BW \le 1000$$

  where $B_o = 100$ MHz

- Analysis

  The cost model was derived for a fixed transmission bandwidth of 1 GHz. Varying the parameter baseband channel bandwidth thus implies varying the number of baseband channels. This effect is included in the cost expressions by the term $10^{\frac{B_o}{BW}}$. The models are based on comercially available equipment for the lower bandwidths and developmental equipment for the 1 GHz bandwidth.

- Sources

  Scientific Atlanta and Delta Microwave

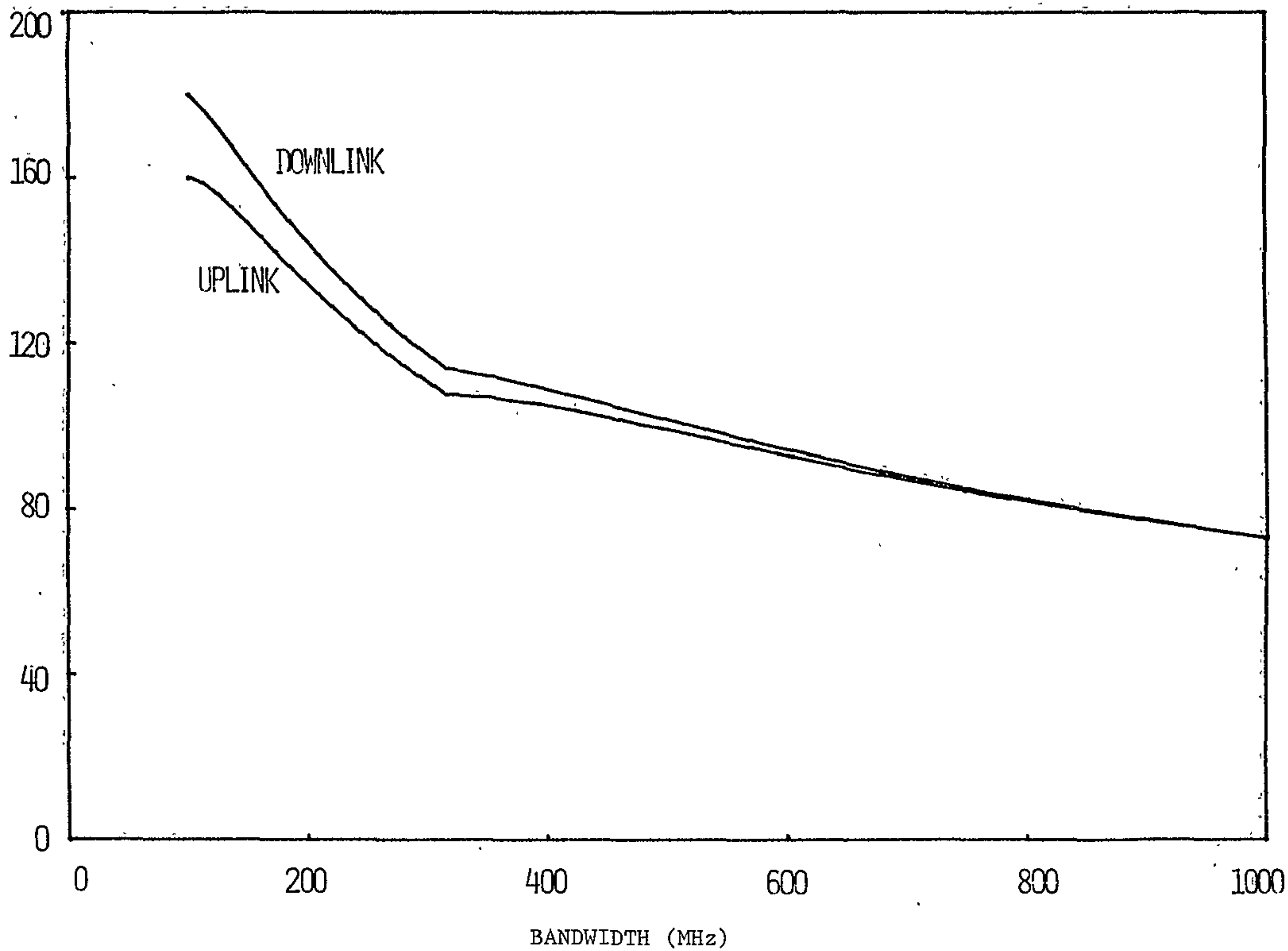

Figure C.8. Ground Signal Processing Subsystem

TDMA signal processing cost model

Processing components for a 1 Gbit/sec TDMA signal processing subsystem are priced as follows:

Component	Cost (K $ 1976)
PSK modulator	30
PSK demodulator	60
scrambler/preamble generator	20
descrambler/preamble receiver	20
control and synchronization	152
buffer storage	2552
	2834

These subsystems require high parallelism to achieve the required data rate. The buffer storage is the critical factor in the subsystem cost. No memory technology available is likely to be able to handle Gbit data rates at significantly lower cost.

Bulk Data Storage Cost

- Dependent variable

  Cost, C (K $ 1976) Range: 425-4425

- Independent variables

  Data rate, R (Mbit/sec) Range: 100-1000

  Data volume, V (Mbit) Range: 1000-6000

- Equation

  $C = 2.5\,R + 0.125\,V + 50$

- Source

  Data Processing Magazine, October, 1970 [10]

LANDLINE INTERFACE

Landline Interface Costs

- Dependent variables

  Highspeed modem cost, C_1 (K \$ 1976) Range: 40-440

  Television headin cost, C_2 (K \$ 1976) Range: 40-760

  Multiplexed voice interface cost, C_3 (K \$ 1976) Range: 35-635

- Independent variables

  Two-way data rate, R (Mbs) Range: 0-100

  Number of 6 MHz television channels, N. Range: 1-25

  Number of 6 MHz baseband MMX voice channels, M. Range: 1-25

- Equations

  $C_1 = 40 + 4R$

  $C_2 = 10 + 30N$

  $C_3 = 10 + 25N$

DIVERISTY LINK

Subsystem cost model

- Dependent variable

  Cost, C (K $ 1976) Range: 0-1410

- Independent variable

  Diversity distance, L (m_i) Range: 0-10

- Equations

$$C = 100.7\ L \quad \text{for first one-way link}$$

$$= 40.3\ L \quad \text{for return one-way link}$$

BUILDINGS

Building costs

Main site building and land - $100K (1976)

Diversity site building and land - $50K (1976)

SATELLITE ANTENNA

Subsystem cost model

- Dependent variable

  Cost, C (K $ 1976) Range: 145-11086

- Independent variables

  Antenna diameter, D (M) Range: 1-5

  Operating frequency, F (GHz) Range: 18-60

  Number of feeds, N. Range: 1-10

- Equations

  $C = (0.8 + 0.2N)(61.924 + 82.716\ D^{2.2464})$ $\quad F = 18$

  $= (0.8 + 0.2N)(61.924 + 145.34\ D^{2})$ $\quad 30 \leq F \leq 60$

  interpolate between these expressions for $18 < F < 30$

- Source

  Technology Forecasting for Space Communications

  Task 1 Report, Hughes Aircraft Company, November, 1974 [4]

Subsystem weight model

- Dependent variable

  Weight, W (lb) Range: 9.25 - 223.0

- Independent variables

  Antenna diameter, D (M) Range: 1-5

  Operating frequency, F (GHz) Range: 18-60

  Number of feeds, N. Range: 1-10

- Equations

  $W = 0.165 + 8.0877\ D^{2.012} + N$ $\quad F = 18$

  $= 8.9125\ D^{2} + N$ $\quad 30 \leq F \leq 60$

  interpolate between these expressions for $18 \leq F \leq 30$

- Source

  same as for cost model

Antenna gain model

- Dependent variables

  Diameter, D (M) Range: 43 - 68

- Independent variables

  Diameter, D (M) Range: 1-5

  Antenna operating frequency, F (GHz) Range: 18-60

- Equation

  $G - 18.33 + 20 \log F + 20 \log D$

- Source

  Georgia Tech Radar Short Course, text [11]

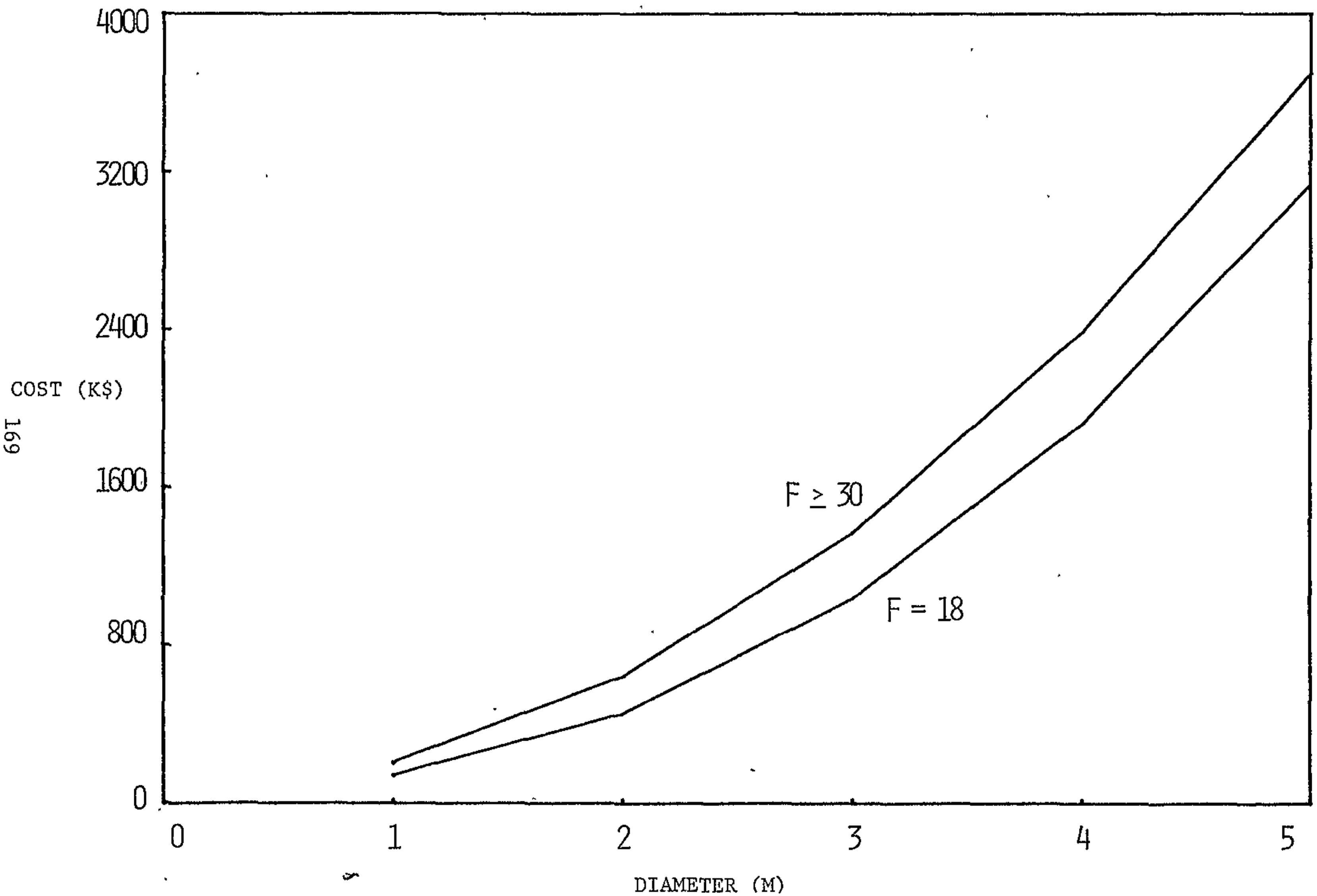

Figure C.9. Space Antenna Subsystem Cost

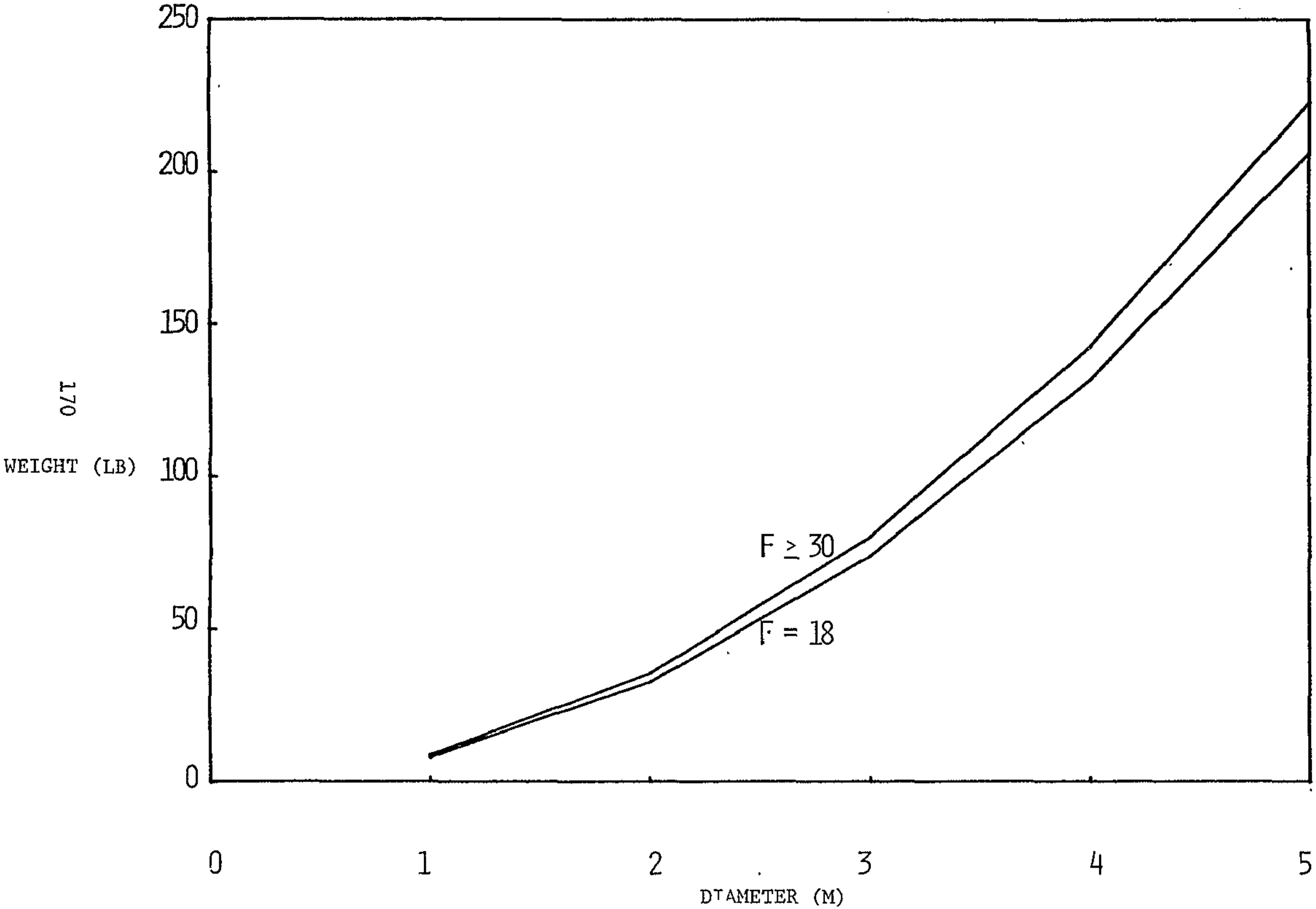

Figure C.10. Space Antenna Subsystem Weight

SATELLITE TRANSMITTER

Subsystem cost model

- Dependent variable

  Cost, C (K \$ 1976) Range: 0-900

- Independent variables

  HPA Power, P (w) Range: 0-1500

  Operating frequency, F (GHz) Range: 18-60

- Equations

$$C = a\,[C_{HPA}(P) + C_{UC} + C_{LO} + C_{IF} + C_F)$$

$$= a\,(0.53\,P + 37)$$

where

$C_{HPA}(P)$	$= 0.53\,P$	(high power amplifier)
C_{UC}	$= 15$	(up-converter)
C_{LO}	$= 10$	(local oscillator)
C_{IF}	$= 10$	(IF amplifier)
C_F	$= 2$	(40-41 GHz filter)

and

$a = 1.0$	$30 < F \leq 60$
$a = 0.8$	$20 < F \leq 30$
$a = 0.64$	$18 \leq F \leq 20$

Subsystem weight model

- Dependent variable

  Weight W (lb) Range: 10 - 30

- Independent variables

  Transmitter power, P (w) Range: 0-1500

  Operating frequency, F (GHz) Range: 18-60

  Transmitter bandwidth, BW (MHz) Range: 100-1000

- Equations

$$W = b\,[9.93 + 0.939\,P^{0.187} + 10\,(BW-100)/900]$$

where	$b = 1.0$	$30 < F \leq 60$
	$= 1.1$	$20 < F \leq 30$
	$= 1.21$	$18 \leq F \leq 20$

Transmitter efficiency

- Dependent variable

  Transmitter efficiency, E. Range: 0-1

- Independent variables

  Transmitter power, P (w) Range: 0-1500

  Transmitter frequency, F (GHz) Range: 18-80

- Equation

  $E = 0.01\ (A + B\ P^C)$

where A, B and C depend on frequency

F	A	B	C
18	20.000	1.1646	0.5997
30	19.5392	0.5424	0.7042
40	19.0272	0.4264	0.7282
50	18.5152	0.3105	0.7522
80	16.976	0.0583	0.8563

For other frequencies calculate efficiency by linear interpolation. In all cases, E is limited to be less than 1.0.

- Source

  Technology Forecasting for Space Communication, Task Six Report: Spacecraft Communication Terminal Evaluation, Hughes Aircraft Company, June 1973. [4]

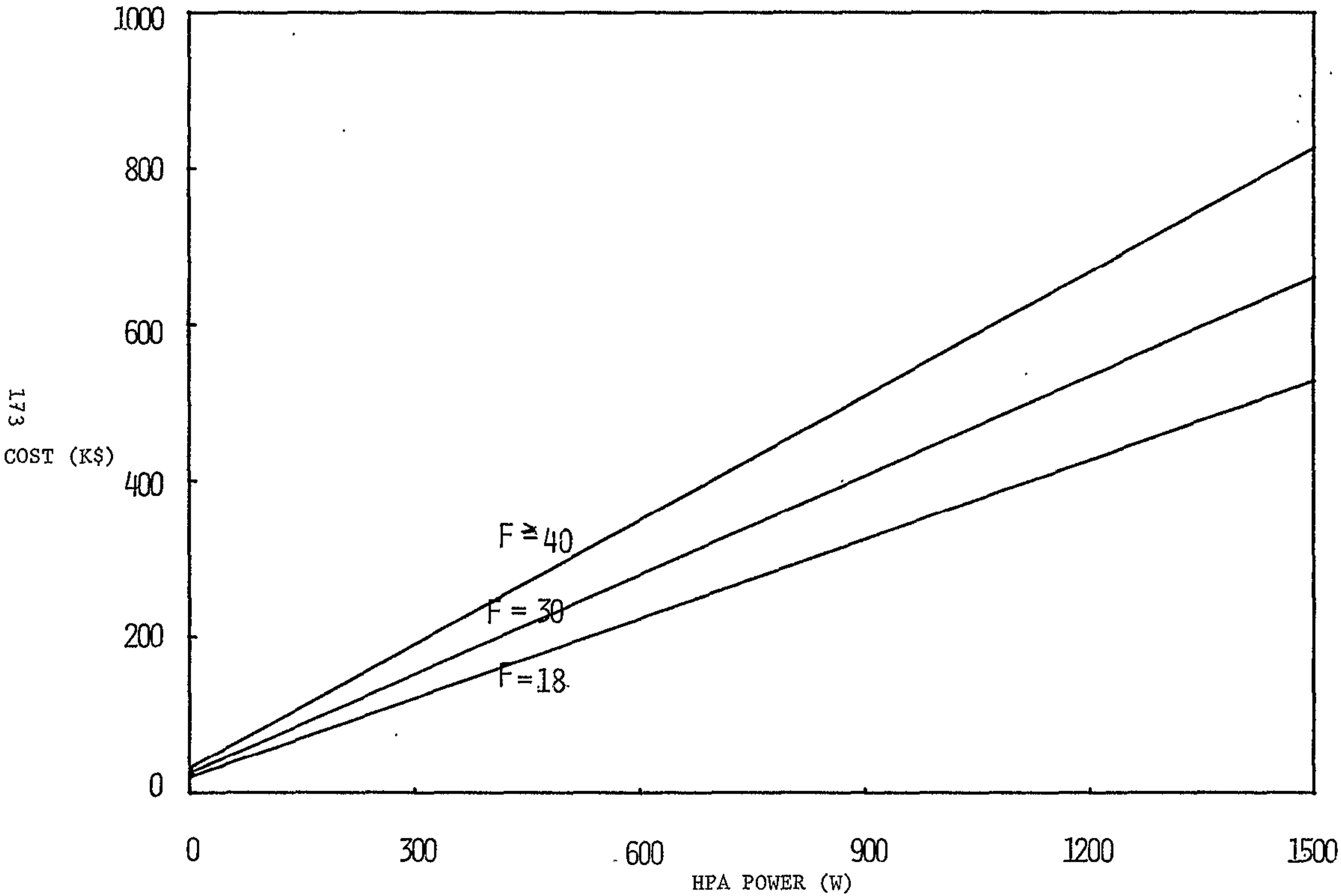

Figure C.11. Space Transmitter Subsystem Cost

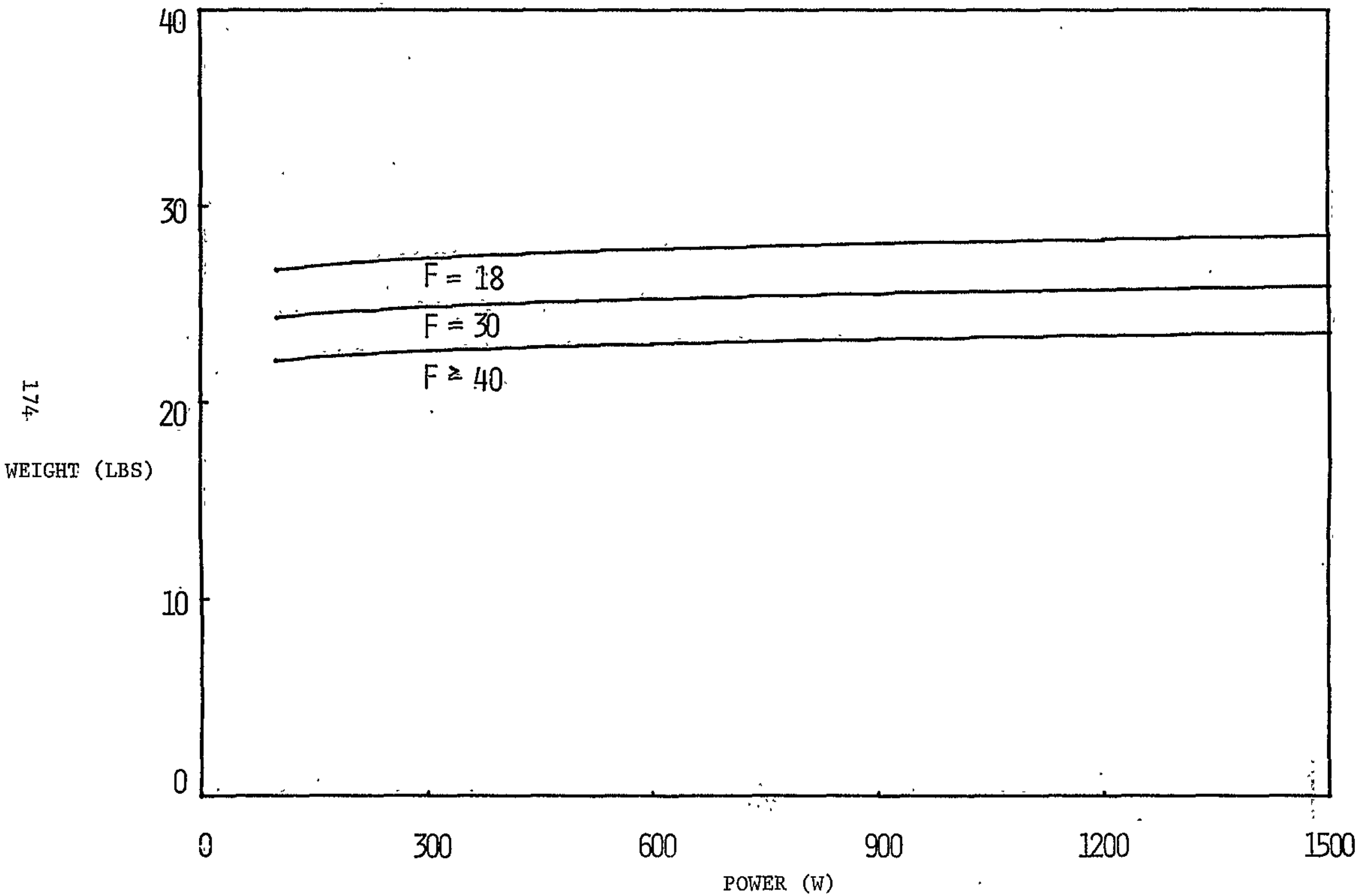

Figure C.12. Space Transmitter Subsystem Weight

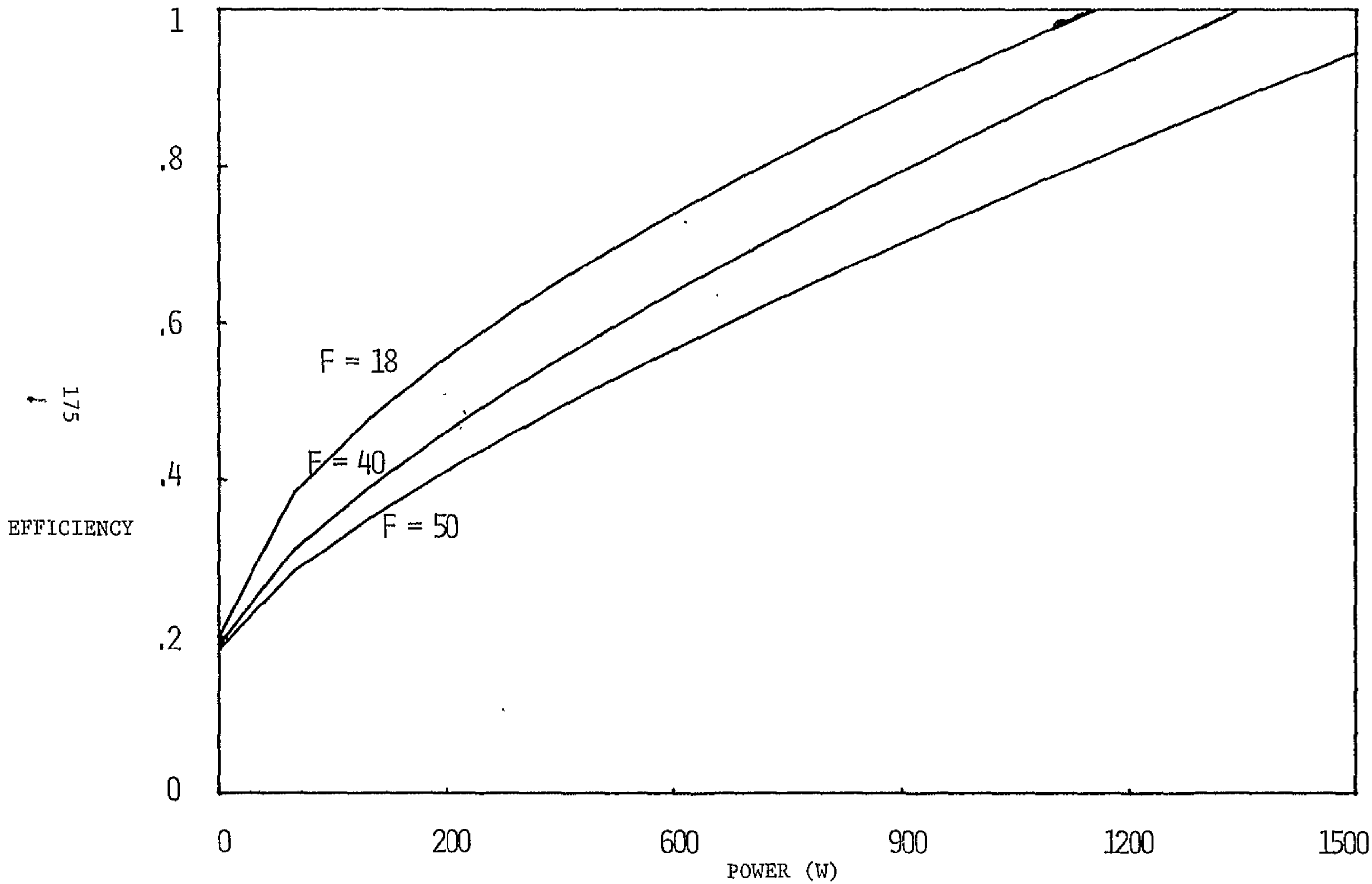

Figure C.13. Space Transmitter Subsystem Efficiency

SATELLITE RECEIVER

Subsystem cost model

- Dependent variable

  Cost, C (K \$ 1976) Range: 120–230

- Independent variables

  LNA noise figure, NF (linear) Range: 1–4

  Operating frequency, F (GHz) Range: 18–60

- Equations

$$C = a\,(C_{LNA}\,(NF) + C_{MIXER} + C_{LO} + C_{IF} + C_F)$$

$$= a\left(\frac{8.966}{NF-1} + 108 + 49\right)$$

where

$$C_{LNA}\,(NF) = \frac{8.966}{NF-1} + 108$$

$C_{MIXER} = 17$

$C_{LO} = 30$ (local oscillator)

$C_{IF} = 10$ (IF amplifier)

$C_F = 2$ (filter)

and $a = 1.0$ $30 < F \leq 60$

$a = 0.8$ $20 < F \leq 30$

$a = 0.64$ $18 \leq F \leq 20$

Subsystem weight model

- Dependent variable

  Weight, W (lb) Range: 10–12.1

- Independent variable

  Operatingfrequency, F (GHz) Range: 18–60

- Equation

  $W = 10$ $30 < F \leq 60$

  $= 11$ $20 < F \leq 30$

  $= 12.1$ $18 \leq F \leq 20$

- Assumptions

  Receiver weight is assumed to be independent of operating frequency for the frequency range of interest.

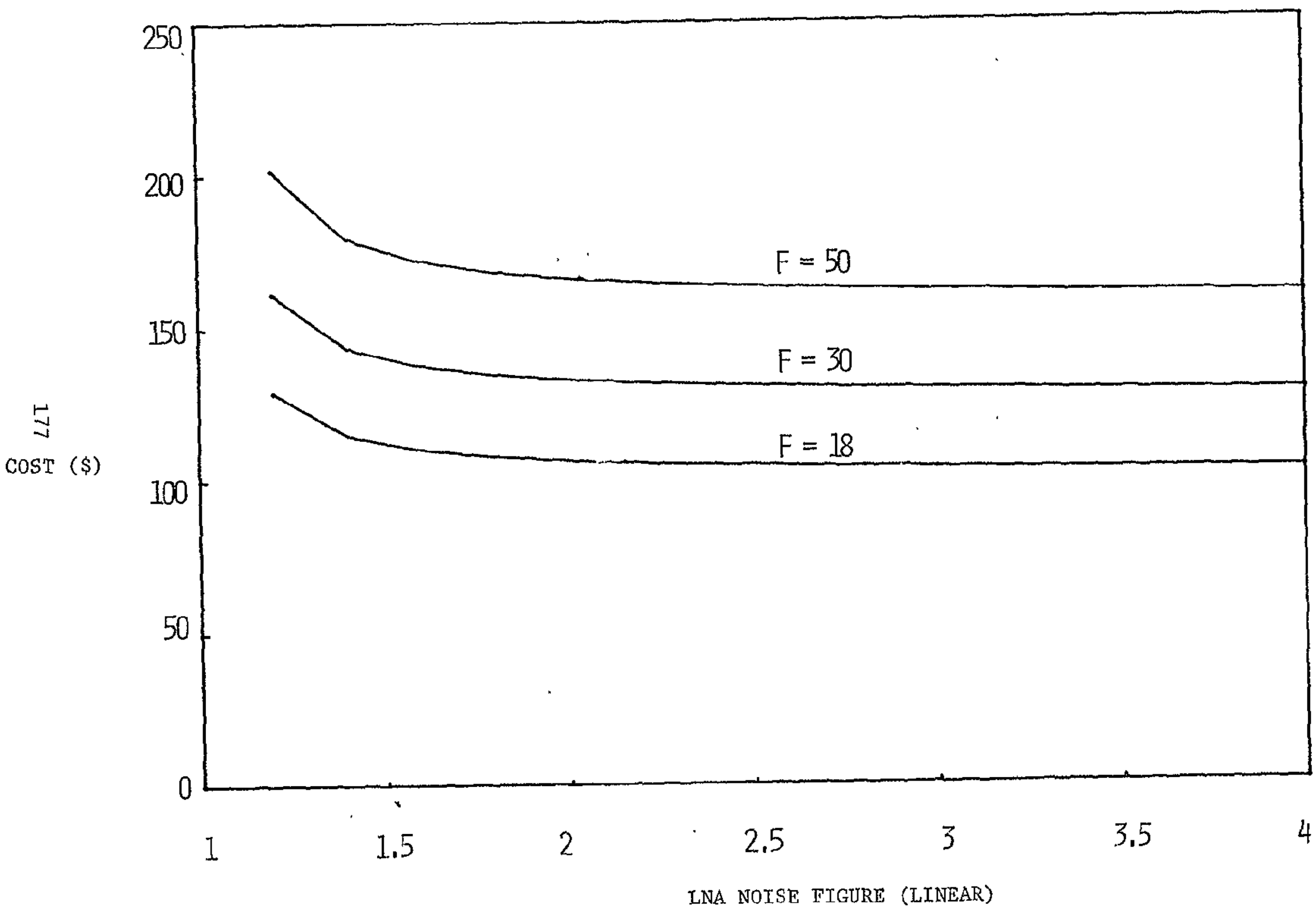

Figure C.14. Space Receiver Subsystem Cost

FDMA space switching cost model

- Dependent variable

  Cost, C (K $ 1976) Range: 3.5-216.5

- Independent variables

  Number of channels, N. Range: 1-6

  Number of subchannels per channel, M. Range: 1-5

- Equation

$$\begin{aligned} C = & (M)\,(2N)\,(0.65M + 0.1) && \text{(Switches)} \\ & + (N)\,(M)\,(2.15 - 0.15M) && \text{(Filters)} \\ & + (N)\,(0.5M - 0.5) && \text{(Combiner)} \end{aligned}$$

- Analysis

  Refer to Figure 4.4 for an interpretation of the terms of this equation. In this illustration there are six channels and five sub-channels per channel. The following list describes each term.

  Switches

  (M) - number of switch matrices

  (2N) - number of single pole M-throw switches per matrix

  (0.65M + 0.1) - cost of one SPMT switch

  Filters

  (N) - number of filter banks

  (M) - number of bandpass filters per bank

  (2.15 - 0.15M) - cost of a bandpass filter with bandwidth $\frac{1}{M}$ GHz (For $M \geq 15$ this term equals 1.0)

  Combiners

  (N) - number of combiners

  (0.5M - 0.5) - cost of an M-combiner

- Sources

  Switch Data - Electromagnetic Sciences

  Filter Data - Delta Microwave

FDMA space switching weight model

- Dependent variable

  Weight, W (lb) Range: 0.98-66.2

- Independent variables

  Number of channels, N. Range: 1-6

  Number of subchannels per channel, M. Range: 1-5

- Equation

$$W = ((M)\ (2N)\ (0.16\ M + 0.08) \qquad \text{(Switches)}$$
$$+ (N)\ (M)\ (0.5) \qquad \text{(Filters)}$$
$$+ (N)\ (0.3\ M - 0.3))/0.4536 \qquad \text{(Combiners)}$$

- Analysis

The equation for weight has the same component counts as the cost model with the following terms used for unit weight.

(0.16 M + 0.08) - weight of one SPMT switch

(0.5) - weight of a bandpass filter

(0.3 M - 0.3) - weight of an M - combiner.

Note that the beam-switching cost and weight are accounted for in the "number of feeds" term of the satellite antenna model.

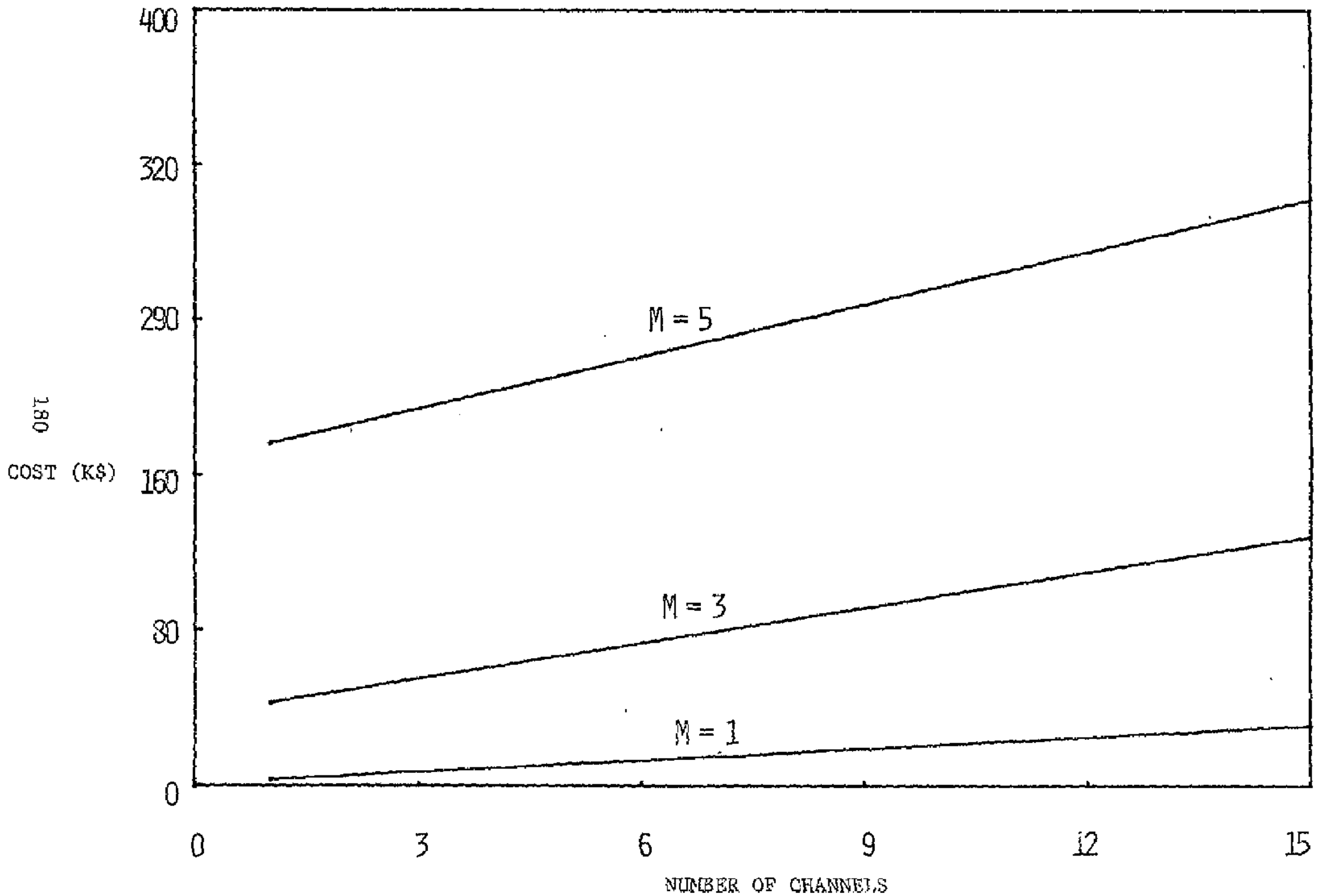

Figure C.15. FDMA Space Switching Cost

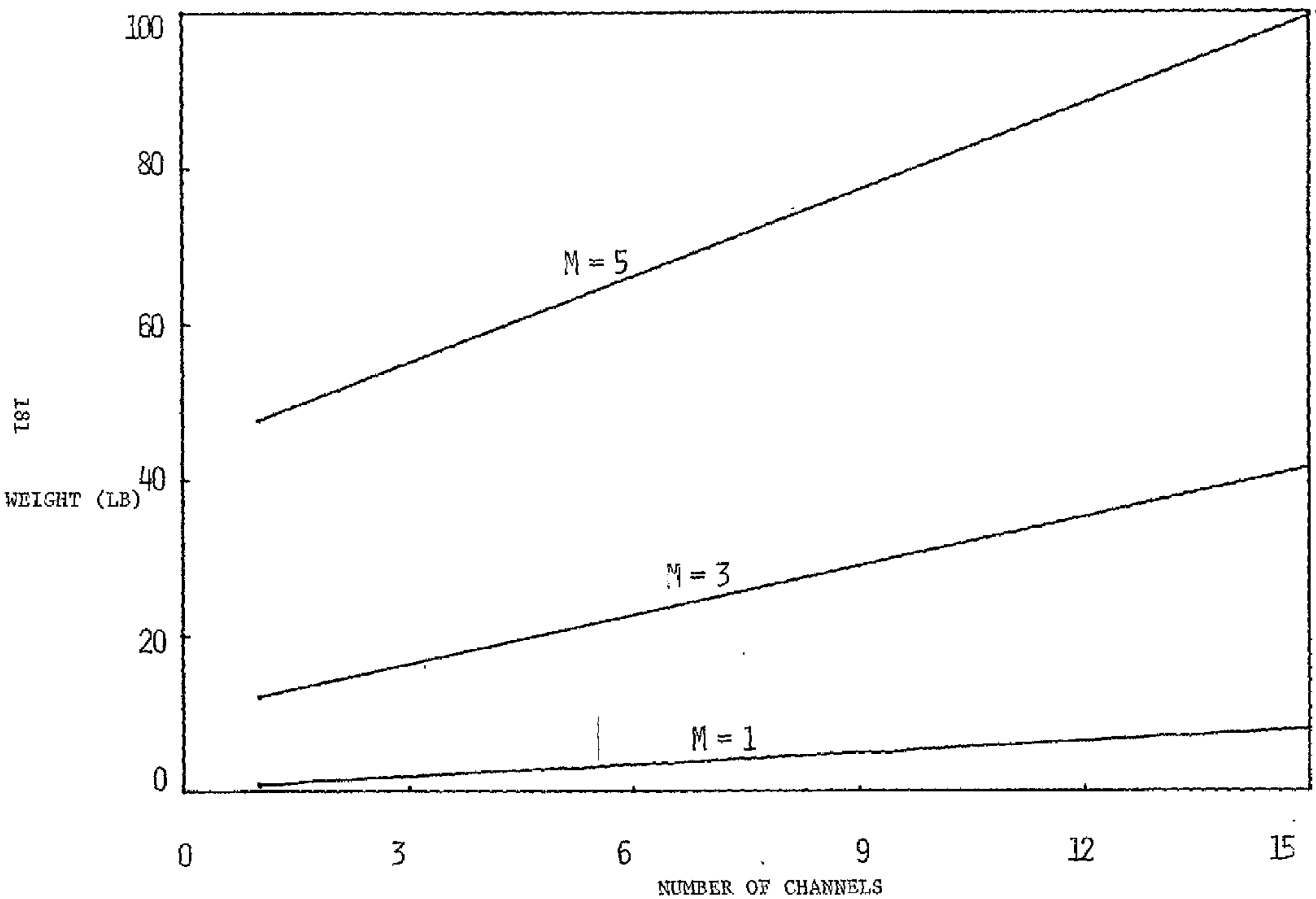

Figure C.16. FDMA Space Switching Weight

TDMA space switching cost model

- Dependent variable

  Cost, C (K $ 1976) Range: 4.85-619

- Independent variable

  Number of channels, N. Range: 1-15

- Equation

  C = (2N) (1.3 N + 0.2) (Switches)

  + (N) (1.85)

- Analysis

  Refer to Figure 4.5

  Switches

  (2N) - number of SPNT switches in the switch matrix

  (1.3 N + 0.2) - cost of one SPNT switch for TDMA switching application at 40-41 GHz.

  Filters

  (N) - number of filters

  (1.85) - cost of a bandpass filter with 1 GHz bandwidth at 40-41 GHz

TDMA space switching weight model

- Dependent variable

  Weight, W (lb) Range: 0.98-02.0

- Independent variable

  Number of channels, N. Range: 1-15

- Equation

  W = (2N) (0.16 N + 0.08) (Switches)

  + (N) (0.5) (Filters)

- Analysis

  This equation is similar to the TDMA cost model with terms for element weights included.

  (0.16 + 0.08) - weight of one SPNT switch

  (0.5) - weight of one 1 GHz bandwidth filter

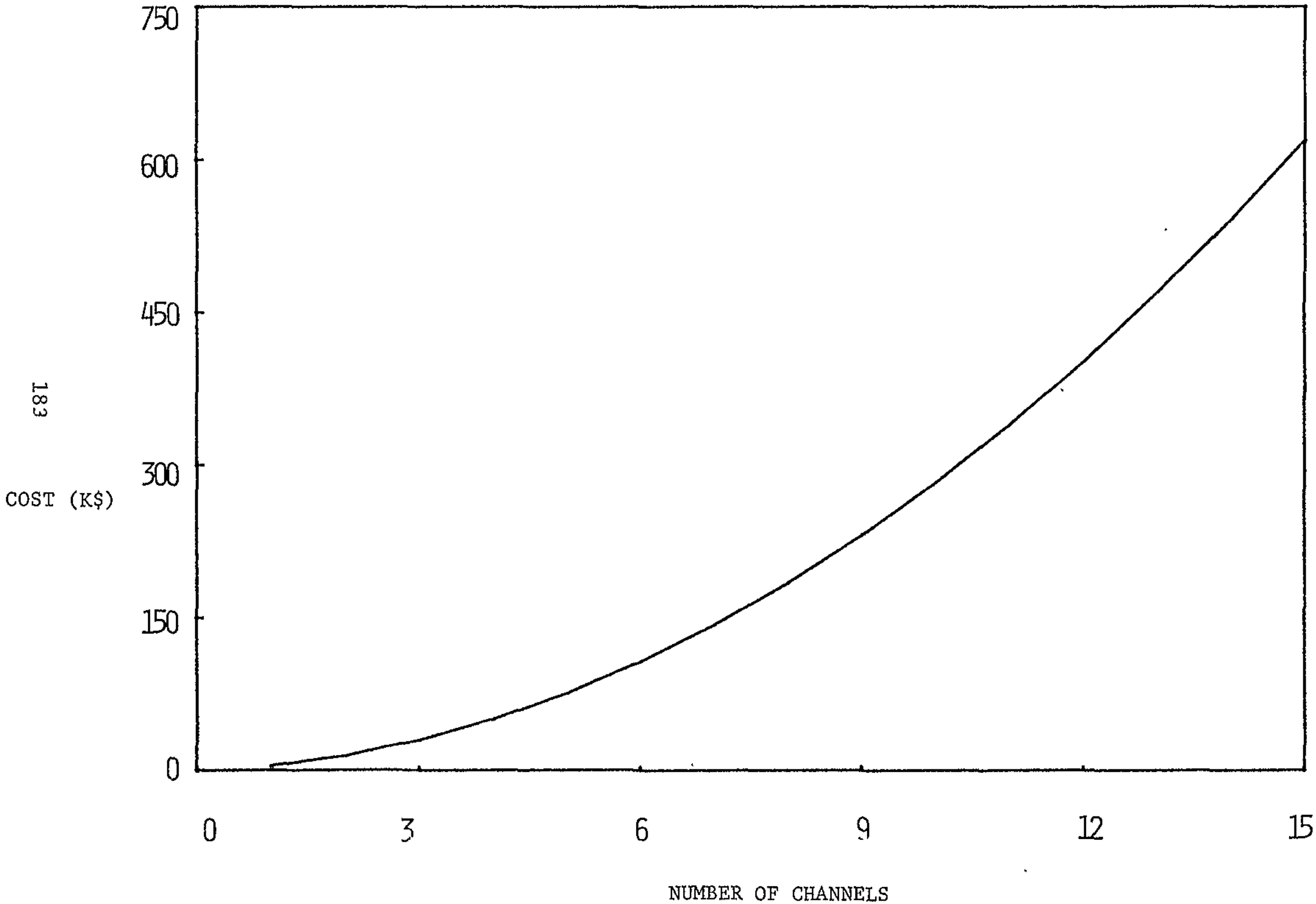

Figure C.17. TDMA Space Switching Cost

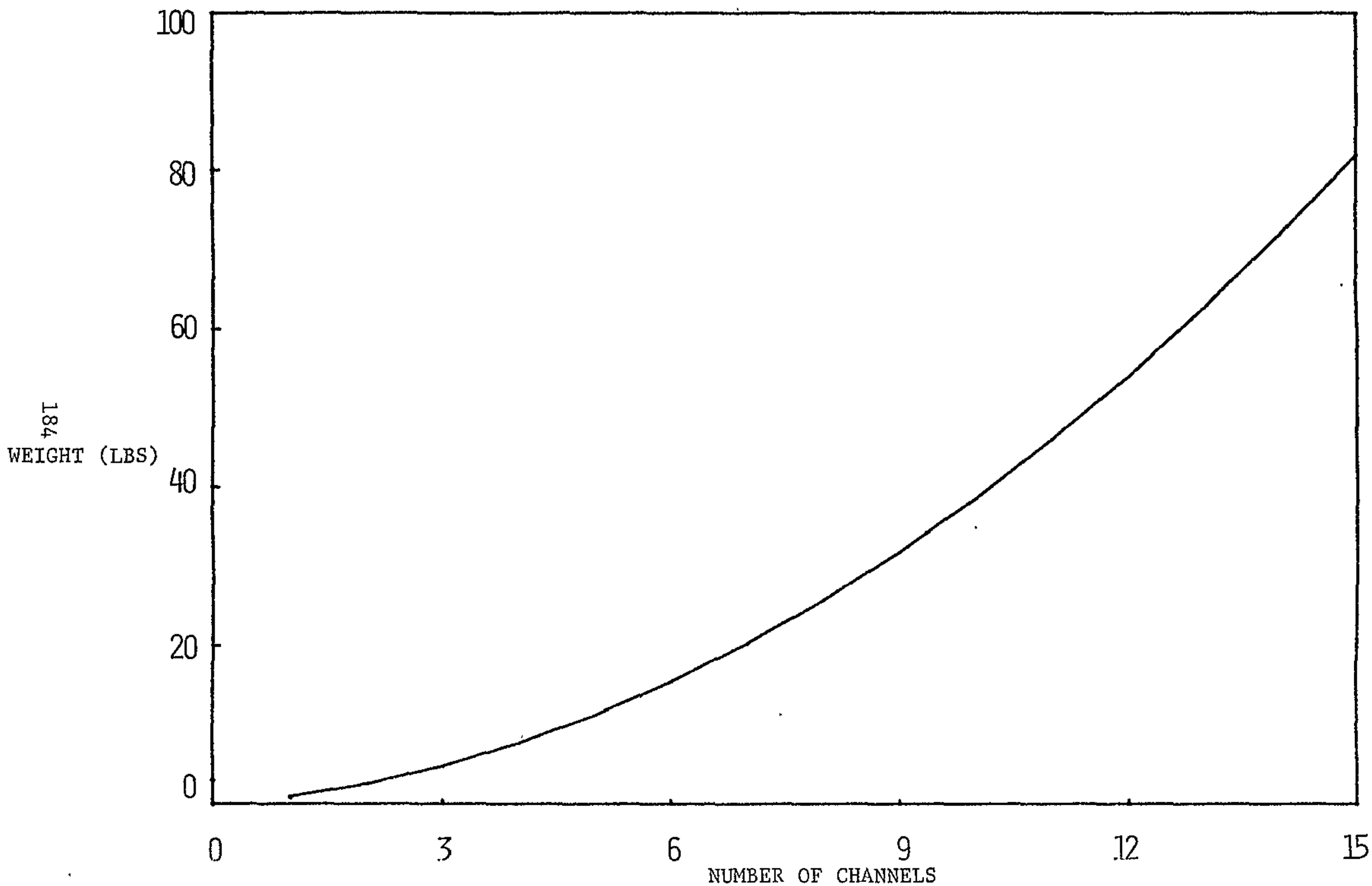

Figure C.18. TDMA Space Switching Weight

ATTITUDE CONTROL SYSTEM

Subsystem weight model.

- Dependent variable

  Weight, W_{ACS} (lb) Range: 13-430

- Independent variables

  Attitude control tolerance, B (deg) Range: 0.01-2.0

  Satellite weight, W_{SAT} (lb) Range: 500-10,000

- Equation

  $$W_{ACS} = W_{SAT}\ (0.024 + 0.0019/\sqrt{B})$$

- Source

  Data for WESTAR and ATS-6

Subsystem cost model

- Dependent variable

  Cost, C (K \$ 1976) Range: 545-5505

- Independent variable

  Attitude control system weight, W_{ACS} (lb) Range: 13-430

- Equation

  $$C = 103\ W_{ACS}^{0.5194} + 17.19\ W_{ACS}^{0.8569}$$

- Source

  Unmanned Spacecraft Model, Third Edition, SAMSO, August, 1975. [3]

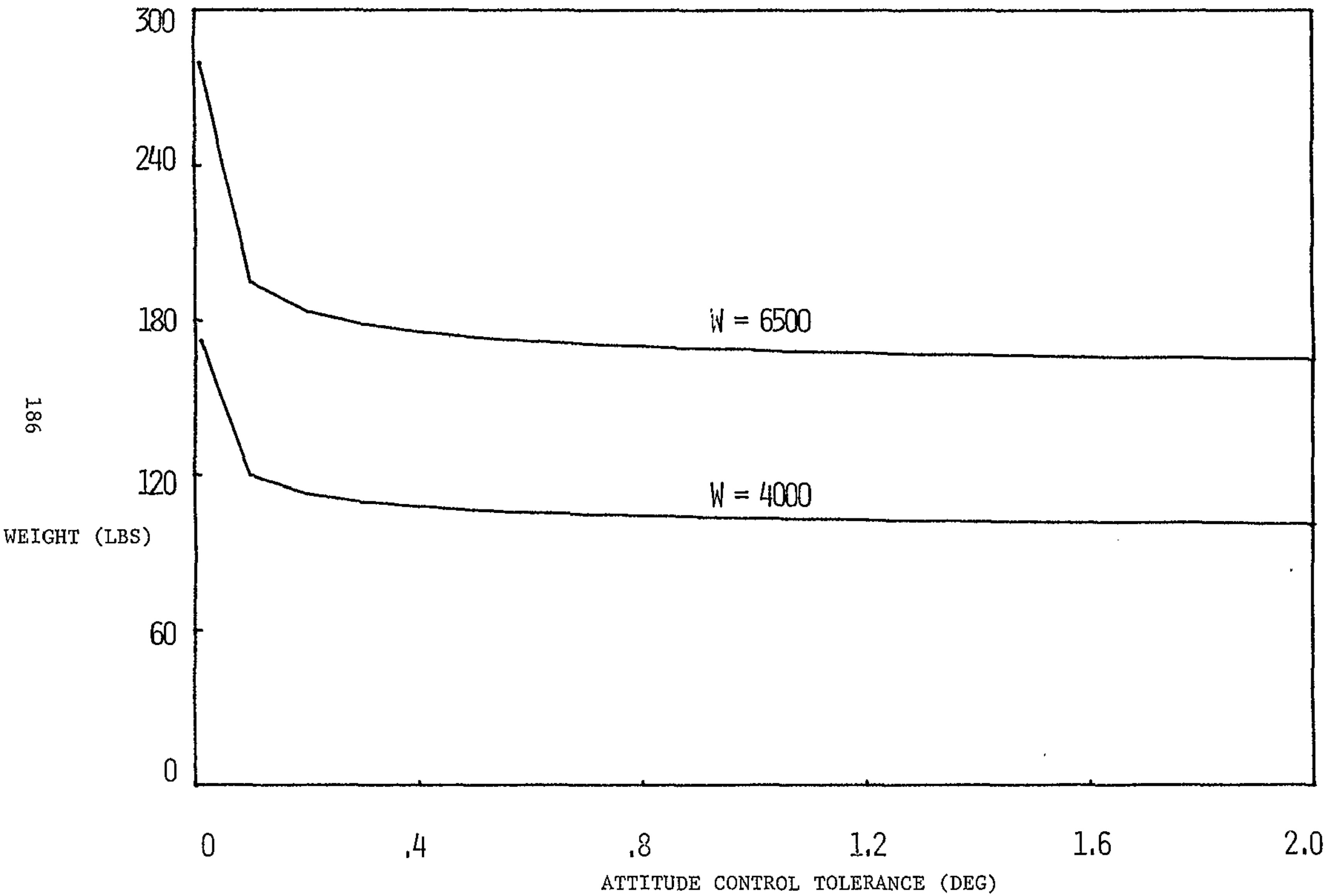

Figure C.19. Attitude Control System Weight

C-3

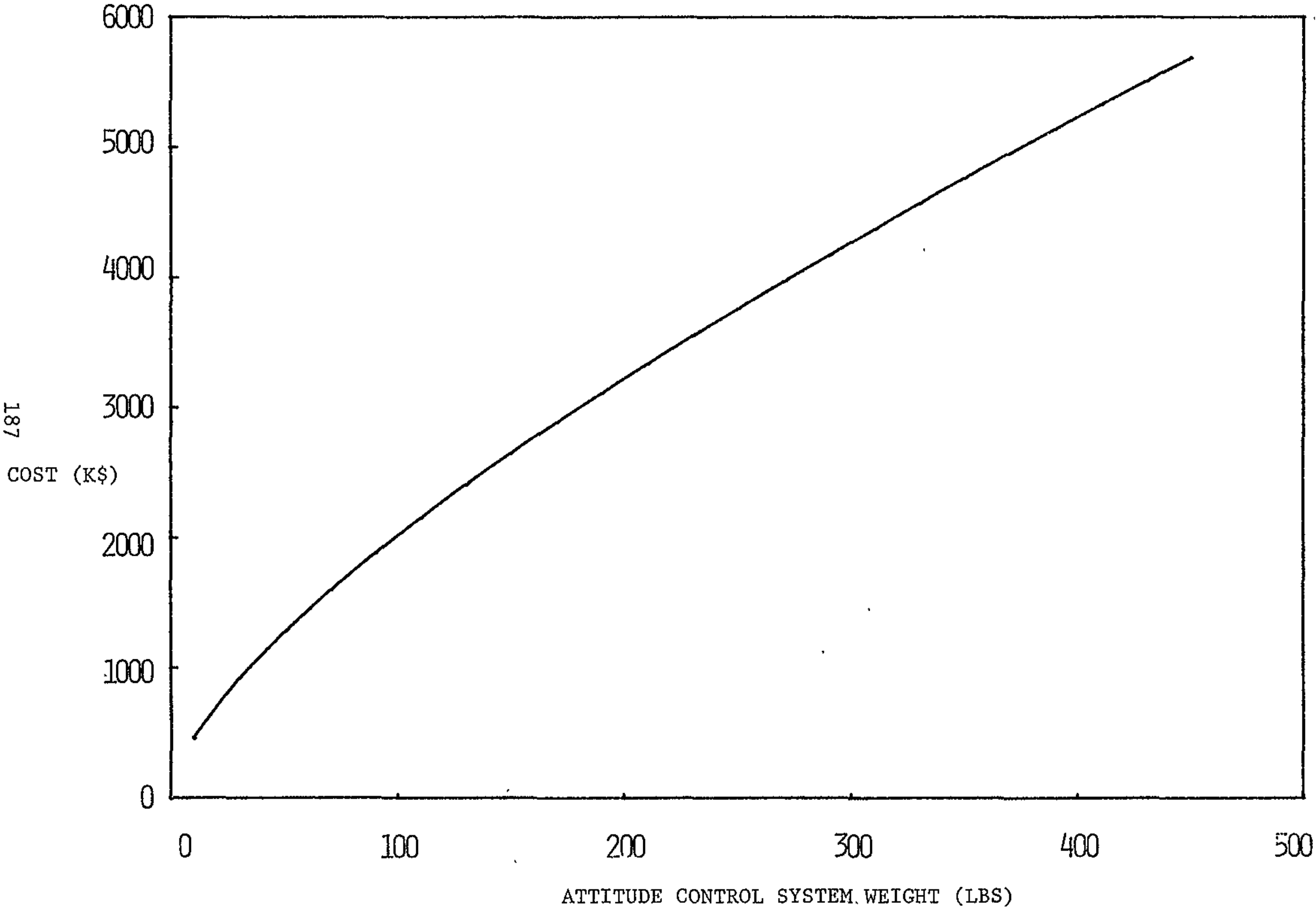

Figure C.20. Attitude Control System Weight (LBS)

STATION KEEPING SYSTEM

Subsystem weight model

- Dependent variable

  Weight, W_{SKS} (lb) Range: 60-1800

- Independent variables

  Station keeping accuracy, E (deg) Range: 0.001-0.1

  Satellite weight, W_{SAT} (lb) Range: 500-10,000

- Equation

  $$W_{SKS} = W_{SAT} \left[0.12 - 0.03 \log (10E)\right]$$

- Source

  Hughes Aircraft Company [4]

Subsystem cost model

- Dependent variable

  Cost, C (K \$ 1976) Range: 926-9536

- Independent variable

  Station keeping system weight, W_{SKS} (lb) Range: 60-1800

- Equation

  $$C = 72 (W_{SKS})^{0.52} + 9.5 (W_{SKS})^{0.86}$$

- Source

  Unmanned Spacecraft Model, SAMSO, August 1975 [3]

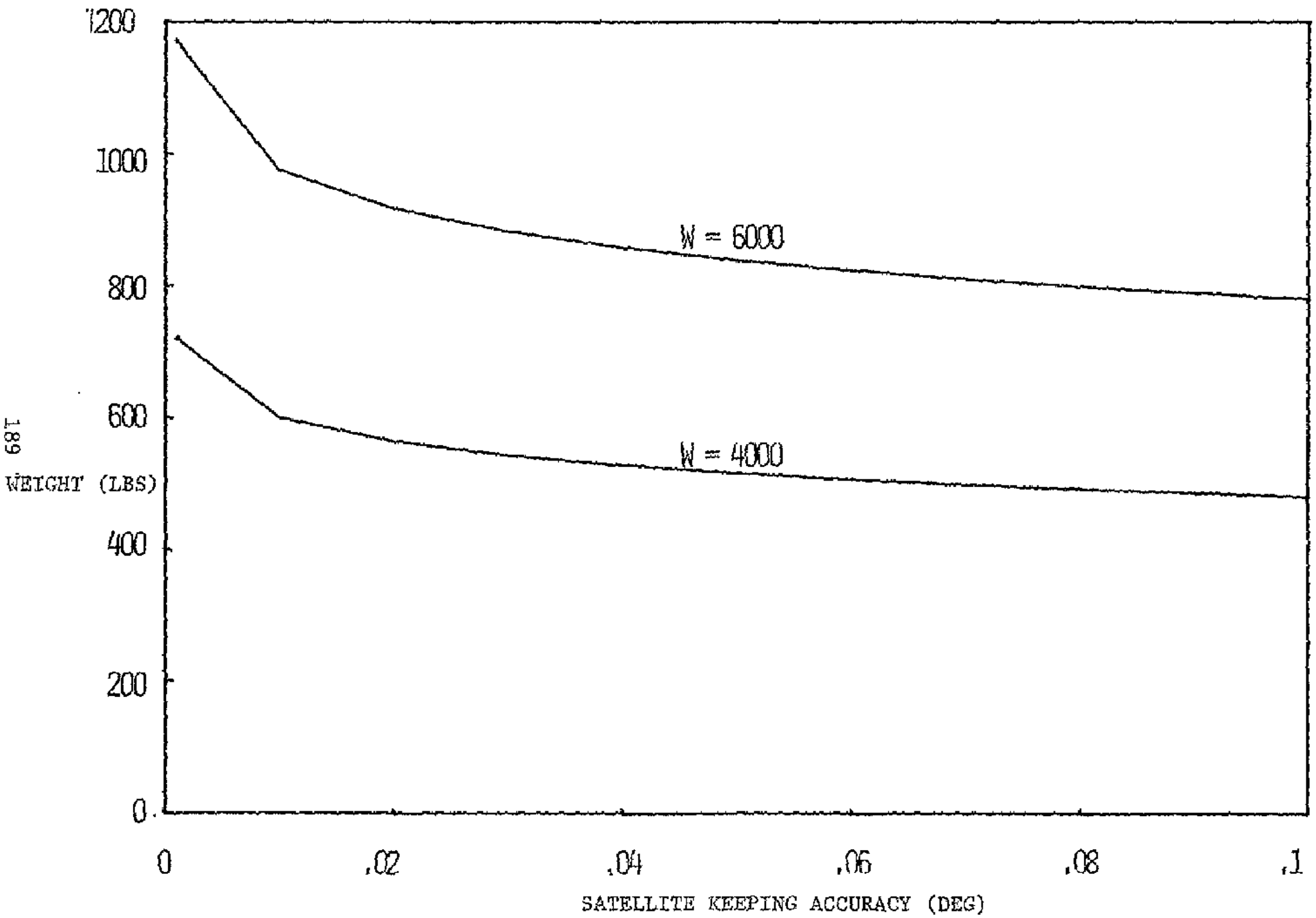

Figure C.21 Station Keeping System Weight

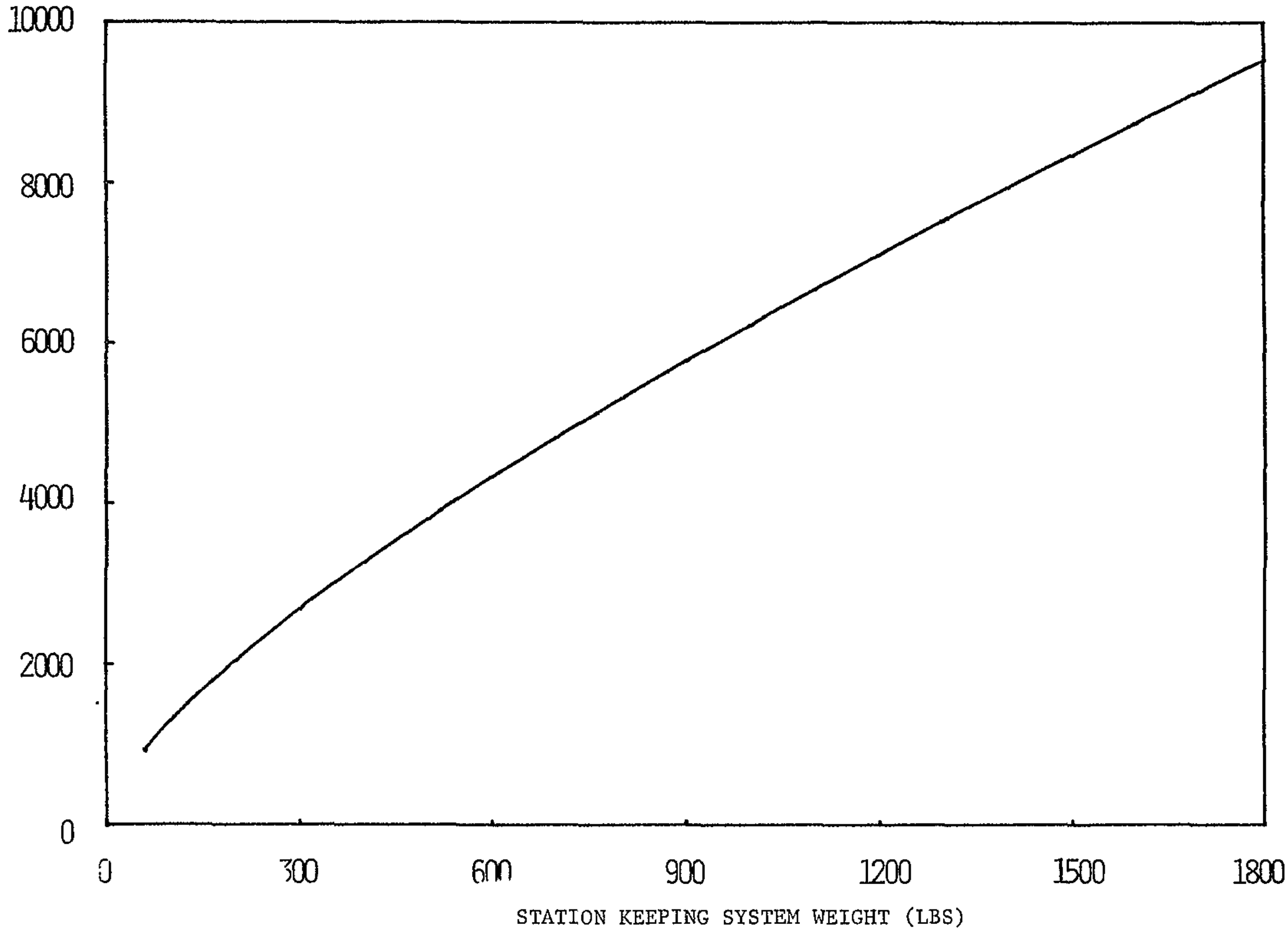

Figure C.22. Station Keeping System Cost

STRUCTURE AND THERMAL CONTROL

Subsystem weight model

- Dependent variable

  Weight, W_{STC} (lb) Range: 80-2653

- Independent variable

  Satellite weight, W_{SAT} (lb) Range: 500-10,000

- Equation

  $W_{STC} = (W_{SAT} - 200)/3.762$

- Assumptions

  This model is based on average values for the weights of structure materials. Extremely light materials (with associated high costs) are not used.

- Sources

  General Electric and RCA

Subsystem cost model

- Dependent variable

  Cost, C (K $ 1976) Range: 3603-26984

- Independent variable

  Structure and thermal control weight, W_{STC} (lb) Range: 80-2653

- Equation

  $C = 131.55 + 33.33\, W_{STC}^{0.54} + 9.99\, W_{STC}^{0.72}$

- Source

  Unmanned Spacecraft Cost Model, SAMSO, July 1975 [3]

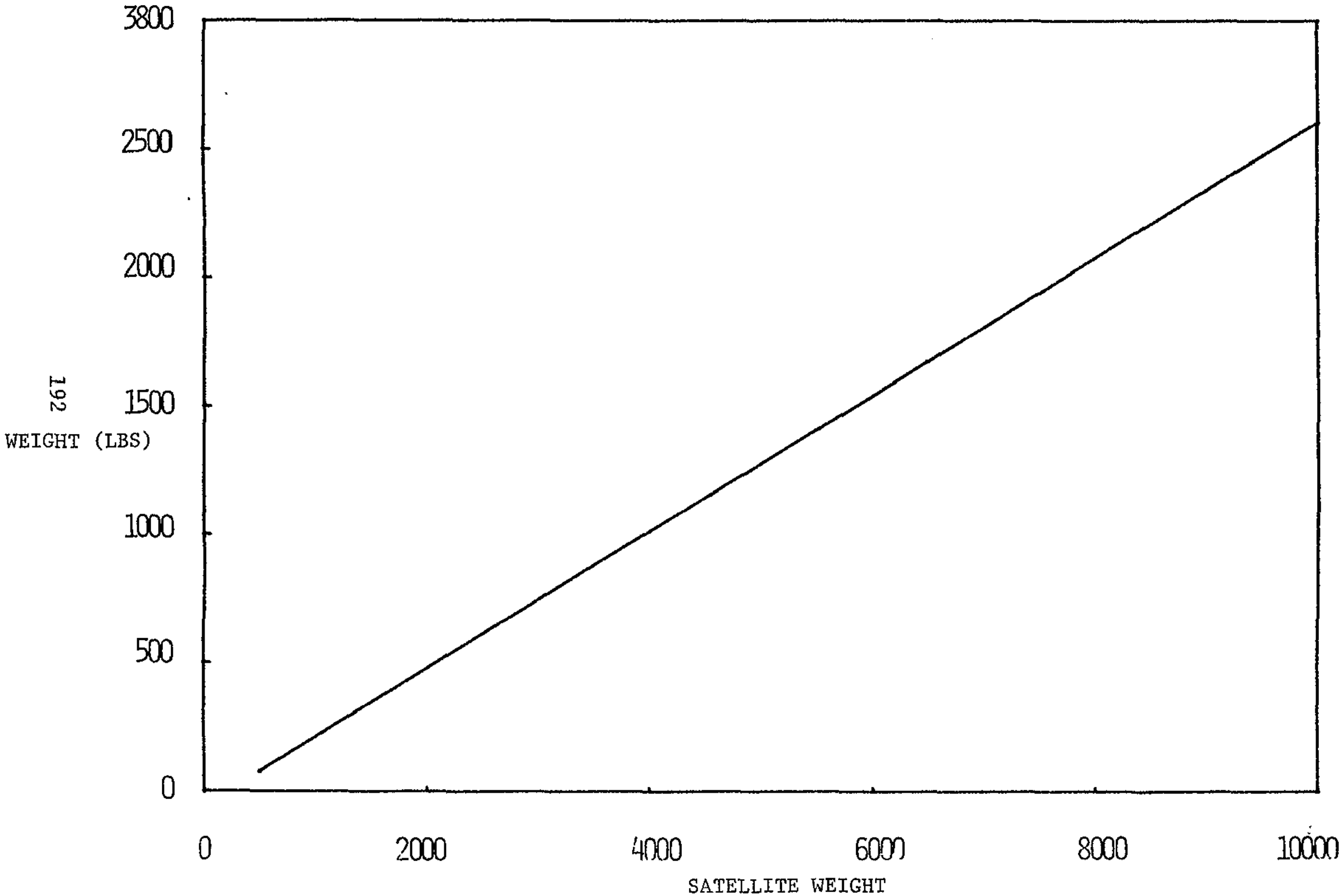

Figure C.23. Structure and Thermal Control Weight

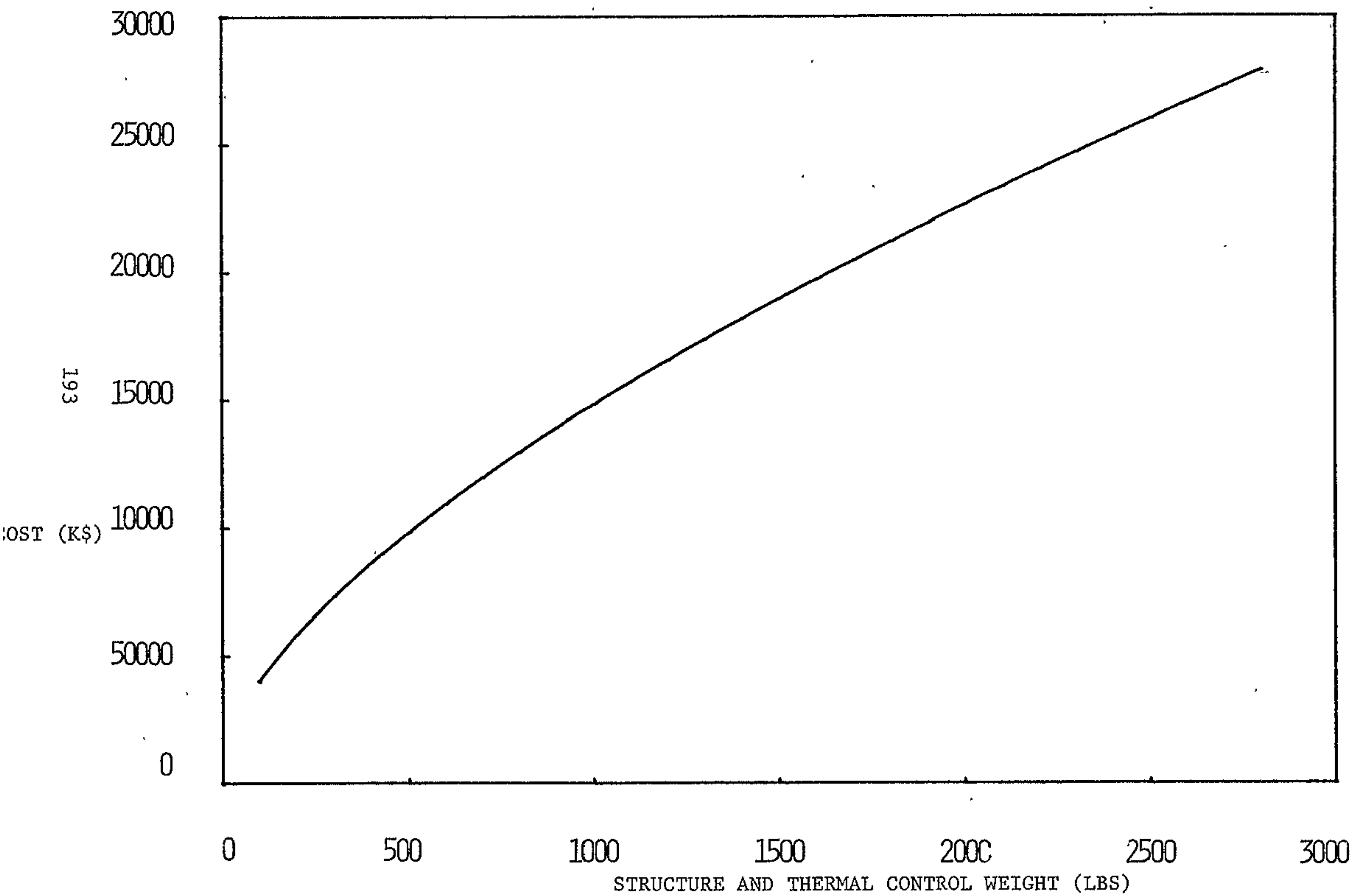

Figure C.24. Structure and Thermal Control Cost

SATELLITE POWER SUPPLY

Subsystem cost model

- Dependent variable

  Cost, C (K $ 1976) Range: 3.1-1384

- Independent variable

  Power supplied, P (W) Range: 0-8000

- Equation

  $$C = 3.1258 + 2.6804\, P^{0.69486}$$

- Source

  Technology Forecasting for Space Communications, Hughes Aircraft Company, November, 1974 [4]

Subsystem weight model

- Dependent variable

  Weight, W (lb) Range: 1-1601

- Independent variable

  Power supplied, P (W) Range: 0-8000

- Equation

  $$W - 1 + 0.2P$$

- Source

  Same as for cost model

Prime power requirements

- Dependent variable

  Satellite prime power, PP (W) Range: 0-18500

- Independent variables

  Transmitter efficiency, ET Range: 0.1-1

  Transmitter power, P (W) Range: 0-1500

  Maximum number of active transmitter, N. Range: 1-15

- Equation

  $$PP = N \;\; 1.5\, P/ET \qquad 0 \le P \le 500$$

  $$= N\,(1.1\, P + 200)/ET \qquad 500 < P \le 1500$$

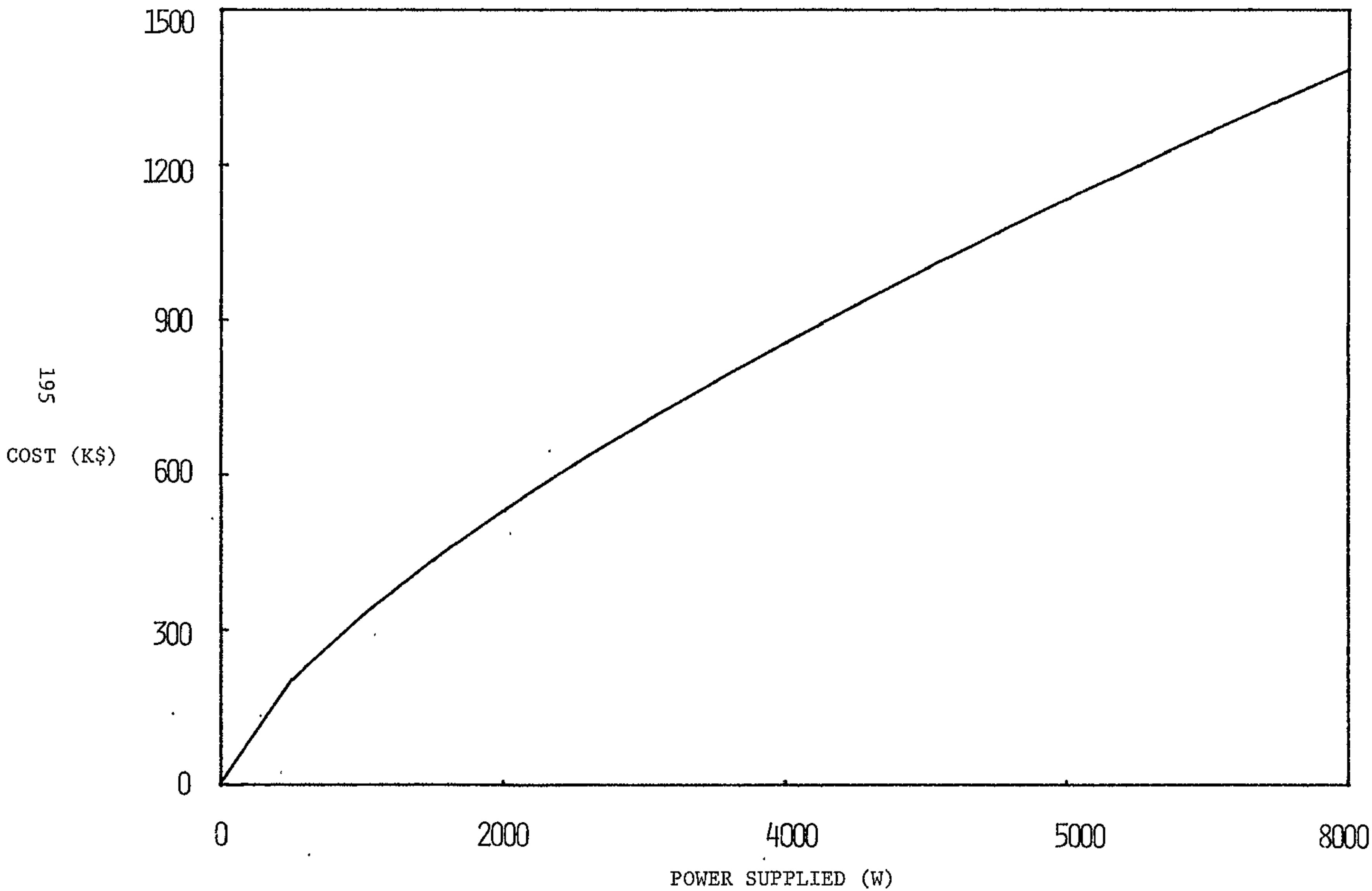

Figure C.25. Electrical Power Supply Cost

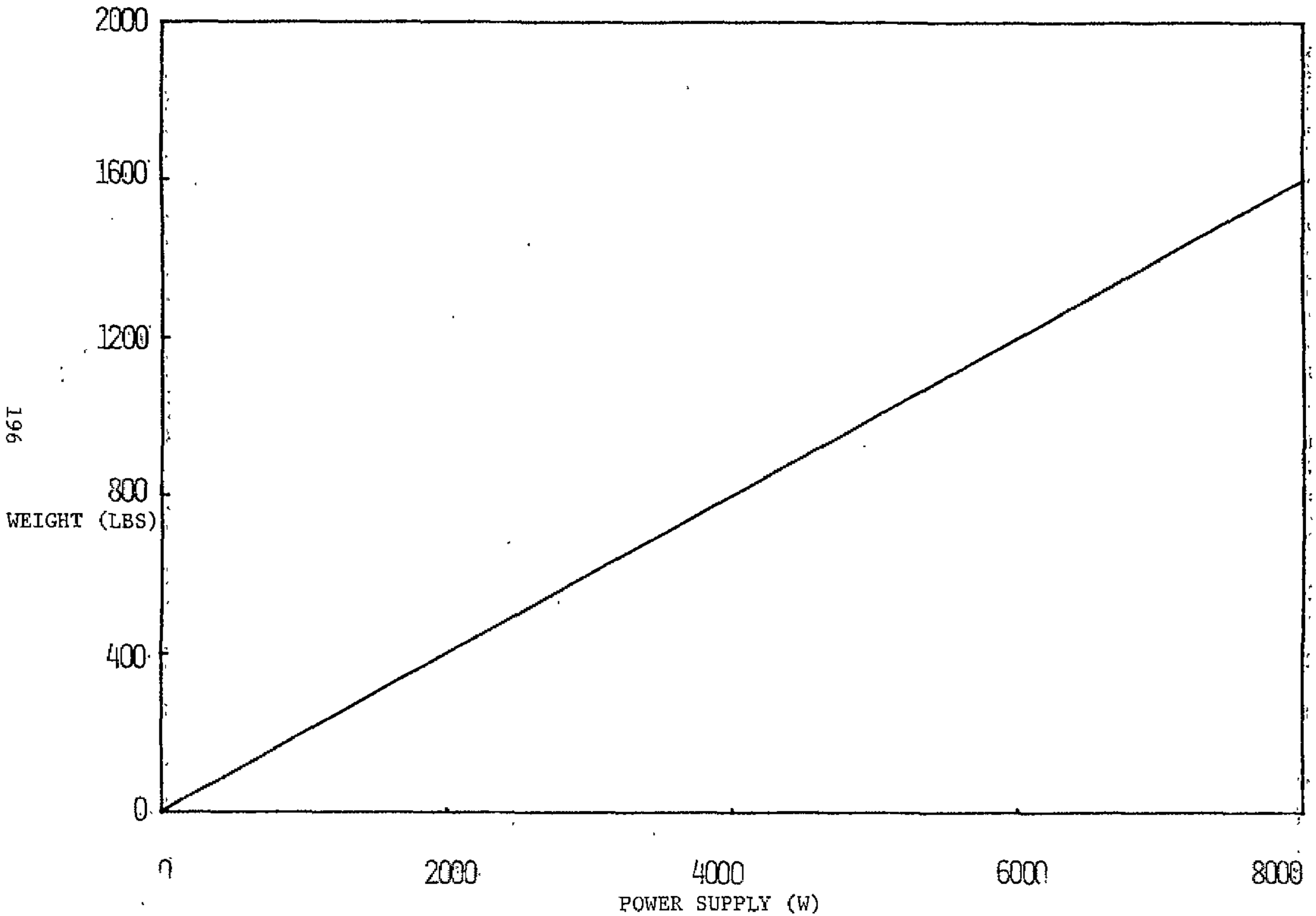

Figure C.26. Electrical Power Supply Weight

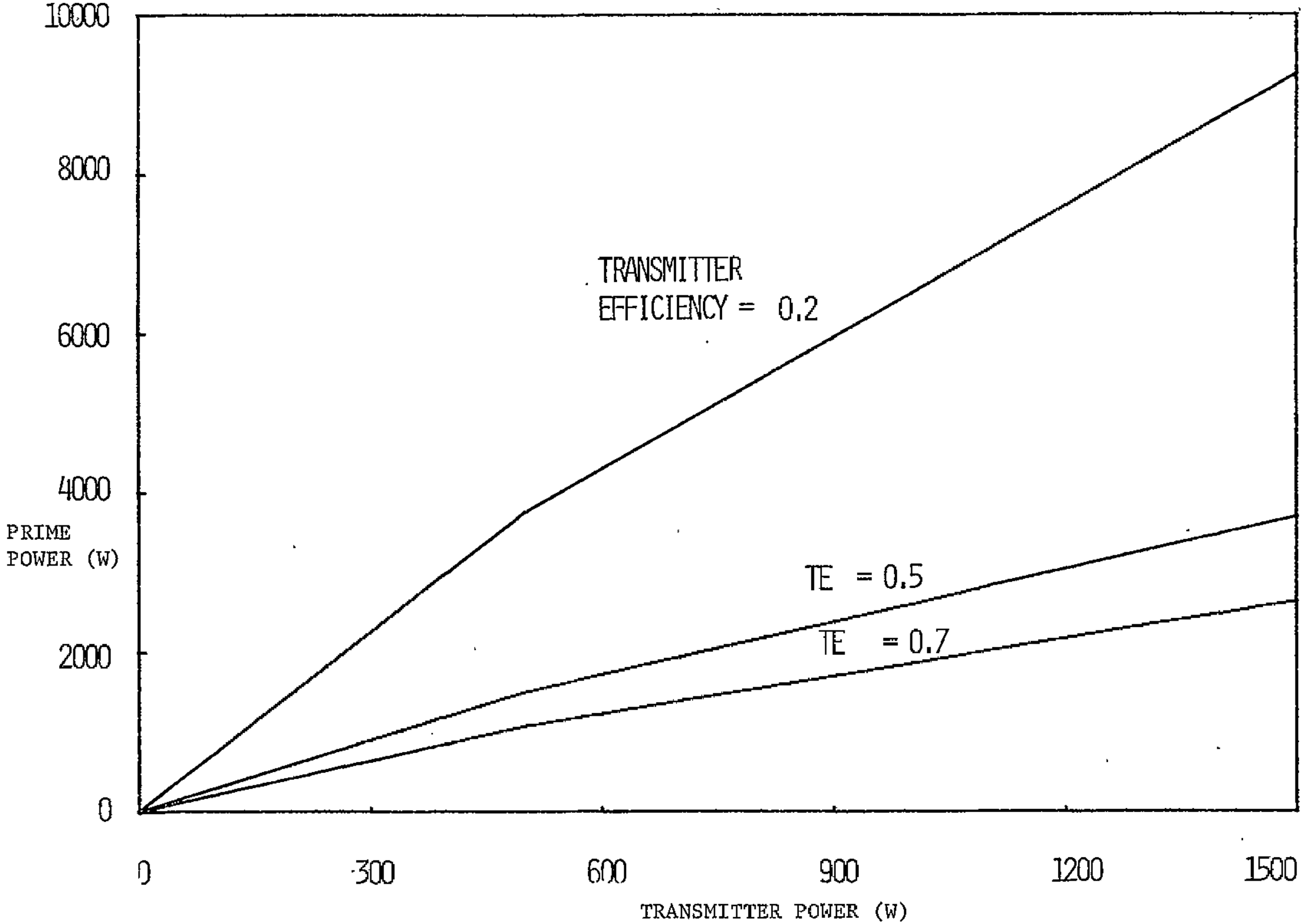

Figure C.27. Electrical Power Supply, Prime Power Requirements

APPENDIX D

SUBSYSTEM MODEL ELASTICITIES

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APPENDIX D

LIST OF FIGURES

Appendix D
Subsystem Model Elasticities

The plots given in this appendix provide a measure of the sensitivity of cost and weight models to changes in the associated model parameters. These elasticities are defined as follows:

$$E_{sc} = \frac{\Delta C_s}{C_s} \bigg/ \frac{\Delta P_s}{P_s}$$

$$E_{sw} = \frac{\Delta W_s}{W_s} \bigg/ \frac{\Delta P_s}{P_s}$$

where:

E_{sc} = subsystem cost elasticity

E_{sw} = subsystem weight elasticity

C_s = subsystem cost

W_s = subsystem weight

P_s = primary subsystem parameter

These elasticities may be interpreted as the per cent change in cost or weight for a 1 per cent change in parameter.

In the discussion in Section 6.2.4 the system electicities were defined as

$$E_{tc/s} = \frac{\Delta C_t}{C_t} \bigg/ \frac{\Delta P_s}{P_s}$$

$$E_{tw/s} = \frac{\Delta W_t}{W_t} \bigg/ \frac{\Delta P_s}{P_s}$$

where:

$E_{tc/s}$ = system cost elasticity with respect to P_s

$E_{tw/s}$ = system weight elasticity with respect to P_s

C_t = system cost

W_t = system weight

Since these system elasticities are computed by varying a sub-system parameter, simple relations exist among the various elasticities. They are

$$E_{sc} C_s = E_{tc/s} C_t$$

and $$E_{sw} W_s = E_{tw/s} W_t$$

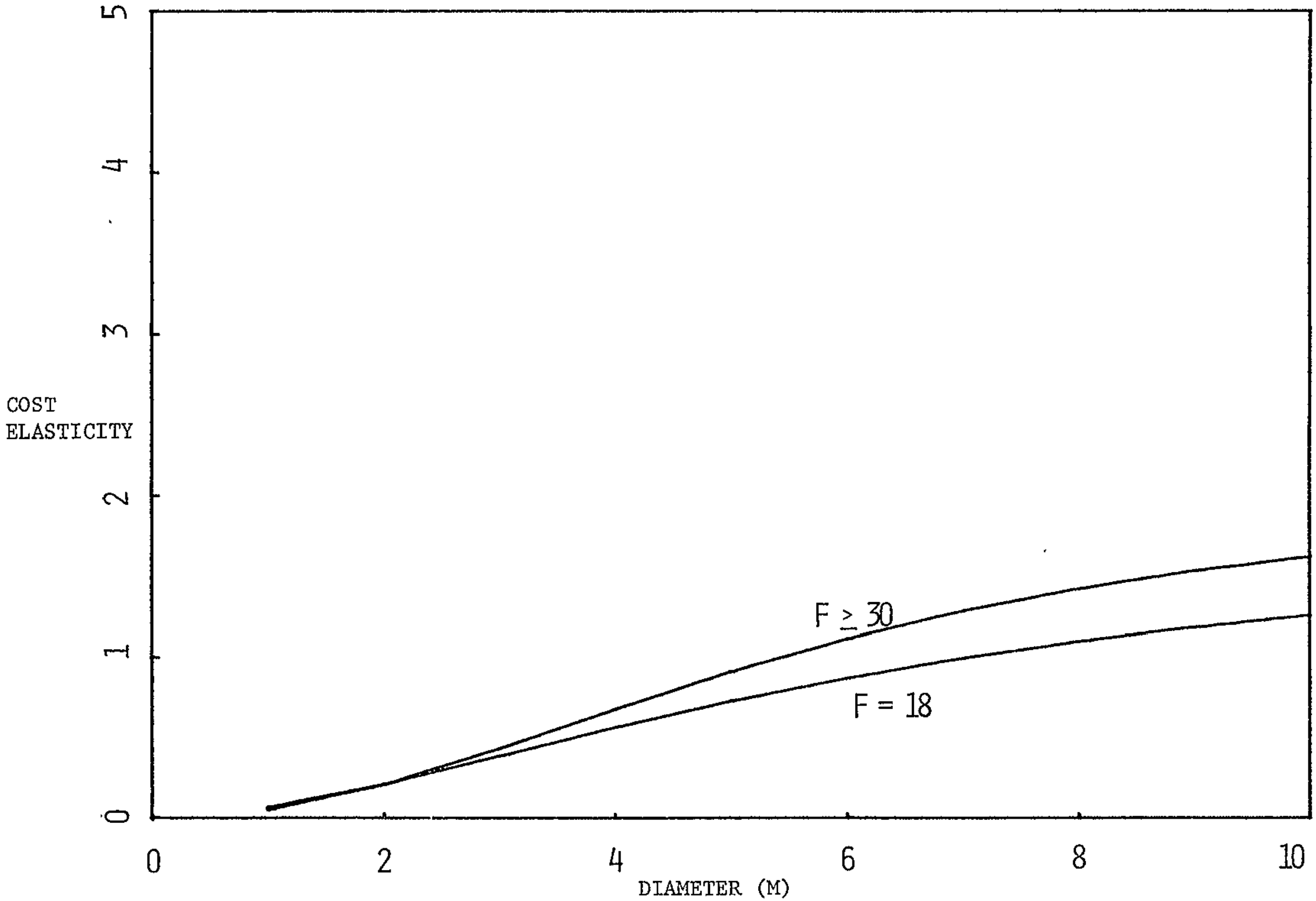

Figure D.1. Ground Antenna Cost Elasticity
(Point-to-Point Case)

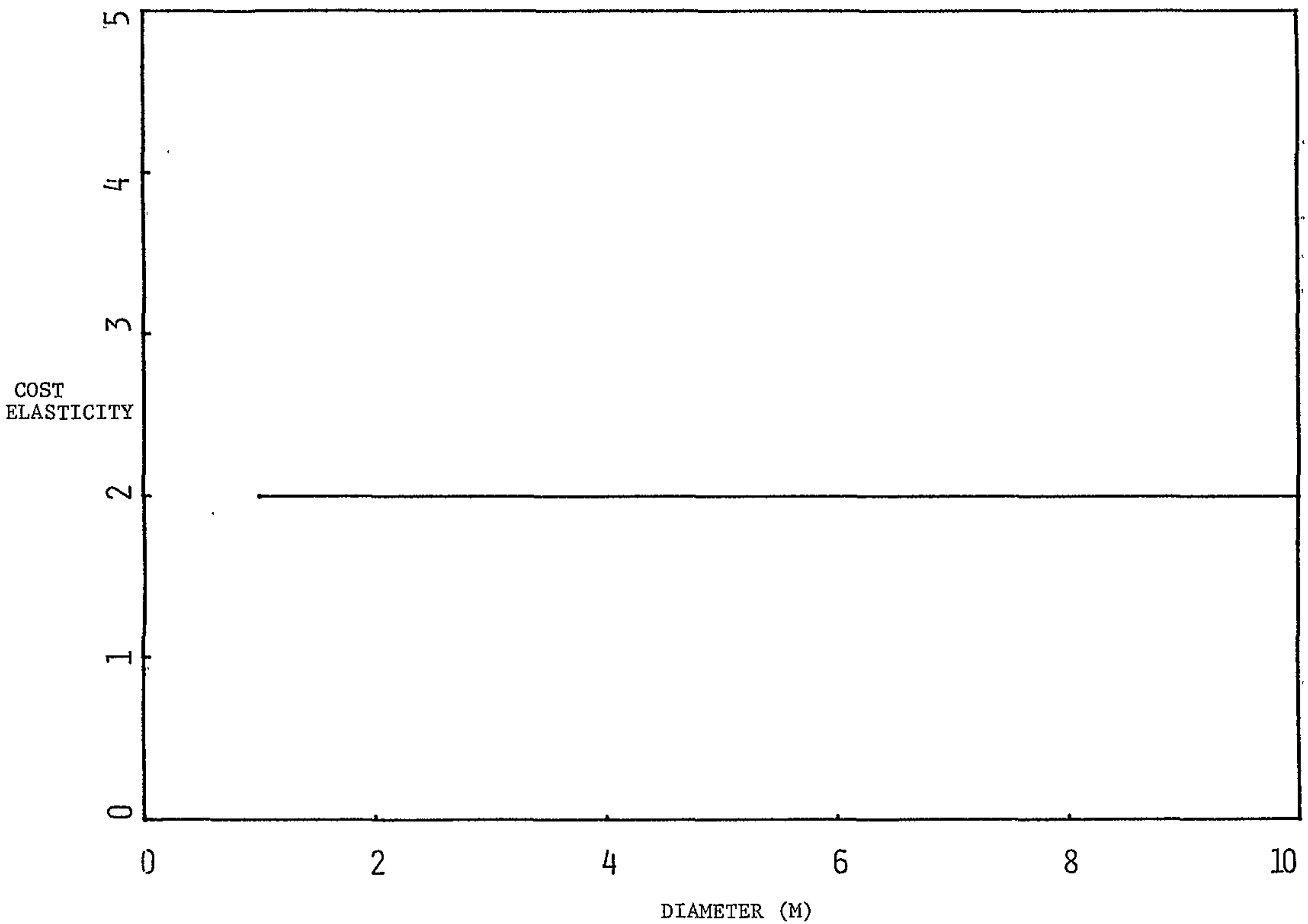

Figure D.2. Ground Antenna Cost Elasticity
(Broadcast Case)

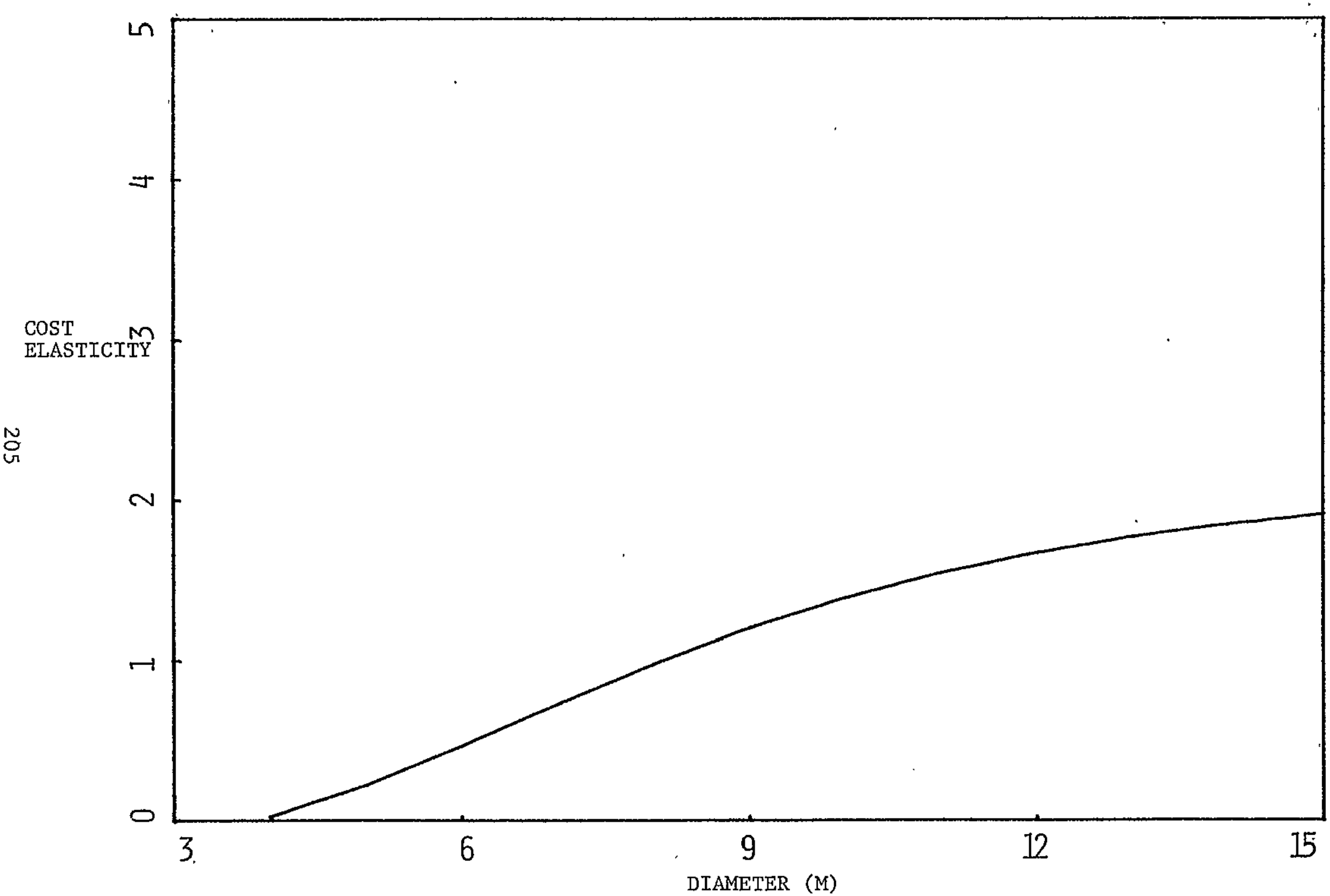

Figure D.3. Radome Cost Elasticity

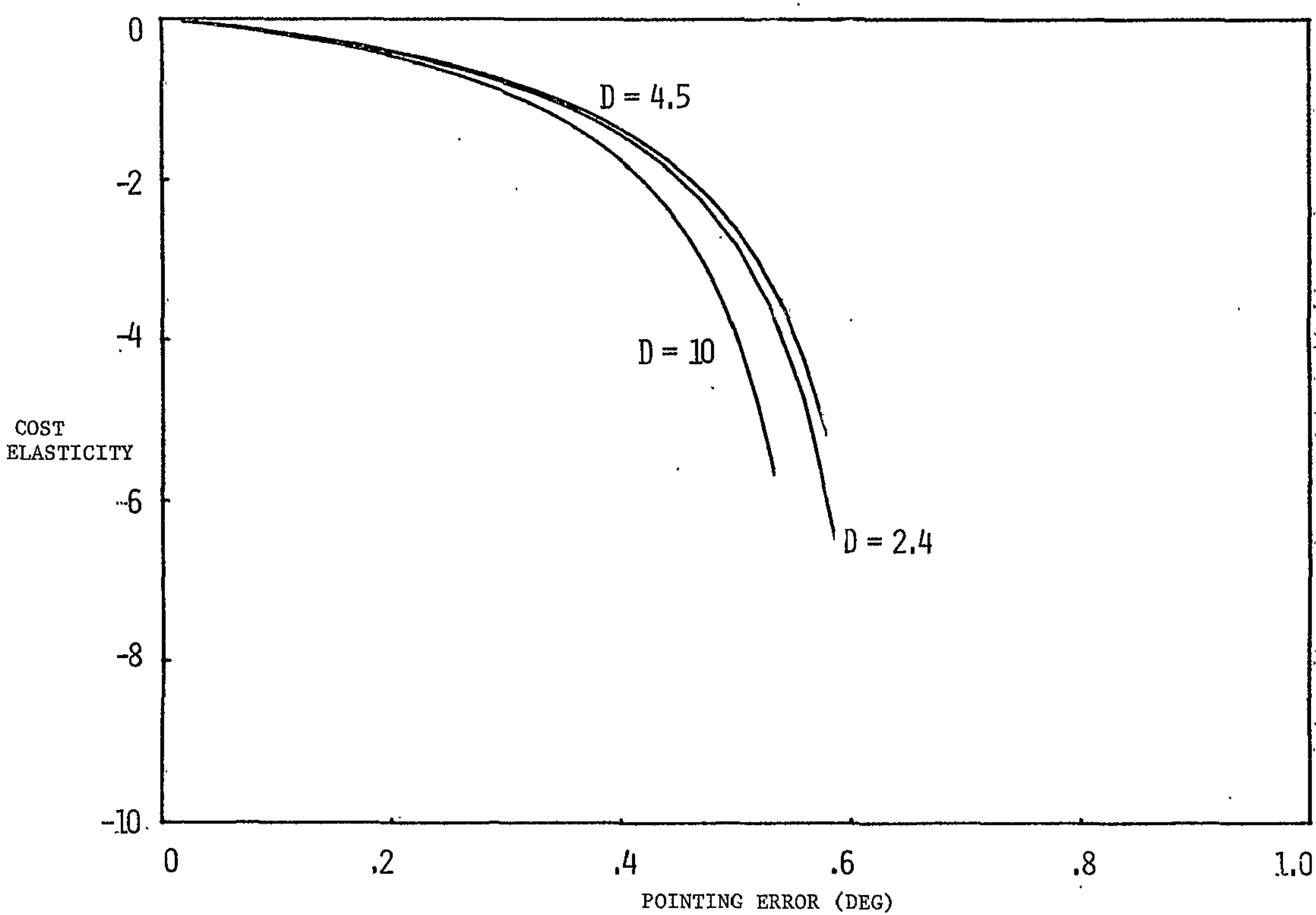

Figure D.4. Ground Pointing and Control Cost Elasticity

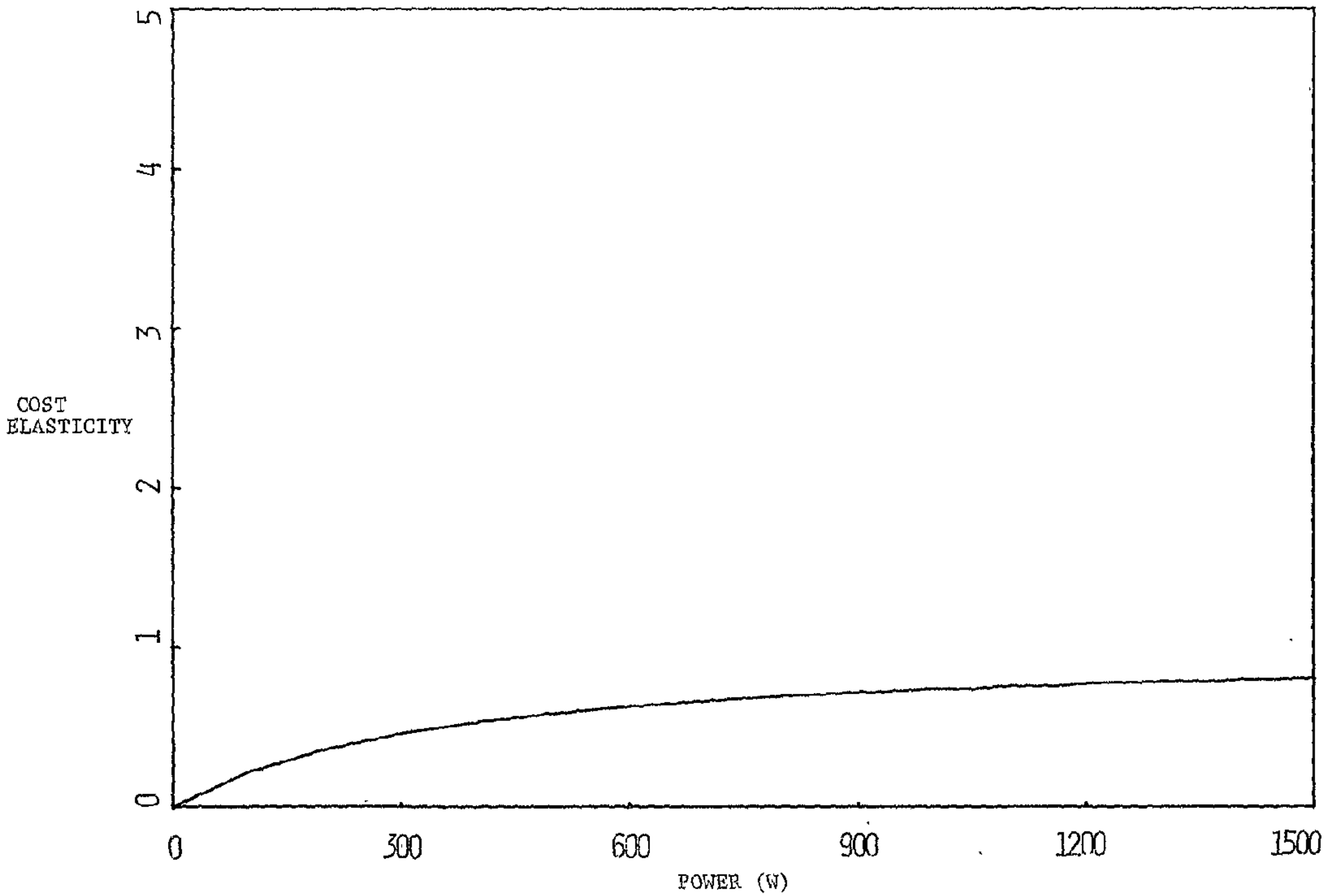

Figure D.5. Ground Transmitter Cost Elasticity

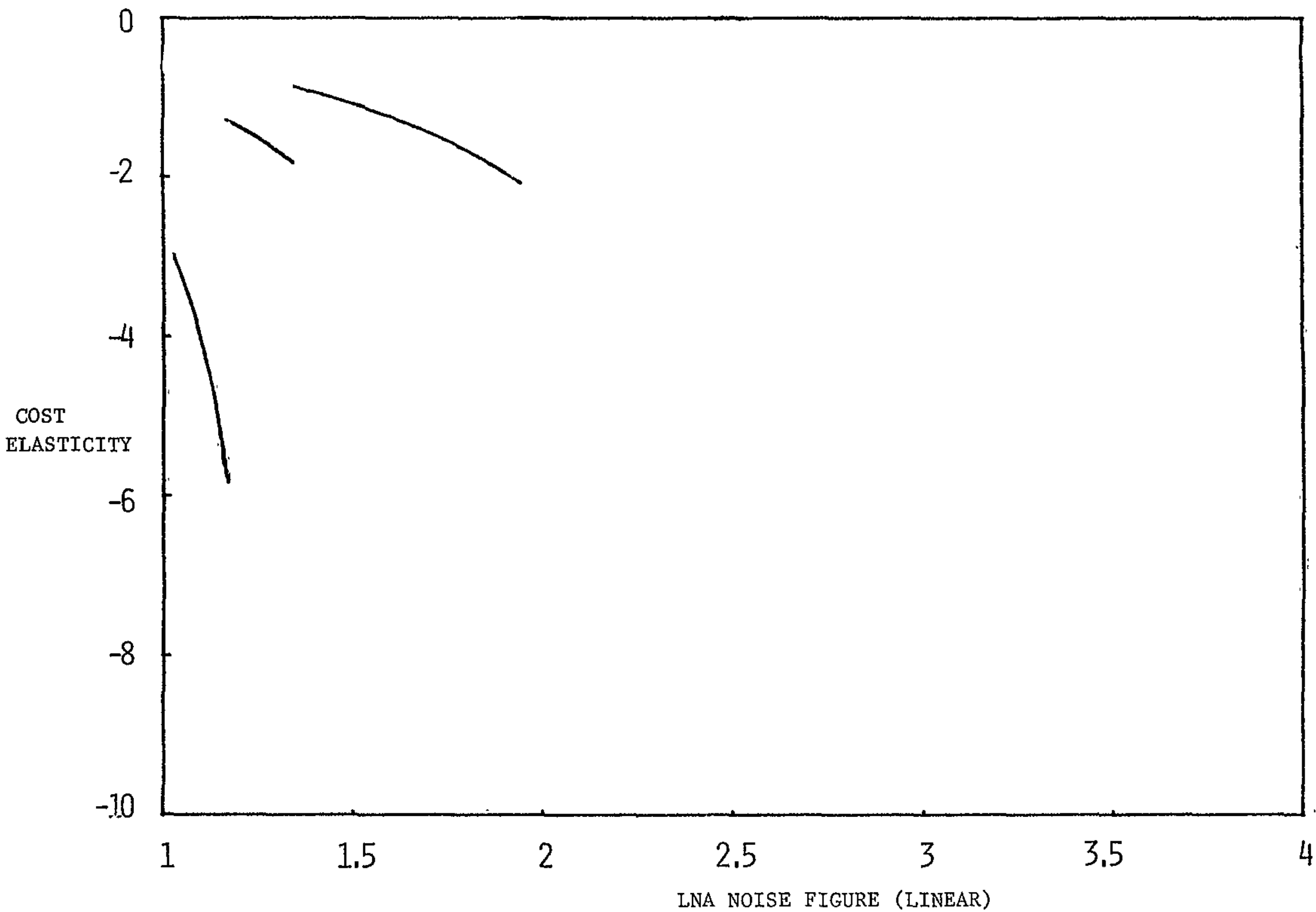

Figure D.6. Ground Receiver Cost Elasticity

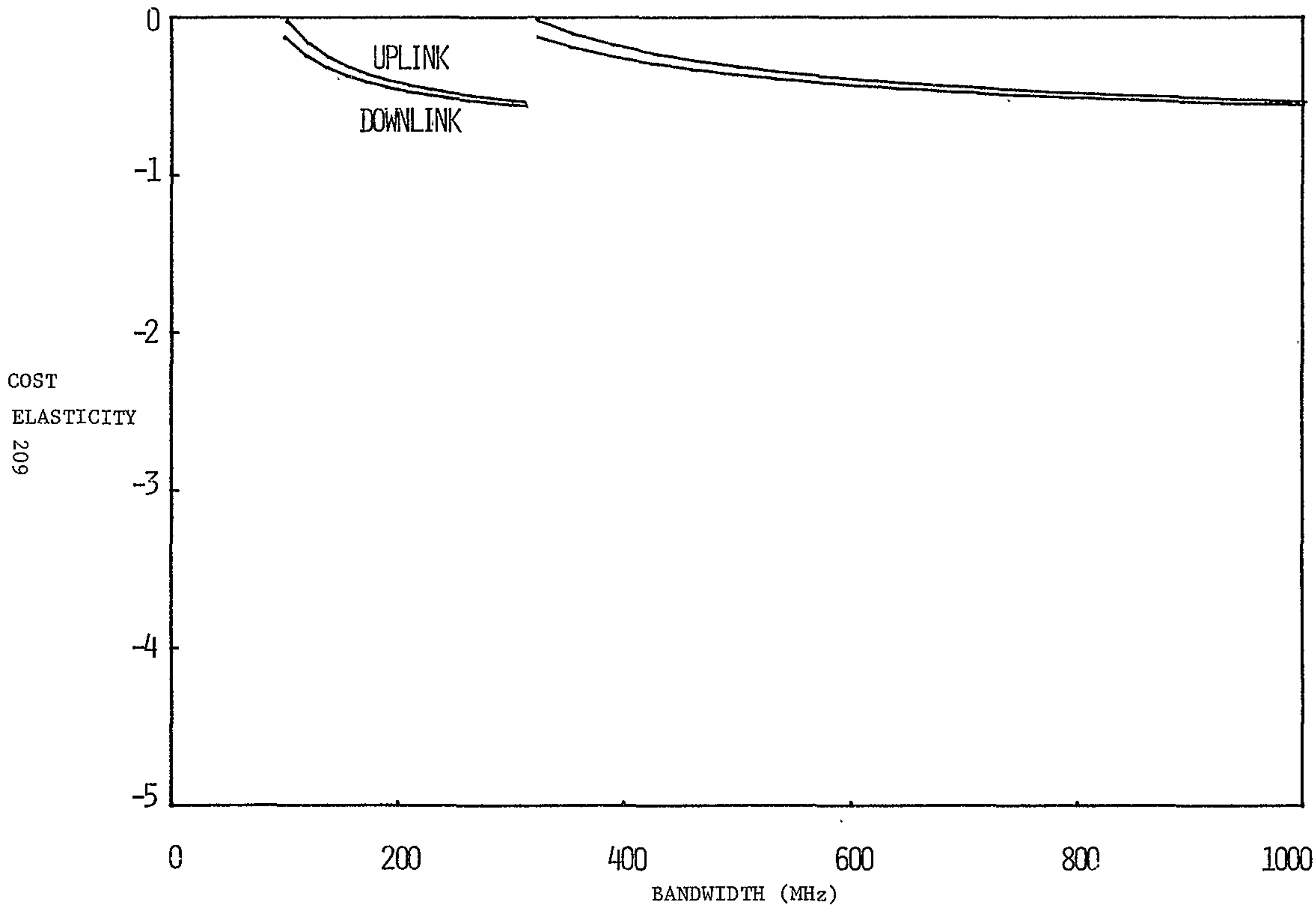

Figure D.7. Ground Signal Processing Cost Elasticity

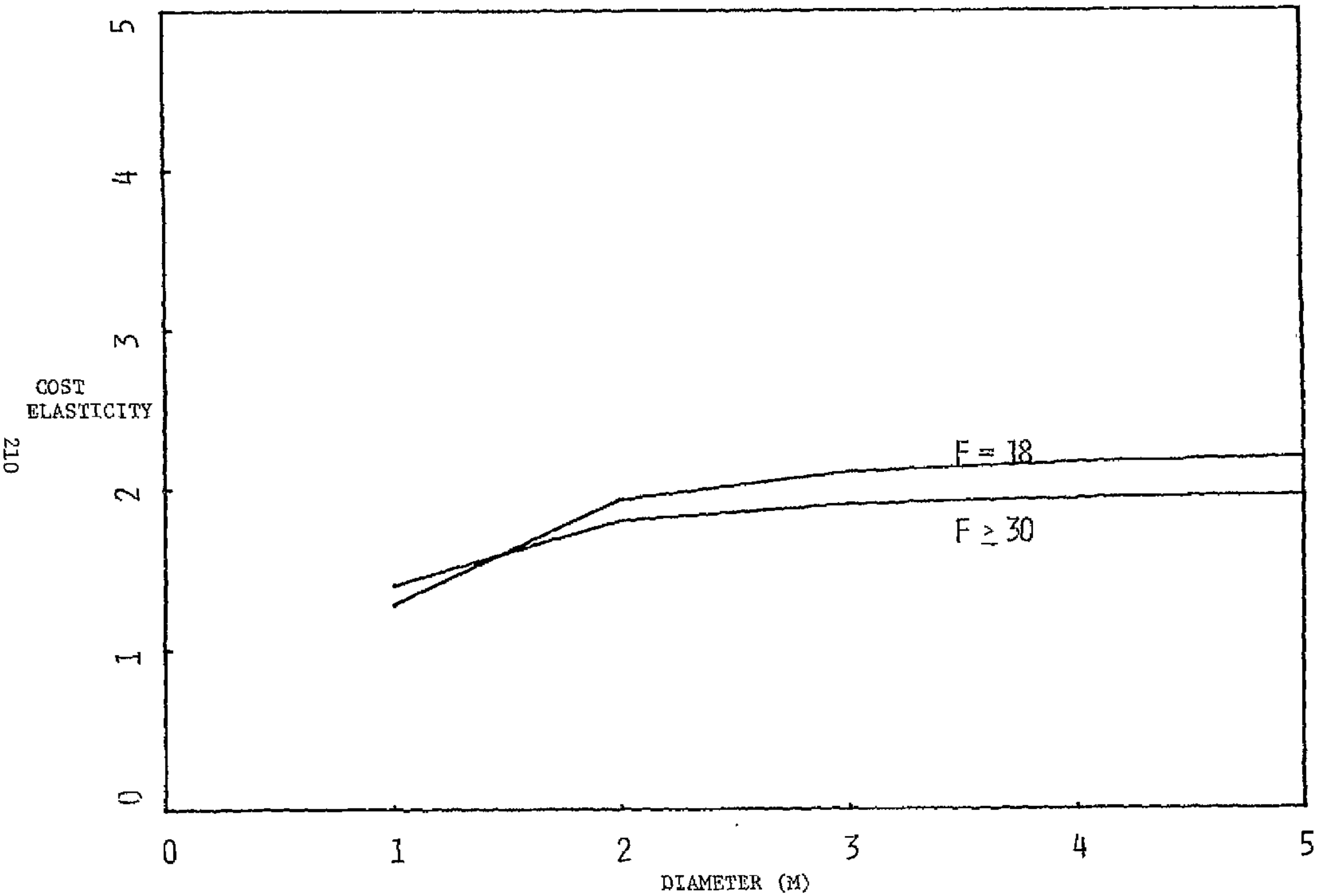

Figure D.8. Satellite Antenna Cost Elasticity

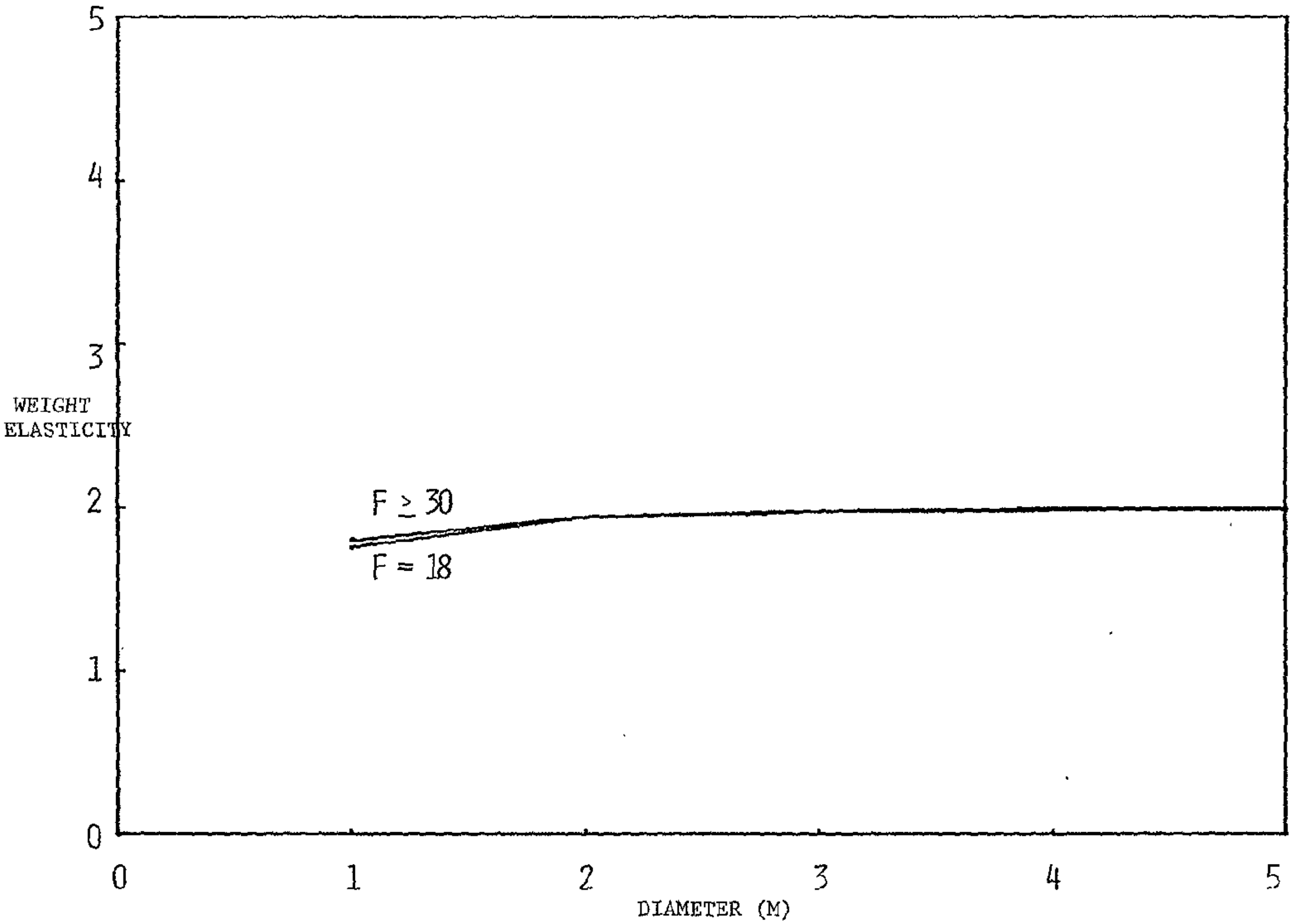

Figure D.9. Satellite Antenna Weight Elasticity

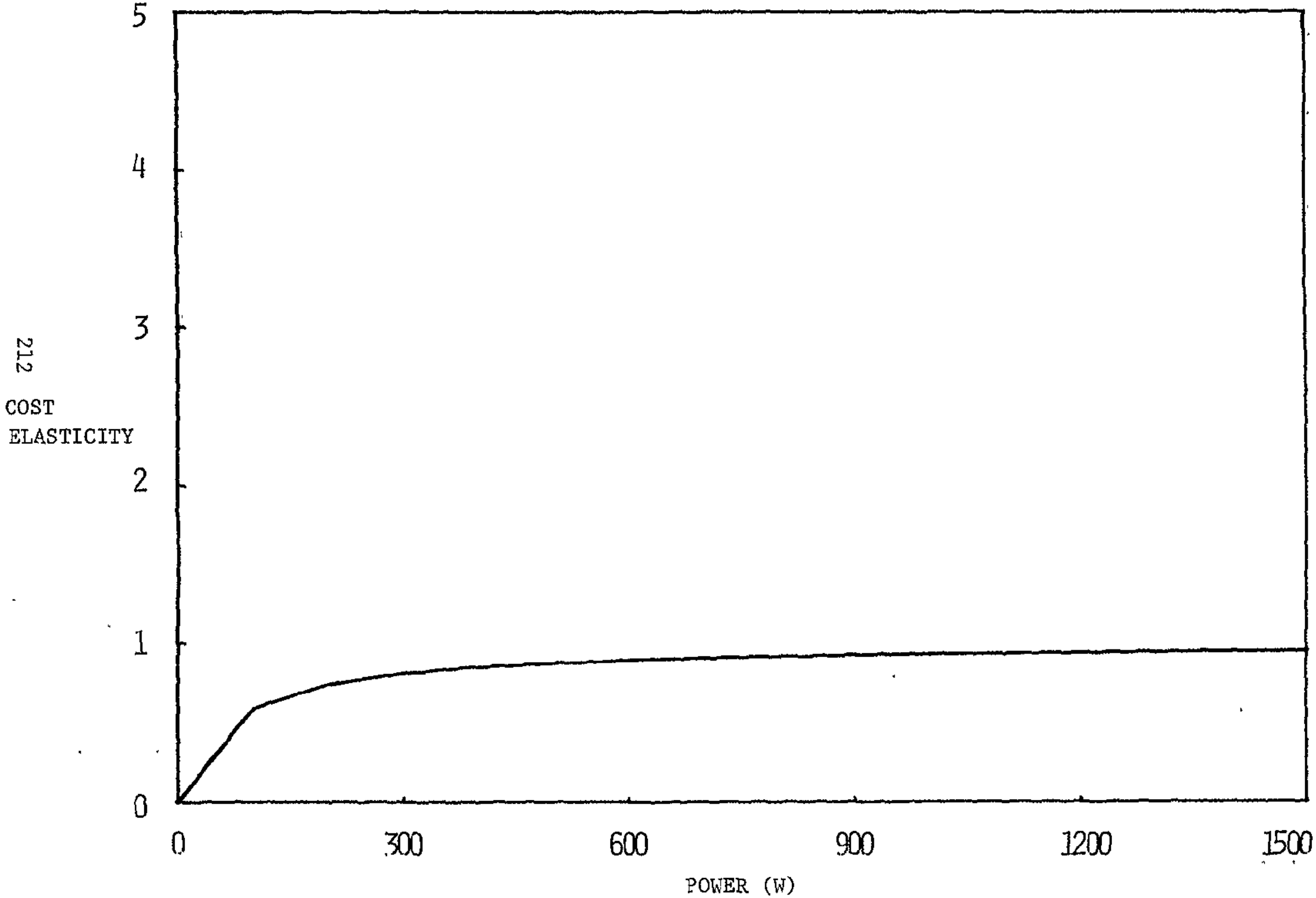

Figure D.10. Satellite Transmitter Cost Elasticity

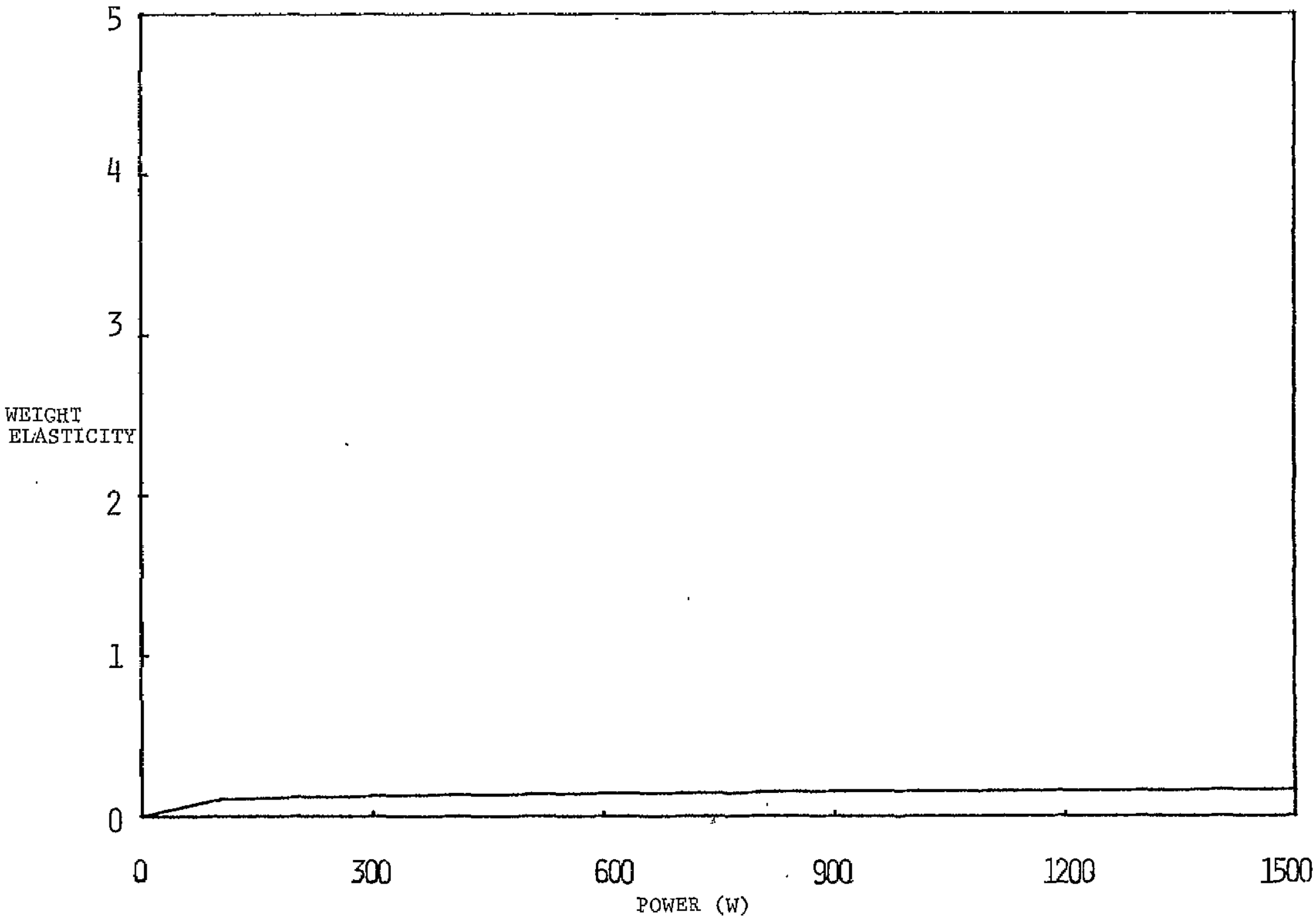

Figure D.11. Satellite Transmitter Weight Elasticity

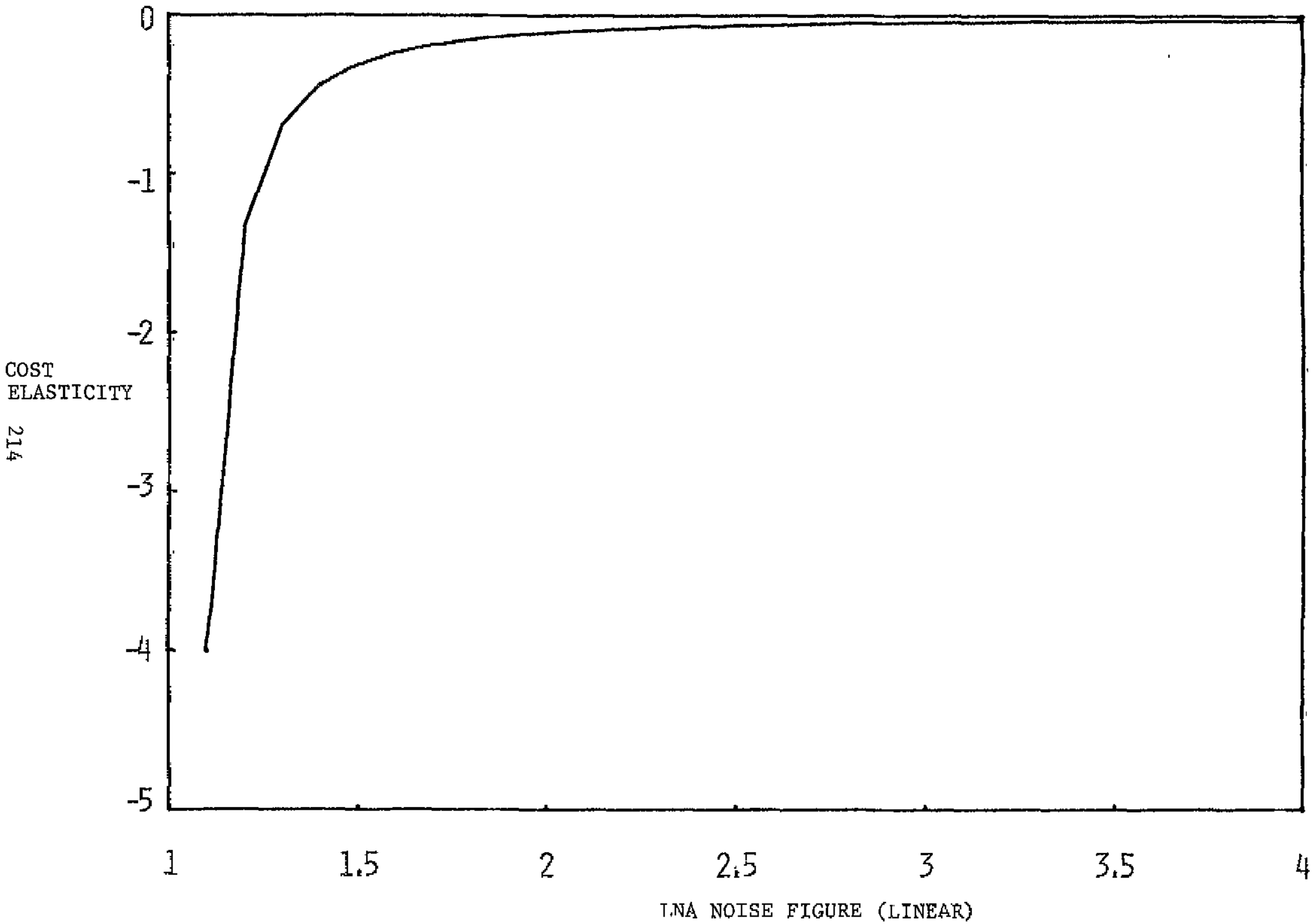

Figure D.12. Satellite Receiver Cost Elasticity

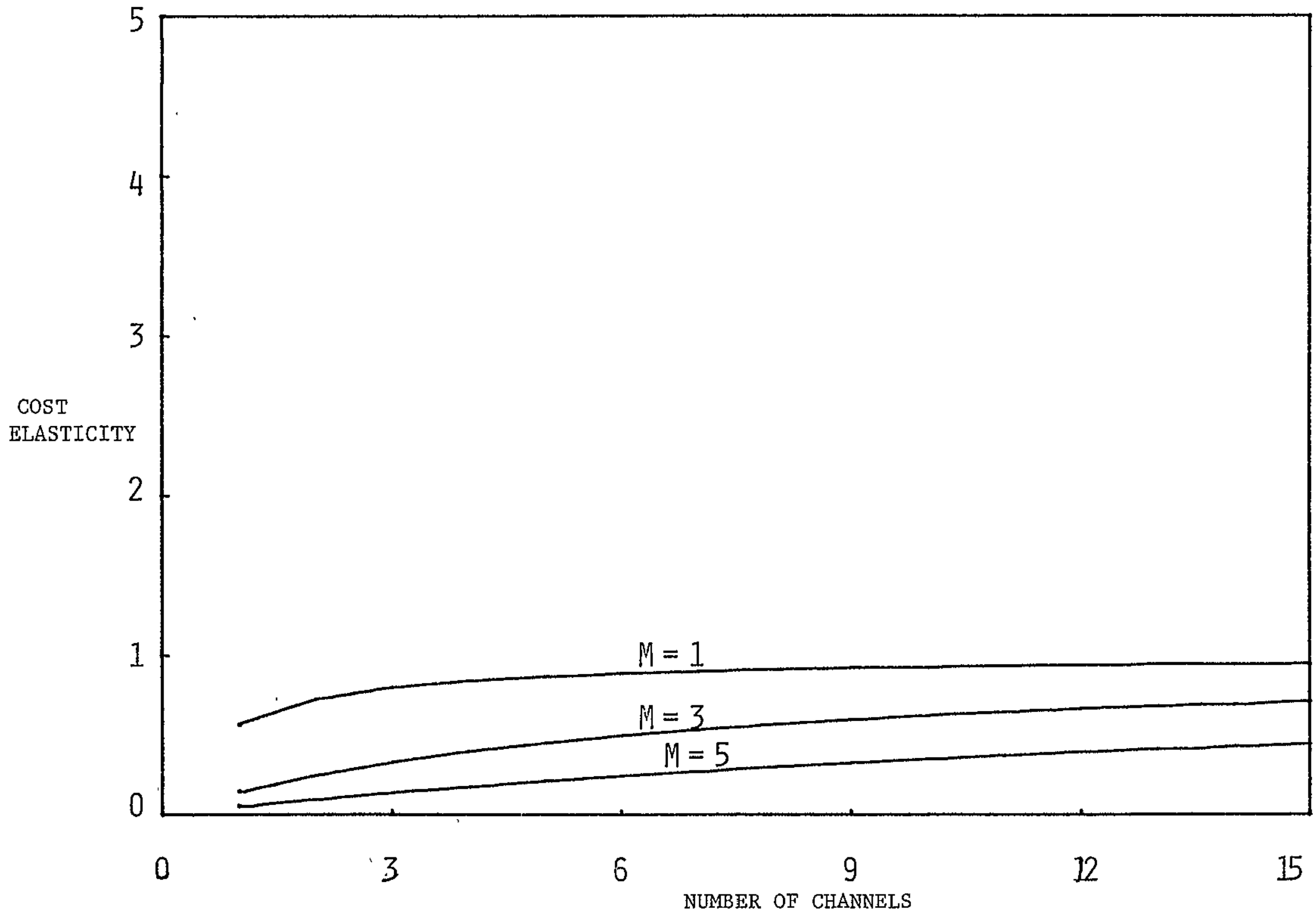

Figure D.13. FDMA Space Switching Cost Elasticity

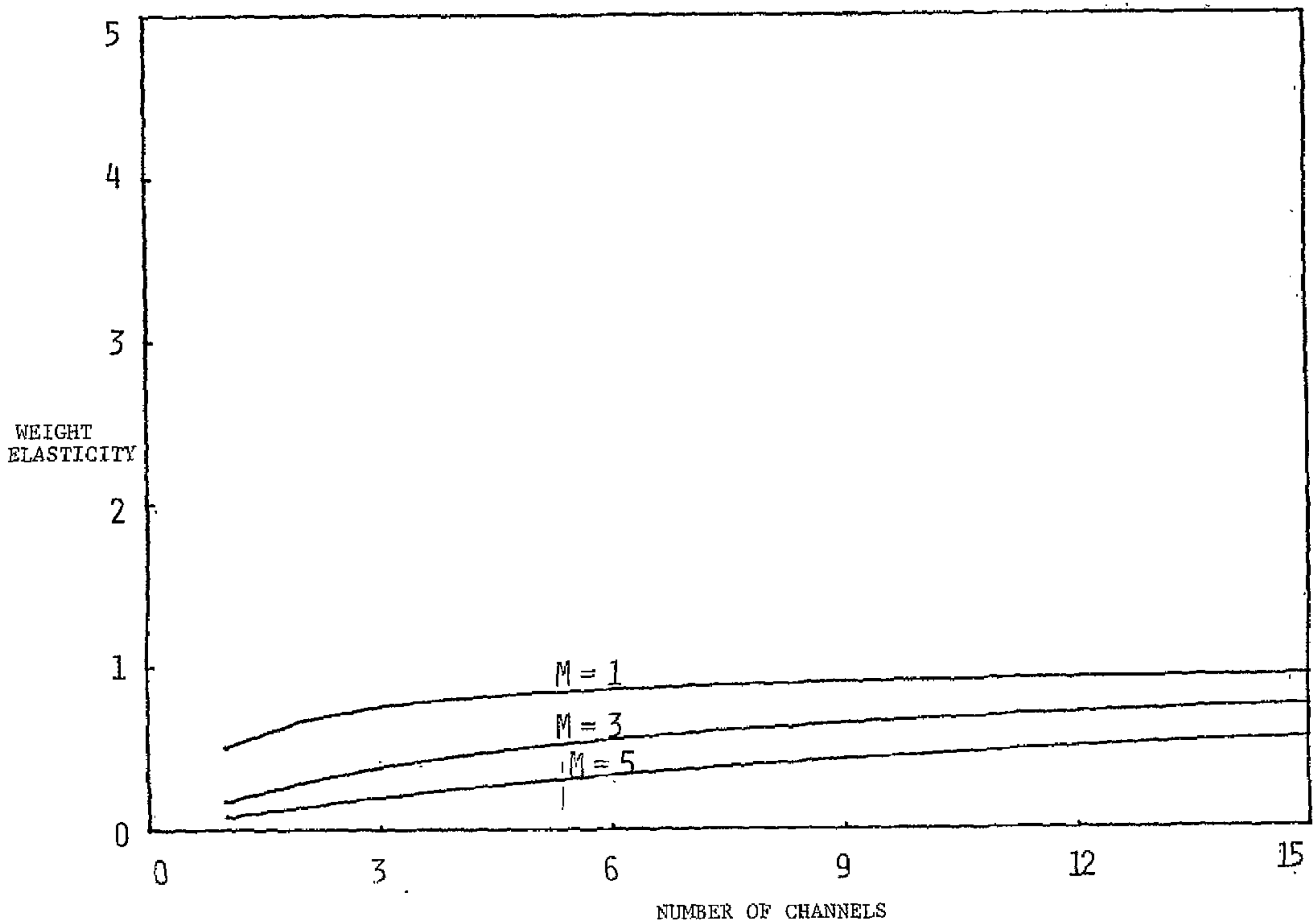

Figure D.14. FDMA Space Switching Weight Elasticity

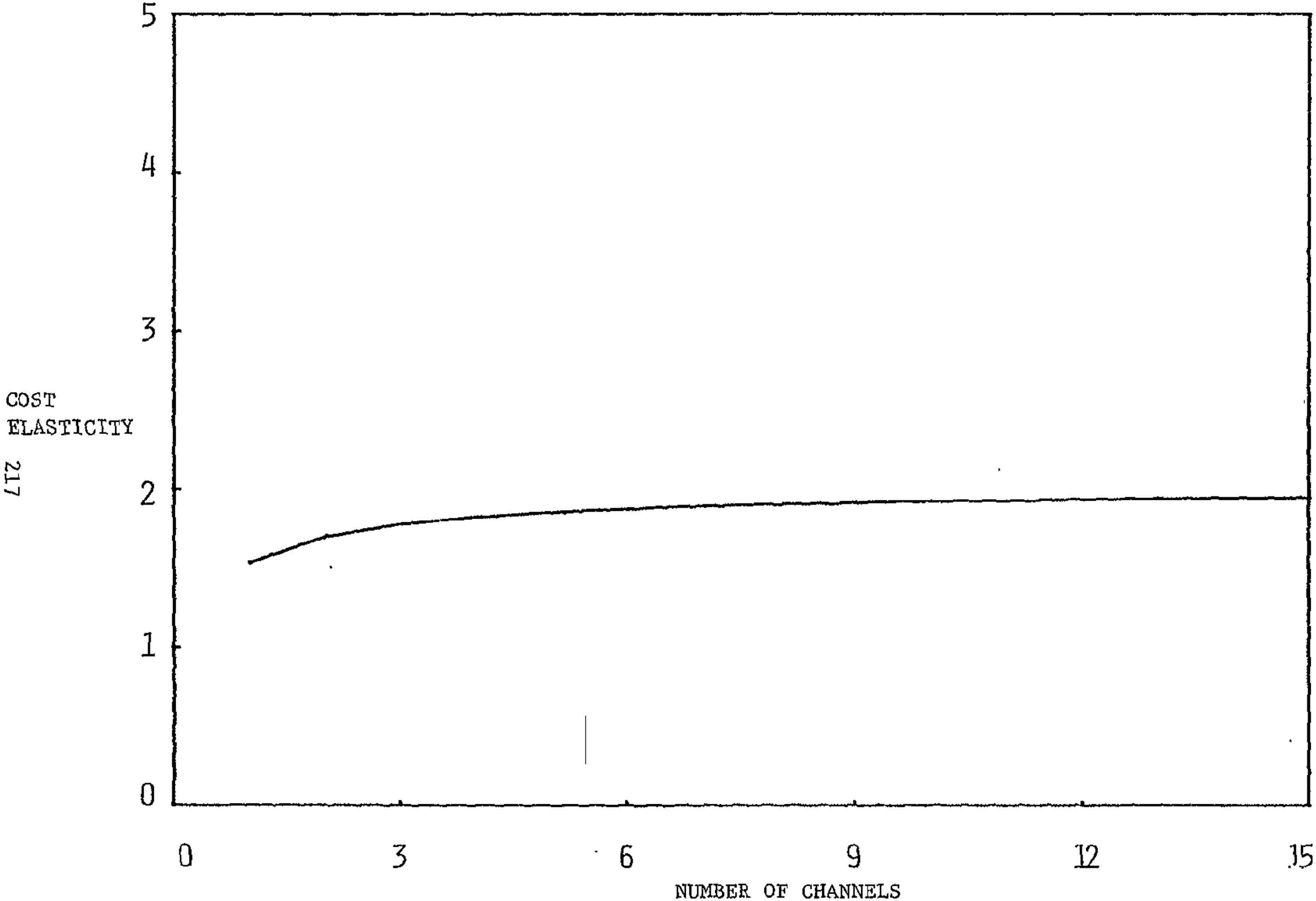

Figure D.15. TDMA Space Switching Cost Elasticity

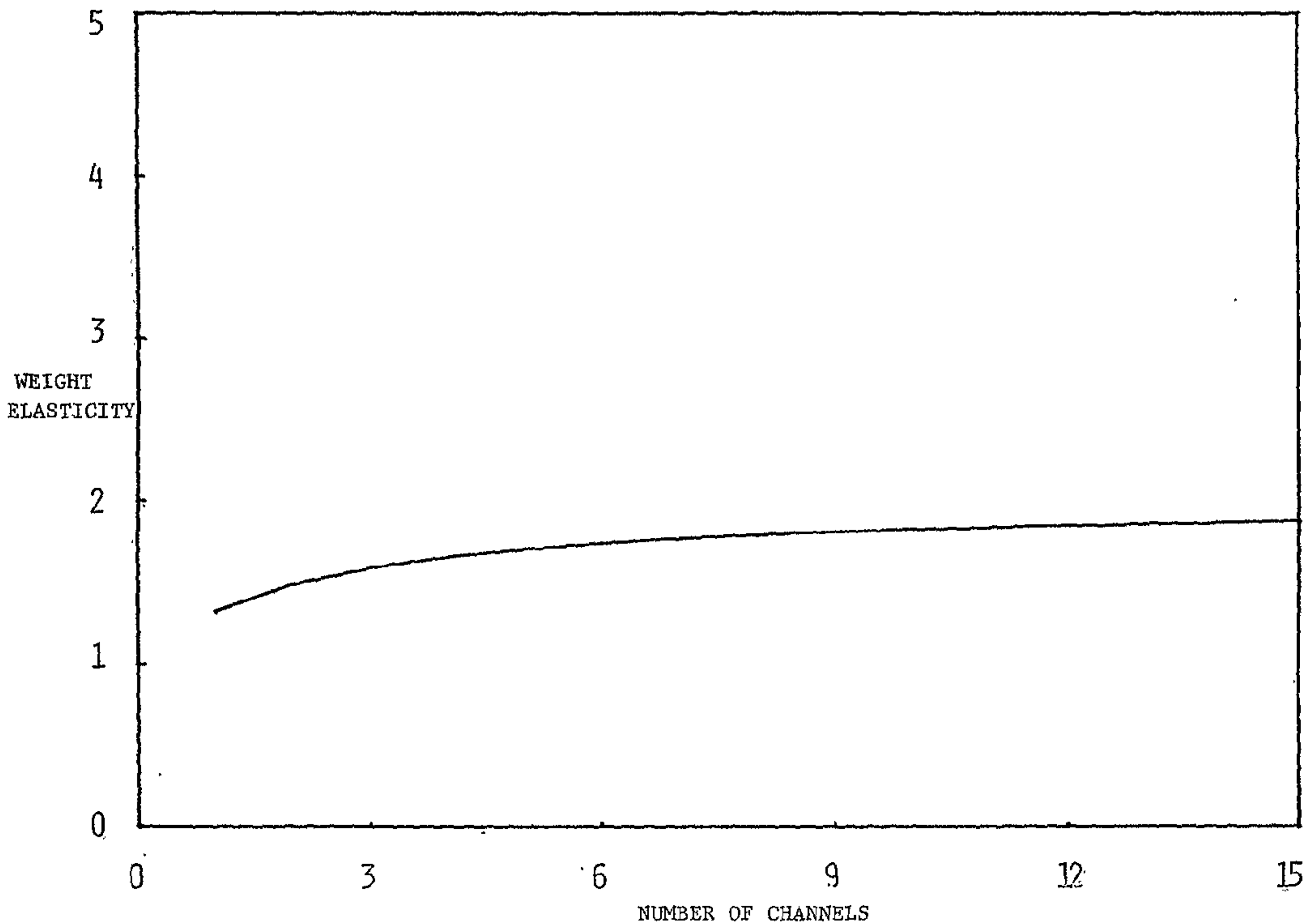

Figure D.16. TDMA Space Switching Weight Elasticity

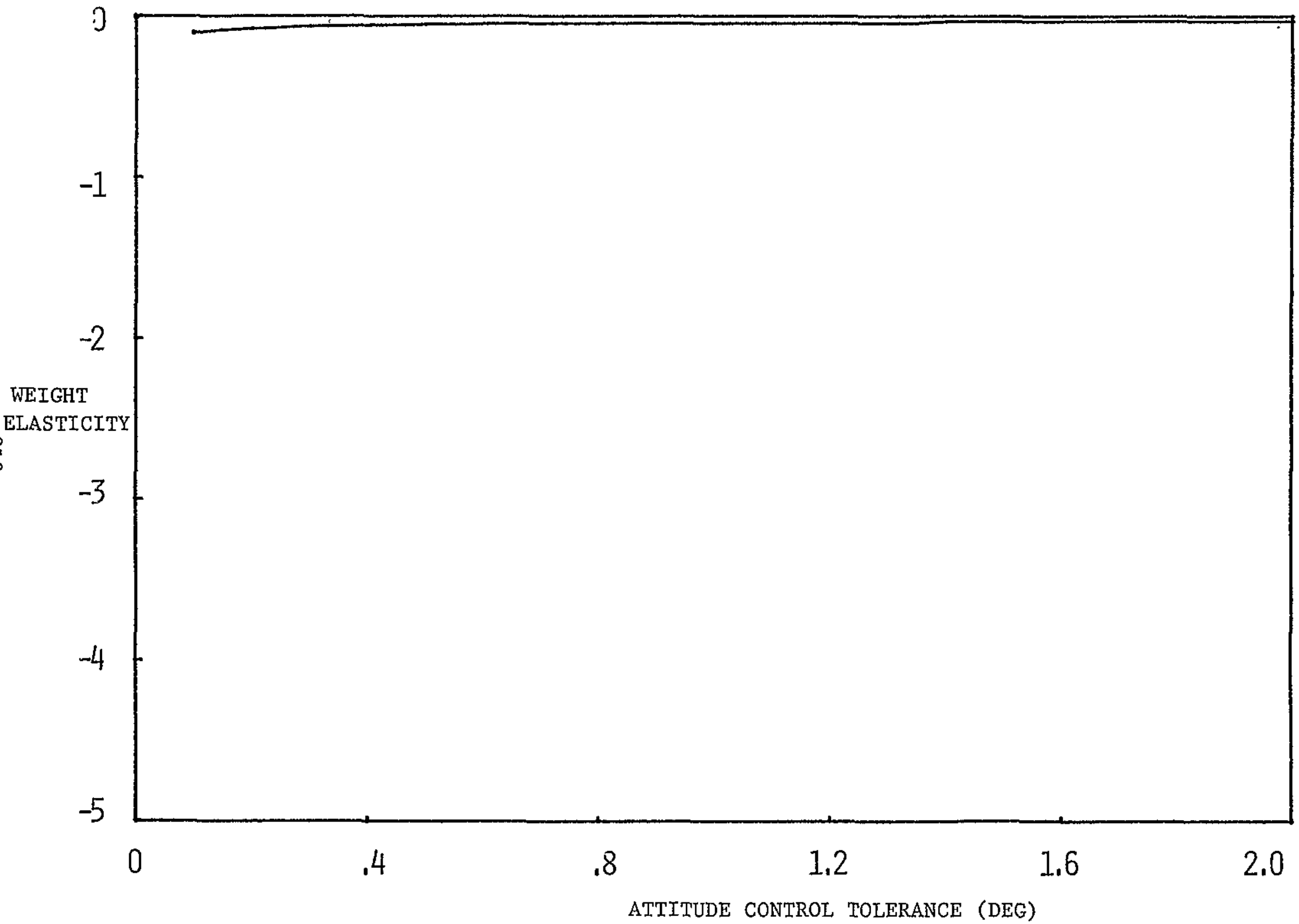

Figure D.17. Attitude Control Weight Elasticity

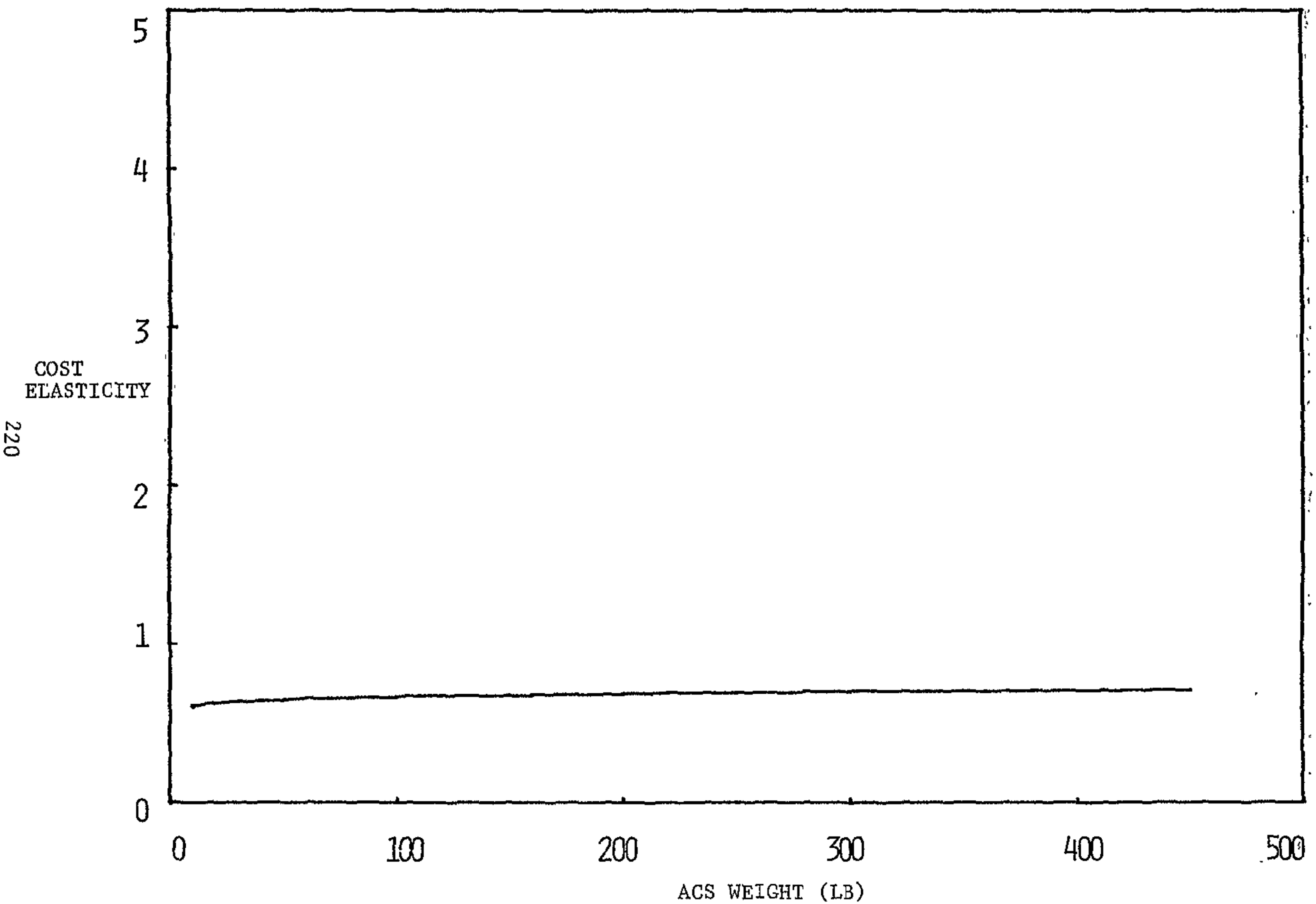

Figure D.18. Attitude Control System Cost Elasticity

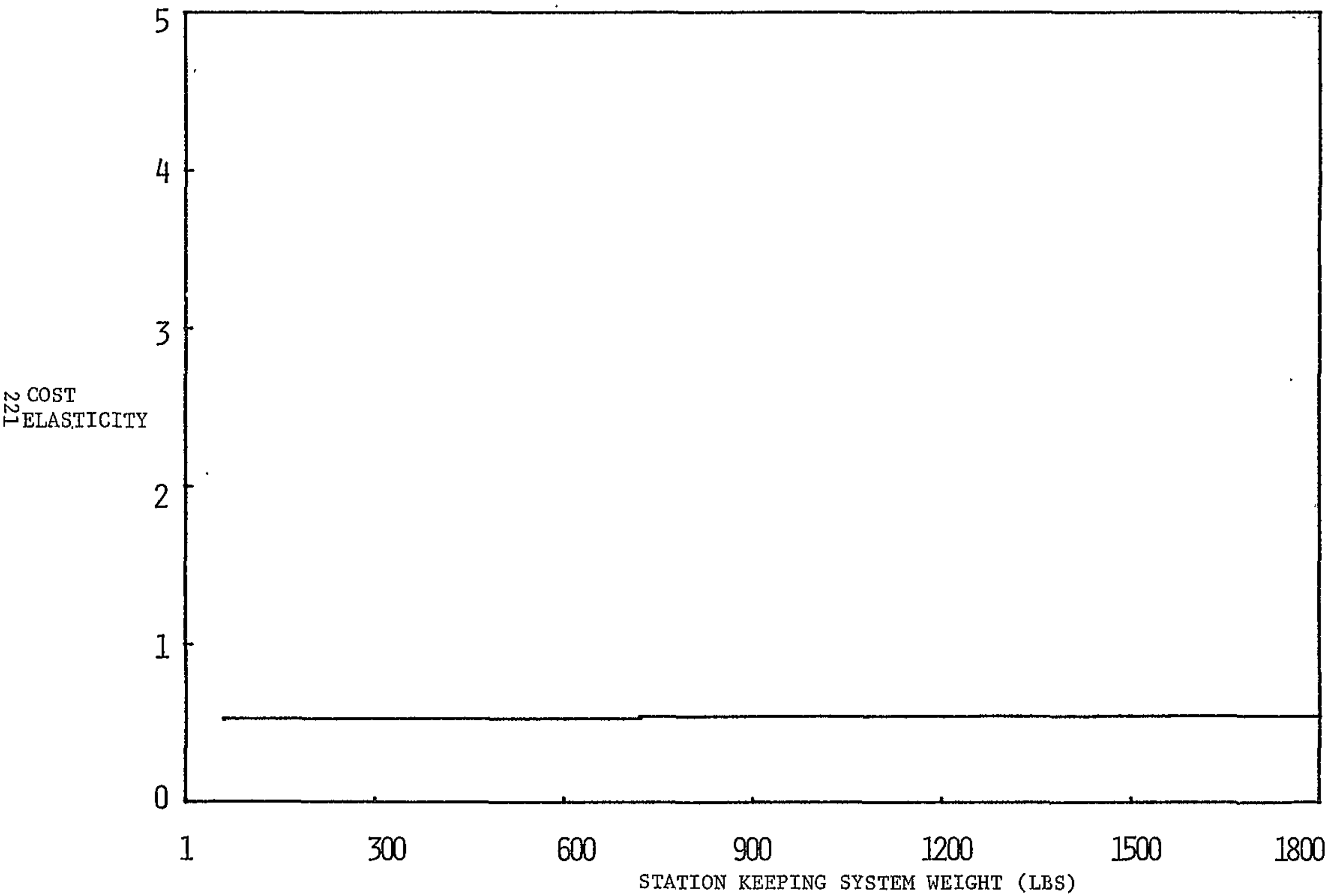

Figure D.19. Station Keeping Cost Elasticity

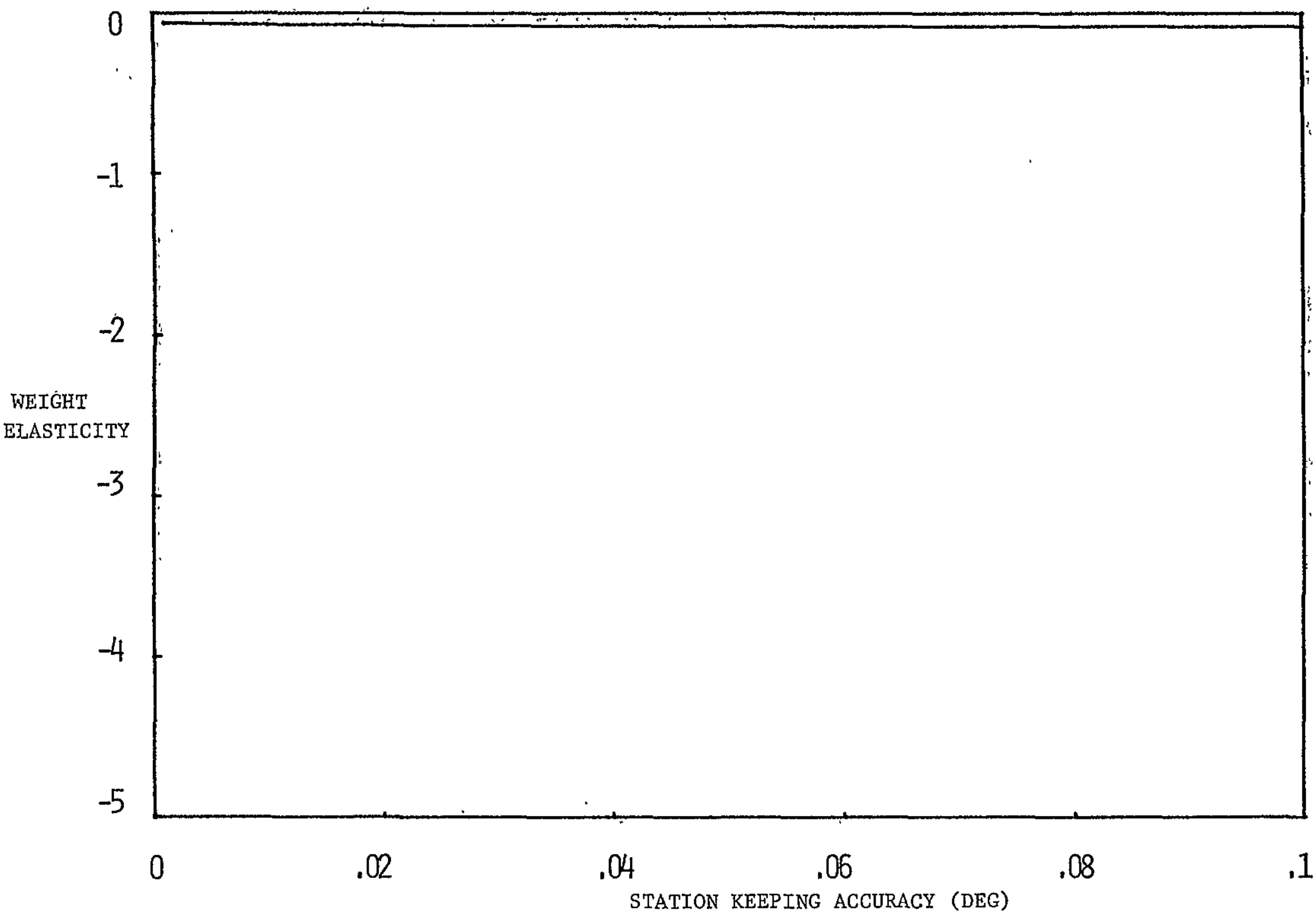

Figure D.20. Station Keeping Weight Elasticity

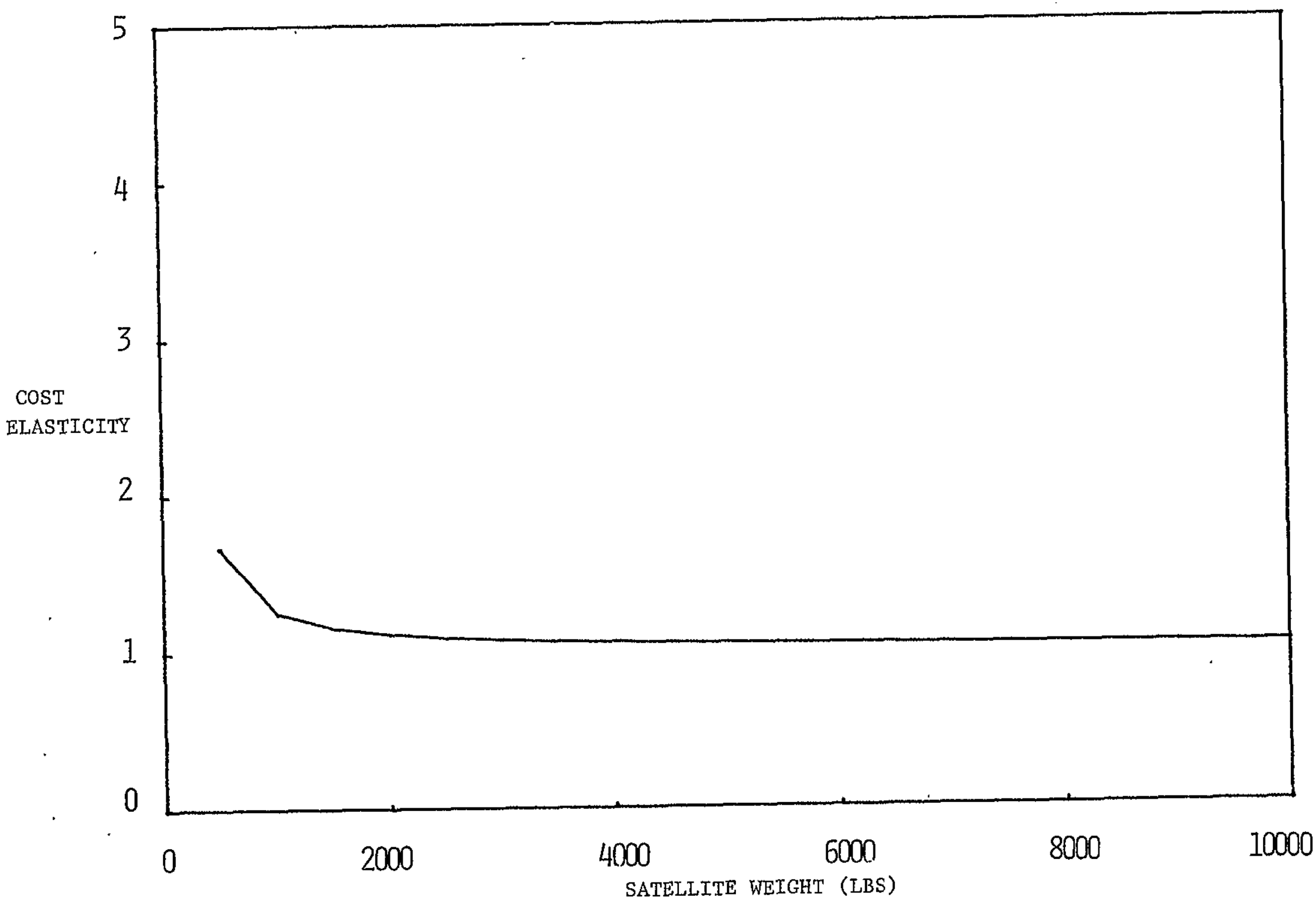

Figure D.21 Structure and Thermal Control Weight Elasticity

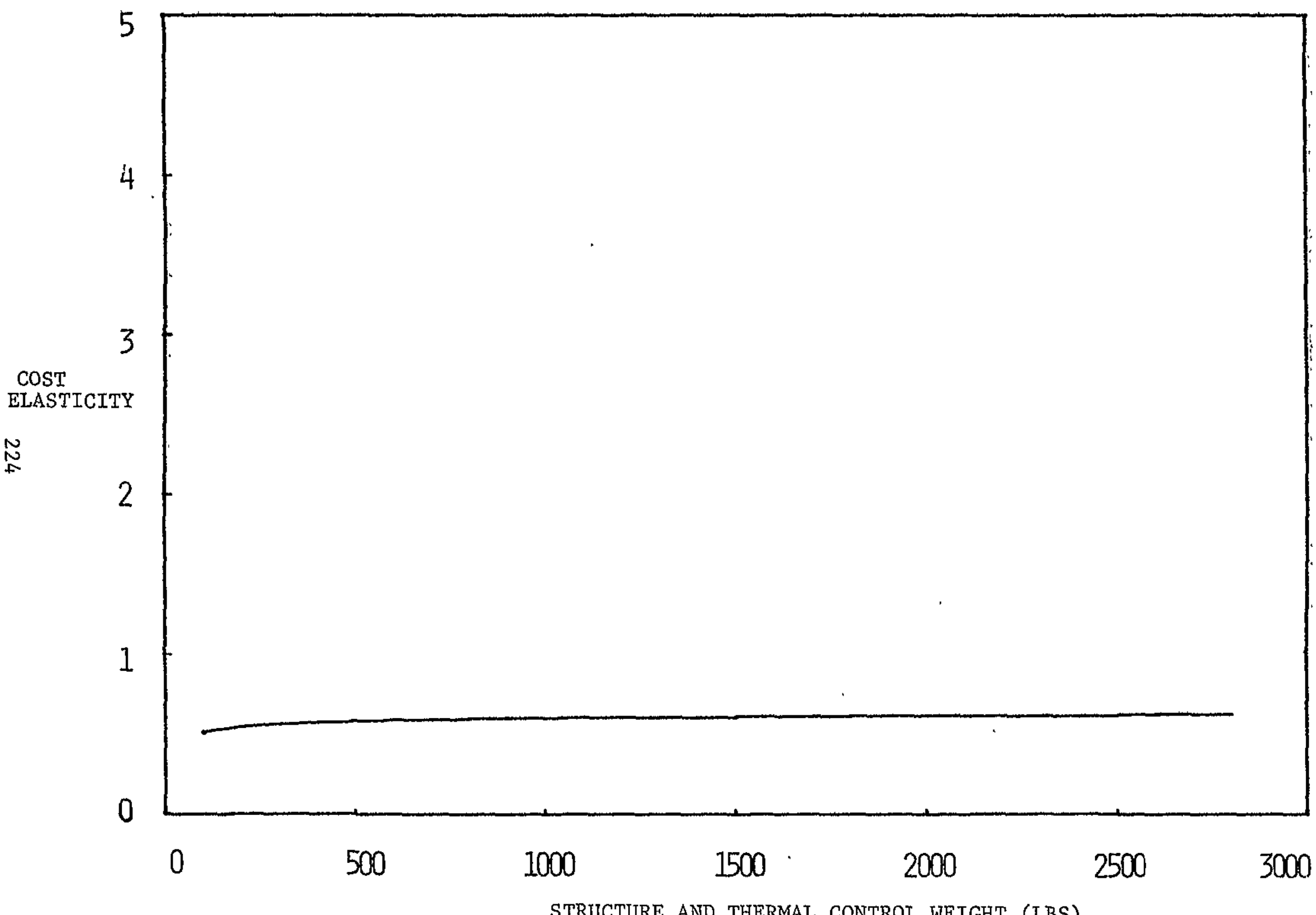

Figure D.22. Structure and Thermal Control Cost Elasticity

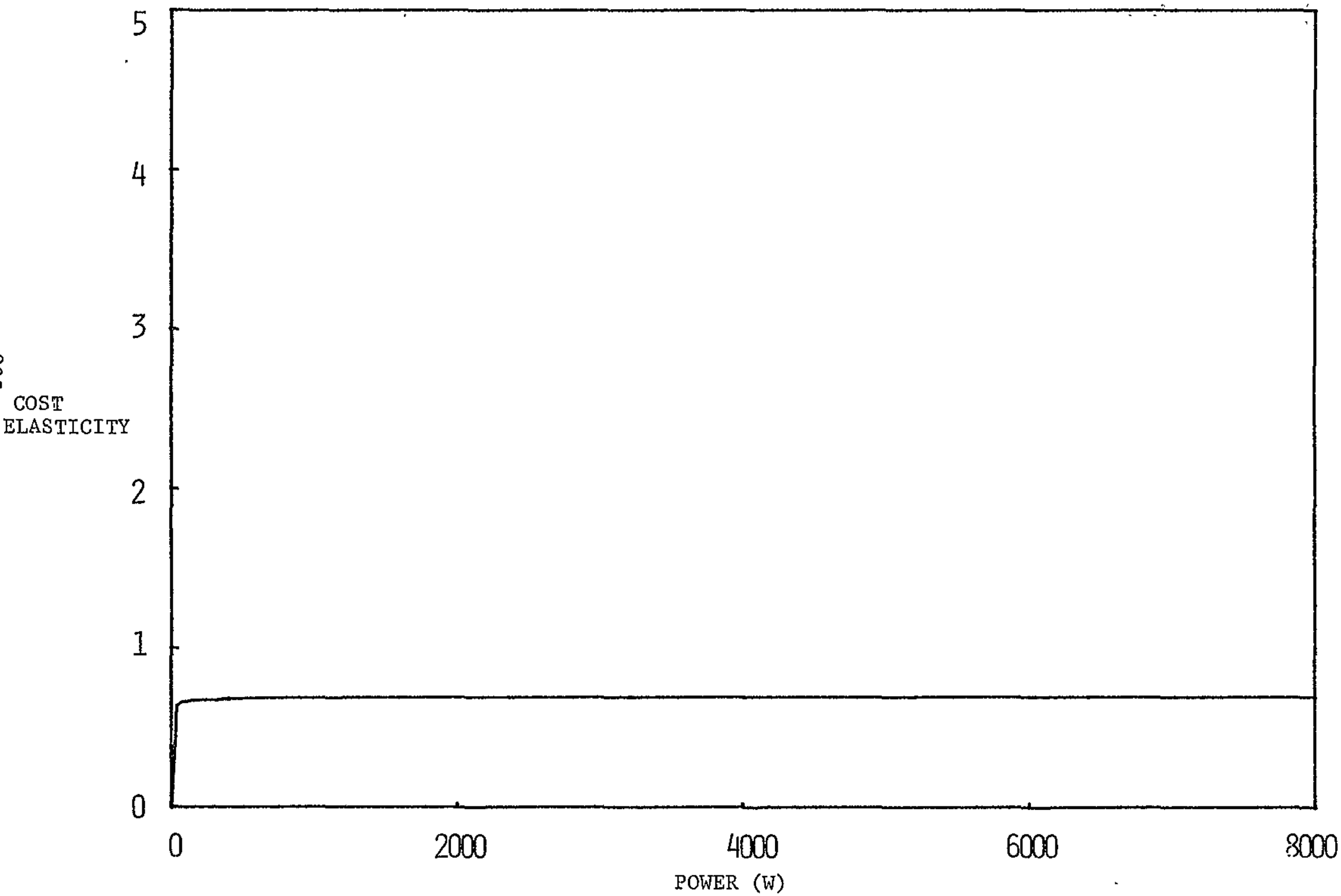

Figure D.23. Electrical Power Supply Cost Elasticity

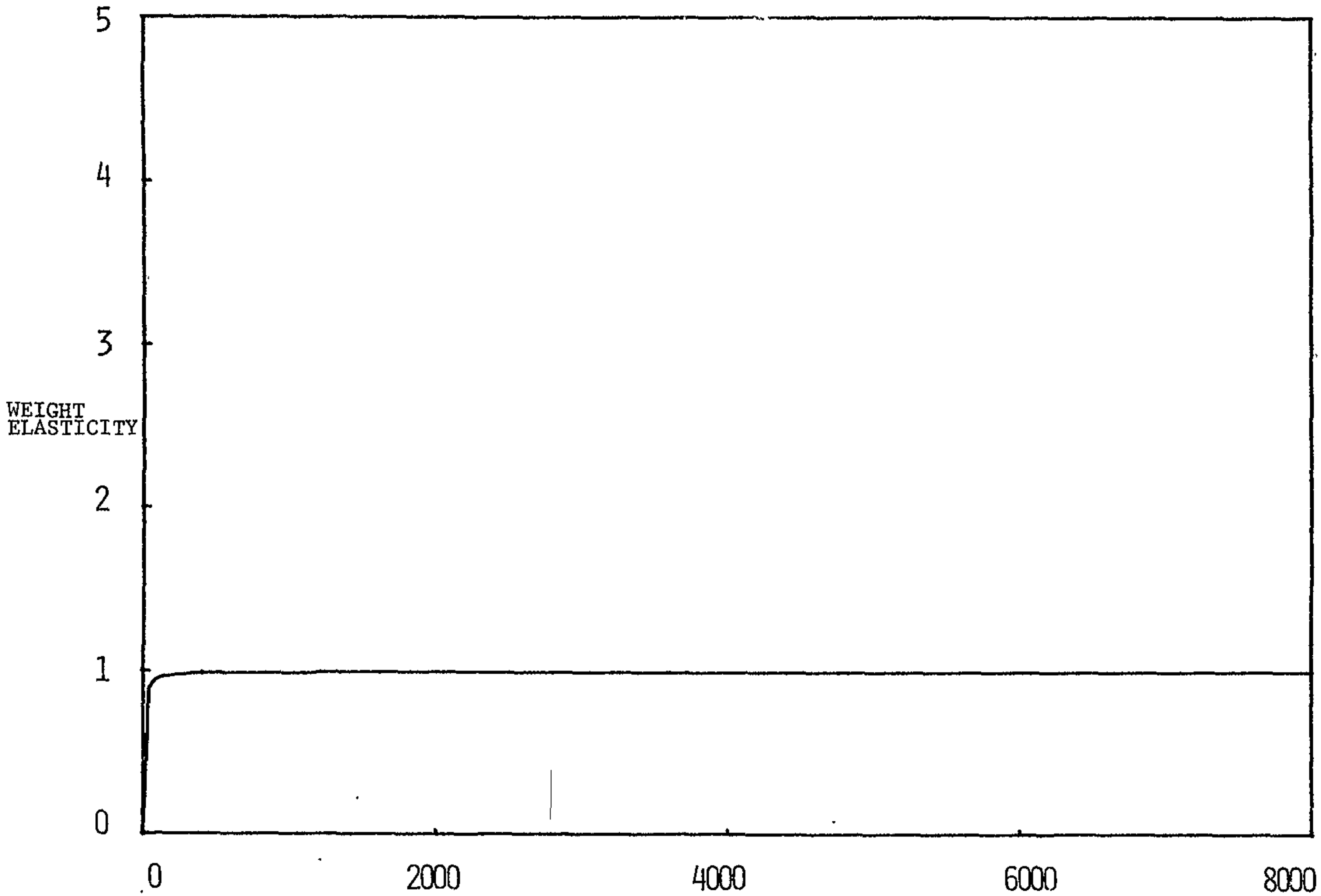

Figure D.24. Electrical Power Supply Weight Elasticity