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COST BENEFIT ANALYSIS OF SPACE COMMUNICATIONS TECHNOLOGY

by

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ENGINEERING EXPERIMENT STATION
GEORGIA INSTITUTE OF TECHNOLOGY

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NASA Lewis Research Center

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16. Abstract

This research program addresses the questions of (1) whether or not NASA should support the further development of space communications technology, and if so, (2) which technology's support should be given the highest priority. Insofar as the issues deal principally with resource allocation, an economics perspective is adopted. The resultant cost benefit methodology utilizes the Net Present Value concept in three distinct analysis stages to evaluate and rank those technologies which pass a qualification test based upon probable (private sector) market failure. User-preference and technology state-of-the-art surveys were conducted (in 1975) to form a data base for the technology evaluation. The program encompassed near-future technologies in space communications earth stations and satellites, including the non-communication subsystems of the satellite (station keeping, electrical power system, etc.). Results of the research program include confirmation of the applicability of the methodology as well as a list of space communications technologies ranked according to the estimated net present value of their support (development) by NASA. Volume I is the Executive Summary (21 pages) and Volume II is the Final Report (449 pages).

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FOREWORD

The "Cost Benefits of Space Communications Technology" project under Contract NAS 3-19700 was conducted by the Engineering Experiment Station (EES) at Georgia Tech in conjunction with the School of Industrial Management (IM). The program was administered under Georgia Tech Project A-1739 by the Systems Engineering Division of the Applied Engineering Laboratory.

This report describes the work performed during the period May 1975 through May 1976. The program was managed by the NASA/Lewis Research Center Space Flight Systems Study Office. The NASA Program Manager was Mr. Steven M. Stevenson.

The Georgia Tech Project Director was Mr. Larry D. Holland with Dr. Peter Sassone serving as Associated 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, the project team was comprised of the key personnel listed below along with their principal area of contribution.

P. G. Sassone (IM/EE)	Cost-Benefit Methodology
J. G. Gallagher (EES)	Millimeter and Optical Systems
S. L. Robinette (EES)	Applications
F. H. Vogler, Jr. (EES)	Communication Systems/Systems Analysis

SUMMARY

This research program addresses from an economic point of view the questions of (1) whether or not NASA should support the further development of space communications technology and (2) which technology support, if any, should be given the highest priority. The objective of the program is an assessment of the potential benefits from a cost-benefit viewpoint of NASA space communications technology. The developed cost-benefit methodology consists of a qualitative test for appropriateness of government support and a set of three quantitative stages of analysis based on the concept of net present value (NPV). The qualification test for government involvement is based upon probable market failure from such phenomena as externalitites, public good, excessive risk, unemployment, economies of scale, balance of payment, and national security. The overall methodology is sub-divided into three parts: screening, assessment, and ranking. Screening is composed of the qualitative test for government involvement, NPV estimation, and NPV sensitivity analysis. The assessment methodology approximates the probability density function of the net present value whose mean is estimated in the screening methodology. The ranking methodology is based upon several statistics which are measurable from probability density functions.

User-preference and technology state-of-the-art surveys were conducted to form a data base for the technology evaluation. The research program encompasses near-future technologies in space communications, earth stations, and satellites, including the non-communication subsystems of the satellite such as the station keeping, electric power, attitude control, etc.

Results of the research program include the conclusion that the screening, assessment, and ranking methodology provide a consistent, tractable, defensable, and quantitative approach to evaluating potential NASA R & D programs. The five technologies ranking highest in terms of their mean net present value are, in decreasing net present value, as follows:

(1) Millimeter Communications Systems
(2) Solid state power amplifier
(3) Low cost earth station
(4) Multi-beam antenna
(5) Ion engine.

Economic evaluation of the technologies from a cost-benefit viewpoint has shown that certain technologies should be implemented with government support to accrue maximum benefits to the nation as a whole. Based on this analysis, NASA should play an important role in advancing future communications technology.

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ABBREVIATIONS

ATFE	Advanced thermal flight control experiment
ATS	Applications technology satellite
BTL	Bell Telephone Labs
CATV	Community antenna television
CBA	Cost-benefit analysis
CCD	Charged coupled device
CCIR	Consultative Committee on International Radio
CDF	Cumulative distribution function
CDMA	Code division multiple access
CTS	Communications technology satellite
DSCS	Defense satellite communications system
EAB	Equivalent annual benefit
ECOM	U. S. Army Electronics Command
EOS	Earth observations satellite
FCC	Federal Communications Commission
FDMA	Frequency division multiple access
FET	Field effect transistor
GaAsFET	Gallium arsenide field effect transistor
GSFC	Goddard Space Flight Center
HPA	High power amplifier
JPL	Jet Propulsion Laboratory
LDRL	Laser data relay link
LHS	Left hand side
MIC	Millimeter wave integrated circuit
MICOM	U.S. Army Missile Command
MIT	Massachusetts Institute of Technology
MODEM	High speed digital modulation/demodulation
NPV	Net present value
PDF	Probability density function
PCM	Pulse code modulation
PN	Pseudo-noise

ABBREVIATIONS (Cont'd)

PV	Present value
REB	Relativistic electron beam
SAW	Surface acoustic wave
TDA	Tunnel diode amplifiers
TDMA	Time division multiple access
TCS	Technology classification structure
TEA	Transferred-electron amplifier
TED	Transferred-electron device
TEO	Transferred-electron oscillator
TIM	Trapped inverted microstrip
TTC	Telemetry,tracking and command
TWT	Travelling wave tube

SECTION 1
INTRODUCTION

The Space Communications Technology developed early in the NASA space program has formed the basis for the current space communications industry and for the associated United States leadership in the field. U. S. government budget cuts forced NASA to reduce the space program, and NASA choose to terminate its space communications technology programs to implement the budget reduction. The argument was made that space communications technology had matured to the point where U.S. industry would implement the technology R & D programs necessary for continued growth of the industry. For various reasons, this has not occurred: when left on its own, U. S. industry has not funded the necessary space communications R & D programs. Foreign nations, exploiting U.S.-developed technology and receiving strong financial backings by their governments, have become increasingly competitive in the development and marketing of space communications technology. If the United States is to retain its lead in space communications, meet future demands efficiently, and possibly provide new socially beneficial services, it will be necessary to increase the rate of implementation of technological innovations into operational telecommunication services. Prior to the expenditure of additional resources for new technology development and demonstration, it is necessary to have a measure of the potential benefits, risks, and costs involved in the development and application of such technological innovations. This report presents a methodology for such measurement with application to space communications technology.

Two major considerations are involved in the issue of U. S. government support of space communications technology development. First, is it indeed desirable that the U. S. government financially support the development and demonstration of space communications technology? Second, (assuming an affirmative answer to the first), which technologies should receive the highest priority in such a development program?

The objectives of this program are to provide NASA decision makers with a methodology to be used as an aid in determining the appropriateness of space technology support programs and to perform economic evaluations of alternative R & D programs based upon this methodology. These objectives have been met by (1) developing a cost-benefit assessment procedure, (2) conducting user need and technology state-of-the-art surveys, and (3) applying the methodology to the results of the surveys to produce a ranking of potential space communications technology development programs.

1.1 Cost Benefit Methodology

The R & D evaluation methodology was developed to meet five criteria. First, the overall methodology must be internally consistent. It was recognized early that the methodology would have to be developed as a series of filters. Since a large number of advanced technologies would have to come under scrutiny, it was recognized that time and resources would not permit a detailed investigation of each one. Hence, a screening of technologies was demanded, where the screening would filter the entire set of technologies and reject the least promising. Only those technologies successfully passing through the screening would be subjected to a formal assessment. Finally, only those technology development programs which proved worthy under the formal assessment would go on to be ranked for implementation priority. Thus, the evaluation methodology consists of three steps: screening, assessment, and ranking. It is clear that these three methodologies which comprise the overall evaluation methodology must be consistent with each other. That is, each should be based on the same conception of what constitues a "good" R & D program. It would be self-defeating if, for example, projects which failed screening would tend to do very well in a formal assessment. Internal consistency among the three methodologies is achieved by grounding each in the same cost-benefit criterion: net present value. The differences among the steps are accounted for by the level of detail, not by the conceptual approach.

The second criterion is relevance. By this is meant that the methodology must properly address the correct research issue, and must lead to quantitative results which logically establish the true value of a specified potential NASA R & D program. Simply put, the methodology must be relevant to the issues. The importance of the formal consideration of this criterion becomes evident when one faces the distinction between the social value of an R & D project and the social value of NASA's performance of that R & D project. Ordinary cost-benefit analysis would address the former. However, the latter is the real issue in this research. The methodology must be so framed as to address the latter issue.

The third criterion is tractability. The methodology must strike the proper balance between realism (thus complexity) and abstraction (simplification). The methodology must account for the salient aspects of the problem, yet remain simple enough to be operational.

The fourth criterion is replicability. The methodology must be consistent with the scientific method: i. e., it must permit the same results to be achieved by different investigators. Thus, as much as possible, the methodology must be based on objective, rather than subjective, inputs.

The final criterion is defensibility. The methodology must be theoretically and practically sound. It must prove reasonable to even avowed critics.

These criteria, coupled with the necessity to treat numerous technologies and the complications of government undertaking activities which might be considered to be in the private domain, gave rise to a three-stage evaluation procedure. The three stages, as mentioned, are screening, assessment, and ranking.

1.1.1 Methodology Outline

The screening methodology has three components: qualification, net present value (NPV) estimation, and sensitivity analysis. Qualification attempts to determine whether and to what extent the technology in question qualifies as a legitimate government research program. Legitimacy is established by reference to the set of characteristics which economists have determined apply to projects more efficiently undertaken in the public, rather than the private, sector. Priority is always accorded the private sector; however, certain structural conditions of the economy and/or characteristics of the project itself may intervene to foil the blind beneficence of the competitive economy. In such cases, it may be argued, government is properly involved in the provision of the good.

The NPV estimation is based upon partitioning of the flow of benefits and costs of the project into time stages which roughly correspond to periods in the life cycle of the technology. A key parameter in the estimation is the "delay factor" which indicates how long private development of the technology would lag its NASA development. This factor results in assigning a NPV of zero to a project which simply displaces an equivalent private program, and assigns the full project NPV only when the private sector would never undertake the project. Sensitivity analysis is performed on the parameters of the NPV estimating equation. One at a time, each parameter is valued over $\pm 50\%$ while all other parameters remain fixed at their most likely values. The sensitivity analysis highlights the critical parameters requiring most attention in any subsequent detailed assessment.

The assessment methodology is a more sophisticated use of the NPV estimation equation which incorporates not only the polled expert's estimates of the input variables (development times, costs, etc.) but also their confidence in the estimates (variance). Gaussian probability density functions are assumed for the input parameters, and linearized version of the NPV function is used to approximate the resultant NPV probability density function. This resultant NPV PDF allows estimation of the likelihood that the value (NPV) of NASA supporting the technology development project will exceed any particular value (e.g., zero). That is, one has available not only the expected value (mean) but also a measure of the spread (variance).

The ranking methodology acts on those potential R & D projects which survive assessment. Ranking is a two-step process. First, a full Monte Carlo simulation of the NPV of the project is performed which results in an empirical probability density function and its associated cumulative density function. Since each PDF has a number of statistics associated with it, ranking cannot be reasonably based on a single statistic (such as mean value). Rather, different positions toward risk are parametrically adopted, along with relevant statistics, and ranking are derived for each risk attitude.

1.2 User Need and Technology State of the Arts Surveys

User need and technology surveys were conducted to establish the group of technologies for evaluation by the cost-benefit methodology developed in the program. Each survey included a review of the pertinent literature, telephone interviews with industry and government agencies, and visits to some of the industries and government groups. The objectives of the user survey were to ascertain present and future needs, technology choices, demand projections, and opinions on the degree of demonstration required for user acceptance of new technology items. For purposes of this program, users were subdivided as to user of technology directly, and user of resultant information. User classification included educational television, cable television, business data transactions, common carrier, message service, social services, transportation, and electronic mail service. Results of the survey included itemization of the present user needs, future user needs, desired improvement in the technology, and expressed need for future technology demonstration. Also included in the results are estimations of the numbers of earth stations needed in each category and the channel capacity requirements of the future for international and domestic communications. In general, the survey results reflected some "new services" which will be able to be supplied at reasonable costs by space communications technology but which are not economically feasible with terrestrial communications technology. No truly new services in the sense of not being technically possible with terrestrial communications were encountered.

The technology state-of-the-art survey successfully utilized existing literature to a greater extent than did the user need survey; however, truly current state of the art data was obtained only by direct contact with and visit to the technology industry. Since the technology survey included not only the direct space communications technology but also that of ground station and support system for the overall satellite itself, efficient use of the large amount of technology survey material required development of the technology classification structure (TCS) for efficient use of the resulting survey material. The TCS has three main divisions for ground stations, launch and injection technologies, and the satellite. The satellite technologies are further subdivided as to structure, support (électric and thermal), and communications equipment. Ground station technology is considered including user connection, modulation and multiple access techniques, transmitter, receiver, antenna, and propagation studies. Satellite technologies include satellite structure materials and configuration, station keeping, attitude control, electrical power, thermal control, spacecraft antenna, and transponder (including microwave millimeter, and laser).

1.3 Application of the Methodology

As a result of the user need and technology state of the art surveys, a set of nine space communications technologies capable of meeting anticipated requirements has been selected for evaluation by the cost-benefit methodology:

low cost earth station direct demodulation receiver
ion engines
RF attitude sensors
advanced solar arrays
adaptive heat pipes
satellite multi-beam antennas
satellite solid state power amplifiers
millimeter communications systems
laser communication systems.

Each of these technologies is analyzed by the screening, assessment, and ranking methodologies in this report.

Application of the cost-benefit methodology to a potential technology support program requires specification of the sources and magnitudes of the benefit to be accrued. In turn, the benefits can be quantified only after a base line is established for comparison. In this program, the base line scenario is defined in term of the projected demand for space communications (in terms of thousands of half circuits), projected capacities per satellite, projected satellite life time, projected satellite costs, as well as projections of the percent of the market sold by U. S. concerns and the percent utilization by the U. S.

Estimates of the lower bound, most likely value, and upper bound for each of the input parameters in the NPV model have been estimated for each of the nine technologies by polling "experts" in industry or government groups. These values have been used, along with the baseline scenario, in the application of screening, assessment, and ranking methodologies to the technologies.

Section 2 through 5 present the cost-benefit methodology for the screening, assessment, and ranking of space communications technologies. Sections 6 through 9 then present the result of the user-need and technology state of the art surveys which form a data base for application of the cost-benefit methodology in sections 10 through 14. Conclusions of the project are presented in Section 15.

PART 1

METHODOLOGY

SECTION 2

THE GOVERNMENT'S ROLE IN R&D - QUALIFYING TECHNOLOGIES FOR ADVANCEMENT BY NASA

It is not reasonable, in a market oriented economy, to assume that government projects - the expenditure of public funds to achieve a goal - should be adopted without very careful justification. As suggested above, our economic system is structured to give priority to the private sector. Only when the private sector fails to pursue the maximum social welfare (driven by Adam Smith's "invisible hand") is there a strong argument for government activity. Indeed, many economists would argue that "market failure" is one of the few firm justifications for public sector activity. In the following pages, the causes of market failure are discussed. A technology should be considered appropriate (i.e., qualified) for government (NASA) development only if the market would fail to efficiently pursue its development in a timely fashion.

An industry decision to adopt a new technology depends on whether the private benefits outweigh the private costs. A public agency, such as NASA, must be concerned with whether social benefits outweigh social costs. It may happen that, for some technology, while private costs exceed private benefits, the social benefits exceed the social costs. This is a situation in which the technology possibly should be implemented, or in some way subsidized, by government.

Before proceeding, an explanation of the relevent terms associated with a cost benefit analysis is in order. The following terms will be discussed: private and social cost, externality, public good, institutionalized rules, risk, international value of dollar, unemployment, economies of scale, non-competitive markets and national security.

A private cost is what the individual (person, household or firm) must give up in order to receive some good or service. A social cost is what society as a whole must give up in order that the good or service be received by some individual. For most goods and services, the social and private costs are identical. For example, the individual who purchases a suit of clothes for $100 gives up $100 worth of other goods and services he could have purchased. Likewise, society as a whole (under fairly general assumptions) gave up $100 worth of other goods and services in order that the $100 suit could be made. Sometimes, however, social and private costs diverge. The individual who pays $500 for one year's worth of courses at a state university has given up $500 worth of the goods and services he might have purchased. However, the year's worth of courses has cost society much more (on average) than $500, since the state university is subsidized. The social cost of a state university education exceeds the private costs. Similar statements can be made about private and social benefits.

The measure, or yardstick, for costs is what must be given up, and the measure of benefits is willingness to pay. Thus, whereas some individual might be willing to pay $500 for a year of state university education, society as a whole might be willing to pay, for example, $1000 for a year's education for that person. The $1,000 would include the $500 the individual would be willing to pay plus very small amounts other persons would be willing to pay toward that person's education because they feel, for any number of reasons, personally better off if that person becomes educated. They might feel, for example, that that person's education may make him less likely to become a criminal, or to wind up on welfare rolls, or simply that his education will make him a more pleasant potential neighbor. Thus the social benefits of education, as measured by society's willingness to pay, exceed the private benefits.

When social and private costs, or social and private benefits, diverge an externality exists. Externalities may arise from numerous, and largely differentiated, circumstances. When an externality exists, and is judged significant, there is good reason to suspect that the private sector of the economy is not providing the socially optimal amounts of some goods or services.* In this case, it is considered to be in the best interest of society that an appropriate correction of private activity be effected by the public sector. Typically, the correction can take two forms: direct public intervention or indirect public intervention. The former might be characterized by actual public provision of the good or service, or by regulation of private producers, while the latter by various financial inducements by government to the private sector to encourage a modification of its production plans. With regard to education, the public sector's intervention has been of the direct variety: public education is "produced" directly by local and state governments. A good example of the indirect approach by government is the case of individual home ownership. Society has decided that the social benefits of individual home ownership exceed the private

*By socially optimal is meant that collection of goods and services which maximizes the welfare of society, subject to the overall availability of resources.

benefits (for reasons too lengthy to get into here). To appropriately modify private sector behavior, the federal government allows interest payments to be deducted from gross income for tax purposes. This reduces the real cost (to the individual) of borrowing and thus reduces the real cost of home ownership. Some individuals who would not have otherwise purchased a home are now induced to do so.

For the mathematically inclined, and for those unconvinced by the foregoing argument (the argument being that when social or private costs or benefits diverge, public intervention can improve overall welfare), a more rigorous argument is developed in Appendix I.

The example in the Appendix illustrates the general nature of an externality: one party is affected by the decisions of another party, yet the latter party does not take the former into account in making his decision. If the latter is somehow induced to take proper account of the former, the externality is said to be internalized. Internalizing an externality leads to an overall increase in social well-being. It is generally recognized (at least among economists) that it is government's responsibility to see that significant externalities become internalized. This is the economic basis for the instances of desirable government intervention in private decision-making.

As mentioned previously, externalities may arise in a number of ways. Following is a listing and discussion of some of the major occasions for externalities.

A <u>Public Good</u> is any good (or service) with <u>both</u> these characteristics:

(a) Non-competativeness in Consumption. This means that some person's consumption of the good does not decrease its availability to anyone else. In other words, it is physically possible for more than one person to simultaneously get the full benefits of the good.

(b) Non-Excludability. This term means that once the good is provided, it is difficult or impossible to exclude any from freely consuming it.

The classic example of a public good is national defense. It is clearly noncompetative since one's consumption of national defense does not in any way diminish the amount of national defense available for others. Other examples of public goods are lighthouses, clean air, some large parks or recreation areas, and police service

Public goods permit explicit recognition of the fact that some goods may at once be greatly demanded by consumers and yet not supplied by profit - oriented firms. This follows from non-excludability, since the firm which provides the good would have no way of exacting payment for its consumption. Put another way, the benefits of providing a public good are non-appropriable; the firm producing the good cannot reap the benefits. This is in stark contrast to the provision of a public good, such as bread. This firm may easily withhold the rights to a loaf of bread pending payment to the firm by the demands of a specified sum of money.

Principally with respect to accepted accounting procedures and the tax system, externalities are built directly into some circumstances in the form of Institutionalized Rules and Procedures. Several examples will illustrate the point. Suppose that ten years ago a firm signed an agreement leasing office space for $1,000 per year for 20 years. Suppose the firm is free to sublease, if it desires. Suppose the current market value of the office space is $5,000 per year, and finally, suppose the firm's profits excluding the lease payments are $3,000 per year. The final profit figure based on accounting procedures would be $2,000; $3,000 less the out-of-pocket costs of $1,000 for rent. The current value of the space would never be considered. The true final profit figure, as determined from economics, is -$2,000. This is because the firm can shut down, sublease the space for $5,000, and earn a net profit of $4,000. By choosing to earn $2,000 instead of $4,000, the firm is really losing the difference: $2,000 per year. Thus profit is -$2,000. A decision to stay in business based on the accounting profit results in a misallocation of resources: the office space is not being used by the firm to which it is of greatest value, i.e., the firm willing-to-pay $5,000 per year.

As another example, consider excise taxes levied on the producers of certain goods. This directly causes private costs to diverge from social costs, and causes a less than optimal amount of the good to be produced and consumed. In the absence of the tax, costs to the firm and society are presumably identical: land, labor, capital. With the tax, the firm pays an additional charge, yet social costs are unchanged. This action leads to a cut in production.

<u>Interdependent Production or Consumption</u>, along with public goods, is perhaps the most significant class of externalities. The initial discussion of externalities drew on a consumption interdependence: person A's utility depended on B's consumption of x_1. For completeness, Appendix I includes a brief discussion of production interdependence based on a pollution example. In the example two firms are assumed to be located along a river; the upstream firm

discharges an effluent into the river as a byproduct of its production process, and the downstream firm draws water from the river for use in its production. The downstream firm must treat the water, at some cost, to remove impurities. The more impurities, the greater the cost. Each firm's goal is the maximization of its own profit. The overall social goal is the maximization of the value of production. It is quantitatively shown in the appendix that a production interdependence--one firm's cost function dependent on the output of another--gives rise to an externality. That is, the interdependence results in social and private costs diverging, leading to a non-optimal resource allocation.

Many, if not most, commercial and industrial undertakings involve some degree of risk: the possibility that the eventual returns will differ from the planned returns. Most analysts agree that, faced with risk, society's best interests are served when projects and their magnitudes are chosen to maximize expected returns. That is, given N possible projects with costs of $C_1 \ldots C_N$, and expected returns *$R_1 \ldots R_N$, and total financial resources of $\overline{C} < \sum_{i=1}^{N} C_i$, the socially optimal set of projects is that total set which maximizes

$$\text{Net Social Benefit} = \sum_{i=1}^{N} Q_i \, (R_i - C_i)$$

subject to $\sum_{i=1}^{N} Q_i C_i \leq \overline{C}$, where Q_i is a 0, 1 variable: 1 if the project is chosen, 0 otherwise. The underlying rational is straightforward, If a large number of projects are to be chosen, those yielding less than the expected returns will be balanced out by those yeilding more. Over a large number of projects, the "expected" net social benefit is likely a very good predictor of the actual benefits. Thus, the maximization of "expected" benefits is the best guide to maximizing actual (but yet unknown) benefits.

Leaving aside the issue of whether net social benefits equal net private benefits (for that issue is addressed in other sections of this discussion), the question remains as to whether firms are motiviated to adopt the expected profit (granting for the moment that profit equals benefit) criterion. As can be readily appreciated, there are important situations in which the expectations rule is

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*Let $R_{11} \ldots R_{1M}$ be the M possible returns on project 1, and let $P_{11} \ldots P_{1M}$ be the probabilities with which those returns are anticipated, then

$$R_1 = \sum_{j=1}^{M} P_{1j} R_{1j}, \text{ and}$$

likewise for $R_2 \ldots R_N$

likely to be violated. That is, there are situations when it is in the firm's best interest to not maximize expected profit. This situation occurs when only a limited number of projects are to be selected and an adverse payoff on any one may spell disaster for the firm. As an extreme example, consider Table 2.1. A firm has $2,000 to commit to projects. The table details the costs, possible returns, probabilities of those returns and expected profit, E(Π), for each project.

TABLE 2.1

Example of the Influence of Risk on Private Decision-Making

POSSIBLE RETURNS:	$-100,000	$-10,000	$20,000	$200,000	COST	E(Π)
PROJECT			Probabilities of above Returns			
1	.5	0	0	.5	$2,000	48,000
2	0	.5	.5	0	$1,000	4,000
3	0	.4	.6	0	$1,000	7,000

An example of E(Π) illustrates the approach:

$$E(\Pi \text{ for Project 3}) = [0 \cdot (-100,000) + .4(-10,000) + .6(20,000) + 0 \cdot (200,000)] - 1,000 = 7,000$$

With $2,000 available, the firm can choose to initiate one of the following:

Projects(s)	E(Π)	Money Left Over
1	48,000	0
2	4,000	1,000
3	7,000	1,000
2 & 3	11,000*	0
None	0	2,000

It is clear that the expected value rule gives rise to project 1. Yet, Table 2.1 shows that if 1 is chosen, there is a 50% chance of a return of -$100,000.

*The projects are assumed independent of each other, so the expected values may be added.

A firm, particularly a small firm wherein a major loss would threaten its existence, would reasonably refuse to accept such risk. We would expect that projects 2 and 3 would be adopted.

The example demonstrates that when risks are high, the socially optimal decision rule of maximizing expectations is not likely to be followed. Basically, the cause is divergence of social and private values. The private firm values a 50% chance of a $100,000 loss different than a trillion dollar economy values it. Society can easily bear the loss of $100,000 in goods and services, the typical individual cannot.

The international value of U. S. currency is determined by the forces of supply and demand in the market for dollars. When a firm in another country desires to purchase goods from a domestic firm, it must pay the American firm in dollars. That is, it must find someone with American dollars and offer to trade its own currency for dollars at some rate of exchange. The more foreign firms desiring to buy U.S. goods, the greater the demand for dollars, and the more must be paid (in foreign currency) to get them. Thus, a higher worldwide price of dollars is established when the demand for dollars increases. U.S. firms, wishing to purchase foreign goods, and having to pay for those goods in the appropriate foreign currency, can now purchase a given amount of foreign currency for less U.S. dollars (or equally, can now purchase more foreign currency for the same amount of dollars). The real effect of an increased demand for dollars, in terms of the flow of goods between foreign and domestic firms, is that we are now able to trade less of our goods for more of theirs. To the extent competition forces these benefits (in the form of lower prices) to be passed on to the U.S. consumers, social welfare is improved by the increased foreign demand for dollars.

It happens, however, that there is a divergence of private and social benefits in this process. The firm which succeeds in developing a new product with substantial foreign demand does not reap all the benefits associated with the more favorable trade balance and thus is not motivated to pursue to foreign sales to the extent socially desirable. For the firm, by stimulating foreign demand for a U.S. product, makes the terms of trade (number of dollars per unit of foreign currency) more favorable for all domestic firms. All firms dealing in international trade receive a benefit (lower foreign prices) due to the one innovative firm. Since the latter cannot charge other domestic firms for this benefit, it pursues its foreign sales only to the point where marginal private benefits = marginal costs, not the greater quantity where marginal social benefits = marginal costs. It appears, then, that government has a legitimate role in furthering U.S. efforts. There is a caveat in this, however. Higher values for U.S. currency will tend to diminish foreign demand for U.S. products, since their price will have risen. This will be a cost to some domestic firms. Thus, there is a balance to be struck in the price of U.S. currency: too high can be as damaging as too low.

Unemployment is a classic case of the divergence of private and social cost, and has far reaching consequences for national economic policy. The basic consideration is simply stated: when a firm hires an unemployed person, that person represents a real cost to the firm: so many dollars per month. Nonetheless, that person's employment costs society nothing: since that individual was producing nothing in his unemployed state, society gives up nothing to have him employed by the firm. This contrasts sharply with the case in which the firm hires a person away from another firm. Society then gives up his production in one employment in return for his production in another. Society gains only if the value of his production now exceeds what it was previously. It follows that it is in society's best interests for government to stimulate the employment of unemployed persons.

With regard to Economies of Scale (Natural Monopolies), increasing returns to scale (or diminishing average cost) presents a situation in which the free market fails to provide the socially optimal amounts of goods involved, and generally fails to organize production in the most efficient manner. From elementary economic reasoning, it is evident that the socially optimal production of a good is that amount such that the social willingness-to-pay for the last item just equals the social cost of producing it. To see the sense of this proposition, suppose it is not adhered to, and the quantity produced is less than this amount. Then there is some individual willing to pay, say, 10 for another unit while the cost of producing it is, say, 5. Clearly, to product the unit and sell it to the demander (for a price ≥ 5 and < 10) makes him better off. Since he is better off, and no one worse off, society as a whole is better off.

Economies of scale are said to occur when the cost of producing successive units declines. That is, over the entire range of production, average cost declines. In consequence of this, average cost always exceeds marginal cost (see curves AC and MC in Figure 2.1). Employing the principle that marginal cost must equal marginal revenue to maximize profit, $\overline{Q}$ is the firm's output. Q^*, the socially optimal output is given by the intersection of marginal cost and demand. The firm, it may reasonably be assumed, has little interest in maximizing social welfare. Rather, its principal concern must be profit, and profit is maximized when marginal revenue just equals marginal cost, at $\overline{Q}$. Note that at $\overline{Q}$,

$$\begin{aligned} \text{Profit} &= \text{Total Revenue} - \text{Total Cost} \\ &= (\text{Price x Quantity sold}) - (\text{Average Cost x Quantity Sold}) \\ &= \bar{P} \times \bar{Q} - \bar{C} \times \bar{Q} \\ &= \text{Rectangle } \bar{P}WX\bar{C} \end{aligned}$$

However, if the firm produced Q^*,

$$\begin{aligned} \text{Profit} &= P^*Q^* - C^*Q^* \\ &= \text{Negative of Rectangle } C^*YZP^*. \end{aligned}$$

That is, the firm could actually incur a loss if it produced the socially optimal quantity. The situation gets worse, however. So far we have been assuming that the entire market is served by a single firm. Suppose, instead, that two identical firms share the market. In this case it can be shown that each will now produce less than half of what the single firm could produce. In other words, competition actually worsens the situation. The more firms there are, the less is produced; and even one firm alone only produces $\bar{Q} < Q^*$. The example applies to a number of real situations, particularly the production of utility-type services. In most cases, the government has stepped in, franchised a single firm to provide the good, and has regulated its price and output so that something better than $(\bar{P}, \bar{Q})$ occurs.

<u>Non-Competitive Markets</u>. The existence of monopoly power in a market obstructs Adam Smith's "invisible hand" from turning the forces of private greed to serve the social welfare. This case differs from the previous one in that, here, more competition improves, rather than detracts from, social welfare, Otherwise, the analysis is quite similar. The indication of monopoly power is that the firm has influence over the market price of the good in question: the firm's market share is substantial enough that, by increasing or decreasing output, it can

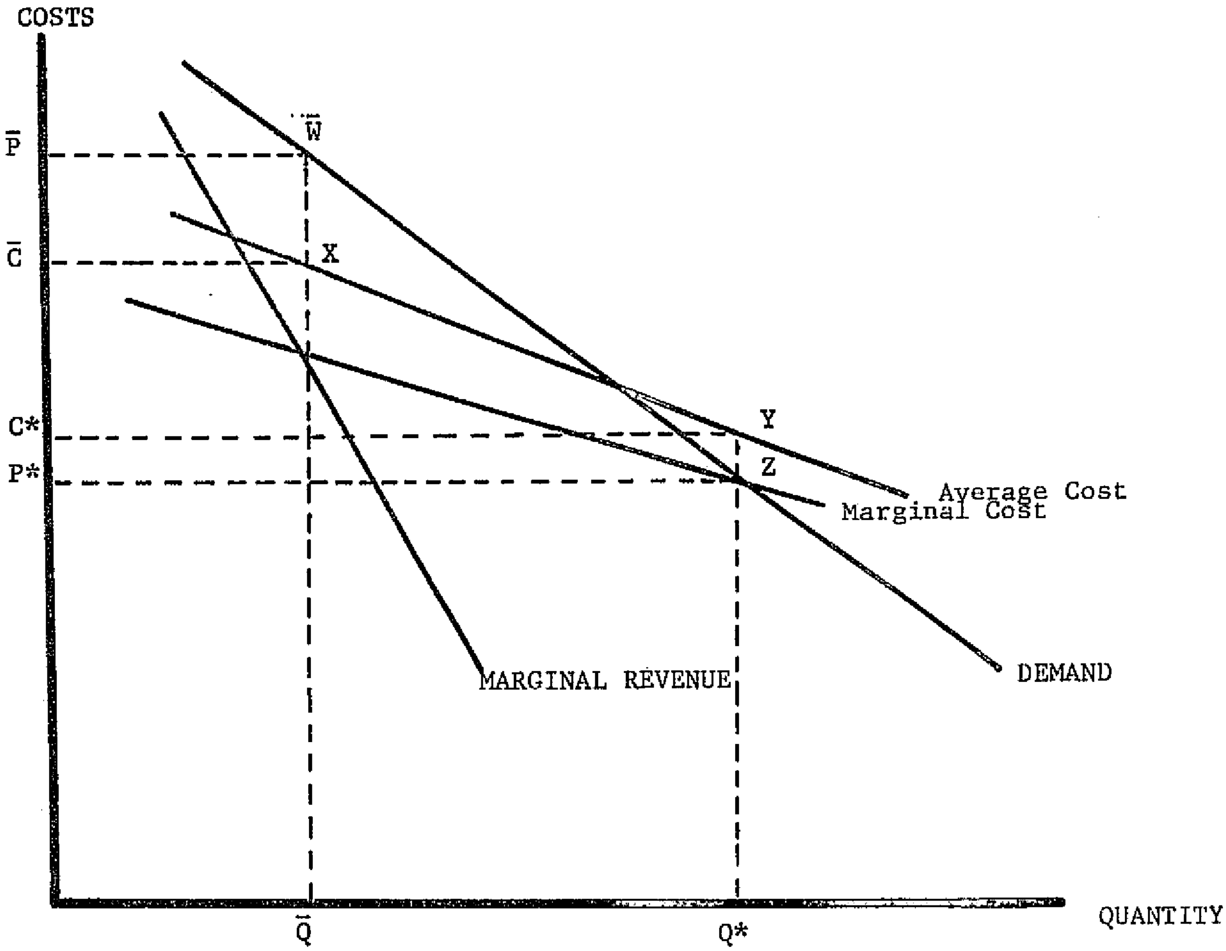

FIGURE 2.1 Diminishing Average Costs and Market Failure

cause the market price to decrease or increase. The firm need not be the only firm in a market for it to exercise monopoly power, it is only necessary that it have some influence over market price. When monopoly power of this sort (decreasing returns to scale) persists, a likely cause is the existence of barriers to the entry of other firms. In the interests of social welfare, the effect of various federal laws is to make such barriers illegal. Nonetheless, the laws re effective only in the most blatant cases. Much monopoly power persists, and it is in the apparent best interests of society that it, or at least its effects, be mitigated.

National Security. A great deal of federal activity proceeds under the aegis of national security. The rationale for government intervention in the economy in the name of national security is straightforward; which is not to say, however, that it cannot be abused. Basically, there appears to be two types of situations of interest.

In the first, society has dire, though very infrequent demand for some perishable good or service. For example, the services of many experienced military-goods firms are required during wartime. It is not prudent to wait for such firms to form when war occurs. However, the peacetime demand for such goods would preclude the economic viability of such firms during peacetime. Thus, it would appear to be in society's best interests for some such firms to be supported by government during peacetime so that they may be available in the event of war. There is no doubt that much actual defense expenditure is for precisely this reason. The "best" number of firms, or the "best" level of support are important questions underlying the analysis of each year's defense budget. It is obvious there are no easy answers to such questions.

The second case involves U.S. dependence on foreign sources for vital raw materials. The well-known economic argument in favor of trade (namely that by each country's specialization in producing the goods for which it has a competitive advantage, and by trading its goods for those of other countries, the world community becomes as well off as possible) breaks down when political factors begin influencing economic decisions. This appears to be the case in much of U.S. - Third World trade. Oil is a prime example, but other materials are involved as well. Recent events suggest that, in the long run, society might be better off paying somewhat higher prices to domestic producers, and thus sustaining their production capabilities, rather than relying on unstable foreign supplies. This argument does not preclude trade in vital materials, only complete dependence on foreign sources.

The foregoing discussion has described situations in which the private sector of the economy fails to act in society's best interests. It is argued that in these circumstances, government intervention is called for. That is, social welfare is improved by government's direct or indirect prodding of private behavior.

Now, contrary to the tone of our remarks, government is hardly monolithic. Rather, there are diverse departments, agencies, administrations, bureaus, etc. To a large extent, these governmental units are organized along functional lines --i.e., all (or most) matters pertaining to particular functions of government are handled by a particular unit. Thus, we have such departments as Defense; Transportation; Agriculture; Health, Education and Welfare; we have the Environmental Protection Agency; the Federal Energy Administration; and the National Aeronautics and Space Administration; etc. Each of these units is charged with furthering the social welfare as it is affected by its own area of interest. It is not surprising that these units occasionally exhibit a provincialism rivaling that of private firms. This suggests that when there are interdependencies among units of government, we might find suboptimal decisions being made because, just as in the case of private firms, the government units are not motivated to take the interdependencies into account in their decision-making. Therefore, once we free ourselves of the monolithic facade of government, we realize that externalities may plague the public sector, as well as the private sector. For example, a unit of government might find that its own sponsorship of a new technology almost, but not quite, passes a cost-benefit test (where only benefits to the sponsoring unit are considered). That unit may decline sponsorship even though other units might gain enough benefits, as side effects, that total benefits actually do exceed total costs.

A different, but related, problem is the inertia in Federal budget allocations. A perusal of budget allocations shows that allocations do not fluctuate much on a year-to-year basis. This year's allocation is a very good predictor of next year's allocation. On average, this would appear entirely reasonable, since on average, national priorities do not shift radically year to year. However, there can be little doubt that occasionally some national priority (social welfare gradient) may shift quicker than the funds to adequately deal with it. This can unduly delay the implementation of some socially beneficial project. Thus, and not surprisingly, institutional rigidities affect public, as well as private, decisions in an adverse manner.

In general, it would not be difficult to show that many of the reasons underlying the failure of the private sector to optimally pursue the best interests of society apply also to government. In large measure, this follows from the decentralized nature of government decision making. Our intention here is not to impugn decentralized government, for it has many benefits. Rather, our intention is to caution against the unhesitating acceptance of a government unit's willingness-to-pay for NASA R&D in its behalf as the true social value of that R&D. Certainly, it is a good guide. But the presence of externalities, rigidities, risk, etc. can mitigate the value of a government unit's willingness-to-pay as a guide to social welfare in the same way that private willingness-to-pay is qualified in the presence of those same factors.

In simple terms, what all this amounts to is recognizing that the refusal of some government unit to sponsor NASA R&D in its behalf does not <u>necessarily</u> imply that such R&D is not in the public interest. However, prudence suggests that, under those circumstances, it is emcumbent upon NASA to establish that the R&D <u>is</u> in society's best interests. And needless to say, however technically successful some NASA R&D may be, it is of no social value unless it is implemented. Thus, NASA R&D performed for some other government unit, in spite of indications that that unit has no intentions of implementing the technology, cannot be justified.

The thrust of the foregoing arguments can be summarized as three conditions which a technology development project must satisfy in order to be judged worthy of NASA pursuit. First, and most clearly, the benefits of the project must outweigh its costs. This established that the project should be undertaken, but it does not establish who should do it. The presumption, at this point, must be in favor of the private sector. Second, if the project were undertaken by government, it should not displace private activity in that area. That is, a government project should not substitute for an equivalent private one. Third, the observed reluctance of the private sector to pursue that project should not be a temporary phenomenon. It should represent an equilibrium. These final two conditions coupled with the first, insure that the project is worth doing, the private sector is not doing it now, and likely will not do it in the future. Thus, the rationale for government action is established.

How can it be determined that these three conditions are satisfied? The first condition is addressed by a cost-benefit analysis. It establishes whether or not the project ought to be done, not who should do it. The second condition is subject to verification by observation and surveys. The third condition presents difficulties, for it would appear to hinge on the ability to foretell the future -- to foretell whether private industry will pursue certain R&D projects at unspecified future dates. Clearly, 100% certain knowledge of these future events is beyond hope. However, by recognizing the forces which shape the future, reasonable predictions may be made. The forces of interest here are those forces which deter private decision makers from pursuing socially optimal courses (courses whose benefits outweigh costs). The forces, then, are externalities, public goods, risk, etc. When these situations are present, we know the private sector is detered from committing its resources, since a sufficient private return is difficult to achieve. Thus, the qualification process addresses the third of the necessary conditions for a justifiable government project.

The qualification process can be implemented in either a qualitative or quantitative manner. In this project, both courses were pursued. The qualitative qualification process involves the following two steps:

1. Gaining a thorough familiarity with a proposed project.
2. Carefully checking each project against the list of characteristics (externality, public good, etc.) to determine whether that characteristic is present in the project.

Clearly, the subjective element is unavoidable here. This is partially overcome by the quantitative incorporation of qualification in the screening process. This is done by estimating how long it would be before private industry initiates an R&D project comparable to the proposed project. As is explained later, this figure directly scales the benefits of the proposed project.

Thus, if the qualitative qualification fails to eliminate a proposed project on the basis of absolute failure to satisfy any of the characteristics, the project is passed through to the quantitative evaluation which still incorporates the qualification hurdle in the so-called "delay factor".

SECTION 3

DEVELOPMENT OF SCREENING METHODOLOGY

3.1 Background

A technology screening methodology provides a basis on which to selectively admit space communication technologies to a formal or more extensive cost-benefit assessment. It is an important function because available resources are insufficient to subject each technology to a formal assessment and, moreover, because it is inefficient to do so.

One of the key requirements imposed on a screening methodology is that it be consistent with the eventual formal assessment. If both screening and assessment are thought of as processes of assigning values* to technologies, then a good screening methodology assigns values as close as possible to those values which assessment would assign.

Another requirement is that the screening methodology be tractable. Its application should be relatively quick and easy. It should consume considerably less resources than assessment.

Other requirements are that screening must be defensible to potentially hostile critics, and it should be quantitative. The consistency and tractable requirements dictate that "conservative" approaches and estimates be employed wherever possible. The quantitative requirement is imposed, not through any naive belief that quantitativeness *per se* is desirable, but through the recognition that a quantitative approach makes explicit many otherwise hidden assumptions and allows a more objective assessment of results.

The literature on R&D project selection can offer some guidance in the construction of the screening methodology. In accordance with Moore and Baker [2 approaches to project selection can be classified into four broad groups: scoring, economic, constrained optimization, and risk analysis.

Scoring Models are used to compute a single ordinal score for a project based on values assigned to a number of key variables. These models are easiest to implement, but suffer a number of potentially disabling flaws. A simple example of a scoring model is the approach one might take in deciding

*A value can be an ordinal rank or a cardinal measure.

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on a new automobile. Key decision variables might include purchase price, fuel economy, seating capacity, and estimated reliability. Each automobile model under consideration could be given a rating of 1 to 10 on each variable. Then each model's final score might be the sum or product of the individual ratings. Although the approach is highly tractable, its arbitrariness is evident in rating the variables, weighting the ratings (uniform in the foregoing example), and in the functional form combining the individual ratings.

Economic Models are based on present value, benefit-cost ratio or internal rate of return calculations. They are less tractable, but more defensible than scoring models. They are deterministic and not well suited to optimizing variables, such as timing, size, location, as more complex approaches might be.

Constrained Optimization Models, as the name suggests, employ operation research techniques to optimize certain aspects of project selection, from the choice of integral projects to the design of projects by parameter determination.

Risk Analysis Models postulate probability distributions for certain variables and analyze the projected results in terms of probability density functions.

The constrained optimization and risk analysis models are relatively difficult to implement; however they embody many desirable features, notably considerations of risk and uncertainty.

The approach that was adopted in this study attempts to embody the strong points associated with the various modeling approaches, and yet satisfy the criteria of consistency, tractability, defensibility, and quantitativeness. Specifically, efforts were made to devise a single net present value formula such that the proper specification of a limited number of variables will enable a "score" to be computed for each potential R&D project. Use of the NPV criterion in screening assures consistency with formal cost-benefit assessment since NPV is usually the appropriate criterion in CBA. Limiting the number of variables involved in the screening equation is an attempt at maintaining tractability, while choice of the most relevent variables contributes to defensibility. Throughout, quantátive estimates drive the analysis.

3.2 Structure

NASA management must decide whether it is in the nation's best interest for it to pursue various space communication technologies. The conceptual approach to determining the proper course of action is to identify and weigh what is lost and what is gained by NASA's investment of resources in the development of particular space communication technologies. Needless to say, a necessary condition for NASA to initiate an R&D effort is that the gains to society outweigh the losses.

The art of identifying, gauging and comparing societal losses and gains has been formalized under the rubric of cost-benefit analysis (CBA). CBA posits alternative scenarios--a description of resource use and consumption opportunities if the project _is_ undertaken and if the project _is not_ undertaken--and attempts to determine the value of the difference between them. Essentially, such cost benefit analysis involves determining differences on an annual basis and applying a discounting procedure to find a present value.

Since in general, the cost benefit analysis procedure does have its pitfalls, it is imperative that a careful step-by-step process be followed to insure that the final result prove a fruitful and true decision aid.* The first step is the construction of the alternative scenarios for each R&D project under consideration. However, since all the technology development projects are related in the sense that each is a part of a space communication system, there will be similarities in the scenarios for each project. Thus, the appropriate approach is the construction of a general form for the scenarios, a form which can be utilized for each specific technology project.

Figure 3.1 is a schematic representation of the general form of alternative scenarios for any given R&D project. Emanating from the left most node, the decision point, are links representing the alternative decisions which management can adopt. The upper line is a branch or path representing NASA's decision to go ahead with the R&D. Along this branch, two additional possibilities are encountered: industry may adopt the technology item (for eventual commercial application) or not. In the latter eventuality, the NASA R&D effort went for nought, and the resources consumed must be considered wasted. Given industry adoption, three "phases" or "stages" follow, In sequence, these are an industry R&D period, during which the NASA R&D is extended or modified to suit the intended commercial applications; an industry construction phase, during which start-up costs, if any, are encountered*, and finally, the implementation phase, when the technology is in operation and benefits are being derived from its use.

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*e.g., the construction of an assembly line, or the construction of equipment to produce items embodying the new technology.

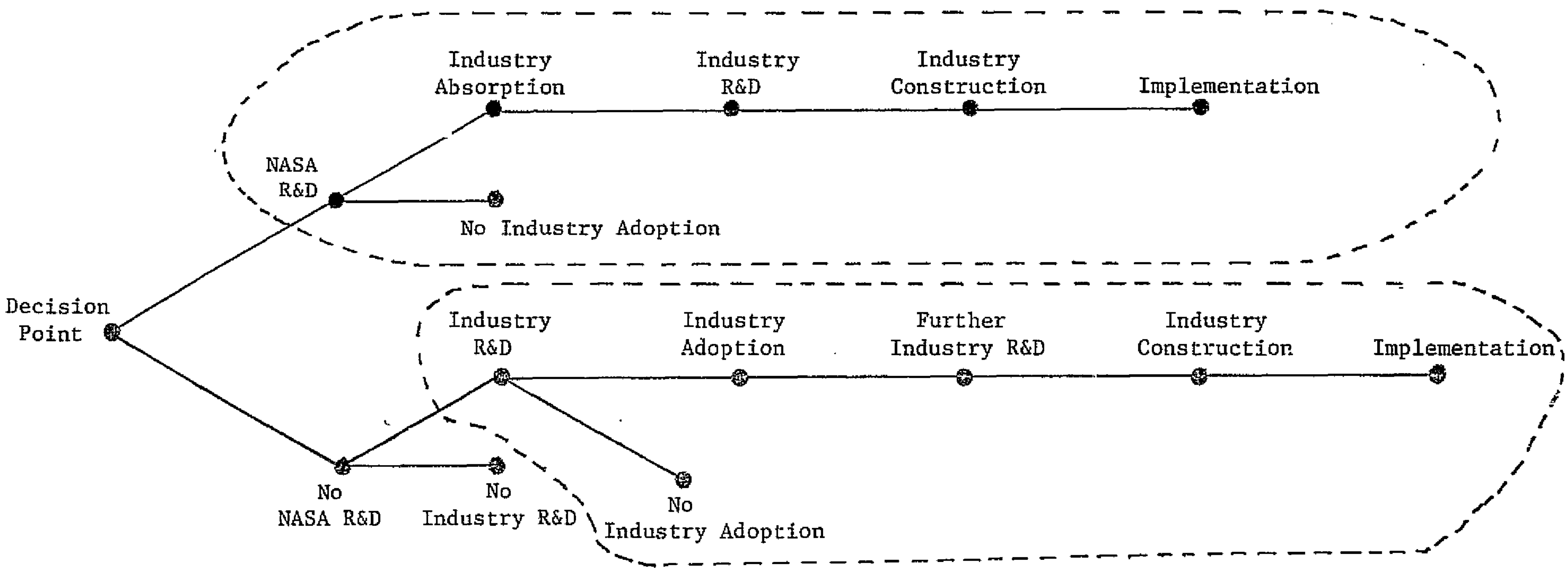


Figure 3.1. Schematic Representation of Screening Decision Process

The alternative to the foregoing scenario is the decision by NASA not to pursue the technology. In this case, industry may perform the R&D or not. Should industry perform the R&D, successive stages parallel those in the first scenario. In fact, if it is assumed that NASA and private industry are equally efficient in the performance of R&D, and that each scenario is chronologically identical to the other, then the parts of each scenario contained within the dashed borders of Figure 3.1 are, in terms of resource inputs and outputs, identical. This observation serves as the basis for determining and evaluating the differences between the scenarios.

Some points should be made about the nature of the diagram of Figure 3.1. First, note in the figure the existence of an asymmetry between the scenarios. The lower scenario contains an end point "NO INDUSTRY R&D" which has no parallel in the upper scenario. Also, although the decision for NASA to pursue the R&D can be taken as a more or less immediate start-up of the work, the industry decision to perform the R&D after NASA's refusal to do so can come several months or many years after NASA's decision not to undertake the development of that technology. In terms of the figure, although the length of time between the nodes "DECISION POINT" and "INDUSTRY R&D" is temporarily elastic, the possibility of "NO INDUSTRY R&D" is effectively accounted for by the (present value-wise) equivalent statement that the industry R&D occurs in the very distant future. This approach exploits the idea of the line elasticity mentioned above. Figure 3.2 illustrates the new symmetry.

Let us temporarily continue with the assumption that real resource inputs and outputs are unaffected by the year in which the R&D project is begun. That is, the flow of annual costs and benefits is independent of the start-up time. As we shall see, this assumption leads to a particularly simple and intuitively appealing form for analyzing differences in scenarios, that is, differences resulting from NASA decisions to pursue a technology or leave it to industry.

In order to develop this approach, let x_i represent the net benefits accruing to society due to the project in the i^{th} year after initiation. Ordinarily, x_j is negative in the initial years and positive thereafter. Thus, for a project that has effects for 25 years beginning, say, in 1977, the scenario corresponding to NASA's initiation of the R&D in 1977 can be

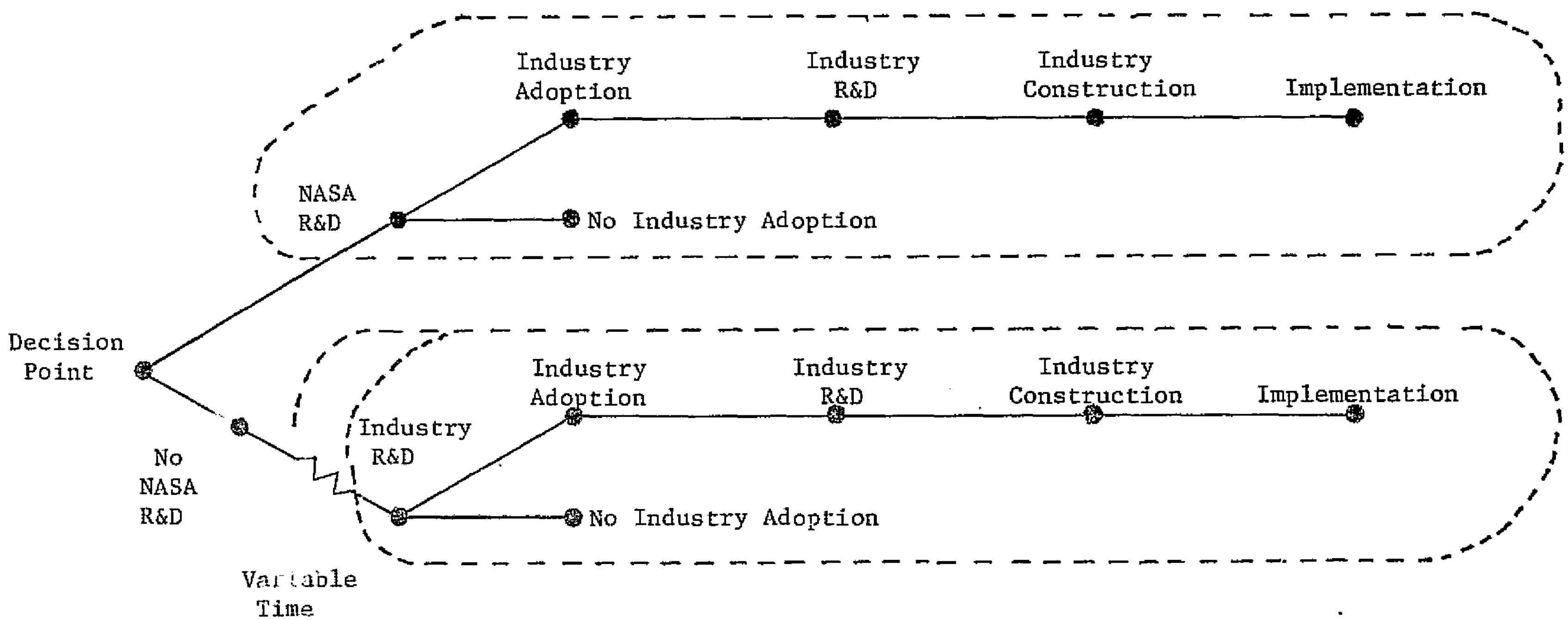


Figure 3.2. Re-establishing Symmetry Between Scenarios

represented as follows:

Calendar Year	1977	1978	1979	. . . 2001
Index For Years	0	1	2	24
Net Benefits	x_o	x_1	x_2	x_{24}

The alternative decision, NASA refusal to pursue the R&D project and industry adoption of the project τ (tau) years after what would have been the NASA start date, can be represented as

Calendar Year	1977	1977+ τ	1977+τ+1 .	.2001+τ
Index for Years	0	τ	$\tau+1$	$\tau+24$
Net Benefits		x_o	x_1	$+_{24}$

The value of NASA's performance of the R&D is the present value* of the difference between the first and second decision paths, or scenarios, and can be written as

$$NPV = \frac{X_o - 0}{(1 + d)^o} + \ldots + \frac{X_\tau - X_o}{(1 + d)^\tau} + \frac{X_{\tau+1} - X_1}{(1 + d)^{\tau + 1}} + \ldots + \frac{0 - X_\tau}{(1 + d)^{\tau + 24}}$$

where d is the discount rate and τ is as stated above.

In a perhaps more straight forward form,

$$NPV = \left[\frac{X_o}{(1 + d)^o} + \frac{X_1}{(1 + d)^1} + \ldots + \frac{X_{24}}{(1 + d)^{24}}\right] - \left[\frac{X_o}{(1 + d)^\tau} + \frac{X_1}{(1 + d)^{\tau+1}} + \ldots + \frac{X_{24}}{(1 + d)^{\tau+24}}\right]$$

Denoting the first term on the right hand side in the above equation as Y and the second as Z, note that

$$Z = \frac{Y}{(1+d)^\tau}$$

and since

$$NPV = Y - Z$$

then

$$NPV = Y - \frac{Y}{(1+d)^\tau}$$

or

$$NPV = \left(1 - \frac{1}{(1+d)^\tau}\right) Y \qquad (3.1)$$

---

*Throughout, we use the term net present value, NPV, to denote the present value of net benefits.

Therefore, when the sequence of costs and benefits is independent of the start-up time, the value of NASA Pursuing the R&D depends on two factors: Y, the net present value of the R&D project itself, and $1 - \frac{1}{(1+d)^{\tau}}$, henceforth referred to as the delay factor, since it accounts for how much delay (τ years) would occur if NASA did not perform the R&D itself.

Some additional observations on the delay factor are in order. First, note that the delay factor always assumes a value ≤ 1 and > 0. This is the range of values because the question being addressed is "Should NASA perform the R&D?" or, more analytically, "What is the value (to society) of NASA's performing the R&D?" The question here is not "Should the R&D be done (by any element of society)?" nor "What is the value of the R&D?" Indeed, affirmative (or positive) answers must be given to the latter duo of questions as a necessary condition for affirmative (or positive) answers to be proffered to the former. In the simple example above, Y denotes the NPV of (anyone) doing the R&D starting now (1977). Clearly NVP > 0 if and only if Y > 0, and a project will not be undertaken if NPV < 0. The fact that NPV $\leq$ Y reflects the fact that, in a sense, precedence is being accorded private industry. NASA's performance of the R&D derives value only in the absence (or delay) of private R&D.

Second, but related to the first point, is the limit behavior of the delay factor:

$$\lim_{\tau \to 0} \left[1 - \frac{1}{(1+d)^{\tau}}\right] = 0$$

$$\lim_{\tau \to \infty} \left[1 - \frac{1}{(1+d)^{\tau}}\right] = 1$$

If τ is close to 0, implying industry would soon do the R&D in the absence of NASA's work, the value of NASA's doing the R&D is very low. Likewise, for high τ, indicating a long delay before the R&D would be undertaken, the value of NASA's undertaking the project approaches Y.

Another important aspect of this model is that, as long as Y > 0 (that is, as long as the project is worth doing), society always at least breaks even (NPV $\geq$ 0) when NASA does the R&D. This aspect reflects the assumption that the R&D is never duplicated--if NASA does it, industry does not need to. It also reflects the assumption that the resources industry would have devoted to that R&D project if NASA had not pursued the project, but which are now "freed", have a marginally profitable (at the discount rate used in the NPV calculations) use. Thus, NASA's undertaking of the R&D work causes neither unemployment of resources in private industry, nor extra profits because a more profitable R&D project replaces the subject project. It is assumed that if industry does not do the subject project, it is replaced with an equally attractive one.

3.3 The Basic Screening Equation

In the two proceeding subsections, the purpose of screening and the approach to the problem were discussed; in this subsection, the basic screening equation is constructed. However, to do so requires one more simplifying device. The general NPV formulation assumes a knowledge of annual costs and benefits. In the context of R&D project selections, this knowledge is very specific information. So specific, in fact, that it can easily lead to intractability. Less refined data inputs are needed. We take our lead, in this regard, from Figures 3.1 and 3.2, which represent our scenarios in four stages:

- -NASA R&D Time
- -Industry R&D Time
- -Industry Construction Time
- -The Implementation Period

During the first three stages, only costs are incurred; during the final stage, both costs and benefits are experienced. Since each of the first three periods are relatively short (three years might be a typical maximum length of any period), the distribution of the total costs of a period over the years in that period is not a crucial consideration. Thus, the approach is to attempt to estimate the total costs of an entire phase, and assume that the costs are evenly distributed over the years in that phase. The NPV equation is easily modified to handle this wrinkle. The only restriction is the equation treat the stage lengths as variables, since the length of the various stages will differ project to project. To see how this is done, consider a simple example of two stages whose lengths are T_1 and T_2, respectively. Costs are X and Y respectively for each stage.

$$NPV = \frac{X/T_1}{(1+d)^0} + \frac{X/T_1}{(1+d)^1} + \ldots + \frac{X/T_1}{(1+d)^{T_1-1}} + \frac{Y/T_2}{(1+d)^{T_1}} + \frac{Y/T_2}{(1+d)^{T+1}} + \ldots + \frac{Y/T_2}{(1+d)^{T_1+T_2-1}}$$

$$NPV = X/T_1 \sum_{t=0}^{T_1-1} \frac{1}{(1+d)^t} + Y/T_2 \sum_{t=0}^{T_2-1} \frac{1}{(1+d)^{T_1+t}}$$

$$NPV = X/T_1 \frac{\sum_{t=0}^{T_1-1} (1+d)^t}{(1+d)^{T_1}} + Y/T_2 \frac{\sum_{t=0}^{T_2-1} (1+d)^t}{(1+d)^{T_1+T_2}} \qquad (3.2)$$

Thus, NPV can be quickly calculated for any given X, Y, T_1, T_2. Note that the final equation can be thought of as a variable weight scoring model. Contrary to the arbitrariness of the usual scoring models, however, this model has both form and weights (the coefficients of $\frac{X}{T_1}$ and $\frac{Y}{T_2}$ arising from a standard economic model). For the scenarios depicted in Figures 3.1 and 3.2 the NPV screening equation contains eleven variables and one parameter, the discount rate:

- P_A = probability of private industry adoption of the new technology, given the NASA R&D effort,
- τ = number of years which would elapse before industry would undertake the primary R&D effort, if NASA did not,
- T_1 = number of years the NASA R&D effort would take,
- T_2 = number of years supplemental industry R&D would take,
- T_3 = number of years industry "construction" or "tooling-up" would take,
- T_4 = number of years the technology would remain operation, i.e., the number of years over which the benefits or costs of the technology developed by the NASA R&D effort would be experienced,
- X = total NASA R&D costs (during T_1),
- Y = total industry supplemental R&D costs (during T_2),
- Z = total industry construction costs (during T_3),

d = discount rate,

B = current present value of the benefits of the technology at the beginning of stage 4,

C = current present value of the costs of the technology at the beginning of stage 4.

Some explanation is in order concerning the last two variables B and C. Each technology resulting fron an R&D project will have a time stream of benefits and costs in stage four - the implementation stage. Since the entire model is based on the present value approach, an equivalent treatment of the stream of benefits and costs is the present value of that stream at the beginning of the stream. Analytically,

$$NPV = \sum_{t=0}^{N} \frac{X_t}{(1+d)^t} = \sum_{t=0}^{M} \frac{X_t}{(1+d)^t} + \frac{1}{(1+d)^{M+1}} \sum_{t=0}^{N-M-1} \frac{X_{M+1+t}}{(1+d)^t}$$

where X_t is net benefit in year t. The factor in the last term on the right hand side is the current (for year M+1) present value of the stream of net benefits from M+1 to N. By applying a discount factor of $\frac{1}{(1+d)^{M+1}}$ to that term, the overall present value is determined.

Thus, the overall present value of the benefit is

$$B = \frac{B_{T_1+T_2+T_3+1}}{(1+d)^0} + \frac{B_{T_1+T_2+T_3+2}}{(1+d)^1} + \ldots + \frac{B_{T_1+T_2+T_3+T_4}}{(1+d)^{T_4-1}} = \sum_{t=0}^{T_4-1} \frac{B_{T_1+T_2+T_3+1+t}}{(1+d)^t}$$

The cost, C, is defined analogously.

The basic screening equation is:

$$E(NPV) = \left[1 - \frac{1}{(1+d)^T}\right] \cdot \left\{ P_A \left[- X/T_1 \left(\frac{\sum_{t=0}^{T_1-1} (1+d)^t}{(1+d)^{T_1}} \right) + -Y/T_2 \left(\frac{\sum_{t=0}^{T_2-1} (1+d)^t}{(1+d)^{T_1+T_2}} \right) \right. \right. \quad (3$$

$$\left. + -Z/T_3 \left(\frac{\sum_{t=0}^{T_3-1} (1+d)^t}{(1+d)^{T_1+T_2+T_3}} \right) + (B-C) \left(\frac{\sum_{t=0}^{T_4-1} (1+d)^t}{(1+d)^{T_1+T_2+T_3+1}} \right) \right] + (1-P_A) \left[-X/T_1 \left(\frac{\sum_{t=0}^{T_1-1} (1+d)^t}{(1+d)^{T_1}} \right. \right.$$

The equation, upon inspection, should appear straightforward, The delay factor, discussed above, scales the NPV of the R&D project itself, which is the rest of the right hand side. (Recall Equation 3.1. P_A accounts for the branch in Figures 3.1 and 3.2 showing the possibility the R&D effort could go for nought, i.e., the resources could be used but no benefits are ever derived. The complicated expressions involving d are simple extensions of 3.2. The expectations operator on the LHS simply reflects the presence of P_A in the RHS.

3.4 An Extension of the Basic Model

The development thus far is based on the assumption that the benefits and costs are independent of calendar time--that they depend only on years elapsed after project initiation. For the R&D projects being investigated, this is not a satisfying assumption. For the magnitude of most of the anticipated benefits stemming from space communication technology R&D depend crucially on the number of satellites into which the new technology is fitted, and the number of available satellites depends more on calendar time than on NASA R&D. It may be reasonably assumed that communication satellites will be used in the future to supply needed communication channels, and the satellites will employ whatever state-of-the-art technology is available. It should be expected, then, that the benefits accruing in the first year of stage four will be greater if the corresponding calendar year is 1990 rather than 1982.

Table 3.1 is useful for developing the modification of the screening equation. Let t index the years in stage four, the implementation phase in the life-cycle of the technology. Assume that if NASA pursues the R&D project, stage four will begin in 1982. The benefits stream, then, begins in 1982. Note that NASA undertaking of the R&D corresponds to a delay of zero year. If NASA opts not to undertake the project, and industry delays one year before beginning the R&D cycle, the columns headed $t_{\tau=1}$ becomes relevant and the first year of stage four has benefits of 141 rather than 100. Likewise, when $\tau=2$, the benefit stream begins with a value of 173.

To highlight the difference that this approach makes, consider a stream of net benefits which might arise if a project were undertaken immediately. The stream is shown in the row of Table 3.2 labeled Scenario A. Now suppose that if NASA decides to forego the project, a delay of two years

TABLE 3.1
EXAMPLE ILLUSTRATION OF TYPE I BENEFITS

INDEX OF YEARS	0	1	2	3	4	5	6...
NET BENEFITS							
SCENARIO A	-100	-50	-20	10	20	30	40...
SCENARIO B			-100	-50	-20	10	20...
SCENARIO C			-100	-50	-20	30	40...

TABLE 3.2
EXAMPLE ILLUSTRATION OF TYPE II BENEFITS

CALENDAR							
YEAR	INDEX	$t_{\tau=0}$	B_t	$t_{\tau=1}$	B_t	$t_{\tau=2}$	B_t
1982	1	1	100				
1983	2	2	141	1	141		
1984	3	3	173	2	173	1	173
1985	4	4	200	3	200	2	200
1986	5	5	224	4	224	3	224
1987	6	6	245	5	245	4	245

will occur before industry decides to forge ahead with that R&D. If benefits are independent of calendar time, Scenario B properly describes the sequence of events. Scenario B is simply A slipped by 2 years. This was the premise on which the delay factor was derived. However, if the benefit stream depends on calendar time, Scenario C is a proper description. Once the first three years of costs are incurred, the benefits flow as though there were no delay. This situation might occur when the technology developed by the R&D permits the same channel capacity to be launched into orbit on fewer boosters. Therefore, the benefits are savings in launch costs. If the technology becomes available in a year when two launches were originally scheduled, and assuming the technology allows launches to be cut by 50%, the benefits in the first year of implementation (the first year of stage 4) amount to the dollar value of one launch. On the other hand, if the technology becomes available in a later year in which eight launches would have been scheduled, then the first year of stage 4 has benefits amounting to the value of four launches.

The screening Equation (3.3) must provide a proper evaluation of type C scenarios when they arise. That is, it must enable comparisons of A and C scenarios. Equation 3.3, as it stands only compares A types with B types. Fortunately, as a glance at Table 3.2 suggests, a modification of 3.3 is easily made. Since the benefits in A and C are identical after some initial period, that later period may be ignored in the decision process. For it is the difference in the scenarios which matters, and there are differences only in the initial years. In Table 3.2 for example, Scenarios A and C differ in years 0 through 4 and are identical thereafter. Thus, the decision must be based on years 0-4 exclusively.

This discussion may now be generalized. Recall that stages 1, 2, 3 incur only costs. Denote the present value* of those costs by PV (S_{123}). Beginning in stage 4, benefits are incurred (although, since costs are also incurred, net benefits are not necessarily positive). From Table 3.2 it's clear that the number of benefit years of interest equals the number years of delay. These are the "extra" years of benefits received through early start-up of the R&D project. In the case of the example, these "extra"

*as they would be calculated in Scenario A, i.e., assuming immediate start-up.

years were indexed 3 and 4 in which benefits of 10 and 20 were received. Denote the present value of those "extra" net benefits as PV(XB). Scenario types A and C may now be easily compared.

Scenario A is preferable to Scenario C if

$$PV(S_{123}) \cdot \left[1 - \frac{1}{(1+d)^{\tau}}\right] + PV(XB) > 0 \qquad (3.4)$$

Stated in another way, the NPV of A (in comparison with C) is

$$NPV = PV(S_{123}) \cdot \left[1 - \frac{1}{(1+d)^{\tau}}\right] + PV(XB) \qquad (3.5)$$

Note that the above equation includes the delay factor. In the following example, the hypothetical data of Table 3.2 were used with the discount rate equal = 10%. Substituting this data into Equation 3.4 gives for the factors,

$$PV(S_{123}) = \frac{-100}{(1+.1)^0} + \frac{-50}{(1+.1)^1} + \frac{-20}{(1+.1)^2} = -161.98$$

$$\left[1 - \frac{1}{(1+.1)^2}\right] = 0.17$$

$$PV(XB) = \frac{10}{(1+.1)^3} + \frac{20}{(1+.1)^4} = 21.17$$

and the value of the LHS of 3.4 is (-161.98) x (0.17) +21.17 = -6.37. Therefore, given the choice between starting the project immediately (scenario A) or delaying the start by 2 years (scenario C), the better choice is to delay. The value of delaying the costs by two years outweighs the extra benefit which are foregone.

3.5 Sensitivity Analysis Procedure

The sensitivity analysis is carried out in a straightforward manner. A variable is selected to which NPV is sensitive, i.e., on which NPV depends. While all other variables are held at their baseline values, this variable is alternately set at predetermined points over a selected range and NPV calculated for each value. For convenience in computerizing the sensitivity analysis, the continuous form of the NPV equation as described in subsection 4.3 has been implemented. A convenient representation of the analysis is effected by plotting NPV against the values of the chosen variable. In this study, the range chosen is typically ± 50%, and values chosen at 5% or 10% intervals for use in the NPV calculations.

While the final decision by NASA to pursue a technology development program must include consideration of the cost of applicable launches, these costs have not been included in our analysis here as a matter of convenience. For it is expected that a number of experiments would be placed in orbit by one launch vehicle, so that the launch costs would be spread over a number of programs. A launch, then, is best considered as a cost of a package of experiments, and any attempt now to prorate costs on the basis of an unknown package would be completely arbitrary. It is sufficient for NASA to determine whether the benefits of the technologies in a package exceed their costs by at least the cost of the necessary launch(es).

3.5 Sensitivity Analysis Procedure

The sensitivity analysis is carried out in a straight forward manner. A variable is selected to which NPV is sensitive, i.e., on which NPV depends. While all other variables are held at their baseline values, this variable is alternately set at predetermined points over a selected range and NPV calculated for each value. A convenient representation of the analysis is effected by plotting NPV against the values of the chosen variable. In this study, the range chosen is typically ±50%, and values chosen at 5% or 10% intervals for use in the NPV calculations.

SECTION 4

DEVELOPMENT OF ASSESSMENT METHODOLOGY

4.1 General Concepts

Risk analysis performed under the rubric of assessment methodology is a natural extension of sensitivity analysis performed under the banner of screening methodology. Sensitivity analysis indicates the range of variation in NPV as a particular variable is varied but it does not allow for

1) simultaneous variation in two or more input variables, and
2) the probability that variations of different magnitudes occur, either on a variable by variable basis, or on a joint basis.

The differences between sensitivity analysis and risk analysis can be illustrated with a general form of the NPV equation:

$$NPV = f(\tau, P_A, d, X, Y, \ldots)$$

Sensitivity analysis chooses a particular variable, say X, and while holding all other variables constant at τ, P_A, etc., finds the relation NPV = $g(X|\overline{\tau}, \overline{P}_A, \ldots)$ over some relevant range of X. Although this technique certainly provides information about the behavior of NPV as any one variable is varied, it does not fully explore the dependence of NPV on its arguments. For example, even if a sensitivity analysis were performed on each variable, little information would be provided on the movement of NPV as both X and Y changed. As a very simple example, suppose

$$NPV = Z_1 \cdot Z_2$$

and it is thought that the relevant ranges for the variables are

$$0 \leq Z_1 \leq 10, \ 0 \leq Z_2 \leq 10$$

A sensitivity analysis chooses a "best" value for each variable and varies one variable while all others are held at these fixed values. Suppose these "best" values are

$$\overline{Z}_1 = 5, \ \overline{Z}_2 = 5$$

Then the sensitivity analyses would involve investigations of the functions

$$NPV = Z_1 \cdot \overline{Z}_2 = Z_1 \cdot 5, \ 0 \leq Z_1 \leq 10 \text{ and}$$

$$NPV = \overline{Z}_1 \cdot Z_2 = 5 \cdot Z_2, \ 0 \leq Z_2 \leq 10$$

Plots of these relations exhibit all their relevant features. The single equations show NPV ranging from 0 to 50. These graphs give no information about NPV if neither Z_1 nor Z_2 equals 5 as is evident when a plot of the complete relation NPV = $Z_1 \cdot Z_2$ is considered. As can be seen in Figure 4. , the NPV in fact ranges between 0 and 100 and the sensitivity of NPV to either of the variables increase with the value of the other variable.* It is in this limited sense that a simple sensitivity analysis can be misleading.

It should be noted that elasticity calculations based on relations derived in a simple sensitivity analysis can also be misleading. This may be counter-intuitive because elasticity, based on percentage variations, is free of dependence on units of measurement.

For a relation

$$NPV = f(Z_1, Z_2, Z_3, \ldots)$$

the elasticity of NPV with respect to Z_i is denoted by

$$\xi_{NPV, \ Z_i}$$

and is defined as

$$\frac{\% \ \Delta \ NPV}{\% \ \Delta \ Z_i} \ .$$

*If Z_1 is varied by one unit, say 5 to 6, while A_2 is held at 1, NPV goes from 5 to 6. However, if A_2 were held at 10, NPV would move from 50 to 60.

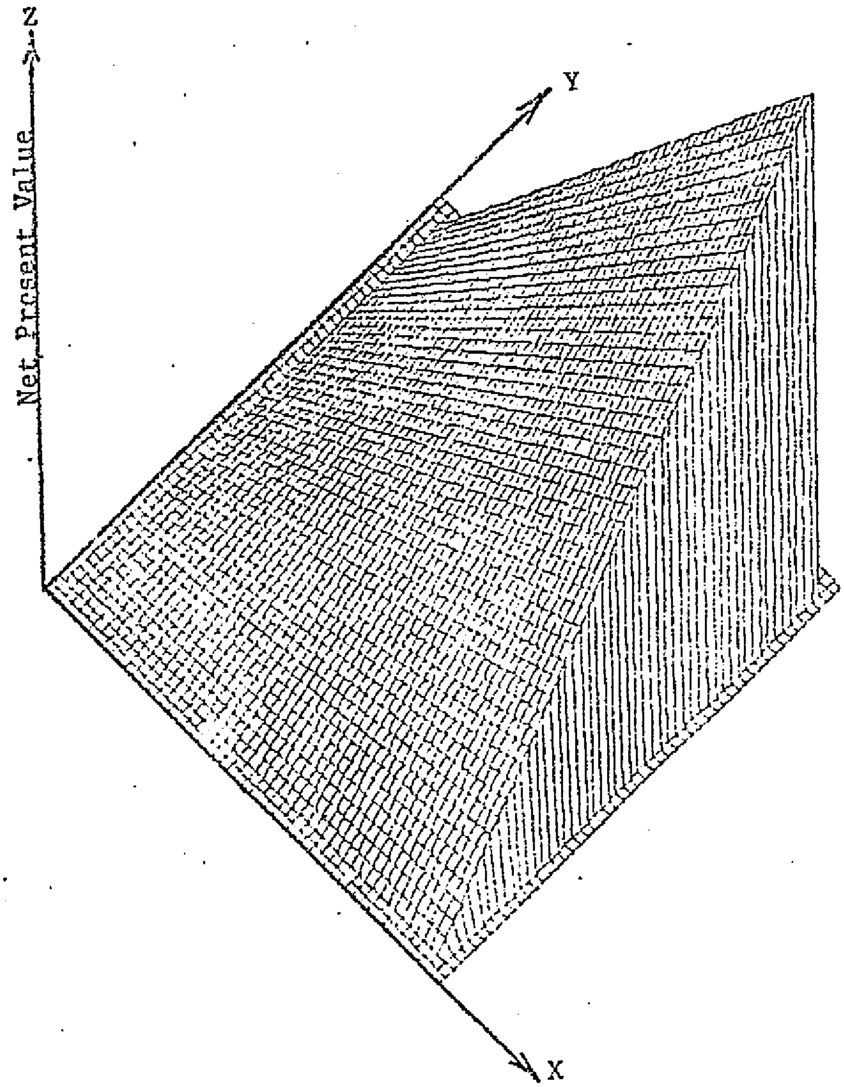


Figure 4.1. Example: NPV = X·Y

Further,

$$\frac{\%}{\%}\frac{NPV}{Z_i} = \frac{\frac{dNPV}{NPV}}{\frac{dZ_i}{Z_i}} = \frac{Z_i}{NPV}\frac{dNPV}{dZ_i}$$

Thus,

$$\xi_{NPV,\ Z_i} = \frac{Z_i}{NPV}\frac{dNPV}{dZ_i}$$

For some very special cases, an elasticity value deriv[?] from a sensitivity analysis can be correct. For example, in the above example, the relation

$$NPV = 5Z_1$$

was derived from a sensitivity analysis with Z_2 set at 5. Using this formula to compute elasticity, we have

$$\xi_{NPC,Z_1} = \frac{Z_1}{NPV} \cdot 5 = \frac{Z_1}{5Z_1} \cdot 5 = 1$$

This result is interpreted to mean that a 1% increase in Z_1 causes a 1% increase in NPV.

Now the true relation was specified as

$$NPV = Z_1 \cdot Z_2$$

Computing the elasticity based on the formula yields

$$\xi_{NPV,Z_1} = \frac{Z_1}{NPV} \cdot Z_2 = \frac{Z_1}{Z_1\ Z_2} \cdot Z_2 = 1$$

Thus, it happened that the sensitivity analysis gave rise to the proper elasticity value. It's easily seen, however, that this is not a general result.

Suppose NPV = $Z_1 \cdot Z_2 + Z_3$, and set $Z_2 = 5$, $Z_3 = 5$. The relation derived from sensitivity analysis on Z_1 is

$$NPV = 5Z_1 + 5$$

from which it follows that

$$\xi_{NPV,Z_1} = \frac{Z_1}{5Z_1+5} \cdot 5 = \frac{5Z_1}{5Z_1+5}$$

However, the true elasticity is

$$\xi_{NPV,Z_1} = \frac{Z_1}{Z_1Z_2+Z_3} \cdot Z_2 = \frac{Z_1Z_2}{Z_1Z_2+Z_3}$$

In general (i.e., for values of Z_2 and Z_3 not necessarily equal to 5),

$$\frac{5Z_1}{5Z_1+5} \neq \frac{Z_1Z_2}{Z_1Z_2+Z_3}$$

In addition to sensitivity analysis being potentially misleading in range estimates, plots, and elasticity calculations, a simple sensitivity analysis does not yield any information about the likelihood of different NPV values occuring. Since it is usually known which values of the input variables are more likely (to be true) than other values, there is clearly information being lost (or at least not being properly considered) in the simple sensitivity process. As will be elaborated upon later, this information can be quite significant.

A sensitivity analysis which takes account of the probability distributions of the input parameters can be called a risk analysis model. Although a risk analysis model need not necessarily take account of the joint variation in variable values, the model employed in the assessment stage of the analysis does take such joint variation into account.

In the next section a discussion will be given on some of the more formal aspects of a multivariate risk analysis assessment model that is part of the total methodology that has been developed.

4.2 The Multivariate Risk Analysis Model

As was seen in the foregoing general discussion of multivariate risk analysis, the approach generalizes and extends the ideas of sensitivity analysis and syntheses in a single NPV probability function virtually all the quantitative information relevant to the decision.

The purpose in this sub-section is to set out the details of the development and implementation of the multivariate risk analysis model as it applied to assessing the costs and benefits of alternate space communication technologies.

The key to operationalizing this methodology is in identifying the sets of independent variables which affect NPV and defining, in a meaningful way, the probability distributions over those variables. Once this is accomplished, the NPV's can be generated mechanically. With an approach incorporating random sampling, population parameters can be inferred from sample statistics, and the best estimate of the population distribution of NPV's constructed. It is this NPV distribution, in density cumulative form, which is the resulting decision-aid.

With regard to forming sets of independent variables, the procedure adopted is to assume most variables are independent of each other. Thus, the time delay variable, the discount rate, the cost in each stage, the benefit in the final (operation stages), and the probability of proceeding from one stage to the next were all assumed independently distributed. There is concern, however, that the time length of each stage is not independent of cost. Because of the nature of "crash" research programs, short stage-length might result in high costs. To alleviate this dependence when it occurs, it was decided to treat time as a constant in each stage. Such treatment is reasonable since R&D programs usually are carefully scheduled to dovetail with other programs. The management of such programs might be more inclined to concentrate more or less resources on the program as needed to maintain a schedule, rather than appreciably modify the schedule.

The number of variables which enter the assessment equation depends on the number of stages needed to adequately represent the course of resource inputs and outputs associated with any particular R&D effort. Two variables enter the equation independently of the number of stages; these are the discount rate and the time delay variable. With each stage are associated four variables:

- the time duration of that stage,
- the probability that that stage will be reached given the prior stage is reached (i.e., 1 - the probability that the project is terminated after the previous stage),
- the annual dollar value of benefits during that stage, and
- the annual dollar value of costs during that stage.

For a four stage process, the potential number of variables for which a probability density function (PDF) must be specified is $2 + 4 \cdot 4 - 1 = 17$. However, considerably fewer PDF's are needed. First, the discount rate is not a stochastic variable. Second, of the N-1 probability variables, typically only one or two will be treated as stochastic. Third, the benefit value of all but the final stage(s) will be zero. Finally, to alleviate the dependence problem mentioned above, the time variables usually will be treated as constants. In practice, a four stage risk analysis may need incorporate as few as seven stochastic variables.

In general, for N stages, the potential number of variables entering the analysis in 2 + 4N-1: 2 is the number of stage-independent variables, 4N-1 is the number of stage related variables. One is subtracted from 4N since, as the premise of the analysis, the probability of the first stage is defined as one.

Having discussed the formation of sets of independent variables, we now turn to the problem of defining the probability distribution over the possible outcomes. In the general discussion it was assumed, for expositional simplicity, that each variable could assume three possible values - high, middle, or low - and probabilities (summing to unity) were assigned to those three values. In the actual implementation, it is desirable to characterize the distribution of each input variable by a continuous PDF. This treatment allows for more flexibility in adapting the analytic representation to the empirical evidence.

Each input variable can be characterized by three parameters:

a most likely value (denoted as M),

a minimum value (denoted as A), and

a maximum value (denoted as B).

In general, the most likely (modal) value is not symmetrically situated with respect to the minimum and maximum values. That is, the distribution is skewed. It happens that a Beta distribution provides a very convenient and appropriate analytic form for characterizing the available three parameter input data. The Beta function is a four parameter distribution designated as B(a, b, c, d). The parameters a and b translate the distribution along the horizontal axis and c and d jointly determine the shape of the generally skewed distribution. The parameters a and b are simply the minimum and maximum of the distribution. A useful theorem for this development states that if X is distributed B(a, b, c, d), and $Z = \frac{X-a}{b-a}$, then Z is distributed B(0, 1, c, d). The PDF for a 0-1 normalized Beta variable, Z, is

$$B(Z) = Z^{c-1}(1-z)^{d-1} \cdot G(c,d)$$

where
$$G(c,d) = \frac{\Gamma(c) \cdot \Gamma(d)}{\Gamma(c+d)}$$

and
$$0 \leq Z \leq 1$$

Values selected randomly from the appropriate Beta distribution can then be used in generating the final NPV PDF. Since most Beta random number generators provide values in the 0-1 range, it is necessary to form a correspondence between the Beta distribution representing the actual values of the variable and a Beta distribution on the 0-1 interval. After a random drawing is performed on the 0-1 Beta PDF, the selected value is transformed back to its corresponding actual value for use in the NPV calculation. These several transformations are best accomplished by first mapping M, A, and B onto the 0-1 interval as

$$M \rightarrow m \equiv \frac{M-A}{B-A}$$

$$A \rightarrow 0$$

$$B \rightarrow 1.$$

From the above theorem, where the symbol means "assigned to" the transformed variable has PDF $B(0, 1, c, d)$ since the original variable was constructed as $B(A, B, c, d)$.

Clearly it is necessary to specify values for c and d to define the appropriate 0-1 Beta distribution. Since all three input data parameters M, A, and B collapse to m on the 0-1 interval, two independent parameters, c and d must be determined from one input parameter, m. Clearly, another input parameter is needed.

This problem is resolved by resorting to a convenient hueristic. Assume that the total dispersion in the Beta random variable is 6σ, as would be very nearly true for a normally distributed variable since the Beta variable ranges from 0 to 1/6. Now m and σ are available for the calculation of c and d.

The following results are the basis for the calculations of c and d.

If X is distributed $B(0, 1, c, d)$, then:

$$\text{Expected Value of } X = \frac{c}{c + d}, \tag{4.1}$$

$$\text{Variance of } X = \frac{cd}{(c + d)^2 \, (c + d + 1)}, \text{ and} \tag{4.2}$$

These two relations alone are not sufficient to identify the two Beta parameters c and d from the input parameters m and σ since m is a modal value and its relation to the expected value of X is still unspecified. The following relation alleviates the problem [3].

$$\text{Expected Value of } X \approx 1/3 \, [2m + \tfrac{1}{2}] \tag{4.3}$$

This is a useful hueristic relation between the mean and mode of X.

Equations 4.1 and 4.3 may be combined to express the relation between c, d, and the input value, m.

$$\frac{c}{c + d} \approx \frac{2m + 1/2}{3}$$

which may be rearranged in the form

$$m = \frac{5c - d}{4(c + d)}$$

With m and σ as known constants, equation 4.2 and 4.4 are sufficient to determine c and d. The solution is

$$c = \frac{K^2 + 34K - 1}{(1 + K)^3} \text{ , and} \tag{4.5}$$

$$d = cK \text{ where} \tag{4.6}$$

$$K = \frac{5 - 4m}{1 + 4m} \tag{4.7}$$

Equation 4.3 is being treated as an exact relation. Tests which were made as part of this development indicate this treatment introduces insignificant error to resulting estimates of c and d.

9.3 Illustrative Example

An example will illustrate the approach outlined in the above development. Suppose a cost-benefit analysis is to be performed of a new technology for extracting oil from shale. Because most of the key variables influencing NPV exhibit a fair degree of uncertainty it is decided to present the results of the CBA in the form of a multivariate risk analysis. This form of analysis and presentation captures all the salient aspects of the problem and provides the decision-maker with a powerful decision tool. One of the variables of interest is the "development" cost of the new technology - the cost of bringing the technology from the laboratory stage to an operational mode. Suppose the estimates of this cost are

Most Likely Value:	M = \$15,000,000
Minimum Value:	A = \$12,000,000
Maximum Value:	B = \$25,000,000

It is assumed that this information can be adequately characterized by a Beta PDF, B(A,B,C,D) where C and D reflect M and an assumed $\sigma \frac{B-A}{6}$.

The objective is to transform this Beta PDF into a normalized Beta PDF, B(0,1,c,d). Computerized random choices from this normalized PDF may be drawn; an inverse transformation performed to scale the variables.

back up to their real value in the (A, B) interval; and these values then combined with random drawings from distributions on the other key variables to calculate a sample of NPV's.

For the above example,

$$m = \frac{\$15,000,000 - \$12,000,000}{\$25,000,000 - \$12,000,000} = .23$$

and, it is assumed

$$\sigma = .17.$$

From equation 4.7,

$$K = \frac{5 - 4(.23)}{1 + 4(.23)} = \frac{4.08}{1.92} = 2.13$$

and from equations 4.5 and 4.6,

$$c = 2.48$$
$$d = 5.28.$$

The normalized distribution is B(0, 1, 2.48, 5.28). Random drawings from this normalized Beta distribution are used to complete the corresponding full scale values. The later figures are calculated by the inverse transformation

$$X = x(B - A) + A$$

where x is the normalized Beta variable and X is the corresponding full scale value. Figure 4.2 is a histogram depicting the frequency distribution of a sample of size 100, and Figure 4.3 is a graph of the theoretical distribution of B(0, 1, 2.48, 5.28).

Once a set of values is generated for each stochastic variable influencing NPV, the final NPV calculations can be made. Figure 4.4 is a frequency distribution for the NPV of a project based on a 1000 point sample from the distribution of each stochastic variable. Figure 4.5 is the corresponding

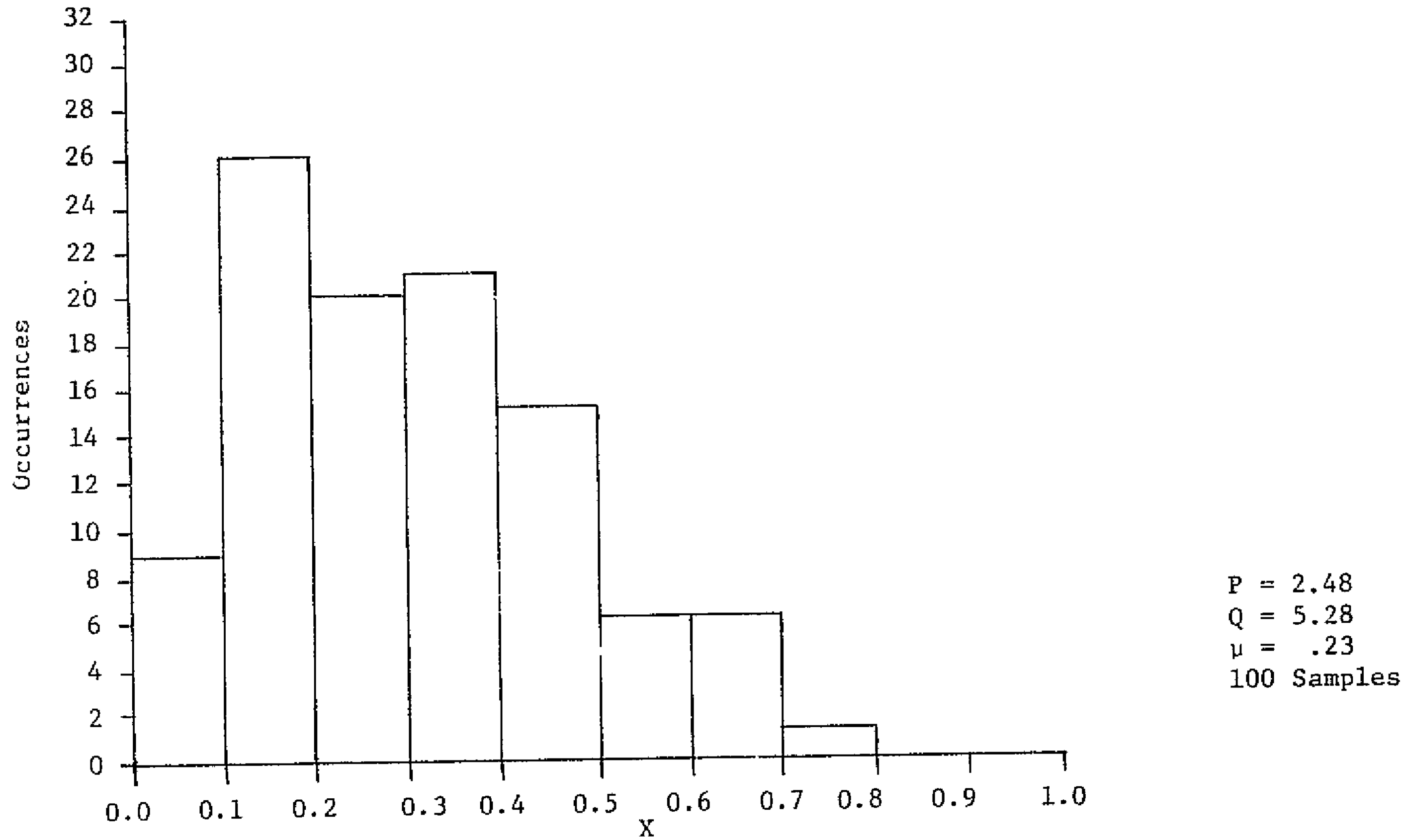


Figure 4.2. Beta Random Number Generator Histogram

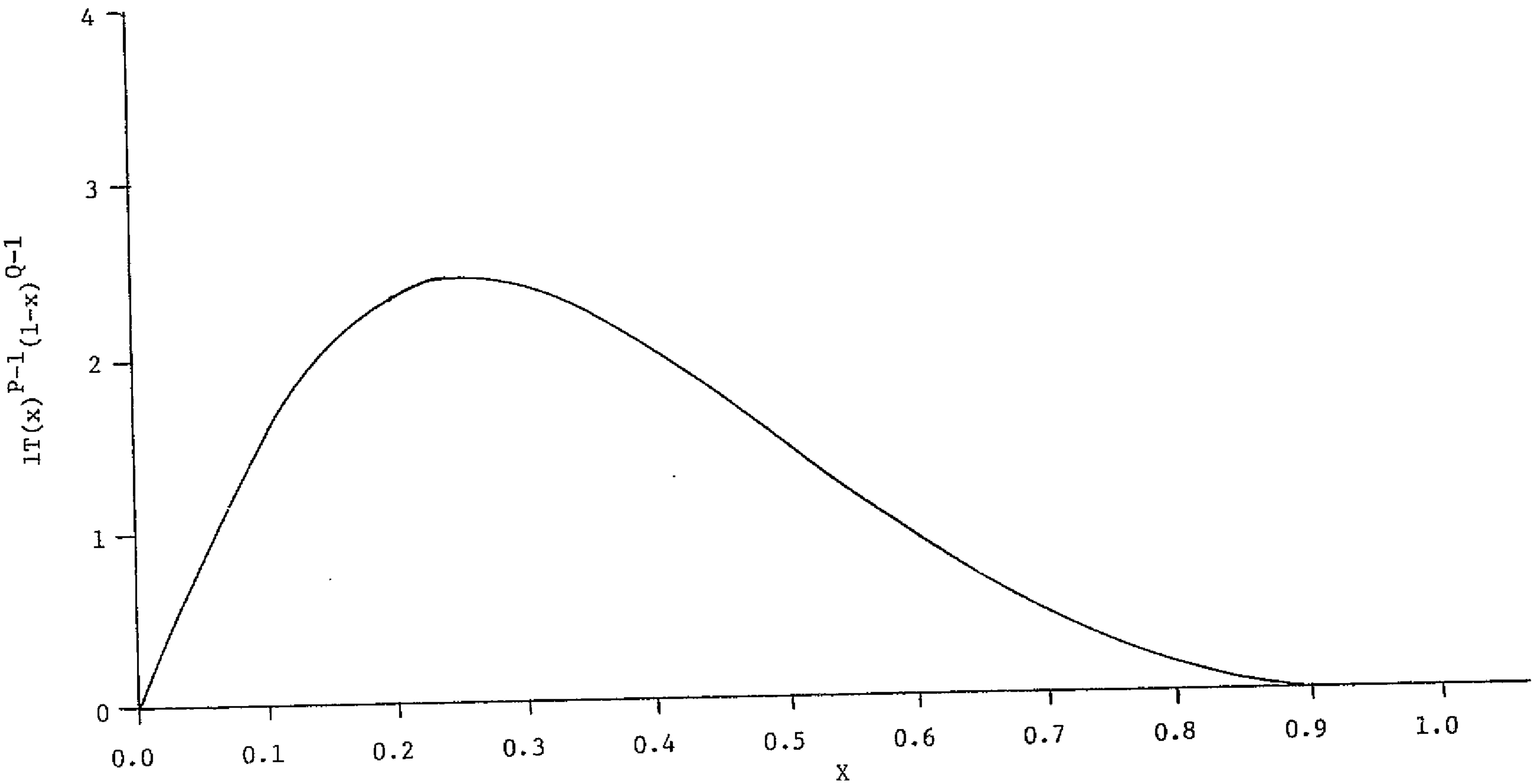


Figure 4.3 . Beta Distribution Probability Density Function

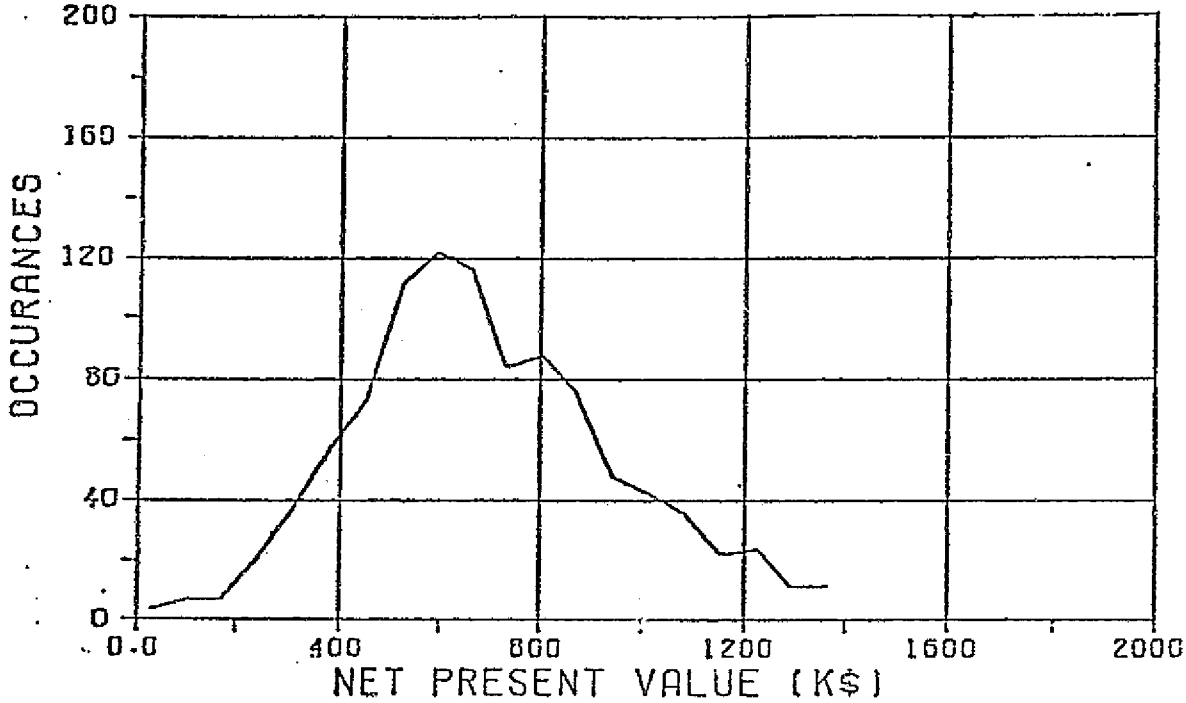


Figure 4.4. Frequency distribution for the NPV of a project (1000 point sample).

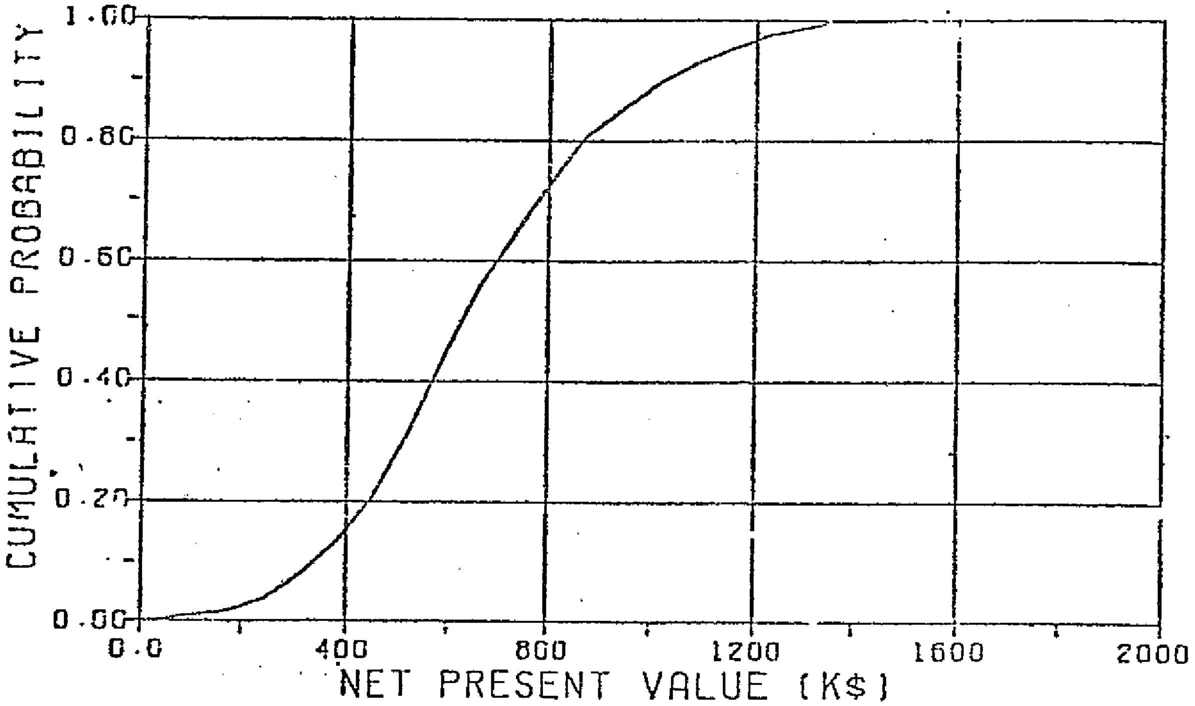


Figure 4.5. Cumulative density function for the NPV of a project.

cumulative density function. This is the display that we consider to be most useful to decision-makers. For the example project, the probability of a positive NPV is near unity, and the probability of a NPV in excess of $1 million is about 10%. The mean NPV is about $600,000. The NPV is between $400,000 and $800,000 with a probability of about 60%.

4.3 Linearized Multivariant Risk Analysis Model

Application of the multivariant risk analysis model described in sub-section 4.2 requires the use of a Monte Carlo-type simulation which evaluates the NPV equation repeatedly for many random samples of the input parameters. An alternate approach which quickly provides an approximation to the NPV probability distribution function is described in this sub-section.

Application of the screening sensitivity analysis led to the observation that the NPV equation is very nearly linear over the range of interest in the input variables. This observation, together with the simple expression for the PDF of a linear function of Gaussian random variables [4], led to the development of a linearized model for the multivariant risk analysis. When a random variable can be written as a linear function of the form

$$y = C_0 + \sum_{j=1}^{J} C_j (x_j - M_j)$$

with the input random variables normally distributed

$$x_j \sim N(M_j ; \sigma_j^2),$$

the resulting random variable will also be normally distributed with mean C_0 and with variance given by the following:

$$\sigma_y^2 = \sum_{j=1}^{J} (C_j \sigma_j)^2 .$$

The development of the linearized risk analysis model for communications technology assessment requires two assumptions: linearity of the NPV equation in the region of interest and validity of approximating the distributions of the input random variables as being Gaussian. The first assumption has been validated by the sensitivity analyses performed during study. Arguments for the validity of the Gaussian assumption on the input parameters should be based upon comparison of the approximate results with results from the full Monte Carlo-type risk analysis simulation. Such comparisons conducted during the course of the program support the argument for validity of the linearized methodology.

Development of the linearized risk analysis model requires linearization of the NPV equation and formulation of the resulting variance or standard deviation equation. For this analysis the continuous form of the NPV model is used. For an N-stage process, the continuous form of the NPV equation is as follows.

$$NPV = \left\{\frac{1-e^{-\tau d}}{d}\right\} \left\{ \sum_{n=1}^{N} \left(\left[\prod_{m=1}^{n} P_m \right] \cdot \left[B_n - C_n \right] \cdot \left[\prod_{m=0}^{n-1} \left(e^{-dT_m} \right) - \prod_{m=0}^{n} \left(e^{-dT_m} \right) \right] \right) \right\} .$$

The linearized form is developed from a truncated Taylor series as follows

$$NPV \approx f(M_1, M_2, \ldots, M_J) + \sum_{j=1}^{J} \left\{ \frac{\partial f}{\partial x_j} \Big|_{\underline{u}} (x_j - M_j) \right\} ,$$

where $NPV = f(x_1, x_2, \ldots, x_J)$.

The required partial derivatives of the NPV with respect to the random input parameters are

$$\frac{\partial (NPV)}{\partial \tau} = \left\{ \frac{(NPV) \cdot d}{e^{\tau d} - 1} \right\},$$

$$\frac{\partial (NPV)}{\partial P_i} = \left\{ \frac{1 - e^{-\tau d}}{P_i \, d} \right\} \left\{ \sum_{n=i}^{N} \left(\left[\prod_{m=1}^{n} P_m \right] \cdot \left[B_n - C_n \right] \cdot \left[\prod_{m=0}^{n-1} \left(e^{-dT_m} \right) - \prod_{m=0}^{n} \left(e^{-dT_m} \right) \right] \right) \right\}$$

for $P_i \neq 0$,

$$\frac{\partial (NPV)}{\partial (B_i - C_i)} = \left\{ \frac{1-e^{-\tau d}}{d} \right\} \cdot \left\{ \left[\prod_{m=1}^{i} P_m \right] \cdot \left[\prod_{m=0}^{i-1} \left(e^{-dT_m} \right) - \prod_{m=0}^{i} \left(e^{-dT_m} \right) \right] \right\},$$

and

$$\frac{\partial(NPV)}{\partial\ T_i} = \left\{1-e^{-\tau d}\right\}\left\{\left[\prod_{m=1}^{i}\left(P_m\ e^{-dT_m}\right)\right]\cdot\left[B_i - C_i\right] - \sum_{n=i+1}^{N}\left(\left[\prod_{m=1}^{n} P_m\right]\left[B_n - C_n\right]\right.\right.$$

$$\left.\left.\left[\prod_{m=0}^{n-1}\left(e^{-dT_m}\right) - \prod_{m=0}^{n}\left(e^{-dT_m}\right)\right]\right)\right\}.$$

The resultant linearized NPV expression is

$$LNPV = \left\{(NPV)_o + (\tau - \tau_o)\left(\frac{\partial(NPV)}{\partial\tau}\right)_o + \sum_{i=1}^{N}\left[(P_i - P_{i_o})\cdot\left(\frac{\partial(NPV)}{\partial\ P_i}\right)_o + \left([B_i - C_i] - \right.\right.\right.$$

$$\left.\left.\left.[B_i - C_i]_o\right)\cdot\left(\frac{\partial(NPV)}{\partial(B_i - C_i)}\right)_o + (T_i - T_{io})\cdot\left(\frac{\partial(NPV)}{\partial\ T_i}\right)_o\right]\right\}.$$

A computer program, called QWKRISK, has been developed which accepts the mean and standard deviation of the assumed Gaussian distribution for each of the input parameters, and produces the standard deviation of the linearized NPV expression. Comparison of the resultant standard deviation from QWKRISK and from the full Monte Carlo simulations for each of the technologies treated is presented in the applications sections of this report. In general, the correspondence is quite good, and it is recommended that the linearized approach be utilized in future studies to conserve computer time.

SECTION 5

THE RANKING METHODOLOGY

In an assessment (multivariate risk) analysis, each technology of interest is characterized by a cumulative density function (CDF) over the NPV of that NASA R&D project. In the absence of a scalar "figure of merit" for each technology, ranking technologies from most promising to least promising becomes a non-trivial task. The problem is reflected in the fact that the assessment methodology described in Section 4 varies statistically derived values to be compiled about each technology. Calculations can be made to determine the following:

Minimum NPV
Maximum NPV
Mean NPV
Median NPV
Modal NPV
Probability (NPV $\geq$ K), K = any dollar value
Standard Deviation of NPV
Range of NPV, i.e., MAX-MIN

Technologies may be ranked according to any of the above statistics. However, each statistic produces a ranking which may be different from the rankings produced by each other statistic. As an illustration, the three hypothetical CDF's of three different technologies shown in Figure 5.1 will be used in establishing rankings by the three ranking criteria: 1) greatest minimum value, 2) greatest maximum value and 3) greatest mean value.

These three criteria result in the following rankings when applied to the three technologies.

Criterion 1	Criterion 2	Criterion 3
A	B	B
B	C	A
C	A	C

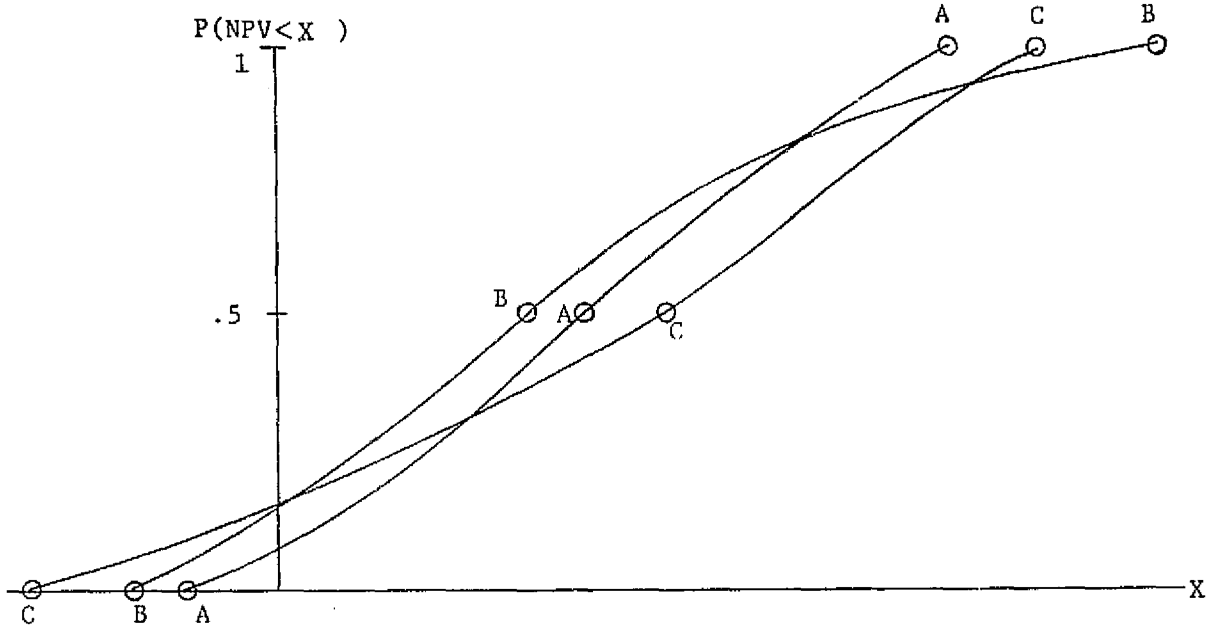


Figure 5.1. Possible Ranking Relations

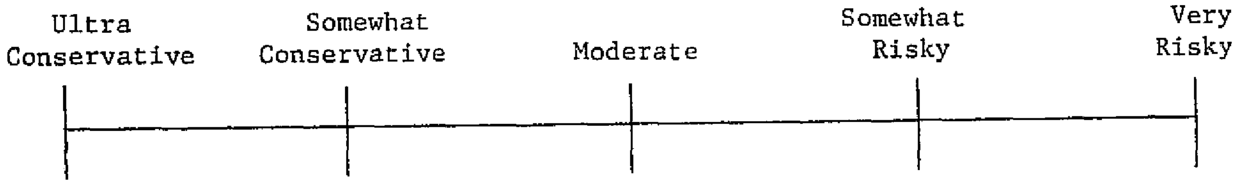


Figure 5.2. The Risk Spectrum

The rankings show it is possible for a technology to be ranked first by one criterion, second by another, and last by still another. Indeed, each of the three technologies in the example satisfy that description. A priori, there is no reason to prefer the ranking from one statistic over the ranking from another, independent of the decision-maker's own criteria. That is, the various statistics do not themselves answer the ranking question. Rather, the objectives of the decision-maker must somehow be accounted for. The best statistic, then, is one which best reflects the decision-maker's goals and his willingness to trade-off among sub-goals. Let us approach the issue "parametrically" by considering different potential tasks a decision-maker would adapt. These different tasks can be viewed as different approaches to risk. Indeed, a risk spectrum along which decision criteria (hence underlying statistics) lie might be utilized. Such a spectrum is presented in Figure 5.2.

Statistics may be associated with each point of the spectrum, and criteria may be formed from these statistics as shown in Table 5.1.

TABLE 5.1

APPROACHES TO RISK, CORRESPONDING STATISTICS, AND RANKING CRITERIA

Approach	Statistic	Criterion*
Ultra-Conservative	Minimum NPV	π_1 B $\pi_2 \leftrightarrow$ MIN NPV_1 > MIN NPV_2
Somewhat Conservative	Prob(NPV > 0)	π_1 B $\pi_2 \leftrightarrow$ Prob(NPV_1 > 0) > Prob(NPV_2 > 0)
Moderate	$\mu - k\sigma$, $k>0$	$\pi 1$ B $\pi 2 \leftrightarrow$ $\mu_1 - k\sigma_1 > \mu_2 - k\sigma_2$
Somewhat Risky	μ	π_1 B $\pi_2 \leftrightarrow$ $\mu_1 > \mu_2$

* "π_1 B π_2" means project 1 is better than project 2. "$\leftrightarrow$" means if and only if.

TABLE 5.1 (continued)

Very Risky	Maximum NPV	π_1 B $\pi_2 \leftrightarrow$ MAX NPV_1 > MAX NPV_2

There is no one "right" approach to be taken in ranking technologies. Also, the alternate approaches are not necessarily mutually exclusive. It may (indeed, it is likely to) be the case that different criteria yield the self-same ranking. Additionally, the different criteria may be used lexicographically, that is, the criteria are ranked in order of importance, and technologies are compared first on the basis of the most important criteria. If a tie results, the second criterion is used, and so on. When there is no tie, the ranking process stops. Yet another task is to use certain criteria as constraints, e.g., that Prob(NPV > 0) must be at 75% or that MIN NPV must exceed $1,000,000.

The foregoing discussion presumes that each technology is independent* of each other technology. This is not always an appropriate assumption, since many of the technologies under consideration involve components of larger systems. The development of a technology is of little or no value if it can be used only in conjunction with another technology which is yet to be developed. When such jointness occurs, there is no meaningful way to separate the value of the sum of the technologies into additive terms. Fortunately, the very difficulty of the conceptual allocation problem suggests the solution: there is no need to artifically assign values to individual technologies in the case of jointness. Rather, the undertaking of both (or "all" in the case of jointness among more than two technologies) must be considered a single R&D project. With all jointness thus intervalized in a single larger R&D project, by definition that larger project is independent of other projects. The larger project may now be ranked along with the other (assumed) independent projects by the criteria and statistics

*One technology is independent of another, if the CDF of the first is invariant with respect to whether or not the second is developed.

suggested above.

Ranking of joint products can and should be undertaken, in seeming contrast to the foregoing remarks. While it is true that ranking along the NPV dimension is ruled out, ranking along other relevent dimensions it not. Specifically, joint technologies should be ranked by "time to completion of R&D". Thus, if two technologies are joint, and the first has an R&D time of one year and the second an R&D time of 3 years, then the latter is ranked higher than the former. This gives priority to starting the R&D project with the longer lead time, <u>given the composite project has been adopted</u>.

Overall then, technologies are ranked lexicographically: first along an NPV dimension, and then, for joint technologies, along a time dimension. The following example will clarify the ranking procedure. Suppose there are ten technologies to be ranked. The technologies are labeled A, B, C,..., J. Suppose B, C, and E form a joint group; and D and G also form a joint group. Label the first group S_1 and the second S_2, so

$$S_1 = B, C, E, \text{ and}$$

$$S_2 = D, G$$

Assume the NPV ranking statistic is simply the mean value of the technologies' density functions, and assume the following means have been calculated:

$$\mu_A = 25 \qquad \mu_I = -50$$

$$\mu_F = 150 \qquad \mu_J = 250$$

$$\mu_H = 0 \qquad \mu_{S_1} = 210$$

$$\mu_{S_2} = 100$$

For the joint technologies, the following times-to-completion are estimated:

B	5 years	D	2 years
C	1 year	G	4 years
E	2 years		

The 2-dimensional ranking is pictured in Figure 5.3. The horizontal axis has first priority. It states J is better than S_1 which is better than F, etc. Once S_1 is adopted, the vertical axis shows the priority ordering among the components of S_1.

The ranking procedure followed above assumed no financial constraints on NASA. While this is somewhat unrealistic, it is instructive to determine the union strained technology ranking. This is a guide to long range budgeting for NASA planners. In the face of a financial constraint, a somewhat different ranking procedure must be followed to insure optimal results. Rather than ranking by NPV, the ranking should be done in accordance with the benefit/cost ratio. Under a financial constraint, the benefit/cost ratio ranking maximizes the NPV of the set of chosen projects. Paradoxically, ranking by the benefit/cost ratio, not NPV, maximizes overall NPV in the presence of a financial constraint. Thus, the relevant statistic is:

$$\frac{B}{C} = \frac{\text{Present Value of Benefits}}{\text{Present Value of Costs}}$$

and the ranking procedure is to rank and choose according to B/C until available funds are expended.

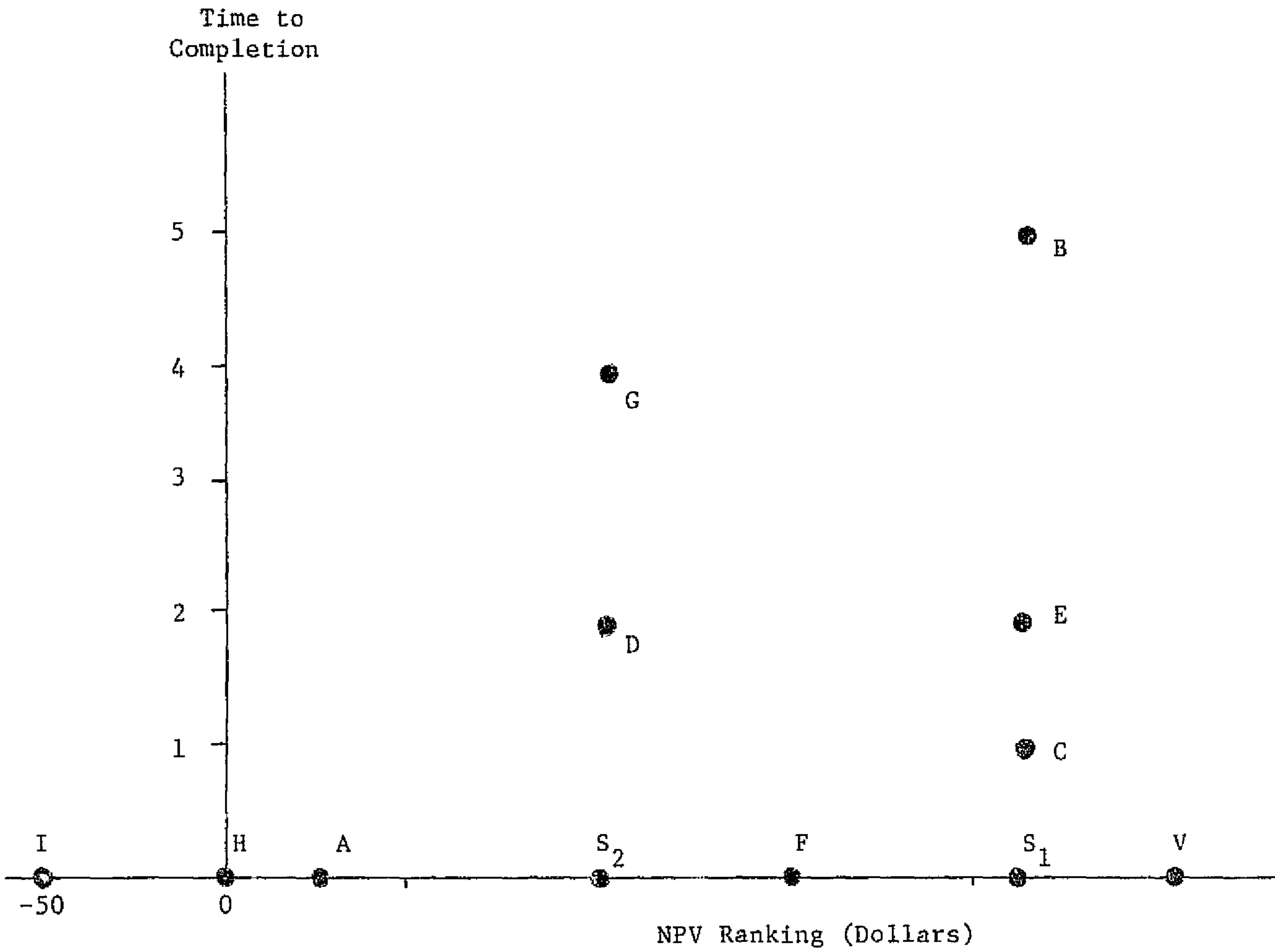


Figure 5.3. Lexicographic Ranking

PART II

SYNTHESIS OF CONCEPTUAL SYSTEMS

SECTION 6

ELEMENTARY CONCEPTS OF SPACE COMMUNICATION SYSTEMS

Commercial satellite communication systems in use today are in many respects similar to terrestrial microwave links. A link in either system consists of a transmitting station, a repeater station(s), and a receiving station. In the case of the satellite system the satellite is the repeater. The ANIK and WESTAR satellites can each support a minimum of 12 communications links and the recently launched RCA satellite can support a minimum of 24. These satellites can support exactly 12 and 24 links respectively if single carrier per transponder access is used. A link using this access technique begins at the user whose application, for example, may be bulk data transmission. The data could be modulated at the user site with a high speed modem and sent via terrestrial links to a satellite earth station. The modulated data carrying signal could be used to FM modulate an intermediate frequency (IF) signal. The IF signal would then be mixed with a microwave frequency signal (RF). The RF signal will be amplified and filtered to occupy a 36 MHz wide band of the RF frequency spectrum allocated for transmission to synchronous satellites. The RF signal will be introduced into waveguide feeding a large (30 meter for Intelsat stations) parabolic reflector antenna. An antenna on the satellite will gather and focus the RF signal into the satellite waveguide system where a network of filters will separate the allocated RF spectrum into the several 36 MHz wide bands (12 for ANIK and WESTAR and 24 for the RCA satellite). Each 36 MHz band will be power amplified, translated in frequency and introduced into the waveguide equipment for transmission to Earth. The equipment in the satellite which amplifies and translates one 36 MHz RF band is known as a transponder. The RF frequency is translated from a signal near 6 GHz transmitted from Earth to a signal near 4 GHz for transmission to Earth. Translation is required to prevent receiver interference caused by the transmitted signals. A large Earth station antenna will then gather the RF energy radiated by the satellite. Receiving equipment will then translate the RF signal to IF, demodulate the IF, and send the resulting signal via terrestrial links to the receiving user where a high speed modem will demodulate it reproducing the original data.

The quality of the satellite communication system depends upon the quality of each of the several links which comprise it. The quality of a link may be measured using several received signal standards all of which are a concern to the system designer. Some of these standards are distortion (phase, amplitude and frequency), depolarization, interference from other links, antenna pointing errors and white thermal noise introduced at all points in the system. All of these standards may be combined into a single standard. This single standard used by most system designers is the RF signal carrier power to receiver noise power ratio (C/N). Each component in a link contributes to this ratio by supplying an increase (gain) to the noise and carrier powers introduced into that component or by introducing noise directly. A simplified but useful expression for C/N known as the link equation is

$$C/N = P_t+G_t+G_r-N_t-N_r-L_{fs}-L_r-D_m-P_1-P_p$$

where C/N = carrier to noise ratio

P_t = transmitter power

G_t = transmitting antenna gain

G_r = receiving antenna gain

N_r = receiver noise

N_t = transponder noise

L_{fs} = free space loss plus atmospheric attenuation

L_r = loss due to rain

D_m = design margin

P_1 = polarization loss

P_p = positioning loss

The demodulation process from IF to baseband frequency is usually non-linear; therefore, the C/N ratio is not directly proportional to the baseband signal power to noise power ratio (S/N) which is the ultimate measure of link quality as the baseband signal is the signal of interest to the user.

If FM demodulation is used the following expression may be used to calculate S/N [5]:

$$\frac{S}{N} = \frac{C}{N} \times \frac{3}{2} m^2 \times \frac{B}{b}$$

where (S/N) = signal-to-noise ratio after demodulation (baseband)

C/N = carrier-to-noise ratio at the receiver input

C = received carrier power before demodulation

$N = KT_rBF$ = equivalent receiver noise power before demodulation

F = receiver noise figure

$K = 1.38 \times 10^{-23}$ watt-sec/°K = Boltzmann's constant

T_r = 290°K = room temperature

B = receiver bandwidth before demodulation

b = bandwidth at receiver output after demodulation (baseband)

$m = \Delta F/b$ = modulation index or deviation ratio

ΔF = peak frequency deviation for peak modulation by the full baseband signal

The system capacity of a communication link is defined as the maximum rate of transmitting information through that link. For a simple digital communication system which transmits data as pulses with n recognizable levels (amplitude, phase, or frequency, etc.) with pulse-to-pulse interval τ , the system capacity is given by:

$$C = (1/\tau)\log_2(n) \quad \text{bits/second.}$$

The maximum rate of transfering information is seen to increase with system bandwidth (allowing more frequent pulse transmission and smaller values of τ) and with the number of recognizable levels of signal in the presence of noise. A more general expression for communications system capacity in which the system bandwidth and signal to noise ratio appear explicitely is given by:

$$C = (B)\log_2(1 + S/N) \qquad \text{bits/second.}$$

For a fixed allowable bandwidth, as is often the case in space communications systems, specification of a required rate of information transfer (capacity) estalished the required value of S/N. Application of the relationships between C/N and S/N for the applicable modulation method then results in a specified minimum allowable value for C/N for adequate link performance. Given the minimum C/N and cost-performance characteristics of communication subsystems, the system designer can examine the available engineering trade-offs to meet the required link performance at the minimum cost.

The methodology and applications described in this report are intended as aides to the decision maker in specifying space communication technologies which, if developed, would allow provision of either increased communication capacity (and therby services) or decreased cost of a specified capacity. The user-need and technology state of the art surveys of Sections 7 and 8 provide the necessary data base for application of the technology evaluation methodology developed in previous sections.

SECTION 7
USER SURVEY

7.1 Nature

The purpose of the survey was to ascertain and define the needs, choices, and preferences of the providers/users of space communications technology, which would influence the rate of innovation introduction into future satellite communication systems. The survey sought to determine user acceptance of (or resistance to) new concepts, and to measure demand for space communications.

The survey elements consisted of a list of user organizations to be contacted and a set of questions to be asked of each user contacted. The list of user organizations was structured to include providers of satellite communication services (since providers of service are users of the technology) and also users of satellite communication services. The latter category included business, government, and social service agencies.

The questions to be asked in the course of the survey were designed to elicit information deemed to be useful for the cost-benefit study. The structure of the cost-benefit screening methodology itself depended to some extent on the user survey information; while the information required depended on the demands of the cost-benefit methodology.

Users of presently active space communications facilities were unaware of the implications of the new technology. Many of those contacted were immersed in problems common to any new, high technology enterprise during 1975--adequate financing. They were preoccupied with converting existing technology into productive enterprises.

7.2 Provider/User Survey

Contact was established with representative members of the satellite communications industry, government agencies, and others who either provide or use satellite communications technology. The initial list assembled for the survey was generated from news items and other references in technical and trade literature and included 60 organizations. Thirteen were providers; 47 were users of satellite communication services. Providers were defined as those organizations which owned a working satellite, or had active applications for licenses before FCC to own satellites. Users were defined as those organizations which neither owned nor intended to launch satellites. The 47 users included 19 government and non-profit public service organizations, and 28 profit-oriented organizations.

Out of the initial list of providers and users of satellite communication technology, 42 were contacted. Eight were providers of satellite communication service; 34 were users. Of the users, 17 were government/public service agencies and 17 were private corporations. Table 7.1 lists the organizations contacted.

The following subsections list 5 providers, 11 government/public service users, and 12 profit-oriented users of satellite communication technology. These organizations responded to contacts and furnished some of the desired information. The listing includes key letters that define the type of contact made. The key letters are:

T - Responded via telephone

Q - Responded via questionnaire

L - Responded by sending literature

P - Responded through personal interview

7.2.1 Providers Responding

American Satellite Corporation (TL) - As of February 1975, the American Satellite system consisted of 4 government traffic earth stations, 3 commercial earth stations, and 6 additional proposed earth stations. American Satellite Corporation provides private line voice, data, facsimile, and wideband communication services over 3 transponders leased full-time on WESTAR. They plan to launch a satellite in 1977.

AT&T/GTE/COMSAT General (L) - The joint endeavor by AT&T, GTE Satellite Corporation, and COMSAT General will launch 3 geosynchronous satellites, each of which has a capacity of 24 one-way transponders (1,200 voice circuits per transponder), 9 earth stations (2 of which are owned by other carriers) and terrestrial links from the earth stations to facility junction offices. The FCC license stipulates that access must be available to other users.

RCA Global Communications (TQ) - The RCA SATCOM system will accommodate any combination of video, switched or point-to-point voice, teleprinter, data, facsimile, or other wideband transmission. During Phase I of the system, RCA first based 2 transponders full-time from TELESAT on ANIK II, and then

TABLE 7.1

ORGANIZATIONS CONTACTED IN
SATELLITE COMMUNICATION USER SURVEY

Providers	Users	
	Government Related Agencies	Private Industry
Amercian Satellite Corporation	Educational Television Center	American Broadcasting Co.
AT & T/GTE/COMSAT	Archdiocese of San Francisco	American Television and Communications Corp.
INTELSAT	Corporation For Public Broadcasting	Cox Cable Communications, Inc.
RCA Global Communications	Educational Television Services	National Data Corporation
CML (IBM/COMSAT)	Georgia Department of Education	Teleprompter Corporation
Western Union Telegraph Co.	Bureau of Mass Communications	United States Lines, Inc.
National Satellite Service (Hughes)	New York State Department of Education	American Can Company
Western Tele-Communications, In.c	Appalachian Regional Commission	American Trucking Association
	Department of Justic (LEAA)	Home Box Office
	Office of Telecommunications Policy	Muzak Corporation
	Public Broadcasting Service	Prudential Grace Lines, Inc.
	U.S. Postal Service	Canadian Broadcasting Corporatio
	Federation of Rocky Mountain States, Inc.	American Petroleum Institute
	Southern Education Communications Association	Coca-Cola Company
	U.S. Geological Survey	Southern Pacific Communications
	Department of Transportation	Telecable Corporation
	Federal Aviation Administration	ITT World Communications
	Maritime Administration of Department of Commerce	
	Medical University of South Carolina	
	American National Red Cross	

leased 5 transponders full-time from Western Union on WESTAR. Under Phase II, RCA will eventually have 17 earth stations operational on up to three, 24-transponder satellites. Launch of the first satellite was in December 1975.

Western Union Telegraph Co. (TP) - The system provides for private voice channels, data at 9600 bits/sec., and black and white facsimile (on a data basis) over 2 ANIK type, 12 transponder satellites. A total of 15 earth stations are currently funded with a projected need for 5 more; a third satellite will be needed as a spare.

CML Satellite Corporation (T) - CML plans to pioneer 12-14 GHz commercial satellites providing high-speed computer-to-computer service, with sophisticated systems having high information capacity. Higher radiated power and the higher frequencies (as compared to the 4-6 GHz satellites) will permit the use of smaller earth station antennas, and the penetration of downtown locations.

7.2.2 Users--Government/Public Service

American National Red Cross (T) - Communications were set up in a disaster area, as experimental demonstration.

Educational Television Center Archdiocese of San Francisco (TQL) - Live/interactive teleconferencing for teachers was set up in CTS experiments.

Corporation for Public Broadcasting (T) - Programming will be provided to a nationwide network of educational television stations.

Educational Television Services, Georgia Department of Education (TP) - PBS programming will be received, taped, and rebroadcast.

Bureau of Mass Communications, New York State Department of Education (TQ) - Bibliographic data exchange between libraries was planned, but aborted for lack of funds.

Appalachian Regional Commission (T) - Service education program included 2-way interactive seminars.

Department of Justice (LEAA) (TP) - Fingerprints and criminal justice information transfer were proposed.

Public Broadcasting Service (T) - Programming service was provided to PBS member stations.

U. S. Postal Service (TL) - Electronic mail service is being examined.

Federation of Rocky Mountain States, Inc. (TL) - Social services made available including educational, career, and community oriented programs.

U. S. Geological Survey (TQ) - One-way high resolution video required.

7.2.3 Users--Private Industry

American Broadcasting Co. (TQ) - Radio and television programming will be distributed to nationwide network.

American Television and Communications Corporation (TQ) - Will offer independent programming over CATV as received from Home Box Office.

Cox Cable Communications, Inc. (TQ) - Will distribute programming as received from Home Box Office to CATV networks.

National Data Corporation (TQ) - Leasing two-way data, and two-way voice circuits.

Teleprompter Corporation (TQ) - Will distribute programming as received from Home Box Office, to CATV systems.

United States Lines, Inc. (TQ) - Requires voice and data links to ships (via maritime satellite).

American Can Company (T) - Requires occasional facsimile and voice links.

Home Box Office (T) - Independent programming will be provided to CATV systems.

Muzak Corporation (T) - Industrial, business, and entertainment background. Music will be provided direct to customers.

Prudential Grace Lines, Inc. (T) - Communications to ships (via maritime satellite) will be required.

Canadian Broadcasting Corporation (QL) - Television programming is provided to a nationwide network.

American Trucking Association (T) - May require communications and dispatch network run similar to airlines.

7.3 Methodology

7.3.1 Telephone Survey

Four of the five providers and 22 of the 23 users who were contacted were interviewed by telephone. The telephone interviews were structured in the following manner: An introduction was given, stating name, organization, and purpose of call indicating that a survey for NASA in regards to recent and proposed usage of communication satellites. The intent of the survey was to find out what NASA can contribute in research and development to meet needs for new technology. Information was then obtained from the various contacts. The initial question was whether the contact considered his firm to be a "user" or a "supplier" of comunication satellite services. Other questions included in the survey are outlined below.

Users were asked to give their present usage in the categories:

1. voice
2. data
   - error rate requirement
   - 1 or 2 way transmission
   - baud rate
   - would a delay be permissible?
3. video
   - color or black and white
   - 1 or 2 way
   - would a delay be permissible?
4. number and geographic distribution of earth stations.

Also they were asked to predict their future usage, if any, and to identify high cost problem areas.

Suppliers were asked to give an estimate of present demands for service from earth stations in terms of:

- equivalent voice channels
- video channels (color or black and white)
- data networks (baud rates).

They were also asked to identify:

- high cost problem areas
- technology choices and preferences
- degree of demonstration required for the technology.

Satisfactory telephone interviews were completed with 26 of the 42 organizations that were contacted in the sense that each of the agencies had personnel who were aware of the satellite communications technology used by the organization. Reponses to the interviews that were completed have been evaluated in Table 7.2 where poor, fair and good refers to

TABLE 7.2

EVALUATION OF RESPONSES TO
TELEPHONE INTERVIEWS

CATEGORY	QUALITY OF RESPONSE			
	Poor (No.)	Fair (No.)	Good (No.)	Total (No.)
Providers	1	1	2	4
Government Related	1	2	7	10
Private Industry	1	2	9	12

the general relative quality and quantity of the information obtained.

7.3.2 Mail Survey

Questionnaires were mailed to the 42 potential contacts listed in Table 7.1. The questionnaire without the cover letter that was mailed to the 8 providers and 34 users of satellite communications is given in Table 7.3.

Out of 42 questionnaires mailed, 11 were returned. Some companies did not consider the questionnaire related to their needs, but sent literature about their satellite communication services instead of replying to the questions. The better relative response to telephone queries as compared to the mailings should be noted. Two recipients of the questionnaires telephoned their responses.

Table 7.4 is an assessment of the responses to the questionnaires.

7.3.3 Personal Interviews

Interviews were held with key personnel of the following organizations:

1. Western Union/WESTAR Sales, Atlanta, Georgia.
2. Educational Television Services, Georgia Department of Education, Atlanta, Georgia.
3. U. S. Department of Justice, LEAA, Washington, D.C.

7.3.3.1 Western Union/WESTAR

The information obtained from this organization included the following:

1. investment costs--$200,000 for each 2-way earth station, $100,000 for receive only stations
2. tariffs--$500, $700, and $1,000 per voice channel per month over U.S. continental links graded as 0-1000 miles, 1000-1900 miles, and over 1900 miles
3. planned earth station complement--20 by September 1975.
4. Rates--up to 60% cheaper than terrestrial links.

Service offered, besides voice channel rental, includes full-time leasing of transponders--5 to RCA GLOBCOM, 3 to American Satellite Corp. Types of uses for the satellites include voice, data, facsimile (Xerox). Initially, the demand for channels and transponders was slow, such that a

TABLE 7.3

USER NEEDS FOR SATELLITE COMMUNICATION

1. Does your organization now use or plan to use satellite communications?
   No ____ Yes (Present) ____ Yes (Future) ____
2. If your answer was "yes", please indicate type and amount of usage.
   Present Usage:
   No. of equivalent voice circuits used: ______________
   Terminals: Between* ____________________ and ____________________
   Between ____________________ and ____________________
   *For example, Between New York and Detroit.

   No. of Transponders: ______________
   No. of earth stations; (Receive only) _____ (Two-way) __________

   Future Usage:
   No. of additional voice circuits planned for next five years ______
   Next ten years __________

   New Terminals: Between ____________________ and ____________________
   Between ____________________ and ____________________
   No. of transponders planned for future: Next five years _________
   next ten years ________.
   No. of earth stations needed: In five years _______. In ten years ___
3. Please rank order of importance (No. 1 indicating highest importance) the types of satellite communication service:
   Two-way telephone: _____
   Low-speed data: Two-way _____ One-way _____
   High-speed data: Two-way _____ One-way _____
   Facsimile: _________
   Video: Two-way _____ One-way _____
   Black and White _____ Color _____
   Other: ______________
4. System characteristics you need:
   Commercial telephone system links to earth stations are:
   Preferable ____ Usable _____ Not usable _____
   Satellite terminals (eliminating telephone links) at final user input and/or output points can be justified only if each terminal cost does not exceed: $100,000 ____ $10,000 ____ $1,000 ____
   $100 ____ Other: ______________
   Special requirements. (Please rank order of importance, with No. 1 being most important):
   Coded transmissions ____
   High quality audio _____
   Verification of message received _____
   High resolution video _____
   Error rates below 10^{-6} _____
5. Your needs, preferences, and choices among possibly feasible space communication technologies:
   Megabit per second digital data, computer-to-computer transmission ____
   Typewritten copy input, conversion to digital stream, transmission through a satellite, and reconversion to printed copy before delivery ______
   Worldwide television coverage relayed in real time _____
   "Closed-circuit" television, by coded transmission, between "Informa-Center" and a large number of terminals: (One-way) _____ (Two-way) __
   Other technology preferences:

6. Further comments. (Use this section for any comments you consider applicable to satellite communication user needs but not listed above.)

TABLE 7.4

EVALUATION OF RESPONSES TO
MAILED QUESTIONNAIRES

CATEGORY	QUALITY OF RESPONSE			
	Poor (No.)	Fair (No.)	Good (No.)	Total (No.)
Providers	1			1
Government Related		2	1	3
Private Industry	1	5	1	7

"retail" market had to be exploited. MAILGRAM is an example of such a retail service. Transmission/receive time for a MAILGRAM may require only 20 minutes--it is delivered with next outgoing mail at reception point.

7.3.3.2 Educational Television Services

Two experiments are to be undertaken, one at 14 GHz and one at 4 GHz. The 14 GHz experiment is to employ one downlink at Atlanta and one uplink in North Carolina. The 4 GHz operation will employ two downlinks and one uplink in Atlanta.

The main problem is the high cost of earth stations ($62,000). Satellites with high power (2.50W) could lower the cost of earth stations to about $10,000. Rooftop antennas for schools should be $500 to $1,000. Cassette/mail distribution is currently being used at a rate of $17/cassette, $1,500 for record/playback versus $900 for playback only.

7.3.3.3 LEAA

The Law Enforcement Assistance Administration, U. S. Department of Justice, funded studies that examined the question of LEAA use of satellite communications facilities. Two reports on the subject were:

1. "National Law Enforcement Telecommunications Network Analysis--Final Report, Phase II," Norman B. Reilly, et al, JBL, for LEAA, 20 February, 1975.
2. "NALECOM Satellite Usage Study," Rockwell International, Collins Radio Group, for JPL, NAS 7-100, EP 37-2146, 12 February 1975.

Reference 1 was an analysis of nine alternative approaches to the NALECOM (National Law Enforcement Communications) network, with ranking. A satellite communications network was analyzed that consisted of two regional terrestrial switchers, 14 ground stations, and one leased transponder which would support 28kbps, full duplex data, as well as video transmission. Four non-satellite network options ranked higher than satellite communications by technical evaluation criteria and eight options were found to cost less than the satellite network.

Reference 2 analyzed the technical requirements of satellite communications for law enforcement: (1) color TV with audio, (2) digital transmission at T/1 (1.544 Mbps) data rates, and (3) digital transmission at 50 Kbps.

C-2

User requirements as seen by LEAA were reflected in the study's work statement to answer the questions:

1. Can the ground stations be located within a city? (i.e., at a criminal justice facility) or must they in most cases be located outside city limits where security is a problem? What security measures are available (and what are the costs) for protecting or monitoring of remote stations?
2. What is the potential for unwanted monitoring of the uplink or downlink transmissions by unwanted persons? What would be the cost and complexity of clandestine monitoring equipment? How can these efforts be circumvented, and at what cost and complexity?
3. Is there any potential for false message injection? If so, what are the costs and complexity of hardware for providing false messages? What techniques can be used to circumvent false message injection and what are the costs and complexity?
4. What are costs and complexity of hardware to jam (disrupt) communications and for hardware to circumvent potential jamming?
5. What redundancy in ground stations is necessary to provide average availability of 0.99 video and 0.995 for digital data transmission?

LEAA did not plan, as of September 1975, to use satellite communications for transmitting criminal justice information.

7.3.3.4 Broadcast and Fixed Satellite Services

The purpose of Working Group D, Evolution and Requirement Committee, FCC Joint Industry/Government/CCIR, is to determine the evolution of demand and/or uses for the 11.7-12.2 GHz band for broadcast and fixed satellite services. The working group output will form part of the joint industry/government committee report, which in turn will permit the FCC to prepare the U. S. position for the 1977 World Administrative Radio Conference (WARC) of the International Telecommunications Union (ITU). The 1977 WARC is to make decisions about broadcast satellite service in the 11.7-12.2 GHz band.

Working Group D was divided into three subgroups:

D-1 Review of Present Terrestrial Distribution Services for Television Broadcasting and Terrestrial/Satellite Fixed Services.

D-2 Potential Users, Time Schedule, Evolution of Services, and Technology Needs.

D-3 Probable Developments for Social Services Applications of Satellites in the 12 GHz band.

Potential uses of broadcast satellites were defined by the working group and Table 7.5 lists these uses. Most of these uses are being realized, such as CATV program distribution, and some are having a significant economic impact. Others, such as electronic mail service and electronic funds transfer, could have even more impact.

It might be mentioned that in the group discussions, it was pointed out that direct-to-home broadcast/reception would severely damage local broadcast companies, and would eliminate local event coverage.

7.3.4 Literature Survey

The literature that was surveyed included the following NASA publications:

Television and Education: N75-16705

Economics of Maritime Satellite: N75-13907
N75-14016

Health Care by Satellite: N75-15868

Satellites for Electronic Mail: N75-18464
N75-18465
N75-18466

Commercial Trends in Satellites: N74-11700

Satellites for Mobile Communication and Surveillance: N74-12884

Satellite Requirements in the 1980's: N74-16888
N-74-14891

Europe's Next Generation of Satellites: N74-17682
N74-28675

Historical Survey of Communication Satellites: N74-27625

Satellite Trends: N74-31642

Television by Satellite: N74-32599

Remote Telephone and TV via Satellite: N73-23109

Priority Basis Satellite Applications in U.S.A.: N73-31784

TABLE 7.5

POTENTIAL USES OF BROADCAST SATELLITES

Network Television Program Distribution
Network Radio Program Distribution
Closed Circuit Television Distribution
Closed Circuit Radio Distribution
Business Teleconferencing
Medical Teleconferencing
Community Reception of Educational Television
CATV Program Distribution
Subscription Broadcast Programming and Data Service
Electronic Mail Service
Biomedical Services
Leased Private Telephone Circuits
Leased Data Transmission Circuits
Leased Low-Speed Message Services
Wide-Band Common Carrier Facilities
High Density Data Services
Single Channel Per Carrier (SCPC) Services
Weather Distribution Services
Individual Direct-to-Home TV Broadcast Reception
Safety/Navigational Services
Specialized Services
Emergency Services
Interaction Services

7.3.5 Analysis of Methods

The personal interview proved to be the most effective method of obtaining information, but telephone interviews ranked a close second. Mailed questionnaires were very ineffective. When cost is considered, telephone interviews were the most cost effective, followed by personal contact. The personal contacts were made only after telephone interviews identified the contact as a useful source of information.

7.4 Survey Results

7.4.1 User Classifications

The survey revealed activity or active interest in the use of satellite communications in the following areas:

1. Educational television, national program distribution
2. Cable television, national program distribution
3. Business transactions, point-to-point telephone links for voice, data, and facsimile
4. Radio and television, on-the-spot events
5. Common carrier, long haul service
6. Message service, mailgram and electronic mail
7. Social services, coverage of remote areas for medical service, and emergency/disaster radio links
8. Transportation, wide area mobile radio and maritime service
9. Data service companies, computer networks
10. Government, electronic funds transfer and message service

7.4.2 Types of Service

The types of service in satellite communications system can be classified as:

1. Telephone, two-way voice
2. Video, one-way, two-way single frame, television
3. Radio, one-way, two-way, fixed sites, mobile
4. Data, low-medium, or high speed data; teletype
5. Facsimile, black and white, color

7.4.3 Needs of Users

The present needs of users were found to include:

1. Smaller earth station antennas, costing under $7,000
2. Lower-cost earth stations, at less than $10,000
3. Rooftop receiving antennas, costing less than $1,000
4. Broadcast TV, radio, and common carrier to remote areas

5. Program distribution for reception and redistribution
6. Digital data redundancy to lower error rates
7. Television transmitter mobile vans
8. Improved reliability

The needs of future users, as deduced primarily from the literature survey, will include the following:

1. Error rates approaching one part in 10^{12}
2. Automatic exchange switching equipment in the satellites
3. Higher efficiency in the use of message space (time/bandwidth occupancy
4. High resolution video, for both television and single frame transmissions
5. Decrease in beamwidth (spatial specificity)
6. Increase in number of transponders in each satellite
7. Improved security of information
8. Wide area, reliable mobile radio
9. National personal paging alert system
10. Extended educational television broadcast/program distribution
11. Navigational systems
12. Data rates approaching 60 Mbps
13. Digitized television broadcast to home receivers

7.4.4 Data Obtained

At the time of the users' survey in the first half of 1975, the users' demand forecast was determined to be as shown in Table 7.5.

The estimate of demand versus cost for receiving antennas is shown in Figure 7.1.

The desire for improvements in space communications technology, in order of the number of responses from users were:

1. High resolution video
2. High quality audio
3. Verification of message as recieved (error correction)
4. Coded transmissions
5. Megabit per second data transmission
6. Error rates below one part per million

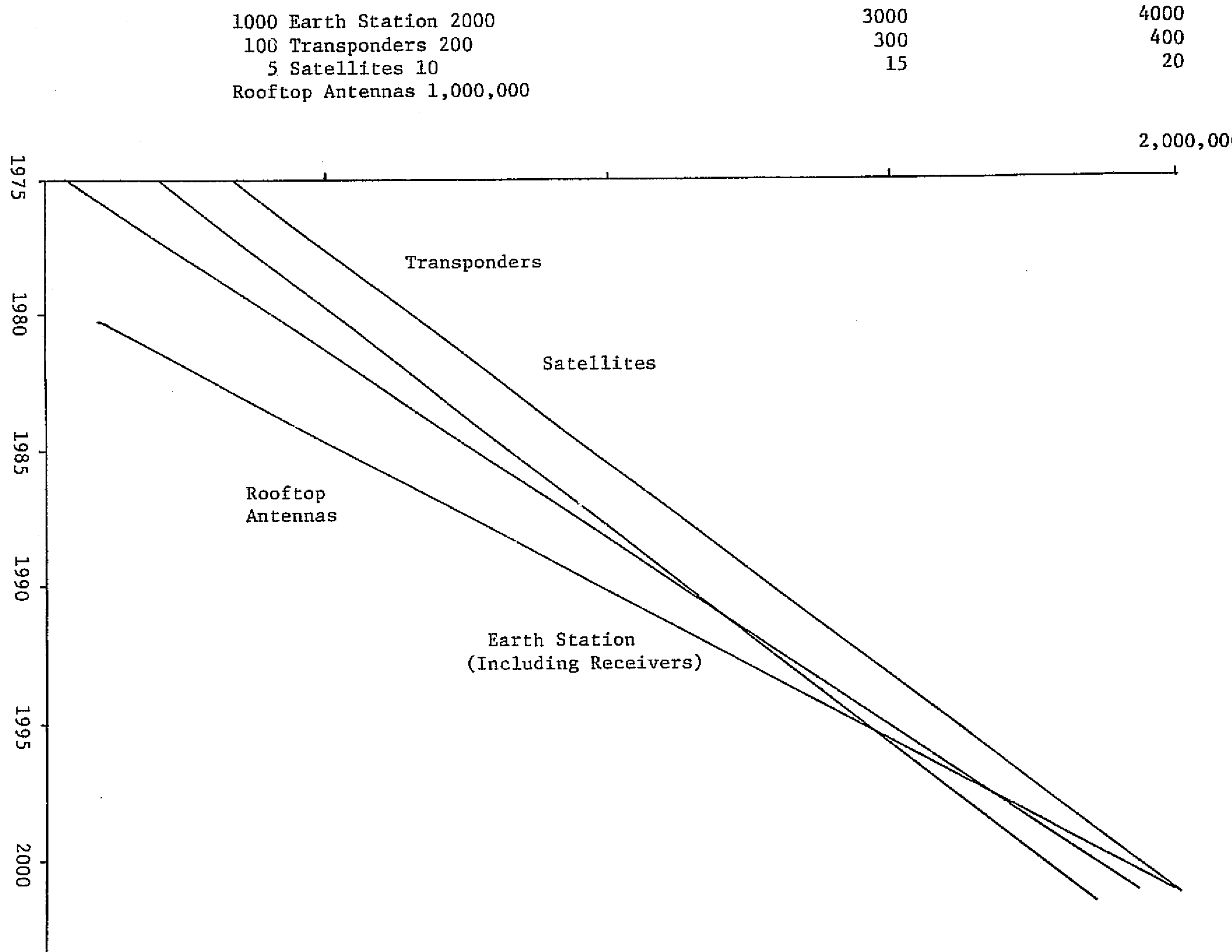


Figure 7.1. Estimated Demand Versus Cost for Receiving Antennas

7. Typed copy in/typed copy out
8. Closed circuit television, from one transmitter to several receiving points
9. Worldwide, real time television coverage

There were only three statements expressing needs for further demonstration. These were:

1. Determine the requirements for CATV earth stations by comparing the picture quality at users' sets in CATV with users' sets when receiving broadcast TV. The CATV operators believe the FCC requirements for 10 meter receiving antenna dishes to be unrealistically stringent.
2. Demonstrate that transmissions of data have an acceptably low error rate.
3. Establish a criterion for reliability of operations, based on users' requirements.

7.5 Projection of User Needs

The channel requirement forecasts for international, U.S. domestic, and foreign domestic satellite communications which resulted from the user survey are given in Section 10, "Baseline Scenarios." Forecast quantitites of earth stations are given in Figure 7.2, and Table 7.6.

7.6 Concluding Observations

The users can be divided into three organizational categories: (1) profit-oriented businesses, (2) government agencies, and (3) non-profit, public welfare agencies. They have little knowledge of the system requirements of satellite communications. The first category is preoccupied with financing, with operating costs, and with system reliability. The second category is preoccupied with costs and efficiency of throughput. The third category is striving to make a case for government funding of high-cost projects which will benefit those who are in some sense underprivileged. The information that proved most usable came not from the primary users, but from technical people who were aware of the goals and objectives of the users.

If the U.S. shares orbital positions with Canada and South America, there may be room for only about fifteen U.S. satellites at each operating frequency. The coveted assignments at 2 to 6 GHz will be filled quickly.

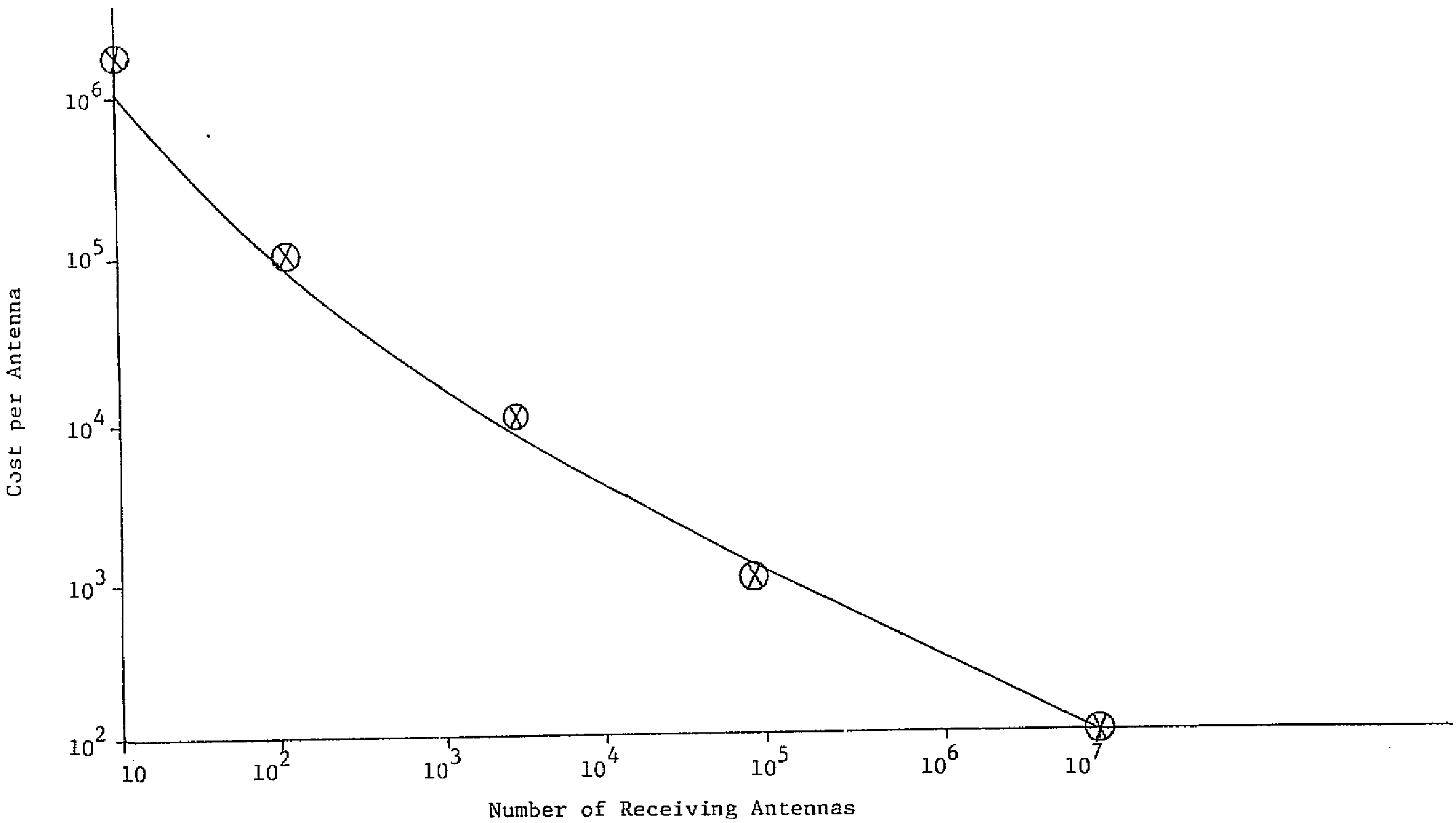


Figure 7.2. Estimated Demand/Cost for Receiving Antennas.

TABLE 7.6

USERS' DEMAND ESTIMATE

	Number Data Sources	Usage Circuits Voice	Usage Circuits Video	Transponders	Earth Stations	Rooftop Antennas
Present	8	24	4	42	60	---
Future 5 Years	27	281	---	116	857	100,000
10 Years	34*	346	---	169	1561	---

* Includes literature

Users fall into a number of categories. The Federal Reserve Clearing House, Social Security, Defense Department, Postal and Western Union represent high-service, volume, digital data, two-way users. If the USPS succeeds in its plans for electronic mail service its usage potentially constitutes a volume of 80 million pieces of mail per day. Western Union currently transmits about one million mailgrams per week with perhaps 10% by satellite. The USPS plans to build 125 two-way earth stations. Western Union presently has 5 two-way earth stations and is planning 15 additional stations within six months. Cost of two-way stations is about $200,000 each. Some customers of Western Union plan to use portable two-way terminals, at a cost of $250,000 each, for television transmissions.

The Corporation for Public Broadcasting represents a second category which uses satellies for (primarily) one-way video transmissions. PBS will use 12-14 GHz transponders on board the Communications Technology Satellite (CTS). Plans call for 160 receive-only earth stations with eight-foot dishes to be built by rebroadcasters of PBS programs at a cost of about $7,000 each. Four transponders in satellites would be leased for PBS program transmissions. The Educational Television Service of the Georgia Department of Education is an example of a rebroadcaster.

Home Box Office is another example of a one-way video user. The company has leased two 4-6 GHz transponders from RCA GLOBECOM for 70 hours a week transmissions to CATV systems anywhere in the U.S. (Until GLOBECOM is launched, RCA has leased five transponders on WESTAR to provide service to its customers, such as Home Box Office.) Teleprompter Corporation, Cox Cable Corporation, and American Television and Communication Corporation are examples of receive-only CATV customers of Home Box Office. These three companies are building, or planning to build, thirty receive-only earth stations with 10 meter diameter dishes, at costs of 80 to 100 thousand dollars each. The FCC is presently approving only the large diameter antennas for CATV reception and rebroadcast.

The reduction of costs for earth stations is a need expressed by all users. Higher operating frequencies (such as the PBS transmissions) permit the use of a smaller antenna, which is sized to produce a narrow beam so as to reduce interference from or to spatially adjacent satellites. The half-power beamwidth requirement is about 0.5 degree, which is turn specifies a dish diameter of about 100 wavelengths. Methods of reducing sidelobes in the region of 2.5° to 5.5° off-axis would be desirable, if it also permits a reduced cost for the antenna.

A third category of users of satellites is represented by Muzak Corporation. This company participated in experiments through ANIK II, and WESTAR (by lease with RCA). They plan to have <u>100,000</u> receive-only earth stations, and would use one transponder (about <u>36 MHz</u>) to transmit only <u>four</u> music programs.

The frequency band 11.7-12.2 GHz has no satellite radiated flux density limits, so the CTS satellite, which is experimental, and the CML satellite, which will be commercial, may transmit downlink signals at power levels which will permit the "rooftop" antennas required by such users as Muzak.

The higher frequency transmissions suffer increasingly from rain attenuation. At 12 GHz, heavy rain attention is about ten times the attenuation at 5 GHz; and at 22 GHz, it is about one thousand times the 5 GHz attenuation. For equal signal levels at the earth, the effective radiated power of satellites operating at 5, 12 and 22 GHz would have to be in the ratio 25, 250, and 25,000 watts. To reduce costs of earth station <u>receivers</u>, this ratio would have to be even higher.

SECTION 8
TECHNOLOGY SURVEY

8.1 Summary of Technology State-of-the-Art Survey

The main objective of this study was to assess the potential benefits of NASA space communications technology. As a part of that assessment, a survey has been made of technology currently available for application, technology in the development stage, and technology in the planning stage. This survey of the state-of-the-art of space communications technology has considered the total communication system, including directly associated ground equipment as well as the space segment. Correlations have been established between new technology items and the forecasted needs and applications for space communications. Table 8.0 gives an outline of this section.

8.1.1 Survey Methodology

A review of related technical reports and articles available in the open literature was conducted by (1) reviewing literature already available in the Engineering Experiment Station staff files, (2) using the technical indices of the Georgia Tech Library, (3) reviewing pertinent literature supplied by NASA/Lewis, (4) monitoring related periodicals, and (5) periodically reviewing the NASA/SCAN abstracts. The relevant articles were copied and filed according to the technology classification structure described below.

A literature review provides a broad basis of information on the related technologies, but current state-of-the-art information is available only through direct contact with those engineers in industries and government agencies currently working with the fast-moving space communications technology. Accordingly, telephone interviews and visits by Georgia Tech personnel were conducted with several companies and agencies. Space communication industry facilities visited during the technology survey include Scientific-Atlanta, Inc., Westinghouse (Baltimore), General Electric (Valley Forge, Pennsylvania), Watkins Johnson (San Francisco), Comsat Laboratories (Clarksburg, Maryland), Varian (San Francisco), Aerospace Inc., TRW, Aeronutronic/Ford, Lockheed Missile and Space Division, AYDYN Energy Systems, Hughes Space and Communication Group, and Hughes Electron

TABLE 8.0

TECHNOLOGY STATE-OF-THE-ART SURVEY

8.1 Summary of Technology State of the Art Survey

8.1.1 Survey Methodology

Literature Review
Personal Interviews
Technology Classification Structure (TCS)

8.1.2 Resultant Technologies of Most Interest

8.2 Compilation of Technologies Encountered During the Survey

8.3 Ground Station Technologies

8.3.1 User Connection

8.3.2 Modulation and Multiple Access Techniques

8.3.3 Transmitter

8.3.4 Receiver

8.3.5 Antenna

8.3.6 Propagation

8.4 Launch and Injection Technologies

8.4.1 Launch

8.4.2 Injection

8.5 Satellite Technologies

8.5.0 Structure

8.5.1 Station Keeping

8.5.2 Attitude Control

8.5.3 Electrical Power

8.5.4 Thermal Control

8.5.5 Antenna

8.5.6 Transponder

8.6 Millimeter Communication System

8.7 Laser Communication System

Dynamics Division. Government agencies visited included U. S. Air Force SAMSO, NASA/Ames, and NASA/Goddard. In addition to the visits at these facilities, later telephone conversations were held with these "experts" to discuss specific technologies and to solicit opinions as to parameter values for the cost-benefit analyses.

A technology classification structure (TCS) was developed for orderly handling of technical literature and interview documents. The TCS is as shown in Table 8.1, and serves as an outline for the major portion of this section. Subsection 8.2 contains a detailed listing of many sub-technologies and devices classified according to the structure.

8.1.2 Resultant Technologies of Most Interest

A set of nine space communication technologies capable of meeting anticipated requirements as determined by the user survey has been selected for evaluation by the cost-benefit methodology developed in Part I:

Low Cost Earth Station Direct Demodulation Receiver
Ion Engines
RF Attitude Sensors
Advanced Solar Arrays
Adaptive Heat Pipes
Satellite Multibeam Antennas
Satellite Solid State Power Amplifiers
Millimeter Communication Systems
Laser Communication Systems

Each of these technologies will be analyzed by the screening, assessing, and ranking methodologies in Sections 11 through 14.

8.2 Compilation of Technologies Encountered During the Survey

Many technologies at the system, subsystem, and device levels were researched to varying depths during the technology state-of-the-art survey. Table 8.2 contains an itemization of many of these technologies, classified according to the TCS. The following sections discuss in more detail most of the more important technologies.

8.3 Ground Station Technologies

8.3.1 User Connection

The specific equipment and technology required for future development for satellite communication ground stations will depend on the functions that the users require of the systems. Specific user demands will also impact the overall design of the ground stations, including siting and

TABLE 8.1

TECHNOLOGY CLASSIFICATION STRUCTURE (TCS)

I. Ground Station
  A. User Connection
  B. Modulation Techniques
  C. Receiver/Transmitter
  D. Antenna
  E. Propagation Media

II. Launch and Injection
  A. Launch
  B. Transfer Orbit
  C. Synchronous Orbit (Satellite Locations)

III. Satellite
  A. Structure
    1. Station Keeping
    2. Attitude Control
  B. Support
    1. Electric Power
    2. Thermal Control
  C. Communication Equipment
    1. Antenna
    2. Transponder

TABLE 8.2

TECHNOLOGY ITEMIZATION

I. Ground Station

A. User Connection

1. Equipment
   a. Baseband Multiplexer (multiple-access)
   b. Concentrator Control
   c. Switching Matrix
   d. High Speed Modem
   e. Cable TV Headend
   f. Commercial Video Interface
   g. Terrestrial Link (external)

2. Techniques
   a. Single Channel per Carrier/Single Customer per Transponder
   b. Multiple Channel per Transponder/Multiple Customer per Transponder (FDMA, TDMA)
   c. Digital TV (DITEC)
   d. TV Rebroadcast
   e. Summing and Distribution

B. Transmitter

1. Modulator
2. Local Oscillator (Baseband, IF, and RF)
3. Multiplier Chain (RF local oscillator)
4. Filters (IF Band-Limiting, Sharp Cutoff)
5. Amplifiers (Feed-Forward, TWT, Klystron, Thermoelectrically cooled, Buffer)
6. Multiplexer
7. Differential Encoder
8. Oscillator (Gunn, Gunn Effect Pump)
9. Mixer (Balanced, Schottkey Diode)
10. RF Isolator
11. RF Circulator
12. Diplexer

C. Receiver

1. Demodulator
2. Upconverter (Ground Station Transponder)
3. Local Oscillator (Baseband, IF and RF)
4. Multiplier Chain (RF local oscillator)
5. Filters (Bandpass: tuned RF for demultiplexing, IF Band-Limiting)
6. Amplifiers [MIC Transistor Preamp, IF AGC, Parametric, Tunnel Diode, GaAs Schottky Varactor (Paramp)]
7. Group Delay Equalizer
8. Demultiplexer
9. Oscillator (Gunn, Gunn Effect Pump)
10. Mixer (Balanced, Schottkey Diode)
11. Phase Canceller
12. Diplexer

D. Antenna

1. Parabolic Dish
2. Horn Antenna
3. Conical-Beam Antenna
4. Wideband Cross Polarization Feeds
5. Radome
6. Multibeam Antenna (Offset Feeds, Cassagrain Antenna, Parabolic Torus)
7. Cancellation Device
8. Parabolic Cylinder
9. Planar Array
10. Linear Array
11. Switched Beam Antenna
12. Electronically Steered Beam
13. Corrugated Feedhorn
14. Step-Track Antenna

II. Launch and Injection

A. Launch

1. Expendable Booster
2. Reusable Shuttle
3. Strap-On Motors (Delta 3914)

B. Transfer Orbit

1. Transfer Orbit Engine
   a. Solar Electric
   b. Liquid Propellant
2. Apogee-kick Motor
3. Omni Antenna
4. Attitude Conrol

III. Satellite

A. Structure

1. Vehicle
   a. Equipment
      (1) Spin Bearing (gas, hydraulic, magnetic)
      (2) Nitrite-Acrylic Copolymer retainer material
      (3) Frame (sheet metal core, honeycomb panels, aluminum, magnesium, beryllium)
   b. Techniques
      (1) Spinning
      (2) 3-D Stabilized

2. Station Keeping
   a. Thrusters
      (1) Ion Engine (Cesium, Mercury)
      (2) Hydrozine
      (3) H_2O_2
   b. Sensors
      (1) Ground Based
      (2) Satellite Based
      (3) Radar Measurement Between 2 Satellites

TABLE 8.2 (Continued)

3. Attitude Control
    a. Sensor
        (1) RF Interferometer
        (2) Stellar Tracking (Polaris)
        (3) IR Horizon Tracker (high frequency, static, scanning)
        (4) Radar Measurement Between Satellites
        (5) Solar
        (6) Beacon Tracker
        (7) Monopulse-Antenna Auto-Track
        (8) Rate Integrating Gyro
    b. Actuators
        (1) Momentum/Reaction Wheel [Bearings (self lubricating--polymide, graphite, molybdenumdisulfide/antimonytrioxide, Teflon, Tungsten Sulfide, Barium Fluoride, Esters, Fluoridated Synthetic Polyfluralaklether; Magnetic), Double Gimbal Wheel]
        (2) Reaction Jets
        (3) Nutation Damper
        (4) On-Board Processor

B. Support

1. Electric Power
    a. Generation (solar cells)
    b. Storage (battery cells, battery recharging circuitry)
    c. Distribution (voltage, frequency, regulation)

2. Thermal Control
    a. Heat Pipes (active, passive, variable conductance)
    b. Pumps
    c. Valves
    d. Fluid Loops
    e. Second Surface Mirrors
    f. Phase Change Material
    g. Passive Radiator
    h. Heater
    i. Louvers

C. Communications

1. Antenna
    a. Equipment
        (1) Arrays (slot, phased)
        (2) Parabolic Reflectors
        (3) Plano-convex Lens
        (4) Antenna Material (graphite, kevlar, epoxy)
        (5) Switchable Feeds
        (6) Waveguide Lens
        (7) Polarization Correctors
        (8) Microstrip Antenna Element
        (9) Variable Converge Antenna
        (10) Large Reflectors

b. Techniques
   (1) Multiple Beam Isolation
   (2) Mechanical Antenna Movement
   (3) Sidelobe Suppression
   (4) Polarization Isolation
   (5) Multiple Reflectors
   (6) Offset Feed
   (7) Cancellation (polarization correction)
   (8) Shaped Beam
   (9) Multiple Shaped Beams

2. Transponder
   a. RF Generation (thermionic, solid state, hybrid)
   b. Preamp (TDA, FET parametric amplification)
   c. Mixer (Schottky barrier, image enhancement)
   d. Local Oscillator (bulk-effect diodes, central synthesizer, individual Xtal controlled source)
   e. Post Amplifier (Transistor--FET, Bipolar, TDA)
   f. Power TWT Amplifier
   g. Isolators
   h. Circulators (latching)
   i. Filters (Chebyshev, composite, invar, Lita O_3)
   j. Multiplexer Filter Matrix
   k. Switch Matrix (SSTDMA)
   l. Butler Matrix
   m. Frequency Down Converter
   n. Switches (waveguide, coax)
   o. On-Board Digital Processor (compression, coding, digital demodulation)
   p. Laser (waveguide, YAG:Nd, CO_2, integrated)
   q. High Speed Photo Detector
   r. Laser Modulators
   s. Auto Track (mod/combiner,lightweight receiver)

architectural design, and will even determine the classes of communication service offered.

The initial emphasis in the development of satellite communications has been on providing the same services as, and interface connections to, terrestrial communications networks. The concept has basically been to replace terrestrial networks for transmissions over long distances, transmitting voice, data, teletype, and video signals as multiplexed channels modulating a microwave carrier. Radio and television sigansl are received by ground stations and delivered over local loops for rebroadcast by local stations. There is an emerging demand, however, for both dedicated ground stations and for satellite broadcast service.

A fast-growing usage of satellite communications which bypasses local telephone loops and radio and television rebroadcast is exemplified by the availability from Home Box Office Co. of centralized programming, which is transmitted via satellite to dedicated ground stations that feed the received television signals into cable TV networks. Other potential demands for transmissions to dedicated ground stations include those of educational television networks, electronic mail, electronic funds transfer, national law enforcement, electronic publishing, movie distribution, etc. Table 8.3 lists potential users of fixed, dedicated ground stations [1].

Another class of potential users of dedicated ground stations include mobile termina/fixed terminal systems, as summarized in Table 8.4 The first entry--emergency and disaster--potentially includes a nationwide personal alert system. The last entry--state government--might only apply to Alaska and other states where the environment precludes terrestrial telephone networks, or where satellite systems are less costly.

Table 8.3 groups services which interface with local loop telephone networks, and which presently include baseband switching functions in ground stations.

Tables 8.3, 8.4 and 8.5 suggest that ground stations can be classified according to usage (dedicated or multiple access), service (fixed, broadcast, or mobile), size, signal quality, and cost. The most intensive development of ground station technology has centered on the large, costly, two-way,

TABLE 8.3

SATELLITE COMMUNICATION SYSTEM REQUIREMENTS AND TRENDS

HIGH MESSAGE VOLUME USERS --- DEDICATED GROUND STATIONS

Service Network	Network Coverage	Channels Required For Total Coverage: Voice Slow-Speed Data	Video	No. Channels/ Data Rate	Ground Station Requirement Trends	Service Trends
Elementary school	National regional, state	2600	20	2600 / 300 KBps	Rooftop Antennas on Indv. schools	Broadcast Satellite
Higher education	National regional	160	60	1500 / 300 KBps	Rooftop Antennas on Indv. schools	Broadcast Satellite
Value transfer	National	30 K / 50 KBps	-	Uses grouped slow-speed channels	High Security coding, High Data Rate	-
Securities and commodities exchange	National	8 K / 50 KBps	-	Uses grouped slow-speed channels	High Security for Transactions	-
Reservations and Tickets	National	15 K / 50 KBps	-	Uses grouped slow-speed channels	High Security, High Data Rates	-
Electronic mail	National	-	-	20 / 4 MBps	High Security, High Data Burst Rates	-
Movie distribution	National	-	-	20 / 4 MBps	Could Use Electronic Mail Service	-
Electronic publishing	National	-	-	1000 / 2 KBps	-	-
RF environment monitoring	Global	-	-	1 / 1 GBps	Very High Data Rates	
National law enforcement	State, national	1000 / 2 KBps	-	1000 / 600 KBps	High Security	-
High-speed computer	National	-	-	5/1 GBps 100/100 MBps	High Security	-

TABLE 8.4

SATELLITE COMMUNICATION SYSTEMS REQUIREMENTS AND TRENDS

LOW MESSAGE VOLUME USERS --- MOBILE AND DEDICATED TERMINALS/GROUND STATIONS

		Channels Required For Total Coverage				
Service Network	Network Coverage	Voice Slow-speed Data	Video	No. Channels/ Data Rate	Ground Station Requirement Trends	Service Trends
Emergency and disaster	National	100 / 200 Bps	-	-	Portable video	Broadcast Satellite
NASA space operations	Global	100	20	4 / 200 MBps		-
Earth and ocean data relay	Global	-	-	15 / 200 Bps	High data volume	
Marine communications	Global	2000 / 2.4 KBps	4	-	-	-
Aircraft communications	Global, National	1000 / 2.4 KBps	-	-	-	-
United Nations	Global	100	20	1 MBps	High security	
State Government	State	2000 / 2 KBps	200	3000 / 50 KBps	Except for Alaska, need is questionable	-

TABLE 8.5

SATELLITE COMMUNICATION SYSTEM REQUIREMENTS AND TRENDS

MULTIPLE ACCESS, SWITCHING GROUND STATION NETWORK/TELEPHONE UTILITY INTERFACING

Service Network	Network Coverage	Channels Required For Total Coverage: Voice Slow-speed Data	Video	No. Channels/ Data Rate	Ground Station Requirement Trends	Service Trends
Library	National, Regional	516	-	120 / 300 KBps	Rooftop, Antennas on Individual Libraries	Video
Telecon-ferencing	National, regional	-	260	-	-	-
Biomedical	National, regional	1500 / 50 KBps	325	-	-	-
Commercial broadcast	National	-	60	-	-	Broadcast Satellite
Public broadcast	National, regional	30	10	-	-	Broadcast Satellite
Telephone	National	280 K / 50 KBps	400	1000 / 6 MBps	Privacy	Satellite borne baseband switch
Business	National	140 K / 50 KBps	140	Uses video / Ch/∿20 MBps	High security	Satellite borne baseband switch, trunk lease
General computer	National, international	20 K / 50 KBps	-	130 / 10 MBps	High security	Satellite borne baseband switch, trunk lease
General services	National	100 K 50 KBps	40	Uses groups of slow-speed ch	-	-
Ground vehicle communications	Regional	800 K	-	-		Trunk lease
Religious programs	National	-	20	-	-	Broadcast Satellites
Home communications	Regional	-	20	-	Lower cost CATU headend receivers	Broadcast Satellites
Area support network	Regional	10,000 / 50 K	100	10 / 1 MBps	Privacy	Satellite borne baseband switch

multiple-access fixed service stations, such as the RCA SATCOM installation [6] shown in Figure 8.1, which will serve the classes of users listed in Table 8.5, interconnecting Alaskan users and furnishing long-distance connections to the rest of the U. S. and to Canada. The functions of the user connections and the subsystems shown in Figure 8.1 include:

1. Space-division, local-loop, baseband switching
2. Baseband channel multiplexing
3. Channel concentration control
4. High speed digital modulation/demodulation (MODEMS)
5. Video amplification/equalization
6. Community antenna television (CATV) headend signal conditioning
7. Telephone network signal conditioning
8. Area support network, thin-line service:
   a. Television and radio reception and retransmission, and
   b. Single carrier per channel FM telephone signal reception, transmission and distribution.

8.3.2 Modulation and Multiple Access Techniques

Where a satellite system consists of many ground stations per satellite, there is a potential for cost reduction in transferring some of the ground station functions to the satellite. In the thin-route system shown in Figure 8.1, as it is being developed [7] for Alaska, a telephone call from one bush community to another must pass twice through the satellite transponder. The first pass would be from the caller to the switching terminal at Talkeetna, where demand access equipment would direct the signal through an available channel, back through the satellite to its destination. TDMA [8] or some other multiple access design is being investigated, but it promises to be costly to implement.

The inclusion of baseband switching capability in the satellite would improve Alaskan thin-route service, perhaps at reduced overall system cost.

The dedicated ground stations of high-message-volume, fixed service users as listed in Table 8.3 will generally require less baseband switching capability, fewer channels, and fewer interface connections than the type of system exemplified by Figure 8.1. The needs for high security of these

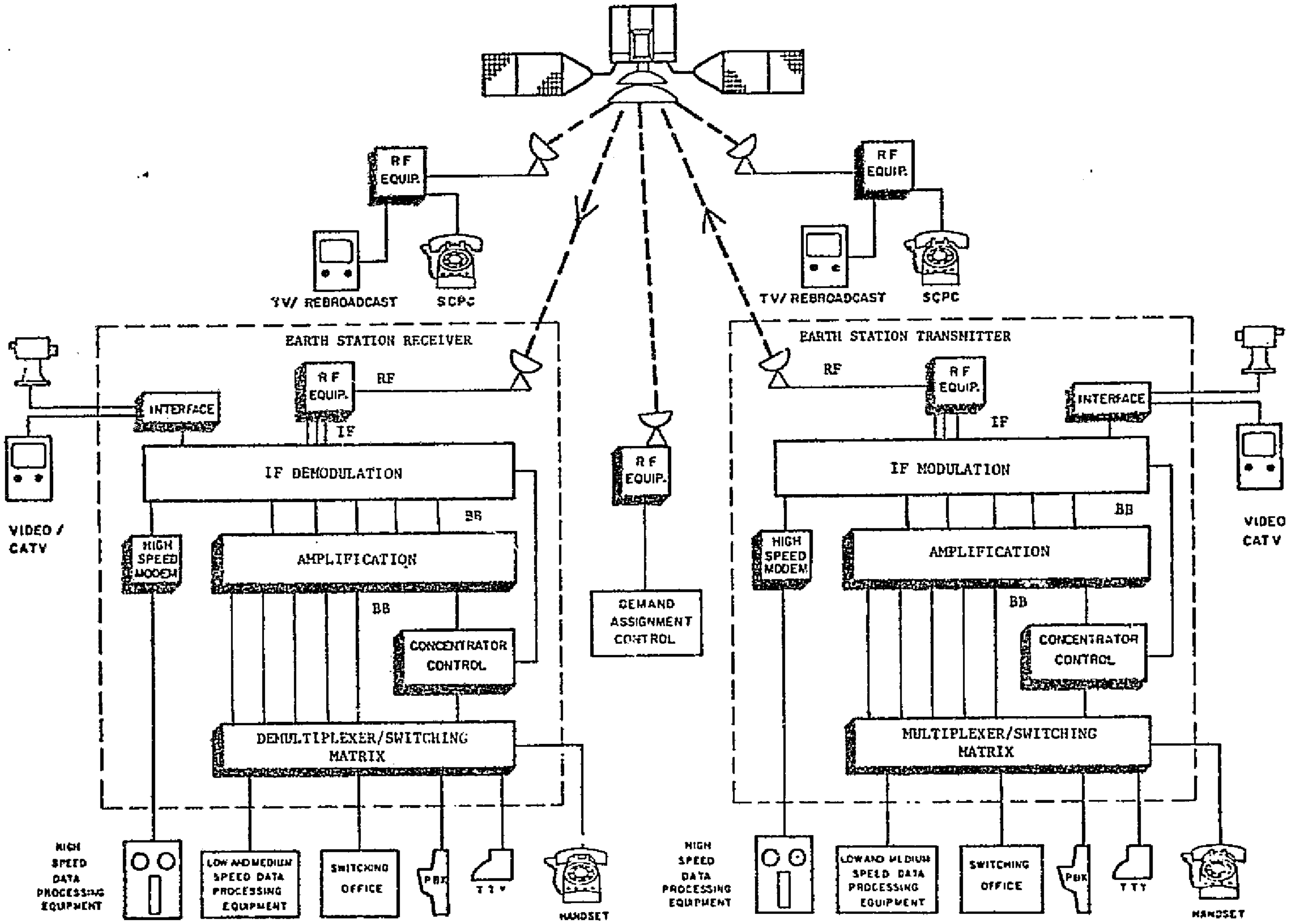


Figure 8.1 Major system components [6].

users will however require that the integrity of uncoded messages be insured. Encoding/decoding equipment for satellite communication ground stations, and the design of secure facilities should only require adaptation of military practice.

High speed modems are presently available, but some development of advanced technology may be required to meet the needs of electronic mail transmission for very-high-speed burst transmissions. Very-high-speed modems and their associated buffer storage equipments would also serve the potential needs for global weather prediction, environmental monitering, etc.

Two areas requiring research, development and demonstration of demand are rooftop antennas and broadcast satellites. An economic justification exists for developing rooftop antennas and satellite broadcast service for educational television. The justificiation lies in savings that would be realized by bypassing the present programming distribution bottleneck--the one or two-per-state ground station/tape recording centers. A low-cost (ca. $1000) rooftop antenna ground station at each school would permit real time classroom display, and would permit recording fewer tapes for program storage.

A broadcast satellite dedicated to educational television would also enrich the choices of all viewers, if rooftop antennas for home reception can be developed. A realistic target for an individual home antenna/down-converter would be about $100.

The rooftop antenna ground station, with rebroadcast on a clear VHF channel, would also afford a possible approach to a nationwide, personal, emergency alarm system.

Table 8.6 summarizes the potential demands in satellite communications that would require research and development of advanced technology for ground station components.

8.3.3 Transmitter

There are two basic types of transmitters which may be used in a ground station: a single multicarrier wideband amplifier covering the entire band of operation, or many smaller wideband tubes, each restricted to the portion of the satellite band assigned to the earth terminal, in

TABLE 8.6

REQUIREMENTS FOR ADVANCED TECHNOLOGY
GROUND STATION COMPONENTS

COMPONENT	TECHNOLOGY IMPROVEMENT	AGENCY:	COST TARGET
Antenna	Small Size	Schools, Homes, Business	$1,000 $100 $1,000
Encoder/Decoder	High Speed	Government Banks, Stock Brokers, Reservations, Tickets	$100,000
MODEM/Buffer	Satellite Borne/ High Speed, High Capacity, Low Error Rate	Postal Service High Speed Computers	$1,000,000/ $100,000
Satellite Borne Baseband Switching Matrix	Miniaturization, Remote Repair, Long-Life	Message Utility Companies	$10,000,000
TV Receiver/ Telephone	Digitized transmission	Homes/telephone companies	$100/ $1,000,000

a single carrier mode. The practice of using one TWT as the final amplifier in a multicarrier FM system has resulted in a steady increase in the TWT power requirement, which is currently at about the 12 KW level for commercial communication satellite systems. Current research includes utilizing low power (400-watt) TWT's multiplexed with filters to form the equivalent of a single high power amplifier. The discussion in this section is limited to using single tubes, but for the sake of comparison, Table 8.7 shows the advantages and disadvantages of the two types of transmitters operating at 500 MHz with a 40 MHz bandwidth.

A large number of available tube types can furnish the expected power levels required for earth stations. However, needs from the standpoint of transmission properties as well as power output limit the types to the traveling wavetube or multiple cavity klystron. Of these two, the TWT appears better suited because of its bandwidth and other transmission properties as compared to the klystron.

Growth curves of power output and efficiency for a TWT are given in Figures 8.2 and 8.3. These curves show the growth trend for high powered TWT's of the type being considered for contemporary earth station design. Future increases in efficiency are expected through more widespread application of the tapered Helix pitch and depressed collector operation concepts.

Characteristics of example tubes suitable for ground terminal applications are shown in Table 8.8. Millimeter wave sources are treated in a separate section and are not included therein. A commercial series of TWT high power amplifiers (HPA's) covers power levels of 100 to 700 watts in the 5.925 to 6.425 GHz frequency band. These HPA's have been designed for uplink service in satellite communications earth stations. Table 8.9 summarizes the general specifications for ground stations travelling wavetube amplifiers.

Ground station tubes have been of the 4, 6 and 8 KW type and future tubes have design goals of 50 KW power output. However, such high powers may not be consistent with low intermodulation and high bandwidths. Industry generally believes that amplifiers with higher power, greater efficiency, increased instantaneous bandwidth, less signal distortion, reduced cooling requirements, and longer operating life are needed to meet performance and cost objectives of new ground systems.

TABLE 8.7

COMPARISON OF SINGLE TUBE AND MODULAR TRANSMITTERS

Type of Transmitter	Advantages	Disadvantages
Single-Tube Transmitter	1. Simplicity due to single tube 2. Carrier frequency assignment flexibility 3. 1-for-1 spare	1. High power output per tube 2. Large high-voltage power supplies 3. Water cooling 4. Intermodulation and cross-talk 5. Inefficiency for small stations 6. Difficulties of remote control
Modular Type Transmitter	1. Lower power tube 2. Station size flexibility 3. No intermodulation or crosstalk 4. Air cooling 5. Lower standby investment 6. High reliability due to low-power air cooled tube and low voltage power supplies	1. Restrictions on carrier frequency assignment with wideband transponders 2. Complex multiplexer and switching circuitry

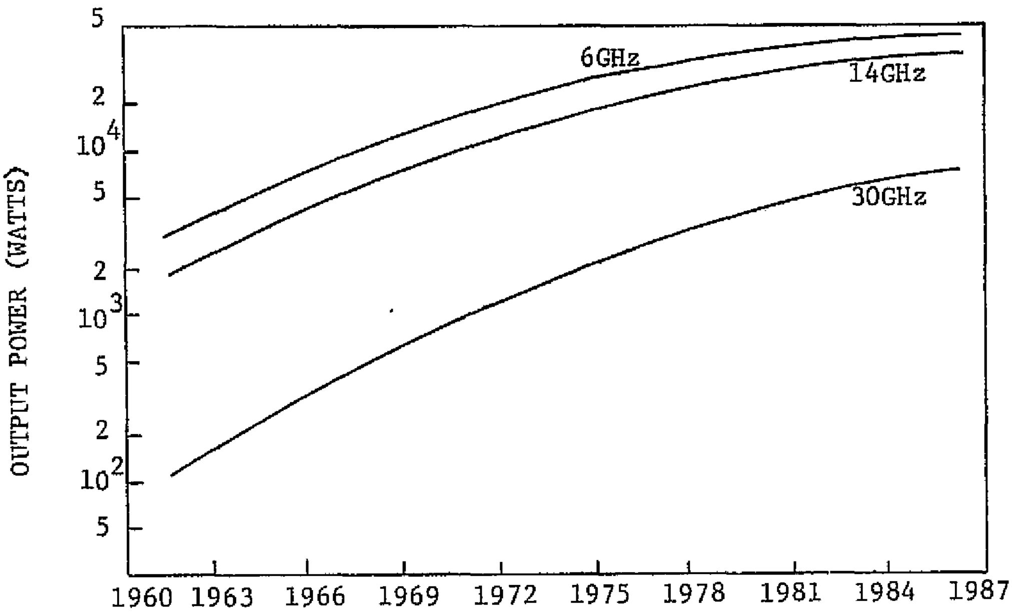


Figure 8.2. Earth Station TWT Power Output Capability

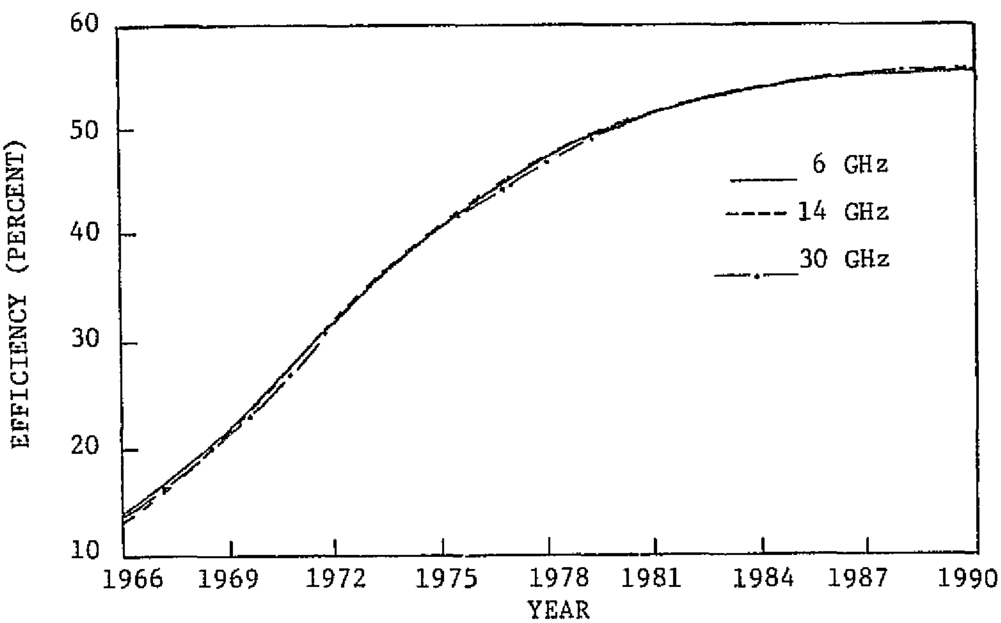


Figure 8.3. Earth Station TWT Efficiency

TABLE 8.8

TYPICAL POWER-FREQUENCY-GAIN CHARACTERISTICS
OF GROUND STATION TUBES/TRANSMITTERS

POWER WATTS	FREQUENCY GHZ	GAIN dB	BANDWIDTH MHz	GROUP DELAY
650	6	75	500	.1ms/MHz
1200	14	37	85	.04ms/MHz
650	6	40	500	.1ms/MHz
20	6	44	–	–
5	8	40	–	–

TABLE 8.9

GENERAL SPECIFICATIONS
FOR GROUND-STATION TWTA

Frequency:	5.925-6.425 GHz
Power output: (dBm min at output flange)	100 W, +49.3 400 W, +55.5 600 W, +5725 700 W, +57.8
Bandwidth:	500 MHz
P_o settability:	Within $\pm$ 0.2 dB
Gain at rated output:	75 dB min
Gain stability:	$\pm$0.25 dB/24 hr
Gain variation:	$\pm$1 dB max over 500Hz Band
Gain slope:	$\pm$0.04 dB/MHz over any 36-MHz Transponder Band

8.3.4 Receiver

The ground station receiver is one of the more critical components in the ground segment from a state-of-the-art point of view. It is the receiver which must be sensitive to the relatively weak signal provided by the antenna and amplify the signal with minimum noise introduction. Paramps, GaAS FET's and image-enhanced mixers are suitable for the small ground station receivers [9]. Cooled paramps are being used in many large ground stations [10]. Table 8.10 is a list of the low noise receivers taken from a Stanford [9] report updated with information from current literature [10].

Paramps are cooled thermoelectrically or cryogenically. The minimum noise temperature obtainable with these methods is 35°K and 15°K respectively. FET low noise receivers are used in many small earth stations operating in the 4-6 GHz range and used for television reception or low capacity voice. Image-enhanced mixers are under development [9] and should provide performance similar to the GaAs FET receivers.

Microwave television receivers have been transformed from specialized equipment to relatively common equipment for small ground terminals. Table 8.11 taken from the Stanford report [9] gives desirable video receiver performance parameters. Direct demodulation techniques have been recently introduced for use as video receivers. Hewlett-Packard and Hughes have built direct demodulation video receivers. The Hughes version is an advanced technique and illustrated in Figure 8.4 [10].

8.3.5 Earth Station Antenna

Antennas for microwave communications have been in use for many years. Recently, high capacity satellite communications have been introduced placing a new requirement on the microwave communications industry including the ground station antenna manufacturers. The antenna industry has found it necessary to produce a variety of products to meet the needs of various users.

Using communication techniques such as single channel per carrier (SCPC) or broadcast satellites, the need for small earth terminals has increased. A small remotely located terminal could provide several duplex voice circuits and/or television reception for small communities assuming a synchronous satellite(s) providing SCPC and/or broadcast services is

TABLE 8.10

Important Technical Features of Low-Noise Receivers

Available Frequency Range (GHz)	2–14	2–36	12
Available Noise Temperature (°K)	190–500	15–175	275–300
Circuit Complexity	Medium	High	Low-Medium
Prime Power Required (watts)	5	50–250	0
Degradation of Noise Temperature at 50° C	50° K	5° K	25° K

TABLE 8.11

Video Receiver Performance Parameters

Number of Selectable Channels	Any one of five, selectable over the entire 500 MHz allocation
Channel Bandwidth	30 MHz
Intermediate Frequency	70 or 120 MHz
Input Power Range	-70 dBm to -50 dBm (preamp assumed)
Dynamic Threshold	Less than 11 dB
Peak-to-peak Video Signal to rms weighted noise ratio	46 dB for 11 dB carrier-to-noise ratio, input, minimum
Signal-to-hum ratio	50 dB for peak-to-peak signal to rms noise and hum in a 1 kHz low-pass baseband bandwidth
Differential Gain & Phase	Less than 8% and 5 degrees, rf to baseband, with emphasis
Video Frequency Response	± 0.5 dB from 30 Hz to 4.2 MHz
Video Output Level	1 to 1.3 Volts peak-to-peak
Video De-Emphasis	CCIR recommendation 405-1 for 525 line system
Number of Audio Channels	2 per video
Audio signal-to-noise ratio	45 dB for 11 dB carrier-to-noise ratio input, minimum
Audio Frequency Response	10 Hz to 10 kHz ± 3 dB
Audio Output Level	+ 8 dBm ± 2 dB into 600 Ω balanced

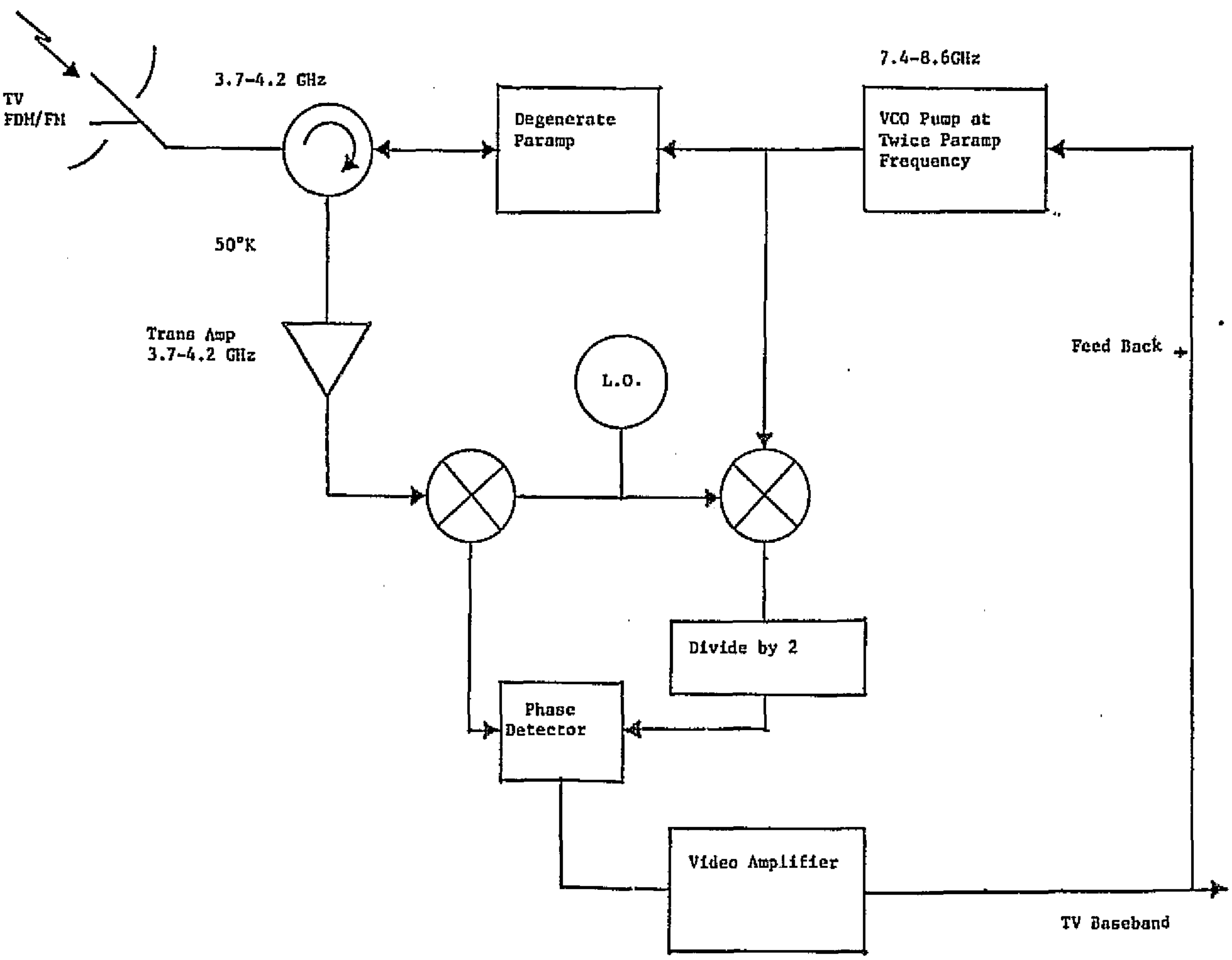


FIGURE 8.4

Direct Demodulation Video Receiver

properly positioned in longitude. Antennas from one meter to several meters in diameter have been used for this purpose. For example, the ATS-6/ Rocky Mountain Experiment employed 150, 10-ft. diameter parabolic reflector antennas to receive television programming at 2.54 GHz [10] Antennas as small as 0.6 meter have been built. These small antennas present a beam-width problem at microwave frequencies. Wide beamwidth antennas are more likely to receive interfering signals from adjacent satellites. Table 8.12 gives a list of small and medium earth station antennas which have been built.

Medium-sized earth station antennas have been manufactured for both transmit/receive and receive only functions. These antennas have narrower beamwidths but are subject to interference from adjacent satellites through sidelobe reception. Methods of improving sidelobe performance include removing obstructions from the aperture and using corrugated horns [11]. A prime-focus feed using no support structure to block the aperture has been used in a 10-meter CATV receive-only antenna [10].

Large earth station antennas up to 30 meters in diameter are employed in the Intelsat network. Medium and large antennas must have tracking capabilities due to their narrow beamwidths. An alternative to tracking by repositioning the dish is to steer the beam with movable feed horns. Movable feed horns are used in the parabolic torus antenna built by COMSAT [11]. This antenna is fixed, and all beam relocation and tracking is accomplished by mechanically moving the feed horns.

In addition to movable feed horns, another desirable feature of the large earth station antenna is multiple switched beams which have two advantages. The first allows the antenna to access more than one satellite at a time which will be necessary in a highly flexible communications network. The second advantage will be improved network reliability accomplished by quickly switching beams from a satellite which is not totally operational to one that is.

8.3.6 Propagation Media

Propagation media of concern in satellite communications consists of the few hundred miles of Earth's atmosphere and the few thousand miles of space between earth stations and the satellites in synchronous orbit.

TABLE 8.12

EARTH STATION ANTENNAS

DIAMETER	FREQUENCY (GHz)	GAIN (dB)	BEAMWIDTH (degrees)	REMARKS
.6 m	11.7-12.2	34.9	2.77	
1 m	11.7-12.2	39.6	1.6	
1.6 m	11.7-12.2	43.9	.96	
10 m	4	50.2	.56	CATV receiver
16 ft	12	52.5		CTS
16 ft	14	53.8		CTS
1-1.5 m	6			emergency transmitter
4.5 m	3.7-4.2	43.7		TV receiver
10 ft horn	3.7-4.2	43.7		TV receiver
4 ft				music program receiver
30 ft				2 offset cassegrainian feeds
32x55 ft torus	3.9	50	.53	3 movable feeds
32x55 ft torus	6.9	54	.34	3 movable feeds
30 m	4-6			Intelsat standard earth station

This media affects space communications in five ways:

(a) Free space loss is simply loss due to the radiated beam divergence. Free space loss is characteristic of the media and cannot be overcome.

(b) Atmospheric attenuation is caused by energy absorption and scattering by atmospheric molecules. Atmospheric attenuation is a function of frequency and in general is a greater problem at higher frequencies. Certain atmospheric molecules (oxygen, for example) resonate at specific frequencies. The radiant energy at the resonant frequency is converted to kinetic energy of the molecules resulting in considerable absorption for the specific frequencies.

(c) Rain attenuation is one of the major problems which occurs During the heaviest periods of rain. Communication outage is practically unavoidable. Most systems today are designed with a margin to allow for rain attenuation, but the obtainable margins do not allow for service in the worst conditions. Rain losses are generally localized and can be overcome by use of space diversity or transmit power variation [12]. Space diversity is implemented by providing two or more receivers separated by several miles. The strongest signal from the several receivers is used for communications purposes. Transmit power may be increased during periods of high attenuation. For example, if site A is receiving via satellite from sites B and C and transmitting via satellite to site D, then during a period of rain at site A, B and C will increase the power to signals whose destination is A and A will increase its transmit power for signals whose destination is D.

(d) Noise power exists in the propagation media and is received by the earth station. Noise degrades the received signal and needs to be reduced as much as possible. Thermal noise is power radiated by electrons vibrating at random and is a function of temperature and bandwidth.

$$N = KBT$$

where N is the received noise power, K is Boltzmann's constant, B is the receiver bandwidth, and T is the absolute temperature which the antenna "sees." Energy radiated from other communcation equipment may also be received as noise and is the only controllable noise source in the media. Various FCC regulations and international agreements are designed to regulate this noise source.

(e) Depolarization of signals is caused by phase and amplitude distortion occurring in the atmosphere [12]. Equipment designed to receive polarized signals is used in satellite systems to increase communication capacity through frequency reuse. When the signal is partially depolarized two things occur: (a) received signal power is reduced, and (b) noise is increased in adjacent receivers which are designed to receive signals with other polarizations.

8.4 Launch and Injection Technologies

8.4.1 Launch

Communications satellites launched in the past few years were placed in orbit by Atlas or Delta vehicles. The sequence of events to put a satellite into synchronous orbit using these two vehicles is (a) place the satellite into a low earth orbit inclined with respect to the equator, (b) transfer the satellite from a low earth orbit to an elliptical orbit with apogee near 36000 km, and (c) provide thrust at apogee of the transfer orbit to circularize the orbit and bring the orbit plane to near 0° inclination with the equator [13]. The Atlas and Delta vehicles each have three motorized stages. One stage is used for each of the three steps in the above sequence. A successful mission requires successful operation of all three stages. Each stage has a probability of failure and, therefore, a probability of success. The product of each of the three success probabilities gives the overall probability of mission success. Table 8.13 gives these probabilities based on data gathered between 1962 and 1970 [14]. The Titan III-C is included in Table 8.13. It is not a staged vehicle and could be used for direct injection into synchronous orbit with a higher reliability than a staged vehicle. The three vehicles in Table 8.13 have been improved over the years. The payload capabilities of the vehicles have increased at the rate of approximately 30% per year [14]. These increases are shown in the plot of Figure 8.5.

8.4.2 Synchronous Orbit

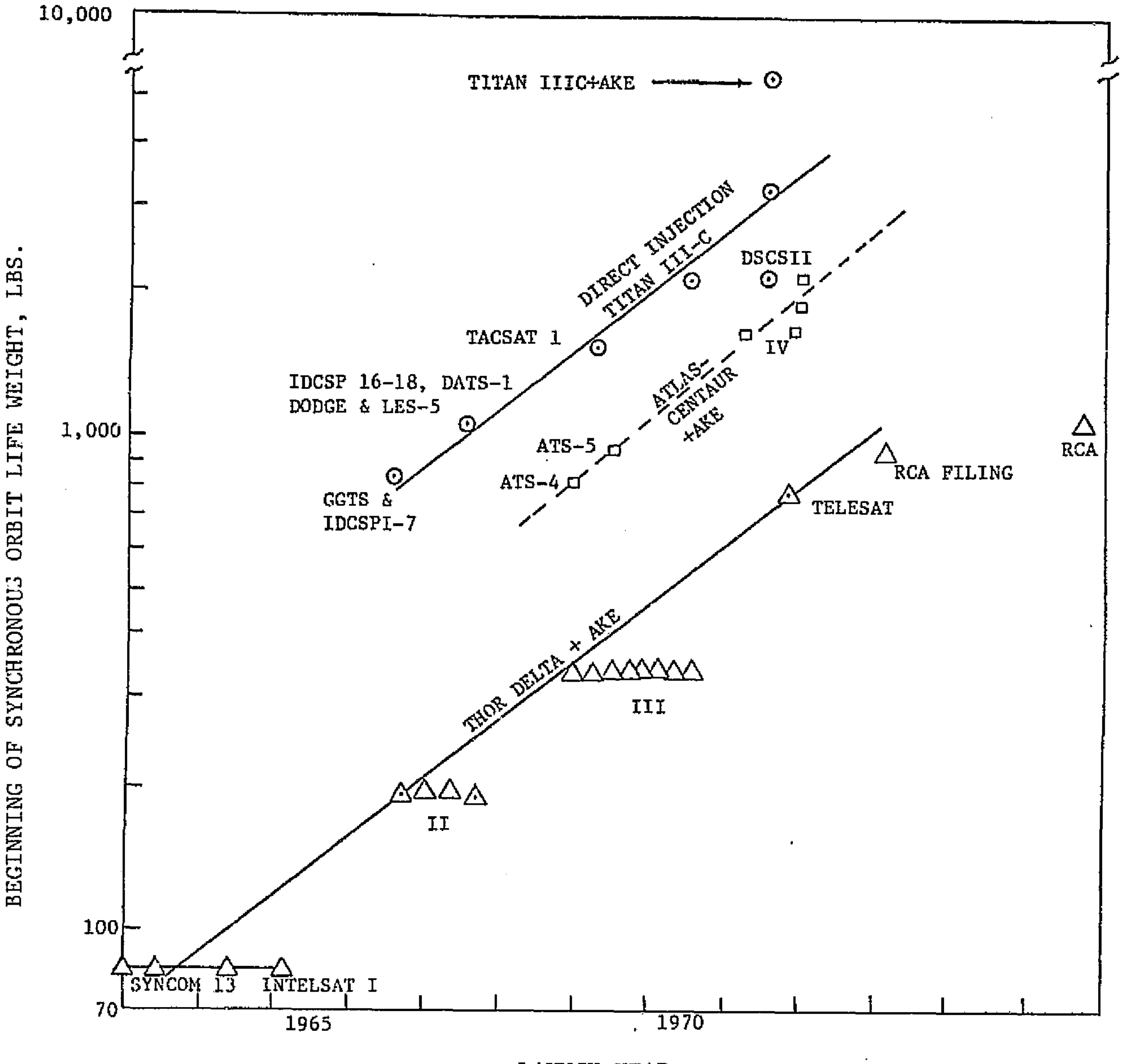
Satellite spacing in synchoronous orbit is a major factor in determining the total capabilities of satellite communications. As stated in previous paragraphs, interfering signals may be received from satellites adjacent to the satellite of interest through antenna sidelobe reception or in the case of wide beamwidth antennas reception through the primary

TABLE 8.13. RELIABILITIES OF VARIOUS LAUNCH VEHICLES - 1962 to 1970 [14]

LAUNCH VEHICLE FAMILIES FOR 1962-70									
SECOND OR FINAL STAGE	FIRST STAGE (s)								SECOND STAGE OVERALL +
	ATLAS	ATLAS D	ATLAS F	THOR		TITAN II *	TITAN III-B	TITAN III-C	
n.a	1.0*	0.89	1.0	-	-	1.00*		0.93	
Agena B	0.82*	1.00	-	0.95	1.00*				0.89
Agena D	0.86			0.87	0.92		0.95		0.90
Centaur	0.74								0.74
Able Star *				0.73*					
Delta				0.92					0.92
Allair *				0.83*					
Burner II	0.00			1.00					0.91
First Stage Overall +	0.82	0.90	1.00	0.90	0.92		0.94	0.93	
		0.84		0.91					

*Not in use in 1969-70

+These overalls are the row or column sums and represent the combined upper/lower stage performance.



OPTIMUM TRANSFER ORBIT

Figure 8.5. Launch Vehicle Performance History [14]

half power beam and sidelobes. The same situation exists for satellites receiving interfering signals from ground stations other than the one of interest. Regulatory agencies have put sidelobe performance restrictions on ground station antennas and are considering beamwidth restrictions as well. An analytic methodology has been developed by Reinhart[15] for determining orbit spacing requirements given satellite and earth station configurations. The FCC has considered minimum orbit spacing of 3°-4° for current satellite configurations [16].

The requirements for minimum orbit spacing will lead to competition between countries for orbit real estate. For example, the orbit arc allowing access to Canada is part of the orbit arc which allows access to the continental U.S., Mexico or Central America [15], to name a few. For this example Canada will be forced to enter into an agreement with these other countries to minimize interference when the orbit arc becomes highly used in the future.

8.5 Satellite Technologies

Technologies associated with the communication satellite have been subdivided into six areas: station keeping, attitude control, electrical power, thermal control, antenna, and transponder. Technologies under these categories are discussed in this subsection. Millimeter and laser communication technologies are discussed separately in Subsections 8.6 and 8.7, respectively.

8.5.0 Spacecraft Structure

Satellite structure considerations are primarily spin versus non-spin configurations and material selections. Until the launch of the RCA SATCOM in late 1975, all commercial communication satellites were spinners. The RCA satellite utilizes three-axis body stabilization. Primary features of spinning communication satellites include (1) simplified stabilization, (2) a despun antenna farm, and (3) a cylindrical spinning body whose surface is covered with solar cells. With the trend of increasing power requirements and increasingly complex antenna systems, the spinning configuration offers less advantage because only 30% of its solar cells are effectively illuminated simultaneously and because the increasing mass of the despun antenna package reduces the inherent stability of the gyrostat configuration. Also, difficulties encountered with the spin bearings which have resulted in fractional degree misalignment of the antenna system tend to increase with increasing satellite size. Three-axis body stabilized satellites offer the advantages of improved solar cell efficiency and the absence of spin axis bearings, but do increase the requirements of the thermal control system since the nonspinning satellite is not uniformly illuminated by solar energy. Attitude control systems for three-axis stabilized satellites have long been employed for noncommunication satellites, and application of the sensor and actuator technology should present no particular difficulties.

Current developments in materials for communication satellite structures include sheet metal core and lightweight honeycomb equipment panels, with extensive use of aluminum, magnesium, and beryllium on the RCA SATCOM. Satellite antenna reflector material for the current state of the art is Kevlar. Other weight-saving materials used within the satellite include graphite-fiber epoxy composite filters in the multiplexers replacing the conventional invar filters.

8.5.1 Station Keeping

The gravitational forces of the moon and sun, as well as the gradient of the earth's gravitational field, perturb the orbits of geosynchronous communications satellites. Satellite station keeping systems are required to overcome these distrubance forces. Motion of the satellite (as seen from the ground) increases the complexity of the earth station antenna systems and increase the interference between satellite systems. The current technology for these station keeping thrusters is a chemical reaction engine utilizing hydrazine as the propellant and having a low specific impulse (approximately 220). In the near future, these hydrazine thrusters will be replaced by Cesium or Mercury Ion engines with significantly higher specific impulse (approximately 2000).

The specific impulse of an engine is proportional to its thrust and inversely proportional to the rate at which it consumes propellant. Thus the propellant required to provide a specified thrust for a given length of time is inversely proportional to the specific impulse of the thruster. The mass budget which must be allocated for a station keeping system with current hydrazine technology is significantly greater than that which would be expected with the use of ion engines. A recent Hughes Aircraft Company study has concluded that the weight savings introduced by the use of ion engines is approximately 165 pounds for a small spinner communications satellite and approximately 195 pounds for a larger 3-axis stabilized satellite. These weight savings are after allocation has been made for additional electric power requirements.

Station Keeping requires (1) a measure of the error in satellite location in orbit, (2) a method of algorithm for determining the required thrust direction, magnitude and duration required to correct the station keeping error, and (3) a set of thrusters to accomplish the corrective manuever. Station keeping error is normally measured by a earth tracking station. Earth-based tracking, telemetry and command (TTC) systems are utilized with Intelsat, WESTAR, etc. Autonomous station keeping measurement systems are used on the experimental LES 8/9 satellites. Typical station keeping thruster requirements necessitate a minimum average thrust of about 1 millipound. Recent ion engine activities include an experimental system on the ATS-F satellite where a failure of the cesium feed system during the second attempted firing of the 1 millipound, 150 watt ion engine occurred. The planned ion engine experiment on the Communication Technology Satellite (CTS) was removed because of weight limitations. In recent studies, Hughes Aircraft Company has performed tradeoff and analyses of five, eight, and twelve centimeter ion engines versus hydrazine thrusters. Comsat has proposed the use of higher thrust ion engines used in conjunction with nickel-hydrogen batteries for higher electrical efficiency and longer wear-out lifetimes. Specifications for the ion engine system of the ATS-F experiment are given in Table 8.14. Requirements for thrusting to correct north-south orbital perturbations are significantly greater than those for east-west perturbations. Figure 8.6 shows a plot of the available payload as a function of spacecraft weight at the beginning of the syndronous orbit for system utilizing hydrazine and for systems utilizing ion engines for north-south station keeping. Projected lifetime for current design ion engines is 21,000 hours, or a 7-year lifetime. A typical station keeping accuracy for such a system is 0.1°. The primary limitation on the technology for ion engines seems to be the power supply for the ion engine. This supply requires a number of different high voltage outputs. An area that should be addressed in ion engine studies would be that of locating the boundary of the plume from the ion engine. Angles of from 50° to as high at 90° have been used as estimates for this boundary.

TABLE 8.14

Ion Engine System Specifications for ATS-F

System specifications for each of the two ion thruster systems are:

thrust	0.004N
thrust vectoring	$\pm 3^{\circ}$ in X and Y
specific impulse	2500 s
total impulse	70,000 N-S
input power	150 W
system mass	16 kg (35 lb)
propellant capacity	4400 h at 0.004 N
command channels	13
telemetry channels	12

Table 8.15 describes the characteristics of several types of electric thrusters.

A side benefit to be gained by implementation of ion engines for station keeping is that of control of space charging of the satellite structure. In previous syncrhonous satellites a large voltage build-up has occurred, with discharges damaging electronics and upsetting logic devices. Ion engines have been used on ATS-5 and ATS-6 to safely discharge the spacecraft.

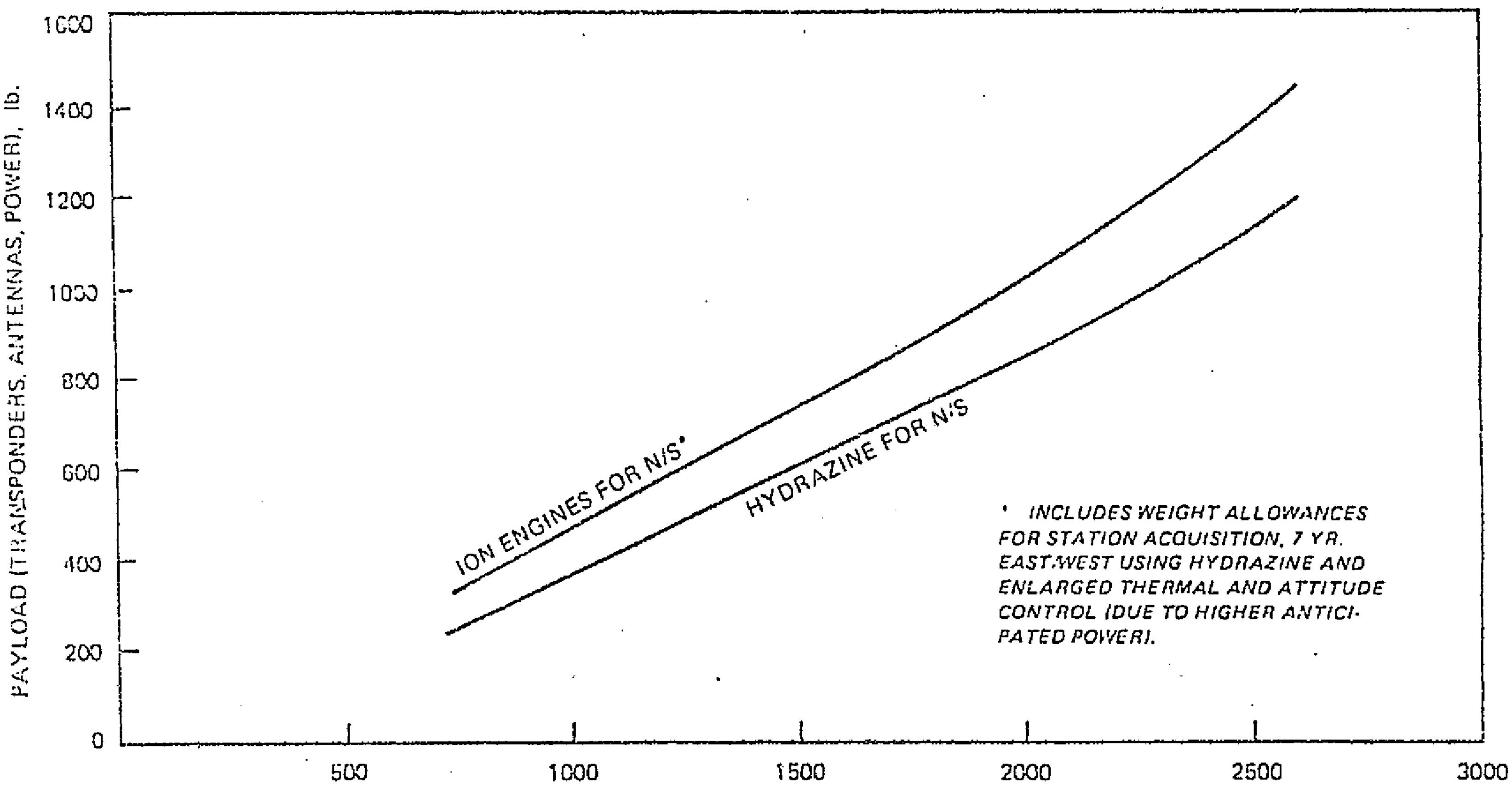


Figure 8.6 SPACECRAFT WEIGHT (BEGINNING OF SYNCHRONOUS ORBIT LIFE WITH APOGEE ENGINE CASING), lb.

TABLE 8.15

ELECTRIC THRUSTER CHARACTERISTICS

	1	2	3	4	5	6	7
Thruster system	Isp (sec)	Fuel weight (kg)	Tankage & feed weight plus electrical system weight (kg)	Specific thrust (w/m-N)	Power required[c] (w)	Power penalty[d] weight (kg)	Total kg 2 + 3 + 6
Decomposed N_2H_4 or NH_3[a]	250	131	13.5 + 0	---	20[a]	1[a]	145
Ion Engine	2100	15.7	4.6 + 9.2	30	133	6	35.5
Colloid Engine	1300	25.2	4.5 + 9.1	18	80	3.7	42.5
Pulsed Plasma Thruster	800[b]	41	2.5 + 16	40	176	8	67.5

[a]For NH_3 system only

[b]At 50 joule/discharge.

[c]At 4.43×10^{-3} N Thrust.

[d]22 w/kg for prime power and conditioning.

8.5.2 Attitude Control

The attitude control system of a spinning communication satellite maintains correct orientation of the satellite spin axis, and the attitude control system of a three-axis stabilized communication satellite maintains the desired orientation of all three body axes of the satellite. Control of satellite orientation is required in order to point the satellite antennas at the desired region of the earth's surface. For a three-axis control satellite, the attitude control also keeps the solar cell array directed toward the sun.

Attitude control systems are composed of (1) attitude sensors, (2) an implemented control law, and (3) the actuators. With current technology the angular accuracy of the attitude control system is limited by the accuracy of the attitude sensors. These attitude sensors may be either (1) infrared earth horizon sensors, (2) star or sun sensors (3) inertial reference systems, or (4) RF earth beacon trackers. Infrared horizon sensors are most frequently used and offer attitude control systems with 0.1 degree accuracy in pitch and in roll, and 0.3 degrees in yaw. Further improvements in the accuracy of these infrared sensors is hampered by the nonspherical nature of the earth's infrared horizon.

With a trend toward smaller beamwidth antennas, future attitude control systems will be required to control larger, more flexible spacecraft with even more stringent attitude-pointing requirements. Estimates of antenna beamwidths of 0.5 degrees and attitude control requirements of 0.05 degrees in 1985 have been made. While RF attitude sensors such as interferometers or monopulse trackers can be used to track a specifically designed and located beacon signal from the earth's surface, they can also be used to track directly the transmitted communication signal from the earth station. These so-called autotrack systems result in direct control over the pointing of the antenna itself and therefore are not subject to the error introduced by thermal distortion of the satellite structure normally encountered between the antenna and the sensor location.

RF attitude sensors apparently are currently flying on military satellites. Their performance figures are said to be good, but advances need to be made in reduction of size, power requirement, weight, and cost for these sensors to be competitive for application on commercial communication satellites.

The primary disturbance torques acting on a geosynchronous communications satellite are due to solar pressure and to misaligned station keeping thrusters. The disturbance torque associated with the misaligned thrusters is less for ion engine thrusters than for hydrozene thrusters because of the lower thrust level. Actuators available for attitude control include thrusters, momentum wheels, control moment gyros, and magnetic torquers. The trends in requirements for attitude control are towards increasingly tighter pointing requirements associated with antenna spot beam requirements, and larger, more flexible solar panel arrays and antennas leading to flexible spacecraft. This latter trend may necessitate the use of distributed control systems on future satellites. The current accuracy state of the art for satellite attitude control systems is approximately 1/10° in the pitch and roll axis, and 2/10° in the yaw axis. Improvements in attitude control tolerances must come from improvements in the sensors themselves. With horizon sensors, one may need to resort to processing, such as Kalman filtering, to improve the sensor accuracy. The use of RF sensors tracking the communication uplink signal in a manner analogous to a monopulse radar tracker offers an opportunity to reduce the thermal distortion pointing errors associated with separately located sensors and communication antennas. Table 8.16 contains some of the key features of present technology attitude control systems appropriate for a 24-transponder domestic satellite weighing about 1000 pounds. Table 8.17 shows the attitude control system performance of the ATS-6 experimental satellite. It is expected that the 1985-era satellites using 0.5 degree antenna beams will require pointing accuracies of 0.05° in pitch and roll, and 0.01° in yaw.

A recent ATS-6 interferometer experiment [17]utilized an 18.5 pound, 15.5 watt, spacecraft interferometer system. As an attitude sensor, the interferometer demonstrated an ability to provide stabilization to better than 0.004° for 43 minutes and a projected long-term stability to the order of 0.01°. Momentum wheels used in the attitude control of ATS-F and similar experimental spacecraft operate at levels of 1 to 2 Newton meter seconds of stored angular momentum. The wheels rotate at approximately

TABLE 8.16

ATTITUDE CONTROL PARAMETERS

Pointing accuracy, 0.1 deg in pitch and roll
  0.3 deg in yaw
Weight, on the order of 37 lb
Expected operating life, 10 years
Reliability, 0.97 for 7-year life
Power, 30 watts

TABLE 8.17

ATS-6 ATTITUDE CONTROL SYSTEM PERFORMANCE

Axes	Control Mode	Accuracy	Stability
Pitch/Roll	Using Earth Sensors or Interferometer	0.5 deg	.01 deg
Pitch/Roll	"Low Jitter" Mode, with E.S. or Interferometer	<.1 deg	.005 deg
Pitch/Roll	Using C-Band Monopulse (Direct pointing only, no "offset" capability)	-	.005 deg
Yaw	Using Polaris Sensor	.1 deg	-

1,000 RPM. An appropriate research area for momentum wheel and control moment gyro actuators is the wheel highspeed bearing technology. Magnetic bearings are presently in the transition stage from being a laboratory curiousity to being an item of practical use [18]. Highspeed bearing research programs must consider such areas as causes of oil depletion, retainer stability, alignment, thermal distortion, contamination, vibration, and metal flaws. Previous research [19] in bearing retainer material has included Nitrile-acrylic copolymer material. Tests of its physical properties have shown it to be suitable as a ball bearing retainer.

One of the biggest error sources in the infrared horizon sensor (horizon radiant noise) is being reduced by moving to a higher frequency sensor--about 14 to 16 microns in the CO_2 band. The yaw accuracy of attitude sensors can be improved by using a sun sensor with the horizon sensors. A typical sun sensor accuracy is only about 2 arc-minutes. Alternately, the use of a biased momentum wheel gives a natural yaw control to alignment of the wheel momentum vector with the normal to the orbital plane. Typical solar torques are on the order of one millifoot pound in magnitude. There is a need for rate gyro development resulting on lower drift rates. The drift specifications on laser gyros are now about 0.015° per hour. Future systems may use a gyro for short-term sensing, and an averaged or Kalman filtered earth sensor for long-term control. Measurement experiments related to this have been performed with WESTAR. Another sensor approach is the use of a large number of inexpensive sensors.

The first Intelsat 4 spinbearing system went into a 90 Hz oscillation resulting in a 0.3° antenna pointing error. Increasing the amount of oil to the bearing for increased life had resulted in a thicker oil film at the bearing which apparently induced slow oscillations in the bearing disturbance torque. Two primary goals in bearing development are (1) to end the wearout mode of failure and (2) to operate at higher speeds, such as 20,000 to 50,000 RPM. Early experiments with magnetic bearings have shown that the magnetic losses themselves are surprisingly high.

An overall geocentric pointing accuracy of 0.032° of arc has been claimed for the new generation of static infrared earth sensors derived from those on the symphony satellite.

Figure 8.7 shows a block diagram for a single channel monopulse tracker applicable to spacecraft antenna autotrack systems.

8.5.3 Electric Power System

Spacecraft electrical power systems consist of subsystems for energy generation, storage, and distribution. The electric power may be generated by solar cell arrays or by nuclear reactors. Although energy can be stored in flywheel devices, it is commonly stored in batteries such as the NiCd, or the more recent NiH_2 batteries. The electrical distribution system can be AC or DC at high or low voltage levels, and regulation may be performed at a central location or individually at the loads.

Previous studies have indicated that nuclear generation of electric power is competitive only if the power requirements of the satellite exceed 10 KW. Communication satellites currently in orbit nominally require about 1 KW and utilize arrays of conventional solar cells. Spinner satellites using the drum surface for mounting of the solar cell have only about a 30% effective area towards the sun. Body stabilized satellites with roll-out or fold-out solar panels can have essentially a 100% effective area arrays. The arrays should be of lightweight and minimum thermal distortion material and low resistance interconnections between solar cells are required. Conventional solar cells are about 10% efficient in the conversion of solar energy to electric energy. Recently developed advanced solar cells called the violet cell and the black cell have efficiencies of 30% and 50%, respectively. Cadmium sulfide solar cells are structurally flexible but have a lower efficiency than the standard silicon cells. Antiradiation coatings are required for each type of solar cell. The two classes of advanced solar cells described above are still not commercially available on a production basis.

Current technology solar arrays produce about 15 watts of power per pound of array. Array pointing mechanisms are required for maximum efficiency operation, and power slip range using technology such as liquid metals are required for transmission of the power from the arrays to the satellite distribution system. Minimization of solar pressure torques is an important consideration in the design of a solar cell array.

The current standard of the industry, the NiCd battery, is relatively heavy and has limited charge/discharge cycling characteristics. Research

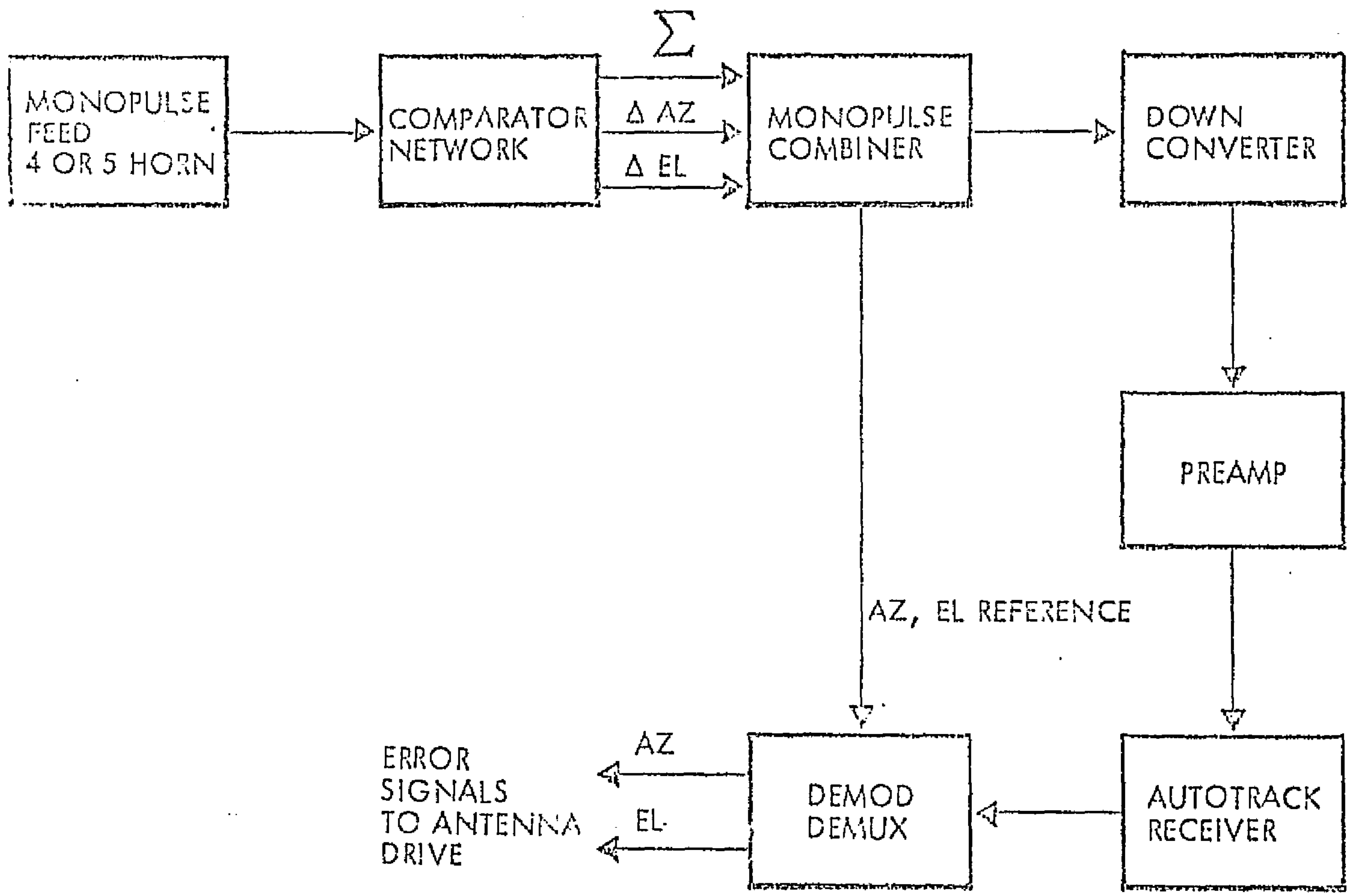


Figure 8.7
MONOPULSE COMBINER MULTIPLEXES AZ AND EL SIGNALS AND MODULATES THEM ON SUM CHANNEL SIGNAL

in the early 1970's in electric energy storage devices centered on H_2O_2 fuel cells. The recent advances of the NiH_2 battery has some of the advantages of the fuel cell. This new battery is lighter than the NiCd by a factor of 2 or 3, and has a larger number of allowable charge/discharge cycles. However, it does require more volume than the NiCd battery. The NiH_2 battery produces no change in its water level as it is being charged; this allows more flexibility in the charging/discharging cycle. The NiH_2 battery is scheduled to fly on an NTS-2 satellite in the fall of 1976. The cost for an electric power system for a typical communication satellite, including the battery, is around $2 million for a 1 KW power system.

The solar cell radiation damage experiment (SCRDE) of the ATS-6 satellite has been transmitting data on 16 different solar cell/cover glass configurations in orbit. The experiment is designed to study the effect of the synchronous orbit environment on selected solar cells and cover glass parameters, such as solar cell thickness and base resistivity, cover glass thickness variation, new cover adhesive processes and materials such as the 7940 and 7070 integral covers and the fluorinated ethylene propylene (FEP) covers, the Comsat violet cell, and backside irradiation effects [20]. All cells performed well through the 325 days in orbit, except the FEP-cover cells which appeared to have increased their rate of degradation during the first eclipse season. Table 8.18 describes the ATS-6 solar cell flight experiment configurations. Figure 8.8 shows the maximum power obtained from each configuration as a function of the number of days in orbit. The relative cost of solar cells as function of cell thickness for different time frames is given in Figure 8.9. Figure 8.10 shows the cost comparisons for solar arrays and batteries and three types of nuclear reactor power sources.

TRW Inc. has found that spacecraft batteries can be reconditioned by draining them down to approximately 1 volt per cell and then recharging them. The batteries come back up to near their original performance status. The current state-of-the-art on solar cell grid contact resistance seems to be about 1/10 of an ohm in experimental arrays. This value was achieved by the use of photolithography and with large area contacts. Anti-radiation coatings impedance matching significantly affects the

TABLE 8.18

ATS-6 SOLAR CELL FLIGHT EXPERIMENT CONFIGURATIONS

Configuration	Resistivity, ohm-cm	Cell Thickness, cm	Cover Glass Thickness cm	Remarks	Location
1	10	0.030	0.0076		Rigid
2	10	0.030	0.015		Rigid
3	10	0.030	0.030		Rigid
4	10	0.030	0.076		Rigid
5	10	0.030	0.0076	Plain 7940 fused silica cover; no filter or coatings on cover	Rigid
6	10	0.030	0.0008	7940 integral cover	Rigid
7	10	0.030	0.0076	7070 integral cover	Rigid
8	2	0.030	0.015		Rigid
9	2	0.020	0.015		Rigid
10	10	0.030	0.015	Cover without UV filter; cover adhesive of 0.005 cm FEP	Rigid
11	10	0.030	0.015		Rigid
12	2	0.025	0.015	COMSAT violet cell: cerium doped microsheet cover without UV filter	Rigid
13	10	0.030	0.013	FEP cover without added adhesive	Rigid
14	10	0.020	0.015		Flexible
15	2	0.020	0.015		Flexible
16	2	0.030	0.015		Flexible

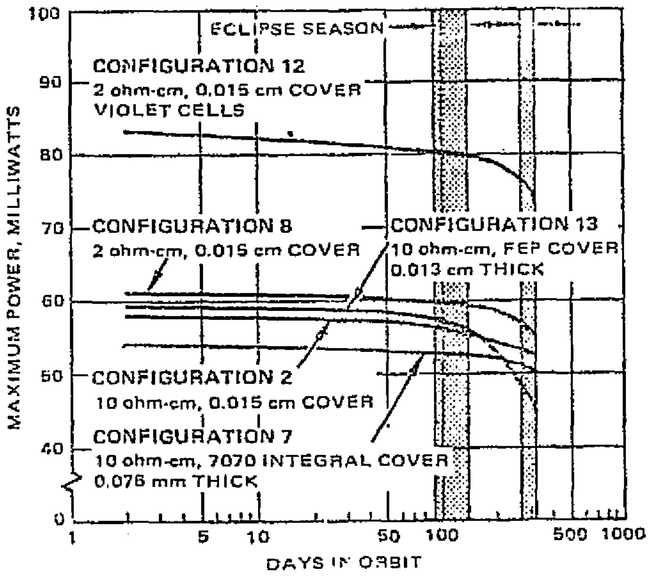


Figure 8.8 ATS-6 Solar Cell Flight Experiment Configurations

efficiency of solar cells. The radio isotope generators used in LES-8/9 satellites produce 150 watts of electric power initially; this is more than twice the output of previous spaceborne sources of this type. Projected output from each generator after 5 years in orbit is 130 watts. The generators utilize silicon/germanium thermoelectric cells and having the highest specific power achieved to date. The generator is fueled by plutonium-238, and measures 15.7 inches in diameter by 23 inches long.

8.5.4 Thermal Control

Satellite thermal control systems are required in order to avoid temperature extremes which increase component failure rate or require more costly components. Temperature extremes also result in thermal distortion of satellite structure, antennas, etc. The severity of the thermal problem is highly dependent upon the satellite configuration. A spinning satellite is more uniformly heated by the sun and has less temperature extremes than does a three-dimensionally stabilized satellite. In addition to heat from solar radiation, heat is produced by power dissipation in the transmitter output amplifiers and by bearing friction. Thermal control techniques include both passive and active systems. Passive radiator panels can be used to

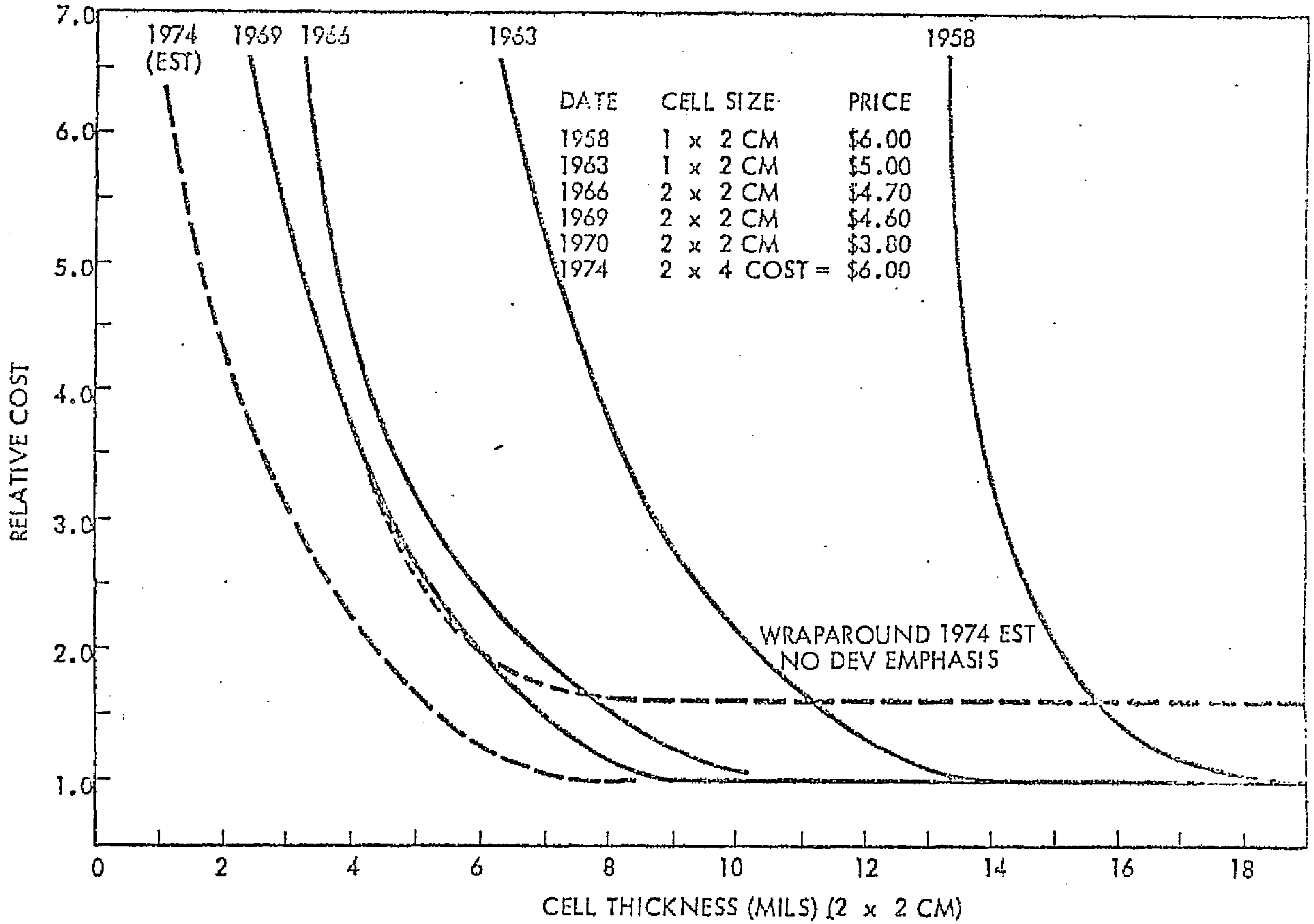


Figure 8.9. Relative Solar Cell Costs

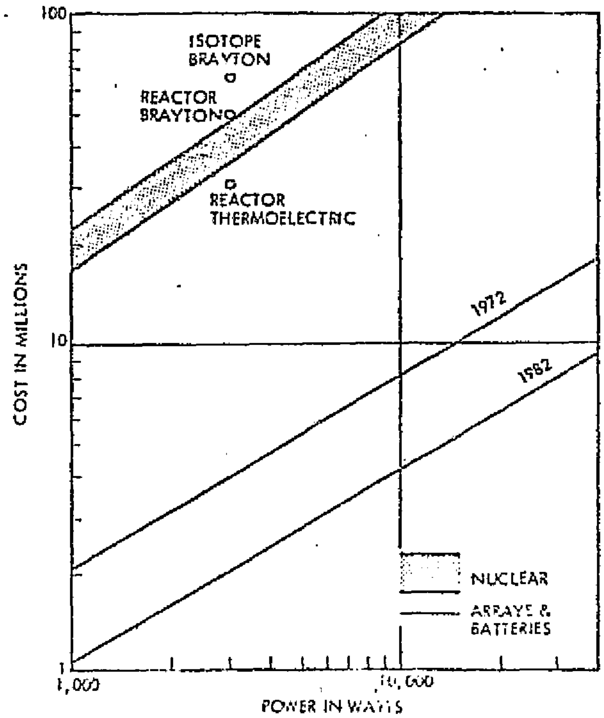


Figure 8.10. Electric Power Generation Costs

control maximum temperatures. Electric heaters can be used to control minimum temperatures, and controllable louvers can be used to reduce the heater power requirements. Fluid loops can be used to transport heat from hot spots to deployable radiators. Heat pipes are useful for efficient conduction of heat from a hot spot to a radiating area.

Passive paint patterns with heaters for cold regions can be used for maintenance of required temperature limits when all units of a satellite operate at a similar power level (for example, the proposed Intelsat 5). However, for communication satellites with a large variation in power dissipation of various subsystems (for example, the military DSCS) the use of heat pipes with the radiator is required. Heat pipes have reached a reliability point where they are flown without particular concern now.

Current research in heat pipes is devoted to the development of bent pipes, longlife heat pipes, and variable conductance heat pipes. Active heat pipe systems incorporate the variable conductant heat pipe, temperature sensors, and the heating of the inert gas of the pipe to vary the conductance. Typical working fluids include ammonia and acetone. Grooved heat pipes are being investigated for minimum temperature differential.

For heat pipe designs where a large heat rejection requirement (500 to 700 watts) with perhaps a high transient requirement with peaks about 10 to 20% of the time, phase change devices (melting) may be useful for the transience. An alternate concept for thermal control is the use of fluid loops where a liquid is pumped around the loop at a high rate. The valves, rather than the pumps, are the lifetime limiting items for these systems. Another desirable quality of heat pipes is graceful deterioration rather than catastrophic failure.

White paints have a solar absorbance factor, alpha, between 0.2 and 0.4. A titanium surface would have alpha approximately 0.7 and an epsilon of 0.1, and would run hot (approximately 1000°).

One thermal control system problem which has been encountered in industry is an instability resulting from coupling between the charge control system for the batteries and the temperature control system for the batteries. Advance analysis techniques utilizing computer modeling should allow design of an inherently stable control system here. Contamination of radiating surfaces is also a problem with thermal control systems. Research is currently being conducted with cascaded heat pipes operating at liquid nitrogen temperature with a 7 watt transfer capability. There is a need for a lightweight heat radiator for traveling wave tube applications with operating temperatures around 230°F, power dissipation around 150 watts, and a system weight of about 3 pounds. The variable conductance heat pipes intended for application as battery temperature control device utilize a noncondensable gas stored in an adjoining reservoir. Within the heat pipe itself, the vapor stays to one side, and the gas stays to the other; the gas is at the heat sink end of the tube, and the vapor is at the end of the bue which picks up the heat. Industry has expressed a need for an incentive for flight testing of variable conductance heat pipes.

The advanced thermal control flight experiment (ATFE) launched aboard the ATS-6 in May of 1974 contained a thermal diode (one-way heat pipe), a feedback controlled variable conductance heat pipe, and a phase change material. All thermal control components performed as expected for the existing flight environment. However, the daily reservoir and radiator temperatures during peak solar imputs are greater than those experienced in ground acceptance tests. These increased temperatures have resulted in a loss of control by the feedback control variable conductance heat pipe for several hours around a period of maximum insolation. The higher temperatures are apparently due to contamination and/or degradation of the second-surface mirrors which cover the reservoir and radiator. Table 8.19 describes the operational modes of the advanced thermal control flight experiment. The temperature control capability of the thermal diode, phase change material, and feedback controlled heat pipe have been demonstrated for almost one year of ATS-6 flight operation. Both the diode and the feedback controller transport approximately 23 watts in the normal and passive modes during maximum conditions. Up to 30 watts has been carried by the feedback controller when the auxillary heater is applied. The thermal conductance of the pipes during forward mode operation is approximately 10 watts/degrees C. The variable conductance operation of the feedback control heat pipe has resulted in temperature stability to within $\pm 2°C$ at 42°C. The same pipe when operated as a passive variable conductance heat pipe demonstrated $32.5 \pm 9.5°C$ control under the same test conditions. The phase change material melts at 28°C and freezes at 27.7°C. Complete melting and freezing of the material has been demonstrated through more than 200 daily cycles. Subcooling has no apparent effect upon the stability of the melting temperature. While variable data has been gained from this experiment, additional effort is required to bring these technologies, especially the closed loop controller, to maturity.

TABLE 8.19

ADVANCED THERMAL CONTROL FLIGHT EXPERIMENT OPERATING MODES

MODE	DESCRIPTION	COMMAND STATUS
Normal	Normal operation of system; Controller provides automatic regulation by FCHP.	ATFE Experiment Turn ON ATFE FCHP Controller ON
Auxiliary	Auxiliary heater ON, to provide additional exercise of FCHP or redundancy if thermal diode should fail.	ATFE Experiment Turn ON ATFE FCHP Controller ON ATFE PCM Box Auxiliary Heater ON*
Passive	FCHP Controller turned OFF: FCHP acts as a passive variable conductance heat pipe.	ATFE Experiment Turn ON
Passive-Auxiliary	FCHP Controller OFF and Auxiliary heater ON as in Auxiliary Mode, to evaluate system with passive control.	ATFE Experiment Turn ON ATFE PCM Box Auxiliary Heater ON
Back-Up	Manual control of the back-up reservoir heater, to provide redundancy in the event the FCHP Controller should fail, or operation at an alternate set point.	ATFE Experiment Turn ON ATFE FCHP Back-Up Reservoir Heater ON/OFF**
Back-Up/Auxiliary	This mode is redundant to the Auxiliary Mode, with manual control of the Back-Up Heater. It can also be used to demonstrate additional FCHP performance at temperatures different from the FCHP controller's set point.	ATFE Experiment Turn ON ATFE FCHP Back-Up Reservoir Heater ON/OFF** ATFE PCM Box Auxiliary Heater ON

*The auxiliary heater is attached to the diode side of the PCM box and has a 20-W electrical output.

**The back-up heater is attached to the FCHP's reservoir and is redundant to the reservoir heater regulated automatically by the controller. It has a 2.8-W output and is turned ON or OFF by command, as needed, to maintain control at the desired set point.

8.5.5 Satellite Antennas

Improved satellite antennas are needed for the use of low-cost earth stations where high effective radiated power is required. Satellite antennas are required then with high gain and multiple beams. Communications satellites can employ reflectors, horns, lenses and phased arrays. For lenses, low-loss dielectric materials are needed while lightweight, low distortion materials are a reflector requirement. For multiple beam applications, beamwidths of less than 1° with gains greater than 43 dB are necessary. Beam shaping will in turn be necessary to illuminate specific areas on earth, while sidelobe reduction must be realized so that sidelobe levels are held to -40 dB. Among the additional requirements for satellite antennas are -

a. Orthogonal polarization isolation between beams must be 40 dB or greater for independent beam operations;

b. Efficient generation of a large number of independent beams from a common spacecraft aperture is needed;

c. Reduction of mass and cost for single large satellites must be a continuing development;

d. The availability of high power transmitters (Subsection 8.5.6) with improved spacecraft antennas with gains up to 30 dB will provide spot beam footprints on earth with enhanced flux density.

The improvements of effective radiated power will provide for the use of receiving terminals in applications no previously possible. It has been suggested that with sufficiently large broadcast satellite power, a useful TV 11 GHz system can be built to provide an entire ground terminal with a cost under $500.

New antenna concepts continue to appear, e.g., the offset feed Cassegrain antenna (BTL), the Tarus antenna (COMSAT) and the flat plate using Fresnel rings (Aeronutronic Ford/Stanford).

The requirements on antennas into the millimeter wavelength region are discussed in Subsection 8.6.1.4 and, except for the high tolerance requirements of the millimeter wavelength region, the majority of the discussion also refers to antennas in the frequency range from 2 GHz to 30 GHz. Considerations for antenna improvement must include:

Lower cost fabrication techniques,

New materials (graphite epoxy, plastic), Maximum efficiency,

New antenna approaches,

Multiple feed systems.

A recently launched synchronous satcom system of RCA has employed graphite fiber epoxy composite materials for the spacecraft's communications input and output multiplexers, antenna horns, waveguide and supports. The system operates on a 6 GHz uplink and a 4 GHz downlink. Parabolic reflectors of the antenna are fabricated from Kevlar, a Du Pont aromatic polyimide material. Twelve vertically polarized and twelve horizontally polarized channels are used with an adjacent channel isolation of 33 dB minimum.

The use of small isolated beams directed to high traffic areas requires large antenna reflectors. The techniques required include further investigation of furled or folded antennas, multiple beam feeds, temperature variations, new materials and the important parameter of flight testing since testing cannot be performed on the ground.

Figures 8.11 and 8.12, taken from a recent NASA Task Team Report on Satellite Communications, show a forecast of developments in gain, mass, and cost for single large satellite antennas and a weight trend plot for a multiple beam antenna at 12 GHz.

8.5.6 Satellite Transponder

During the recent developments of satellite communications systems, solid state devices have played an important role. While low noise TWT's are important for transmitter requirements, many of the low power requirements are being assumed by solid state devices. Thus, receiver front ends in the form of TDA's and now FET's are being realized. Driver oscillators and local oscillators can employ Gunn oscillators and possibly eventually FET's.

The reliability of TWT's is important for the power amplifiers at 4 GHz and above. Below this, the power amplifier can use transmittors. The S-band power amplifier of the ATS-6 satellite serves as an example here. For power levels above 10 W. and at frequencies above 4 GHz, the power amplifier or TWT will continue to be used. The solid state area will continue to work toward the development of a solid state equivalent of the TWT power amplifier at frequencies $\gtrsim$ 4GHz.

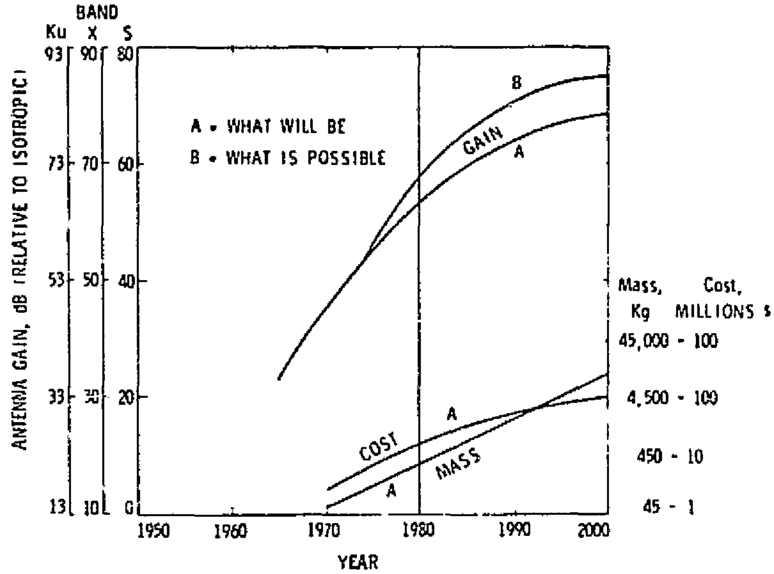


Figure 8.11. Spacecraft Antenna Forecast

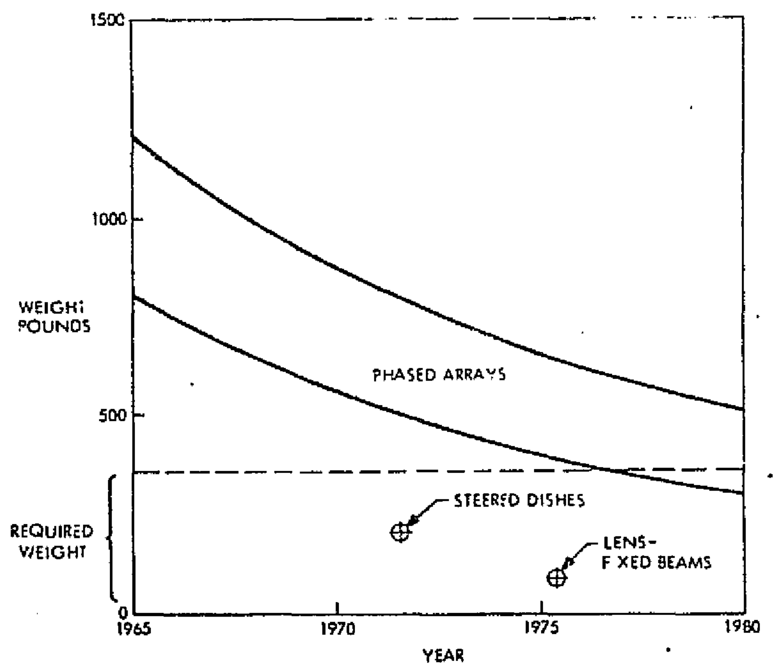


Figure 8.12. Weight Trends of 12-GHz Spacecraft Antennas

The need for increased satellite power and receiver sensitivity is important for realizing systems to meet the future communications requirements. For the case of satellite power requirements, the following developments are important:

1. Increased satellite radiated power to reduce cost and sensitivity requirements of ground terminals. Increased effective radiated power is also a necessity for broadcast satellites.
2. In order to reduce intermodulation content, linearization of the power amplifiers' gain must be improved.
3. Constant improvement in TWTA power output has resulted in a Hughes TWT with 200 w. output at 11 GHz for CTS. At 12 GHz, broadcast satellites have available a 200 W. Litton TWTA and above 500 W. from Siemens and Thomson - CSF. It is possible that continued tube development will result in an output in excess of 1 KW. at 12 GHz.
4. The expectations for FET's are such as to expect them to compete with 15 W. TWT's at 4 GHz and 7 GHz. Their good efficiency and excellent low intermodulation distortion characteristics are attractive. On the other hand, efforts to linearize the TWT will probably increase the effective linear range of these devices.
5. In all spacecraft transmitters, increased efficiency is needed to achieve greater power levels on the satellite.
6. Improvements continue to be made in Ga As IMPATT devices. At a recent Solid-State Circuit Conference, a Ga As IMPATT reflection amplifier was described which delivers 5 W. over a 250 MHz bandwidth at 13.5 GHz. This provides 57 dB of gain for a -20 dB input and to achieve the output level, a double-mesa Read diode is used. A cavity-stabilized IMPATT oscillator has been developed by Bell Labs and has shown a frequency stability of 1.6 ppm/°C. A K_u-band microstrip IMPATT amplifier that delivers 5 W. at 13.5 GHz was also reported by TI and this could be a significant device for communications applications.
7. A recent NASA Task Team Report on Satellite Communications (December, 1975) has presented a group of curves on the characteristics of linear beam tubes (e.g., maximum power vs. frequency, electron tube cost vs. power and 3 dB life vs. rf power) and graphs of solid state transmitter and tube transmitter trends. These are valuable data for assessment of the capability and cost of future communications systems.

The front-end of spacecraft receivers in the microwave region to 12 GHz can contribute significantly to improving the earth/space link as improvements in RF amplifiers are made. Figure 8.2 shows the forecast of device noise temperatures, and Subsection 8.6.1.2 describes some of the receiver technology through the millimeter wavelength region. The trends are such that the simpler, lower cost galliumarsenide FET amplifiers will replace the costly tunnel diode amplifiers (TDA). The FET amplifiers have demonstrated noise figures on the order of 3 dB, compared to approximately 5 dB for the TDA. The forecast for the year 2000 shows a large improvement over the TDA. FET amplifiers are currently available commercially to 12 GHz. It is expected that, as FET's develop and their cost is reduced, they will replace not only TDA's but also TWT's, Gunn-effect and IMPATT amplifiers.

Several interesting aspects of the FET are observed in the rapid advances being made with these diodes:

1. It is predicted that, as costs are reduced, the FET will replace the low-cost Gunn diode in oscillator applications. In turn, as FET rf power increases, they will possibly replace the IMPATTS as higher power sources. The current high cost of the FET has restricted their use to amplifier applications.
2. A recent cost projection in Microwave System News estimates that the FET will drop from the present $100 range to approximately $20 by 1980.
3. It has recently been possible to demonstrate the operation of a 12 to 18 GHz FET which used a 0.5 micron wide gate.
4. Reduction of gate widths will result from improvements in pattern definition processes. Optimization of FET device performance will also result from improvements in the material itself, Ga As epitorial wafers.
5. RCA, Ltd., has employed an FET amplifier in a space system and has demonstrated successful operation.
6. The FET devices are new and have not been given extensive reliability tests. This area will be important for future spacecraft applications. Many small signal Ga As FET's which are commercially available tend to drift with time on the order of a few dB in noise figure and gain for periods ranging from seconds to days. RCA Labs has reported that power FET's do not have the drift problems demonstrated in small signal devices. Avantek has reported that the noise figure and gain drift in small signal microwave FET's can be minimized by depositing a layer of polyerystalline Ga As (PGA).

The trends of uncooled and cooled paramps are such that these devices will be used in cases where FET's cannot meet the low noise temperature requirements. Projections for cooled devices are that noise temperatures on the order of 10° K will be achieved in 1985 for 2 - 18 GHz with paramps (17° K ambient), Josephson junctions and masers as the devices; thermoelectrically cooled paramps are expected to have 30° K - 60° K noise temperatures in this spectral region, while FET's are predicted to have 1.5 dB - 3 dB in this region.

The Schottky barrier mixer devices; which are discussed in Subsection 8.6.1.2, are continuing to develop to contribute to low noise performance. With image enhancement, these devices will improve beyond their current status of a 3 dB conversion loss at 12 GHz.

Transponder switching is an extremely important factor for increasing the capacity of the transponder. This can be achieved by time division multiplex, PCM-phase shift keyed, time division multiple access techniques and further by using multiple beams (space division multiple access). A further two-fold increase is possible by use of polarization diversity, discussed in Subsection 8.5.5.

8.6 Millimeter Communications Systems

The increasing demand of communication system users requires that technologies currently not employed be considered for expanding the capabilities available for applications. The indication is that the number and type of applications for satellite communications will increase significantly in the 1980-2000 time frame. Whether or not these appli ations can be realized depends on the utilization of appropriate technologies. Of particular importance is the potential problem of spectral crowding; obviously, some form of achieving higher capacities is necessary. One such means of spectrum relief is to shift the appropriate services to the millimeter wavelength and/or optical wavelength regions.

In order to provide a measure of the potential benefits to be gained and to allow an assessment of the risks and the costs involved in the development and applications associated with the millimeter and optical regions, it is the objective of the following two sections of this report to establish the state-of-the-art and forecast potential technology developments in the spectral regions of interest, and to investigate associated technical problems (e.g. the impact of atmospheric attenuation). This section, Section 8.6, will survey the millimeter wave technology requirements, while Section 8.7 will treat the optical technology needs.

With a knowledge of the current demand for services and a forecast of the need for these services in view of NASA's long term (1980-2000) goals, an attempt will be made to establish the services and corresponding requirements that could be realized in the 1980-2000 time frame with emphasis on those services that could be provided by millimeter wave optical technology.

A survey of millimeter and optial technology relevant to space communications must cover an enormous number of topics in both the research and development areas. In several of these areas, the required technology does not exist as yet, so that consideration must be given to those schemes which will meet future technology needs. Before embarking on a comprehensive survey, it is necessary to establish the advantages which will accrue from operating at the short wavelengths of the millimeter/optical regions. Table 8.20 lists the advantages of satellite communications in the spectral regions of interest.

In order to perform this survey, several sources were employed for obtaining information. Both telephone conversations and visits were used as a means of contact with industrial suppliers, NASA centers, COMSAT, DOD, and individual investigators. A detailed literature survey has been performed during the course of the survey. The survey which is presented in the following sections has been organized in the following categories:

1. Millimeter Wave Component Technology Required for Communications;
2. Atmospheric Effects in the Millimeter Wavelength Region;
3. Millimeter Wave Communications Systems Concepts;
4. The Potential Use of the Submillimeter Wavelength Region.

Simmilarly, Section 8.7 on Optical Technology has been organized in the following categories:

1. Candidate Optical Communications Systems;
2. Required Optical Component Technology;
3. Atmospheric Effects in the Optical Wavelength Region;
4. Optical Communications Systems Concepts.

TABLE 8.20

ADVANTAGES OF SATELLITE COMMUNICATIONS IN MILLIMETER OR OPTICAL REGIONS

-- High Data Rate Capability
-- Narrow Beamwidths
-- Avoids Spectral Crowding
-- High Attenuation Regions at Millimeter Wavelengths Provides Noninterfering Operation
-- Small Systems
-- Potential Low Cost Systems for High Data Rates

8.6.1 Millimeter Wave Component Technology

The advances made in recent years in millimeter wave component technology has mainly been the result of the extension of low frequency technologies, stimulated by both military requirements and the realization of the need for utilizing greater frequency coverage. The major deterrents to utilizing the millimeter wavelength region have been the lack of sources with adequate power output and the insensitivity of millimeter wave receivers. Recent advances in both radiation sources and receiver devices have improved the situation considerably. In addition, solid state sources are developing rapidly and offer a great size advantage for satellite systems.

The current state of technology for millimeter wave components is the subject of this section. A survey of the industry and literature of millimeter wave components has been made. The results of this survey are presented in such a manner that it will be usable for the cost benefits analysis. Each topic of interest is presented in a subsection, independent of the other subsections, so that continuous up-dating of the material is possible. The following categories are treated in this report section:

- 8.6.1.1 Radiation Sources
    - 8.6.1.1-1 Solid state Sources
    - 8.6.1.1-2 Vacuum Tube Sources
- 8.6.1.2 Receiver Components
- 8.6.1.3 Waveguide Components
- 8.6.1.4 Millimeter Wave Antennas
- 8.6.1.5 Millimeter Wave Integrated Circuits
- 8.6.1.6 Millimeter Wave Components Above 100 GHz
- 8.6.1.7 Millimeter Wave Modulators and Demodulators
- 8.6.1.8 Submillimeter Wave Technology

The availability and current capability of each required component will be seen to have its effect on the feasibility of millimeter wave communications systems and on the prediction of trends in this area.

The format to be followed for each topic is to give a description of the current state-of-the art for the particular item, followed by a summary of the discussion presented in tabular form.

8.6.1.1 Radiation Sources

The development of millimeter wave sources has been significant since World War II. It has been a direct function of the funding which has been available from the various government agencies. The millimeter wavelength region has often been considered to be an inappropriate spectral region for applications and as a result has received insufficient support. Belated recognition by the military and spectral crowding at lower frequencies are resulting in increased realization of the importance of this part of the electromagnetic region.

During the past 10 - 15 years, source development activities have resulted in the availability of several tube sources below 100 GHz. In addition, solid state sources have been continuously pushed from the long wavelength region until now the limitations on the use of solid state sources is imposed by the need for new materials. The availability of these solid state sources will allow satellite communications to be performed at higher frequencies with reduction in size of components and the eventual lowering of costs.

This section on millimeter wave sources will discuss both solid state sources and tube sources, including amplifiers and oscillators.

8.6.1.1-1 Solid State Sources

Solid state sources exist as both oscillators and amplifiers, and, having been developed at low frequencies, can now provide several attractive advantages at millimeter wavelengths. These sources take the form of Gunn effect oscillators and amplifiers, and IMPATT oscillators and amplifier. More recently, Tunnel Diode Amplifiers (TDAs) have been demonstrated as potential devices for millimeter wave systems. Each of these solid state devices have advantages which must be exploited in space communications systems. Although each source must be considered individually, potential functions in millimeter wave communications systems are readily evident. The solid state sources as oscillator/amplifiers can serve as power sources in satellites for millimeter wave communications systems. They have the capability to serve as small local oscillators for fundamental mixing in millimeter wave receivers. An important function of millimeter solid state sources is to serve as the pump source for high frequency parametric amplifiers. In turn, solid state amplifiers can be employed not only for the transmitter end of the propagation link but as an amplifier of the received signal.

Supporting the use of solid state devices in the above functions are their characteristics as compact, efficient sources with excellent lifetimes and potential low noise. They offer great potential for reduced size, weight and cost of the RF sections in millimeter wave systems of the future. Their projected compatibility with integrated millimeter wave circuitry is an additional incentive in considering their applicability to satellite communications needs. In the area of high power transmission capabilities, power combining techniques currently being investigated for IMPATT oscillators offer considerable promise.

To provide a brief survey of the rapidly advancing field of solid state sources, the current state of development, required technology and the direction that planned R&D appears to be headed are discussed for each type of solid state device individually.

Gunn Devices

The Gunn devices are transferred-electron devices (TEDs) in the form of oscillators (TEOs) or amplifiers (TEAs), capable of operating in the millimeter wavelength region. The Gunn devices are very attractive for low noise performance, and it is in this area that the TED has an advantage over IMPATTS. While they exceed the capability of IMPATTS in bandwidth and tunability relative to fm noise levels, the TEDs are lower in power output and efficiencies (by a factor $\gtrsim 2$) for the same operating frequencies and tuning ranges.

In evaluating the applicability of TED's to millimeter wave communications systems, the following advantages must be considered:

Advantages:

Small Size

Potential Low Cost

Simplicity of Construction

Compact Power Supplies

Low Voltage Requirements

Low Current Drain

High Reliability

Broad Bandwidth

Tunability

Low Noise

Low Distortion Effects

The disadvantages of the TED's apply mainly at higher frequencies. While the construction of these devices have simple ohmic contacts, the formation of good ohmic contacts and the chip-to-package bonding present difficulties as higher frequencies are approached. Thus far, the Gunn oscillator is limited to operating frequencies below 100 GHz as the efficiency decreases with higher frequency due to parasitic resistances and time dependence of the Gunn effect. Improved material purity and dissipation are required for operation at higher frequencies than is currently possible.

Despite the above disadvantages, the TED's by their low noise capabilities are excellent candidates for stable efficient paramp pumps, stable low noise local oscillators and broadband low noise amplifiers. Consideration has been given to the problem of whether the Gunn devices are fundamentally limited in their operation above 60 GHz. This, however, appears to be a problem in materials. Indium phosphide (InP) is expected to double the efficiency achievable with GaAs, will have noise figures at least 10 dB better as amplifiers, and will potentially operate to approximately 200 GHz. Actually, InP is superior to GaAs as a TEA or TEO above $\sim$20 - 30 GHz. The prospect of good InP sources with broad tunability will allow low noise fundamental mixing above 100 GHz. Currently, harmonic mixing with higher power, higher noise, lower frequency sources results in limitations on achievable noise figures of receivers. In addition to the LO capabilities, the InP units will have better heat dissipation for pulse devices.

In order to have InP available for these applications, there is a need for basic InP materials work. In addition, composite InP/GaAs holds promise but investigations of this material are also needed. In the United States, Varian is currently considered the leader in InP work, but the major activities in InP development are occurring in Great Britain. Despite the efforts currently being exerted, InP reliability is an unknown quantity because of the small U. S. development of InP devices. In general, the field of TED development is limited to a few organizations because of the large investment required and the production results yet to be achieved.

Among the achievements in the development of Gunn devices, it is possible to point to the following:

1. Narrow band TEA's have operated for years in satellites in the spectral region of 36 - 40 GHz. In addition, the TED's have had the following demonstrated capabilities:

   TEA's: GaAs 18-26 GHz, G = 10 dB, NF = 15 dB
   GaAs 55 GHz, G = 7.5 dB
   GaAs K_a-band, reflection type, 2 stage, output > 100 mW
   GaAs K_a-band, single stage, P_o = 200 mW
   GaAs 240 mW at 38 GHz
   150 mW at 54 GHz < 4% Efficiency
   87 mW at 75 GHz

   TEO's: GaAs 95 GHz, 25 mW

2. 40 GHz varactor tuned TEO has been demonstrated as state-of-the-art.
3. Pulsed TEO's have also been demonstrated.
4. The lifetime of TEO's have been shown to be excellent, thus yielding high reliability. Extensive life tests have been performed through K_a-band.
5. A K_a-band Gunn driver has been developed for satellite communications ground stations. This driver used a new single stage tunnel diode amplifier with P_o = 200 mW and G = 15 dB.

6. As indicated above, wider bandwidths have been demonstrated for TED's than for IMPATTS. A single TED has been demonstrated to operate over the bandwidth of 4 - 31 GHz.
7. Negative resistance has been demonstrated over greater than 50% bandwidth.
8. Low noise InP TEA's have been demonstrated in the 18 - 26 GHz and 26 - 40 GHz frequency bands as possible replacements for TWT's. An amplifier fabricated in the United States has shown a noise figure of 10 dB with a gain of 9 dB at 22 GHz, while a British TEA has been shown to have a 7 dB noise figure.

On the basis of the capabilities that TED's have demonstrated, several developmental activities are underway or will be required in order to be usable devices for communications applications. Included in these considerations are the following topics:

1. Replacement of TWT's with TEA's. It is anticipated that bandwidths of TEA's will increase with the improved bandwidth of associated components such as circulators. The high noise figures, which currently are reported, limit the usefulness of the TEA's to very broad-band applications. However, it is likely that, if lower NF can be achieved over narrow bandwidths, the TEA's could be replacements for paramps and tunnel diode amplifiers.

2. The continued development of TEA's offers the possibility of wideband, low noise amplifiers above 100 GHz.

3. Efforts are underway to provide TEO's as higher frequency paramp pump sources above 100 GHz, and this area of development should continue in the future.

4. In like manner, the TEO's, with continued extension to higher frequencies, can eventually provide LO's above 90 GHz and will permit the use of varactor-tuned LO's above 90 GHz.

5. Integration into millimeter wave MIC's should occur, resulting in compact circuits for system applications. At Georgia Tech, current investigations at the chip level are concerned with the integration of varactor tuned TEO's on a diamond substrate for thermal stability and broad bandwidth.

6. To achieve the goals offered by InP, a program on improved materials and processing techniques is necessary since the United States is at present dependent on foreign sources.

IMPATT Sources

The IMPATT diodes are in some respects complementary to the Gunn devices, yet the two sources are often viewed as competitors and comparisons are made for particular functions. The IMPATTS are characteristically higher power and higher efficiency sources than the Gunn devices, but in turn are much noisier devices. The IMPATTS can consistently give 1/2 W as single units at 60 GHz with 5% efficiency.

As single sources, the following capabilities have been reported:

1. Si IMPATTS have been developed as sources up to 170 GHz for paramp pump applications.

2. The high frequency IMPATTS are double drift region diodes with improved packaging and new waveguide circuitry but low efficiency (1 - 2%). Continued improvement of the package is important since the drop in power is believed to be caused by parasitic lead inductance of present packages.

3. IMPATT diode amplifiers have been demonstrated at frequencies up to 94 GHz. Table 8.21 shows the IMPATT amplifier performance as obtained at Hughes while Table 8.22 shows pulse IMPATT oscillator characteristics from Hughes The IMPATTS are silicon devices.

4. Hughes has been able to integrate both IMPATT sources and amplifiers into millimeter wave circuitry at 60 GHz.

5. IMPATT oscillators have been phase locked at 60 GHz for stability improvement. The free-running spectral outout of these oscillators requires this stability improvement to be utilized in future communications systems. Above 60 GHz severe fm noise makes phase-locking sources difficult.

6. Accelerated life testing has demonstrated MTTF for Si IMPATT diodes of 2.5×10^6 hours at 200°C.

7. The state-of-the-art for silicon double-drift diodes has been shown to be 25 mW at 170 GHz by Hughes while 80 mW at 170 GHz has been reported in Japan. The Si double-drift devices are considered by Hughes-Torrance to be

TABLE 8.21

IMPATT AMPLIFIER PERFORMANCE SUMMARY

Amplifier Description	Small Signal		Large Signal		
	Gain (dB)	Bandwidth (GHz)	Gain (dB)	Power (mW)	Eff. (%)
59 GHz - 1 Diode	10.7	10.0	5.0	315	3.3
57 GHz - Circulator Coupled	11.0	3.0	6.0	180	2.3
59 GHz - 2 Diode	12.0	7.2	5.0	600	2.8
59 GHz - 4 Diode	11.0	7.6	5.0	830	2.1
57 GHz - 3 Stage	31.5	2.5	22.5	480	
94 GHz - Circulator Coupled	10.2	1.5	4.0	100	1.3

TABLE 8.22

PULSE IMPATT OSCILLATORS

Freq. Band	Output Power (Watt)	Efficiency (%)	Pulse Width (μs)	Duty %	Diode Type
X	22.5	5	1	1	NSDR
Ku	5	2.5	1	1	NSDR
Ka	10	10	0.1	1	DDR
W	1.7	2	0.3	0.5	NSDR
D	0.7	4	0.3	0.5	DDR

NSDR = N-Type Single Drift

PSDR = P-Type Complimentary Single Drift

DDR = Double Drift Region

superior to GaAs READ's in power, efficiency and noise above 35 GHz. This can to some degree be attributed to better control of silicon technology plus the benefit of silicon ion implantation technology and compatibility with a diamond heat sink.

8. The GaAs IMPATTS are believed by some investigators to have the promise of lower noise and greater efficiency than silicon, despite the excellent results for Si demonstrated by Hughes. GaAs has performed well to 100 GHz with good reliability, although noise and efficiencies must be improved. At 95 GHz, Varian has obtained in the laboratory an output of 20 mW at an efficiency of 0.7% as compared to 380 mW, 5.5% efficient at 25 GHz.

9. Investigations at 35 GHz have shown that p-type IMPATTS have better fm noise characteristics and higher efficiency than n-type diodes.

In discussing the IMPATT diodes, one can list several drawbacks or improved performance needed for millimeter wave applications. Included in these problems are:

1. Difficulties in interfacing available IMPATT millimeter sources in subsystems.
2. Need for improved temperature stability.
3. Improved reliability.
4. Need to be more reproducible.
5. Reduction of gain variations with temperature.
6. A definite need for lower source noise and improved amplifier NF.
7. Greater bandwidth capabilities are needed.
8. Improvement of packaging, heat sinking and electrical contacts.

For an insight into the current related R&D and future R&D needs for use in millimeter wave communications systems, the following topics should be considered:

1. Research and development has been on-going and should be continued in these categories:

   a. Extension to higher frequencies;
   b. Greater stability and reliability of IMPATTS;
   c. Bandwidth and power output improvements;

d. Integration into millimeter integrated circuits;

e. Materials improvements;

f. Lowering of costs of GaAs diodes;

g. Continued improvement in lifetime of diodes;

h. Continued development of double drift region diodes; an improvement in power and efficiency by a factor of 2 at approximately 40 GHz is anticipated;

i. Noise improvements for LO's;

j. Further investigation of superior noise and efficiency characteristics of p-type IMPATT's.

2. Work which has been performed by TRW on a 34 GHz, 10 watt amplifier for a satellite down-link should be continued and extended to other wavelengths in the millimeter region. The study of noise, modulation products and long term reliability are important.

3. It is important to extend the technology of ion implantation to GaAs. Epitaxial growth and ion implantation have been successfully used for double-drift silicon IMPATT development at 60 GHz, achieving 725 mW at 6% efficiency.

With the achievement of the goals of the above topics, IMPATT devices will allow solid state technology to have an important impact on millimeter wave satellite communications. The continued extension of these sources (oscillators and amplifiers alike) to even shorter wavelenghts ($\lambda \sim 1$ mm) will permit the exploitation of high data rate, very high frequency satellite-to-satellite links. Recent laboratory demonstration of 30 mW at 225 GHz by Hughes under AFAL support indicates that programs to achieve maximum power at these frequencies can be important.

In the next section, power combining techniques are briefly discussed as a solid state means for achieving the higher powers required for transmission in the millimeter wavelength region.

Solid State Power Combining Techniques

The needed capability of moderate power (5 - 10 W) and broad bandwidth (5 - 10% of operational frequency) at 60 GHz and above can potentially be acquired by the use of solid state power combining techniques. Such schemes can provide compact transmitters for communications transceivers in the 40 GHz - 100 GHz bands. In turn, the power combiner technology can be considered desirable relative to tube devices due to

1. Projected longer lifes;
2. Increased reliability;
3. Lower cost and capability to be compatible with MIC techniques;
4. Smaller prime power needs;
5. Reduced size and weight.

The power combining techniques employing IMPATT diodes have been demonstrated in several schemes. IMPATT diodes have been combined in push-pull manner to increase power of single amplifier stage at the chip level. Hughes has demonstrated a relatively wideband combiner (10%) at 60 GHz utilizing hybrid couplers to avoid bandwidth limitations imposed by circulators. This appears to be the only approach suitable for integration.

At lower frequencies, series, parallel and push-pull schemes have been investigated for chip level power combining schemes. The push-pull technique is considered to have the greatest potential, yielding greater RF impedance at lower bias voltages and thereby facilitating combination of several diodes. At X-band, with the use of cavities, power combining has resulted in a 12 W cw output with a 3 dB gain and 4% bandwidth. For systems with amplifiers cascaded, ferrite circulators limit the bandwidth, and this presents severe problems for high frequency applications.

Tunnel Diode Amplifiers

Tunnel diode amplifiers (TDA's) have been considered as low frequency devices, but recent investigations have demonstrated their applicability at wavelengths as short as 3 mm. The convenience of use of these amplifiers contributes to their excellent properties for communications, which includes low AM to PM conversion, very low gain ripple phase nonlinearity and high gain-bandwidth product. The TDA's have definite performance and cost advantages over paramps although paramps exhibit a lower noise figure.

Experimental TDA's have been operated at 30 GHz by Hughes and in the range of 55 - 85 GHz by BTL. The ultimate goal is the development of reliable, low cost TDA's at 50 GHz for communications. The 30 GHz TDA of Hughes had bandwidth of 2.5 GHz and an 8 dB NF while the device of BTL, reported in 1961, had a NF > 10 dB. The higher frequency applications will require development of diodes with a resistive cut-off frequency of 90 GHz or greater. Aerotech Industries has reported new structure and fabrication techniques for millimeter wave tunnel diodes with a cut-off frequency of 90 GHz. The structure produces a low stress, mechanically rugged device.

The TDA has been used in several satellite-borne receivers, however, GaAs FET amplifiers have replaced TDA's at frequencies below 8 GHz, and the trend will continue as the performance of GaAs GET amplifiers improve. Watkins-Johnson currently can supply GaAs FET amplifiers to 12 GHz. The TDA will be a strong candidate for space and ground use in the 18 - 30 GHz communication band if suitable diodes are developed. The TDA has an advantage in gain stability and bandwidth, and 30 GHz would have a size, weight and cost advantage over a paramp which in turn would have the better noise figure.

In order to achieve the indicated capability at millimeter wavelengths, R&D efforts on TDA's should include an effort to affect an increase in the resistive cutoff of the diodes and continued activities to achieve new and improved structures and fabrication techniques, as indicated by Aertech.

Solid state sources are seen as being significant devices for millimeter wave communications systems, and some of the important aspects of these devices are listed in Table 8.23.

8.6.1.2 Vacuum Tube Sources

The conventional radiation sources in the millimeter wavelength region have been vacuum tube devices. In early millimeter wave investigations, signals were generated by nonlinear harmonic generators. The originating signal source at the lower frequency was a reflex klystron or, in some cases, a magnetron. Extension of tube technology has resulted in a variety of oscillators and amplifiers. Development of tube sources has been sporadic depending upon various planned applications. Funding has most often been

TABLE 8.23

MILLIMETER WAVE TECHNOLOGY

Item:	Solid State Sources
Types:	Impatt Oscillators Gunn Oscillators Impatt Amplifiers Gunn Amplifiers Tunnel Diode
Function:	Provide Power Sources for mm Wave Communications Systems; Local Oscillators for Receivers; Amplifier Pump Sources; Amplifiers for Transmitted and Received Signals
Advantages:	Compact, Efficient Sources; Excellent Lifetimes; Potential Low Noise; Reduced Size, Weight and Cost of RF Sections Used in mm Systems of Future; Potential High Power and Reliability in Power Combining Techniques; Compatible with Integrated mm Circuitry

Current State of Development:

1. Si IMPATT Oscillators with Power Combining Techniques Have Produced 5 - 10 Watts at 43 GHz (Hughes/AFAL for Satellite-Aircraft Communications)
2. Si IMPATTS with Power Combining Techniques Have Produced in Excess of 1 Watt (Hughes/AFAL for Satellite-Satellite Communications)
3. Si IMPATTS Have Served as Sources up to 170 GHz (Hughes/AFAL for Mixer and Pump Applications)
4. IMPATTS Above 100 GHz are Double Drift Region Diodes, Have Improved Packaging, New Waveguid Circuitry but Low Efficiency (1 - 2%); Drop in Power is Believed Caused by Parasitic Lead Inductance of Present Package

TABLE 8.23 (Cont.)

MILLIMETER WAVE TECHNOLOGY

Current State of Development (Cont.):

5. Current Work on Indium Phosphide by Varian and Hughes is Conducted to Provide Improved Materials for Higher Frequencies and for Higher Efficiencies and Higher Power
6. IMPATT Oscillators Have Been Phase Locked for Stability Improvement
7. Excellent Lifetimes for Gunn Oscillators and Impatt Diodes
8. Pulsed Gunn Oscillators Have Been Demonstrated
9. Power Combining of IMPATT Sources Has Demonstrated Both Higher Power and Improved Reliability
10. Accelerated Life Testing has Demonstrated MTTF For Si IMPATT Diodes of 2.5 x 10^6 Hrs. at 200°C
11. IMPATT Diode Amplifiers Have Been Demonstrated to Operate up to 94 GHz
12. Both IMPATT Sources and Oscillators Have Been Integrated Inot mm Circuitry at 60 GHz

Required Technology:

Continued Improvement in Lifetimes;

Increased Power Output;

Improved Materials, e.g. GaAs and InP;

Continued Development of Double Drift Region Diodes;

Improved Material Processing Techniques, e.g. Ion Implantation;

Higher Frequency Sources for Amplifier Pumps and Transmitters.

Expected R&D:

1. Improvement of Materials (ECOM; Varian/Hughes)
2. Lowering of Cost of GaAs Diodes (Hughes)
3. Extension to Higher Frequency (Hughes/AFAL)
4. Greater Stability, Reliability of IMPATTS (Hughes)
5. Bandwidth and Power Output Improvements (Hughes/AFAL)
6. Integration into mm Circuits (BSTL.; ECOM; Hughes; AFAL)
7. Extend TDA's to Higher Frequencies

dependent upon DOD requirements. With the advent of solid state sources, vacuum tube technology has not always received the attention that is required. Despite these deterrents, a slow but steady development has occurred.

Millimeter wave low level tube oscillators include backward wave oscillators (BWOs) and reflex klystrons. Reflex klystron oscillators have been employed in various airborne applications under adverse environmental conditions. Tuning ranges of several GHz with power outputs on the order of 100 mW are available in the millimeter spectral region. (Extended interaction klystrons provide tens of watts of power at a few percent tunable bandwidth in these frequency ranges.) The BWO is used to provide tens of milliwatts of power into the hundreds of gigahertz region.

Several choices of millimeter wave power amplifiers are available for both ground stations and the satellite. The traveling wave tube (TWT) is inherently a broadband high gain amplifier for the microwave and millimeter wave regions. As such, it has found wide application in communication systems. TWTs have been used in communications satellites and ground stations for over ten years. These tubes are especially constructed and tested to ensure reliability. As a result, these space TWTs are experiencing lifetimes near 100,000 hours.

Classified programs are in progress to develop space qualified millimeter wave tubes. Several 60 GHz tubes have already been delivered. It should be emphasized that space qualified millimeter wave tubes are quite expensive, especially if a tube at the desired frequency range has not been previously constructed. It is expected that access to these classified programs would be obtained on any ensuing communications work. Data on these new tubes should be particularly useful in assessing the potential for the required amplifiers. Key parameters are average and peak power outputs, gain, bandwidth, and efficiency. NASA is currently pursuing programs to develop highly efficient TWTs at frequencies into the millimeter wave region. For example, multistage depressed collector operation is expected to yield tubes with up to 50 percent efficiency at 40 GHz. Single stage depressed collector operation is used on the 60 GHz tubes discussed above. Hence, TWTs will likely be used as final power amplifiers in satellite communications at millimeter wavelengths. It should be noted that low-noise low-power TWTs have also been widely used in the microwave region as driver amplifiers. For the higher power final amplifier, IMPATTs will probably be competitive with TWTs.

The tube amplifiers and oscillators are important to the success of millimeter wave communications. Despite the attractive features of solid state sources, applications requiring high transmitter power must employ tube sources.

The demands of millimeter wave communication systems impose requirements on transmitter and amplifier devices:

1. For ground station applications, increased power is needed for higher frequencies. In addition, tube efficiencies must be improved. In the case of amplifiers, increased bandwidth, uniformity of gain and constant phase across the band are needed.

2. Spacecraft applications have the same requirements but in addition must achieve these features with reduction in size and power consumption with greater efficiency.

3. Direct broadcast millimeter wave systems are potential applications, and will need significantly greater power possible only with tube sources.

The development of tube technology has resulted in the following advances:

1. Varian Associates has been able to extend the frequency of reflex klystrons to 220 GHz with approximately 10 mW output at the high frequency. These tubes are relatively stable and are readily phase-locked to harmonics of frequency standards. As local oscillators, they are adequate for ground stations but will be replaced by solid state LO's, when available, in satellite systems. These klystrons need further improvements in lifetimes and require high input powers associated with their low efficiencies.

2. Hughes has constructed TWT's at 31 GHz, 38 GHz and 55 GHz. The source at 55 GHz is a solenoid focused TWT amplifier with an output in the 5 - 7 kW range, but is a narrow band tube. Currently, TWT amplifiers are in the design stages at 40 GHz (100/200 W) and at 80 GHz (200 W) for satellite communications applications.

3. Varian has developed Extended Interaction Oscillators (EIO) which are available from 30 GHz to 280 GHz in both pulsed and CW modes. Forty different

tube types exist with a peak output power of 20 kW at 95 GHz and 1 kW (cw) at 35 GHz. These devices have advantage over BWO's in that they require fewer supplies and their frequency output is less sensitive to high voltage changes.

4. Watkins-Johnson has produced a BWO with approximately 10 mW at 50 GHz which are much smaller than carcinotrons and have recorded lifetimes of 10^4 hours. They are, however, high voltage tubes. The CSF (France) carcinotrons are available to 800 GHz and are large, high voltage tubes. The power output varies greatly as a function of frequency. Russian carcinotrons have been developed to provide a complete line of sources to approximately 400 GHz.

5. Recent developments in relativistic electron beams (REB's) offer the promise of high power, efficient, tunable sources throughout the spectrum to wavelengths as short as approximately 100 μm. NRL is the lead lab in the United States. While REB technology is in its preliminary development stages, these devices are capable of providing exceedingly high power for ground-based transmitters. Size presents a problem for satellite-borne systems. Pulsed operation requires increased pulse repetition rates over existing devices, but rates up to a few kHz will be possible. Pulsed gigawatts of power are projected for wavelengths into the submillimeter region. In the case of cw sources, the Russians have developed high power tubes, known as gyrotrons, which have been demonstrated to yield 10 kW at 2.78 mm and 1 kW at 0.95 mm. Projected cw powers for these sources are 100 kW at 3 mm and 10 kW at 1 mm. The cw sources offer the greatest potential for communications applications. No information is currently available on the stability or monochromaticity of the gyrotrons. In the United States, Varian is funded by ERDA and RADC to construct gyrotrons in the wavelength region from approximately 1.25 cm to 2.5 mm.

6. Optically pumped lasers, discussed briefly in subsection 6.8 on the submillimeter wavelength region, are available at wavelengths as long as approximately 2 mm. The characteristics of these devices are treated later, but for the millimeter region they can be considered as low noise but inefficient, low power sources. Few sources with suitable power exist above 100 GHz, and, in many cases, the efficiency of the sources are low. Table 8.24 presents a list of conventional sources taken from the open literature. This list includes several tubes which have been constructed or which are currently under

TABLE 8.24

CONVENTIONAL MM AND SUBMM SOURCES

SOURCE	TYPE	f(GHz)	Power Output (W)	Efficiency (%)	REMARKS
1. WJ-282	Klystron	35.5	10^3	14	Watkins-Johnson CW, Fixed Frequency; Oscillator
2. WJ-266	Klystron	35	10^3	10	Watkins-Johnson CW, Amplifier (10-13 dB)
3. 196H	Klystron	92-95.5	$3x10^3$	--	Hughes 0.0003 duty cycle; oscillator
4. 197H	Klystron	93-95	10^4	--	Hughes; Oscillator; 0.0003 duty cycle
5. QKH-1563	Magnetron	32-35	$65x10^3$ Peak	24	Raytheon; 0.1-1 μs pulse width duty cycle=0.001
6. BLM-076A	Magnetron	34-36	10^3	9	Varian; 0.25 μs pulse width; duty cycle = 0.0005
7. SFD-319	Magnetron	34.5-35.2	10^5	17	Varian; 0.05 μs pulse width; duty cycle = 0.0005
8. BL-246	Magnetron	68.0-71.5	$8x10^3$	6.3	Varian; pulse width = 0.25 μs duty cycle = 0.00055
9. BL-246A	Magnetron	68.0-71.5	10^4	7.9	Varian pulse width = 0.25 μs duty cycle = 0.00055
10. BL-221	Magnetron	69-70.5	10^4	7.9	Varian pulse width = 0.3 μs duty cycle = 0.001
11. BL-234C	Magnetron	69.5-71.5	$0.4x10^3$	6.1	Varian pulse width = 0.25 μs duty cycle = 0.001
12. DX-423	Magnetron	95.53	$8x10^3$	4.5	Amperex pulse width = 0.05 μs duty cycle = 0.002
13. VMS-1043	Magnetron	34-35	$45x10^3$	20	Varian frequency-agile; pulse width = 1.0 μs duty cycle = 0.001

TABLE 8.24 (Cont.)

SOURCE		TYPE	f(GHz)	Power Output (W)	Efficiency (%)	REMARKS
14.	841 H	TWT Amplifier	31.4-31.8	10^3	---	Hughes Max duty cycle = cW Gain = 50 dB
15.	VKQ-2416A	Extended Interaction Oscillator	35	10^3	10	Varian duty cycle = 0.001 pulse duration = 0.5 μs
16.	VKE-2412A	Extended Interaction Oscillator	50-75	10^4	10	Varian duty cycle = 0.001 pulse duration = 1 μs max
17.		Extended Interaction Oscillator	94.0	$8x10^3$	7.9	Varian proposed tube duty cycle = 0.001 pulse duration = 1.0 μs
18.	VKT-2411A1	Extended Interaction Oscillator	140	1	0.21	Varian proposed tube
19.	819H	TWT Amplifier	54.5-55.5	$7x10^3$	---	Hughes Max duty - CW Gain = 20 dB
20.	826HG	TWT Amplifier	93-95	10^3	---	Hughes max duty = 0.001 gain = 30 dB
21.	VRY 2432E1	Extended Interaction Oscillator	280 $\pm$ 15	1	---	Varian proposed tube; CW
22.	VRY 2430E1	Extended Interaction Oscillator	280 $\pm$ 15	10	---	Varian proposed tube; duty cycle = 0.1 max pulse length = 1 ms
23.	C010.1	BWO	275-310	1	---	CSF;CW mode
24.	Ubitron	Undulating Beam Interaction	55	$150x10^3$	~6	GE 250 W average
25.	50M10	Magnetron	50	$20x10^3$	13	OKI duty cycle = 0.00025 pulse width = 0.25 μsec

TABLE 8.24 (Cont.)

SOURCE		TYPE	f(GHz)	Power Output (W)	Efficiency (%)	REMARKS
26.	184H	BWO	135-150	2	—	Hughes CW Oscillator
27.	815H	TWT	135-150	30	--	Hughes Amplifier 12 dB gain

development. The list does not include all sources which exist in the millimeter-submillimeter wavelength region. Table 8.25 briefly summarizes some of the tube requirements and current developments.

In summary, for millimeter wave oscillators both solid state and tube devices must be evaluated. For low-noise low-power drivers, Gunn amplifiers would be leading contenders with IMPATTs and TWTs also a possibility. For the higher power final amplifier, IMPATTs and TWTs will probably be more appropriate.

TABLE 8.25

MILLIMETER WAVE TUBE DEVELOPMENT

Types:	Both Amplifiers and Transmitter Oscillators
Requirements:	For Ground Station Applications, Increased Power at Higher Frequencies; Improved Efficiency; Increased Bandwidth Capabilities; Constant Phase Across Band.
	For Spacecraft Applications, Same Requirements as Above With Reduction in Size; Reduced Power Consumption; Greater Efficiency.
	If Direct Broadcast Millimeter Wave Systems are to be a Reality - Significantly Greater Power is Needed.
Current Status:	1. Several Tubes Have Been Developed Through the Years for Various Specific Applications
	2. Reflex Klystrons Available to 200 GHz; Power From 200 mW to Approximately 10 mW; Poor Lifetimes; High Input Power. MFG: Varian.
	3. Carcinotrons Available to Approximately 800 GHz; Large, High Voltage Tubes; 1 Watt Available to 300 GHz. MFG: CSF of France.
	4. BWO With Approximately 10 mW at 50 GHz Much Smaller Than Carcinotrons; Lifetimes of 10,000 Hrs. Recorded; High Voltage Tubes. MFG: Watkins-Johnson.
	5. Russian Tubes: Complete Line of Carcinotrons to Approximately 400 GHz; High Power Tubes (Gyrotrons With Superconducting Magnets) -- 10 kW at 2.78 mm and 1 kW at 0.95 mm, Both CW.

TABLE 8.25 (Cont.)

MILLIMETER WAVE TUBE DEVELOPMENT

Current Status: 6. Interaction Oscillators (EIO) are Available From 30 GHz to 280 GHz, Both Pulsed and CW; Peak Output Power of 20 kW at 95 GHz and 1 kW (CW) at 35 GHz Have Been Achieved; Family of 40 Different Tube Types Exist; Approximately 200 EIO's Have Been Sold; Requires Fewer Supplies Than BWO's and its Output Frequency is Less Sensitivity to High Voltage Changes. MFG: Varian.

7. Solenoid Focused TWT Amplifier 5 - 7 kW at 55 GHz; Narrow Band Tube. MFG: Hughes (Malibu).

8. TWT Amplifiers in Design Stages at 40 GHz (100/200 W) and at 80 GHz (200 W) for NASA-Lewis. MFG: Hughes (Torrence).

9. TWT's Constructed for Navy (38 GHz) and Army (31 GHz). MFG: Hughes.

10. Several Magnetrons Available to 94 GHz

11. Research on Relativistic Electron Beams at Several Labs

12. Optically Pumped Laser to 2 mm

8.6.1.2 Receiver Components

Millimeter wave receivers are possibly the most important elements of a milimeter wave satellite communications system, for they determine the sensitivity of the system, setting the requirements on transmitter power. The millimeter wavelength region has always been of interest for scientific investigations so that receiver development has had an impetus from radiometry of the environment and radio astronomy in addition to communications applications. Developments which are currently being made in receiver technology can make millimeter devices competitive with the technology of the centimeter wavelength region.

In discussing millimeter wave receiver technology, it is necessary to survey mixers, local oscillators and the configurations employed in applying the local oscillator to the mixer, associated receiver components and the IF characteristics of the systems which have been assembled.

Because of its importance for communications in the millimeter wavelength region, the overall performance of the receiver system has been investigated in detail for frequencies up to 100 GHz. Scientific requirements and other interests have stimulated receiver investigations at wavelengths into the submillimeter region.

Development of components continues to be a necessity. While many significant advances in the state-of-the-art of low noise receiver technology have been made, it is necessary to focus on both the current and projected state-of-the-art millimeter wave "front-end" noise performance.

The most general high-sensitivity receiver front-end is of the heterodyne type in which one or both RF-input sidebands are translated, via a single down-conversion, into a single IF band. In the majority of receiving system applications, including communications, discrete information bearing signals in one input sideband must be received and processed unambiguously with respect to extraneous signals in the other. The use of a double-sideband receiver for single-sideband reception results in a 3 dB degradation in sensitivity.

Therefore, in order to maximize receiver sensitivity in single-sideband front ends, a high degree of rejection is presented to the unwanted sideband by the selectivity of the RF preamplifier, by the presence of a "preselector" bandpass filter preceding the mixer, and/or by the use of a mixer configuration with inherent image-rejection properties. In turn, for millimeter applications, waveguide component losses can be high so that it is extremely important in most system applications to minimize the input circuit losses in functional components such as duplexers, limiters, switches, filters, etc.

In the case of bandpass filters preceding the mixer for rejection of an unwanted sideband, difficulty is experienced at millimeter wavelengths as a result of the high losses which are caused by conventional band-pass filter techniques employed at centimeter wavelengths. Current millimeter wave techniques are resorting to other filter methods such as those offered by quasi-optical techniques. Both JPL and Georgia Tech are investigating quasi-optical schemes. At Georgia Tech, Fabry-Perot interferometers are being tested as a technique for sideband rejection. Problems in this scheme are concerned with reduction of insertion losses and achieving of the proper interferometer finesse to achieve a high degree of rejection.

A variety of approaches to low-noise millimeter-wave reception has evolved in recent years. The approaches have included the utilization of low-noise RF preamplifier mechanisms, low-noise mixer-IF amplifier configurations, and cooling of the front-end package to significantly reduce its internal ambient temperature. The thermal noise power available from a given dissipative element is proportional to the physical temperature of that element so that the noise performance of thermal noise-limited front-end components can be improved significantly by cooling. This is particularly true of parametric amplifiers and converters; and, to a lesser degree, it applies to Schottky barrier mixer diodes.

The relative merits of the various front-ends must be studied for the millimeter wave region. Figure 8.13 shows the receiver front-end noise performance as a function of input signal frequency.

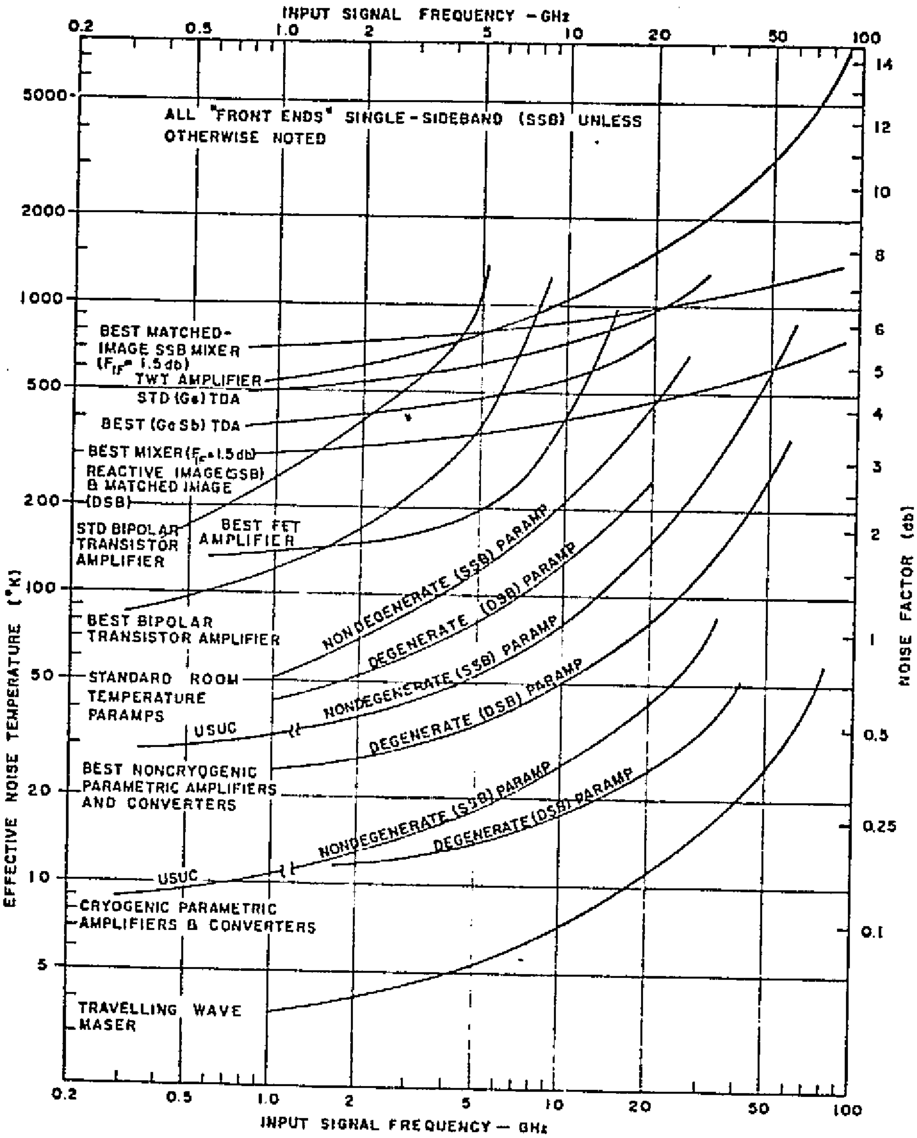


Figure 8.13. Receiver Front-End Noise Performance as Function of Input Signal Frequency - 1974 State-of-the-Art

For the low noise RF preamplifiers in the millimeter region, three amplifiers merit consideration: traveling wave maser amplifiers, parametric amplifiers and converters, and traveling wave tube amplifiers. The traveling wave maser represents the ultimate in virtually noise-free reception at frequencies as high as 50 GHz. Structures are currently under investigation to extend the traveling wave maser technology to 120 GHz. The costliness and complexity of the maser structure have, however, resulted in its replacement by the parametric amplifier in most ultra-low-noise receiver applications.

The parametric amplification mechanism which is applicable to the short wavelength millimeter wave systems is the circulator-coupled, negative-resistance parametric amplifier. In this device, negative resistance, generated at the signal frequency (f_s) provides unlimited reflection amplification, subject to gain-bandwidth constraints. Two paramp configurations are possible: the nondegenerate (single-sideband) with pump frequency $f_p \pm 2f_s$ and the degenerate (double-sideband) with $f_s = f_p/2$. These paramps have been utilized to 60 GHz and are feasible to 100 Ghz. Under Air Force Avionics Lab sponsorship, 94 GHz nondegenerate paramps are being developed by LNR Communications. In turn, IMPATT oscillator development for the Air Force is extending the operating wavelength to 180 GHz so that degenerate operation of paramps can be utilized at frequencies to 90 GHz. Cryogenic considerations, pump source stability and reliability, and compactness of the paramps are all factors which must be analyzed for the millimeter wave communications systems. As materials and techniques improve, noise temperature of the various devices will decrease. Figure 8.14, taken from a recent report, "NASA Task Team Report on satellite Communications," dated December 1975, shows a forecast of noise temperatures of front-end devices. Maser devices, while providing the best noise temperatures, are relatively narrow band and require cryogenic cooling. Among the uncooled devices, the forecast for the year 2000 does not show a great improvement with an uncooled paramp over a mixer-IF combination. The projection of FET's also presents an interestng potential. These devices are currently available to approximately 12 GHz.

In the area of mixer-IF amplifiers, Schottky barrier mixer diode technology has led to the evolution of moderately low-noise Schottky barrier

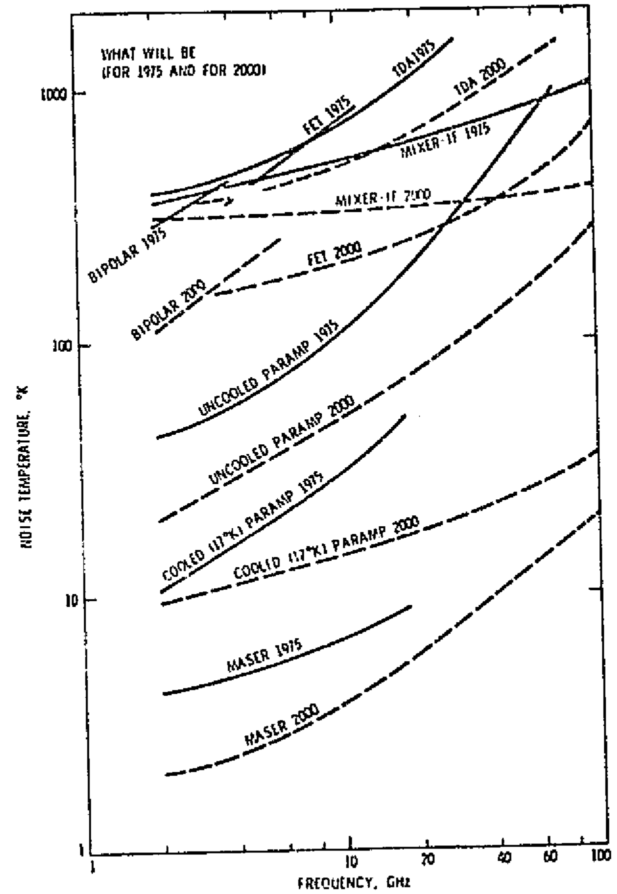


Figure 8.14. Device Noise Temperature Forecast.

mixer-IF amplifier front ends. These configurations are competitive with various RF preamps for single-(and double-) sideband reception, particularly in the millimeter wave region up to 100 GHz. High quality diodes and IF amplifiers are available commercially, and receivers employing these elements have been flown in satellite experiments (e.g., the Nimbus NEMS and SCAMS designs). Investigations at Georgia Tech are concerned with extending low-noise receivers and Schottky barrier diode technology to 300 GHz. Techniques for employing balanced mixers, for implementation of matched-image mixers for single-sideband reception, the use of still higher quality, lower parasitic content Schottky diodes, the realization of improved circuit techniques and the advantages of cryogenic cooling are being evaluated during that program.

With the concentration of efforts which have been made in mixer development, several significant points can be made on the status of mixer technology:

1. Satisfactory waveguide mixers are available commercially to frequencies as high as 100 GHz. Most devices use Schottky barrier diodes in Sharpless wafer mounts. Double sideband NF $\sim$7dB are available. Hughes employs Si Schottky barrier diodes. These are usually available in IF frequencies from 10 MHz to greater than 2 GHz with instantaneous RF bandwidths on the order of 2 GHz (at 1 dB points).

2. Very broadband waveguide mixers have been developed in the 40 - 60 GHz region by NELC.

3. Spacekom has employed a unique balanced mixer configuration with Schottky barrier diodes up to 70 GHz. These units, employing beam lead diodes, have NF = 5.5 - 6 dB with 20 - 25 dB image rejection. While beam lead Schottky-barrier diodes are being produced, efforts to use these elements in a Spacekom mixer at 118 GHz have thus far been unsuccessful. The design offered in this mixer configuration is extremely interesting from the viewpoint of single side-band operation, since other schemes, e.g. Fabry-Perot interferometers, thus far have higher losses than desired and present a more complex configuration than the mixer along presents.

4. Tunable mixers are available commercially inthe 50 - 60 GHz range with NF $\sim$ 7 dB.

5. Excellent receiver development work has been performed by Wrixon of Cork, Ireland and Schneider of Bell Laboratory up to 230 GHz. Total receiver noise figures of 13 dB at 230 GHz and 8 dB at 170 GHz have been achieved. Fundamental mixing at 170 GHz and harmonic mixing at 230 GHz were employed. At JPL, the use of quasi-optical mixer configurations have resulted in the reporting of NF $\sim$ 8 dB from 118 GHz through 184 GHz. The quasi-optical mixer design has been indicated as having the same sensitivity to frequencies as high as 225 GHz.

6. Schottky barrier diodes have been developed at Lincoln Laboratory for use up to 60 GHz, and these have been employed for harmonic mixing against optically pumped lasers in the submillimeter wavelength region.

7. GaAs Schottky barrier diode fabrication and receiver development is currently being performed at Georgia Tech for the spectral region from 100 GHz to 300 GHz for NASA-Goddard.

8. A super-Schottky barrier diodes has been used at Aerospace for X-band, but efforts have not as yet been successfully used in the millimeter wavelength region. This device consists of a superconducting lead "whisker" in contact with a GaAs Schottky barrier diode. It is projected that, if the technology can be extended to approximately 100 GHz, it would result in a NF = 0.5 dB for the mixer, a 1 dB receiver NF with a bandwidth of 1 GHz.

9. The techniques of stripline receivers have been developed up to 230 GHz by Schneider of Bell Labs, and appear to offer excellent coupling of the IF signal from the diode to the IF pre-amp.

10. Cooling to nitrogen temperatures of GaAs Schottky barrier diodes has been demonstrated by Kerr of Goddard Institute and Mattauch of NRAO. Noise figure improvement has resulted from this effort. These researchers, in collaboration with JPL, have been developing excellent Schottky barrier mixers.

In addition to the development work on mixer technology, investigations of receiver front-ends have been progressing in the millimeter region. Since size is an important factor for satellite communications systems, dielectric guide receiver research of IITRI, Hughes and Bell Labs is important. A 60 GHz dielectric guide transceiver with NF = 10.6 dB has been demonstrated by

Hughes. Schneider at Bell Labs has constructed a 60 GHz receiver, pumped at 1/4 of the L. O. frequency yielding a 5.2 dB conversion loss with NF = 7 dB.

The areas related to millimeter receivers which require continued R&D efforts include the following:

1. Lower cost, compact receivers to include both small discrete elements and integrated dielectric components. An eventual monolithic system is desirable for satellite devices. Size, weight and cost will be important in satellite systems.

2. Broadband, up to ∿ 10 GHz, receivers in the 40 - 100 GHz region for satellite communications.

3. Paramp improvements in both lower noise and higher frequency operation should be continued. High frequency pump source work, currently being pursued, is important for high frequency degenerate paramp development.

While paramps have been developed at frequencies as high as 94 GHz, the performance can be improved by the availability of better pump sources. Needed are stable, high power solid state sources to avoid the use of klystrons which are short-lived, large, expensive and require high primary power. An exploratory development program, conducted by AIL for AFAL, has had the objective of providing sources suitable for use as a paramp pump up to 300 GHz. They have been able to achieve frequency tripling from 100 to 300 GHz with an output of 2.1 mW and an efficiency of 1.4 percent. Frequency doublers from 100 to 200 GHz with an output power of 16.5 mW at 6% efficiency and 10.2 mW at 11.4% efficiency have been developed. A 200 GHz quasi-optical doubler was used as a pump source for an experimental degenerate paramp.

4. The advances made in balanced mixer technology will, when fully developed, provide a major contribution to single side-band operation in the millimeter wavelength region. This technology is significant, not only for communication receiver systems but for high frequency radiometery of the atmosphere.

5. Cooled mixer devices with low conversion loss for very low noise applications should be developed. A caution to observe in this area, however, is the additional weight and power consumption imposed on satellite-borne communications systems by the cryogenic apparatus. The use in ground stations should be fully expected.

6. Local oscillators are demanded for millimeter wave systems. In order to avoid the poor noise figures imposed by harmonic mixing techniques, low noise solid state L.O.'s are required for fundamental mixing at all wavelengths to be used for communications systems. Phase stabilization of these sources must also be established.

7. The developments made at JPL in the area of quasi-optical technology are very important for receiver developments. Limitations imposed by conventional waveguide techniques have made L.O. injection to the mixer a difficult and high loss task. The quasi-optical schemes can provide the methods for single sideband receiver operations, low loss injection of the L.O. to the mixer and local oscillator noise filtering. The quasi-optical technique for local oscillator injection will prove superior to directional couplers, ring couplers and coupling cavity techniques.

8. Beam lead technology can provide a very stable diode and must be extended into the milliemter wave region. These devices are available through 60 GHz but should be developed to the region of 100 GHz. Parasitic capacitance will unlikely be a deterrent to their use above 100 GHz.

9. As high frequencies above 100 GHz are employed, open structure mixer configurations can be an advantage for receiver systems. Some such devices have been built in the past, but not with Schottky barrier diodes nor with the design considerations required.

Table 8.26 presents a summary of mixer considerations.

TABLE 8.26

MILLIMETER WAVE TECHNOLOGY

Item:	Receiver Mixers
Types:	Schottky Barrier Diodes Silicon or Gallium Arsenide
Function:	Low Noise High Sensitivity Receiver Mixer
Advantages:	Improved Noise Figures Most Sensitive mm Wave Room Temperature Mixers Radily Integrated into Millimeter Systems

TABLE 8.26 (Cont.)

MILLIMETER WAVE TECHNOLOGY

Expected R&D:

Extension of Mixer Technology to Higher Frequencies for Radiometry Applications (NASA-Goddard/Ga. Tech; JPL/Univ. Va.)

Improved Local Oscillator Power at Fundamental Frequency (Ga. Tech, Cork, NASA-Goddard)

Continued Fabrication Improvements (BTL, Lincoln Lab, GTC)

Cryogenic Investigations (Univ. Va., JPL)

Configuration Development (Ga. Tech, NASA-Goddard)

Current State of Development:

1. GaAs Schottky Barrier Diodes Employed at 230 GHz Receiver with Overall Noise Figure of 13 dB (BTL)
2. Operated at 170 GHz with Noise Figure of 8.2 dB (BTL)
3. GaAs Diode Materials Developed and Available From Several Sources - BTL, Sperry, TRG, Ga. Tech-EES, Lincoln Lab, University of Virginia, Aerospace, Baytron, Cork
4. Improved Operation up to 94 GHz with Cryogenic Cooling (University of Virginia)
5. Super-Schottky Diodes Demonstrated to x-Band (Aerospace)
6. Improved IF Coupling and Matching by Strip Line Techniques (BTL, Cork)
7. Employed as Direct Mixers and Harmonic Mixers (BTL, Lincoln Lab)
8. Silicon Diodes at Frequencies up to 100 GHz (Hughes)
9. Noise Figures Approximately 5 dB up to 94 GHz

Required Technology:

Improved Mixer Configurations

Improved LO Coupling Schemes at Higher Frequencies

More Rugged Structures - Protection Against Shock and Transients

Development of Strip Line Structures

Improved Materials Fabrication

Balanced Mixer Configurations

8.6.1.3 Waveguide Components

Several companies manufacture millimeter wave components with components available to 100 GHz. Custom made components can now be provided in conventional waveguide configurations throughout most of the millimeter wavelength region. Above 100 GHz, there are companies that can provide conventional components to approximately 300 GHz. The losses encountered in fundamental mode guide at these higher frequencies can become prohibitive so that oversize guide or quasi-optic schemes must be employed.

There are currently problems in components which must be solved in the frequency range from 30-100 GHz for improvement of communications systems. These components include circulators and isolators. A few brief comments are given on some of these components.

a. Millimeter Wave Circulators

Millimeter wave ferrite circulators are available at frequencies up to approximately 140 GHz, but as indicated previously are limited in bandwidth. This limitation is highly undesirable in millimeter wave communication systems, for which broad band operation is one of the greatest advantages. Improvement in amplifier bandwidths will in turn result with increased circulator bandwidths. In the region of 50-100 GHz, bandwidths on the order of 4 GHz with 20 dB isolation and up to 0.5 dB have been achieved. Increased bandwidths to at least 5 GHz are needed for wideband 60 GHz IMPATT reflection amplifiers. In order to achieve broader bandwidths and improved isolation, new materials with higher magnetization or higher saturation level will be needed. In addition, materials capable of handling the increasing power of millimeter wave sources are areas of investigation. In turn, with increased bandwidth and isolation, it is necessary to maintain a low insertion loss.

b. Isolators

The problems encountered in millimeter wave circulators are also encountered in millimeter wave ferrite isolators. Both bandwidth and insertion loss are critical. Hughes has been able to achieve 30 dB isolation in the 95 GHz region but these devices have high insertion losses on the order of 1 dB. The problems could be removed by research on materials with higher saturation moment.

c. A complete line of miscellaneous waveguide components must be developed.

1. Phase Shifters - need low loss and low cost phase shifters for millimeter wave phased arrays; ferrite phase shifters not practical above 50 GHz; Pin diode phase shifters for dielectric guides need lower insertion loss, better matching to waveguide; electro-optic type phase-shifters should be investigated; for frequencies above 100 GHz, quasi-optical techniques should be developed.

2. Conformal voltage - scanned arrays for millimeter frequencies are being explored by Ball Research Corporation. These antennas have functioned up to 16 GHz and are projected as possible devices for the 35-40 GHz spectral region. They are sheered with micro-strip phase shifters which should be developed so that a variable permittivity or variable permeability substrate can be used in the antenna feed system. The major requirement is in the microstrip phasor development. Ferrite, semiconductor and electro-optic materials should be investigated.

3. Wavemeters are currently available to 325 GHz, one model by Baytron being a direct digital read-out system. The low Q of the resonators which are currently employed presents a poor response. The best response of a wavemeter is obtained from a small confocal Fabry-Perot interferometer which can be packaged as small as the conventional meter. The high Q of Fabry-Perot resonators can in turn be employed as stalo cavities for source stabilization.

4. Oversize waveguide components and quasi-optical techniques should be investigated more fully as components for higher frequency. As higher powers are employed at the higher frequencies, larger waveguides must be used. In the case of the projected use of very high power relativistic beam sources, pressurized quasi-optical components are currently being considered for future applications.

5. Signal Switching and Routing - For certain types of services, it may be desirable to configure systems which switch between various channels or antenna beams. In addition, instead of a single high power amplifier as discussed in previous paragraphs, it may be desirable, or necessary, to utilize an array of low power amplifiers for the final power amplifier. Such an array would require a feed network to distribute

the drive signal. This network might utilize an N channel corporate divider, a series of 3 dB hybrids, a series feed with progressively increased coupling ports, or some other approach.

Components which are available for switching and controlling millimeter wave signals in the millimeter wavelength region include PIN diode switches, ferrite isolators, diode modulators, variable phase shifters, and couplers. Critical parameters include bandwidth, insertion loss, reliability, phase errors, VSWR, temperature dependence, and cost. The need and availability of suitable components of this type will depend, of course, on the system configuration.

Other signal routing schemes are available in addition to switching the entire RF signal. Channel dropping filters are currently being used by the Bell Telephone System at millimeter frequencies. A few hundred megahertz of bandwidth can be removed from a 50 to 60 GHz signal with relatively low loss and low cross talk. Such a technique might be applicable to the proposed effort. Still another scheme would involve translating the millimeter signal down to a baseband signal and then filtering and switching at these lower frequencies. This is the more likely approach for the ground based transmitting station.

8.6.1.4 Millimeter Wave Antennas

Millimeter antennas have the distinct advantage over microwave antennas of producing higher gains and narrower beamwidths for the same size aperture. These and other considerations can be exploited in systems applications. These benefits are obtained, however, only if proportionately increased tolerance and rigidity are maintained in the antenna. Usually a $\lambda/16$ to a $\lambda/32$ rms surface tolerance must be maintained on a reflector surface for proper performance. This translates into a 0.1 to 0.2 mm rms error at 3 mm. Maintaining these tolerances in a thermal vacuum environment with adequate strength and without excessive weight requires careful selection of materials and careful mechanical design. The structural design of the antenna system is also governed by such factors as accelerations, thermal stability, vibrations, materials compatibility, shock, and cost.

This subsection briefly considers some of the technical tradeoffs which must be considered for antenna components for the millimeter wavelength region. The selection of an antenna type requires a consideration of a number of factors, some of which are included in Table 8.27 other important factors to be stressed in this survey that relate to both satellite and ground applications include antenna configuration, lightweight construction techniques and multiple-beam techniques.

(1) Antenna Configuration

Both single and double reflector antennas have been used at millimeter frequencies. The double reflector antenna (Cassegrain, for example) has the advantage of having its center of mass near the main reflector which simplifies pointing the antenna. In addition it permits the receiver front end to be conveniently mounted near the feed, thus minimizing losses. A major disadvantage of a double reflector is the extra mechanical problem of accurately maintaining the position of the subreflector. Other reflector tradeoff considerations are listed in Table 8.28.

A number of alternatives to a reflector antenna are available at millimeter frequencies. These include lens-horn combinations, corrugated horns such as the scalar feed, slotted arrays, and phased arrays. The beamwidth, beam shape, bandwidth, sidelobe level, beam scan capabilities, weight and losses of each of these types are different.

(2) Lightweight Construction Techniques

It is also vitally important in designing the antenna that the proper tradeoff of performance versus weight be made. To this end, consideration must be given to the use of lightweight construction techniques such as the use of aluminum, beryllium or honeycomb structures. In addition, graphite fiber reinforced plastic as well as fiber-glass lay-up techniques must be examined for the primary reflector. These materials possess very high strength-to-weight ratios. Various mesh reflector designs can be considered for millimeter applications. Table 8-29 shows spacecraft antenna thermal distortion data and the types of materials which can be considered for satellite antennas, while Table 8-30 summarizes the characteristics of some graphite epoxy antennas which have been fabricated.

The technique of placing a stressed-skin covering over a rib or stringer structure is a well-known method for obtaining lightweight, rigid antenna components. A structure of this type operating at 95 GHz was designed, fabricated, and tested in a recent Georgia Tech program for Applied

TABLE 8.27

ANTENNA DESIGN PARAMETERS

Signal	Platform	Antenna	Tracking	Hardware	Other
Duty factor	Stability	Beam shape	Acquisition technique	State-of-art in rf components	Packaging
Modulation	Attitude	Beamwidth	Error slope	Mechanical components	Environment
Intensity	Motion rates	Gain	Ambiguity	Electrical components	Simplicity
Dynamic Range	Positioning modes	Sidelobe level	Angle detection circuitry	Receiver sensitivity	Reliability
		Null depth	Accuracy		Quality assurance
		Type of element/feed	S/N ratio		Human factor
		Element number	Signal processing		
		Element spacing	Target spacing		
		Scan sector			
		Bandwidth			

TABLE 8.28

REFLECTOR TRADEOFF CONSIDERATIONS

Reflector Aspects	Tradeoff Considerations
Aperture illumination	Gain
	Sidelobe level
	Beamshape
	Beamwidth
	Bandwidth
Reflector type	Weight
	Shape Tolerance
	Slew rates
	Transmitter/receiver location
Feed geometry	Polarization performance
	Square or round
	Illumination
	Cost of fabrication
Feed network	Size and blockage
	RF losses
	Complexity
Angle tracker aspects	Multihorn
	Quadridged
	Reflector F/D ratio

TABLE 8.29

SPACECRAFT ANTENNA THERMAL DISTORTION DATA FOR AN 8 FOOT DIAMETER REFLECTOR

Material & Fabrication Technique	Temperature Coefficient of Expansion Used in Analysis (in/in/°F)	Weight (lb.) Dish, Sub-Reflector & Struts Including Paint	Solar-Induced Effects			
			Max. Edge Defl. (inches)	Beam Squint (degrees)	Gain Loss (dB)*	Difference Boresight** (degrees)
0.010" Graphite-epoxy skins on 3/4" aluminum honeycomb	0.92×10^{-6}	27.24	0.008	0.0075	0.14	< 0.01
0.10" Invar skins on 3/4" Aluminum honeycomb	Varies with Temperature $0.7\text{-}1.2 \times 10^{-6}$	62.99	0.015	0.013	0.40	< 0.01
1/16" Solid Beryllium Shell	6.5×10^{-6}	35.87	0.043	0.088	3.96	< 0.01

*At 60 GHz

**Divergence between main beam peak and tracking pattern null

TABLE 8.30

SUMMARY OF SEVERAL KNOWN GRAPHITE EPOXY ANTENNAS RECENTLY FABRICATED (SOURCE: JPL)

Number Made	Construction	Dia.	Surface Tol.	Application
2	laminated	72"	.0025	R&AD*
1	honeycomb	60"	.004	R&AD
1	laminated	96"	.002	R&AD
1	honeycomb	96"	<.010	R&AD
6	honeycomb	58"	<.010	Viking
1	honeycomb	144"	in fab.	Mar-Jup-Sat
3	honeycomb	48"	.003	R&AD
2	honeycomb	108"	.0045	R&AD
1	honeycomb	72"	.001	Satellite(?)

TWO WEIGHT VALUES HAVE BEEN QUOTED

(1) Several 58" reflectors with spars and subreflector weigh $\approx$ 12 lbs.

(2) An 80 cm reflector (with unknown supports) weighs $\approx$ 4 lbs.

*Research and Advanced Development

Physics Laboratory. The approach combines the advantages of a high section modulus (related to stiffness) with low weight.

Reflecting surfaces or other components for large antennas sometimes employ panels formed by sandwich construction techniques. These panels consist of either metal or fiberglass skins top and bottom separated by a shear-carrying material, usually a honeycomb or rigid foam core. These panels are designed to maintain their curvature without additional support.

Where figures of revolution are involved, metal spinning is the fabrication technique usually employed. Such reflectors may also be fabricated of fiberglass with the reflecting surface consisting of a fine wire mesh stretched over the mold, or a metal-sprayed surface applied directly to the mold. These latter techniques, however, have often displayed limited service life. Once the curvature has been obtained, both fiberglass and metal skins require reinforcement to maintain their shape, unless a sandwich construction is employed.

(3) Multiple-Beam Antennas

The need for adaptive multibeam antenna systems has already been established by a number of investigations. Multiple beam antennas are becoming a necessity for proposed operational satellite systems. Multiple beam antennas must be used when the communication link must be pointed at a number of different points in space. This is especially true for the satellite if it must relay information between several ground stations that are widely separated. If more than one satellite is involved, similar capability might be necessary for the ground stations.

Multiple antenna beams can be generated either by using one aperture or through the use of several apertures. Considerable savings in volume and weight can often be realized by using a single aperture which can take the form of either a complete phased array, a small array feeding a collimating device, or a number of separate feeds in conjunction with a collimating device. The antenna designs will vary depending on the operational function of the system. By use of a parametric tradeoff study, the antenna type for a given mission can be determined.

(a) Phased Arrays

The phased array offers the greatest flexibility in the number of beams and beam shapes that can be obtained as well as in the rapidity in changing from one beam configuration to another. A large number of design considerations must be taken into account in selecting the method of implementing a phased array. The selection of element spacing, type of spacing (e.g., rectangular, triangular, or hexagonal) and whether the array is thinned or not determines the allowable scan sector, the presence and level of grating lobes, the number of elements required and the complexity of the beam forming and beam steering computer. Element thinning can reduce the number of active elements in the array by as much as 50 percent, as was done in HAPDAR.

Series and corporate feeding is used to achieve a relatively compact structure. Phase shifter losses are usually cumulative for a series feed but are not for the corporate one. A space fed array can be used if room is available to simplify the RF distribution network. Transmission type and reflection type lenses can both be used for a space fed array. However, the feed for the reflection type array must be offset to reduce aperture blockage and the structure does not package as nicely as the transmission type of lens for many applications since the exit aperture and feed must be on the same side of the lens.

Multiple beams can be obtained from an array by rapidly switching one beam to a number of different positions using the phase shifters of a totally phase steered array or by utilizing some type of interconnection matrix to simultaneously obtain a number of beams. The penalty that must be paid for the flexibility of a totally phase steered phased array is quite high. Cost, size, and weight are usually all high for a completely phase steered array. To reduce these factors, techniques are used such as combination of phase-frequency scanning, instead of pure phase scanning. Alternate approaches to multiple beam performance exist.

(b) Beam Switching

Beam switching as a means of beam agility might be a useful alternate to a phased array. For example, multiple beams can be simultaneously generated in space by using a cluster of feeds along the focal locus of a collimating device such as a lens or a reflector. Using an electronic switching network (instead of phase shifters) the beam can be switched to any one of a number of beam positions (to maximize the signal), thus avoiding the complexity of the electronic equipment associated with the adaptive technique.

(c) Multi-frequency Operation

Simultaneous operation at more than one frequency from a single aperture can be achieved in a number of ways, including: interlacing of several arrays, each operating at a different frequency, into one aperture; utilization of wideband elements; and through use of different elements, separated physically, each operating at a different frequency. To illustrate the first approach, Provencher has reported the results of an interlaced array operating at L, S and C bands simultaneously. Ridged horns and orthogonal polarization were used to achieve a compact structure with low cross coupling between bands. However, a substantial amount of work needs to be done to improve the sidelobe performance of this type of array.

If the individual elements in the array or the subarrays can be made broadband enough, one array can be used to handle more than one frequency rather than having to interleave arrays. Certainly corrugated horns can be built which can operate over an octave bandwidth, and they can be dual polarized. In addition, corrugated horns possess high beam efficiency, low sidelobes and equal beamwidths in all planes. Using cascaded mode couplers, single horns have been made to operate at 4, 6, and 7 GHz and at 4, 6, and 11 GHz with separate outputs for each frequency. Concentric coaxial cables can also be combined to permit multifrequency operation from a single feed.

Still another approach for providing multifrequency operation is through use of a separate feed at each frequency with the feeds physically separated. The practicality of this particular approach depends on the specific application for which it might be considered. If the beams do not have to look at the same spot on the earth at the same time, a mechanically rotated feed system might provide adequate coverage. A five frequency radiometer system has been built around this concept using a multi-spoke feed and a parabolic torus reflector. If a fan beam is required, beam squint can be avoided by using a parabolic cylinder and stacking the feeds of different frequency one above the other along the focal axis of the reflector.

(d) Polarization Effects

For systems employing frequency reuse with orthogonal polarizations to increase channel capacity, the bandwidth and polarization isolation of antenna feed components such as orthomode transducers, polarizers, and waveguide become extremely critical. These components have to be designed to minimize cross-polarization effects.

Table 8.31 briefly summarizes some of the antenna considerations.

TABLE 8.31

MILLIMETER WAVE TECHNOLOGY

ITEM: Millimeter Wave Antennas

TYPE: Satellite-Borne Lightweight

FUNCTION: Antennas Required for 35 GHz, 40 GHz, 80 GHz, and above 100 GHz

ADVANTAGES: Lightweight small temperature coefficient of expansion
Relatively low solar-induced effects
Tolerances adequate for millimeter wave antennas

CURRENT STATE OF DEVELOPMENT:

1. Antennas fabrication from fiber epoxy composite materials on aluminum honeycomb (see tables).

REQUIRED TECHNOLOGY:

1. Extend fabrication to higher frequency antennas.
2. Lower fabrication costs.
3. Space environment testing.

EXPECTED R&D:

1. Development of mm antennas (NASA/Goddard).
2. Space environment exposure (LDEF).
3. Design of antennas for particular applications - multiple-beam antennas; broadcasting systems beamswitching; multiple frequency operation.

8.6.1.5 Millimeter Wave Integrated Circuits

The potential miniature size, low loss, and low cost of the newly developed class of active millimeter wave integrated circuits in dielectric waveguide configurations may be of benefit to satellite communication systems in the millimeter region. While solid state millimeter wave devices have developed rapidly into components in recent years, the cost of waveguide circuit components is relatively high, partly due to the close tolerances required at millimeter wavelengths. The rectangular dielectric waveguide, on the other hand, can be used for effective low loss millimeter wave transmission. In turn, it is possible to integrate active devices into the dielectric guide. The new devices offer low loss and low cost active millimeter wave integrated circuits capable of performance comparable to those of the conventional waveguide circuits.

The status of millimeter wave integrated circuits is such that:

1. Hughes and Bell Telephone Laboratories have demonstrated source integration and Hughes has developed a millimeter wave exciter/modulator at 60 GHz.

2. Microstrip and MIC components have been demonstrated in the millimeter wavelength region. Bell Laboratories has been able to reduce losses in microstrip systems. Above 60 GHz, microstrip guides become small and have severe ohmic losses.

3. Low cost and small size are important for satellite communications.

4. Dielectric guides, because of small losses, will be the MIC above 60 GHz, must become more reliable and be available for lower costs. Cost data will become available as production volume increases.

5. Matching techniques must be improved to lower losses. A major problem is in interfacing MIC's into a system. For the longer millimeter wavelength region (8-10 mm) the microstrip circuits have an advantage over dielectric guide systems and are much less dispersive than dielectric guides.

6. The MIC technology must be extended to materials other than silicon, e.g., GaAs, and must result in the development of monolithic systems.

7. Current research related to communications needs includes launchers, mixers, circulators and filters for K_a-band and filters, combiners and dividers to 80 GHz. MIC mixers and up/down converters have been developed to 60 GHz.

8. For MIC's in the 90-100 GHz region, dielectric waveguide configurations must be studied. Loss per wavelength of alumina microstrips relative to that of alumina dielectric waveguides is about 17:1 at 90 GHz. Alternate approaches are considered to be fin line techniques above 100 GHz and trapped inverted microstrip (TIM) lines up to 70 GHz. In general, dielectric waveguide will be larger than microstrip, thereby facilitating easier fabrication and handling.

9. Dielectric waveguide work has thus far been narrow-band; because of the high Q nature of the medium, the dielectric waveguide may likely be restricted to relatively narrow-band applications.

The field of integrated circuits looks promising from the viewpoint of future millimeter wave communications. Considerable development is needed before the technology can be utilized. However, extensive contributions are currently being made, and it has been possible here to discuss only a few of the advances which are being made. Table 8-32 summarizes some of the effects of interest.

8.6.1.6 Millimeter Wave Components Above 100 GHz

The satellite communications applications above 100 GHz can utilize the windows at 150 GHz and 230 GHz for satellite-to-ground links, and the H_2O absorption line at 183.3 GHz or the 118 GHz O_2 absorption line for propagation above the atmosphere. As spectral crowding becomes a problem at longer millimeter wavelengths or higher data rates become a necessity, the spectral region above 100 GHz will be developing as a potential satellite communications area. Several of the technologies, sources, receivers, solid state devices, have been discussed in previous sections, and developments in the spectral region above 100 GHz will be an extension of the technology developed at longer wavelengths. In the case of solid state devices, new materials and new concepts will have to be developed. Sources in the form of BWOs (carcinotrons), Extended Interaction Oscillators, klystrons and REBs will provide transmitter power. Local oscillators, RF amplifiers and modulators must have continued development of existing devices. The lack of use of lowest mode waveguide, due to its high losses, will result in the use of quasi-optical techniques. As receiver development currently being pursued at JPL, Bell Labs, Goddard Space Institute, Cork and Georgia Tech continues, it is expected that system sensitivities will approach those of lower frequencies.

TABLE 8.32

MILLIMETER WAVE TECHNOLOGY

Item:	Integrated Millimeter Circuits
Types:	Dielectric Waveguide Strip Guide Microstrip
Function:	Receiver Front-Ends Exciter-Modulators Power Combining Units Receiver/Transmitter Subsystems
Advantages:	Reduces Size, Weight and Costs Avoids Mechanical Discontinuities of Waveguide Components Low Loss Low Voltage Requirements Applicable From mm to IR Wavelengths Reliability Readily Scaled to Higher Frequencies Provides Means for Satellite-Borne Multichannel Systems Can Employ Existing MIC Technology

<u>Current State of Development</u>:

1. Demonstrated Source Integration (BTL, Hughes)
2. Developed mm Wave Exciter/Modulator (Hughes/AFAL)
3. Basic Components Demonstrated (ECOM, ITT, Hughes)
4. Developed Techniques for Silicon Planar Strip Guide Approach (Hughes)
5. Reduced Losses in Microstrip Conductor Patterns and Coupling Structure (BTL)

TABLE 8.32 (Cont.)

MILLIMETER WAVE TECHNOLOGY

Required Technology:

1. Extend to Materials Other Than Si, e.g. GaAs
2. Extend to Higher Frequencies
3. Develop Monolithic Systems
4. Develop High Quality, Large Quantity Production Techniques
5. Improved Matching to Antennas, etc.
6. Multi-System Techniques for one Substrate

Expected R&D: BTL, AFAL ECOM, Hughes, ITT

1. Experiments in Progress to Develop an Effective Means of Coupling to Planar Strip Guiding Structure Both from Wave Guide and Discrete Devices
2. Development of Complete Monolithic System
3. Inclusion of More Components into Circuits

8.6.1.7 Millimeter Wave Modulators and Demodulators

As available bandwidth increases, as would be the case for operation at millimeter wavelengths, more emphasis will be placed on high speed modulation and demodulation. To a large extent, the technology required for modulation and demodulation will depend on the concept that is applied for channel utilization. For example, Time Division Multiple Access (TDMA), Frequency Division Multiple Access (FDMA), and Code Division Multiple Access (CDMA) each introduces unique modulation and demodulation requirements. Modulation and demodulation will be especially critical for such applications as digital TV and high speed data communications. Unique modulation and demodulation requirements which may develop as a result of millimeter wave operation must be assessed for each individual system. Recent integrated circuit modulators have been constructed by Hughes for the 60 GHz region and have demonstrated a capability for modulation bandwidths in excess of 1 GHz.

(1) Modulation Techniques

With regard to modulation concepts, it is possible to consider m-ary PSK, differential PSK, FM, and PM as viable modulation concepts. Two and four-phase PSK have proven particularly advantageous for satellite communications systems developed to this point. Particular emphasis will be placed on multiplex technology and the modulation concepts which could be applied. As a minimum, FDMA, TDMA, and CDMA and various combinations of these multiplexing techniques have to be considered. Particular attention must be paid to techniques which are compatible with projected services. For example, TDMA, because of theproblem of synchronization, may not prove to be viable with a large number of multiple users.

(2) High-Speed Processors

Emphasis will have to be placed on high speed real time processors which are likely to be required as the bandwidth increases for future millimeter wave systems. Such digital operations as optimum detection, encoding and decoding, and data buffering may require processing rates beyond the current state-of-the-art. Of course, it may also be the case that in the event of Frequency Division Multiple Access, the processor speed required for each channel may be well within the current technology.

Of particular interest are recent developments in the areas of ultra-high-speed digital LSI, charge coupled devices (CCDs), surface acoustic wave (SAW) devices, and microwave LSI devices. These various signal processing device technologies may be of significant benefit to the high data rate signal processors likely to be required in shifting to the millimeter wavelength region. These microminiaturized component technologies will likely lead to significant reductions ins size, weight, complexity, power, and cost so that increased use of on-board processing could be considered for future satellites. In particular, advances in these signal processing technologies combined with advances in solid state phased array technology and microwave integrated circuits could lead to reduced complexity and higher reliability for on-board electronically steered multiple beam antennas. A brief discussion of potential satellite applications of these signal processing components follows.

Thirty-two bits of correlation can now be realized on one low power LSI chip with clock rates greater than 150 MHz. These chips are cascadable for longer word lengths. Potential advantages in communication systems include reduced acquisition times and increased channel capacity in TDMA systems as well as reduced complexity in beam formation/steering processors. In addition, the internally matched microwave transistor has led to the development of microwave (up to 5 GHz) LSI devices which could significantly reduce the size and weight of phased array receiver and transmitter components.

Charge coupled devices could reduce the complexity of satellite analog signal processing circuitry through their inherent elimination of analog-to-digital converters. CCDs also offer tremendous advantages in size, weight, cost, and power dissipation in digital processing applications. Clock frequencies of 135 MHz have been reported in laboratory devices and up to 1 GHz rates have been postulated for future devices. Potential communication applications include low power, small size memories; beam forming/steering processors; and high speed, low power data buffers and shift registers.

Surface acoustic wave (SAW) devices can offer significant size and weight advantages in communication equipment. Nondispersive long delay lines, bandpass filters, and programmable PSK correlators are a few of the SAW devices which could benefit millimeter wave communication systems. The programmable SAW correlator (tapped delay line) can offer flexibility, fast programming speed, and low cost, size and weight in processing PSK signals, including pseudo-noise (PN), and could be advantageous in satellite systems having multiple users with a variety of identification codes.

8.6.1.8 Submillimeter Wave Technology

The submillimeter wavelength region is potentially a spectral region which is a compromise between the millimeter and optical region, capable of wide-bandwidth transmission and having less stringent acquistion, pointing and tracking requirements than the optical region. Because of its high atmospheric attenuation, satellite-to-satellite or aircraft communications will be the most appropriate submillimeter application. A brief description of the potential use of the 1 mm to 10 μm region is given in Subsection 8.6.4 so that only a few comments are given here on components.

Sources have always been lacking in this spectral region. However, recent developments in lasers, both direct discharge and optically pumped have made it possible to consider their use as both transmitters and local oscillators. Efficiency improvements are necessary for these devices, as is smaller size of the lasers. Relativistic electron beam devices appear as the highest power and greatest efficiency (∿40% predicted). Stability and size of these sources must be studied. No solid state sources exist so that entirely new concepts must be innovated to yield small, low power solid state devices for this spectral region.

Devices must be developed for the region:

a. Schottky barrier mixers and superheterodyne receivers are advancing and currently can be used over a large part of the spectrum.

b. Saturation absorption amplifiers and optically pumped laser amplifiers must be developed.

c. Quasi-optical devices will be employed throughout the spectrum. Although no dielectric waveguide devices exist in this region, such technology should be developed.

d. Modulators have received little consideration in this region, and nonlinear optical methods must be fully explored.

The spectral region can provide a very large band for communications. The impetus given by source and detector development should stimulate a development of components which will be required for systems applications.

8.6.2 Millimeter Wave Atmospheric Effects

The role of the atmosphere in satellite-to-earth propagation links is a significant one, for which a large number of measurements and considerable theoretical investigations have been performed. Despite this accumulation of information, the planning of millimeter wave communication systems requires continuing atmospheric investigations and extension of observations to shorter wavelengths.

Figure 8.15 illustrates the effects of the atmosphere on electromagnetic propagation from centimeter wavelengths into the visible spectrum. The curves show horizontal attenuation by clear air (oxygen and water vapor absorption), by condensed water vapor (fog and clouds) and by precipitation (rain). Models have been formulated to account for excess propagation introduced by precipitation and that introduced by fog conditions. The effects of clouds and fog at shorter wavelengths are seen to be extremely detrimental to propagation. The stronger atmospheric absorption due to molecular constitutents also confines communications to applications involving aircraft and satellites.

The transmission qualities of the atmosphere are a function of several parameters of the atmosphere. Of particular interest are the characteristics during inclement weather, i.e., rain, fog, haze and clouds. The water vapor absorption in the atmosphere is the major attenuator in the wavelength region from approximately 15 μm into the microwave region.

At longer millimeter wavelengths, the oxygen molecule plays a prominent role in determining the position of transmission windows. In the region of 60 GHz, the attenuation, shown in Figure 8.16, is very strong and provides a spectral region applicable for covert communications. The zenith attenuation, shown in Figure 8.16 is extremely high with peaks of several of the O_2 lines at high altitudes affording additional attenuation. Because of these relatively narrow peak attenuations, communication from aircraft to satellites is limited in bandwidth to less than 80 MHz. It is seen from Figure 8.16 that the magnitude of the O_2 zenith attenuation is such that detection on the ground of 60 GHz communications between aircraft or satellites is virtually impossible. As a function of altitude, shown in Figure 8.17, the attenuation decreases significantly so that, at very high altitudes, propagation at frequencies between the

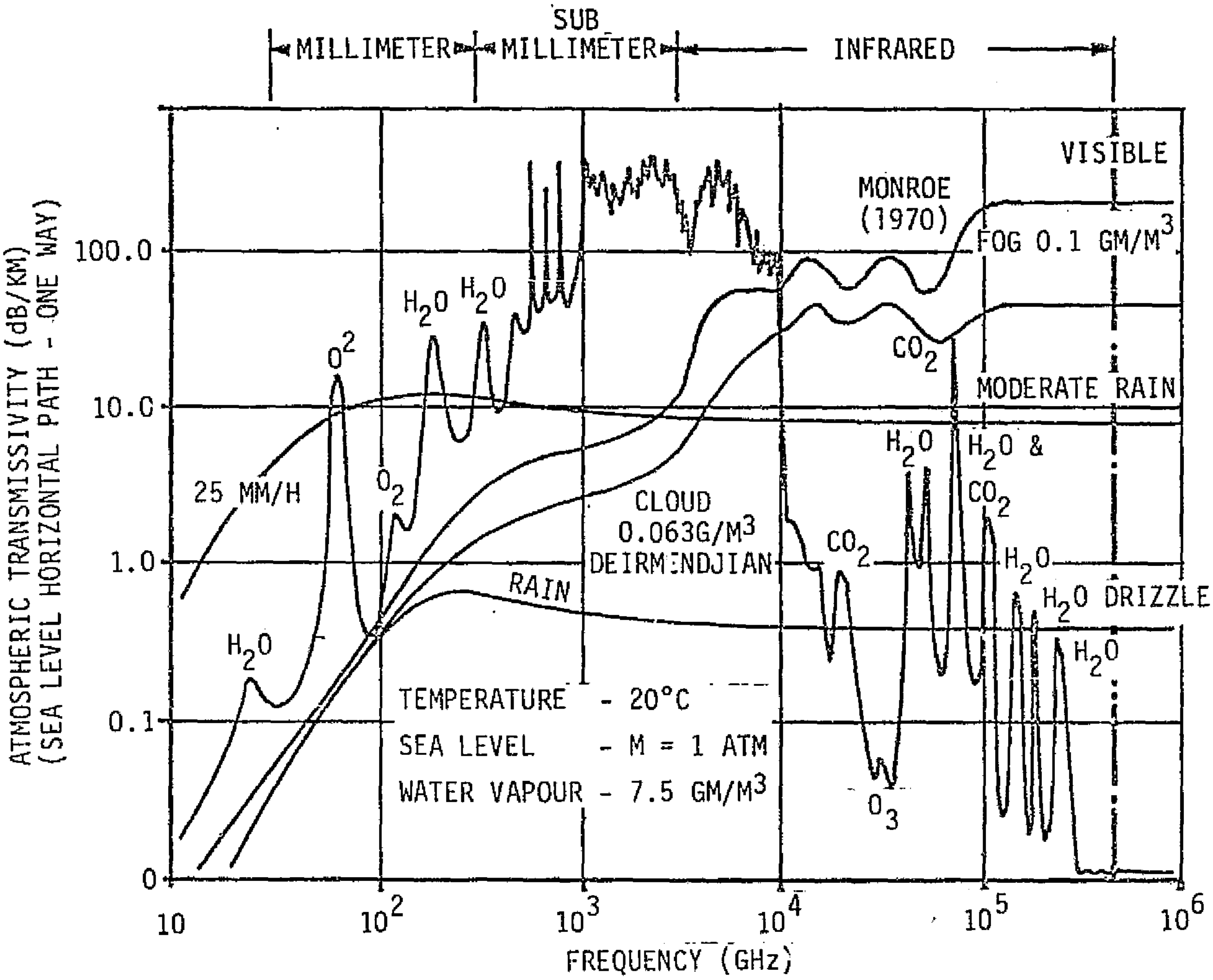


Figure 8.15. Effects of Gaseous Constituents and Precipitation on the Transmission of Radiation through the Atmosphere.

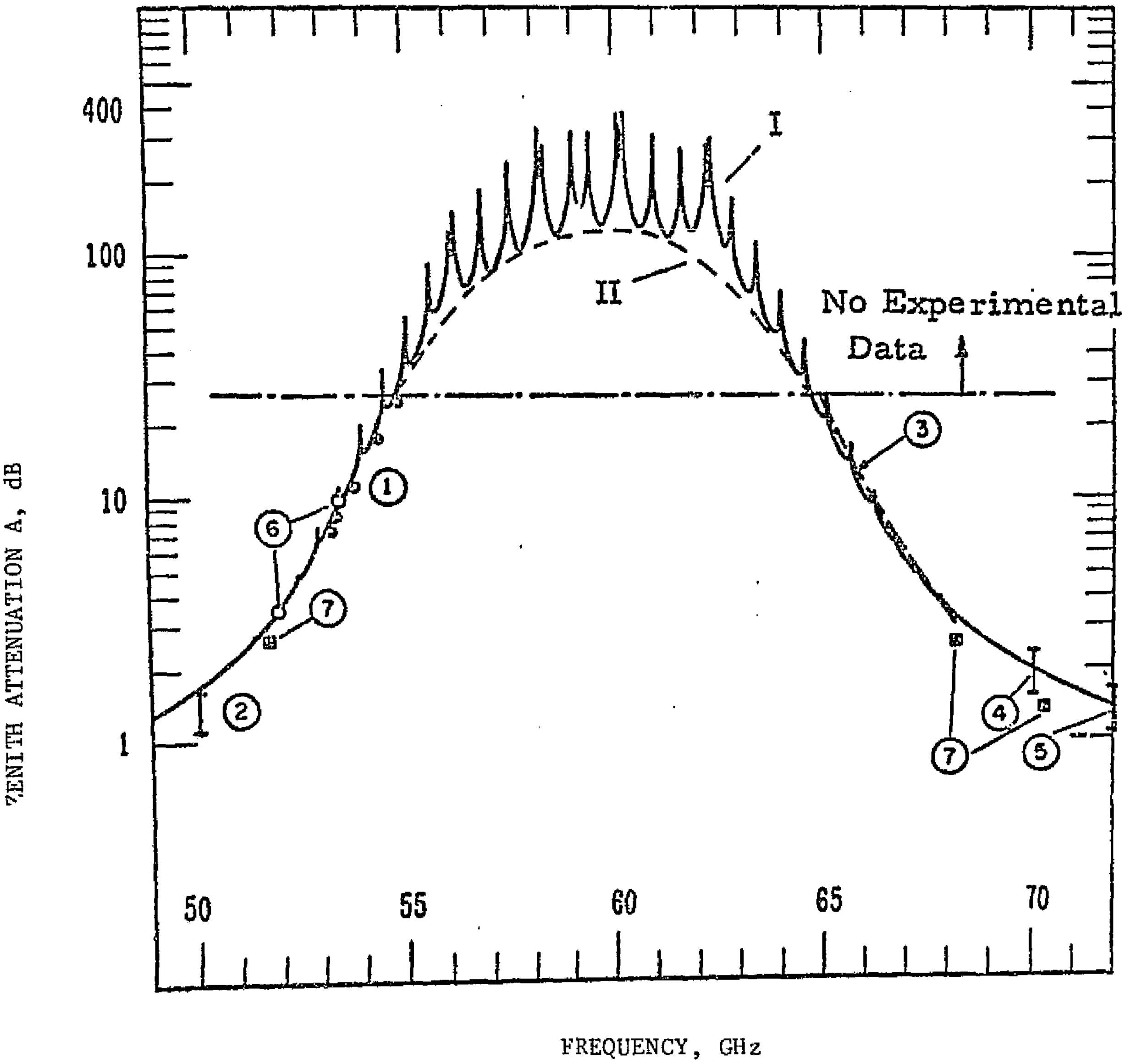


Figure 8.16. Zenith Attenuation Due to O_2 at 60 GHz. [21]

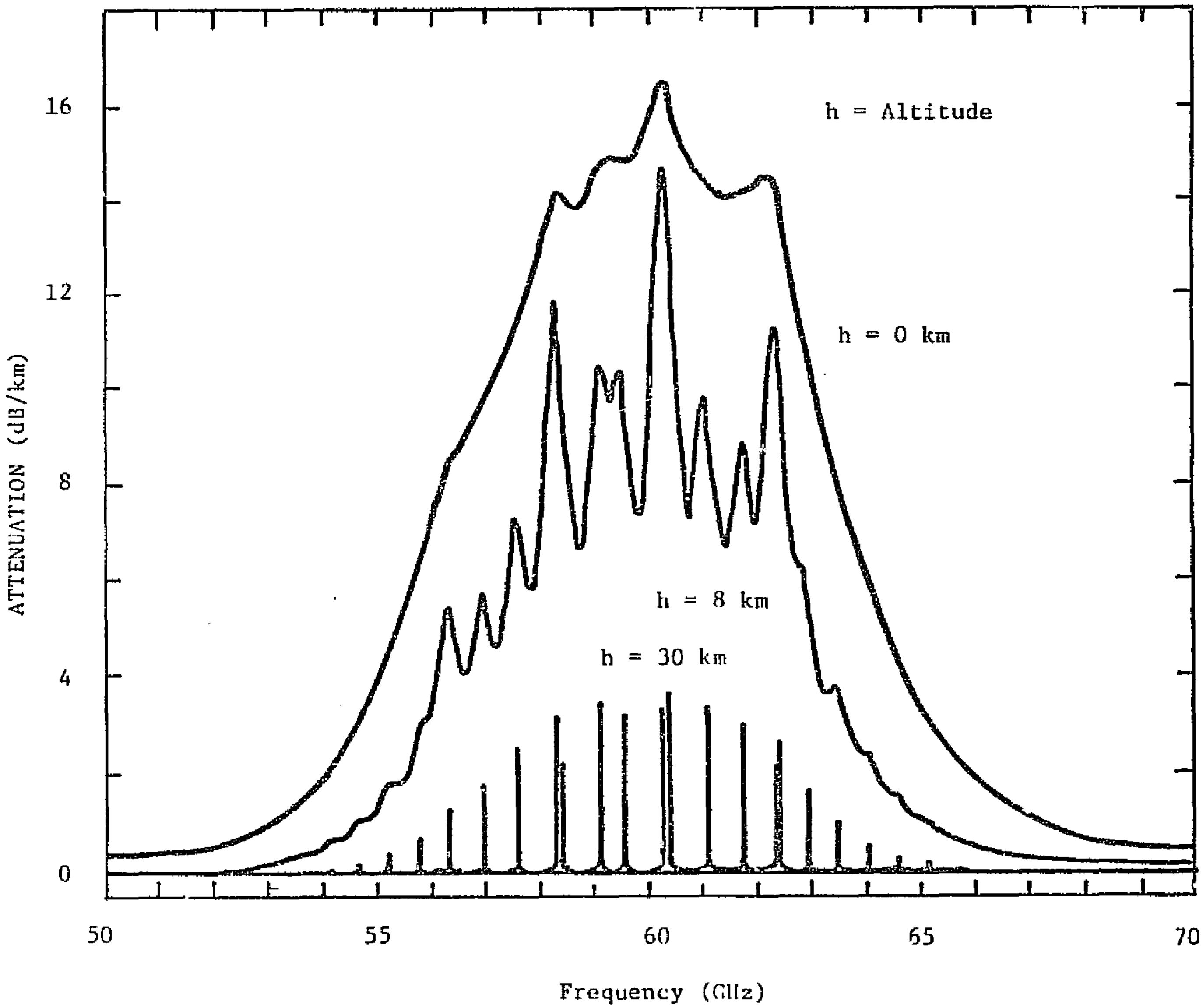


Figure 8.17. Attenuation Due to Oxygen as a Function of Altitude

individual lines of the O_2 complex suffers very little attenuation. To calculate the total attenuation from a particular altitude to a satellite, use can be made of curves such as that given in Figure 8.18 in which the abscissa is the lower altitude and the ordinate is the attenuation from this lower altitude up through the remaining atmosphere. In turn, the attenuation from ground to a given altitude can be determined for these O_2 curves by taking the difference of the attenuations for the altitude h and that for h = 0. Excellent treatment of atmospheric O_2 has been performed by Liebe [21] who has presented detailed data important for propagation applications.

In addition to its complex of lines at 60 GHz, O_2 has a strong individual transition at 118 GHz. In the atmosphere, these lines are superimposed on the water vapor lines with the resulting millimeter wave absorption shown in Figure 8.19 This figure presents the average atmospheric absorption of the millimeter wavelength in dB/km for sea level and 4 km altitude. Curve A at sea level is the long wavelength end, with O_2 included, of the absorption curves for the atmospheric H_2O.

For computational purposes, the clear weather atmospheric attenuation has been presented in several forms, which in general are consistent but, for need of further experimental data, variations in detail can be noted.

The total attenuation for one way transmission through the atmosphere is given in Figure 8.20. At the lower frequency end of the graph, the attenuation as a function of the angle from zenith is given. With oxygen included, the total absorption for one way transmission through the atmosphere at various millimeter region frequencies is given in Figure 8.21 as a function of elevation angle.

The importance of the atmosphere is seen from the propagation link equation:

$$P_R = \frac{P_s G_s G_R e^{-\alpha R}}{R^2} L_R L_P L_{Pol} \tag{8-1}$$

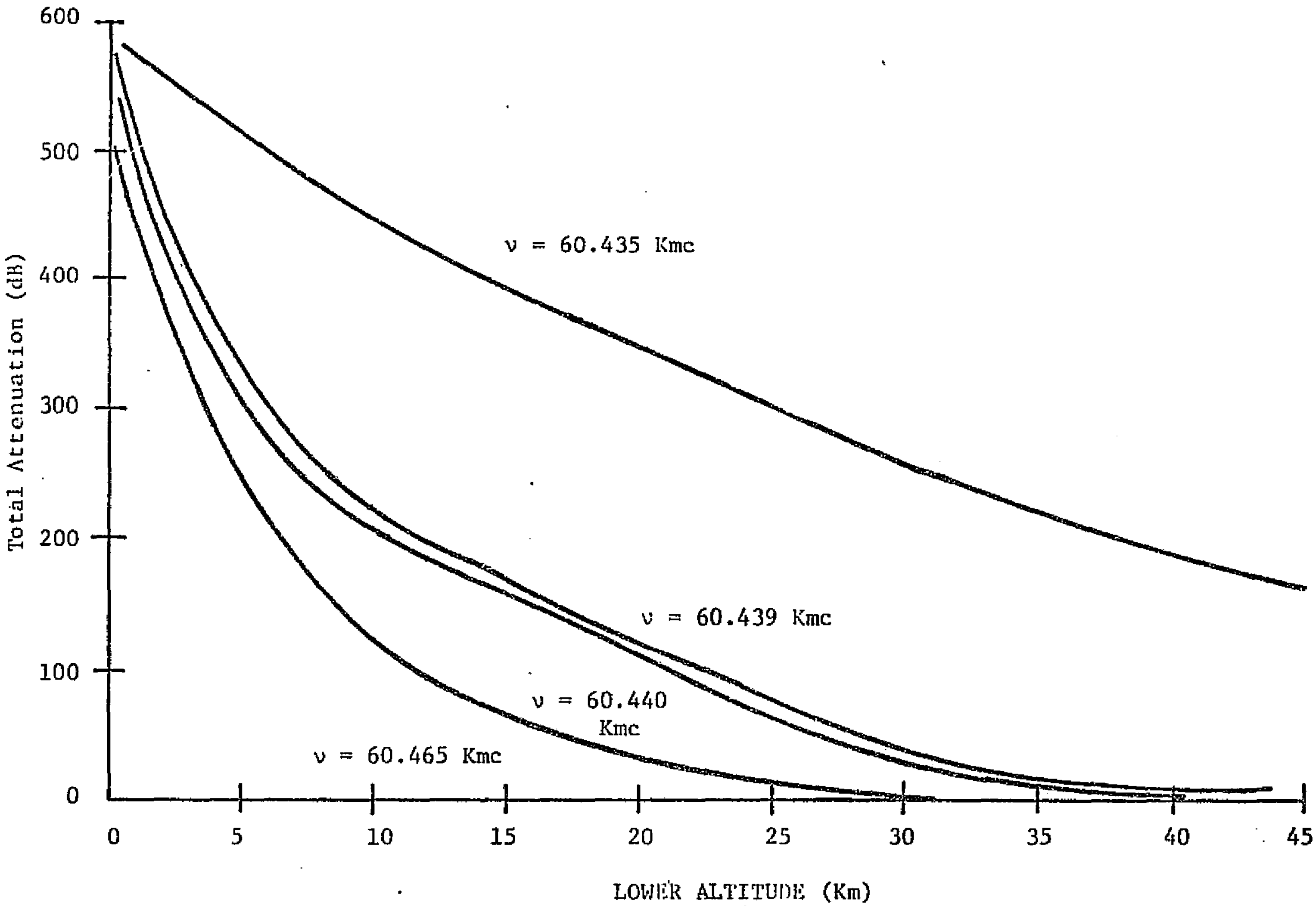


Figure 8.18. Atmospheric Attenuation Due to O_2 Lines From a Lower Altitude Through The Higher Atmosphere at 0° Zenith Angle

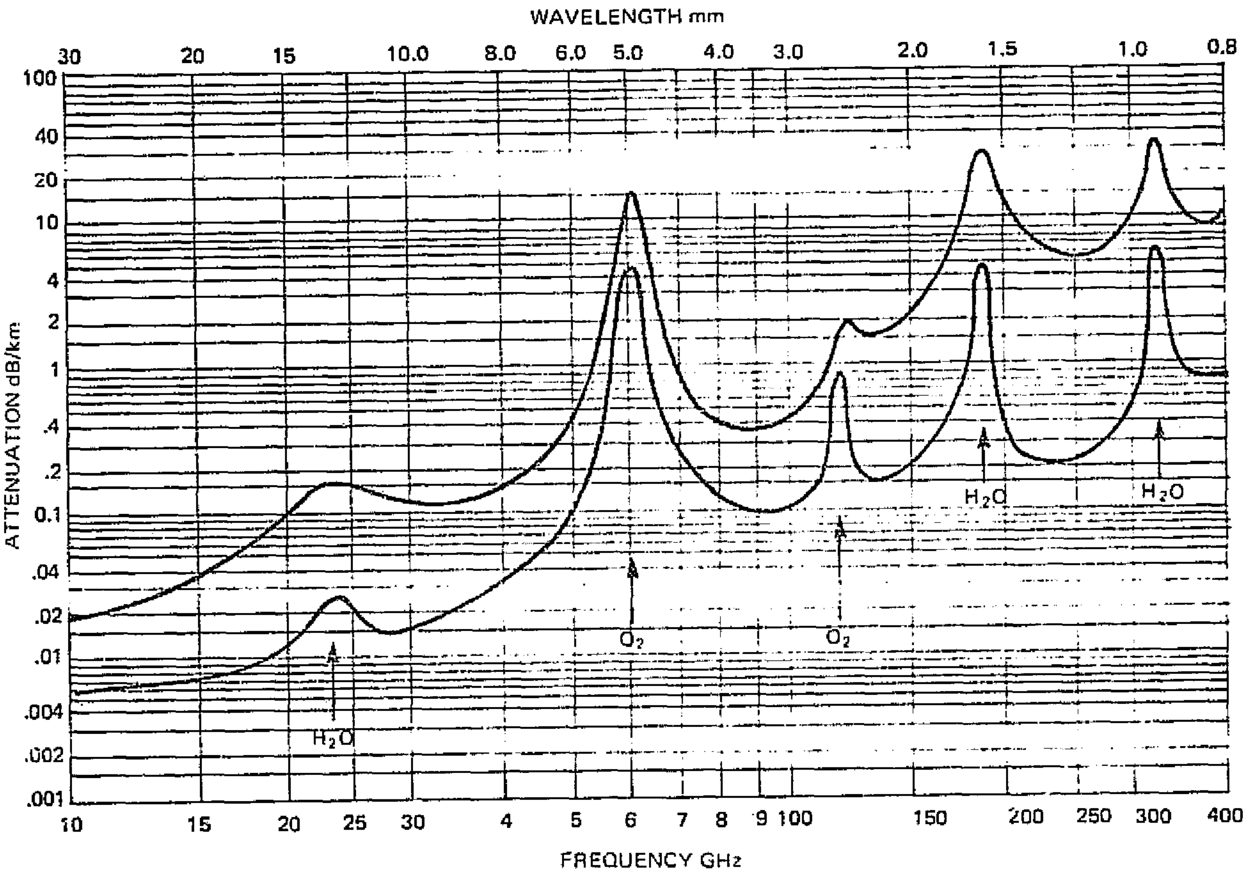


Figure 8.19. Average Atmospheric Aborption of Millimeter Waves. [23].

A – Sea Level
T = 20°C
P = 760 mm
P_{H_2O} = 7.5 gr/m^3

B – 4 km
T = 0°C
P_{H_2O} = 1 gr/m^3

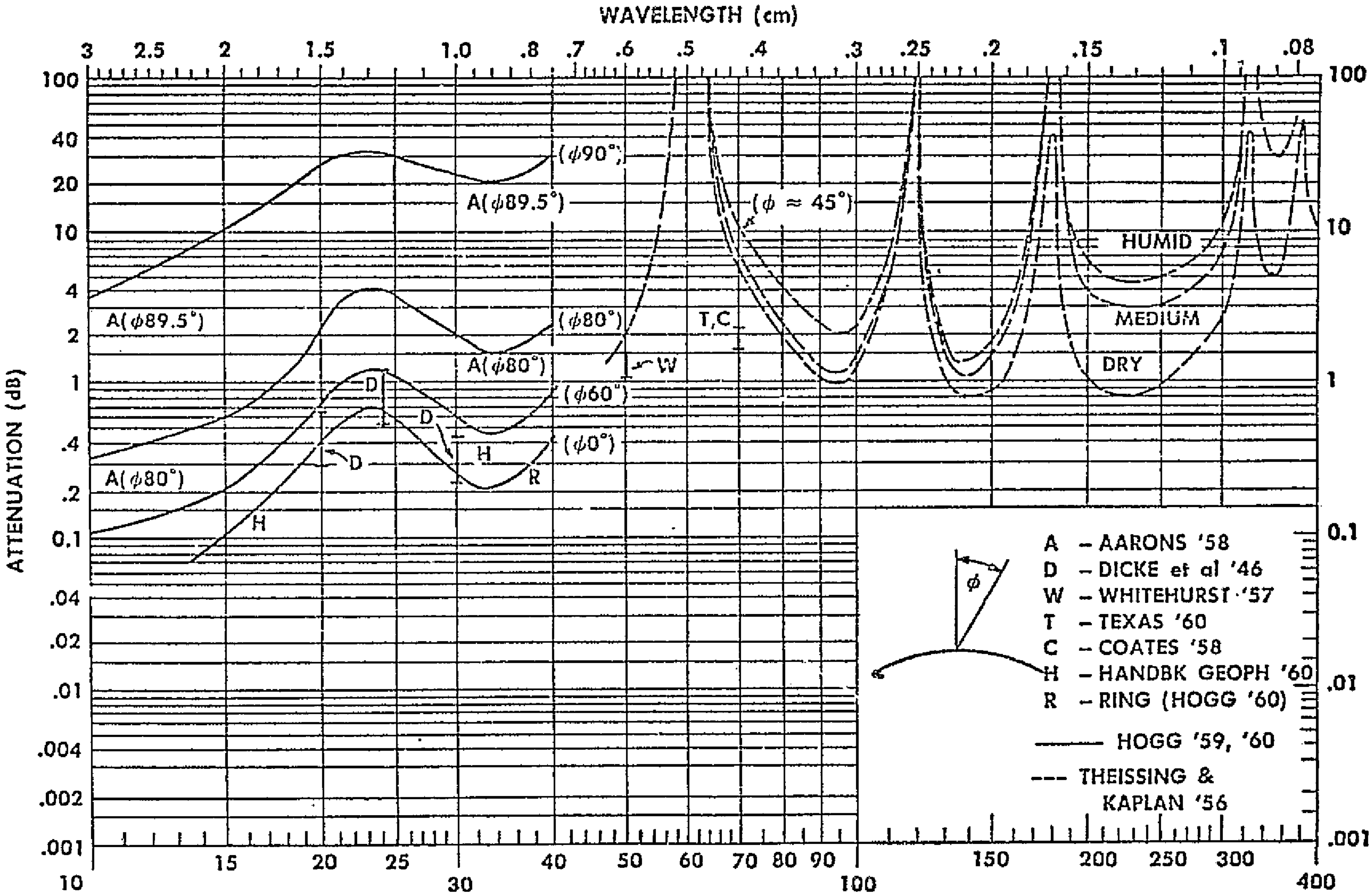


Figure 8.20. Total Attenuation For One-Way Transmission Through The Atmosphere [23]

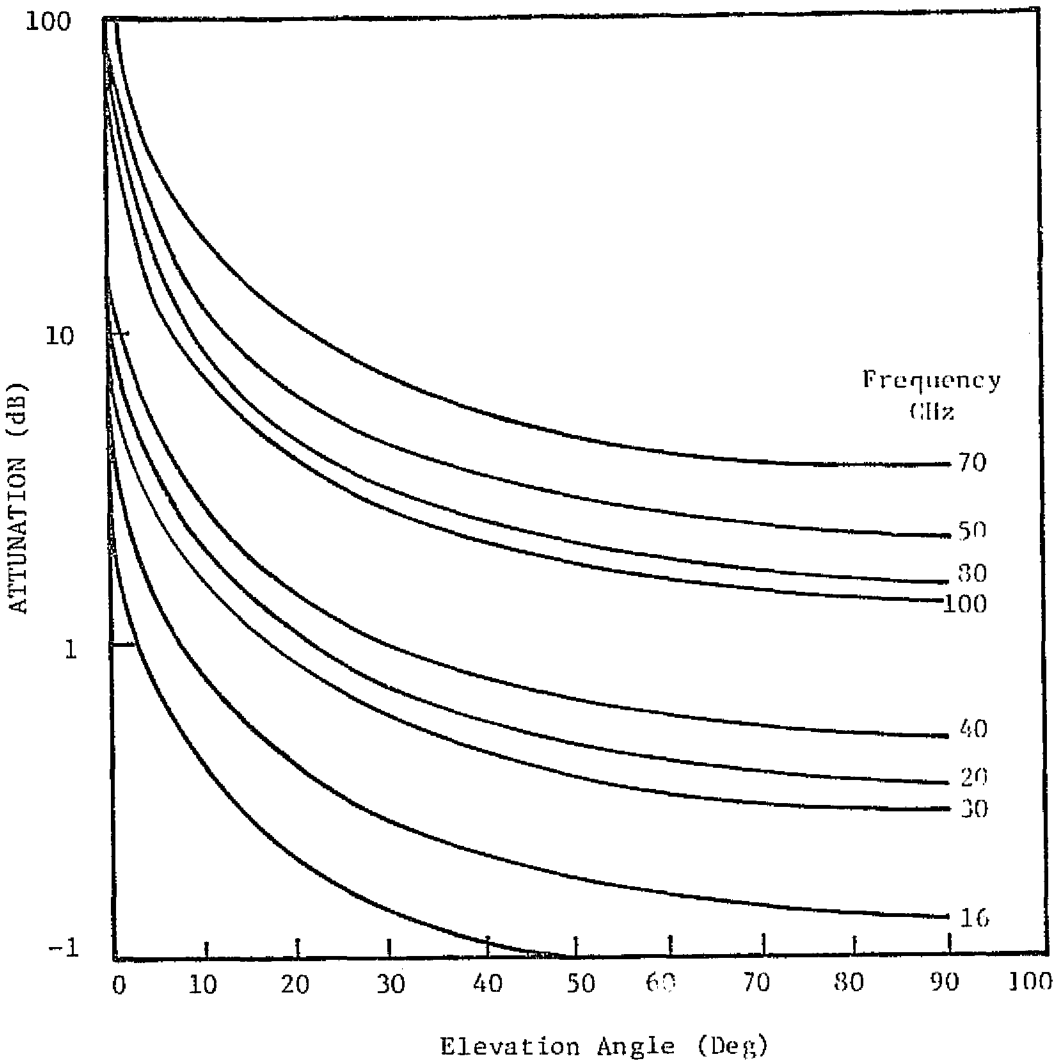


Figure 8.21. Total Absorption versus Antenna Angle for Paths Through The Atmosphere at Various Frequencies ($P_o = 7.5$ g/m^3).

where P_R = power received

P_s = transmitter power

G_s = transmitter antenna gain

G_R = receiver antenna gain

α = clear air attenuation

R = transmitter/receiver range

L_R = rain loss

L_P = pointing losses

L_{Pol} = polarization losses.

$$\text{For } P_R = \frac{C}{N} BkT_R \tag{8-2}$$

where $\frac{C}{N}$ = carrier-to-noise ratio

B = receiver bandwidth

k - Boltzmann's constant

and T_R = receiver temperature, the link (e.g. down link) equation takes the form (in dB)

$$(P_s + G_s) + (G_R - T_R) - L_{FS} - L_{Pol} - L_P - L_R$$

$$- B + 228.6 - C/N = 0 \tag{8-3}$$

where $(P_s + G_s)$ = satellite EIRP

$(G_R - T_R)$ = Earth station G/T

$L_{FS} = e \frac{-\alpha R}{R^2}$ = free space loss

and 228.6 = Boltzmann's constant.

The atmospheric effects are evident in Equation (8-3). The factor L_{FS} includes the clear air attenuation while the loss factor L_R should include not only losses due to rain but also that resulting from clouds and fog.

In addition to the clear atmospheric absorption discussed above, other characteristics must be considered as causing attenuation or degradation of the propagated signal. Among these parameters are clouds and fog, rainfall and hail, refraction, reflection and scattering, polarization rotation and decorrelation effects.

Precipitation, haze and fog have deleterious effects on propagation in the millimeter and submillimeter wavelength regions. Rain attenuation presents one of the most perplexing problems encountered in the design and operation of millimeter wave propagation systems. Recent interest in millimeter and submillimeter applications has resulted in both experimental and theoretical investigations. Radiometry and satellite propagation studies have yielded direct measurement of attenuation for $\lambda > 1$ cm [24]. Observations are being made to acquire long term statistics at a number of frequencies in the millimeter region and at different locations.

The attenuation due to a distribution of spherical raindrops is

$$A(\mathrm{dB/km}) = 4.343 \int N(a)\, Q(a, \lambda)\, da$$

where $N(a)da$ is the number of drops per cubic meter with radii between a and $a + da$(cm), and $Q(a,\lambda)$ is the attenuation cross section (m^2) of a single spherical drop of radius a(cm) at wavelength λ(cm).

The relationship between raindrop size and rainfall rate was investigated emp_rically by Laws and Parsons [25] and later distribuitions were developed by Marshall and Palmer [26]. They showed that drop size distribution measurements can be represented by the relation

$$N(a) = N(o)e^{-\Lambda a}$$

where $N(o)$ = value at zero radius and $\Lambda = 82\ R^{-0.21}$ where R is the rainfall rate, in mm/hr.

Medhurst applied measured drop terminal velocities and measured Laws and Parsons drop size distribution to calculate the attenuation coefficient for 2 to 100 GHz.

Gunn and East [27] have proposed an exponential expression relating attenuation and rainfall rate,

$$A(\mathrm{dB/km}) = \alpha R^{B}$$

where α and B are frequency dependent constants, and R as above is the rainfall rate (mm/hr). This expression has shown reasonably good agreement with measured values over short terrestrial paths.

The probability of occurrence of a given attenuation level, or more precisely, the probability that the attenuation has equalled or exceeded a given level, is extremely important for the design of systems where rain attenuation plays a significant part. A knowledge of this factor provides the basis for the power margin requirements for the link or conversely will indicate the expected outage time for a given link margin.

An important aspect of satellite communications is the need for spatial diversity. Only a limited amount of diversity gain data exists for millimeter wavelength earth space propagation paths [28]. The diversity gain is defined as the difference between the path attenuations associated with the single terminal and diversity modes of operation for a given percentage time. The diversity gain is a function of the single terminal fade depth as well as the terminal separation distance.

In the case of attenuation due to absorption and scattering by hydrometeors, several extensive calculations have been carried out. Figure 8.22 shows the variation of attenuation in dB/km with frequency for various rainfall rates, as determined by Setzer[29]. The only significant difference among the results of the various authors occurs in the calculation of attenuation for low rainfall rates, on the order of 0.25 mm/hr. At frequencies approaching, or greater than, 100 GHz, depending on the rain intensity, the rate of increase of specific attenuation with frequency levels off and, at even higher frequencies, the attenuation declines. Measurements made at

ATTENUATION BY RAIN

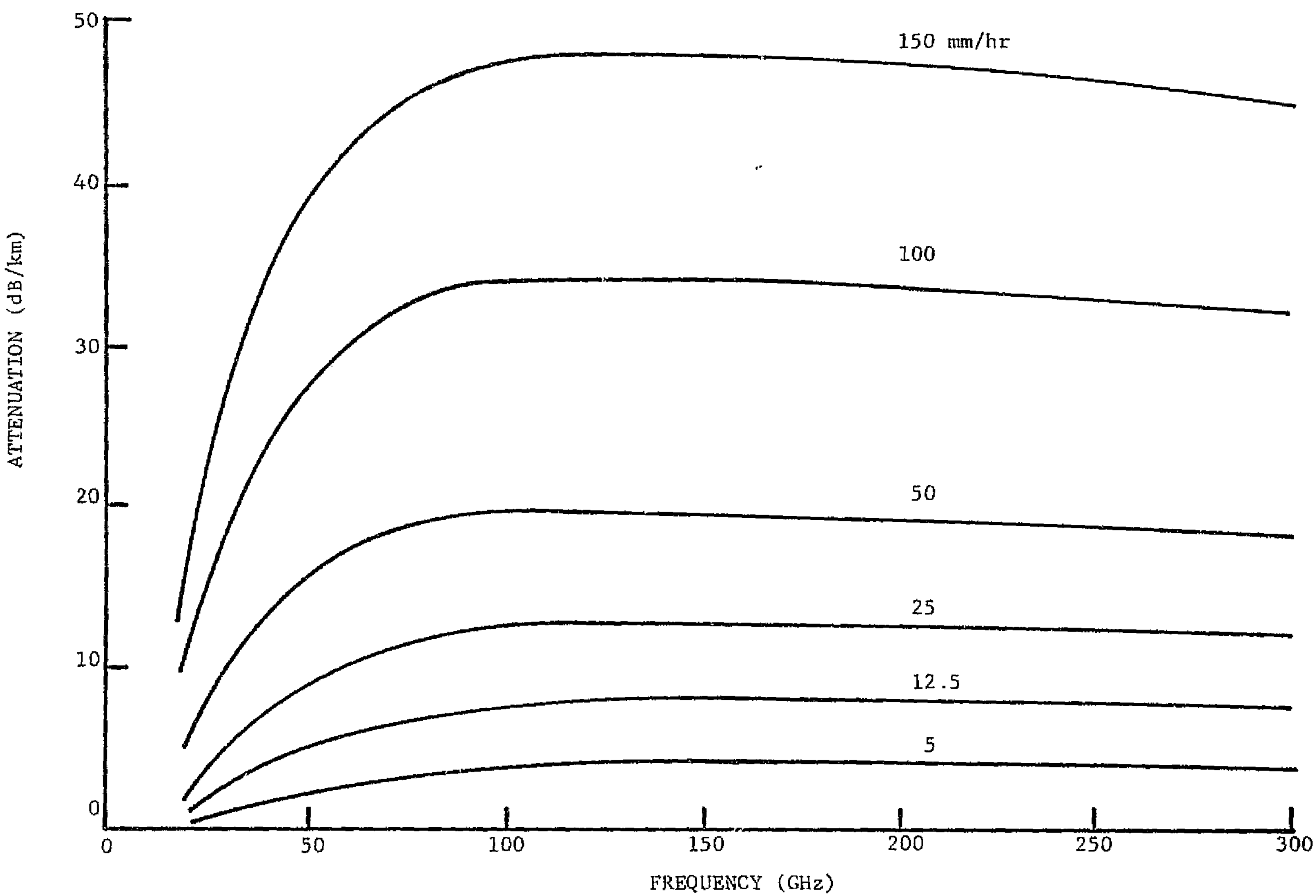


Figure 8.22. Variation of attenuation in dB/km with frequency for various rainfall rates.

110 and 890 GHz [30] show general agreement with these predictions, but, probably owing to inadequate particle size distribution measurements, the attenuation at 890 GHz was found to exceed that at 100 GHz by a factor of 1.25.

Detailed calculations of attenuation due to fog have been made by Ryde and Ryde [31] , and some of these results appear in Strom's report [32]. In particular, Figure B-7 of Strom's report is important for fog of various visibilities and cloud attenuation. The Appendices of Reference 12 treat several propagation parameters and show the need which must be filled at shorter millimeter wavelengths.

The transmission through clouds, similar to fog, has also been investigated. Figure 8.23 shows the absorption by ice clouds from a Raleigh approximation. The effects of ice clouds are relatively small until wavelengths of approximately 300 μm are reached. Waterclouds, on the other hand, show considerably more absorption, as indicated in Figure 8.24 but at millimeter wavelengths, transmission is far greater than it is in the infrared. The scattering and extinction coefficients for low lying stratus clouds have been calculated and are shown in Figure 8.25.

The importance of the atmospheric effects on millimeter wave communications requires continued investigations in all windows of the spectrum. Of particular importance are:

1. Determination of the cumulative probability distribution function (per unit of time abscissa is exceeded) with attenuation as the abscissa independent variable. The attenuation statistics are based on actual propagation data from specific geographical locations. Analyses must be made of past and current data and attenuation due to the weather class designations must be determined. The information obtained provides the probability density functions of carrier attenuation for specific intervals of time and weather conditions.

2. Attenuation due to the components, rain, clouds, etc. must be documented in detail.

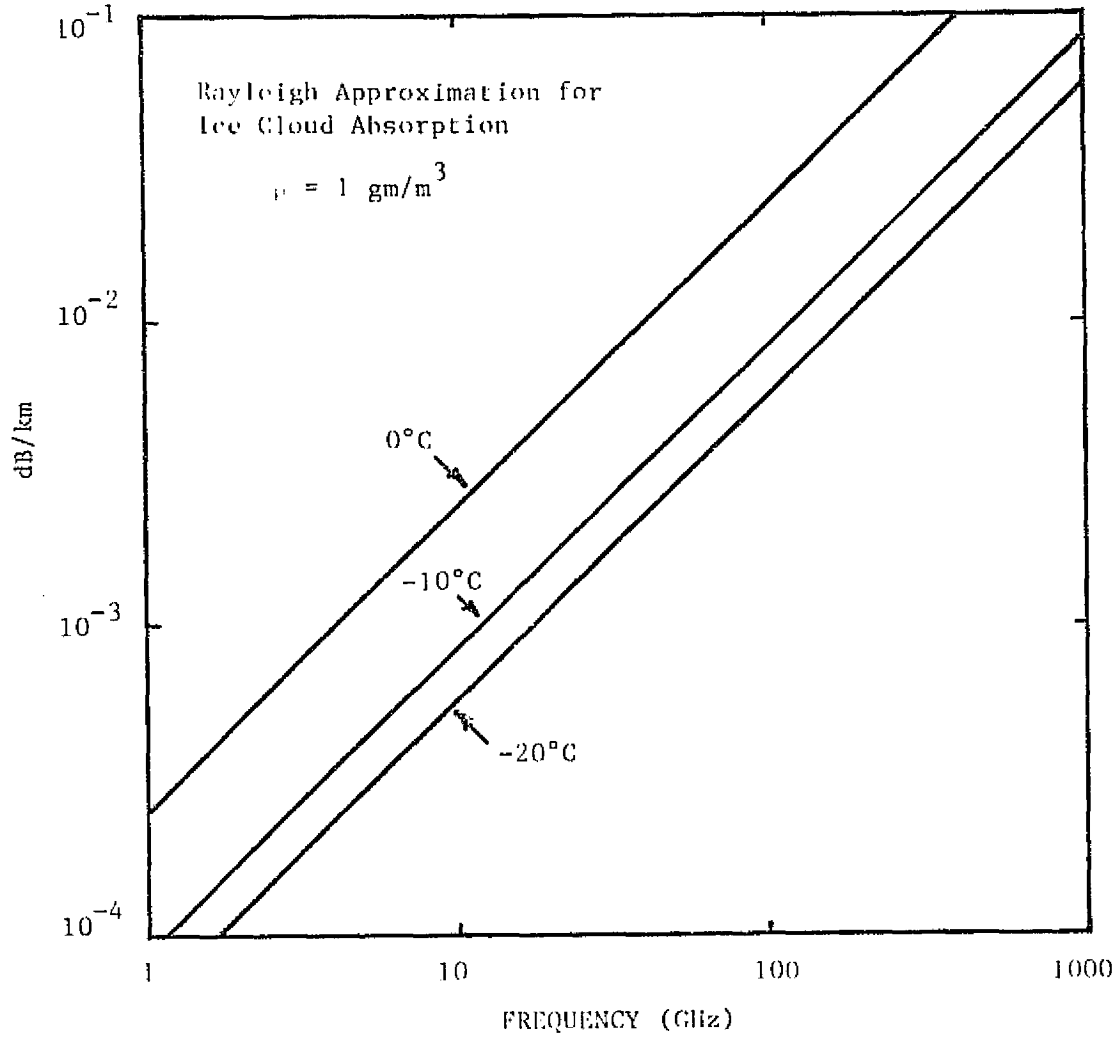


Figure 8.23. Microwave Absorption by Ice Clouds from 1 to 1000 GHz as Given by Tabulated Data of Atlas et al.

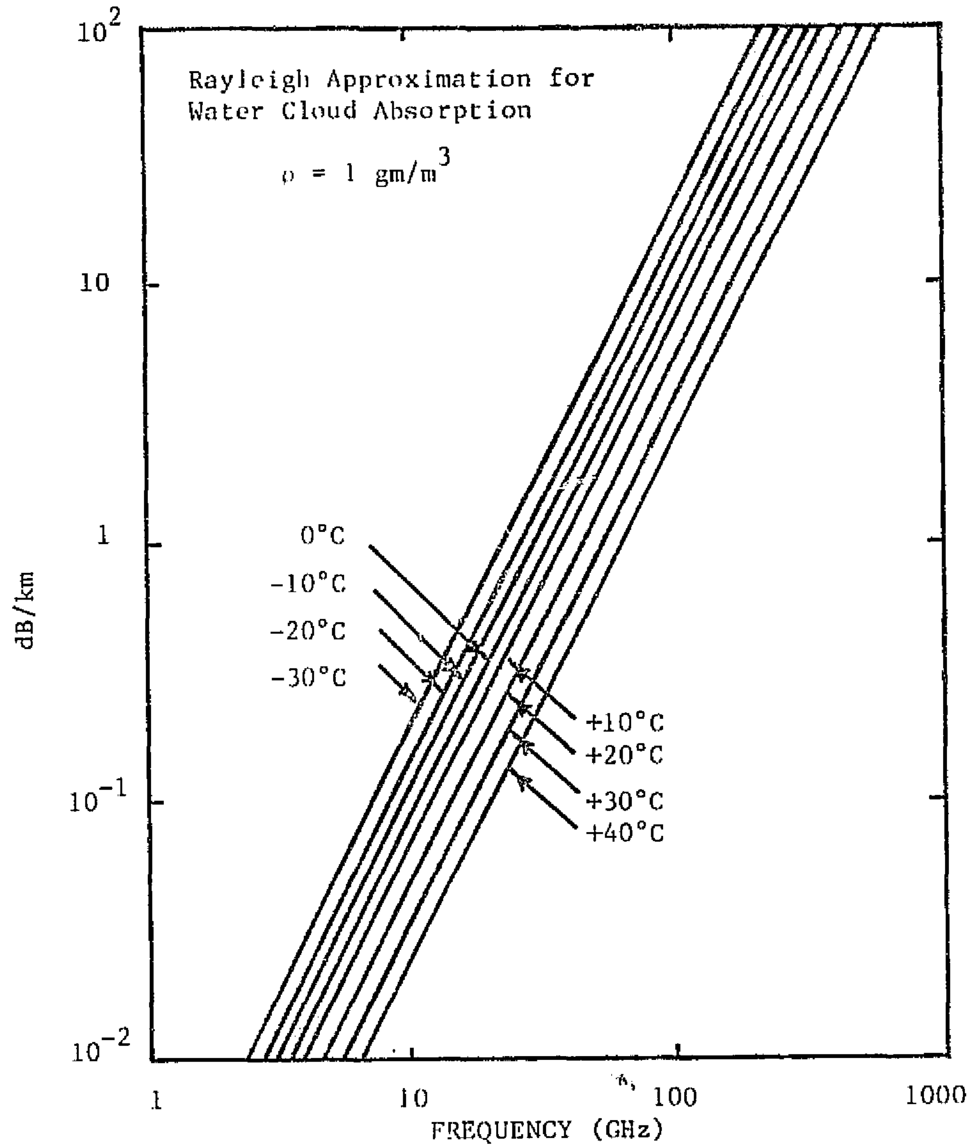


Figure 8.24. Microwave Absorption by Water Clouds from 1 to 1000 GHz as Given by the Rayleigh Approximation Formula of Staelin (1966).

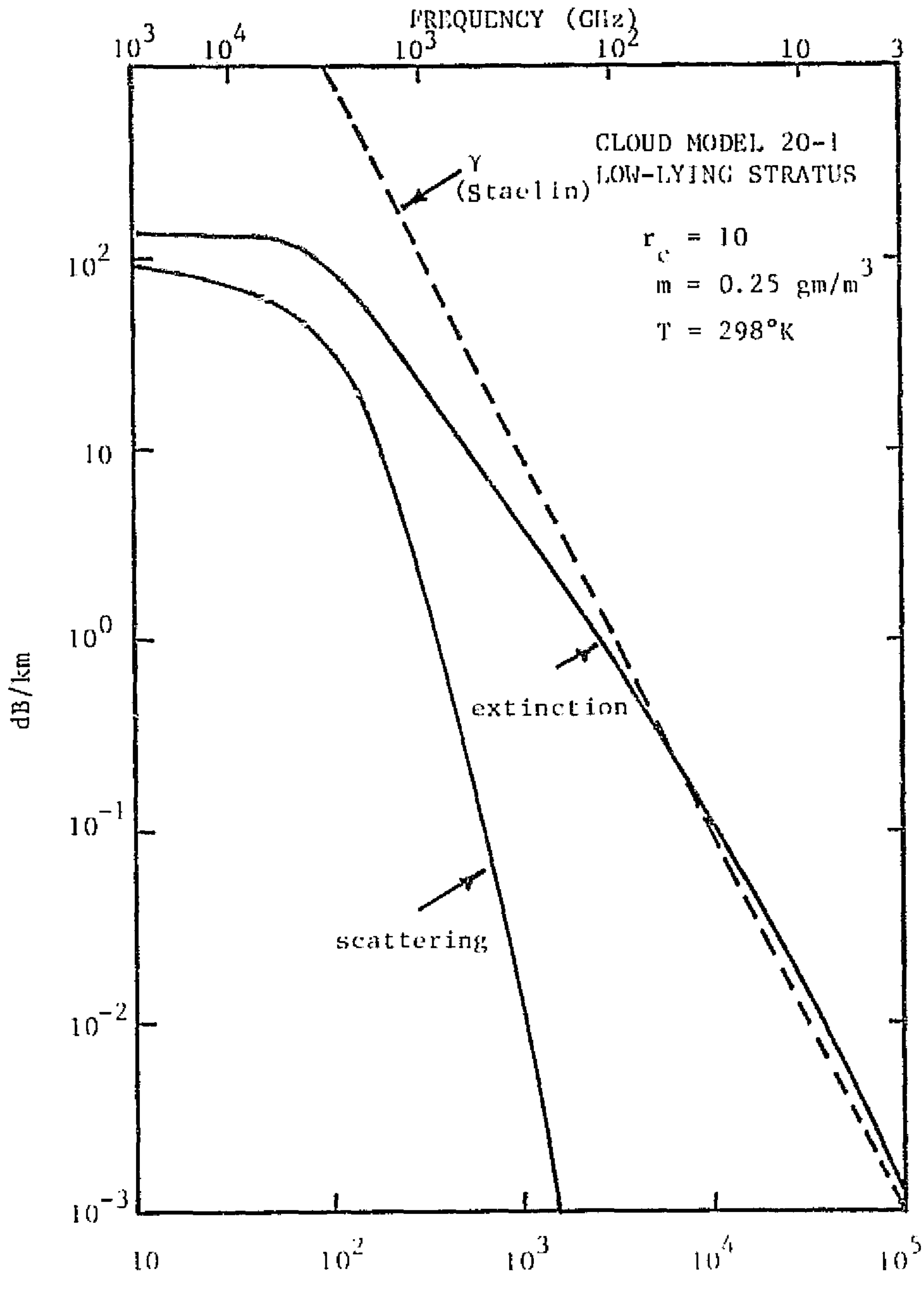


Figure 8.25. Scattering and Extinction Coefficients Computed for Lowlying Stratus as a Function of Wavelength with the Empirical Formula of Staelin (1966) Shown for Comparison.

3. One of the important techniques is the use of space diversity which will increase the probability of maintaining communications from a satellite to a pair of terminals on the ground. It is important that spatial diversity be established, i.e. the required number and spacing of ground terminals, for all geographical locations within the United States. Storm cell characteristics must be known in addition to design requirements such as reliability, fade margin, wavelength, range of zenith angle and available power.

4. The atmospheric characteristics must be determined for all window regions up to 150 'Hz in order to provide data for future planning of millimeter wave communications systems.

The atmospheric effects of importance to millimeter wave communications are summarized in Table 8.33.

TABLE 8.33

MILLIMETER WAVE TECHNOLOGY

Item: Millimeter Wave Atmospheric Transmission Studies

Type: Satellite-to-Ground Transmission
Ground-Based Solar Radiometric Measurements
Propagation in the Presence of Hydrometeors

Functions: Provide Data on Communication Paths Through the Atmosphere in Clear and Inclement Weather

Advantage: Provides Propagation Information in Transmission Windows on the Millimeter Wavelength Region; Data on Spatial Diversity: Allows Prediction of Cumulative Attenuation for Various Localities; Provides Means for Comparing Propagation in the Millimeter Wavelength Region with Data at Other Wavelengths; Provides Data at Millimeter Wavelengths for Propagation Through Clouds

Current State of Development:

1. GSFC Millimeter Wave Experiment (ATS-6) Provides First Available Data Above 15 GHz for Satellite-to-Ground Measurements
2. Sun-Tracking Experiments to 94 GHz (BTL)
3. Radiometric Measurements to 300 GHz (Univ. Texas, Appleton, Aerospace, ADTEC, etc.)
4. Russian Investigations to Approximately 400 GHz
5. Laboratory Experiments (Martin-Marietta, NBS, OT, Texas)
6. Cumulative Attenuation Measurements and Predictions
7. Detailed Calculations have been Performed
8. Dimer and Flucturation Measurements (Appleton)
9. Spatial Diversity Measurements have been Performed (Aerospace)

TABLE 8.33 (Cont.)

MILLIMETER WAVE TECHNOLOGY

Required Technology:

1. Radiometric Observations in Atmospheric Windows of the Millimeter Wavelength Region
2. Propagation Measurements (Similar to ATS-6) as High as 94 GHz in Frequency
3. Adequate Meteorological Measurements Simultaneously with Propagation Measurements
4. Prediction of Geographical and Seasonal Model Atmospheres
5. Accurate Attenuation Calculations and Measurements in Millimeter Transmission Windows
6. Detailed Fluctuation Measurements
7. Comparative Propagation Studies (with Other Wavelength Regions)
8. Propagation Parameters of Interest -
   Attenuation, Depolarization, Site Diversity, Bandwidth Coherence, Scintillations, Prediction Techniques, Refractive Effects, Statistical Properties of Rain, Multiple Scattering Effects

Planned R&D:

1. Radiometric Observations in the Windows at 140 GHz and 230 GHz (Ga. Tech, NASA-Goddard)
2. Attenuation Measurements at 94 GHz (Ga. Tech, NASA-Goddard)
3. Fluctuation Measurements (Appleton)
4. Propagation Measurements at 300 GHz (MICOM, Ga. Tech)
5. Laboratory Studies - Simulated Atmospheric Conditions 40-140 GHz (OT)
6. Continuing Radiometry and Propagation Programs - Univ. Texas, NOAA, AEROSPACE, NASA-Goddard, MIT, JPL, BTL

8.6.3 Millimeter Wave Communications Systems Concepts

The need to extend the spectrum to alleviate overcrowding and to transfer large amounts of information is recognized as an important requirement for millimeter wave communications. The spectral region provides the means for communications from satellite-to-satellite and to various ground terminals. For example, a spacecraft-to-spacecraft communications link would provide an increased service area for each user ground terminal. There are many areas of the world which would benefit from a spacecraft-to-spacecraft link to communicate with areas not serviced by a single satellite. In Section 13.1, an example of a satellite-to-ground 40 GHz millimeter wave communication system is discussed. A number of millimeter communications systems can be postulated based on the projected requirements of future users. This section briefly discusses some of these systems which should be evaluated in future work.

a. One of the most important applications of millimeter wave (and Optical) communications systems will be in wide-band data relay links. With the large number of environmental monitoring low orbiting satellites which are envisioned for the future, millimeter/optical systems can play an important role. Millimeter waves can be employed for any of the following sections of a total link:

1. Low-orbiting satellite-to-synchronous satellite;
2. Synchronous satellite-to-synchronous satellite;
3. Synchronous satellite-to-ground.

The millimeter wave system can constitute part or all of a total link. The synchronous-to-synchronous link could consist of a 60 GHz system, avoiding interference with terrestrial applications. Communications from the orbiting vehicle to the synchronous satellite is less critical for the longer wavelength of millimeter communications than for the optical wavelengths. In addition to the data relay satellites for environmental monitoring, the large amounts of data which will continue to be accumulated and processed in the areas of computer data transfer and management, and financial data communications will eventually be handled by millimeter wave systems.

b. A requirement of high priority is the need of mobile communications. Communications capability for mobile terminals is severely limited at present.

The large number of mobile vehicles (vessels, aircraft, land mobile vehicles) which are currently used and predicted for future use requires a high quality, reliable communications technology. A conservative estimate sets the number of land mobile transmitters in the U. S. to exceed 7 million by 1980. A compact, inexpensive millimeter receiver, transmitter system from earth to satellite and return would provide a real time system on a global basis. Development of advanced techniques for multiple access by large numbers of small terminals and millimeter equipment for low-cost mobile terminals is required for this application.

c. The use of millimeter waves for broadcast services is a concept which must be fully explored in the future. With the development of high power sources and antenna techniques, the possibility of broadcasting from satellites to a single time zone or more than one is a desirable millimeter wave application. Multiple beam antenna technology will permit the broadcasting to chosen areas without radio interference effects is promising. Current use of portions of the spectrum already heavily occupied by terrestrial systems creates a major, complex frequency management problem, which can be eased by the use of millimeter wave satellite systems.

d. The use of new communications technologies and services will become available as millimeter wave techniques are employed. The greater bandwidth will provide the means for having a larger number of picturephone channels per transponder that could be handled by current satellite links. Extension to other services, e.g. library or educational must be included in assessments of millimeter wave applications.

8.6.4 The Potential Use Of The Submillimeter Wavelength Region

The use of submillimeter waves for terrestrial communications or ground-to-satellite communications is not very promising because of the large atmospheric attenuation from approximately 25 μm to 1 mm wavelength. A few windows in the long wavelength end of the submillimeter region (e.g. 1.3 mm, 0.85 mm and 0.75 mm) can be employed for ground based communications. The possibility of communication between high-flying aircraft and satellites, synchronous-to-synchronous or synchronous-to-low orbit spacecraft exists in the submillimeter wavelength region where no interference with terrestrial communications is possible. The enormous spectral region offered between 2 mm and 10 μm can handle most exoatmospheric communications requirements which can be projected for several decades.

The improvements which have been made in recent years in submillimeter technology indicate that complete communications systems can be assembled in the near future. Over 500 optically pumped sources have been developed across the submillimeter wavelength region, and these can be employed as local oscillators or transmitters. Direct discharge lasers also exist at discrete wavelengths and can be used as transmitters. A recent development in transversely excited HCN lasers at 337 μm by F. Kneubühl of ETH (Zurich) will probably result in the highest power laser sources available in the submillimeter wavelength region. Waveguide laser technology has been developed by D. Hodges of Aerospace Corp, and these optically pumped sources will probably yield the packaged sources for airborne applications. The stability of submillimeter lasers has been established several years ago by a group at Martin Marietta who phase-locked the HCN laser at 337 μm (890 GHz) to a 5 MHz frequency standard. The long term stability of the phase-locked laser was approximately 6 parts in 10^{12}. With receiver development currently being performed, relativistic beam devices (REBs) providing high output power and quasi-optical techniques being demonstrated, the submillimeter wavelength region will be a potential spectral region for high data rate applications. The longer wavelengths of this region will ease the problem of acquisition and tracking so that the establishing of a link between a low orbiting satellite and a synchronous satellite as the orbiting vehicle comes over the horizon will be achieved better in the submillimeter region than in the optical region.

8.7 Optical Communications Systems

As with millimeter wave communications, optical communications can be employed to meet the increasing demands of communications systems users. Table 8.20 can be considered as listing the advantages of optical systems as well as millimeter waves. The inclement weather effects on optical propagation dictate the optimum use of optical systems as being satellite-to-satellite applications. The other advantages of Table 8.20 indicate that optical technology will provide the basis for the high data rate systems of the future.

In the sub-sections which follow, a brief discussion is given of the optical communications systems which are considered for satellite systems. The fact that laser technology is in its infancy has resulted in some reluctance in applying these techniques; however, great advances have been made by the United States Air Force on YAG:Nd and doubled YAG:Nd systems and by NASA on CO_2 systems so that the most pressing need for satellite optical communications is the performance of test flights and comparison of the two systems.

8.7.1 Candidate Optical Communications Systems

The optical region has been considered since the advent of the laser as an excellent part of the electromagnetic spectrum for communications. As a result, as various lasers have become available, they have usually been surveyed for use as sources for optical communications. Table 8.34 indicates those optical communications systems which have been considered the leading candidates. In recent years, this list has been narrowed to the first three systems, i.e. CO_2 10.6 μm system, the 1.06 μm YAG:Nd system and the doubled YAG:Nd system at 0.53 μm. Actually, a comparison of laser communications systems, taken from a Hughes report, is given in Table 8.35. The important factor for comparison is the Figure of Merit, M in the next to last column. This factor, M, is a product of several factors and has been given by Hughes as M = (laser efficiency) x (modulator figure-of-merit) x (bandwidth) x $(P_T/P)_{min}$ $X(\lambda)^{-2}$.

This figure-of-merit shows the CO_2 laser as the strongest contender and Table 8.35 further indicates that short pump life is a reason for exclusion of the doubled YAG:Nd system. There are merits for both these optical

TABLE 8.34

CANDIDATE OPTICAL COMMUNICATIONS SYSTEMS

1. CO_2 Laser Communication System at 10.6 Microns
2. YAG:Neodymium Laser System at 1.06 Microns
3. Doubled YAG:Neodymium Laser System at 0.53 Microns
4. Helium-Neon Laser System at 0.6328 Microns
5. Gallium Arsenide Diode Laser System at 0.90 Microns
6. Ultraviolet Wavelength Laser System

TABLE 8.35

COMPARISON OF LASER COMMUNICATION SYSTEMS

Laser	λ, microns	Laser Power, W	Lifetime, hr		Laser Efficiency, %	Modulator Power, W	Modulator Figure of Merit	Maximum Bandwidth, Hz	$P_T/P_{R_{min}}$	Figure of Merit, M	Reason for Exclusion
			Device	Pump							
Argon	0.51	1.0	5,000		0.01	1.0	1.0	10^9	5×10^{17}	67	Low laser efficiency
Doubled YAG	0.53	1.3		500	0.03	1.1	0.9	10^9	1.6×10^{17}	53	Short pump life
He Ne	0.6328	0.005	>20,000		0.1	1.4	0.7	10^9	1.6×10^{15}	1	Low $P_T/P_{R_{min}}$
Ga-As	0.9	0.010	1,000		10	1.0	1.0	10^3	2.0×10^{15}	≪1	Low band-width
Nd:YAG	1.06 W pump	0.6		500	0.06	5	0.2	10^9	1.6×10^{16}	5.7	Low $P_T/P_{R_{min}}$ Short pump life
Nd:YAG	1.06 KR_B pump	0.1		10-400	0.03	5	0.2	10^9	2.7×10^{16}	0.499	Low $P_T/P_{R_{min}}$ Short pump life
Nd:YAG	1.06 LED pump	0.05		10-400	0.1	5	0.2	10^9	1.4×10^{16}	0.882	Low $P_T/P_{R_{min}}$ Short pump life
He-Ne	1.15	0.005	>20,000		0.1	5	0.2	10^9	1.1×10^{15}	<1	Low $P_T/P_{R_{min}}$
He-Ne	3.39	0.005	>20,000		0.05	2*	0.5	10^9	4.3×10^{16}	<1	Low $P_T/P_{R_{min}}$
CO_2	10.6	1.0	>10,000		10	12*	0.08	0.5×10^9	2.70×10^{19}	341	

*Intracavity coupling modulation.

communications systems as their advocates have indicated. Recent advances in YAG:Nd efficiency would place the laser efficiency in the 1 - 2% region so that the Figure-of-Merit of both the YAG:Nd and doubled YAG:Nd systems would exceed that of CO_2. The simplicity of the YAG system receivers and the capability to achieve higher data rates ($\gtrsim$ 1 Gbps) are factors favoring the doubled YAG:Nd system. On the other hand, the short pump lamp lifetime continues to be a problem, damage to the crystal doubler must be avoided and the difficulty of pointing at shorter wavelengths must be considered. The latter is a currently solvable problem, and, with continued development, the difficulties associated with both systems will be removed. The lifetime of experimental CO_2 laser tubes is currently approaching 30,000 hours. It is now the consensus of the laser communications community that laser communication components that are presently being developed are suitable for an operational laser communication system in the early 1980's. In the light of these developments and the availability of components, the most important development will come from the flight-testing of these systems. The doubled YAG:Nd laser system will be satellite-borne in 1976-1977 by the Air Force, but funding curtailment at NASA will delay the CO_2 tests.

8.7.2 Required Optical Component Technology

The technology required for optical communications spans a multitude of disciplines as does that required for the millimeter systems. Because of the short wavelengths of the optical region, the requirements on precision become more demanding than in the longer wavelength regions. Table 8.36 list some of the general categories of optical technology which are required for optical communications. The listing is applicable to both CO_2 and the YAG:Nd systems. Table 8.37 shows some of the CO_2 technology needs while Table 8.38 shows a similar breakdown for the YAG:Nd laser communication system. A brief discussion of these needs follows.

1. The CO_2 laser sources have received considerable support under NASA-Goddard programs and, as a result, are currently developed to the stage of being capable of satellite applications. The developments have resulted in frequency stable lasers with good lifetimes. Work by U. Hochuli of the

TABLE 8.36

Required Optical Technology:

1. Laser Source
2. Wideband Detector Capability
3. High Data Rate Modulation
4. Lifetime Improvement
5. Testing of Acquisition Techniques
6. Environmental Testing of Optical Components (LDEF)
7. Flight Testing of Optical Communications System (Satellite-to-Satellite)
8. Propagation Experiments (Satellite-to-Ground)

TABLE 8.37

CO_2 LASER COMMUNICATIONS SYSTEM

Technology Needs:

1. Flight Testing of Currently Developed CO_2 Laser System in Satellite-to-Satellite Application
2. Testing in Proposed Space Shuttle Experiments
3. Continued Improvement in Lifetime of Conventional Mode Laser Tubes. Current Lifetimes are in Excess of 30,000 Hours
4. Improved Lifetime of Waveguide Lasers. Detailed Testing is Required.
5. Frequency Stability Improvements. Stark Effect Stabilization and Lamb Dip Tests Should be Performed Over Long Periods
6. Increased Data Rates Over the Current 300 Megabit Rate. There is a Need for Improved Modulation Techniques
7. Increased Bandwidth in Current Detector Capability.
8. Space Environmental Testing of System Components, e.g. LDEF
9. As a Long Range Objective, the Development of 10.6 Micrometer Integrated Optical Components will Provide Improvements in Packaging and Performance. Example: An Integrated Modulator Will Provide Compactness, Lower Voltage Operation and Improved Performance

TABLE 8.38

YAG: NEODYMIUM LASER COMMUNICATIONS SYSTEM

Technology Needs:

1. Performance of Planned Air Force Experiments
2. Testing in Proposed Space Shuttle Experiments
3. Improvement in Lifetime of Excitation Flash Lamps or Better Pumping Techniques
4. Continued Improvement in Modulator and Doubler Materials. Higher Threshold to Damage
5. Freedom from Distortion of Doubled Mode-Locked Signals
6. Space Environmental Testing of System Components, e.g. LDEF
7. Testing of Pointing and Tracking Techniques
8. Improved Laser Efficiency
9. Reduction of System Size, Weight and Power Consumption

University of Maryland has extended the lifetime of small CO_2 lasers to 30,000 hours. The development of waveguide lasers by Hughes has provided compact tunable sources (on the order of 1 GHz) with a high potential for local oscillators in Doppler-shifted receiver applications. For these sources, lifetime improvements are important. Since the waveguide CO_2 lasers are relatively new, detailed testing is necessary. Frequency stabilization improvements are necessary. Stark effect stabilization is employed and should probably provide stabilization on the order of a part in 10^9. The use of BeO or alumina tubing projects the possibility of having sources which do not require water-cooling thereby lessening the weight and size of satellite-borne systems. For the conventional normal mode CO_2 lasers, stabilization techniques exist in the form of Lamb dip fluorescence which can result in stabilization on the order of a part in 10^{11} - 10^{12}. Improvement over the 10% efficiency of the CO_2 lasers which are employed is highly desirable. Efficiencies as high as 20% or more have been achieved but this is not the case for sealed-off small CO_2 lasers.

The current status of the YAG:Nd laser is such that continued improvement in the lifetime of excitation flash lamps or better pumping techniques are required. Laser efficiency has always been a problem for the YAG:Nd laser, and this must be improved for future optical communications systems. Recent improvements in laser efficiency has been experienced in YAG:Nd laser designator devices, and this capability must be transferred to the communications technology. Efficiencies on the order of 1 - 2% have been achieved.

2. In the case of the CO_2 laser communications system, increased data rates over the current 300 megabit rate is a necessary requirement for future applications. The power consumption involved in high data rate modulation for 10.6 μm must be reduced considerably. New materials and new modulation techniques should be explored.

For the YAG:Nd laser, it is important that improvement in modulators and doublers be continued. Barium sodium niobate and lithium tantalate have been shown by the Air Force to be appropriate materials for doublers and modulators respectively but higher thresholds to damage are required for long term operations. In the doubling of mode-locked signals freedom from pulse distortion and deterioration must be guaranteed.

3. Reduction of system size, weight and power consumption should be a goal of future operations. The improvement in source efficiency will contribute significantly to lowering of the power consumption. As a long range objective, the development of 10.6 μm integrated optical components will provide improvements in size, weight, power consumption and performance. An example of this possibility is afforded by integrated waveguide modulators which will provide, in addition to compactness and improved performance, lower voltage operation.

4. Environmental testing of system components under space operational conditions will provide important data for system design. Satellite testing planned by the Air Force and provided by the Shuttle Long Duration Exposure Facility (LDEF) will fill the role for space environmental testing. As indicated previously, the most important developments for optical communications is the availability of flight testing of the systems. Performance of planned Air Force flight experiments will furnish data on the doubled YAG:Nd system while the carrying out of proposed joint Space Shuttle experiments will yield data on both CO_2 and YAG:Nd systems. For the currently developed CO_2 system, funding should be provided to flight test in a satellite-to-satellite application. It is in this role that the value of the CO_2 laser will be most evident.

5. For CO_2, increased bandwidth capability over that provided by existing 10.6 μm detectors must be possible if higher data rates are to be achieved.

6. The narrow beam widths of laser communication systems require accurate pointing, acquisition and tracking techniques which, while proven in the laboratory, must be tested under flight conditions. Geosynchronous-to-geosynchronous satellites and geosynchronous-to-orbiting satellite situations must be examined. The latter link places the most stringent requirements on the pointing and tracking apparatus and is important for the data relay systems.

8.7.3 Atmospheric Effects in the Optical Wavelength Region

The effects of the atmosphere on optical propagation is much more severe than in the longer wavelength microwave and millimeter regions. Clear air absorption does not present a serious problem for the most convenient laser frequencies and appropriate transmission windows exist in the 10.6 μm, 1.06 μm and visible spectral regions. For 10.6 μm and 1.06 μm, the clear air attenuation is not the limiting factor in transmission. The effects of rain, cloud and fog are the most serious. Figure 8.18 shows the effects of all atmospheric constituents. The situation is such that total fog attenuation might be several tens of decibels for a 1 kilometer range but attenuation for clouds is much more serious than this, essentially completely blocking laser transmission. Studies have been performed by Hughes to ascertain the feasibility of employing spatial diversity in the optical wavelength region. The investigation was concerned with determining the probability of cloud cover being present at several sites simultaneously. Six sites were chosen in the United States to examine the probability of sunlight, using this as a measure of cloud cover probability. The combined probability of sunshine for one, two and three stations were also calculated. The sunshine probability was calculated for each of the six stations for the four seasons of the year. The annual probability was also determined. From Table 8.39 it is seen that when three stations are available, it is possible to have clear line of sight to at least one of these three stations greater than 99 percent of the year. The six sites chosen for the ground station receiving network were:

Yuma, Arizona (YUM)
Amarillo, Texas (AMA)
Lander, Wyoming (LND)
Evansville, Indiana (EVV)
Washington D. C. (DCA)
Tampa, Florida (TPA)

While it is possible to have a main trunk link from a synchronous data relay satellite to an earth station using a laser link, it will probably require two or three earth receiving terminals. The narrow beam of the laser will also necessitate reorientation, acquisition and tracking of the satellite-borne laser. Further investigations of the feasibility and economics of this technology is needed. Propagation experiments proposed at the Shuttle Communications Experiments Workshop should also be performed when Shuttle flights

TABLE 8.39

PROBABILITY OF A CLEAR LINE-OF-SIGHT

SELECTED COMBINATIONS OF NETWORK STATIONS	PROBABILITY OF A CLEAR LINE-OF-SIGHT PERCENT				
	JANUARY	APRIL	JULY	OCTOBER	ANNUAL
1. (YUM)	83	94	92	93	91
2. (LND)	66	66	76	67	69
3. (AMA)	71	75	81	76	76
4. (EVV)	46	65	82	73	65
5. (TPA)	63	74	61	67	68
6. (DCA)	46	57	64	61	58
1 & 2	94	98	98	98	97
1 & 3	95	99	99	98	98
2 & 3	90	91	95	92	91
2 & 4	82	88	96	91	89
3 & 4	84	91	97	93	91
3 & 5	89	93	93	92	92
4 & 5	80	91	93	91	91
4 & 6	71	85	94	89	86
5 & 6	80	89	86	88	87
1, 2 & 3	98	99+	99+	99	99
2, 3 & 4	95	97	99	98	97
3, 4 & 5	93	98	99	98	97
4, 5 & 6	93	96	97	96	95

become available.

In addition to the attenuation of laser signals by atmospheric constituents, the effects on polarization, scattered radiation and coherence are important aspects of the propagation of optical communications signals which must be carefully studied if satellite-to-ground optical links are to be a reality.

8.7.4 Optical Communications Systems Concepts

The spectral region offering the greatest capability for high data rate communications is the optical region. The extremely large bandwidths which are potentially available can handle requirements beyond what can currently be predicted. Despite the atmospheric attenuation problems, it has been shown that communications from satellite to ground will be possible. Satellite-to-satellite applications will be the most appropriate use of optical systems. In Section 13.2, a cost benefits analysis of such a system is performed. The narrow beams of laser systems will provide the capability for multi-beam, non-interfering optical communications to several diverse points.

An application of great importance is the data relay link which has been considered as an application for several different spectral regions. The millimeter wave regionwould be an appropriate spectral region for this application. On the other hand, many of the millimeter wave applications discussed in sub-section 8.6.3 should be considered for the optical communications applications. In the light of its importance, a few brief remarks should be made on the data relay link concept.

Data rates for space communications are projected to increase from 10^8 to 10^9 bps during the 1975 to 1980 time frame. The requirements for these large data rates exist in several areas of communication and necessitate the use of high data rate systems in many links (synchronous-synchronous, synchronous-low orbiting satellites and satellite to ground). A radical new step in obtaining data from scientific satellites is the data delay satellite concept, shown in Figure 8.26. In this concept, a data relay

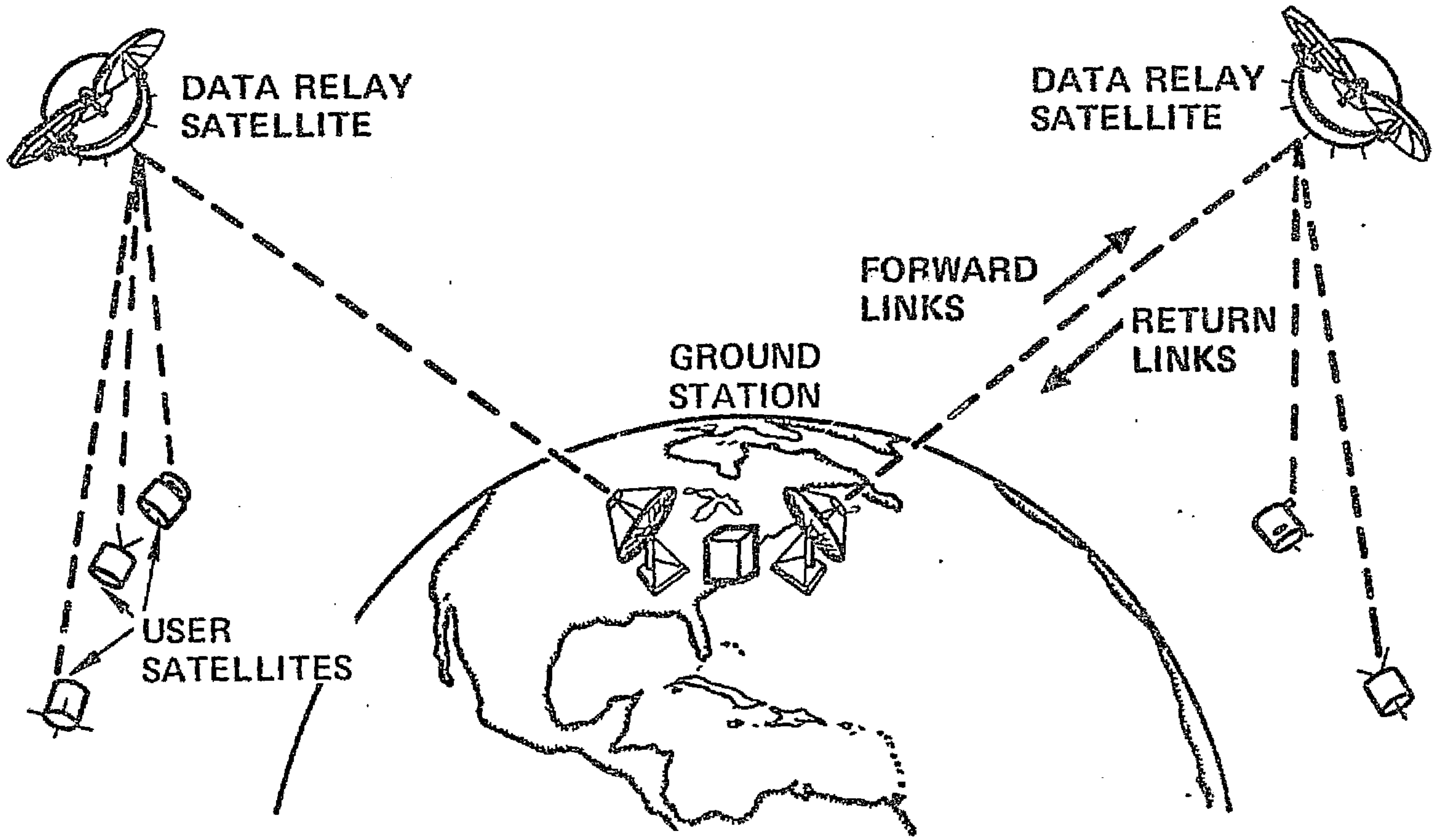


Figure 8.26. Data Relay Satellite Concept.

satellite is utilized to relay data and commands between low earth orbiting user satellites and a central ground station. The data relay satellite must operate at a variety of frequencies to accommodate the current scientific user satellites, but such a system can replace a large number of ground stations and is, therefore, economically attractive. System definition studies have been performed on data relay satellite systems operating in the RF region, and comparisons have been made with laser communication systems more detailed consideration must be given to the use of millimeter wave systems for data relay links.

In order to analyze the cost benefits of Satellite Data Relay Links, several program requirements must be considered. A leading candidate for such high data systems is the Laser Data Relay Link (LDRL). Experimental versions of this system exist, and performance of experiments have been planned by both the U. S. Air Force and NASA. A co-operative program has been proposed. Although current funding does not include the performance of these experiments, the purpose of the proposed program is to determine the feasibility of laser communications for wideband data transmission from spacecraft. The Air Force phase of the experiment calls for a high data rate Nd:YAG laser transmitter intended for synchronous-to-synchronous satellite applications and for secure synchronous satellite-to-ground applications. The NASA system would be a high data rate CO_2 laser transceiver intended for low altitude satellite-to-synchronous satellite needs for data relay applications.

A large number of applications of space-to-space relay systems can be expected with the next generation of space systems. Included in these applications is the Earth Observations Satellite (EOS) and similar earth sensing satellites which share a requirement for wideband data transmission from a low-altitude satellite to an associated ground data center. It has been pointed out that recovery of data is most appropriate performed by a synchronous satellite data relay link. The techniques can be employed in several frequency bands, but for the anticipated data rates, either a millimeter or optical system must be considered. The Tracking and Data Relay Satellites (TDRS) will provide continuous real-time tracking and data acquisition service for satellites in near-earth orbit (up to 5000 km altitude).

A major element of this system is the use of 2 geostationary satellites and an on-orbit spare in order to relay RF signals received from various lower altitude spacecraft, including shuttle, to earth stations in continental U. S. TDRS will consist of broadband multiple-access frequency communications repeaters with UHF, S-band and K_u-band subsystems for low, medium and high data rate users. TDRS will provide range and range-rate information of the low altitude satellites to ground stations for tracking purposes and will transmit ground generated commands and voice to these satellites.

The objective of the LDRL experiment is to provide a compact, high performance laser data relay link, capable of transmitting wideband data from a low-altitude satellite through a relay satellite to ground station. The experiment could use the space shuttle as a terminal for complete space-to-space tests and will provide information on data quality and quantity transmitted over laser relay link.

The taking and recovering of data on a reasonable duty cycle using conventional methods of on-board storage and intermittent or direct readout to ground stations is unlikely and it is for this reason that EOS and similar missions are considered as prime candidates for future operational use of wideband CO_2 laser data relay links. NASA and the Air Force have considered the EOS mission as a baseline laser data relay link application; the differences between various wavelengths that might be considered for space-to-space relay links were examined briefly. The following characteristics are improtant in the preference for higher frequencies in the data relay system:

<u>RF system characteristics</u>:

Large antenna ($\sim$3 m in diameter) on low altitude satellite; susceptible to multipath; RFI from terrestrial sources; requires frequency allocations which can be increasingly difficult to obtain in future years; difficult to meet high data rate requirements.

<u>Laser system characteristics</u>:

Small antennas (12-20 cm in diameter); light weight; reasonable prime power required; freedom from multipath, RFI and spectral crowding.

A recent NASA report has considered the advantages of satellite-to-satellite communication and has indicated the many applications of data relay satellites. For the conceptual system considered here, we limit the discussion to a data relay system for the EOS. The comparison can be made for an EOS direct to ground link with an EOS to TDRS to ground link.

Consider the following conceptual system: EOS-to-TDRS-to-ground link for data rate of 800 Mbps for the EOS altitude = 450 N.MI. The most appropriate link for this system is the 10.6 μm CO_2 laser system for the EOS to TDRS link with a K_u band carrier for the TDRS to ground link. The cost for one system is:

10.6 μm	EOS-TDRS Link	\$3.32M
K_u-band	TDRS-Ground Link	7.95M
		\$11.27M

Compared with the following:

EOS direct-to-ground;

	EOS Telecom	Ground Recurring	Stations Nonrecurring	For 7-yrs.
2.25 GHz	\$6.37M	\$1.12/yr	\$9.85M	24.06M
7.25 GHz	6.23	1.12	9.83	23.90
14.5 GHz	6.73	1.12	10.85	25.42
21.0 GHz	8.19	2.24	15.20	39.07
10.6 μm	4.92	3.36	29.87	58.31

while other wavelengths for the EOS-TDRS-Ground link show the following <u>total</u> costs:

	EOS-TDRS	TDRS-Ground	Total
7.25 GHz	9.11 M	16.21 M	25.32
14.5 GHz	9.41	16.51	25.92
21.0 GHz	10.94	18.11	27.45
60.0 GHz	12.62	19.81	32.43

A comparison should be made of the 10.6 μm CO_2 laser with the YAG:Nd^{3+} laser communication system.

NASA development costs are those projected previously for the laser communications system. This is for only one EOS-TDRS-ground link. A projection for future systems can be made. An estimate is that four + one spare TDRS will be eventually flown with possibly 3 EOS per TDRS.

SECTION 9

CONCEPTUAL SYSTEMS INCORPORATING INNOVATIONS AND MEETING USER NEEDS

Results of the user survey described in Section 7 and the technology survey of Section 8 have been combined to select a set of conceptual technology systems which will meet the near future user needs by incorporating technical innovations. These conceptual systems are then analyzed by the cost-benefit methodology developed in Sections 1 through 5 of this report. The selected conceptual systems range from ground station items to satellite subsystems to total communication systems. They have been selected so as to be representative of the total group of space communication technologies. The conceptual systems technologies are as follows:

- Low Cost Earth Station Receiver Technology
- Ion Engine Technology
- Millimeter Communication System Technology
- Laser Communication System
- RF Attitude Sensor
- Satellite Solid State Power Amplifier
- Multibeam Antennas
- Advanced Solar Arrays
- Adaptive Heat Pipes

Each of these conceptual system technologies is analyzed in Sections 11 through 14, and a description of the concepts and the mechanisms of the benefits are given there. Ion engine technology is analyzed in Section 11; low cost earth station technology is analyzed in Section 12; and the remaining seven technologies are analyzed in Section 13. Section 10 describes the baseline scenarios used in application of the methodology of Part I to the conceptual systems developed in Part II.

PART III

APPLICATION OF METHODOLOGY

SECTION 10

SCENARIO DEFINITION

10.1 Approach

Application of the cost-benefit analysis (CBA) methodology presented in Part I requires specification of a standard situation against which each of the proposed technology development projects can be evaluated. In accordance with the screening equations, evaluation of net present values of any proposed technology development program requires specification of the following set of parameters: discount rate, time delay factor, probability of industry adoption, NASA R&D time, industry R & D time, industry construction time, operation time, total NASA R&D cost, total industry R&D cost, total industry construction cost, annual gross benefits, and annual gross costs. Rather than the separate annual gross benefit and annual gross cost, it is the net annual benefit which is important. Of the above list of parameters, the most difficult ones to evaluate are the net benefits. Sources of benefits for the projects under consideration are (1) cost-effective services to USA, (2) profit from the sale of satellites to other countries, (3) balance of payment considerations, and (4) employment considerations. Of these the primary benefit is that gained from cost-effective provision of communication services to the USA.

The one element common to each technology cost-benefit analysis is the necessity of estimating the size of the market for the technology in question. Prediction of the market size for the technology to be utilized in space communications has three basic steps. First, the estimated required channel capacity of satellite communications for the western world is estimated in thousands of half-circuits. These estimates are based upon Intelsat's projections for the international communications, application of a similar projection to the United States and foreign domestic satellite needs and previous estimates by other investigators. Second, projections are made of the estimated satellite capacity as a function of time; that is, projections of the channel capacity per satellite for the interval 1976-79, 1980-89, 1990-99 . These projections are consistent with those made recently by Intelsat for their own planning purposes. More will be said below about the relationship between the projected satellite capacity and the technology development under consideration. The third item is the market prediction methodology. Satellite launches have two parts: that due to growth and that due to replacement of older satellites.

Once an approximate launch schedule for communication satellites for the western world has been established by the procedure outlined above, one must address the issue of what share of the western world market will be held by the United States. Certainly the benefits to the United States which result from the development of technology for communication satellites are different for satellites which are constructed, owned and operated in this country than for those satellites built here but owned and operated by foreign countries. The communication satellites of the western world may be envisioned in four groups: (1) U.S. constructed and U.S. operated, (2) U.S. constructed and foreign operated, (3) foreign constructed and U.S. operated, and (4) foreign constructed and foreign operated. Of these four categories, only the first two have benefits to the U.S. resulting from the technology development. Calculation of benefits for the first group does not require separation of benefits accruing to the satellite manufaturer as profits and benefits accruing to the operator or users of the satellite; all benefits go to the United States. In the second class however (satellites constructed in the United States for a foreign country's use), the benefits accruing to the United States are the profit to the satellite manufacturer and, to a somewhat smaller degree, the benefits associated with increased employment and improved balance of trade. In any case, calculation of benefits for the second class requires separation of profit to the manufacturer and savings to the owner; only the benefit accruing to the manufacturer is appropriate. The cost-benefit analyses of this report assume that the "U.S. constructed and U.S. operated" benefits (including U.S. share of INTELSAT) adequately approximate the total benefits.

The influence of technology development upon the share of the western world market held by the U.S., and its impact upon the cost method analysis is not quantatively treated in this report.

The actual baseline scenario can be viewed at any of several levels of complexity. In the simplest case where only those satellites constructed in the United States for use by citizens of the United States are considered, the information needed is a projection of the estimated required channel capacity together with an estimate of the channel capacity per satellite as a function of time. The channel capacity per satellite versus time figure is assumed to be directly related to the development of the critical technologies at specific times. The cost-benefit analysis then consists of varying the time of availability of these technologies by performing the NASA R&D programs relative to the technologies.

Four types of scenarios are of interest in a cost-benefit study of government sponsored R&D. These may be termed the project scenario, the baseline scenario, the full shift scenario, and the partial shift scenario. The latter two are polar alternative scenarios. The nature of a cost-benefit study is the comparison of a project scenario with an alternative scenario. The alternative scenario may be one of the aforementioned polar possibilities, or an intermediate one formed as a weighted combination of these extremes, or the baseline scenario.

The project scenario is the stream of resource inputs and outputs corresponding to the more or less immediate adoption of the R&D project. The baseline scenario assumes the R&D project is not undertaken. The inputs and outputs of the other scenarios are calculated as differences from the baseline. The full shift scenario assumes the input-output stream of the project scenario remains unchanged, except that the stream is shifted, or slipped, some years into the future. The partial shift scenario assumes the R&D cost phases are shifted into the future, but the benefits in the final stage equal the benefits in the project scenario.

Since costs and benefits are relative, not absolute, dollar values cannot be associated with each of the four identified scenarios. Rather a scenario can only be assessed relative to another scenario. Thus, dollar values are associated with the project, full shift, and partial shift, scenarios by comparing each to the baseline scenario. It is the differences between scenarios which are valued. The project scenario can then be compared with an alternative scenario in either of two ways: (a) the direct method, in which since two scenarios are involved, they may be assessed relative to each other; and (b) the direct method, in which if each of the two scenarios has already been valued by comparison to the baseline, these values may be differenced. It should be noted that (a) is informationally more efficient than (b).

To bring this discussion into sharper focus, let X_1 represent the <u>physical</u> flow of inputs and outputs in the project scenario; X_2, X_3, X_4 are the physical flows for the full shift, partial shift, and baseline scenarios, respectively. Let V be a function which assigns dollar values. V is defined only on <u>differences</u> between scenarios. Thus, $V(X_1)$ is <u>not</u> defined, whereas $V(X_1 - X_4)$ is defined. Method (a) above finds $V(X_1 - X_2)$ directly, while (b) finds $V(X_1 - X_2)$ by evaluating $V(X_1 - X_4) - V(X_2 - X_4)$. The results are identical. However, the former does not demand knowledge of X_4.

Equation 3.3 in Part I compares the project scenario with the full shift scenario, while equation 3.5 in Part I compares the project scenario with the partial shift scenario.

10.2 Baseline Calculation

Many space communication technologies to be developed have benefits which can be expressed as a more cost-effective delivery of communication services. The benefit of NASA-induced technology development is then the difference in costs of providing the communication services over an extended period of time with (1) early introduction of the technology and (2) normal (later) introduction of the technology. Evaluation of the benefit requires estimation of the technology's value per satellite and of the market demand for communication satellite services.

Benefits of the NASA technology program to this nation are assumed to accrue primarily from communication satellites manufactured and used in this country. Secondary benefits will accrue from increases in foreign sales of U.S. manufactured communication satellites. Estimation of the primary benefits then requires prediction of the demand for U.S. communication satellite services and estimation of the portion of this market to be supplied by U.S. satellite manufacturers.

Table 10.1 describes the models used for demand, satellite cost, satellite capacity, and portions of sales and use and Table 10.2 gives the baseline parameter values. Figures 10.1, 10.2, and 10.3 portray the resulting estimates of market demand, satellite capacity, and satellite cost through the year 2000 for U. S. domestic communication satellites. Figures 10.4, 10.5, and 10.6 present similar data for the combined Atlantic and Pacific regions of the INTELSAT system (thousands of half circuits per satellite.

The capacity per satellite is that which is anticipated in the absence of development of the specific technology being analyzed at a given time; i.e., a nominal growth rate of and satellite capacity is taken as the baseline, and adjustments are made to account for the specific technologies being evaluated. The satellite cost is projected to increase at a rate somewhat less than that of the satellite capacity so as to result in a lower cost per channel with increasing time.

Attributes of satellite technology which contribute to effective delivery include lower cost equivalent systems, higher capacity systems with less than proportional increase in cost, and increases in expected satellite lifetime. Evaluation of the cost difference for the total period with and without early introduction of a specific communication system requires estimation of the two launch schedules. The number of satellite launches required in a given year depends upon (1) the increase in demand for communication services, (2) the required replacements of earlier-launched satellites whose nominal end of life occurs in that year, and (3) the channel capacity per satellite available with the then-current technology. The cost is then the number of satellites launched multiplied by the cost per satellite. A computer simulation program has been developed at the Enginnering Experiment Station which generates a launch schedule consistent with the models given in Table 1 (demand, satellite capacity, and satellite cost) for any specified set of initial conditions (i.e., the initial capacity in orbit, the times of the previous launches, and the expected lifetime of each satellite). The program also computes the annual expenditures discounted back to the base year and the cumulative discounted expenditures. Scenarios involving different introduction times for a specific technology can be compared by generating the launch and cost schedule for each scenario and by comparing either the set of annual expenditures or the cumulative expenditure at some time significantly past the second technology

TABLE 10.1

SATELLITE LAUNCH SCHEDULE BASE LINE

Satellite Capacity $= C_o\ (1+d_1)^t$

Satellite Cost $= P_o\ (1+d_1 d_2)^t$

Demand $= D_o\ (1+d_3)^t$

$$\text{Percent Sold by US} = \begin{cases} p_1\ (t+1) + p_2, & x_1 \leq t \leq x_2 \\ 100 & t < x_1 \end{cases}$$

Percent Used by US $= p_3$

$$\text{Satellite Lifetime*} = \begin{cases} L_o, & o \leq t \leq y_1 \\ L_i, & y_i \leq t \leq y_{i+1} \end{cases} \qquad i = 1,2,3\ldots$$

where t = (year of interest) - 1975

*The computer program allows an arbitrary number of piecewise-constant segments of satellite lifetime. The baselines as used in this study use two such segments

TABLE 10.2

BASE LINE PARAMETER VALUES

	INTELSAT (Atlantic & Pacific)	DOMSAT (US)
P_o	$35M	$35M
d_1	.11	.1
C_o	10K half ckts	14K half ckts
d_2	.69	.75
D_o	17K half ckts	24K half ckts
d_3	.18	.2
p_1	-2	-1.7
p_2	93	110
p_3	50	100
L_o	7 years	7 years
y_1	1985	1985
L_1	8 years	8 years
y_2	2000	2000
x_1	3 (1978)	5 (1980)
x_2	25 (2000)	25 (2000)

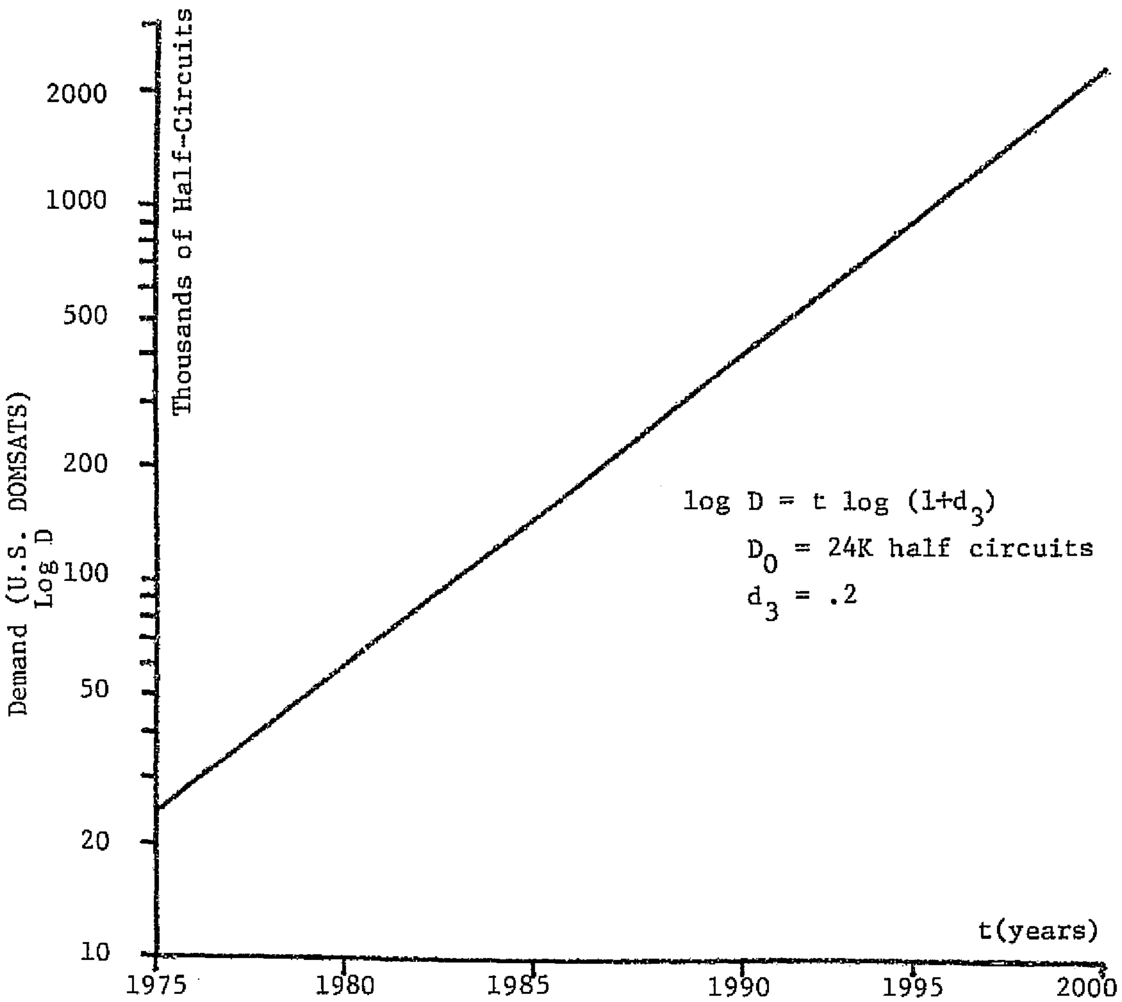


FIGURE 10.1. Projected Demand for U. S. DOMSATS

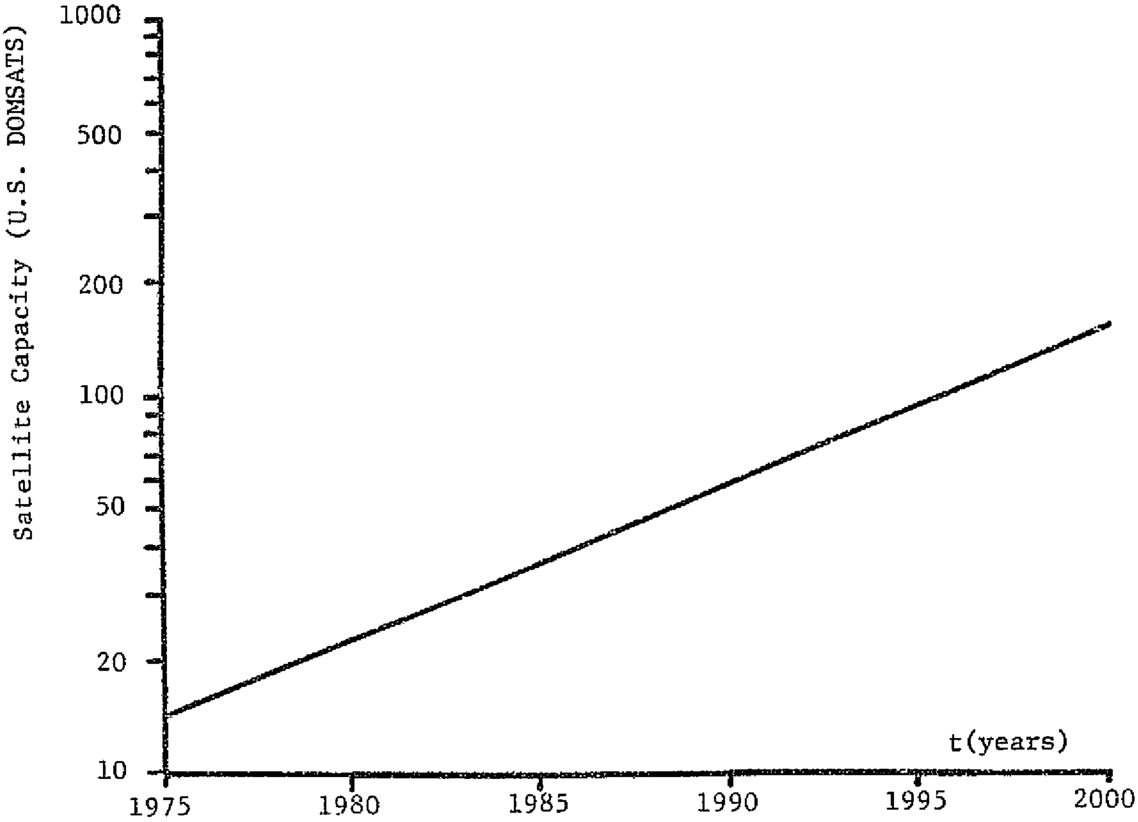


Figure 10.2. Projected DOMSAT Capacity (k half-ckts/satellite)

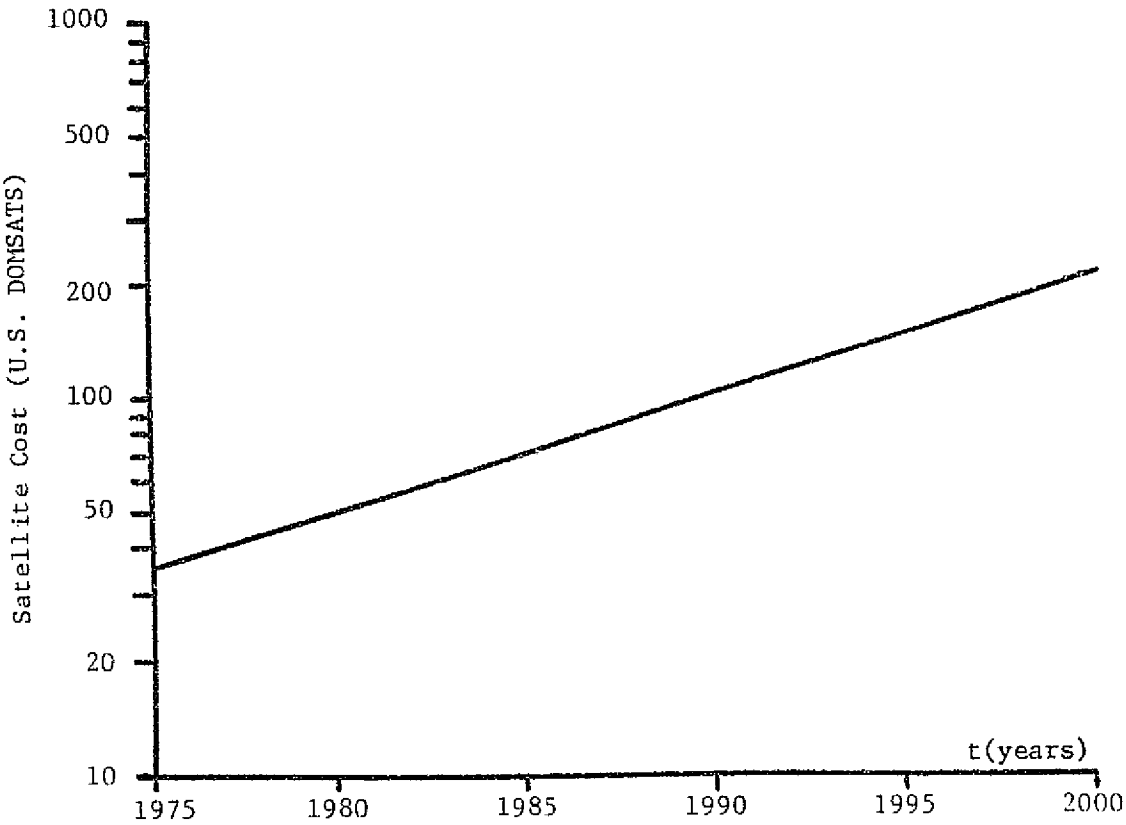


Figure 10.3. Projected DOMSAT Costs

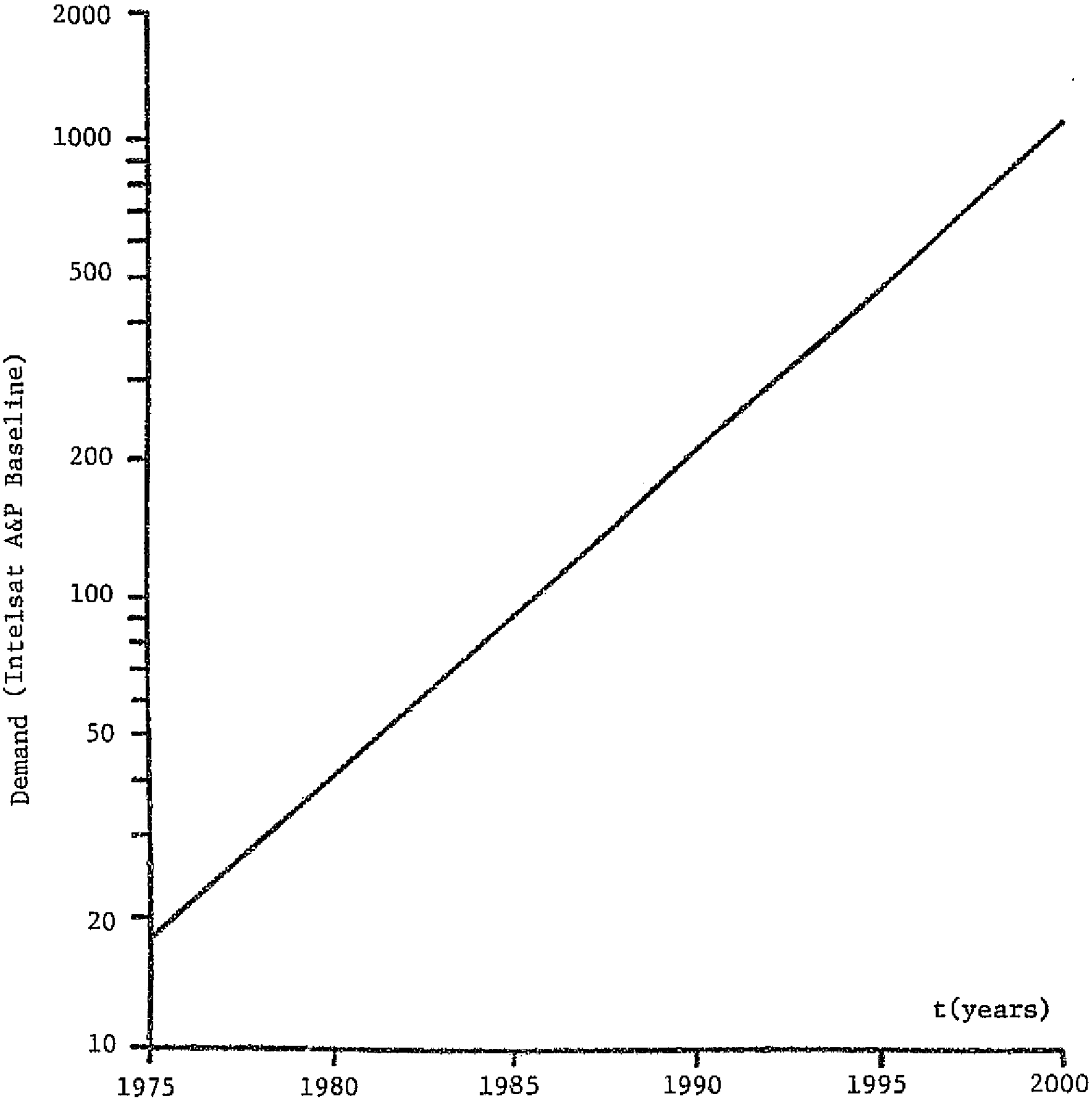


Figure 10.4. Projected Demand for Intelsat

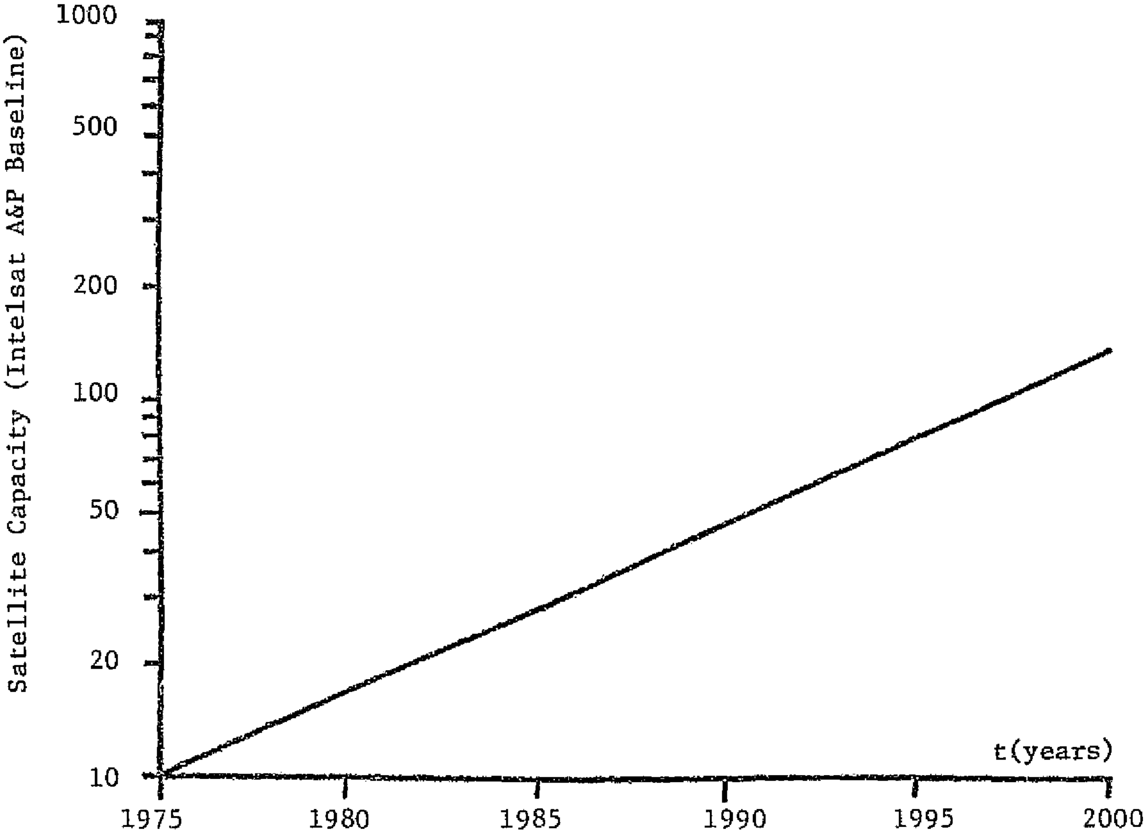


Figure 10.5. Projected Intelsat Capacity (k half-ckts/satellite)

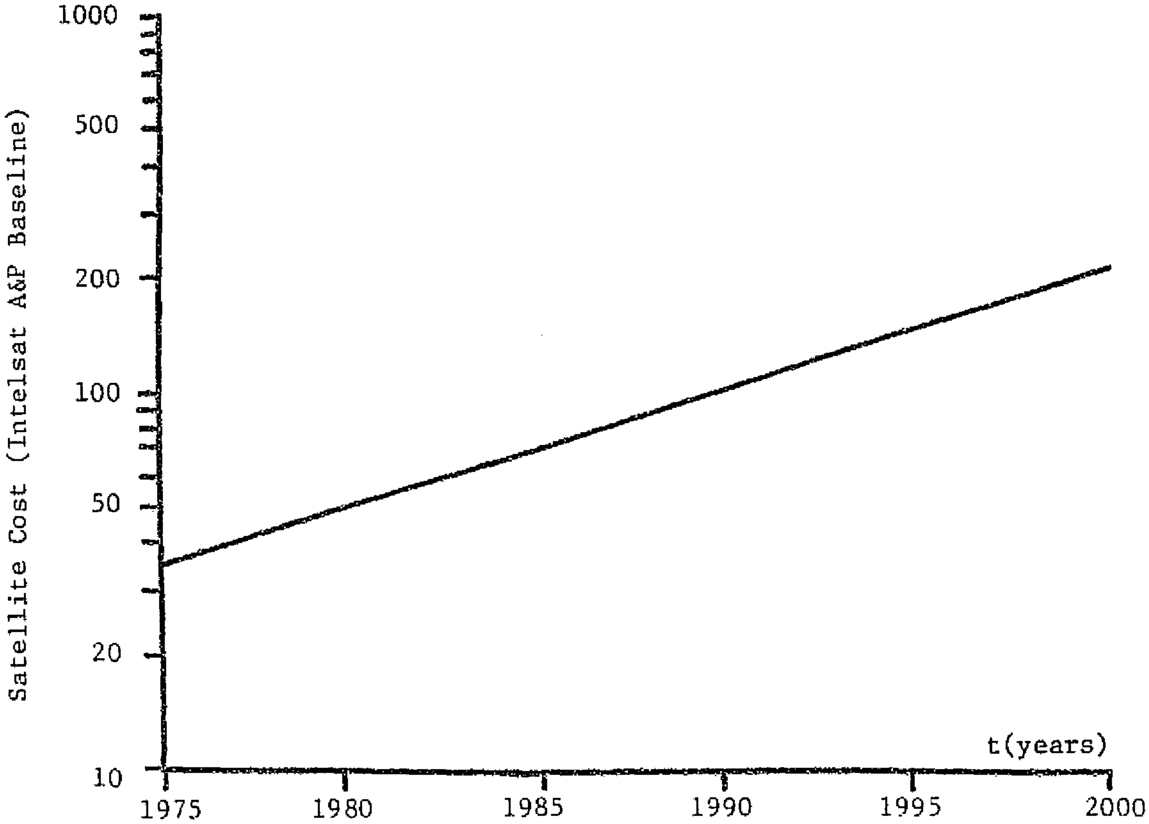


Figure 10.6. Projected Intelsat Costs

introduction date. The later time must be selected such that the effects of any lifetime extension associated with technology is included.

Experience with the launch schedule simulation has indicated a significant sensitivity with respect to the assumed initial conditions regarding launch time of satellites in orbit at the beginning of the simulation. This sensitivity is often large with respect to the cost saving associated with the technology introduction. A second simulation program which artificially allows fractional-satellite launching (launches capacity equal to demand increase plus replacement needs on a per channel basis) has been developed and used for emphasizing the impact of technology development upon the cost of providing the necessary communications services. This later program was used for estimation of benefits in the following analyses.

The output of either of the launch schedule simulation programs provides a basis of comparison of early and late technology development in terms of the different operating costs (discounted back to the base year). The computer programs implemented for screening, assessment, and ranking assume that the benefit is expressed as a constant equivalent annual benefit during the operational phase. Accordingly, the discounted benefit of early technology introduction determined from the launch simulation program is transformed into an equivalent annual benefit (EAB) as input data for insertion into the cost-benefit analysis methodology programs by first computing the constant annual benefit

$$CAB = \left\{ \frac{(\gamma)\ (1+d)^{T_1+T_2+T_3}}{\sum_{t=1}^{T_4} \left(\frac{1}{1+d} \right)^t} \right\}$$

and then dividing that number by the technology lag term which is a pre-multiplier in the NPV equation:

$$EAB = CAB/\ [1-1/(1+d)^{\tau}],$$

there T_i is the length of the i^{th} phase, is the technology delay time, d is the discount rate, and γ is the discounted net benefit of the early technology scenario.

10.3 Considerations in Benefit Identification

In the net present value expression, the total frame is subdivided into four intervals: a basic R&D phase, an applied R&D phase, a prototype development phase, and an operational interval. In one type (Type I) of benefit approximation, the operational interval extended to the time the technology became obsolete. In the second type of benefit identification, the operating region (benefit period) begins when the technology would become available through NASA support and ends when the technology would have become available without NASA support. In the first type, the net present value of the technology development is evaluated by calculating the net benefit in each year of operation of the device, prorating the net benefits back to the base year (1975) at the appropriate discount rate, and summing the discounted benefits. In this approach, the benefit associated with the NASA development program is calculated by multiplying this technology benefit by a delay factor which is dependent only upon the discount rate and the time delay resulting from NASA not pushing this technology. This approach assumes that the benefits which result from the introduction of the technology depend upon the time since introduction of the technology and not upon absolute time. It is most applicable for technologies whose rate of application is determined not by a changing market but rather by an increasing user acceptance of the device; i.e., demonstrated performance. It is not particularly applicable to a situation in which the market for devices using the technology is rapidly changing.

The second type of benefit identification, which is best fitted for a technology whose rate of usage is dependent upon a changing market and not upon the length of time since its introduction is given by our second approach. In this Type II Benefit Approximation, the first three intervals of basic research, applied research, and prototype development are handled the same as in the Type I approach. However, the benefit region is not the useful period for the technology but rather is the period of time after the technology would have first become available with NASA support and before it becomes available without NASA support. This Type II approach seems most applicable for our application in which the available market for communication satellites is assumed to have an exponential growth with time.

The most critical element in the estimation of the net present value of the project, regardless of the model used for the operating region, is specification of the net benefits per year. Consider first the class of technologies whose benefits expresses itself either as an increased capacity per satellite or as an increased lifetime of a satellite. The benefit then is simply a more economical method of supplying the required channel capacity. The difficulty in evaluating these benefits is the discrete nature of the communications satellite launch profile. For example, a 10% increase in the channel capacity per satellite or a 10% increase in the lifetime of such a satellite will modify the future launch schedule of such satellites. However, the ratio of required channel capacity to channel capacity per satellite is relatively small, and the time between launches of satellites is relatively large. As a result of this, the benefit of supplying a technology which increases the effective capacity of a satellite a few years earlier than it would normally be available may or may not result in any change in the launch schedule during the interval; certainly an increased lifetime per satellite does not yield any apparent reductions in launch costs until such time has passed that the additional lifetime of the satellite is being used. These factors make it difficult to determine a net benefit per year of the operating interval. Thus evaluation of the benefits associated with an earlier arrival of a given technology would seem to require evaluation of (a) a launch schedule using the old technology to meet the projected market demand for several years, (b) and a similar projected launch schedule utilizing the net technology with its increase in capacity per satellite to meet the projected market needs. The difference in the launch costs per year between the two profiles, discounted back to the base year, can then be summed over the several decades to determine the best estimate of the benefits associated with the introduction of the technology. A major drawback to this approach is the strong dependence of the results upon assumptions as to previous launch schedules, times that previous satellites will be inoperative, and the accuracy of the projected market demands. The detailed simulation to determine an accurate launch schedule and predicted cost per year requires more accurate input data than is deemed to be available for the future years. That is, the analysis needs more detail than the accuracy of the available input data would warrant.

Nonetheless, it is apparent that the actual net benefits per year during the operating interval are highly dependent upon launch schedules in future years. The prime benefits resulting from the introduction of the technology are indeed the reduced launch costs of future years. What is needed is an approximate method for calculating the benefits per year and one or more examples using projected launch schedules as a means of validating the approximate model. The approximate model which has been selected and computerized assumes that the benefits can be approximated by a "fractional satellite" launch schedule.

The baseline and method of evaluating benefits up to this point has been discussed in terms of unit satellites. No consideration has been given to applications of this technology to non-communications satellites nor to the sale of components for commercial satellites built in other countries. The international nature of the Intelsat membership has resulted in teaming for bidding on the next generation of Intelsat satellites such that no single manufacturer nor even one country will supply all components for the satellite. This combined builder situation will propagate itself naturally into the domestic satellite sales. Also some of the technologies under consideration, such as the solid state power amplifiers, likely will find application in non-satellite areas.

10.4 On Summary

The total methodology which has been developed for the benefit cost analysis of alternate space communications technologies is composed of a set of three consistent methodologies: screening, assessment, and ranking. In each methodology, the underlying approach is the calculation of the net present values (NVP) of alternate proposed technology development programs, with an increasing level of detail as one proceeds from screening towards ranking.

Application of the screening methodology produces both the estimated NPV of the proposed technology development program and a graphical sensitivity analysis of the NPV with respect to each input parameter. In the assessment methodology, each of the screening input parameters is supplemented with an estimate of the range of parametric values in either standard deviation or minimum and maximum modal values. Application of the assessment methodology (a form of risk analysis) produces an estimate of the standard deviation of the NPV of the proposed technology development program. This estimate assumes a Guassian NPV distribution. (This is an assumption which can be intuitively argued from the law of large numbers.) The ranking methodology is a comparison of key parameters of the NPV cumulative distribution functions (CDFs) for the individual technology development programs. This CDF is generated for each technology being ranked by a Monte Carlo simulation which utilizes either a Beta or a Guassian random number generator for selecting input parameters of the NPV equation and repeatedly evaluates the NPV for the random samples of input parameters.

The Monte Carlo simulation used in the ranking process produces a sample-estimate NPV CDF; the analytic estimation of the CDF's standard deviation (σ) calculated in the assessment methodology assumed a Gaussian CDF. The Monte Carlo simulation requires significantly more computer time than does the analytic (assessment) method. Application of the Chi-squared confidence test to specific examples during this project has indicated that the Monte Carlo simulation results are close to being Gaussian such that the analytic estimation is generally a valid approximation.

Since each stage of the quantitative cost benefit methodology is an evaluation of the NPV of NASA-induced early technology development, each methodology requires estimation of the same parameters (but no varying degrees of specification). The overall methodology not only has commnality between its three parts, but also is intentionally formulated for maximum commonality in its application to widely varying technologies. This commonality is accomplished in the computer programs by use of an NPV model with four generalized phases of the scenario: (1) basic R&D (NASA), (2) applied R&D (industry), (3) prototype development, and (4) operation. Input data for each methodology includes (a) the probability of going into the pase, (b) the time duration (length) of the pase, (c) the annual costs of the phase, and (d) the annual benefits of the phase. In addition, one specifies the discount rate to be used in the analysis and the expected delay time in development of the technology without NASA efforts. The assessment and ranking programs also require specification ranges for these variables.

By allowing the benefits of the technology development program to be entered into the methodology models as an estimate of the annual benefits during the operational phase, one can use the same basic methodology for all technologies even though the form of their benefits may be radically different. Estimation of the annual benefits for technology development is made separately in the analysis of each technology by methods appropriate for the technology.

SECTION 11

DETAILED COST-BENEFIT ANALYSIS OF ION ENGINE TECHNOLOGY

Application of the screening and assessment methodologies and development of the data base for ranking of a technology (ion engine) whose value is largely dependent upon the number of communication satellites launched is demonstrated in this section. A similar demonstration for a technology (direct demodulation) applicable to low-cost earth stations is presented in Section 12. The cost-benefit analysis for the other technologies being evaluated is presented in summary form in Section 13 with many of the associated plots located in the Appendix.

11.1 Benefit Mechanism for Ion Engine Technology

The gravitational forces of the moon and sun, as well as the gradient of the earth's gravitational field, perturb the orbits of geosynchronous communication satellites. Satellite station keeping systems are required to overcome these disturbance forces. Motion of the satellite (as seen from the ground) increases the complexity of the earth station antenna systems and increases the interference between satellite systems. The current technology for these station keeping thrusters is a chemical reaction engine utilizing hydrazine as the propellent and having a low specific impulse (approximately 220). In the near future, these hydrazine thrusters will be replaced by Cesium or Mercury Ion engines with significantly higher specific impulse (approximately 2000).

The specific impulse of an engine is proportional to its thrust and inversely proportional to the rate at which it consumes propellant. Thus the propellant required to provide a specified thrust for a given length of time is inversely proportional to the specific impulse of the thruster. The mass budget which must be allocated for a station keeping system with current hydrazine technology is significantly greater than that which would be expected with the use of ion engines. A recent Hughes Aircraft Company study has concluded that the weight savings introduced by the use of ion engines is approximately 165 pounds for a small spinner communications satellite and approximately 195 pounds for a larger 3-axis stabilized satellite. These weight savings are after allocation has been made for additional power requirements. A typical 40 MHz communication satellite transponder weighs about 25 pounds, requires about 30 watts of electrical power, and has a revenue capability of 1-2 million dollars per year. Consideration of the weight and power requirements of the transponder led Hughes to conclude that the introduction of ion engine technology into communications satellites would allow the addition of one transponder to spinner communications satellites (Delta 2914 class) or 2 transponders to 3-axis stabilized communication satellites (Atlas-Centaur class). The nonrecurring cost of an ion engine system (assuming fully developed engineering models exist) is estimated at 1 to 2 million dollars. The recurring cost of the ion engine system is estimated at 500 thousand dollars. Both estimates are in terms of 1975 dollars.

11.2 Screening of Ion Engine Technology

As a result of discussions of the impact and development costs of ion engines with several industrial and government groups, the parameter values shown in Table 11.1 have been selected. The basic research and development program includes the orbital demonstration over a significant length of time of an ion engine system. It is estimated that such a program would require three years and cost five million dollars. The likelihood of U.S. industry implementing ion engines in commercial communication satellites after such a NASA R&D program is estimated at 95%. The application program is estimated to require an industrial expenditure of 1.5 million dollars over a three-year period for applied research and development and prototype development. It is assumed that ion engine technology would continue to be incorporated in communication satellites for ten years after its introduction without significant modifications to the basic technology. As in all analyses of this report, the discount rate is assumed to be 6 percent. Since ion engine technology is at a reasonably advanced stage (having had partial success on the ATS-F vehicle) it is estimated that the time delay in the availability of ion engines resulting from NASA not pursing ion engine development is only two years.

A calculation of the equivalent annual benefit (EAB) for the NASA sponsored development of ion engine technology is based on the fractional satellite launch schedules of Tables 11.2 and 11.3. Tables 11.2a and 11.2b

TABLE 11.1

INPUT PARAMETERS FOR SCREENING OF ION ENGINE TECHNOLOGY

```
SCREENING FOR :ION ENGINES

 ******  INPUT PARAMETERS ARE AS FOLLOWS  ******

TIME DELAY FACTOR (YRS) ...............      2.00
DISCOUNT RATE .........................       .06

NASA DEVELOPMENT
CONDITIONAL PROBABILITY ...............      1.00
ANNUAL BENEFITS (K$) ..................      0.00
ANNUAL COSTS (K$) .....................   1666.67
LENGTH OF INTERVAL (YRS) ..............      3.00

INDUSTRY R&D
CONDITIONAL PROBABILITY ...............       .95
ANNUAL BENEFITS (K$) ..................      0.00
ANNUAL COSTS (K$) .....................    750.00
LENGTH OF INTERVAL (YRS) ..............      1.00

INDUSTRY CONSTRUCTION TIME
CONDITIONAL PROBABILITY ...............      1.00
ANNUAL BENEFITS (K$) ..................      0.00
ANNUAL COSTS (K$) .....................    375.00
LENGTH OF INTERVAL (YRS) ..............      2.00

OPERATION TIME
CONDITIONAL PROBABILITY ...............      1.00
ANNUAL BENEFITS (K$) ..................   6700.00
ANNUAL COSTS (K$) .....................       .00
LENGTH OF INTERVAL (YRS) ..............     10.00


THE NET VALUE (K$) INCLUDING LAG TIME EQUALS --

                 3133.6
```

LAUNCH SCENARIO FOR THE ION ENGINE TECHNOLOGY INTRODUCTION INTO THE U. S. DOMSAT MARKET

TABLE 11.2a

**** US DOMSAT--1981 INTRODUCTION OF ION ENGINE TECHNOLOGY ****

YEAR	SATELLITE LIFE (YEARS)	COST PER SATELLITE (M$)	SATELLITE CAPACITY (K CKT/2)	NO. OF LAUNCHES	DISCOUNTED US-US COST (M$)	DISCOUNTED US-FOR COST (M$)
1975	7	35.0	14.0	1.00	35.00	0.00
1976	7	37.6	15.4	.31	11.64	0.00
1977	7	40.4	16.9	.34	12.20	0.00
1978	7	43.5	18.6	.37	13.47	0.00
1979	7	46.7	20.5	.40	14.88	0.00
1980	7	50.2	22.5	.44	16.43	0.00
1981	7	56.0	26.8	.82	31.46	0.00
1982	7	60.1	29.3	.97	36.91	0.00
1983	7	64.4	32.0	.69	26.03	0.00
1984	7	69.1	35.0	.75	28.34	0.00
1985	8	74.1	38.3	.83	30.84	0.00
1986	8	79.5	41.9	.91	33.54	0.00
1987	8	85.4	45.9	.99	36.45	0.00
1988	8	91.6	50.3	1.29	46.82	0.00
1989	8	98.3	55.2	1.44	52.13	0.00
1990	8	105.6	60.5	1.38	49.45	0.00
1991	8	113.3	66.3	1.51	53.61	0.00
1992	8	121.7	72.8	1.22	42.81	0.00
1993	8	130.7	79.8	1.73	60.15	0.00
1994	8	140.3	87.6	1.99	65.10	0.00
1995	8	150.7	96.2	2.07	70.41	0.00
1996	8	161.8	105.6	2.36	79.29	0.00
1997	8	173.8	116.0	2.59	86.23	0.00
1998	8	186.7	127.4	2.74	90.00	0.00
1999	8	200.6	139.9	2.99	99.46	0.00
2000	8	215.4	153.7	3.06	102.98	0.00
2001	8	231.5	168.9	3.53	120.18	0.00
2002	8	248.7	185.5	3.86	132.80	0.00
2003	8	267.2	203.9	4.21	146.73	0.00
2004	8	287.0	224.1	4.64	163.68	0.00
2005	8	308.4	246.3	5.08	191.13	0.00

PROJECTED COST OF SATELLITES (INCLUDING LAUNCH) BETWEEN 1981 AND 1982 FOR U. S. MANUFACTURE AND U. S. USE - $68.38 MILLION

TABLE 11.2b

**** US DOMSAT--1983 INTRODUCTION OF ION ENGINE TECHNOLOGY ****

YEAR	SATELLITE LIFE (YEARS)	COST PER SATELLITE (M$)	SATELLITE CAPACITY (K CKT/2)	NO. OF LAUNCHES	DISCOUNTED US-US COST (M$)	DISCOUNTED US-FOR COST (M$)
1975	7	35.0	14.0	1.00	35.00	0.00
1976	7	37.6	15.4	.31	11.64	0.00
1977	7	40.4	16.9	.34	12.20	0.00
1978	7	43.5	18.6	.37	13.47	0.00
1979	7	46.7	20.5	.40	14.88	0.00
1980	7	50.2	22.5	.44	16.43	0.00
1981	7	54.0	24.8	.88	32.79	0.00
1982	7	58.1	27.3	1.04	38.30	0.00
1983	7	64.4	32.0	.69	26.03	0.00
1984	7	69.1	35.0	.75	28.34	0.00
1985	8	74.1	38.3	.83	30.84	0.00
1986	8	79.5	41.9	.91	33.54	0.00
1987	8	85.4	45.9	.99	36.45	0.00
1988	8	91.6	50.3	1.29	46.82	0.00
1989	8	98.3	55.2	1.44	52.13	0.00
1990	8	105.6	60.5	1.38	49.45	0.00
1991	8	113.3	66.3	1.51	53.61	0.00
1992	8	121.7	72.8	1.22	42.81	0.00
1993	8	130.7	79.8	1.73	60.15	0.00
1994	8	140.3	87.6	1.99	65.10	0.00
1995	8	150.7	96.2	2.07	70.41	0.00
1996	8	161.8	105.6	2.36	79.29	0.00
1997	8	173.8	116.0	2.59	86.23	0.00
1998	8	186.7	127.4	2.74	90.00	0.00
1999	8	200.6	139.9	2.99	99.46	0.00
2000	8	215.4	153.7	3.06	102.98	0.00
2001	8	231.5	168.9	3.53	120.18	0.00
2002	8	248.7	185.5	3.86	132.80	0.00
2003	8	267.2	203.9	4.21	146.73	0.00
2004	8	287.0	224.1	4.64	163.68	0.00
2005	8	308.4	246.3	5.08	191.13	0.00

PROJECTED COST OF SATELLITES (INCLUDING LAUNCH) BETWEEN 1981 AND 1982 FOR U. S. MANUFACTURE AND U. S. USE - $71.09 MILLION

LAUNCH SCENARIO FOR ION ENGINE TECHNOLOGY INTRODUCTION INTO THE INTELSAT ATLANTIC AND PACIFIC MARKET

TABLE 11.3a

**** INTELSAT ATLANTIC AND PACIFIC--1981 INTRODUCTION OF ION ENGINE TECHNOLOGY ****

YEAR	SATELLITE LIFE (YEARS)	COST PER SATELLITE (M$)	SATELLITE CAPACITY (K CKT/2)	NO. OF LAUNCHES	DISCOUNTED US-US COST (M$)	DISCOUNTED US-FOR COST (M$)
1975	7	35.0	10.0	1.00	17.50	17.50
1976	7	37.7	11.1	0.00	0.00	0.00
1977	7	40.5	12.3	.30	5.35	5.35
1978	7	43.6	13.7	.31	4.82	4.82
1979	7	46.9	15.2	.86	13.14	13.14
1980	7	50.5	16.9	.83	12.52	12.52
1981	7	56.3	20.7	.34	5.24	5.24
1982	7	60.4	22.8	.90	12.26	12.26
1983	7	64.8	25.0	.39	5.86	5.86
1984	7	69.6	27.6	.55	8.15	8.15
1985	8	74.7	30.4	.59	8.54	8.54
1986	8	80.3	33.5	.87	12.40	12.40
1987	8	86.2	37.0	.89	12.48	12.48
1988	8	92.6	40.8	.72	9.90	9.90
1989	8	99.5	45.1	.99	13.37	13.37
1990	8	106.9	49.8	.82	10.85	10.85
1991	8	114.8	55.1	.94	12.19	12.19
1992	8	123.4	61.0	.71	9.00	9.00
1993	8	132.6	67.4	1.02	12.64	12.64
1994	8	142.5	74.6	1.20	14.44	14.44
1995	8	153.2	82.6	1.26	14.79	14.79
1996	8	164.7	91.5	1.24	14.15	14.15
1997	8	177.0	101.3	1.42	15.73	15.73
1998	8	190.3	112.3	1.40	15.11	15.11
1999	8	204.6	124.4	1.52	16.62	16.62
2000	8	220.0	137.9	1.49	16.43	16.49
2001	8	236.5	152.8	1.71	19.07	19.07
2002	8	254.3	169.4	1.86	21.09	21.09
2003	8	273.4	187.8	1.97	22.65	22.65
2004	8	294.0	208.2	2.06	23.88	23.98
2005	8	316.2	230.9	2.23	26.24	26.24

PROJECTED COST OF SATELLITES (INCLUDING LAUNCH) BETWEEN 1981 AND 1982 FOR U. S. MANUFACTURE AND U. S. USE - $17.50 MILLION

TABLE 11.3b

**** INTELSAT ATLANTIC AND PACIFIC--1983 INTRODUCTION OF ION ENGINE TECHNOLOGY ****

YEAR	SATELLITE LIFE (YEARS)	COST PER SATELLITE (M$)	SATELLITE CAPACITY (K CKT/2)	NO. OF LAUNCHES	DISCOUNTED US-US COST (M$)	DISCOUNTED US-FOR COST (M$)
1975	7	35.0	10.0	1.00	17.50	17.50
1976	7	37.7	11.1	0.00	0.00	0.00
1977	7	40.5	12.3	.30	5.35	5.35
1978	7	43.6	13.7	.31	4.82	4.82
1979	7	46.9	15.2	.86	13.14	13.14
1980	7	50.5	16.9	.83	12.52	12.52
1981	7	54.3	18.7	.37	5.60	5.60
1982	7	58.4	20.8	.88	13.00	13.00
1983	7	64.8	25.0	.39	5.86	5.86
1984	7	69.6	27.6	.55	8.15	8.15
1985	8	74.7	30.4	.59	8.54	8.54
1986	8	80.3	33.5	.87	12.40	12.40
1987	8	86.2	37.0	.89	12.48	12.48
1988	8	92.6	40.8	.72	9.90	9.90
1989	8	99.5	45.1	.99	13.37	13.37
1990	8	106.9	49.8	.82	10.85	10.85
1991	8	114.8	55.1	.94	12.19	12.19
1992	8	123.4	61.0	.71	9.00	9.00
1993	8	132.6	67.4	1.02	12.64	12.64
1994	8	142.5	74.6	1.20	14.44	14.44
1995	8	153.2	82.6	1.26	14.79	14.79
1996	8	164.7	91.5	1.24	14.15	14.15
1997	8	177.0	101.3	1.42	15.73	15.73
1998	8	190.3	112.3	1.40	15.11	15.11
1999	8	204.6	124.4	1.52	16.62	16.62
2000	8	220.0	137.9	1.49	16.48	16.48
2001	8	236.5	152.8	1.71	19.07	19.07
2002	8	254.3	169.4	1.86	21.09	21.09
2003	8	273.4	187.8	1.97	22.65	22.65
2004	8	294.0	208.2	2.06	23.89	23.98
2005	8	316.2	230.9	2.23	26.24	26.24

PROJECTED COST OF SATELLITES (INCLUDING LAUNCH) BETWEEN 1981 AND 1982 FOR U. S. MANUFACTURE AND U. S. USE - $18.59 MILLION

correspond to the U. S. DOMSAT market for introduction in 1981 and 1983, respectively, of the ion engines. Both scenarios correspond to the demand, satellite cost, and satellite capacities of Figures 10.1 through 10.3 except that the satellite capacity is considered to increase by 2000 half circuits and the satellite cost by two million dollars at the time of the introduction of the ion engines. The increase in capacity and cost correspond approximately to the addition of two transponders to the satellite. The sixth column of each table, discounted U.S.-U.S. cost, contains the annual expenditures for satellite purchase and launch, and are the same for Tables 11.2a and 11.2b except for the years 1981 and 1982. The difference in the values between the two tables represent the value of early introduction of ion engine technology into the U.S. DOMSAT market. Tables 11.3a and 11.3b present corresponding data for ion engine applications to the Atlantic and Pacific regions of the Intelsat system. The decrease in satellite construction and launch costs associated with ion engine technology appearing early (1981 rather than 1983) is 2.71 million dollars for the DOMSAT application and 1.09 million dollars for the Intelsat Atlantic-Pacific applications, for a total gross benefit of 3.8 million dollars, discounted to 1975. Application of the equation for equivalent annual benefits (EAB) given in the preceding section yields an EAB (gross) of 6.7 million dollars per year for the assumed 10-year operating interval.

Application of the screening methodology to ion engine technology results in a resultant score or net present value of 3.2 million dollars. Figures 11.1-11.11 are sensitivity plots which show the effect upon this screening score of variations in the assumed input parameters. All sensitivity plots vary the input parameter from 50% to 150% of its nominal value. With the exception of sensitivity with respect to discount rate, all resulting sensitivities are essentially linear. The sensitivity plot for a net present value as a function of discount rate is seen to reach a maximum NPV for a discount rate of about 7.5%. This nonlinear form of NPV as a function of discount rate, with a maximum occurring within a reasonable discount rate range, has occurred on several of the technologies being screened. Table 11.4 presents the slopes of the sensitivity plots for ion engine technology.

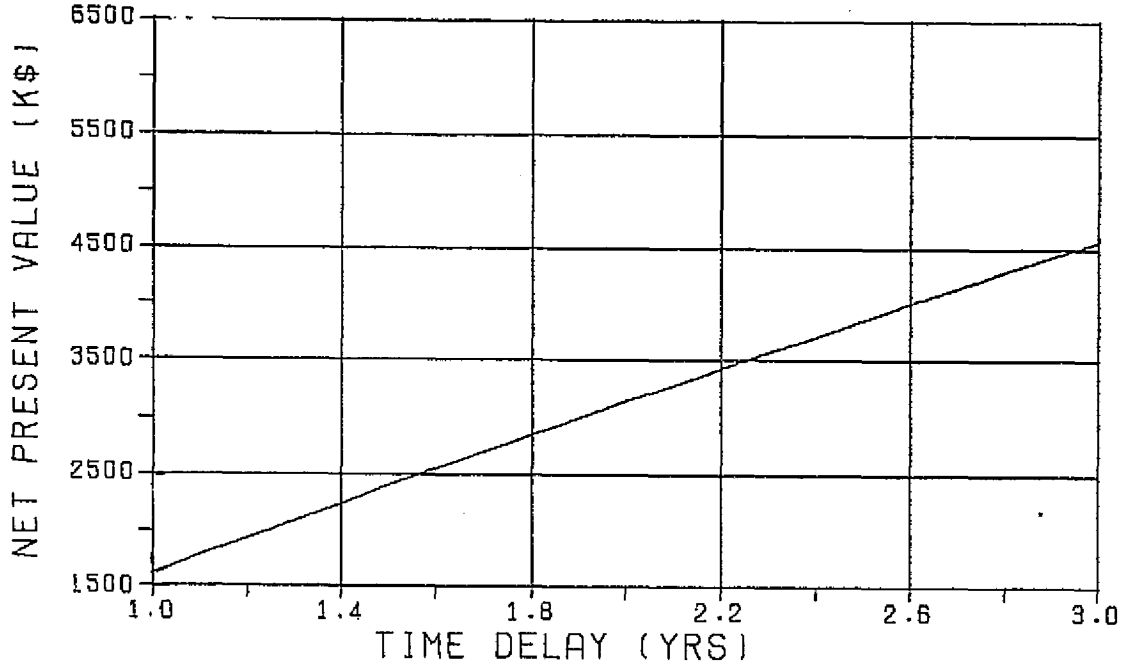


Figure 11.1 Sensitivity of Ion Engine NPV with respect to Time Delay in Absence of NASA Support.

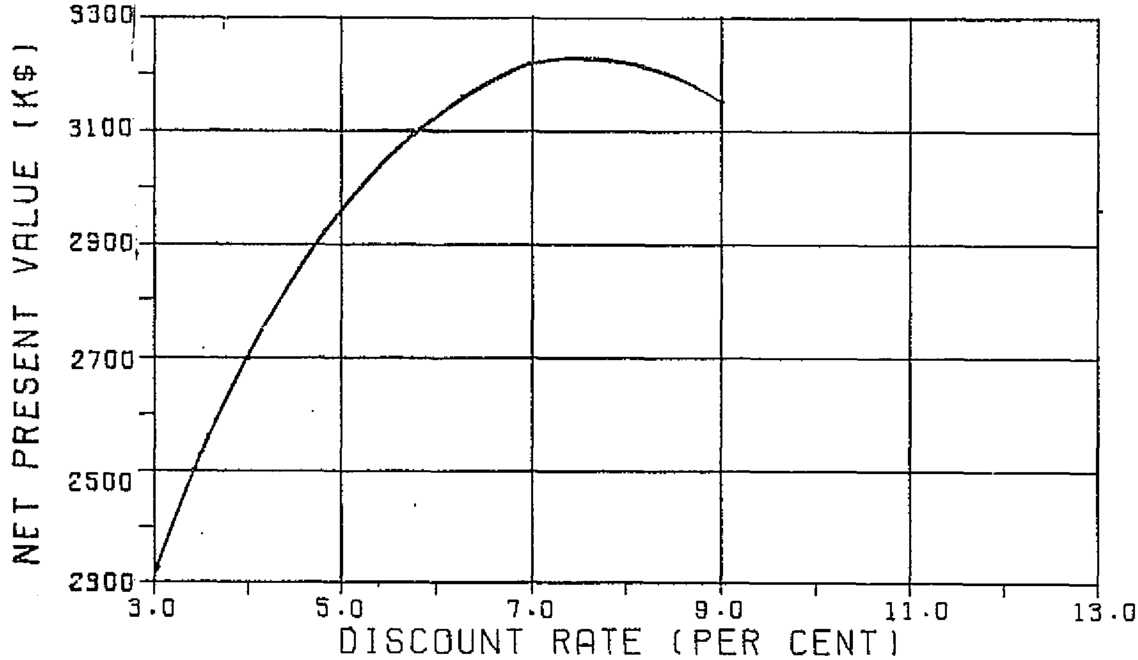


Figure 11.2. Sensitivity of Ion Engine NPV with Respect to Discount Rate.

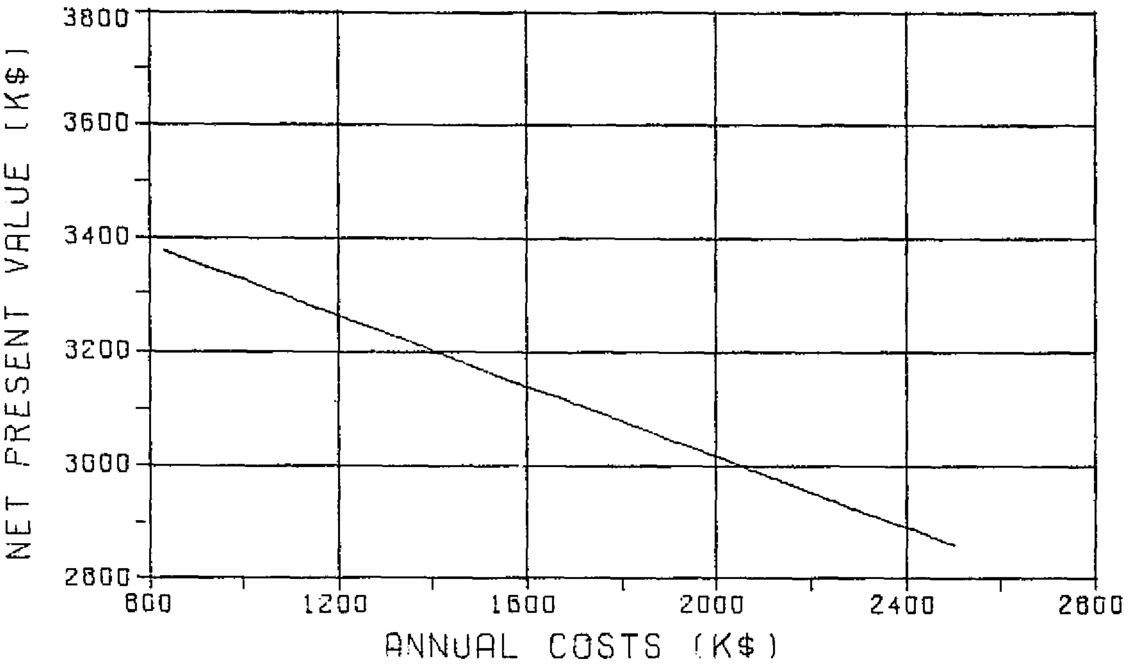


Figure 11.3. Sensitivity of Ion Engine NPV with Respect to Annual Costs for Basic R&D.

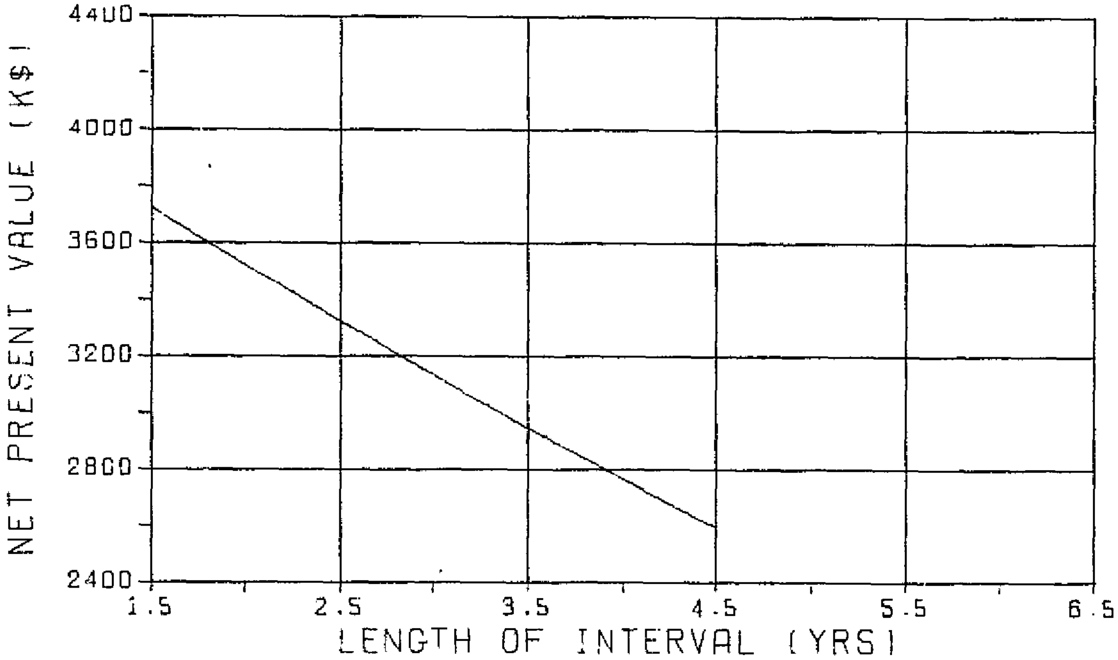


Figure 11.4. Sensitivity of Ion Engine NPV with Respect to Length of Basic R&D Interval.

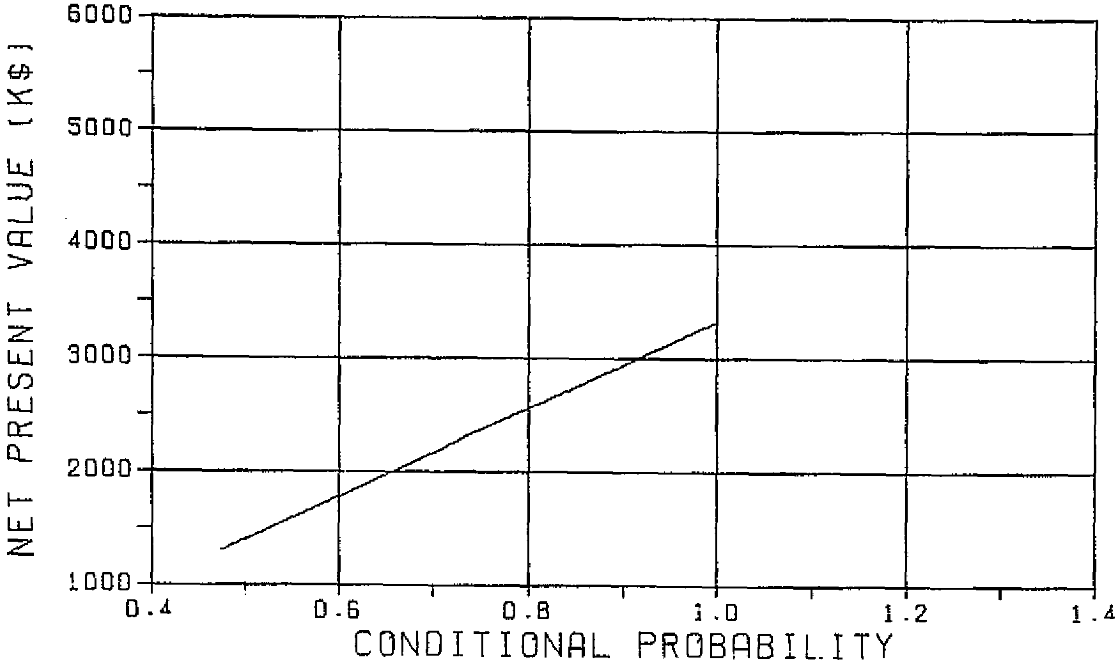


Figure 11.5. Sensitivity of Ion Engine NPV with Respect to Probability that Industry will Implement the Technology.

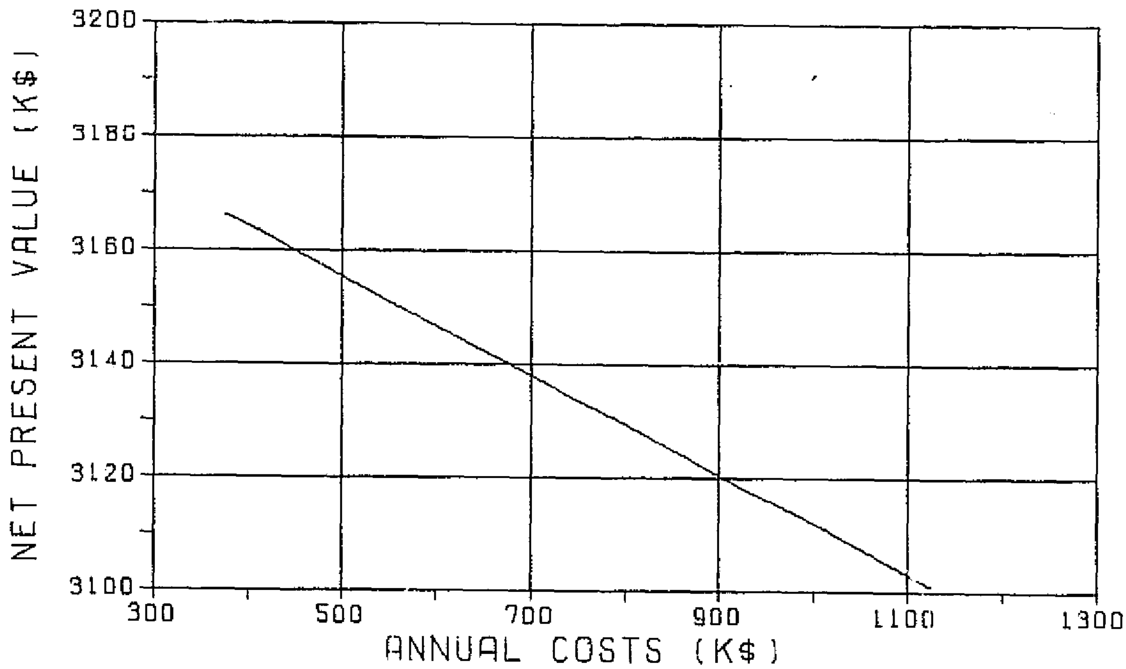


Figure 11.6. Sensitivity of Ion Engine NPV with Respect to Annual Costs During Applied R&D Interval.

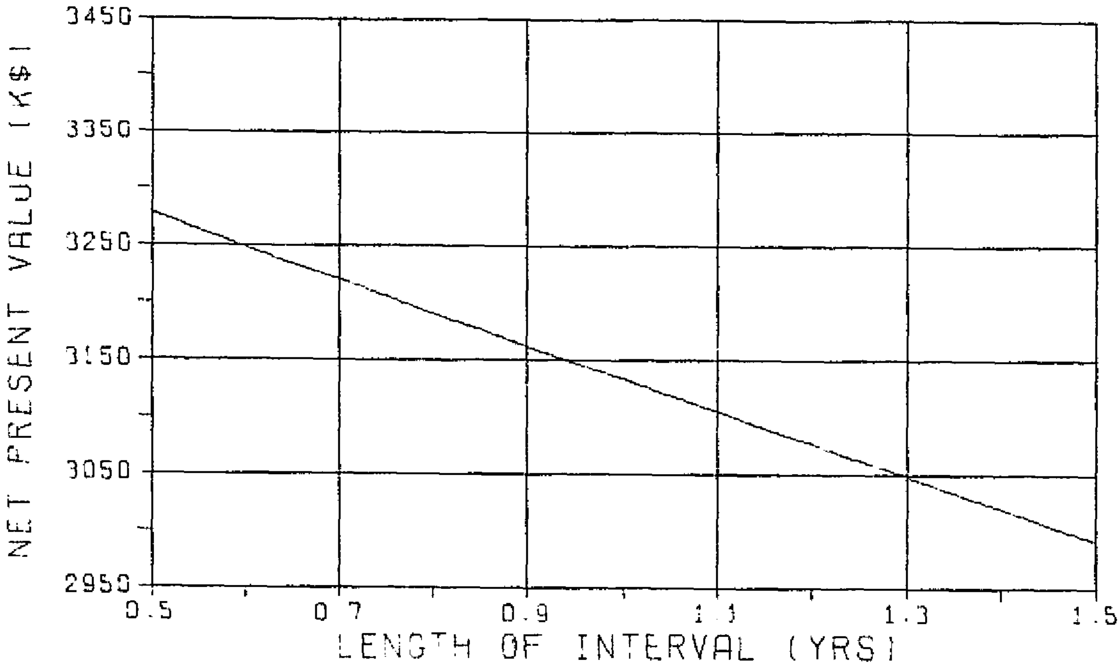


Figure 11.7. Sensitivity of Ion Engine NPV with Respect to Length of Applied R&D Interval.

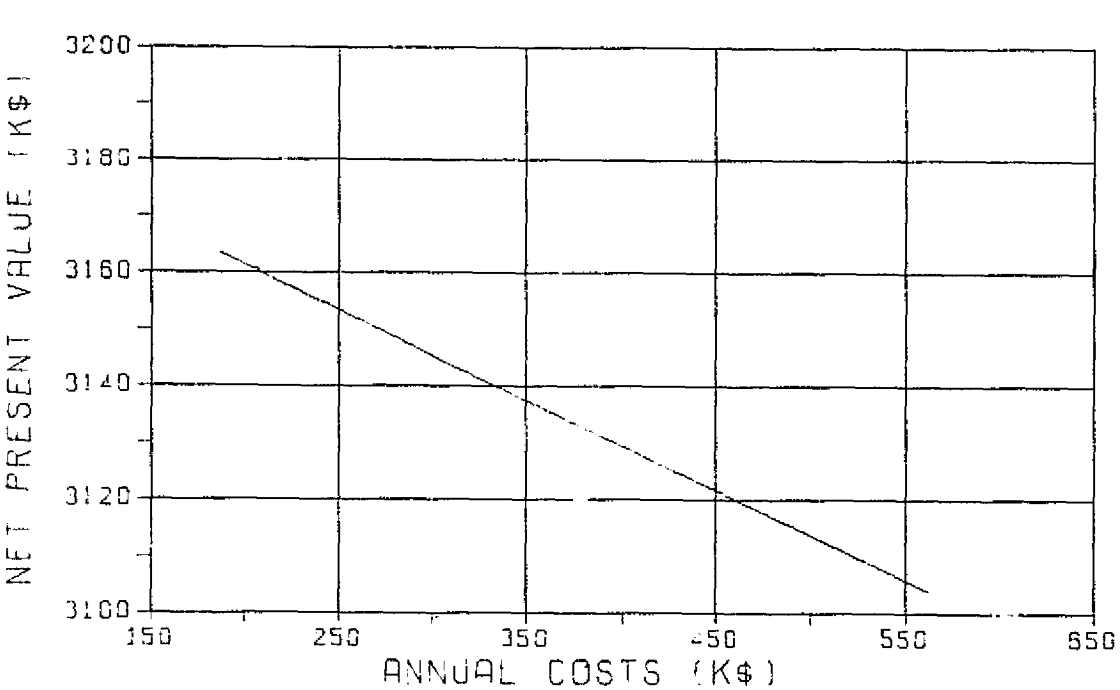


Figure 11.8. Sensitivity of Ion Engine NPV with Respect to Annual Costs in Industry Construction Interval.

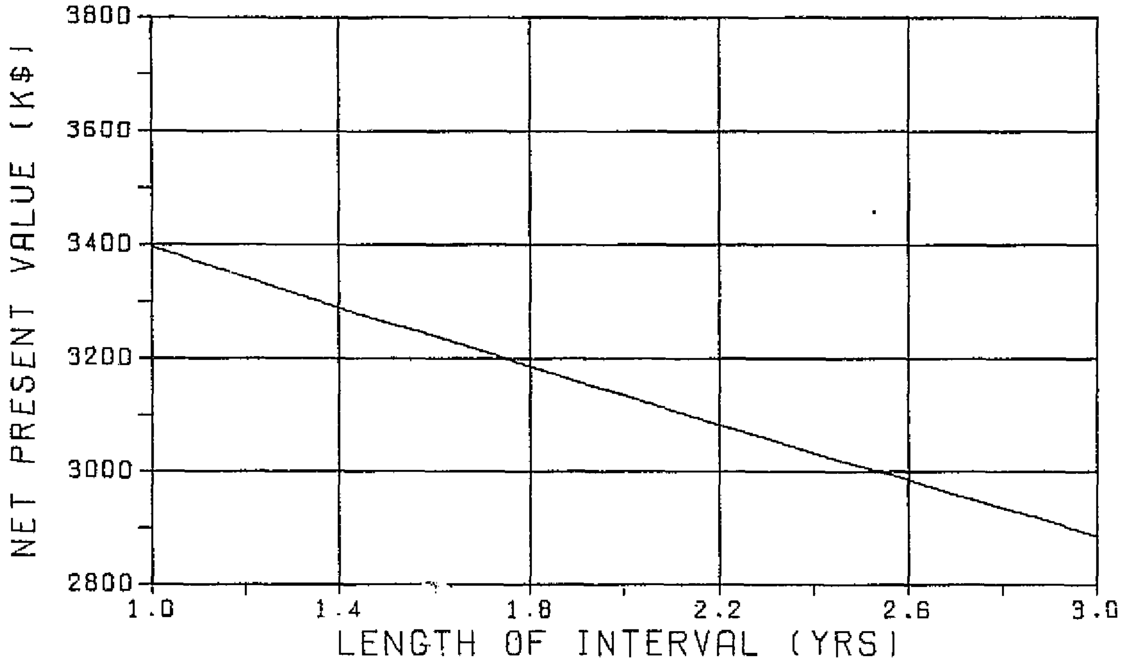


Figure 11.9. Sensitivity of Ion Engine NPV with Respect to Length of Industry Construction Interval.

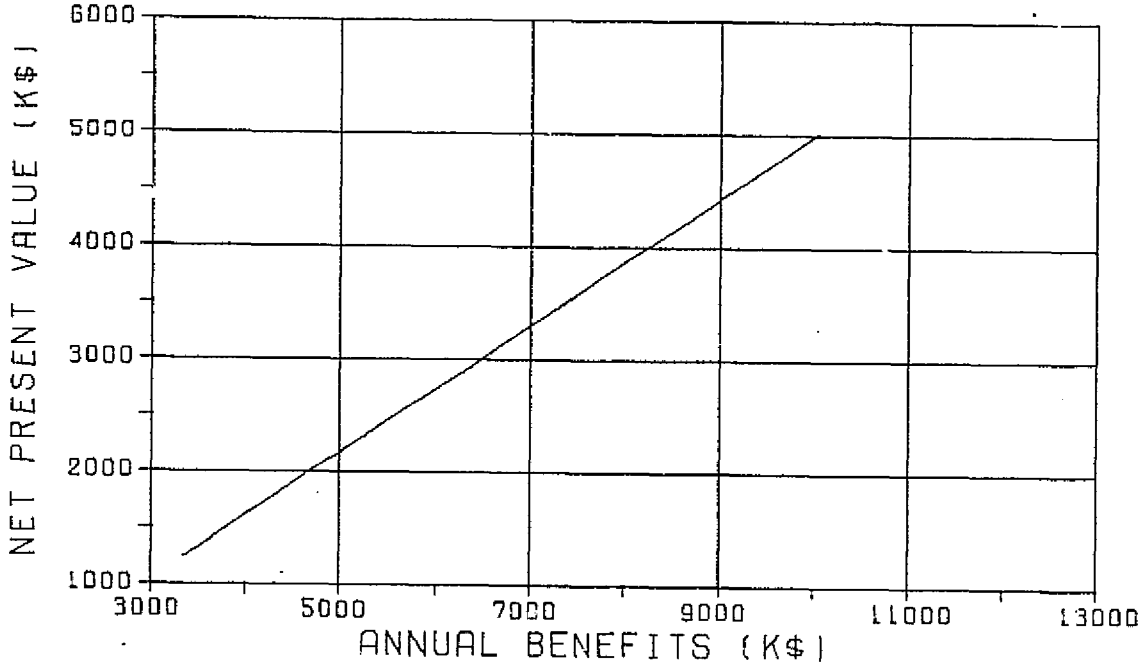


Figure 11.10. Sensitivity of Ion Engine NPV with Respect to Annual Benefits.

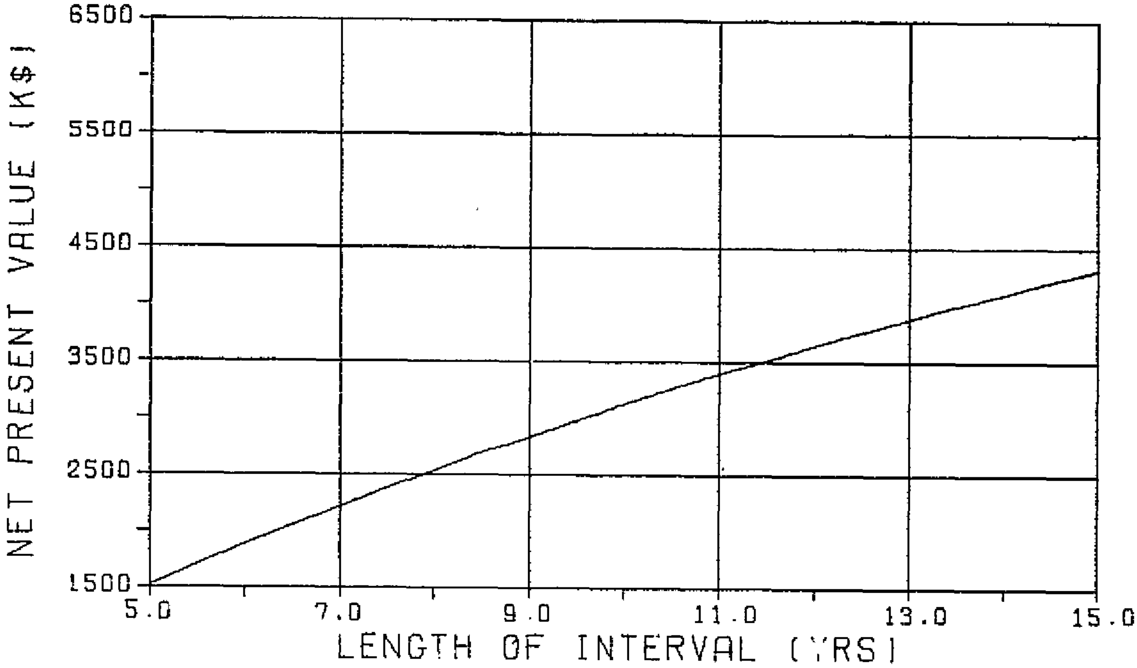


Figure 11.11. Sensitivity of Ion Engine NPV with Respect to Length of Operating Interval.

TABLE 11.4

SLOPES OF ION ENGINES NPV SENSITIVITY PLOTS

Variable	Slope
Time Delay	500 k$/year
Annual Costs for Basic R&D	-.30 k$/year
Length of Basic R&D Interval	373.33 k$/year
Probability that Industry will Implement the Technology	3773.58 k$
Annual Costs During Applied R&D Interval	-0.08 k$/k$
Length of Applied R&D Interval	-275 k$/year
Annual Costs in Industry Construction Interval	-.15 k$/k$
Length of Industry Construction Interval	-250 k$/year
Annual Benefits	.56 k$/k$
Length of Operating Interval	290 k$/year

11.3 Assessment of Ion Engine Technology

Application of the assessment methodology requires specification of lower and upper bounds and the modal value for each of the input parameters of screening. Alternately, the mean and standard deviation may be specified for each parameter. In either case, the analytic approximation used in assessment assumes a Gaussian distribution for the parameters. (The Monte Carlo simulation method utilized in obtaining data for the ranking methodology does not make the simplified assumption but rather uses the Beta distribution.) Table 11.5 contains the input data used for assessment of ion engine technology.

The assessment (risk analysis) for ion engines indicates that the assumed Gaussian distribution of the net present value of the technology development has a mean value of 3.2 million dollars and a standard deviation of 779 thousand dollars. Figure 11.12 contains both the probability density function and the cumulative distribution function for a normalized Gaussian distribution. Note that the abscissa variable in each plot is NPV (as in the Monte Carlo simulation CDF plots used in the ranking methodology), but normalized by subtraction of the mean and division by the standard deviation of the distribution. These two constants, μ and σ are the values of the mean and standard deviations printed at the end of the assessment (risk analysis) program.

11.4 Data for Ranking of Ion Engine Technology

The relative ranking of the technology development programs will be based upon parameters taken from the NPV cumulative distribution functions (CDF) for the technologies. These CDFs are established by a Monte Carlo simulation using Beta distribution random number generators for the input parameters of the NPV equation. For ion engine technology, the input parameter ranges are the same as those presented in Table 11.5 for assessment. Table 11.6 shows the Monte Carlo CDF for ion engine technology after 600 random samples of input parameter values were processed. The table represents sufficient information for the construction of a histogram of the net present value and presents the sample mean and sample standard deviation values after 100 samples were processed; after 200 samples were processed; ...; and after 600 samples were processed. The sample mean after 600 samples is 3.2 million

TABLE 11.5

QUICK RISK ANALYSIS FOR : ION ENGINES

****** INPUT PARAMETERS ARE AS FOLLOWS ******

DISCOUNT RATE .... .06

VARIABLE	INPUT BETA PARAMETERS MIN	MODAL	MAX	COMPUTED MEAN
TIME DELAY (YRS)	1.25	2.00	2.75	2.00
NASA DEVELOPMENT				
CONDITIONAL PROBABILITY	1.00	1.00	1.00	1.00
ANNUAL BENEFITS (K$)	0.00	0.00	0.00	0.00
ANNUAL COSTS (K$)	666.67	1666.67	2666.67	1666.67
INTERVAL LENGTH (YRS)	3.00	3.00	3.00	3.00
INDUSTRY DEVELOPMENT				
CONDITIONAL PROBABILITY	.90	.95	1.00	.95
ANNUAL BENEFITS (K$)	0.00	0.00	0.00	0.00
ANNUAL COSTS (K$)	383.00	500.00	617.00	500.00
INTERVAL LENGTH (YRS)	3.00	3.00	3.00	3.00
OPERATION TIME				
CONDITIONAL PROBABILITY	1.00	1.00	1.00	1.00
ANNUAL BENEFITS (K$)	3416.00	6833.00	10250.00	6833.00
ANNUAL COSTS (K$)	.00	.00	.00	.00
INTERVAL LENGTH (YRS)	8.00	10.00	12.00	10.00

THE EXPECTED NET VALUE (K$) EQUALS --

3210.4

STANDARD DEVIATION EQUALS --

779.2

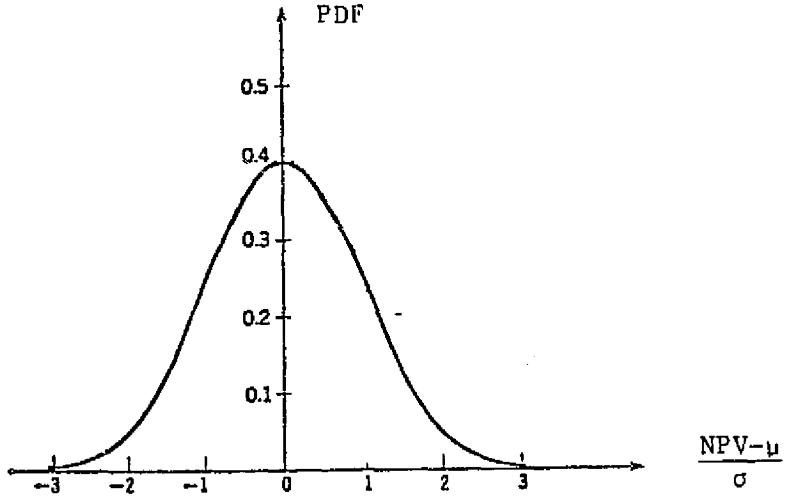


FIGURE 11.12a

Gaussian Probability Density Function,
Normalized for Mean μ and Standard Deviation σ.

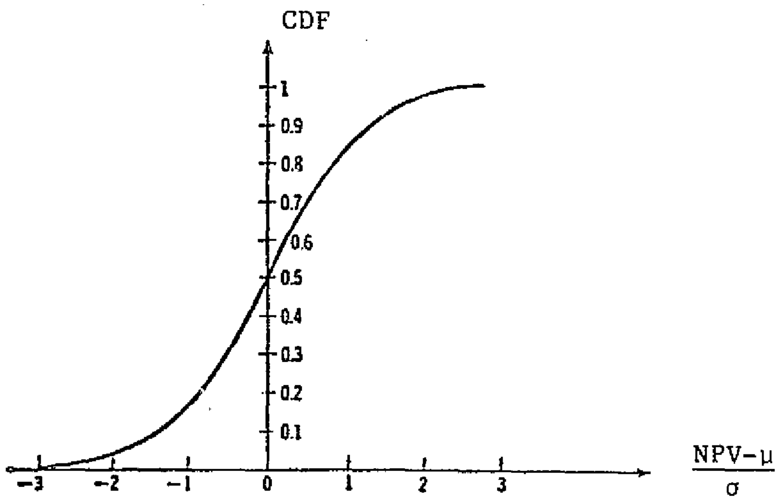


FIGURE 11.12b

Gaussian Cumulative Distribution Function, Normalized
for Mean μ and Standard Deviation σ.

TABLE 11.6. SAMPLE-ESTIMATE CDF FOR ION ENGINE TECHNOLOGY

INTERVAL	ENDPOINTS		OCCURRENCE	FREQUENCY (%)
1	600.0	900.0	0	0
2	900.0	1200.0	1	0
3	1200.0	1500.0	0	0
4	1500.0	1800.0	8	1
5	1800.0	2100.0	39	7
6	2100.0	2400.0	49	8
7	2400.0	2700.0	75	13
8	2700.0	3000.0	85	14
9	3000.0	3300.0	80	13
10	3300.0	3600.0	73	12
11	3600.0	3900.0	77	13
12	3900.0	4200.0	57	10
13	4200.0	4500.0	23	4
14	4500.0	4800.0	18	3
15	4800.0	5100.0	7	1
16	5100.0	5400.0	4	1
17	5400.0	5700.0	2	0
18	5700.0	6000.0	1	0
19	6000.0	6300.0	1	0
20	6300.0	6600.0	0	0

Total Occurrences between NPVMIN and NPVMAX = 600
Total Occurrences below NPVMIN = 0
Total Occurrences above NPVMAX = 0

NO. OF SAMPLES	MEAN	STANDARD DEVIATION
100	3211	761
200	3166	778
300	3190	795
400	3178	777
500	3202	771
600	3202	775

dollars and the sample standard deviation is 776 thousand dollars; these values are in close agreement with those produced in the analytic analysis of assessment. Figure 11.13 contains the histogram of the Monte Carlo simulation results. The height of each bar is proportional to the number of sample NPVs occurring within an interval of width 600 thousand dollars. The interval number is labeled at the bottom of the plot, and a scale indicating the actual NPV is at the top of the plot. The histogram indicates that the distribution is essentially unimodal and near-Gaussian in shape. Figure 11.14 displays the data of the histogram in a different form; here the data points have been normalized by dividing by the total number of occurrences and by the width of the NPV interval so that the resulting curve represents the probability density function (with unity enclosed area). Figure 11.15 shows a plot of the cumulative distribution function, the integral of the probability density function. It is this cumulative distribution function which supplies the parameters to be used in ranking this technology against other technologies in Section 14. For the ion engine technology, it is seen that essentially all of the sample NPVs lie between about 1.2 and 6.0 million dollars.

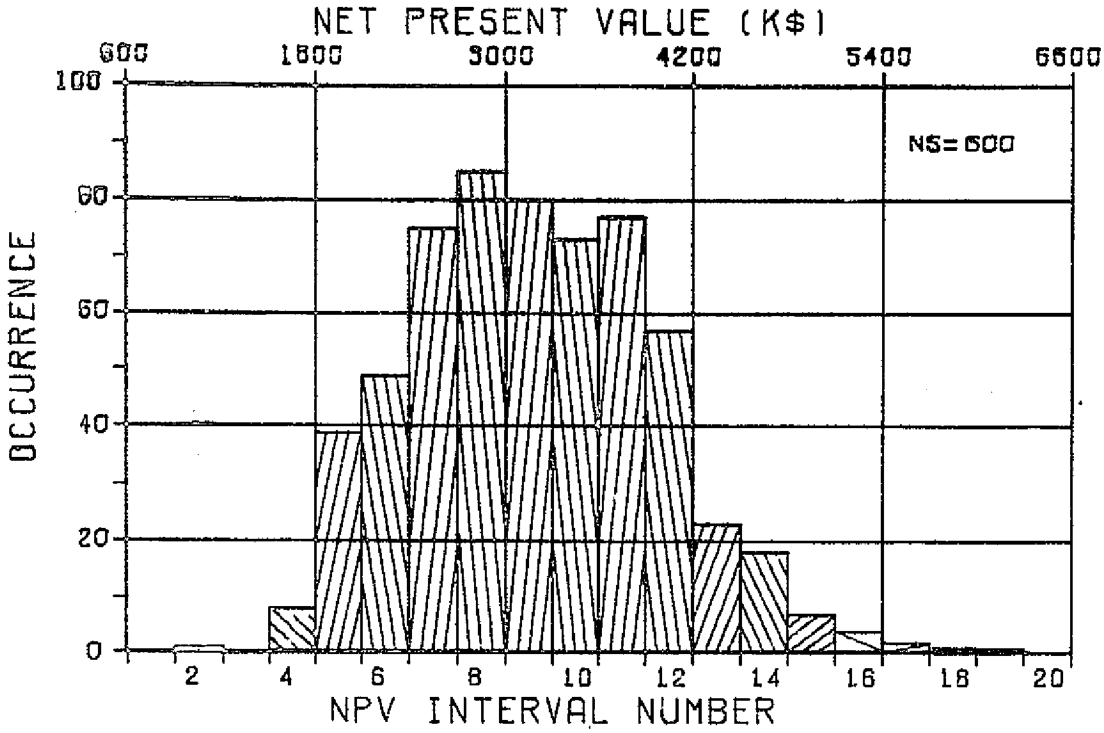


Figure 11.13. Ion Engine NPV Histogram.

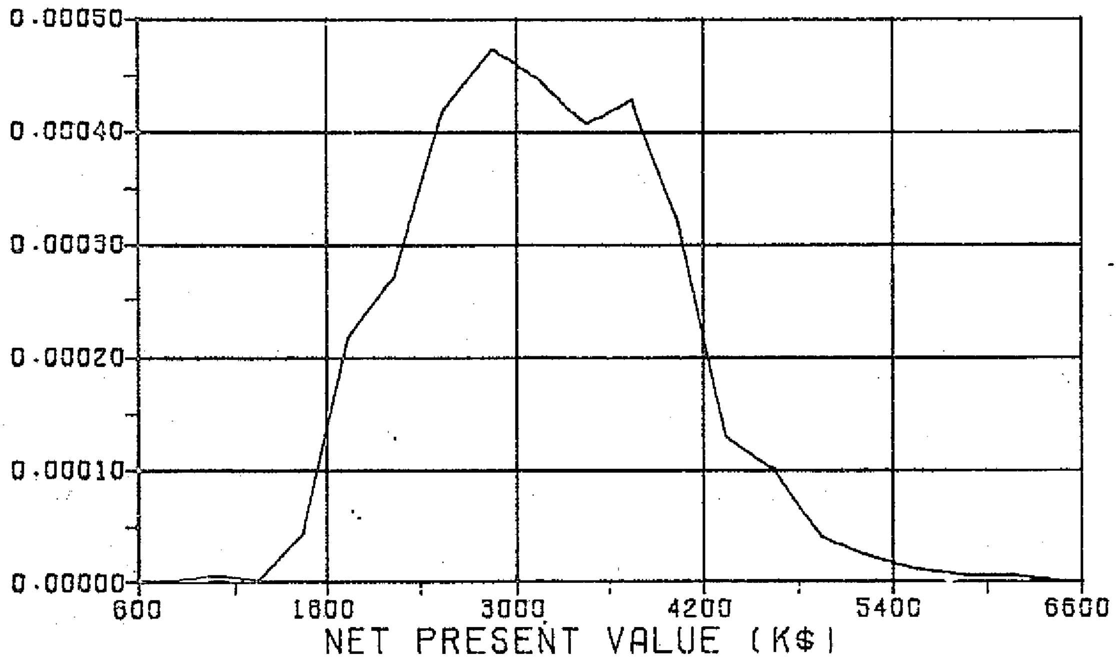


Figure 11.14. Ion Engine NPV Probability Density Function.

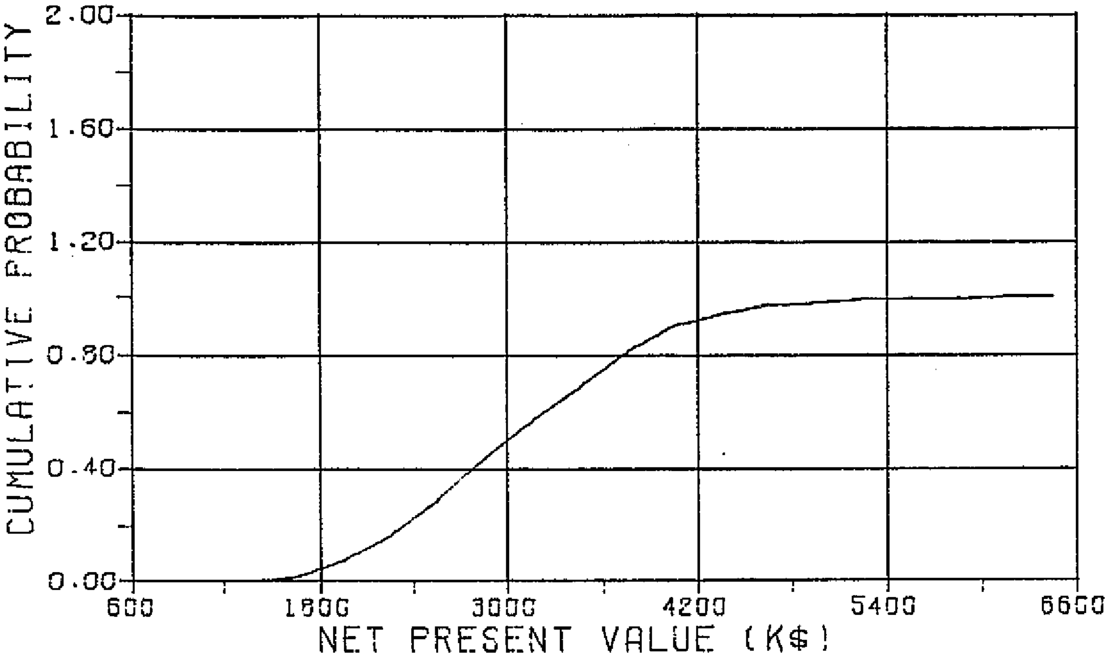


Figure 11.15. Ion Engine NPV Cumulative Distribution Function.

SECTION 12

COST-BENEFIT ANALYSIS OF A LOW COST EARTH STATION TECHNOLOGY

Current technology ground station receivers utilize a low noise amplifier, a mixer with local oscillator to translate the received RF signal to an intermediate frequency, and a demodulation device for recovering the baseband signal. Significant decreases in the cost of the ground station equipment can be realized if a direct demodulation technology not requiring the local oscillator and the mixer can be developed. The potential exists for the development of direct demodulation receivers utilizing uncooled degenerate parametric amplifiers with phase-lock loops. Such a system has been developed at Hughes for limited deviation video signals, and it has been forecast that further development of this technology will result in a $1,000 reduction in the cost of a small earth station (approximately 10 ft. antenna).

12.1 Screening of Direct Demodulation Technology

The parameter values shown in Table 12.1 have been selected to represent the direct demodulation technology program. The basic research and development program is estimated to require one year and cost 150 thousand dollars. The likelihood of U.S. industry implementing this technology after such a NASA R & D program is estimated at 95%. The application program is estimated to require an industrial expenditure of 125 thousand dollars over a one-year period for applied research and development and prototype development. It is assumed that the technology would continue to be incorporated in low cost earth stations for 20 years after its introduction without significant modifications to the basic technology. It is estimated that the time delay in the availability of direct demodulation resulting from NASA not pursing its development is five years.

Calculation of the equivalent annual benefit (EAB) for the NASA sponsored development of direct demodulation technology is based on a cost reduction (savings) of one thousand dollars per earth station. It is further assumed that the sale of such earth stations will increase linearly with time from 500 units/year in 1979 to 10,000 units/year in 1998, for a total sales of 105 thousand units in the twenty-year period. Table 12.2 contains a tabulation

TABLE 12.1

SCREENING PARAMETERS FOR DIRECT DEMODULATION TECHNOLOGY

SCREENING FOR :DEGENERATE PARAMP

****** INPUT PARAMETERS ARE AS FOLLOWS ******

(COSTS AND BENEFITS IN THOUSANDS OF DOLLARS)

TIME DELAY (YRS)	5.00
DISCOUNT RATE	.06
NASA R&D	
CONDITIONAL PROBABILITY	1.00
ANNUAL BENEFITS	0.00
ANNUAL COSTS	150.00
LENGTH OF INTERVAL (YRS)	1.00
INDUSTRY R&D	
CONDITIONAL PROBABILITY	.95
ANNUAL BENEFITS	0.00
ANNUAL COSTS	100.00
LENGTH OF INTERVAL (YRS)	.50
INDUSTRY CONSTRUCTION	
CONDITIONAL PROBABILITY	1.00
ANNUAL BENEFITS	0.00
ANNUAL COSTS	150.00
LENGTH OF INTERVAL (YRS)	.50
OPERATION TIME	
CONDITIONAL PROBABILITY	1.00
ANNUAL BENEFITS	4300.00
ANNUAL COSTS	.00
LENGTH OF INTERVAL (YRS)	20.00

THE NET VALUE (K$) INCLUDING LAG TIME EQUALS --

10870.9

Table 12.2. Benefits of Direct Demodulation Technology

YEAR (K$)	SAVINGS (K$)	DISCOUNTED SAVINGS (K$)
1979	500	472
1980	1000	890
1981	1500	1259
1982	2000	1584
1983	2500	1868
1984	3000	2115
1985	3500	2328
1986	4000	2510
1987	4500	2664
1988	5000	2792
1989	5500	2897
1990	6000	2982
1991	6500	3047
1992	7000	3096
1993	7500	3129
1994	8000	3149
1995	8500	3157
1996	9000	3153
1997	9500	3140
1998	10,000	3118
		$49,350K ('78)

of the yearly savings and the discounted benefits. The gross benefit sums to \$49.35 M (discounted to 1975) and results in an equivalent annual benefit (EAB) of \$4.3 M for the 20-year period. For the input parameter values of Table 12.1, application of the screening methodology to the low cost earth station technology results in a score, or net present value, of \$10.9 M dollars. Figures 12.1-12.11 are sensitivity plots which show the effect upon this screening score, NPV, resulting from variations in the assumed values of the input parameters. All sensitivity plots vary the input parameter from 50% to 150% of its nominal value. With the exception of sensitivity with respect to discount rate, all resulting sensitivities are essentially linear, and a tabulation of their slopes is given in Table 12.3.

12.2 Assessment of Direct Demodulation Technology

Application of the assessment methodology requires specification of lower and upper bounds and modal value for each of the input parameters utilized in screening. Alternately, the mean and standard deviation may be specified. If minimum, modal, and maximum values are specified, the analytic approximation used in assessment computes an "equivalent" mean and standard deviation for a Gaussian distribution. (The Monte Carlo simulation method utilized in the ranking methodology does not make the simplified assumption, but rather uses the Beta distribution.) Table 12.4 contains the input data used for assessment of direct demodulation technology.

The assessment, or risk analysis, for this low cost earth station technology indicates that the assumed Gaussian distribution of the net present value of the technology development has a mean value of 10.5 M dollars and a standard deviation of 2.1 M dollars.

12.3 Data for Ranking of Direct Demodulation Technology

Ranking of the technology development programs will be based upon parameters taken from the NPV cumulative distribution functions. These CDFs are established by a full Monte Carlo simulation using Beta distribution random number generators for the input parameters of the NPV equation. For this low cost earth station technology, the input parameter ranges are the same as those presented in Table 12.4 of the assessment application. Figure 12.12 contains the histogram of the Monte Carlo simulation results. The height of each bar is proportional to the number of sample NPVs occurring

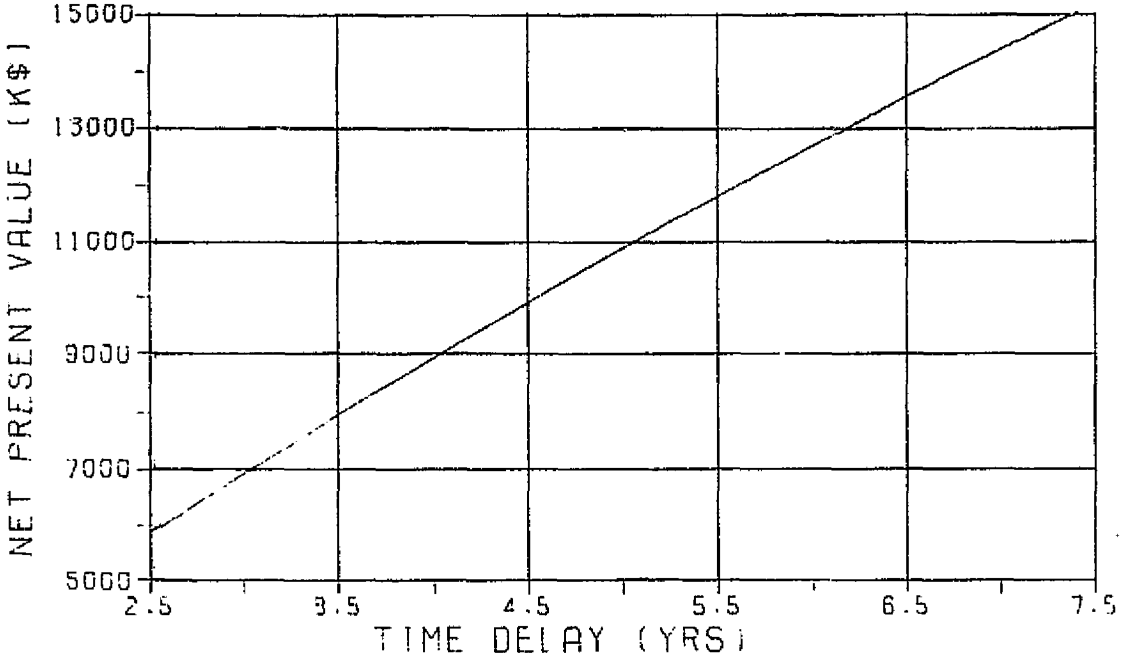


Figure 12.1. Sensitivity of Low Cost Earth Station Receiver NPV with respect to Time Delay in Absence of NASA Support.

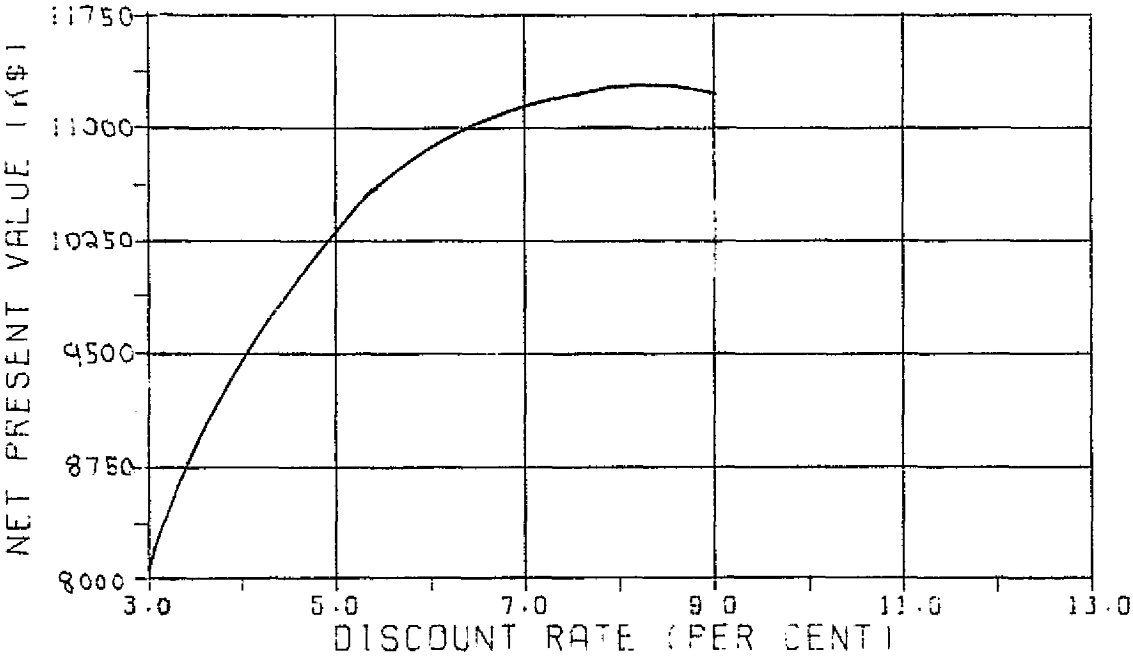


Figure 12.2. Sensitivity of Low Cost Earth Station Receiver NPV with respect to Discount Rate.

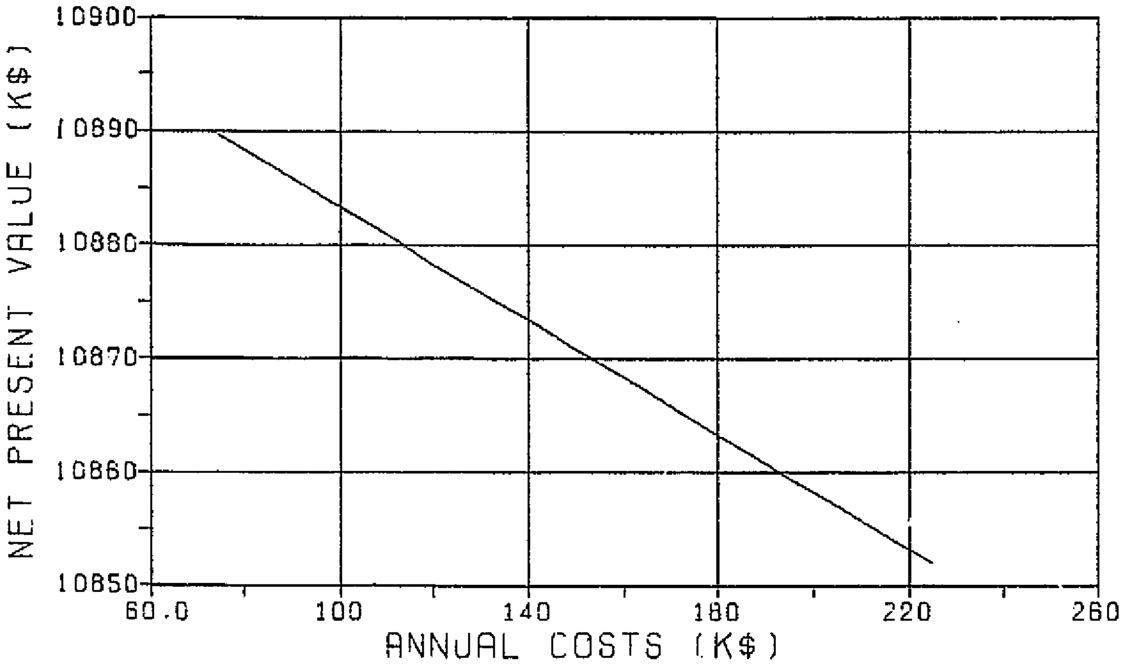


Figure 12.3. Sensitivity of Low Cost Earth Station Receiver NPV with respect to Annual Costs for Basic R&D.

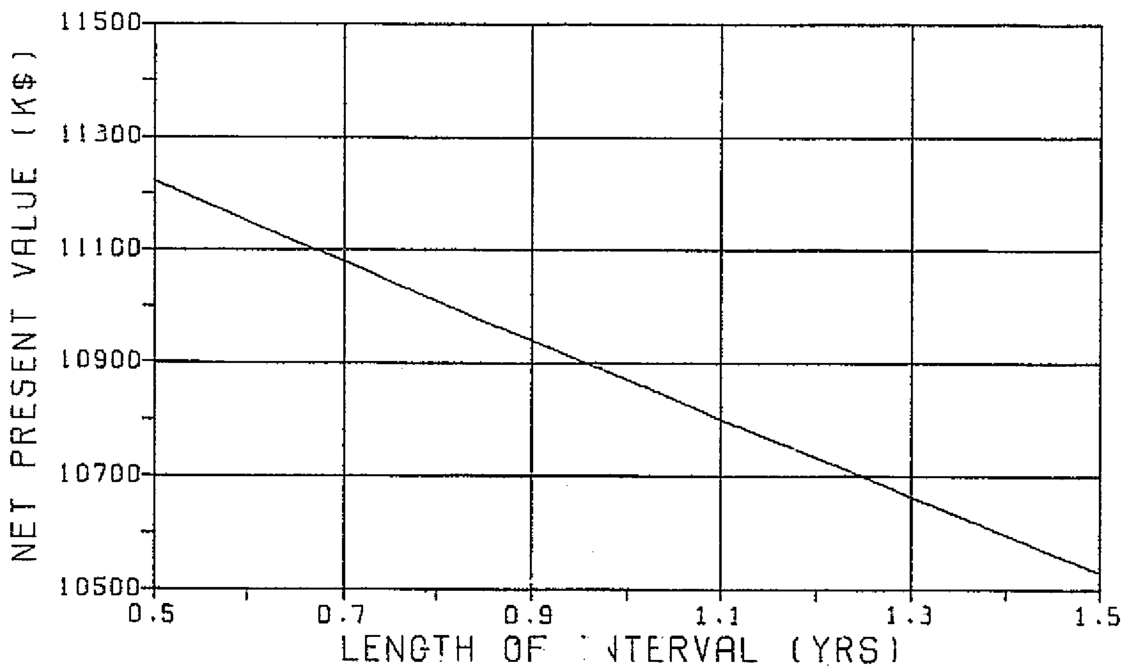


Figure 12.4. Sensitivity of Low Cost Earth Station Receiver NPV with respect to Length of Basic R&D Interval.

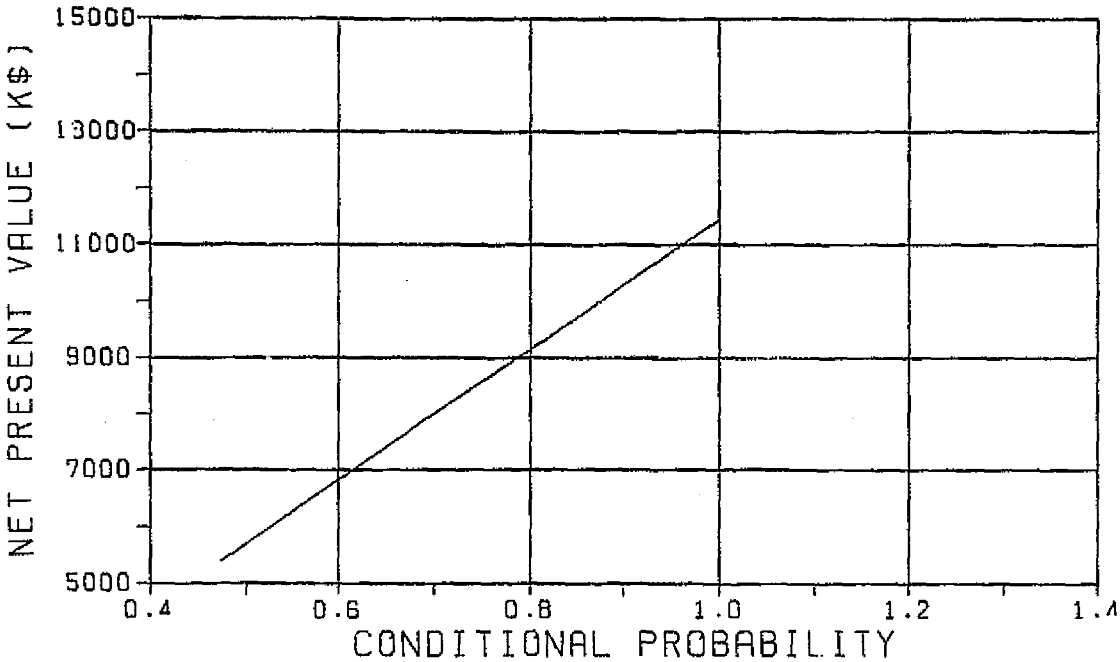


Figure 12.5. Sensitivity of Low Cost Earth Station Receiver NPV with respect to Probability that Industry will Implement the Technology

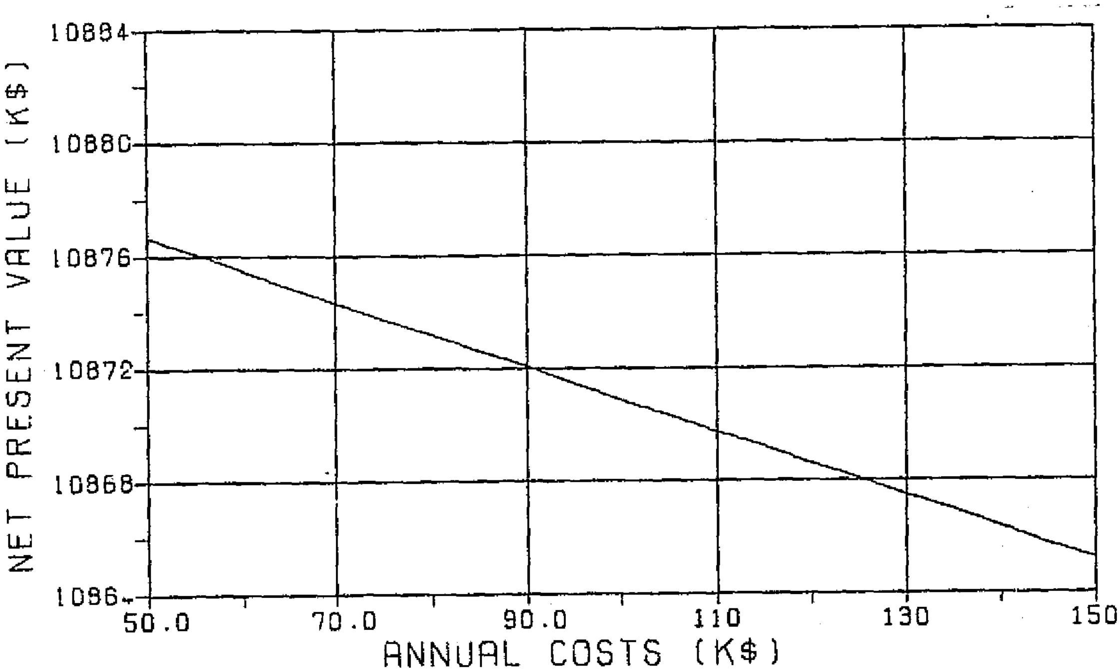


Figure 12.6. Sensitivity of Low Cost Earth Station Receiver NPV with respect to Annual Costs During Applied R&D Interval.

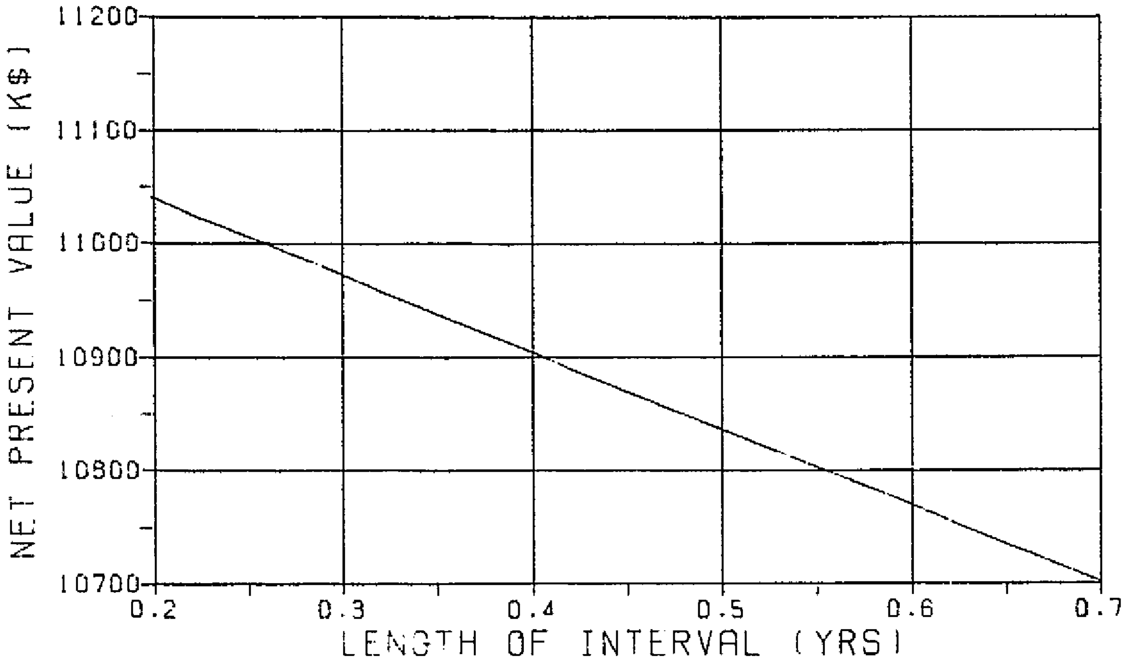


Figure 12.7. Sensitivity of Low Cost Earth Station Receiver NPV with respect to Length of Applied R&D Interval.

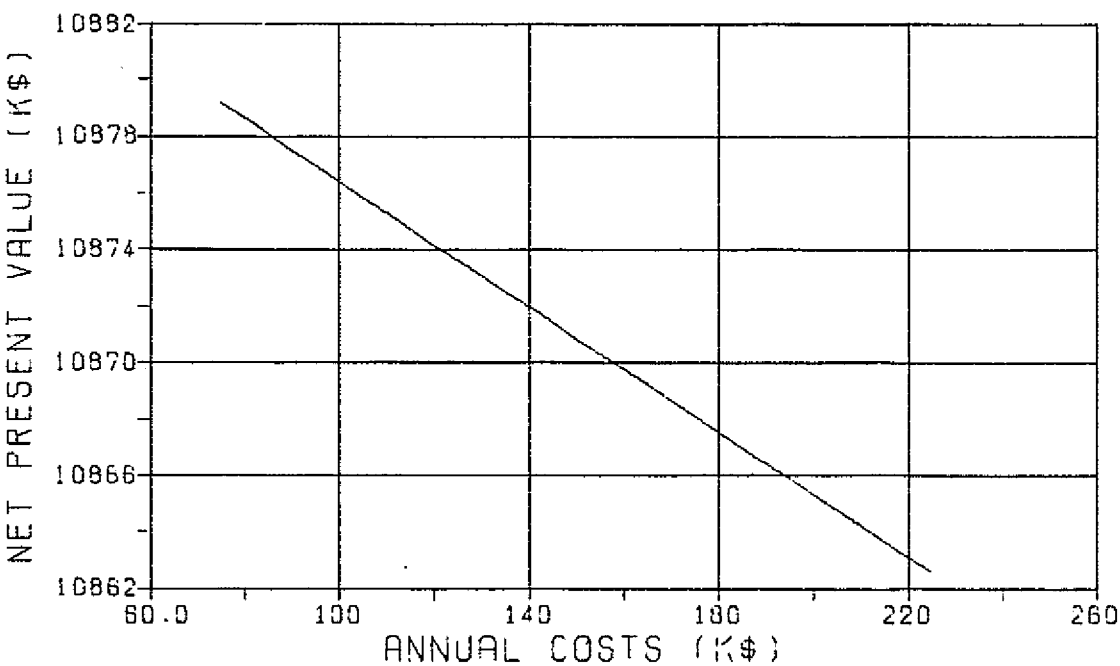


Figure 12.8. Sensitivity of Low Cost Earth Station Receiver NPV with respect to Annual Costs in Industry Construction Interval.

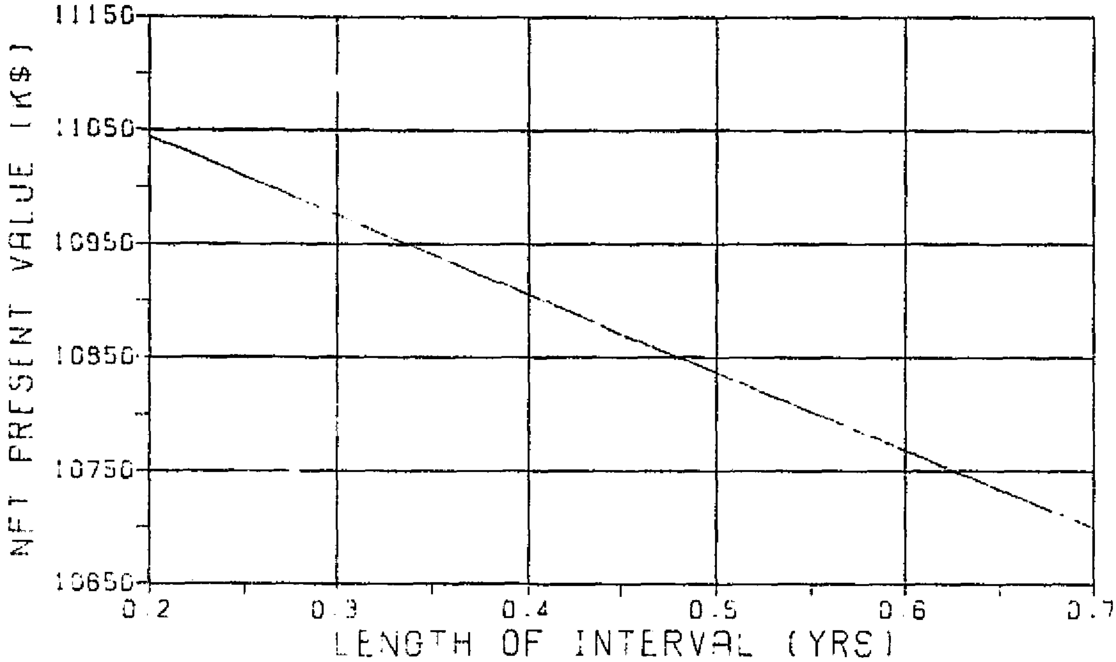


Figure 12.9. Sensitivity of Low Cost Earth Station Receiver NPV with Respect to Length of Industry Construction Interval.

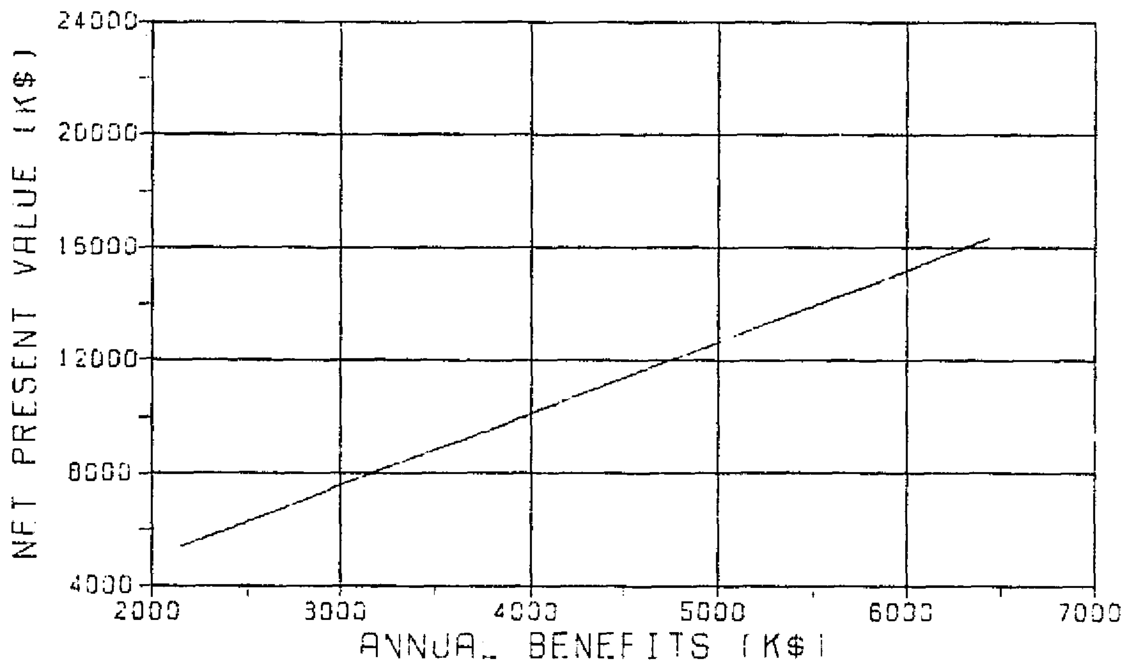


Figure 12.10. Sensitivity of Low Cost Earth Station Receiver NPV with respect to Annual Benefits.

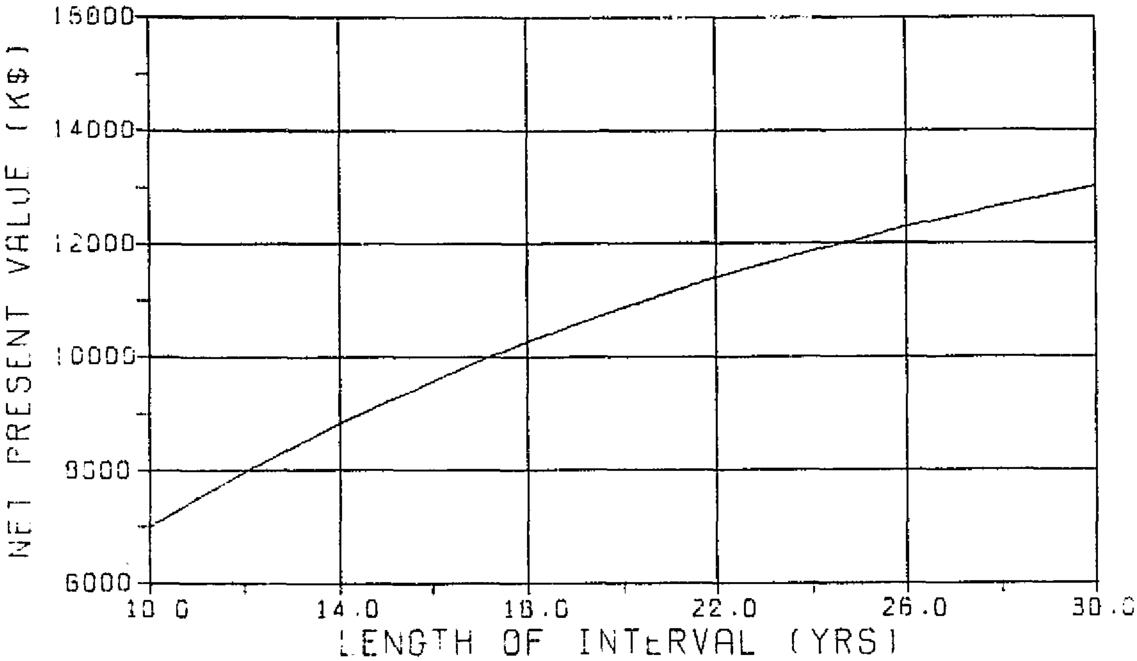


Figure 12.11. Sensitivity of Low Cost Earth Station Receiver NPV with respect to Length of Operating Interval.

TABLE 12.3

SLOPES OF DIRECT DEMODULATION TECHNOLOGY FOR
LOW COST EARTH STATION RECEIVERS
NPV SENSITIVITY PLOTS

Variable	Slope
Time Delay	1800 k$/year
Annual Costs for Basic R&D	-.25 k$/k$
Length of Basic R&D Interval	-650 k$/year
Probability that Industry will Implement the Technology	12,000 k$
Annual Costs during Applied R&D Interval	-.11 k$/k$
Length of Applied R&D Interval	-1600 k$/year
Annual Costs in Industry Construction Interval	-.12 k$/k$
Length of Industry Construction Interval	-700 k$/year
Annual Benefits	2.35 k$/k$
Length of Operating Interval	300 k$/year

within an interval of width 650 K dollars. The interval number is labeled at the bottom of the plot, and a scale indicating the actual NPV is at the top of the plot. The histogram indicates that the distribution is essentially unimodal and near-Gaussian in shape. Figure 12.13 displays the data of the histogram in a different form: here the data points have been normalized by dividing by the total number of occurrences and by the width of the NPV interval so that the resulting curve represents the probability density function (with unity area). Figure 12.14 shows a plot of the cumulative distribution function. The integral of the probability density function. It is this cumulative distribution function which supplies the parameters to be used in ranking. For the low cost earth station technology, it is seen that essentially all of the sample NPVs lie between about 5 M and 16 M dollars.

TABLE 12.4

ASSESSMENT PARAMETERS FOR DIRECT DEMODULATION TECHNOLOGY

QUICK RISK ANALYSIS FOR :DEGENRATE PARAMP

****** INPUT PARAMETERS ARE AS FOLLOWS ******

DISCOUNT RATE .... .06

VARIABLE	INPUT BETA PARAMETERS MIN	MODAL	MAX	COMPUTED MEAN
TIME DELAY (YRS)	3.00	5.00	8.00	5.17
NASA R&D				
CONDITIONAL PROBABILITY	1.00	1.00	1.00	1.00
ANNUAL BENEFITS (K$)	0.00	0.00	0.00	0.00
ANNUAL COSTS (K$)	100.00	150.00	200.00	150.00
INTERVAL LENGTH (YRS)	1.00	1.00	1.00	1.00
INDUSTRY R&D				
CONDITIONAL PROBABILITY	.85	.95	1.00	.94
ANNUAL BENEFITS (K$)	0.00	0.00	0.00	0.00
ANNUAL COSTS (K$)	75.00	100.00	150.00	104.17
INTERVAL LENGTH (YRS)	.50	.50	.50	.50
INDUSTRY CONSTRUCTION				
CONDITIONAL PROBABILITY	1.00	1.00	1.00	1.00
ANNUAL BENEFITS (K$)	0.00	0.00	0.00	0.00
ANNUAL COSTS (K$)	100.00	150.00	300.00	166.67
INTERVAL LENGTH (YRS)	.50	.50	.50	.50
OPERATION TIME				
CONDITIONAL PROBABILITY	1.00	1.00	1.00	1.00
ANNUAL BENEFITS (K$)	2000.00	4300.00	5200.00	4066.67
ANNUAL COSTS (K$)	.00	.00	.00	.00
INTERVAL LENGTH (YRS)	14.00	20.00	26.00	20.00

THE EXPECTED NET VALUE (K$) EQUALS --

10474.3

STANDARD DEVIATION EQUALS --

2091.5

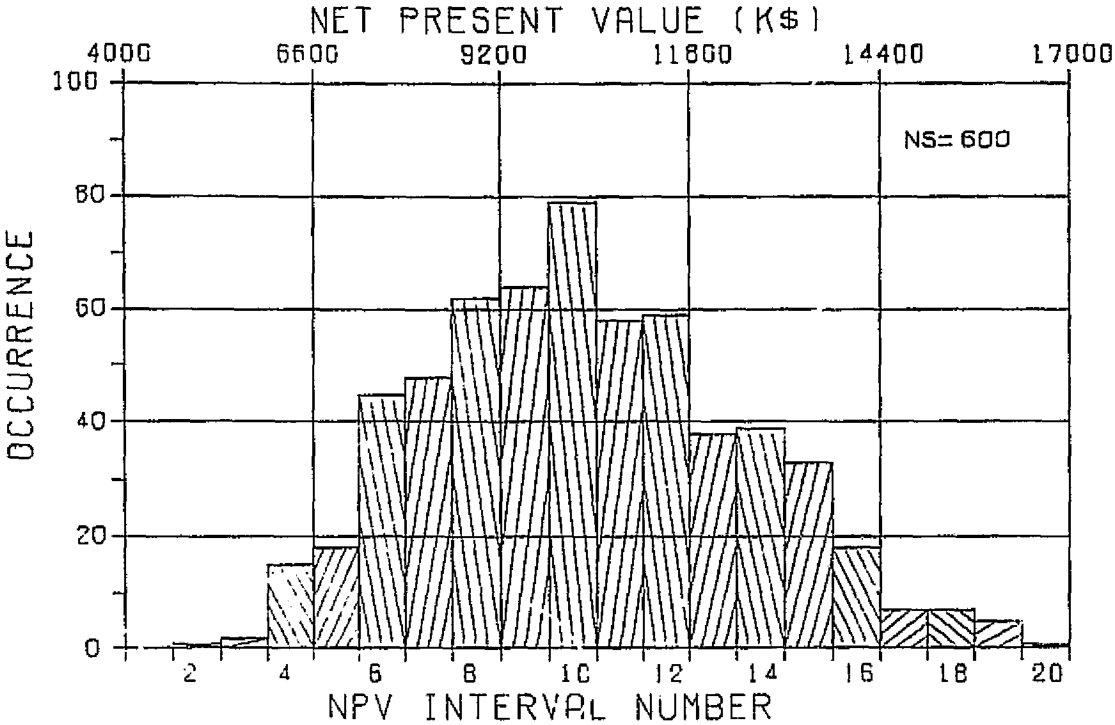


Figure 12.12. Low Cost Earth Station Receiver NPV Histogram.

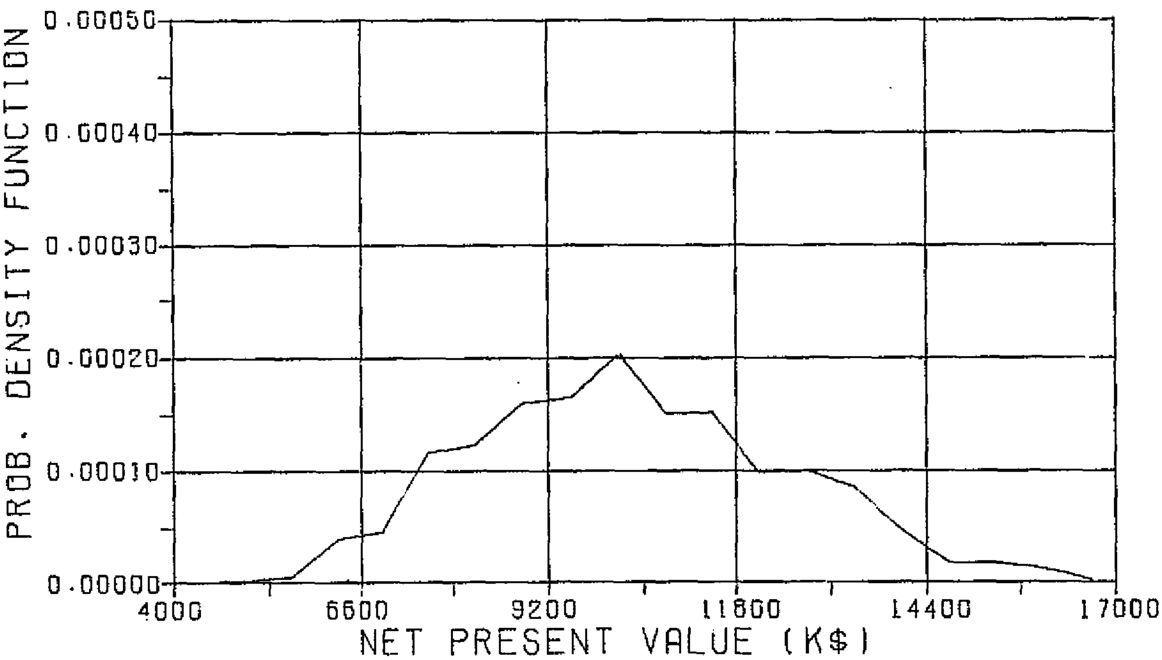


Figure 12.13. Low Cost Earth Station Receiver NPV Probability Density Function

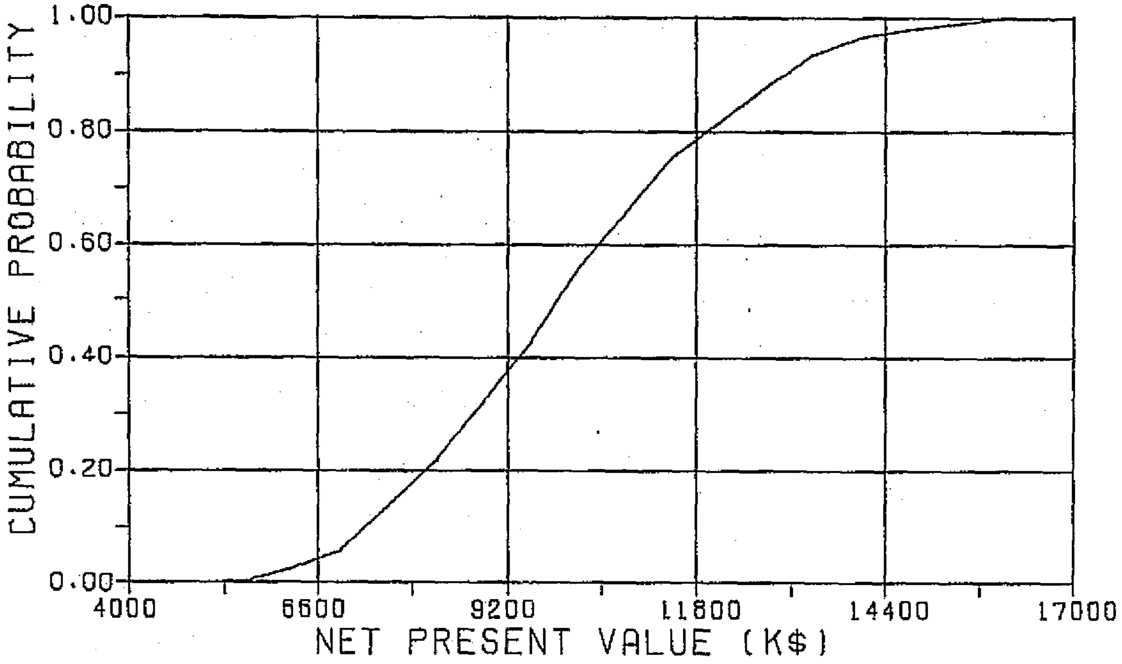


Figure 12.14. Low Cost Earth Station Receiver NPV Cumulative Distribution Function.

SECTION 13

COST-BENEFIT ANALYSIS OF ADDITIONAL TECHNOLOGIES

Detailed analyses of ion engine technology and a low cost earth station technology have been presented in the previous two sections. This section presents, in summary form, the screening and assessment results and data for ranking of seven additional technologies:

- Millimeter Communication System
- Laser Communication System
- RF Attitude Sensor
- Solid State Power Amplifier
- Multibeam Satellite Antennas
- Advanced Solar Arrays
- Adaptive Heat Pipes

The following analyses are essentially the same as in Sections 11 and 12, but the associated sensitivity plots have been placed in Appendix II. The reader should be reminded that application of the assessment and ranking methodologies is normally made for only a portion of the technologies which are screened; the complete methodology is applied to all technologies screened here to demonstrate consistency of the methodologies. The section concludes with a summary of screening and assessment results.

13.1 Millimeter Communication System

The combination of (1) the projected exponential growth in demand for space communication channels and (2) the inherent limitation in the number of synchronous communication satellites sharing a common frequency and area of coverage upon the earth's surface will require the development of space communication technology capable of operating in frequency ranges other than the C-band and Ku-band frequencies currently utilized for space communications. Federal and world regulatory agencies have set aside frequencies around 40 and 80 GHz for space communication systems; the millimeter wave communication technology considered in this evaluation is intended to operate at 40 GHz. A 40 GHz system will not only have the advantage of introducing a new frequency band but also will have twice the RF bandwidth allocated for either of the two lower-frequency bands. If one assumes that the required technology can be developed for dual polarization operation, then the communications capability at 40 GHz could be twice that available at the C or Ku-band. This simplified estimate of course ignores the space diversity requirements associated with the high attenuation in rainfall at this higher frequency, but it also does not account for the positive attribute of tighter antenna beamwidths available for reasonable size antennas. In any case, the introduction of this new communication band is necessary if the space communications industry is to meet the projected demand for services.

The implementation of millimeter wave space communication links will require advances in several technology areas: sources, receiver components, waveguide components, millimeter wave antennas, etc. Table 13.1 contains an itemization of the required sub-technologies and the estimated development cost of each item. Figure 13.1 shows the resulting system block diagram. As a result of discussion of the impact and development costs of millimeter communications technology with several industrial and governmental groups, the screening parameter values shown in Table 13.2 have been selected. The basic research and development program includes subsystem development and a flight demonstration test. It is estimated that such a program would require six years and cost \$42 million (see Table 13.1). The likelihood of U.S. industry implementing millimeter communications technology in commercial communication satellites after such a NASA R&D program is estimated at 80%. The application program is estimated to require an industrial expenditure of \$8 million over a four-year period for an applied research and development and prototype development program. It is assumed that the millimeter communications technology would continue to be incorporated in communications satellites for 20 years after its introduction without significant modifications to the basic technology. It is estimated that the time delay in the availability of millimeter communications technology resulting from NASA choosing to not pursue millimeter communication system development is 10 years.

Calculation of the equivalent annual benefit (EAB) for the NASA sponsored development for millimeter communications technology is based on the fractional

TABLE 13.1

40 GHz MILLIMETER WAVE COMMUNICATION SYSTEM: SATELLITE-TO-GROUND

1. Required Basic Research and Development

a.	Atmospheric investigations at 40 GHz: attenuation, spatial diversity, correlation measurements, fading & fading rates, adverse weather, cumulative attenuation studies, data analysis, ground truth data.	$ .4 M
b.	Solid state transmitter and L. O.	3.0
c.	Modulator	.6
d.	Solid state amplifier	1.5
e.	Multi-spot antenna	2.5
f.	Phase locking experiments	.3
g.	Up-converter RF-40GHz and 4-40GHz	1.1
h.	40 GHz multiplexing	.8
i.	Space-borne 40 GHz components	1.0
j.	ATS type experiments at 40 GHz (commun. exp)	10.0
k.	Ground station equipment: antennas, signal-processing equipment, mm receive/transmit	2.5
l.	Multi-channeled space qualified system	2.5
m.	Flight test in space environment demonstration experiments	15.0
n.	Uncooled Par. Amp.	0.5
o.	Mixer/Receiver	0.5
	TOTAL BASIC R & D COST	$42.2

2. Cost of Subsequent Industrial R & D

a.	Atmospheric investigations at 40 GHz	$ 0.5 M
b.	Solid state transmitter and L. O.	1.0
c.	Modulator	0.4
d.	Solid state amplifier	0.5

TABLE 13. 1 (continued)

e.	Multi-spot antenna	$ 0.7 M
f.	Phase locking experiments	0.15
g.	Up-converter RF-40GHz and 4-4GHz	0.3
h.	40 GHz multiplexing	0.3
i.	Space-borne 40 GHz components	0.3
j.	ATS type experiments at 40 GHz (commum. exp)	0.0
k.	Ground station equipment: antennas, signal-processing equipment, mm receive/transmit	0.5
l.	Multi-channeled space qualified system	0.6
m.	Flight test in space environment demonstration experiments	0.0
n.	Uncooled Par. Amp.	0.5
o.	Mixer/Receiver	0.3
TOTAL		$6.05 M

3. Industrial Construction Communication System $2.0 M

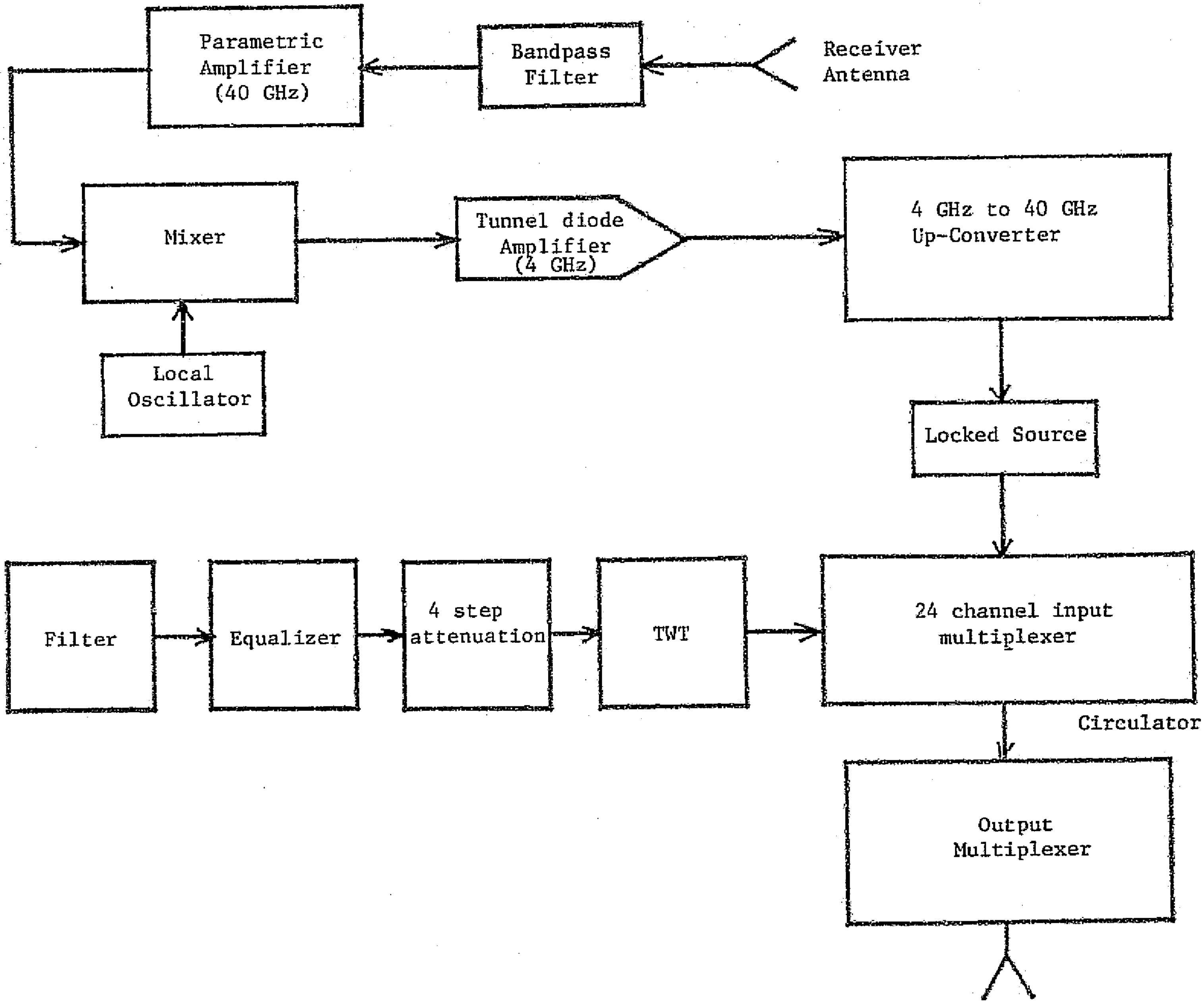


Figure 13.1. Millimeter Communication Receiver

TABLE 13.2

SCREENING PARAMETERS FOR MILLIMETER COMMUNICATIONS

SCREENING FOR : MM COMMUNICATIONS

****** INPUT PARAMETERS ARE AS FOLLOWS ******

TIME DELAY FACTOR (YRS)	10.00
DISCOUNT RATE	.06
NASA DEVELOPMENT	
CONDITIONAL PROBABILITY	1.00
ANNUAL BENEFITS (K$)	0.00
ANNUAL COSTS (K$)	7000.00
LENGTH OF INTERVAL (YRS)	6.00
INDUSTRY R&D	
CONDITIONAL PROBABILITY	.80
ANNUAL BENEFITS (K$)	0.00
ANNUAL COSTS (K$)	3000.00
LENGTH OF INTERVAL (YRS)	2.00
INDUSTRY CONSTRUCTION	
CONDITIONAL PROBABILITY	1.00
ANNUAL BENEFITS (K$)	0.00
ANNUAL COSTS (K$)	1000.00
LENGTH OF INTERVAL (YRS)	2.00
OPERATION TIME	
CONDITIONAL PROBABILITY	1.00
ANNUAL BENEFITS (K$)	18000.00
ANNUAL COSTS (K$)	.00
LENGTH OF INTERVAL (YRS)	20.00

THE NET VALUE (K$) INCLUDING LAG TIME EQUALS --

23770.1

satellite launch schedule of Tables 13.3 and 13.4. Tables 13.3a and 13.3b correspond to the U.S. DOMSAT market for introduction in 1986 and 1996, respectively, of the millimeter technology. Both scenarios correspond to the demand, satellite cost, and satellite capacity of Figures 10.1 through 10.3, except that the satellite capacity is considered to increase by 50% of its 1986 value and the satellite cost to increase by 35% of its 1986 value at the time of the introduction of the millimeter wave technology. The sixth column of each table, discounted U.S.-U.S. cost, contains the annual expenditures for satellite purchases and launch, and is the same for Tables 13.3a and 13.3b, except for the years 1986-1995. The difference in the values between the two tables represents the value of early introduction of millimeter communications technology into the U.S. DOMSAT market. Tables 13.4a and 13.4b present corresponding data for millimeter technology applications to the Atlantic and Pacific regions of the INTELSAT system. The decrease in per channel satellite construction and launch cost associated with the technology appearing early is 34.5 million dollars for the U.S. DOMSAT and 13.5 million dollars for the INTELSAT, for a total gross benefit of 48 million dollars, discounted to 1975. Application of the equation for equivalent annual benefits (EAB) yields an EAB of 18 million dollars per year for the assumed 20 year operating integral.

The resulting screening score (net present value) for millimeter technology is 23.8 million dollars. The sensitivity plots which show the effect upon this screening score of variations in the input parameters are in Appendix II. A tabulation of the slopes of the sensitivity curves is given in Table 13.5.

The expected range of each of the input variables to the screening equation is used in assessment. Table 13.6 presents the input data for the assessment program application of millimeter wave technology. The standard deviation of the assumed Gaussian resultant distribution of net present value is $11.5 million and the mean value is $24 million. Application of this mean and standard deviation to the generalized Gaussian curves of Figure 11.4 will give the analytic approximation to the cumulative distribution function.

LAUNCH SCENARIO FOR MILLIMETER COMMUNICATIONS TECHNOLOGY INTRODUCTION
INTO THE U.S. DOMSAT MARKET

TABLE 13.3a

**** US DOMSAT--1986 INTRODUCTION OF MILLIMETER COMMUNICATIONS TECHNOLOGY ****

YEAR	SATELLITE LIFE (YEARS)	COST PER SATELLITE (M$)	SATELLITE CAPACITY (K CKT/2)	NO. OF LAUNCHES	DISCOUNTED US-US COST (M$)	DISCOUNTED US-FOR COST (M$)
1975	7	35.0	14.0	1.00	35.00	0.00
1976	7	37.5	15.4	.31	11.04	0.00
1977	7	40.4	15.9	.34	12.20	0.00
1978	7	43.5	18.6	.37	13.47	0.00
1979	7	46.7	20.5	.40	14.88	0.00
1980	7	50.2	22.5	.44	16.43	0.00
1981	7	54.0	24.8	.88	32.79	0.00
1982	7	58.1	27.3	1.04	38.30	0.00
1983	7	62.4	30.0	.73	26.90	0.00
1984	7	67.1	33.0	.80	29.19	0.00
1985	8	72.1	36.3	.87	31.56	0.00
1986	8	93.0	53.9	.70	30.50	0.00
1987	8	98.9	57.9	.79	33.47	0.00
1988	8	105.1	62.3	1.04	43.37	0.00
1989	8	111.8	67.2	1.19	48.69	0.00
1990	8	119.1	72.5	1.15	46.54	0.00
1991	8	126.9	78.3	1.28	50.81	0.00
1992	8	135.2	84.8	1.05	40.83	0.00
1993	8	144.2	91.8	1.56	57.69	0.00
1994	8	153.8	99.6	1.66	62.76	0.00
1995	8	164.2	108.2	1.84	68.21	0.00
1996	8	175.3	117.6	2.12	77.14	0.00
1997	8	187.3	128.0	2.35	94.22	0.00
1998	8	200.2	139.4	2.50	88.19	0.00
1999	8	214.1	151.9	2.75	97.77	0.00
2000	8	228.9	165.7	2.94	101.51	0.00
2001	8	245.0	180.9	3.30	118.75	0.00
2002	8	262.2	197.5	3.02	131.50	0.00
2003	8	280.7	215.9	3.38	145.57	0.00
2004	8	300.5	236.1	4.41	162.67	0.00
2005	8	321.9	258.3	4.94	180.27	0.00

PROJECTED COST OF SATELLITES (INCLUDING LAUNCH) BETWEEN 1986 AND 1995 FOR U. S. MANUFACTURE AND U. S. USE - $482.88 MILLION

TABLE 13.3b

**** US DOMSAT--1996 INTRODUCTION OF MILLIMETER COMMUNICATIONS TECHNOLOGY ****

YEAR	SATELLITE LIFE (YEARS)	COST PER SATELLITE (M$)	SATELLITE CAPACITY (K CKT/2)	NO. OF LAUNCHES	DISCOUNTED US-US COST (M$)	DISCOUNTED US-FOR COST (M$)
1975	7	35.0	14.0	1.00	35.00	0.00
1976	7	37.6	15.4	.31	11.04	0.00
1977	7	40.4	15.9	.34	12.20	0.00
1978	7	43.5	18.6	.37	13.47	0.00
1979	7	46.7	20.5	.40	14.88	0.00
1980	7	50.2	22.5	.44	16.43	0.00
1981	7	54.0	24.8	.88	32.79	0.00
1982	7	58.1	27.3	1.04	38.30	0.00
1983	7	62.4	30.0	.73	26.90	0.00
1984	7	67.1	33.0	.80	29.19	0.00
1985	8	72.1	36.3	.87	31.66	0.00
1986	8	77.5	39.9	.95	34.33	0.00
1987	8	83.4	43.9	1.04	37.21	0.00
1988	8	89.6	48.3	1.34	47.69	0.00
1989	8	96.3	53.2	1.50	52.99	0.00
1990	8	103.6	58.5	1.43	50.17	0.00
1991	8	111.3	64.3	1.56	54.31	0.00
1992	8	119.7	70.8	1.25	43.30	0.00
1993	8	128.7	77.8	1.78	60.75	0.00
1994	8	138.3	85.6	1.94	65.67	0.00
1995	8	148.7	94.2	2.11	70.95	0.00
1996	8	175.3	117.6	2.12	77.14	0.00
1997	8	187.3	128.0	2.35	94.22	0.00
1998	8	200.2	139.4	2.50	88.19	0.00
1999	8	214.1	151.9	2.75	97.77	0.00
2000	8	228.9	165.7	2.84	101.51	0.00
2001	8	245.0	180.9	3.30	118.75	0.00
2002	8	262.2	197.5	3.02	131.50	0.00
2003	8	280.7	215.9	3.98	145.57	0.00
2004	8	300.5	236.1	4.41	162.67	0.00
2005	8	321.9	258.3	4.84	180.27	0.00

PROJECTED COST OF SATELLITES (INCLUDING LAUNCH) BETWEEN 1986 AND 1995 FOR U. S. MANUFACTURE AND U. S. USE - $517.37 MILLION

LAUNCH SCENARIO FOR MILLIMETER COMMUNICATIONS TECHNOLOGY INTRODUCTION
INTO THE INTELSAT ATLANTIC AND PACIFIC MARKET

TABLE 13.4a

**** INTELSAT ATLANTIC AND PACIFIC--1986 INTRODUCTION OF ****
**** MILLIMETER COMMUNICATIONS TECHNOLOGY ****

YEAR	SATELLITE LIFE (YEARS)	COST PER SATELLITE (M$)	SATELLITE CAPACITY (K CKT/2)	NO. OF LAUNCHES	DISCOUNTED US-US COST (M$)	DISCOUNTED US-FOR COST (M$)
1975	7	35.0	10.0	1.00	17.50	17.50
1976	7	37.7	11.1	0.00	0.00	0.00
1977	7	40.5	12.3	.30	5.35	5.35
1978	7	43.6	13.7	.31	4.82	4.82
1979	7	46.9	15.2	.96	13.14	13.14
1980	7	50.[illegible]	16.9	.83	12.52	12.52
1981	7	54.[illegible]	18.7	.37	5.60	5.60
1982	7	58.4	20.8	.88	13.00	13.00
1983	7	62.8	23.0	.42	6.17	6.17
1984	7	67.6	25.6	.59	8.53	8.53
1985	8	72.7	28.4	.63	8.90	8.90
1986	8	93.8	45.5	.64	10.67	10.67
1987	8	99.7	49.0	.67	10.90	10.90
1988	8	106.1	52.8	.55	8.77	8.77
1989	8	113.0	57.1	.78	11.99	11.99
1990	8	120.4	61.8	.66	9.85	9.85
1991	9	128.3	67.1	.77	11.19	11.19
1992	8	136.9	73.0	.59	8.34	8.34
1993	9	146.1	79.4	.87	11.83	11.93
1994	9	156.0	86.6	1.03	13.62	13.62
1995	8	166.7	94.6	1.10	14.05	14.05
1996	9	178.2	103.5	1.09	13.53	13.53
1997	9	190.5	113.3	1.27	15.14	15.14
1998	8	203.8	124.3	1.27	14.62	14.62
1999	8	218.1	136.4	1.39	16.16	16.16
2000	9	233.5	149.9	1.37	16.09	16.09
2001	8	250.0	164.8	1.58	18.69	18.69
2002	8	267.8	181.4	1.74	20.74	20.74
2003	8	286.9	199.8	1.86	22.34	22.34
2004	9	307.5	220.2	1.94	23.61	23.61
2005	8	329.7	242.9	2.12	26.01	26.01

PROJECTED COST OF SATELLITES (INCLUDING LAUNCH)
BETWEEN 1986 AND 1995 FOR U. S. MANUFACTURE AND
U. S. USE - $111.20 MILLION

TABLE 13.4b

**** INTELSAT ATLANTIC AND PACIFIC--1996 INTRODUCTION OF ****
**** MILLIMETER COMMUNICATIONS TECHNOLOGY ****

YEAR	SATELLITE LIFE (YEARS)	COST PER SATELLITE (M$)	SATELLITE CAPACITY (K CKT/2)	NO. OF LAUNCHES	DISCOUNTED US-US COST (M$)	DISCOUNTED US-FOR COST (M$)
1975	7	35.0	10.0	1.00	17.50	17.50
1976	7	37.7	11.1	0.00	0.00	0.00
1977	7	40.5	12.3	.30	5.35	5.35
1978	7	43.6	13.7	.31	4.82	4.82
1979	7	46.9	15.2	.96	13.14	13.14
1980	7	50.5	16.9	.83	12.52	12.52
1981	7	54.3	18.7	.37	5.60	5.60
1982	7	58.4	20.8	.88	13.00	13.00
1983	7	62.8	23.0	.42	6.17	6.17
1984	7	67.6	25.6	.59	8.53	8.53
1985	8	72.7	28.4	.63	8.90	8.90
1986	8	78.3	31.5	.92	12.86	12.86
1987	8	84.2	35.0	.94	12.99	12.99
1988	8	90.6	38.8	.75	10.18	10.18
1989	8	97.5	43.1	1.03	13.71	13.71
1990	8	104.9	47.8	.85	11.09	11.09
1991	8	112.8	53.1	.98	12.43	12.43
1992	8	121.4	59.0	.73	9.15	9.15
1993	8	130.6	65.4	1.05	12.83	12.83
1994	8	140.5	72.6	1.23	14.63	14.63
1995	8	151.2	80.6	1.29	14.96	14.95
1996	8	178.2	103.5	1.09	13.53	13.53
1997	8	190.5	113.3	1.27	15.14	15.14
1998	8	203.8	124.3	1.27	14.62	14.62
1999	8	218.1	136.4	1.39	16.16	16.16
2000	8	233.5	149.9	1.37	16.09	16.09
2001	8	250.0	164.8	1.58	18.69	18.69
2002	8	267.8	181.4	1.74	20.74	20.74
2003	8	286.9	199.8	1.86	22.34	22.34
2004	8	307.5	220.2	1.94	23.61	23.61
2005	8	329.7	242.9	2.12	26.01	26.01

PROJECTED COST OF SATELLITES (INCLUDING LAUNCH)
BETWEEN 1986 AND 1995 FOR U. S. MANUFACTURE AND
U. S. USE - $124.73 MILLION

TABLE 13.5

SLOPES OF MILLIMETER NPV SENSITIVITY PLOTS

Variable	Slope
Time Delay	64.17 k$/year
Annual Costs for Basic R&D	-1.63 k$/k$
Length of Basic R&D Interval	-2550 k$/year
Probability that Industry will Implement the Technology	13230.77 k$
Annual Costs During Applied R&D Interval	-.55 k$/k$
Length of Applied R&D Interval	-1450 k$/year
Annual Costs in Industry Construction Interval	-.26 k$/k$
Length of Industry Construction Interval	-1375 k$/year
Annual Benefits	2.73 k$/k$
Length of Operating Interval	335 k$/year

TABLE 13.6

ASSESSMENT PARAMETERS FOR MILLIMETER COMMUNICATIONS

QUICK RISK ANALYSIS FOR : MM COMMUNICATIONS

****** INPUT PARAMETERS ARE AS FOLLOWS ******

DISCOUNT RATE .... .06

VARIABLE	INPUT BETA PARAMETERS MIN	MODAL	MAX	COMPUTED MEAN
TIME DELAY (YRS)	5.00	10.00	15.00	10.00
NASA DEVELOPMENT				
CONDITIONAL PROBABILITY	1.00	1.00	1.00	1.00
ANNUAL BENEFITS (K$)	0.00	0.00	0.00	0.00
ANNUAL COSTS (K$)	4000.00	7000.00	10000.00	7000.00
INTERVAL LENGTH (YRS)	6.00	6.00	6.00	6.00
INDUSTRY DEVELOPMENT				
CONDITIONAL PROBABILITY	.65	.80	.95	.80
ANNUAL BENEFITS (K$)	0.00	0.00	0.00	0.00
ANNUAL COSTS (K$)	1000.00	2000.00	3000.00	2000.00
INTERVAL LENGTH (YRS)	4.00	4.00	4.00	4.00
OPERATION TIME				
CONDITIONAL PROBABILITY	1.00	1.00	1.00	1.00
ANNUAL BENEFITS (K$)	5000.00	18000.00	31000.00	18000.00
ANNUAL COSTS (K$)	.00	.00	.00	.00
INTERVAL LENGTH (YRS)	15.00	20.00	25.00	20.00

THE EXPECTED NET VALUE (K$) EQUALS --

23823.8

STANDARD DEVIATION EQUALS --

11452.3

The Monte Carlo simulation of the NPV of millimeter technology used the same ranges of input variables as in assessment. Figures 13.2, 13.3, and 13.4 present the histogram, probability density function, and cumulative distribution function, respectively, for millimeter communications.

13.2 Laser Communication System

Laser communications systems, like millimeter wave communication systems, will offer the advantages of large bandwidth and high data rate. Potentially, laser systems offer a wider bandwidth but the state of technology development in millimeter systems is more nearly mature than that for laser communications systems. Laser systems offer a significantly tighter beamwidth than the millimeter systems; however, laser propagation is attenuated by weather conditions more than millimeter systems. Future applications of laser space communication systems will include satellite-to-satellite links as well as satellite-to-earth links. Research in laser communication systems is now being conducted with several laser types; CO_2, YAG:NEODYMIUM, HELIUM-NEON, GALLIUM ARSENIDE, etc.

Estimation of the benefits of laser space communications technology is complicated by the several potential applications of the technology. Although one could speculate as to the benefit value by assuming application similar to that used in the millimeter system, an alternate approach has been taken here. The numerical value of the gross annual benefit was systematically varied in the screening application to determine that benefit which results in a small positive net present value of the technology development program. This annual benefit value was then used as the base for the sensitivity analysis, risk analysis, and ranking procedure. This break-even value of annual benefits for the development program is 4.5 million dollars per year.

Development of an optical space communication system requires research and development in laser sources, wideband detectors, high data rate modulation techniques, lifetime improvement, etc. Table 13.7 lists the CO_2 laser subsystems needing development and an estimate of the development costs. The total estimated basic R&D costs is $19.3 million, and it is estimated that four years would be required for the basic research program. The likelihood of U.S. industry implementing laser technology in communication

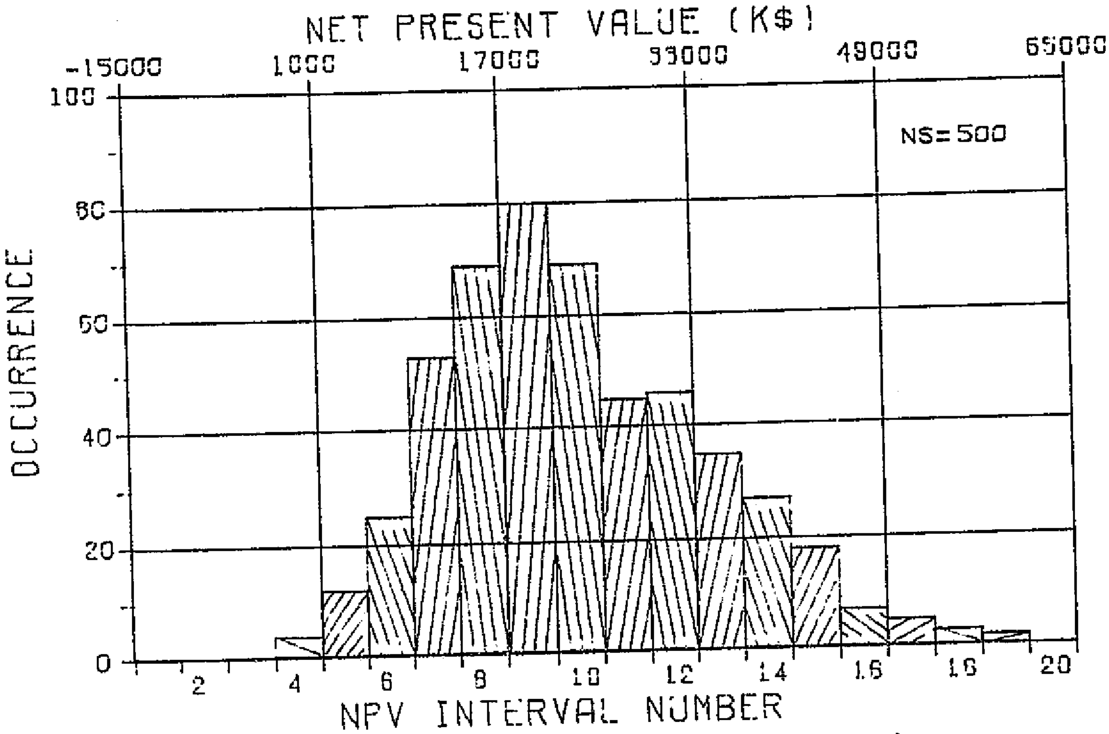


Figure 13.2 Millimeter NPV Histogram.

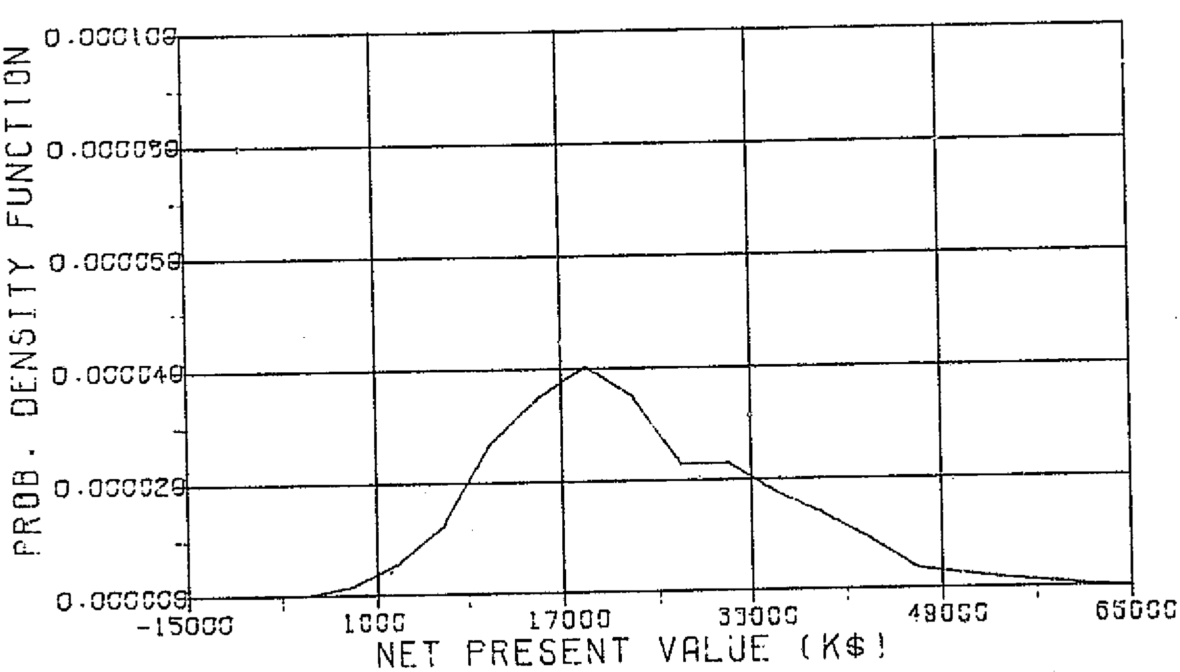


Figure 13.3. Millimeter NPV Probability Density Function.

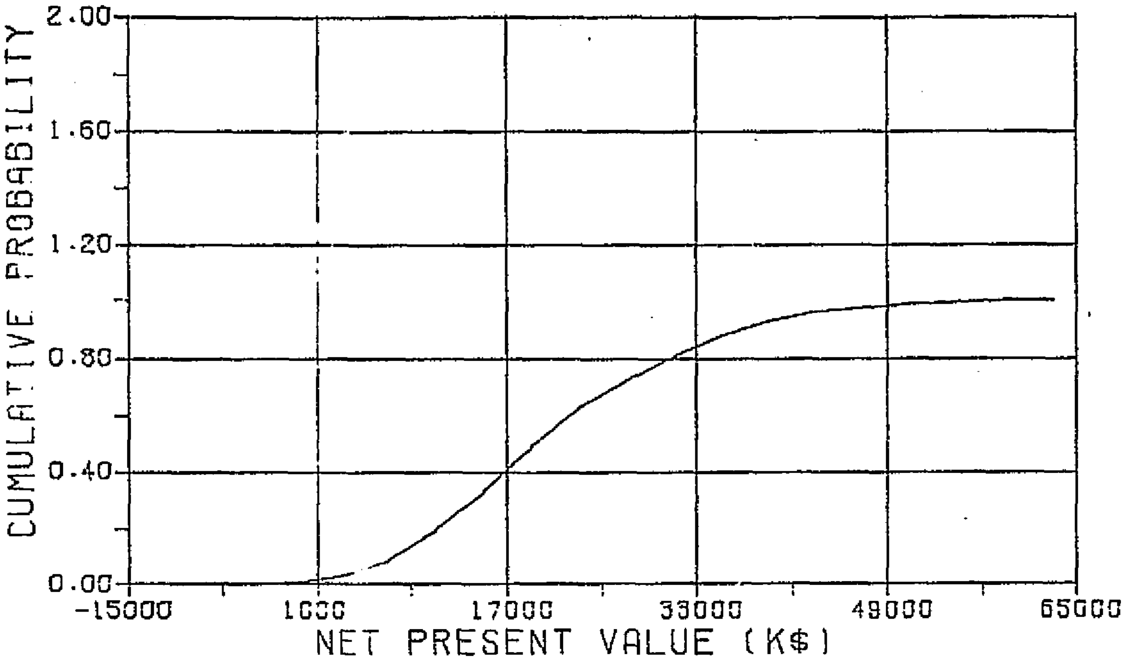


Figure 13.4. Millimeter NPV Cumulative Distribution Function.

TABLE 13.7

CO_2 LASER OPTICAL COMMUNICATIONS SYSTEM: SATELLITE-TO-SATELLITE

1.	Required Basic Research and Development	
a.	Laser tube development - improved lifetime	\$0.60M
b.	High data rate modulation development	\$1.0M
c.	Further receiver work	\$0.60M
d.	Waveguide laser technology	\$0.40M
e.	Background measurements (Spacelab)	\$0.5M
f.	Laser Stabilization Technology	\$0.30M
g.	Engineering Model (Spacelab system) Laser Communication System	\$2.5M
h.	Spacelab CO_2 laser data relay link (e.g., Spacelab/ground)	\$1.5M
i.	Acquisition, pointing and tracking experiments	\$0.75M
j.	Equipment performance evaluation (Spacelab)	\$0.50M
k.	Communication channel measurements	\$0.75M
l.	Communication demonstration experiments	\$1.5M
m.	Atmospheric propagation measurements	\$0.4M
n.	Synchronous orbit satellite-to-satellite communications systems (does not include satellites)	\$8.0M
	TOTAL BASIC R & D COST	\$19.3M
2.	Cost of subsequent industrial R & D	
a.	Laser tube development - improved lifetime	\$0.30M
b.	High data rate modulation development	\$0.40M
c.	Further receiver work	\$0.30M
d.	Waveguide laser technology	\$0.20M
e.	Laser stabilization technology	\$0.20M
f.	Engineering Model (Spacelab system) Laser communication system	\$1.0M
	First Model Test Flight of System	\$4.0M
3.	Industrial construction: communication system (not including vehicle)	\$3.0M

satellites after such a basic R&D program is estimated at 70%. The application program is estimated to require an industrial expenditure of 9.4 million dollars over a three year period for applied research and development and prototype development. It is assumed that laser technology would continue to be incorporated in communication satellites for 20 years after its introduction without significant modifications to the basic technology. It is also estimated that the time delay in the availability of laser technology resulting from NASA not pursuing this technical area is 12 years.

Table 13.8 contains the input parameters for the screening program. The resultant score (NPV) for the "laser system" is $1.1 million. The sensitivity plots which demonstrate the effect upon the screening score of variations in the assumed values of the input parameters are in Appendix II. Table 13.9 gives the slopes of each of the sensitivity curves.

The minimum, modal, and maximum values of the input parameters for the assessment (risk analysis) program are given in Table 13.10. The modal values are the same as the parameters used in the screening analysis. The resulting standard deviation of the assumed Gaussian NPV distribution of $2.7 million. For the mean of $1.1 million and the standard deviation of $2.7 million, there will be a significant likelihood that the NPV will be negative. This will be more evident in the follwoing Monte Carlo simulation results. The basis for ranking of laser communications technology is a 900-sample Monte Carlo simulation whose histogram probability density function, and cumulative distribution function are presented in Figures 13.5, 13.6, and 13.7, respectively. The histogram in Figure 13.5 is seen to be unimodal and near-Gaussian. Either of the three figures can be used to observe that most of the sample NPVs lie between about -$4.4 million and +$5.4 million. One can see from the cumulative probability distribution plot that the probability of a negative NPV is 40%.

13.3 RF Attitude Sensor

The attitude control system for a spinning communication satellite maintains correct orientation of the satellite spin axis, and the attitude control system for a three-axis stabilized communication satellite maintains desired orientation of all three body axes of the satellite. Attitude control

TABLE 13.8

SCREENING PARAMETERS FOR LASER COMMUNICATIONS

SCREENING FOR : LASER COMMUNICATIONS

****** INPUT PARAMETERS ARE AS FOLLOWS ******

(COSTS AND BENEFITS IN THOUSANDS OF DOLLARS)

TIME DELAY (YRS)	12.00
DISCOUNT RATE	.06
NASA DEVELOPMENT	
CONDITIONAL PROBABILITY	1.00
ANNUAL BENEFITS	0.00
ANNUAL COSTS	4825.00
LENGTH OF INTERVAL (YRS)	4.00
INDUSTRY R. AND D.	
CONDITIONAL PROBABILITY	.70
ANNUAL BENEFITS	0.00
ANNUAL COSTS	200.00
LENGTH OF INTERVAL (YRS)	2.00
INDUSTRY CONSTRUCTION	
CONDITIONAL PROBABILITY	1.00
ANNUAL BENEFITS	0.00
ANNUAL COSTS	3000.00
LENGTH OF INTERVAL (YRS)	1.00
OPERATION TIME	
CONDITIONAL PROBABILITY	1.00
ANNUAL BENEFITS	4500.00
ANNUAL COSTS	.00
LENGTH OF INTERVAL (YRS)	20.00

THE NET VALUE (K$) INCLUDING LAG TIME EQUALS --

1131.0

TABLE 13.9

SLOPES OF LASER NPV SENSITIVITY PLOTS

Variable	Slope
Time Delay	1735 k$/year
Annual Costs for Basic R&D	-2.27 k$/k$
Length of Basic R&D Interval	-4500 k$/year
Probability that Industry will Implement the Technology	50000 k$
Annual Costs During Applied R&D Interval	-.43 k$/k$
Length of Applied R&D Interval	-3000 k$/year
Annual Costs in Industry Construction Interval	-.41 k$/k$
Length of Industry Construction Interval	-2675 k$/year
Annual Benefits	2.28 k$/k$
Length of Operating Interval	1250 k$/year

TABLE 13.10

ASSESSMENT PARAMETERS FOR LASER COMMUNICATIONS

QUICK RISK ANALYSIS FOR : LASER COMMUNICATIONS

****** INPUT PARAMETERS ARE AS FOLLOWS ******

DISCOUNT RATE .... .06

VARIABLE	INPUT BETA PARAMETERS MIN	MODAL	MAX	COMPUTED MEAN
TIME DELAY (YRS)	8.00	12.00	16.00	12.00
NASA DEVELOPMENT				
CONDITIONAL PROBABILITY	1.00	1.00	1.00	1.00
ANNUAL BENEFITS (K$)	0.00	0.00	0.00	0.00
ANNUAL COSTS (K$)	2500.00	4825.00	7150.00	4825.00
INTERVAL LENGTH (YRS)	4.00	4.00	4.00	4.00
INDUSTRY DEVELOPMENT				
CONDITIONAL PROBABILITY	.50	.70	.90	.70
ANNUAL BENEFITS (K$)	0.00	0.00	0.00	0.00
ANNUAL COSTS (K$)	2000.00	3133.33	4266.66	3133.33
INTERVAL LENGTH (YRS)	3.00	3.00	3.00	3.00
OPERATION TIME				
CONDITIONAL PROBABILITY	1.00	1.00	1.00	1.00
ANNUAL BENEFITS (K$)	3000.00	4500.00	6000.00	4500.00
ANNUAL COSTS (K$)	.00	.00	.00	.00
INTERVAL LENGTH (YRS)	12.00	20.00	28.00	20.00

THE EXPECTED NET VALUE (K$) EQUALS --

1134.1

STANDARD DEVIATION EQUALS --

2687.7

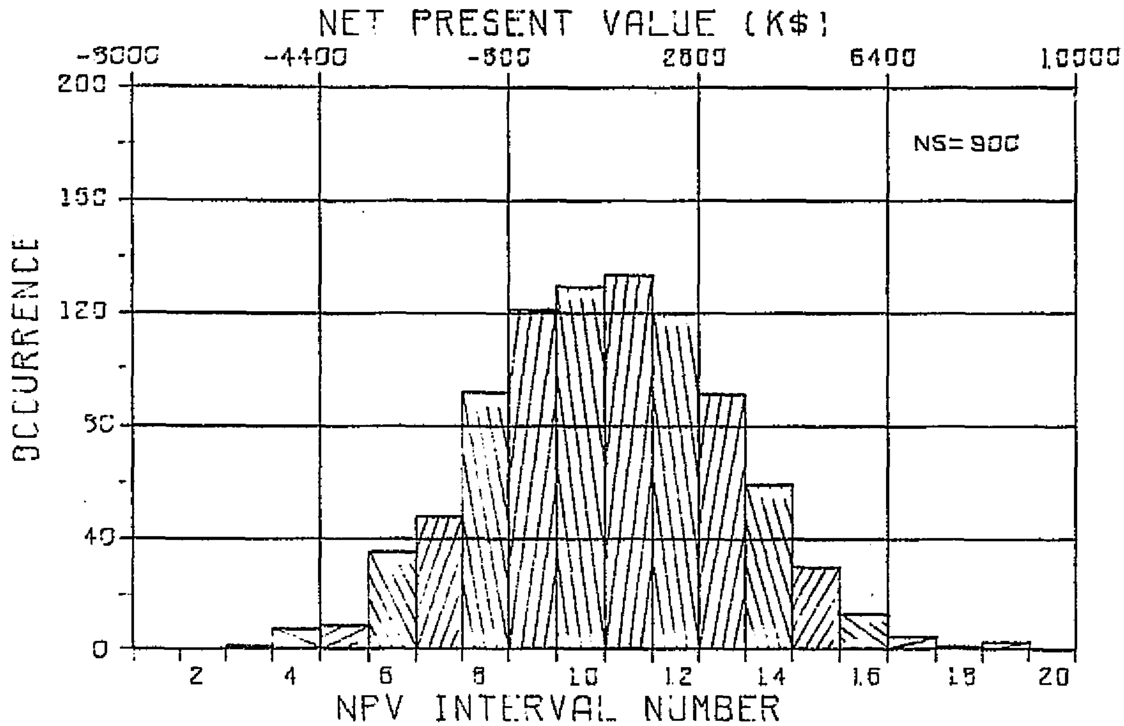


Figure 13.5. Laser NPV Histogram.

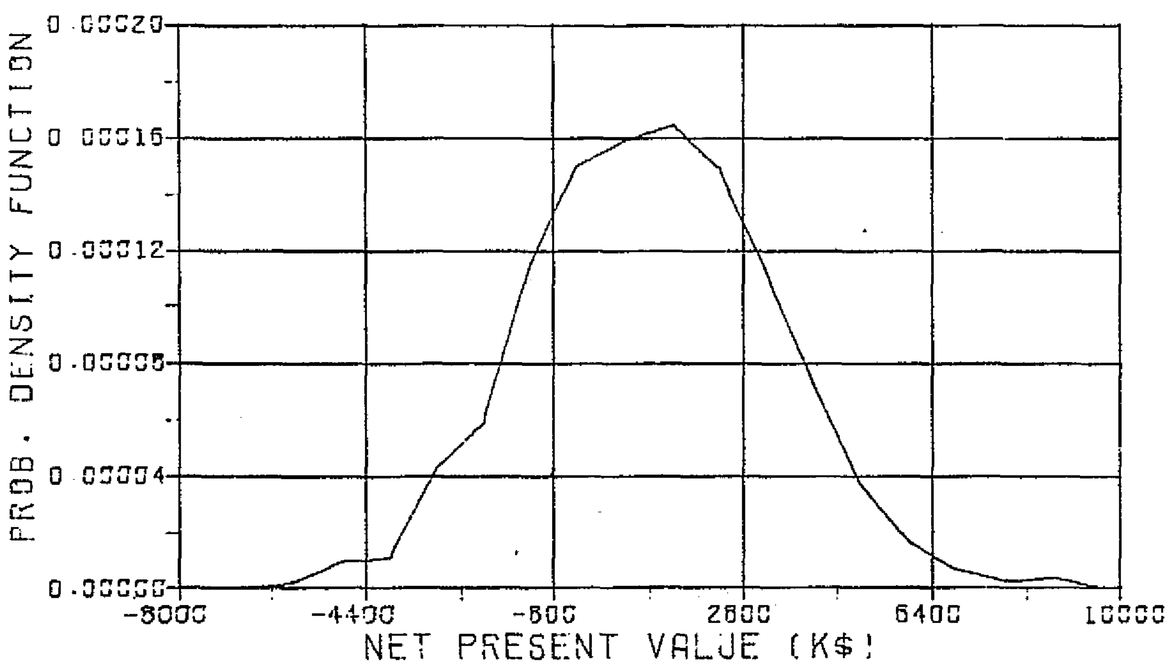


Figure 13.6. Laser NPV Probability Density Function.

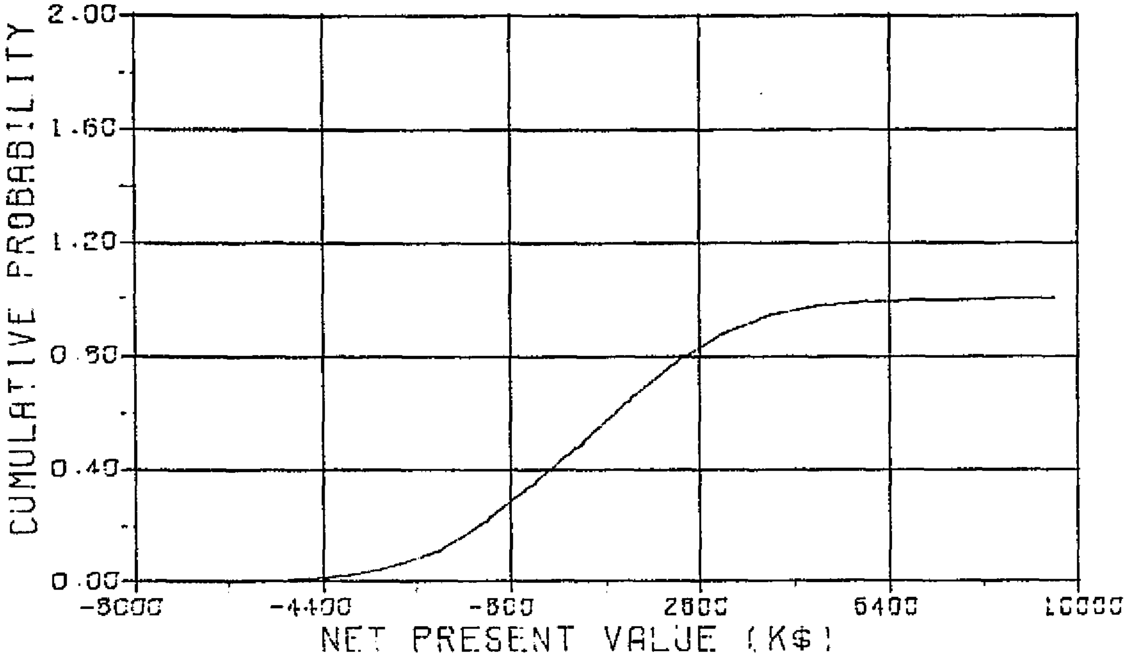


Figure 13.7. Laser NPV Cumulative Distribution Function.

is required in order to point the satellite antennas at the desired region of the earth's surface. For a three-axis control satellite, the attitude control also keeps the solar cell array directed toward the sun.

Attitude control systems are composed of (1) attitude sensors, (2) a control law, and (3) actuators. With current technology, the angular accuracy of the attitude control system is limited by the accuracy of the attitude sensors. These attitude sensors may be either (1) infrared earth horizon sensors, (2) star or sun sensors, (3) inertial reference systems, or (4) RF earth beacon trackers. Infrared horizon sensors are most frequently used and offer attitude control systems with 0.1 degree accuracy in pitch and in roll and 0.3 degree accuracy in yaw. Further improvement in the accuracy of these infrared sensors is hampered by the nonspherical nature of the earth's infrared horizon.

With a trend toward smaller beamwidth antennas, future attitude control systems will be required to control larger, more flexible spacecraft with more stringent attitude-pointing requirements. Estimates of antenna beam-widths of 0.5 degrees and attitude control requirements of 0.05 degrees in 1985 have been made. While RF attitude sensors such as interferometers or monopulse trackers can be used to track a specifically designed beacon signal from the earth's surface, they can also be used to track directly the transmitted communication signal from the earth station. These so-called autotrack systems result in direct control over the pointing of the antenna itself and therefore are not subject to the error introduced by thermal distortion of the satellite structure normally encountered between the antenna and the sensor location.

RF attitude sensors apparently are currently flying on classified military satellites. Their performance figures are said to be good, but advances need to be made in reduction of size, power requirement, weight, and cost for these sensors to be competitive for application on commercial communication satellites. The improved pointing accuracy of the spacecraft communication antenna which is expected to result from the application of RF autotrack systems will allow a corresponding decrease in the power margin of the satellite transmitter and will reduce interference on the ground. For purposes of this cost-benefit analysis, it is assumed that the tighter attitude control results in approximately a 1 dB increase in carrier-to-noise ratio and a corresponding 2% increase in the channel capacity of the satellite. It is also assumed that the cost of these attitude sensors is approximately 50% greater than the cost of the current technology sensors.

As a result of discussions of the impact and development costs of RF attitude sensors with industrial and governmental groups, the parameter values shown in Table 13.11 have been selected. It is estimated that the basic research and development program would require four years and cost $750 thousand. The likelihood of U. S. industry implementing RF attitude sensors in commercial communication satellites after such a NASA R & D program is estimated at 80%. The application program is estimated to require an industrial expenditure of $600 thousand over a two-year period for applied research and development and prototype development. It is assumed that RF attitude sensor technology would continue to be incorporated in communication satellites for eight years after its introduction without significant modifications to the basic technology. As in all analyses of this report, the discount rate is assumed to be 6 per cent. Since RF attitude sensor technology is at a reasonable advanced stage (with related equipment being researched for COMSAT and with some apparent military applications) it is estimated that the time delay in the availability of RF attitude sensors resulting from NASA not pursuing the development is three years.

The satellite capacity is considered to increase by 2% (of the 1982 capacity) and the satellite cost by $125 thousand at the time of the introduction of the technology. Improved attitude (pointing) control is assumed to result in a 1 dB increase in assured S/N within the antenna beam. Since the channel capacity is proportional to log (1 + S/N), an increase of S/N from 20 dB to 21 dB results in a 2% increase in channel capacity.

Calculation of the equivalent annual benefit (EAB) for the NASA sponsored development of the technology is based on the fractional satellite launch schedules of Tables 13.12 and 13.13, for introduction in 1982 and 1985 respectively, of the sensors. The sixth column of each table, discounted U. S. - U. S. cost, contains the annual expenditures for satellite purchase and launch, and are the same for Tables 13. 12a and 13.12b except for the years 1982 through 1984.

TABLE 13.11

SCREENING PARAMETERS FOR RF ATTITUDE SENSORS

SCREENING FOR : RF SENSOR TECHNOLOGY

****** INPUT PARAMETERS ARE AS FOLLOWS ******

(COSTS AND BENEFITS IN THOUSANDS OF DOLLARS)

TIME DELAY (YRS)	3.00
DISCOUNT RATE	.06
NASA R&D	
CONDITIONAL PROBABILITY	1.00
ANNUAL BENEFITS	0.00
ANNUAL COSTS	187.50
LENGTH OF INTERVAL (YRS)	4.00
INDUSTRY R&D	
CONDITIONAL PROBABILITY	.80
ANNUAL BENEFITS	0.00
ANNUAL COSTS	150.00
LENGTH OF INTERVAL (YRS)	1.00
INDUSTRY CONSTRUCTION	
CONDITIONAL PROBABILITY	1.00
ANNUAL BENEFITS	0.00
ANNUAL COSTS	150.00
LENGTH OF INTERVAL (YRS)	1.00
OPERATION TIME	
CONDITIONAL PROBABILITY	1.00
ANNUAL BENEFITS	2700.00
ANNUAL COSTS	.00
LENGTH OF INTERVAL (YRS)	10.00

THE NET VALUE (K$) INCLUDING LAG TIME EQUALS --

1727.6

LAUNCH SCENARIO FOR RF ATTITUDE SENSOR TECHNOLOGY INTRODUCTION INTO THE U.S. DOMSAT MARKET

TABLE 13.12a

**** US DOMSAT--1982 INTRODUCTION OF RF ATTITUDE SENSOR TECHNOLOGY ****

YEAR	SATELLITE LIFE (YEARS)	COST PER SATELLITE (M$)	SATELLITE CAPACITY (K CKT/2)	NO. OF LAUNCHES	DISCOUNTED US-US COST (M$)	DISCOUNTED US-FOR COST (M$)
1975	7	35.0	14.0	1.00	35.00	0.00
1976	7	37.6	15.4	.31	11.04	0.00
1977	7	40.4	16.9	.34	12.20	0.00
1978	7	43.5	18.6	.37	13.47	0.00
1979	7	46.7	20.5	.40	14.88	0.00
1980	7	50.2	22.5	.44	16.43	0.00
1981	7	54.0	24.8	.88	32.79	0.00
1982	7	58.2	27.8	1.02	37.64	0.00
1983	7	62.5	30.6	.72	26.48	0.00
1984	7	67.2	33.6	.79	28.77	0.00
1985	8	72.3	36.9	.86	31.25	0.00
1986	8	77.7	40.5	.94	33.93	0.00
1987	8	83.5	44.5	1.03	36.82	0.00
1988	8	89.7	48.9	1.32	47.23	0.00
1989	8	96.5	53.7	1.48	52.52	0.00
1990	8	103.7	59.0	1.42	49.77	0.00
1991	8	111.5	64.9	1.55	53.91	0.00
1992	8	119.8	71.3	1.24	43.01	0.00
1993	8	128.8	78.4	1.76	60.39	0.00
1994	8	138.4	86.2	1.92	65.32	0.30
1995	8	148.8	94.7	2.10	70.60	0.00
1996	8	160.0	104.1	2.39	79.47	0.00
1997	8	171.9	114.5	2.62	86.39	0.00
1998	8	184.8	125.9	2.77	90.13	0.00
1999	8	198.7	138.4	3.02	99.57	0.00
2000	8	213.6	152.2	3.09	103.06	0.00
2001	8	229.6	167.4	3.56	120.25	0.00
2002	8	246.8	184.1	3.89	132.84	0.00
2003	8	265.3	202.4	4.24	146.75	0.00
2004	8	285.2	222.6	4.67	163.68	0.00
2005	8	306.5	244.8	5.11	191.10	0.00

PROJECTED COST OF SATELLITES (INCLUDING LAUNCH)
BETWEEN 1982 AND 1984 FOR U. S. MANUFACTURE
AND U. S. USE - $92.89 MILLION

TABLE 13.12b

**** US DOMSAT--1985 INTRODUCTION OF RF ATTITUDE SENSOR TECHNOLOGY ****

YEAR	SATELLITE LIFE (YEARS)	COST PER SATELLITE (M$)	SATELLITE CAPACITY (K CKT/2)	NO. OF LAUNCHES	DISCOUNTED US-US COST (M$)	DISCOUNTED US-FOR COST (M$)
1975	7	35.0	14.0	1.00	35.00	0.00
1976	7	37.6	15.4	.31	11.04	0.00
1977	7	40.4	16.9	.34	12.20	0.00
1978	7	43.5	18.6	.37	13.47	0.00
1979	7	46.7	20.5	.40	14.88	0.00
1980	7	50.2	22.5	.44	16.43	0.00
1981	7	54.0	24.8	.88	32.79	0.00
1982	7	58.1	27.3	1.04	38.30	0.00
1983	7	62.4	30.0	.73	26.90	0.00
1984	7	67.1	33.0	.80	29.19	0.00
1985	8	72.3	36.9	.86	31.25	0.00
1986	8	77.7	40.5	.94	33.93	0.00
1987	8	83.5	44.5	1.03	36.82	0.00
1988	8	89.7	48.9	1.32	47.23	0.00
1989	8	96.5	53.7	1.48	52.52	0.00
1990	8	103.7	59.0	1.42	49.77	0.00
1991	8	111.5	64.9	1.55	53.91	0.00
1992	8	119.8	71.3	1.24	43.01	0.00
1993	8	128.8	78.4	1.76	60.39	0.00
1994	8	138.4	86.2	1.92	65.32	0.00
1995	8	148.8	94.7	2.10	70.60	0.00
1996	8	160.0	104.1	2.39	79.47	0.00
1997	8	171.9	114.5	2.62	96.39	0.00
1998	8	184.8	125.9	2.77	90.13	0.00
1999	8	198.7	138.4	3.02	99.57	0.00
2000	8	213.6	152.2	3.09	103.06	0.00
2001	8	229.6	167.4	3.56	120.25	0.00
2002	8	246.8	184.1	3.89	132.84	0.00
2003	8	265.3	202.4	4.24	146.75	0.00
2004	8	285.2	222.6	4.67	163.68	0.00
2005	8	306.5	244.8	5.11	181.10	0.00

PROJECTED COST OF SATELLITES (INCLUDING LAUNCH)
BETWEEN 1982 AND 1984 FOR U. S. MANUFACTURE
AND U. S. USE - $94.39 MILLION

LAUNCH SCENARIO FOR RF ATTITUDE SENSOR TECHNOLOGY INTRODUCTION
INTO THE INTELSAT ATLANTIC AND PACIFIC MARKET

TABLE 13.13a

**** INTELSAT ATLANTIC AND PACIFIC--1982 INTRODUCTION OF RF ATTITUDE SENSOR TECHNOLOGY ****

YEAR	SATELLITE LIFE (YEARS)	COST PER SATELLITE (M$)	SATELLITE CAPACITY (K CKT/2)	NO. OF LAUNCHES	DISCOUNTED US-US COST (M$)	DISCOUNTED US-FOR COST (M$)
1975	7	35.0	10.0	1.00	17.50	17.50
1976	7	37.7	11.1	0.00	0.00	0.00
1977	7	40.5	12.3	.30	5.35	5.35
1978	7	43.6	13.7	.31	4.82	4.82
1979	7	46.9	15.2	.86	13.14	13.14
1980	7	50.5	16.9	.83	12.52	12.52
1981	7	54.3	18.7	.37	5.60	5.60
1982	7	58.5	21.3	.86	12.69	12.69
1983	7	63.0	23.6	.41	6.04	6.04
1984	7	67.7	26.3	.58	8.37	8.37
1985	8	72.9	28.9	.62	8.75	8.75
1986	8	78.4	32.1	.91	12.66	12.66
1987	8	84.3	35.5	.92	12.71	12.71
1988	8	90.7	39.4	.74	10.06	10.06
1989	8	97.6	43.6	1.02	13.55	13.55
1990	8	105.0	48.4	.84	10.98	10.98
1991	8	113.0	53.6	.97	12.32	12.32
1992	8	121.5	59.5	.73	9.08	9.08
1993	8	130.7	65.0	1.04	12.74	12.74
1994	8	140.6	73.2	1.22	14.54	14.54
1995	8	151.3	81.2	1.28	14.87	14.87
1996	8	162.8	90.0	1.26	14.21	14.21
1997	8	175.1	99.9	1.44	15.79	15.79
1998	8	188.4	110.8	1.42	15.16	15.16
1999	8	202.7	122.9	1.54	16.66	16.66
2000	8	218.1	136.4	1.51	16.52	16.52
2001	8	234.6	151.3	1.72	19.10	19.10
2002	8	252.4	167.9	1.88	21.12	21.12
2003	8	271.6	186.3	1.99	22.67	22.67
2004	8	292.2	206.8	2.07	23.89	23.89
2005	8	314.3	229.5	2.25	26.25	26.25

PROJECTED COST OF SATELLITES (INCLUDING LAUNCH)
BETWEEN 1982 AND 1984 FOR U. S. MANUFACTURE AND
U. S. USE - $27.10 MILLION

TABLE 13.13b

**** INTELSAT ATLANTIC AND PACIFIC--1985 INTRODUCTION OF RF ATTITUDE SENSOR TECHNOLOGY ****

YEAR	SATELLITE LIFE (YEARS)	COST PER SATELLITE (M$)	SATELLITE CAPACITY (K CKT/2)	NO. OF LAUNCHES	DISCOUNTED US-US COST (M$)	DISCOUNTED US-FOR COST (M$)
1975	7	35.0	10.0	1.00	17.50	17.50
1976	7	37.7	11.1	0.00	0.00	0.00
1977	7	40.5	12.3	.30	5.35	5.35
1978	7	43.6	13.7	.31	4.82	4.82
1979	7	46.9	15.2	.86	13.14	13.14
1980	7	50.5	16.9	.83	12.52	12.52
1981	7	54.3	18.7	.37	5.60	5.60
1982	7	58.4	20.8	.88	13.00	13.00
1983	7	62.8	23.0	.42	6.17	6.17
1984	7	67.6	25.6	.59	8.53	8.53
1985	8	72.9	28.9	.62	8.75	8.75
1986	8	78.4	32.1	.91	12.66	12.66
1987	8	84.3	35.5	.92	12.71	12.71
1988	8	90.7	39.4	.74	10.06	10.06
1989	8	97.6	43.6	1.02	13.55	13.55
1990	8	105.0	48.4	.84	10.98	10.98
1991	8	113.0	53.6	.97	12.32	12.32
1992	8	121.5	59.5	.73	9.08	9.08
1993	8	130.7	66.0	1.04	12.74	12.74
1994	8	140.6	73.2	1.22	14.54	14.54
1995	8	151.3	81.2	1.28	14.87	14.87
1996	8	162.8	90.0	1.26	14.21	14.21
1997	8	175.1	99.9	1.44	15.79	15.79
1998	8	188.4	110.8	1.42	15.16	15.16
1999	8	202.7	122.9	1.54	16.66	16.66
2000	8	218.1	136.4	1.51	16.52	16.52
2001	8	234.6	151.3	1.72	19.10	19.10
2002	8	252.4	167.9	1.88	21.12	21.12
2003	8	271.6	186.3	1.99	22.67	22.67
2004	8	292.2	266.8	2.07	23.89	23.89
2005	8	314.3	229.5	2.25	26.25	26.25

PROJECTED COST OF SATELLITES (INCLUDING LAUNCH)
BETWEEN 1982 AND 1984 FOR U. S. MANUFACTURE AND
U. S. USE - $27.69 MILLION

The difference in the values between the two tables represent the value of early introduction of the technology into the U.S. DOMSAT market. Tables 13.13a and 13.13b present corresponding data for the sensor applications to the Atlantic and Pacific regions of the Intelsat system. The decrease in satellite construction and launch costs associated with the technology appearing early (1982 rather than 1985) is $1.5 million for the DOMSAT application and $.6 million for the INTELSAT Atlantic-Pacific applications, for a total gross benefit of $2.1 million, discounted to 1975. Application of the equation for equivalent annual benefits (EAB) yields an EAB of $2.7 million per year for the assumed 8 year operating interval.

Table 13.11 contains the computer program input parameters for application of the screening methodology to RF attitude sensor technology. The resultant score, or net present value, is $1.7 million. The sensitivity plots which show the effect upon screening score of variations in the assumed values of the input parameters are in Appendix II. With the exception of sensitivity with respect to discount rate, all resulting sensitivities are essentially linear, and a tabulation of their slopes is given in Table 13.14.

Application of the assessment methodology requires specification of lower and upper bounds and the modal value for each of the input parameters utilized in screening, or the mean and standard deviation of each. The analytic approximation used in assessment assumes a Gaussian distribution. Table 13.15 contains the input data used for assessment of the sensor technology. The assessment, or risk analysis, for RF attitude sensors indicates that the assumed Gaussian distribution of the net present value of the technology development has a mean value of $1.7 million and a standard deviation of $391 thousand.

The relative ranking of the technology development programs being evaluated is based upon parameters taken from the cumulative distribution function for the net present values of the technologies. These CDFs are established by a full Monte Carlo simulation using Beta distribution random number generators for the input parameters of the NPV equation. For RF attitude sensor technology, the input parameter ranges are the same as those presented in Table 13.15 of the assessment application. Figure 13.8

TABLE 13.14

SLOPES OF RF ATTITUDE SENSOR NPV SENSITIVITY PLOTS

Variable	Slope
Time Delay	530 k$/year
Annual Cost for Basic R&D	-0.60 k$/k$
Length of Basic R&D Interval	-130 k$/year
Probability of Industry Implementation	2300 k$
Annual Cost for Applied R&D	-0.11 k$/k$
Length of Applied R&D Interval	-120 k$/year
Annual Cost for Industry Construction	-0.1 k$/k$
Length of Industry Construction Interval	-120 k$/year
Annual Benefit	0.67 k$/k$
Length of Operating Interval	140 k$/year

TABLE 13.15

ASSESSMENT PARAMETERS FOR RF ATTITUDE SENSORS

QUICK RISK ANALYSIS FOR :RF ATTITUDE SENSORS

****** INPUT PARAMETERS ARE AS FOLLOWS ******

DISCOUNT RATE .... .06

VARIABLE	INPUT BETA PARAMETERS MIN	MODAL	MAX	COMPUTED MEAN
TIME DELAY (YRS)	2.00	3.00	4.00	3.00
NASA R&D				
CONDITIONAL PROBABILITY	1.00	1.00	1.00	1.00
ANNUAL BENEFITS (K$)	0.00	0.00	0.00	0.00
ANNUAL COSTS (K$)	75.00	187.50	275.00	183.33
INTERVAL LENGTH (YRS)	4.00	4.00	4.00	4.00
INDUSTRY R&D				
CONDITIONAL PROBABILITY	.60	.80	.90	.79
ANNUAL BENEFITS (K$)	0.00	0.00	0.00	0.00
ANNUAL COSTS (K$)	60.00	150.00	225.00	147.50
INTERVAL LENGTH (YRS)	1.00	1.00	1.00	1.00
INDUSTRY CONSTRUCTION				
CONDITIONAL PROBABILITY	1.00	1.00	1.00	1.00
ANNUAL BENEFITS (K$)	0.00	0.00	0.00	0.00
ANNUAL COSTS (K$)	60.00	150.00	225.00	147.50
INTERVAL LENGTH (YRS)	1.00	1.00	1.00	1.00
OPERATION TIME				
CONDITIONAL PROBABILITY	1.00	1.00	1.00	1.00
ANNUAL BENEFITS (K$)	1350.00	2700.00	4050.00	2700.00
ANNUAL COSTS (K$)	.00	.00	.00	.00
INTERVAL LENGTH (YRS)	8.00	10.00	12.00	10.00

THE EXPECTED NET VALUE (K$) EQUALS --

1692.2

STANDARD DEVIATION EQUALS --

391.4

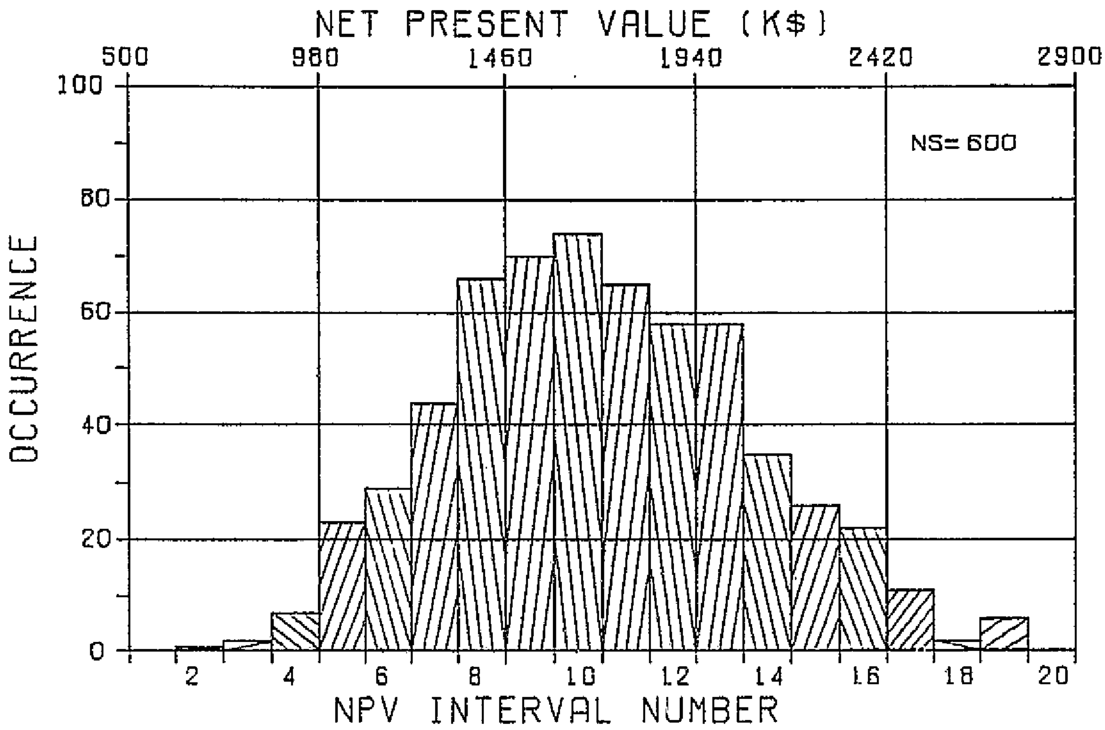


Figure 13.8. RF Attitude Sensor NPV Histogram.

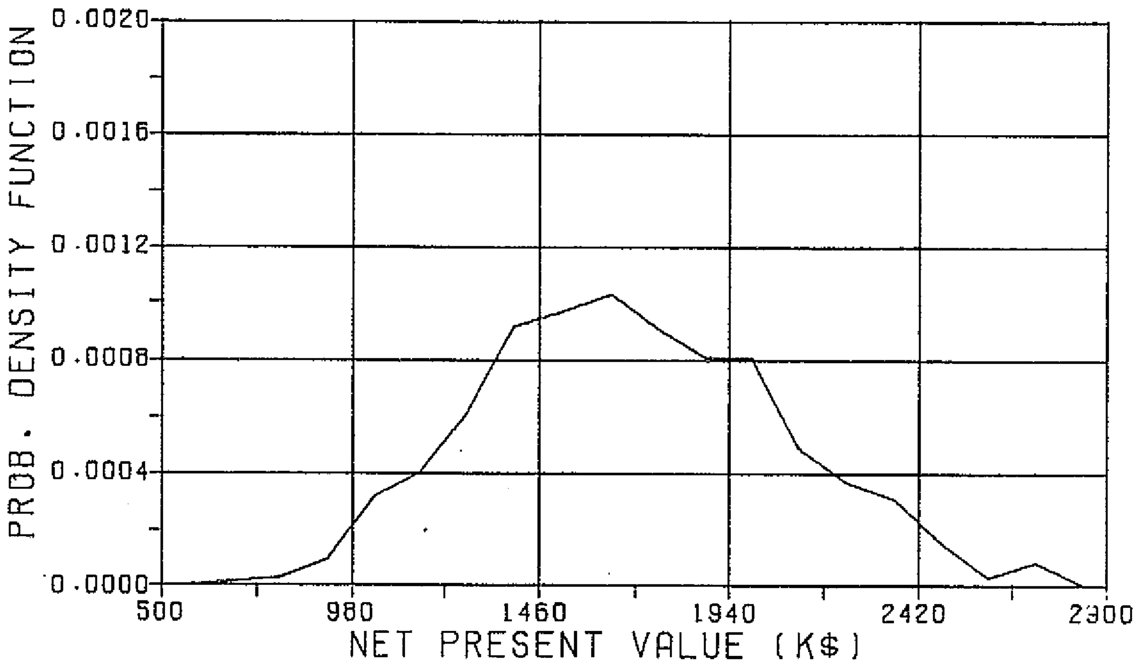


Figure 13.9. RF Attitude Sensor NPV Probability Density.

contains the histogram of the Monte Carlo simulation results. The height of each bar is proportional to the number of sample NPVs occuring within an interval of width $480 thousand. The interval number is labeled at the bottom of the plot, and a scale indicating the actual NPV is at the top of the plot. The histogram indicates that the distribution is essentially unimodal and near-Gaussian in shape. Figure 13.9 displays data of the histogram in a different form: here the data points have been normalized by dividing by the total number of occurrences and by the width of the NPV interval so that the resulting curve represents the probability density function (with unity enclosed area). Figure 13.10 shows a plot of the cumulative distribution function, the integral of the probability density function. It is this cumulative distribution function which supplies the parameters to be used in ranking. For RF attitude sensor technology, it is seen that essentially all of the sample NPVs lie between about $500 thousand and $2.8 million.

13.4 Satellite Solid State Power Amplifiers

Current-technology communication satellites utilize traveling wave tube amplifiers (TWTA) as the final, or power, stage of the transponders. Either low-power, high-gain TWTs or solid state amplifiers may be used to drive the output TWTA, with some present designs using redundant drivers: one solid state and the other a TWT. Solid state power amplifiers are competitive with TWTA's currently up to frequencies of about 6 GHz and power levels of about 5 watts (combined form). Several solid state devices including Inpatts and FETs offer potential for application as power amplifiers in the 12-14 GHz band and above. The development of an FET amplifier for the 12-14 GHz band with a gain of about 4 dB and a power level per device of about 1 watt offers an alternative to low power TWTA's in this new frequency band.

Solid state devices generally offer a longer mean time between failures, a reduced power consumption, and reductions in size and weight when compared with tube technology. For purposes of this cost benefit analysis, it is assumed that the development of a solid state power amplifier for replacement of TWTA's at the 12 GHz band would result in a satellite useful lifetime extension of two years with no significant change in amplifier cost.

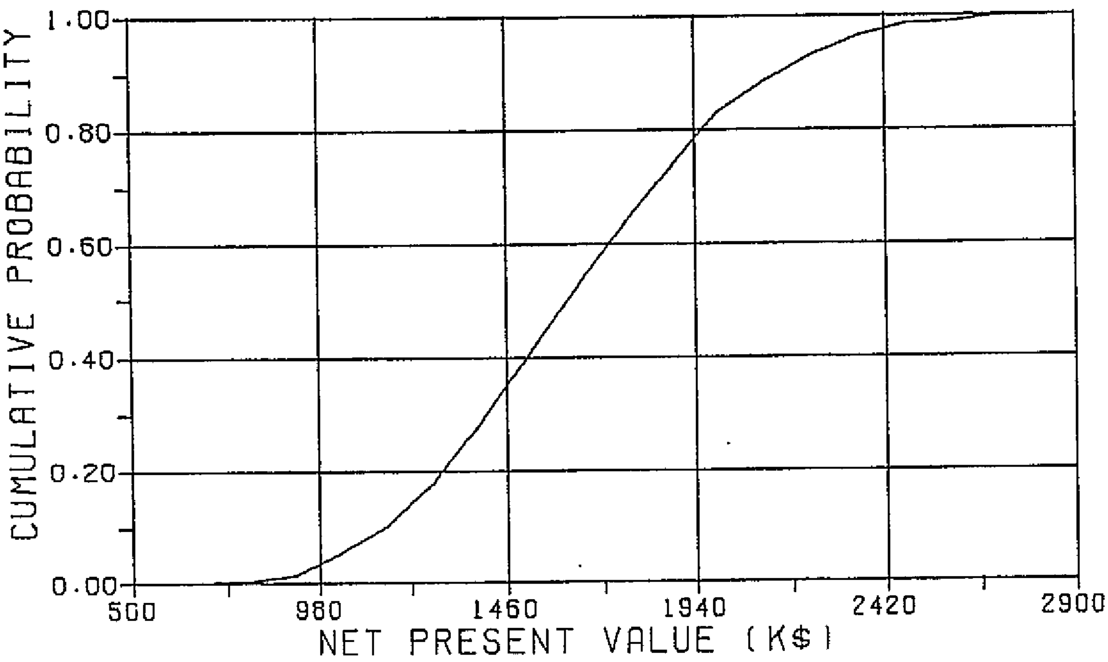


Figure 13.10. RF Attitude Sensor NPV Cumulative Distribution.

As a result of discussions of the impact and development costs of the solid state power amplifiers with industrial and governmental groups, the parameter values shown in Table 13.16 have been selected. It is estimated that the basic research and development program would require 1-5 years and cost $250 thousand. The likelihood of U.S. industry implementing the technology in commercial communication satellites after such a NASA R&D program is estimated at 95%. The application program is estimated to require an industrial expenditure of $240 thousand over a two-year period for applied research and development and prototype development. It is assumed that the technology would continue to be incorporated in communication satellites for ten years after its introduction without significant modifications to the basic technology. It is estimated that the time delay in the availability of the technology resulting from NASA not pursuing its development is four years.

A calculation of the equivalent annual benefit (EAB) for the NASA sponsored development of the solid state power amplifier technology is based on the fractional satellite launch schedules of Tables 13.17 and 13.18. Tables 13.17a and 13.17b correspond to the U.S. DOMSAT market for introduction in 1980 and 1984, respectively, of the technology. Both scenarios correspond to the demand, satellite cost, and satellite capacities of Figures 1-3 except that the satellite lifetime is considered to increase by two years at the time of the introduction of the solid state devices. The sixth column of each table, discounted U.S.-U.S. cost, contains the annual expenditures for satellite purchase and launch. The difference in the values between the two tables represent the value of early introduction of the technology into the U.S. DOMSAT market. Tables 13.18a and 13.18b present corresponding data for solid state amplifier applications to the Atlantic and Pacific regions of the Intelsat system. The savings in satellite construction and launch costs associated with the technology appearing early (1981 rather than 1984) is $16.1 million for the DOMSAT application and $4.9 million for the Intelsat Atlantic-Pacific applications for a total gross benefit of $21 million, discounted to 1975. Application of the equation for equivalent annual benefits (EAB) yields an EAB of $18.3 million per year for the assumed 10-year operating interval.

TABLE 13.16

SCREENING PARAMETERS FOR SOLID STATE POWER AMPLIFIERS

SCREENING FOR :SOLID STATE POWER AMPLIFIERS

****** INPUT PARAMETERS ARE AS FOLLOWS ******

(COSTS AND BENEFITS IN THOUSANDS OF DOLLARS)

TIME DELAY (YRS)	4.00
DISCOUNT RATE	.06
NASA R&D	
CONDITIONAL PROBABILITY	1.00
ANNUAL BENEFITS	0.00
ANNUAL COSTS	167.00
LENGTH OF INTERVAL (YRS)	1.50
INDUSTRY R&D	
CONDITIONAL PROBABILITY	.95
ANNUAL BENEFITS	0.00
ANNUAL COSTS	140.00
LENGTH OF INTERVAL (YRS)	1.50
INDUSTRY CONSTRUCTION	
CONDITIONAL PROBABILITY	1.00
ANNUAL BENEFITS	0.00
ANNUAL COSTS	60.00
LENGTH OF INTERVAL (YRS)	.50
OPERATION TIME	
CONDITIONAL PROBABILITY	1.00
ANNUAL BENEFITS	18300.00
ANNUAL COSTS	.00
LENGTH OF INTERVAL (YRS)	10.00

THE NET VALUE (K$) INCLUDING LAG TIME EQUALS --

22517.5

LAUNCH SCENARIO FOR SATELLITE SOLID STATE POWER AMPLIFIERS INTRODUCTION INTO THE U. S. DOMSAT MARKET

TABLE 13.17a

**** US DOMSAT--1980 INTRODUCTION OF ****
**** SATELLITE SOLID STATE POWER AMPLIFIERS ****

YEAR	SATELLITE LIFE (YEARS)	COST PER SATELLITE (M$)	SATELLITE CAPACITY (K CKT/2)	NO. OF LAUNCHES	DISCOUNTED US-US COST (M$)	DISCOUNTED US-FOR COST (M$)
1975	7	35.0	14.0	1.00	35.00	0.00
1976	7	37.6	15.4	.31	11.04	0.00
1977	7	40.4	16.9	.34	12.20	0.00
1978	7	43.5	18.6	.37	13.47	0.00
1979	7	46.7	20.5	.40	14.88	0.00
1980	9	50.2	22.5	.44	16.43	0.00
1981	9	54.0	24.8	.88	32.79	0.00
1982	9	58.1	27.3	1.04	38.30	0.00
1983	9	62.4	30.0	.73	26.90	0.00
1984	9	67.1	33.0	.80	29.19	0.00
1985	10	72.1	36.3	.87	31.66	0.00
1986	10	77.5	39.9	.95	34.33	0.00
1987	10	83.4	43.9	.81	29.09	0.00
1988	10	89.6	48.3	.89	31.53	0.00
1989	10	96.3	53.2	1.15	40.77	0.00
1990	10	103.6	58.5	1.43	50.14	0.00
1991	10	111.3	64.3	1.59	55.35	0.00
1992	10	119.7	70.8	1.57	54.03	0.00
1993	10	128.7	77.8	1.71	58.43	0.00
1994	10	138.3	85.6	1.49	50.61	0.00
1995	10	148.7	94.2	1.95	65.93	0.00
1996	10	159.8	103.6	2.14	71.25	0.00
1997	10	171.8	114.0	2.25	74.03	0.00
1998	10	184.7	125.4	2.46	79.86	0.00
1999	10	198.6	137.9	2.75	90.58	0.00
2000	10	213.4	151.7	3.07	102.23	0.00
2001	10	229.5	166.9	3.36	113.31	0.00
2002	10	246.7	183.5	3.60	122.91	0.00
2003	10	265.2	201.9	3.92	135.75	0.00
2004	10	285.0	222.1	4.14	144.93	0.00
2005	10	306.4	244.3	4.64	164.66	0.00

PROJECTED COST OF SATELLITES (INCLUDING LAUNCH) BETWEEN 1985 AND 2050 FOR U. S. MANUFACTURE AND U. S. USE - $151,691.23 MILLION

TABLE 13.17b

**** US DOMSAT--1984 INTRODUCTION OF ****
**** SATELLITE SOLID STATE POWER AMPLIFIERS ****

YEAR	SATELLITE LIFE (YEARS)	COST PER SATELLITE (M$)	SATELLITE CAPACITY (K CKT/2)	NO. OF LAUNCHES	DISCOUNTED US-US COST (M$)	DISCOUNTED US-FOR COST (M$)
1975	7	35.0	14.0	1.00	35.00	0.00
1976	7	37.6	15.4	.31	11.04	0.00
1977	7	40.4	16.9	.34	12.20	0.00
1978	7	43.5	18.6	.37	13.47	0.00
1979	7	46.7	20.5	.40	14.88	0.00
1980	7	50.2	22.5	.44	16.43	0.00
1981	7	54.0	24.8	.88	32.79	0.00
1982	7	58.1	27.3	1.04	38.30	0.00
1983	7	62.4	30.0	.73	26.90	0.00
1984	9	67.1	33.0	.80	29.19	0.00
1985	10	72.1	36.3	.87	31.66	0.00
1986	10	77.5	39.9	.95	34.33	0.00
1987	10	83.4	43.9	1.04	37.21	0.00
1988	10	89.6	48.3	1.34	47.69	0.00
1989	10	96.3	53.2	1.50	52.99	0.00
1990	10	103.6	58.5	1.43	50.17	0.00
1991	10	111.3	64.3	1.15	40.02	0.00
1992	10	119.7	70.8	1.25	43.30	0.00
1993	10	128.7	77.8	1.71	58.43	0.00
1994	10	138.3	85.6	1.49	50.61	0.00
1995	10	148.7	94.2	1.96	65.98	0.00
1996	10	159.8	103.6	2.14	71.25	0.00
1997	10	171.8	114.0	2.34	76.90	0.00
1998	10	184.7	125.4	2.63	85.55	0.00
1999	10	198.6	137.9	2.88	94.96	0.00
2000	10	213.4	151.7	3.07	102.24	0.00
2001	10	229.5	166.9	3.19	107.58	0.00
2002	10	246.7	183.5	3.48	118.82	0.00
2003	10	265.2	201.9	3.92	135.75	0.00
2004	10	285.0	222.1	4.14	144.93	0.00
2005	10	306.4	244.3	4.64	164.66	0.00

PROJECTED COST OF SATELLITES (INCLUDING LAUNCH) BETWEEN 1985 AND 2050 FOR U. S. MANUFACTURE AND U. S. USE - $151,707.34 MILLION

LAUNCH SCENARIO FOR SATELLITE SOLID STATE POWER AMPLIFIERS INTRODUCTION INTO THE INTELSAT ATLANTIC AND PACIFIC MARKET

TABLE 13.18a

**** INTELSAT ATLANTIC AND PACIFIC--1980 INTRODUCTION OF SATELLITE SOLID STATE POWER AMPLIFIERS ****

YEAR	SATELLITE LIFE (YEARS)	COST PER SATELLITE (M$)	SATELLITE CAPACITY (K CKT/2)	NO. OF LAUNCHES	DISCOUNTED US-US COST (M$)	DISCOUNTED US-FOR COST (M$)
1975	7	35.0	10.0	1.00	17.50	17.50
1976	7	37.7	11.1	0.00	0.00	0.00
1977	7	40.5	12.3	.30	5.35	5.35
1978	7	43.6	13.7	.31	4.82	4.82
1979	7	46.9	15.2	.86	13.14	13.14
1980	9	50.5	16.9	.83	12.52	12.52
1981	9	54.3	18.7	.37	5.60	5.60
1982	9	58.4	20.8	.88	13.00	13.00
1983	9	62.8	23.0	.42	6.17	6.17
1984	9	67.6	25.6	.59	8.53	8.53
1985	10	72.7	28.4	.63	8.90	8.90
1986	10	78.3	31.5	.92	12.86	12.86
1987	10	84.2	35.0	.54	7.42	7.42
1988	10	90.6	38.8	.57	7.75	7.75
1989	10	97.5	43.1	.93	12.38	12.38
1990	10	104.9	47.8	.80	10.34	10.34
1991	10	112.8	53.1	1.03	13.17	13.17
1992	10	121.4	59.0	.90	11.21	11.21
1993	10	130.6	65.4	1.01	12.34	12.34
1994	10	140.5	72.6	.83	9.87	9.87
1995	10	151.2	80.6	1.10	12.80	12.80
1996	10	162.7	89.5	1.26	14.26	14.26
1997	10	175.0	99.3	1.19	13.03	13.03
1998	10	188.3	110.3	1.26	13.44	13.44
1999	10	202.6	122.4	1.45	15.70	15.70
2000	10	218.0	135.9	1.48	16.15	16.15
2001	10	234.5	150.8	1.64	18.14	18.14
2002	10	252.3	167.4	1.67	18.74	18.74
2003	10	271.4	185.8	1.79	20.41	20.41
2004	10	292.0	206.2	1.82	20.99	20.99
2005	10	314.2	228.9	2.01	23.52	23.52

PROJECTED COST OF SATELLITES (INCLUDING LAUNCH) BETWEEN 1985 AND 2050 FOR U. S. MANUFACTURE AND U. S. USE - $9248.55 MILLION

TABLE 13.18b

**** INTELSAT ATLANTIC AND PACIFIC--1984 INTRODUCTION OF SATELLITE SOLID STATE POWER AMPLIFIERS ****

YEAR	SATELLITE LIFE (YEARS)	COST PER SATELLITE (M$)	SATELLITE CAPACITY (K CKT/2)	NO. OF LAUNCHES	DISCOUNTED US-US COST (M$)	DISCOUNTED US-FOR COST (M$)
1975	7	35.0	10.0	1.00	17.50	17.50
1976	7	37.7	11.1	0.00	0.00	0.00
1977	7	40.5	12.3	.30	5.35	5.35
1978	7	43.6	13.7	.31	4.82	4.82
1979	7	46.9	15.2	.86	13.14	13.14
1980	7	50.5	16.9	.83	12.52	12.52
1981	7	54.3	18.7	.37	5.60	5.60
1982	7	58.4	20.8	.88	13.00	13.00
1983	7	62.8	23.0	.42	6.17	6.17
1984	9	67.6	25.6	.59	8.53	8.53
1985	10	72.7	28.4	.63	8.90	8.90
1986	10	78.3	31.5	.92	12.86	12.86
1987	10	84.2	35.0	.94	12.89	12.89
1988	10	90.6	38.8	.75	10.18	10.18
1989	10	97.5	43.1	1.03	13.71	13.71
1990	10	104.9	47.8	.85	11.09	11.09
1991	10	112.8	53.1	.69	8.79	8.79
1992	10	121.4	59.0	.73	9.15	9.15
1993	10	130.6	65.4	1.01	12.34	12.34
1994	10	140.5	72.6	.83	9.87	9.87
1995	10	151.2	80.6	1.10	12.80	12.80
1996	10	162.7	89.5	1.26	14.26	14.26
1997	10	175.0	99.3	1.33	14.57	14.57
1998	10	188.3	110.3	1.32	14.11	14.11
1999	10	202.6	122.4	1.49	16.09	16.09
2000	10	218.0	135.9	1.50	16.38	16.38
2001	10	234.5	150.8	1.51	16.79	16.79
2002	10	252.3	167.4	1.61	18.09	18.09
2003	10	271.4	185.8	1.79	20.41	20.41
2004	10	292.0	206.2	1.82	20.99	20.99
2005	10	314.2	228.9	2.01	23.52	23.52

PROJECTED COST OF SATELLITES (INCLUDING LAUNCH) BETWEEN 1985 AND 2050 FOR U. S. MANUFACTURE AND U. S. USE - $9253.43 MILLION

The resultant screening score for solid state amplifiers is \$2.3 million. The sensitivity plot slopes are tabulated and given in Table 13.19.

Application from assessment methodology requires specification of a lower and upper bound and Modal value for each of the input parameters utilized in screening, on the mean and standard deviation. The analytic approximation used in assessment assumes a Gaussian distribution. Table 13.20 contains the input data used for assessment of the solid state technology.

The assessment, or risk analysis, for this technology indicates that the assumed Gaussian distribution of the net present value of the technology development has a mean value of \$23 million and a standard deviation of \$5.6 million.

The relative ranking of the technology development programs being evaluated is based upon parameters taken from the cumulative distribution function for the net present values of the technologies. These CDFs are established by a full Monte Carlo simulation using Beta distribution random number generators for the input parameters of the NPV equation. For solid state amplifier technology, the input parameter ranges are the same as those presented in Table 13.20 of the assessment application. Figure 13.11 contains the histogram of the Monte Carlo simulation results. The height of each bar is proportional to the number of sample NPVs occuring within an interval of width \$1.68 million. The interval number is labeled at the bottom of the plot. The histogram indicates that the distribution is essentially unimodal and near-Gaussian in shape. Figure 13.12 displays the data of the histogram in a different form; here the data points have been normalized by dividing by the total number of occurrences and by the width of the NPV interval so that the resulting curve represents the probability density function (with unity enclosed area). Figure 13.13 shows a plot of the cumulative distribution function, the integral of the probability density function. For the satellite solid state power amplifier technology, it is seen that essentially all of the sample NPVs lie between about \$10 million and \$38 million.

TABLE 13.19

SLOPES OF SATELLITE SOLID STATE POWER AMPLIFIER NPV SENSITIVITY PLOTS

Variable	Slope
Time Delay	5100 k$/year
Annual Costs for Basic R&D	-.31 k$/k$
Length of Basic R&D Interval	-5000 k$/year
Probability that Industry will Implement Technology	23,000 k$
Annual Cost During R&D Interval	-.28 k$/k$
Length of Applied R&D Interval	-1400 k$/year
Annual Costs in Industry Construction Interval	-.08 k$/k$
Length of Industry Construction Interval	-1300 k$/year
Annual Benefits	1.25 k$/k$
Length of Operating Interval	1700 k$/year

TABLE 13.20

ASSESSMENT PARAMETERS FOR SOLID STATE POWER AMPLIFIERS

QUICK RISK ANALYSIS FOR :SOLID STATE POWER AMPLIFIERS

****** INPUT PARAMETERS ARE AS FOLLOWS ******

DISCOUNT RATE .... .06

VARIABLE	INPUT BETA PARAMETERS MIN	MODAL	MAX	COMPUTED MEAN
TIME DELAY (YRS)	2.00	4.00	6.00	4.00
NASA R&D				
CONDITIONAL PROBABILITY	1.00	1.00	1.00	1.00
ANNUAL BENEFITS (K$)	0.00	0.00	0.00	0.00
ANNUAL COSTS (K$)	100.00	167.00	250.00	169.67
INTERVAL LENGTH (YRS)	1.50	1.50	1.50	1.50
INDUSTRY R&D				
CONDITIONAL PROBABILITY	.85	.95	1.00	.94
ANNUAL BENEFITS (K$)	0.00	0.00	0.00	0.00
ANNUAL COSTS (K$)	100.00	140.00	250.00	151.67
INTERVAL LENGTH (YRS)	1.50	1.50	1.50	1.50
INDUSTRY CONSTRUCTION				
CONDITIONAL PROBABILITY	1.00	1.00	1.00	1.00
ANNUAL BENEFITS (K$)	0.00	0.00	0.00	0.00
ANNUAL COSTS (K$)	30.00	60.00	90.00	60.00
INTERVAL LENGTH (YRS)	.50	.50	.50	.50
OPERATION TIME				
CONDITIONAL PROBABILITY	1.00	1.00	1.00	1.00
ANNUAL BENEFITS (K$)	10000.00	18300.00	30000.00	18866.67
ANNUAL COSTS (K$)	.00	.00	.00	.00
INTERVAL LENGTH (YRS)	7.00	10.00	13.00	10.00

THE EXPECTED NET VALUE (K$) EQUALS --

23009.7

STANDARD DEVIATION EQUALS --

5610.2

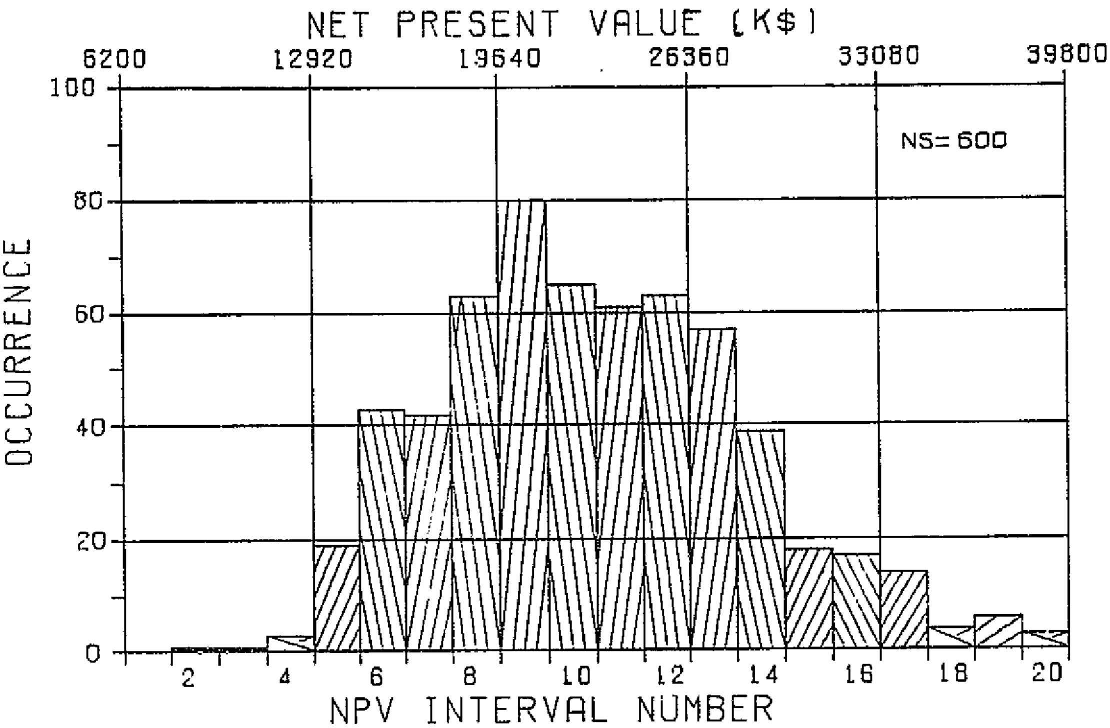


Figure 13.11. Solid State Power Amplifier NPV Histogram.

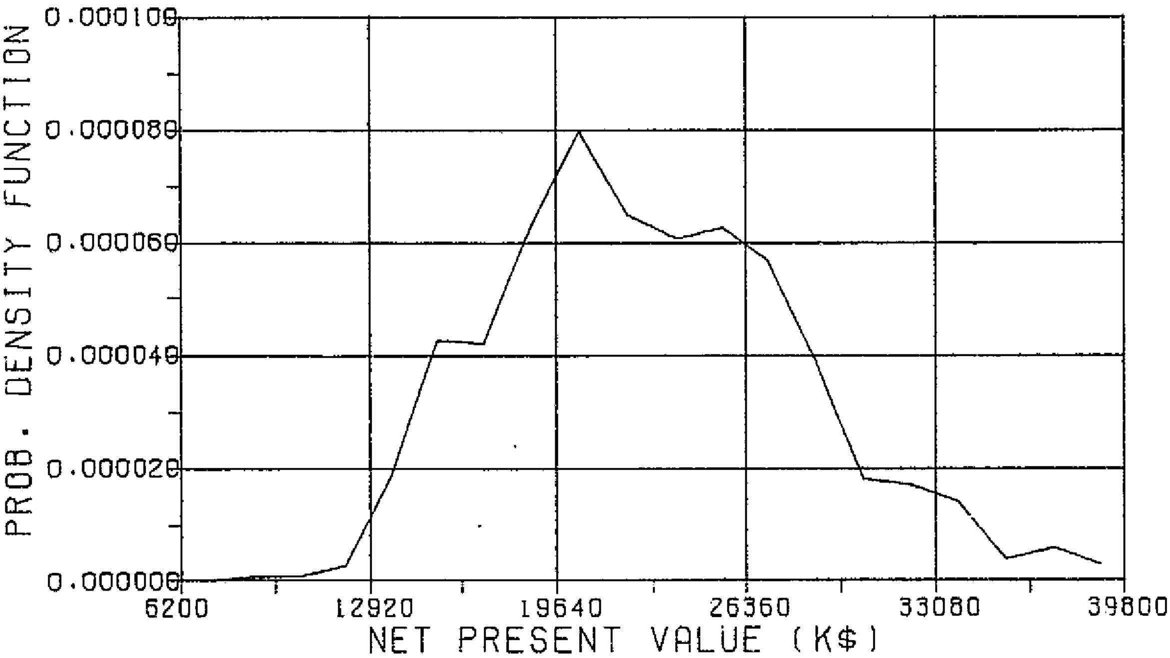


Figure 13.12 . Solid State Power Amplifier NPV Probability Density Function.

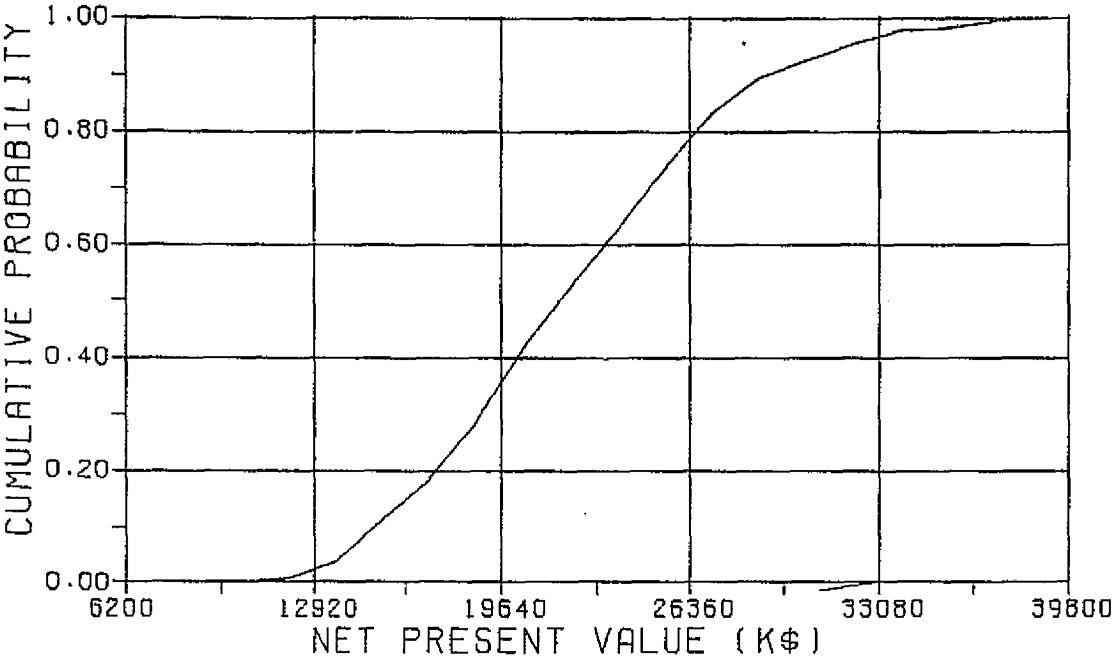


Figure 13.13. Solid State Power Amplifier NPV Cumulative Distribution Function.

13.5 Satellite Multibeam Antennas

Current technology communication satellites use global beam, hemispherical beam, and spot beam antennas. The number of spot beams is small, typically being less than five. The expression "multibeam antenna" is used in this report to refer to a satellite antenna with a large number of beams tightly spaced using orthogonal polarization for adjacent beam isolation and with antenna beam amplitude for isolation between every-other-one of the beams. Such a satellite antenna accomplishes frequency reuse through spatial diversity and has application to a high capacity point-to-point communication satellite for use in the fixed service. Multibeam satellite antenna technology, together with onboard switching, can significantly increase the channel capacity of a satellite. For this cost-benefit analysis, it is assumed that the antenna technology would be responsible for a 25% increase in channel capacity (per satellite) and that the associated increase in cost is 20% of the satellite cost.

As a result of discussions of the impact and development costs of satellite multi-beam antennas with several industrial and governmental groups, the parameter values shown in Table 13.21 have been selected. The basic research and development program is estimated to require two years and cost $2.3 million. The likelihood of U.S. industry implementing the technology in commercial communication satellites after such a NASA R&D program is estimated at 80%. The application program is estimated to require an industrial expenditure of $1.25 million over a two-year period for applied research and development and prototype development. It is assumed that multi-beam antenna technology would continue to be incorporated in communication satellites for fifteen years after its introduction without significant modifications to the basic technology. It is estimated that the time delay in the availability of this technology resulting from NASA not pursuing its development is 8 years.

Calculation of the equivalent annual benefit (EAB) for the NASA sponsored development of multi-beam antenna technology is based on the fractional satellite launch schedules of Tables 13.22 and 13.23. Tables 13.22a and 13.22b correspond to the U.S. DOMSAT market for introduction in 1980 and 1988, respectively, of the advanced antennas. Both scenarios correspond

TABLE 13.21

SCREENING PARAMETERS FOR SATELLITE MULTIBEAM ANTENNA

SCREENING FOR :SATELLITE MULTIBEAM ANTENNA

****** INPUT PARAMETERS ARE AS FOLLOWS ******

(COSTS AND BENEFITS IN THOUSANDS OF DOLLARS)

TIME DELAY (YRS)	8.00
DISCOUNT RATE	.06
NASA R&D	
CONDITIONAL PROBABILITY	1.00
ANNUAL BENEFITS	0.00
ANNUAL COSTS	1500.00
LENGTH OF INTERVAL (YRS)	1.50
INDUSTRY R&D	
CONDITIONAL PROBABILITY	.80
ANNUAL BENEFITS	0.00
ANNUAL COSTS	750.00
LENGTH OF INTERVAL (YRS)	1.00
INDUSTRY CONSTRUCTION	
CONDITIONAL PROBABILITY	1.00
ANNUAL BENEFITS	0.00
ANNUAL COSTS	500.00
LENGTH OF INTERVAL (YRS)	1.00
OPERATION TIME	
CONDITIONAL PROBABILITY	1.00
ANNUAL BENEFITS	2100.00
ANNUAL COSTS	.00
LENGTH OF INTERVAL (YRS)	15.00

THE NET VALUE (K$) INCLUDING LAG TIME EQUALS --

3983.9

LAUNCH SCENARIO FOR SATELLITE MULTIBEAM ANTENNAS INTRODUCTION INTO THE U.S. DOMSAT MARKET

TABLE 13.22a

**** US DOMSAT--1980 INTRODUCTION OF SATELLITE MULTIBEAM ANTENNAS ****

YEAR	SATELLITE LIFE (YEARS)	COST PER SATELLITE (M$)	SATELLITE CAPACITY (K CKT/2)	NO. OF LAUNCHES	DISCOUNTED US-US COST (M$)	DISCOUNTED US-FOR COST (M$)
1975	7	35.0	14.0	1.00	35.00	0.00
1976	7	37.6	15.4	.31	11.04	0.00
1977	7	40.4	15.9	.34	12.20	0.00
1978	7	43.5	18.6	.37	13.47	0.00
1979	7	46.7	20.5	.40	14.88	0.00
1980	7	50.2	29.0	.35	15.84	0.00
1981	7	64.0	30.3	.72	31.80	0.00
1982	7	68.1	32.8	.86	37.36	0.00
1983	7	72.4	35.5	.62	26.37	0.00
1984	7	77.1	38.5	.69	28.75	0.00
1985	8	82.1	41.9	.76	31.31	0.00
1986	8	87.5	45.4	.84	34.07	0.00
1987	8	93.4	49.4	.92	37.04	0.00
1988	8	99.6	53.8	1.29	47.60	0.00
1989	8	105.3	59.7	1.35	53.40	0.00
1990	8	113.6	64.0	1.31	50.29	0.00
1991	8	121.3	69.8	1.44	54.52	0.00
1992	8	129.7	76.3	1.16	43.53	0.00
1993	8	138.7	83.3	1.66	61.15	0.00
1994	8	148.3	91.1	1.82	66.17	0.00
1995	8	158.7	99.7	2.00	71.54	0.00
1996	8	169.9	109.1	2.28	90.54	0.00
1997	8	181.9	119.5	2.52	87.56	0.00
1998	8	194.7	130.9	2.66	91.34	0.00
1999	8	208.6	143.4	2.92	100.91	0.00
2000	8	223.4	157.2	2.99	104.43	0.00
2001	8	239.5	172.4	3.46	121.81	0.00
2002	8	256.7	189.0	3.78	134.53	0.00
2003	8	275.2	207.4	4.14	148.57	0.00
2004	8	295.0	227.6	4.57	165.66	0.00
2005	8	316.4	249.8	5.00	183.22	0.00

PROJECTED COST OF SATELLITES (INCLUDING LAUNCH) BETWEEN 1980 AND 1987 FOR U. S. MANUFACTURE AND U. S. USE - $242.54 MILLION

TABLE 13.22b

**** US DOMSAT--1984 INTRODUCTION OF SATELLITE MULTIBEAM ANTENNAS ****

YEAR	SATELLITE LIFE (YEARS)	COST PER SATELLITE (M$)	SATELLITE CAPACITY (K CKT/2)	NO. OF LAUNCHES	DISCOUNTED US-US COST (M$)	DISCOUNTED US-FOR COST (M$)
1975	7	35.0	14.0	1.00	35.00	0.00
1976	7	37.6	15.4	.31	11.04	0.00
1977	7	40.4	16.9	.34	12.20	0.00
1978	7	43.5	18.6	.37	13.47	0.00
1979	7	46.7	20.5	.40	14.68	0.00
1980	7	50.2	22.5	.44	16.43	0.00
1981	7	54.0	24.8	.98	32.79	0.00
1982	7	58.1	27.3	1.04	39.30	0.00
1983	7	62.4	30.0	.73	26.90	0.00
1984	7	67.1	33.0	.80	29.19	0.00
1985	8	72.1	36.3	.87	31.66	0.00
1986	8	77.5	39.9	.95	34.33	0.00
1987	8	83.4	43.9	1.04	37.21	0.00
1988	8	99.6	53.8	1.20	47.60	0.00
1989	8	106.3	58.7	1.36	53.00	0.00
1990	8	113.5	64.0	1.31	50.29	0.00
1991	8	121.3	69.8	1.44	54.52	0.00
1992	8	129.7	76.3	1.16	43.53	0.00
1993	8	138.7	83.3	1.66	61.15	0.00
1994	8	146.3	91.1	1.82	60.17	0.00
1995	8	158.7	99.7	2.00	71.54	0.00
1996	8	169.8	109.1	2.28	90.54	0.00
1997	8	181.8	119.5	2.52	87.56	0.00
1998	8	194.7	130.9	2.66	91.34	0.00
1999	8	208.6	143.4	2.92	100.91	0.00
2000	8	223.4	157.2	2.99	104.43	0.00
2001	8	239.5	172.4	3.46	121.81	0.00
2002	8	256.7	189.0	3.78	134.53	0.00
2003	8	275.2	207.4	4.14	148.57	0.00
2004	8	295.0	227.6	4.57	165.66	0.00
2005	8	316.4	249.8	5.00	183.22	0.00

PROJECTED COST OF SATELLITES (INCLUDING LAUNCH) BETWEEN 1980 AND 1987 FOR U. S. MANUFACTURE AND U. S. USE - $246.81 MILLION

LAUNCH SCENARIO FOR SATELLITE MULTIBEAM ANTENNAS INTRODUCTION INTO THE INTELSAT ATLANTIC AND PACIFIC MARKET

TABLE 13.23a

**** INTELSAT ATLANTIC AND PACIFIC--1980 INTRODUCTION OF SATELLITE MULTIBEAM ANTENNAS ****

YEAR	SATELLITE LIFE (YEARS)	COST PER SATELLITE (M$)	SATELLITE CAPACITY (K CKT/2)	NO. OF LAUNCHES	DISCOUNTED US-US COST (M$)	DISCOUNTED US-FOR COST (M$)
1975	7	35.0	10.0	1.00	17.50	17.50
1976	7	37.7	11.1	0.00	0.00	0.00
1977	7	40.5	12.3	.30	5.35	5.35
1978	7	43.6	13.7	.31	4.82	4.82
1979	7	46.9	15.2	.86	13.14	13.14
1980	7	60.5	21.1	.66	12.01	12.01
1981	7	64.3	22.9	.31	5.41	5.41
1982	7	68.4	25.0	.73	12.66	12.66
1983	7	72.8	27.2	.36	6.05	6.05
1984	7	77.6	29.8	.51	8.41	8.41
1985	8	82.7	32.6	.55	8.82	8.82
1986	8	88.3	35.7	.81	12.80	12.80
1987	8	94.2	39.2	.84	12.87	12.87
1988	8	100.6	43.0	.69	10.20	10.20
1989	8	107.5	47.3	.94	13.77	13.77
1990	8	114.9	52.0	.78	11.17	11.17
1991	8	122.8	57.3	.90	12.54	12.54
1992	8	131.4	63.2	.68	9.24	9.24
1993	8	140.6	69.6	.99	12.98	12.98
1994	8	150.5	76.8	1.16	14.82	14.82
1995	8	161.2	84.8	1.22	15.16	15.16
1996	8	172.7	93.7	1.21	14.49	14.49
1997	8	185.0	103.5	1.39	16.10	16.10
1998	8	198.3	114.5	1.38	15.45	15.45
1999	8	212.6	126.6	1.50	16.97	16.97
2000	8	228.0	140.1	1.47	16.81	16.81
2001	8	244.5	155.0	1.68	19.44	19.44
2002	8	262.3	171.6	1.84	21.48	21.48
2003	8	281.4	190.0	1.95	23.04	23.04
2004	8	302.0	210.4	2.03	24.27	24.27
2005	8	324.2	233.1	2.21	26.65	26.65

PROJECTED COST OF SATELLITES (INCLUDING LAUNCH) BETWEEN 1980 AND 1987 FOR U. S. MANUFACTURE AND U. S. USE - $79.03 MILLION

TABLE 13.23b

**** INTELSAT ATLANTIC AND PACIFIC--1985 INTRODUCTION OF SATELLITE MULTIBEAM ANTENNAS ****

YEAR	SATELLITE LIFE (YEARS)	COST PER SATELLITE (M$)	SATELLITE CAPACITY (K CKT/2)	NO. OF LAUNCHES	DISCOUNTED US-US COST (M$)	DISCOUNTED US-FOR COST (M$)
1975	7	35.0	10.0	1.00	17.50	17.50
1976	7	37.	11.1	0.00	0.00	0.00
1977	7	40.5	12.3	.30	5.35	5.35
1978	7	43.6	13.7	.31	4.82	4.82
1979	7	46.9	15.2	.86	13.14	13.14
1980	7	50.5	16.9	.83	12.52	12.52
1981	7	54.3	18.7	.37	5.60	5.60
1982	7	58.4	20.8	.88	13.00	13.00
1983	7	62.8	23.0	.42	6.17	6.17
1984	7	67.6	25.6	.59	8.53	8.53
1985	8	72.7	28.4	.63	8.90	8.90
1986	8	78.3	31.5	.92	12.86	12.86
1987	8	84.2	35.0	.94	12.89	12.89
1988	8	100.6	43.0	.68	10.20	10.20
1989	8	107.5	47.3	.94	13.77	13.77
1990	8	114.9	52.0	.78	11.17	11.17
1991	8	122.8	57.3	.90	12.54	12.54
1992	8	131.4	63.2	.68	9.24	9.24
1993	8	140.6	69.6	.99	12.98	12.98
1994	8	150.5	76.8	1.16	14.82	14.82
1995	8	161.2	84.8	1.22	15.16	15.16
1996	8	172.7	93.7	1.21	14.49	14.49
1997	8	185.0	103.5	1.39	16.10	16.10
1998	8	198.3	114.5	1.38	15.45	15.45
1999	8	212.6	126.6	1.50	16.97	16.97
2000	8	228.0	140.1	1.47	16.81	16.81
2001	8	244.5	155.0	1.68	19.44	19.44
2002	8	262.3	171.6	1.84	21.48	21.48
2003	8	281.4	190.0	1.95	23.04	23.04
2004	8	302.0	210.4	2.03	24.27	24.27
2005	8	324.2	233.1	2.21	26.65	26.65

PROJECTED COST OF SATELLITES (INCLUDING LAUNCH) BETWEEN 1980 AND 1987 FOR U. S. MANUFACTURE AND U. S. USE - $80.46 MILLION

to the demand, satellite cost, and satellite capacities of Figures 10.1 - 10.3 except that the satellite capacity is considered to increase by 25% and the satellite cost by 20% at the time of the introduction of the technology (the increases are based upon 1980 capacity and cost). The sixth column of each table, discounted U.S.-U.S. cost, contains the annual expenditures for satellite purchase and launch, and are the same for Tables 13.22a and 13.22b except for the years 1980 through 1987. The differences in the values between the two tables represent the value of early introduction of the technology into the U.S. DOMSAT market. Tables 13.23a and 13.23b present corresponding data on multi-beam antenna applications to the Atlantic and Pacific regions of the Intelsat system. The decrease in satellite construction and launch costs associated with the technology appearing early (1980 rather than 1988) is $4.3 million for the DOMSAT application and $1.4 million for the Intelsat Atlantic-Pacific applications, for a total gross benefit of $5.7 million, discounted to 1975. Application of the equation for equivalent annual benefits (EAB) yields an EAB of $2.1 million per year for the assumed 15-year operating interval.

The resultant screening score is $4 million. Sensitivity plots which show the effect upon this screening score (NPV) of variations in the assumed values of the input parameters are in Appendix II. A tabulation of the slopes of the sensitivity plots is given in Table 13.24.

Application of the assessment methodology requires specification of lower and upper bounds and modal value for each of the input parameters utilized in screening, or the mean and standard deviation of each. The analytic approximation used in assessment assumes Gaussian distributions for the inputs and output. Table 13.25 contains the input data used for assessment of the antenna technology.

The assessment, or risk analysis, for this technology indicates that the assumed Gaussian distribution of the net present value of the technology development has a mean value of $4.1 million and a standard deviation of $1.1 million.

The relative ranking of the technology development programs being evaluated is based upon parameters taken from the cumulative distribution

TABLE 13.24

SLOPES OF MULTIBEAM SATELLITE ANTENNA NPV SENSITIVITY PLOTS

Variable	Slope
Time Delay	430 k$/year
Annual Costs for Basic R&D	-.50 k$/k$
Length of Basic R&D Interval	-750 k$/year
Probability that Industry will Implement the Technology	5800 k$
Annual Costs During Applied R&D Interval	-.27 k$/k$
Length of Applied R&D Interval	-500 k$/year
Annual Costs in Industry Construction Interval	-.26 k$/k$
Length of Industry Construction Interval	-400 k$/year
Annual Benefits	2.2 k$/k$
Length of Operating Interval	290 k$/year

TABLE 13.25

ASSESSMENT PARAMETERS FOR SATELLITE MULTIBEAM ANTENNAS

QUICK RISK ANALYSIS FOR :SATELLITE MULTIBEAM ANTENNAS

****** INPUT PARAMETERS ARE AS FOLLOWS ******

DISCOUNT RATE .... .06

VARIABLE	INPUT BETA PARAMETERS MIN	MODAL	MAX	COMPUTED MEAN
TIME DELAY (YRS)	6.00	8.00	10.00	8.00
NASA R&D				
CONDITIONAL PROBABILITY	1.00	1.00	1.00	1.00
ANNUAL BENEFITS (K$)	0.00	0.00	0.00	0.00
ANNUAL COSTS (K$)	750.00	1500.00	2250.00	1500.00
INTERVAL LENGTH (YRS)	1.50	1.50	1.50	1.50
INDUSTRY R&D				
CONDITIONAL PROBABILITY	.70	.80	.90	.80
ANNUAL BENEFITS (K$)	0.00	0.00	0.00	0.00
ANNUAL COSTS (K$)	375.00	750.00	1125.00	750.00
INTERVAL LENGTH (YRS)	1.00	1.00	1.00	1.00
INDUSTRY CONSTRUCTION				
CONDITIONAL PROBABILITY	1.00	1.00	1.00	1.00
ANNUAL BENEFITS (K$)	0.00	0.00	0.00	0.00
ANNUAL COSTS (K$)	250.00	500.00	750.00	500.00
INTERVAL LENGTH (YRS)	1.00	1.00	1.00	1.00
OPERATION TIME				
CONDITIONAL PROBABILITY	1.00	1.00	1.00	1.00
ANNUAL BENEFITS (K$)	1000.00	2100.00	3500.00	2150.00
ANNUAL COSTS (K$)	.00	.00	.00	.00
INTERVAL LENGTH (YRS)	12.00	15.00	18.00	15.00

THE EXPECTED NET VALUE (K$) EQUALS --

4106.2

STANDARD DEVIATION EQUALS --

1110.3

function for the net present values of the technologies. These CDFs are established by a full Monte Carlo simulation using Beta distribution random number generators for the input parameters of the NPV equation. For the antenna technology, the input parameter ranges are the same as those presented in Table 13.25 of the assessment application. Figure 13.14 contains the histogram of the Monte Carlo simulation results. The height of each bar is proportional to the number of sample NPVs occuring within an interval of width $330 thousand. The interval number is labeled at the bottom of the plot, and a scale indicating the actual NPV is at the top of the plot. The histogram indicates that the distribution is essentially unimodal and near-Gaussian in shape. Figure 13.15 displays the data of the histogram in a different form; here the data points have been normalized by dividing by the total number of occurrences and by the width of the NPV interval so that the resulting curve represents the probability density function (with unity enclosed area). Figure 13.16 shows a plot of the cumulative distribution function, the integral of the probability density function. It is this cumulative distribution function which supplies the parameters to be used in ranking this technology against other technologies being considered. For the multi-beam antenna technology, it is seen that essentially all of the sample NPVs lie between about $1.5 million and $7 million.

13.6 Advanced Solar Arrays

Electric power for communication satellites may be generated either by solar cell arrays or by nuclear reactors. Previous studies have indicated that the nuclear technology is competitive only if the power requirements of the satellite exceed 10 kilowatts. Communication satellites currently in orbit utilize a conventional solar cell which is only approximately 10% efficient in converting the available solar power into electrical power. Improvements in this basic solar cell, primarily at COMSAT Labs, have resulted in development in the violent cell and of the black cell which has an efficiency of about 15%. These latter two cell types, however, are still not available on a production basis.

The cost for the electric power system for a typical communication satellite is around two million dollars (including the batteries) for a

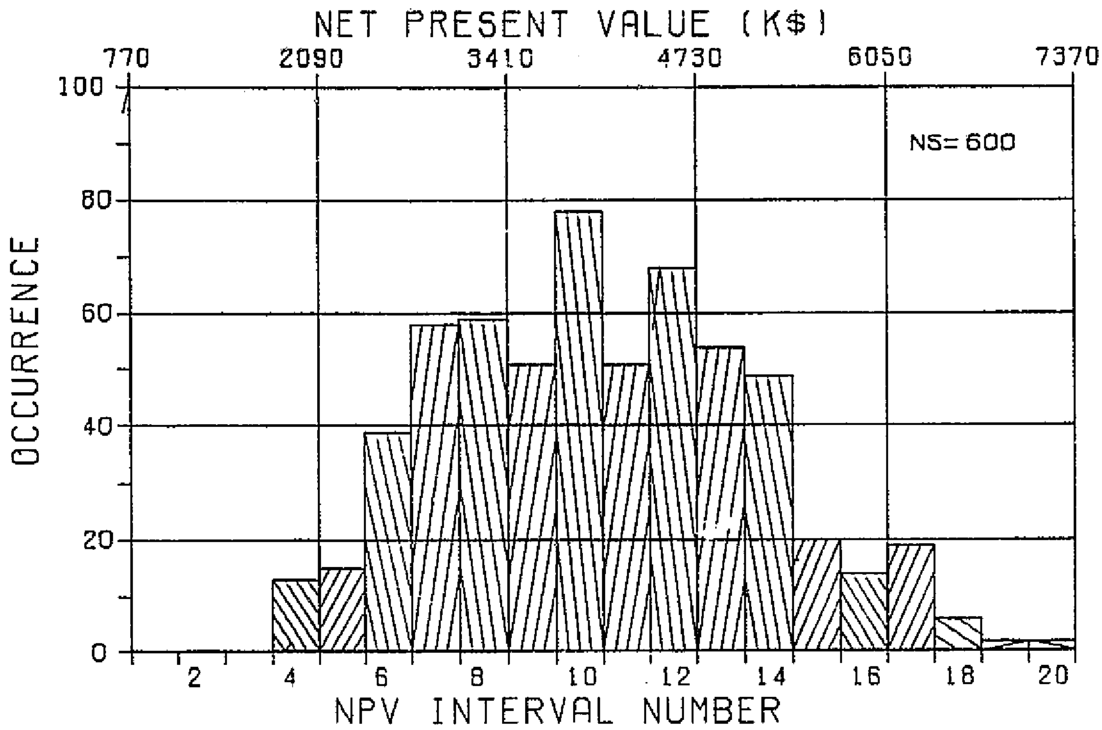


Figure 13.14. Satellite Multibeam Antenna NPV Histogram.

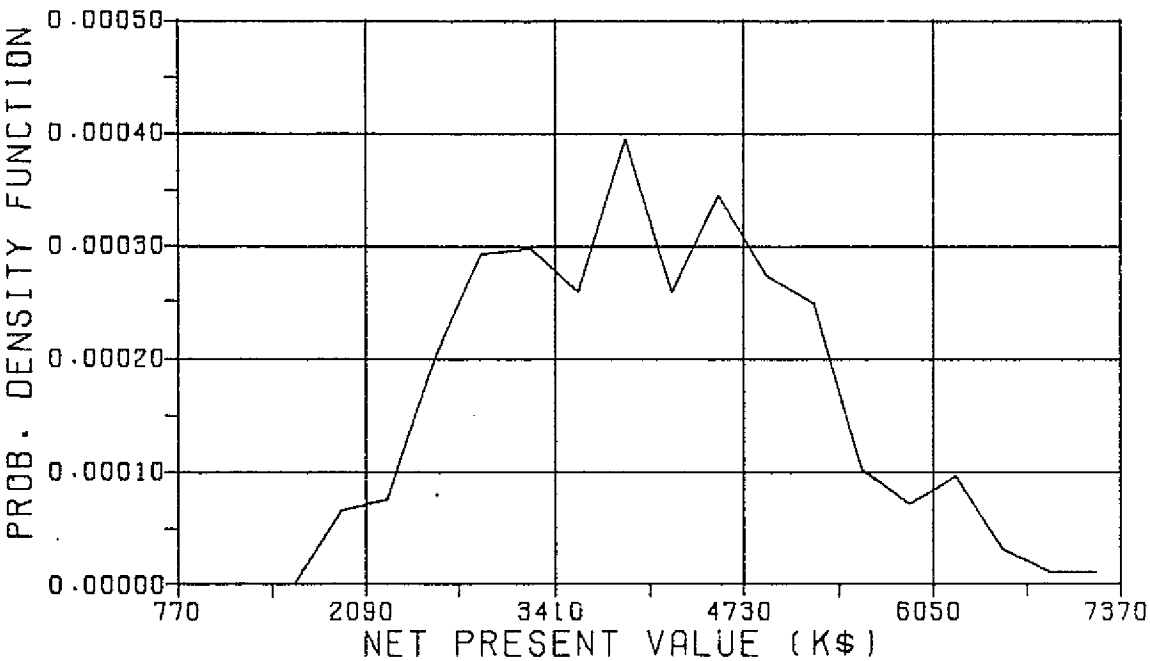


Figure 13.15. Satellite Multibeam Antenna NPV Probability Density Function.

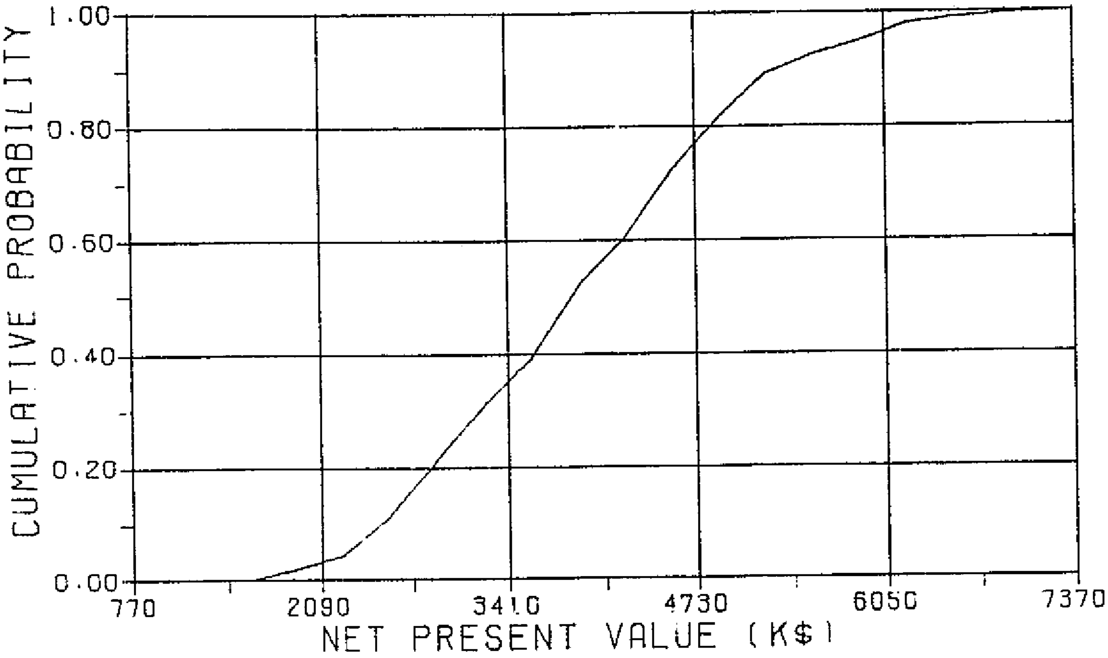


Figure 13.16. Satellite Multibeam Antenna NPV Cumulative Distribution Function

one kilowatt power system. Incremental increases in the efficiency of available solar cells result in significant savings in the cost of a communication satellite. For purposes of cost-benefit analysis, an advanced solar cell technology program directed at further increasing the solar cell and solar array efficiency so as to result in a 10% cost reduction of the power system is assumed.

As a result of the discussions of the impact and development costs of advanced solar cells with several industrial and governmental groups, the parameter values shown in Table 13.26 have been selected. The basic research and development program is estimated to require two years and cost 500 thousand dollars. The likelihood of U.S. industry implementing the technology in commercial communication satellites after such a NASA R&D program is estimated at 95%. The application program is estimated to require an industrial expenditure of 175 thousand dollars over a two-year period for applied research and development and prototype development. It is assumed that the solar cell technology would continue to be incorporated in communication satellites for ten years after its introduction without significant modifications to the basic technology. Since solar cell technology is at a reasonably advanced stage, it is estimated that the time delay in its availability resulting from NASA not pursing its development is only five years.

Calculation of the equivalent annual benefit (EAB) for the NASA sponsored development of solar cell technology is based on the fractional satellite launch schedules of Tables 13.27 and 13.28. Tables 13.27a and 13.27b correspond to the U.S. DOMSAT market for introduction in 1980 and 1985, respectively, of the advanced solar cells. Both scenarios correspond to the demand, satellite cost, and satellite capacities of Figures 10.1 - 10.3 except that the satellite cost is assumed to decrease by 200 thousand dollars at the time of the introduction of the advanced solar cells. The decrease in cost corresponds approximately to a 10% reduction in cost of the electric power supply system. The sixth column of each table, discounted U.S.-U.S. cost, contains the annual expenditures for satellite purchase and launch, and are the same for Tables 13.27a and 13.27b except for the years

TABLE 13.26

SCREENING PARAMETERS FOR ADVANCED SOLAR CELLS

SCREENING FOR *ADVANCED SOLAR CELLS

****** INPUT PARAMETERS ARE AS FOLLOWS ******

(COSTS AND BENEFITS IN THOUSANDS OF DOLLARS)

TIME DELAY (YRS)	5.00
DISCOUNT RATE	.06
NASA R&D	
CONDITIONAL PROBABILITY	1.00
ANNUAL BENEFITS	0.00
ANNUAL COSTS	250.00
LENGTH OF INTERVAL (YRS)	2.00
INDUSTRY R&D	
CONDITIONAL PROBABILITY	.95
ANNUAL BENEFITS	0.00
ANNUAL COSTS	100.00
LENGTH OF INTERVAL (YRS)	1.00
INDUSTRY CONSTRUCTION	
CONDITIONAL PROBABILITY	1.00
ANNUAL BENEFITS	0.00
ANNUAL COSTS	75.00
LENGTH OF INTERVAL (YRS)	1.00
OPERATION TIME	
CONDITIONAL PROBABILITY	1.00
ANNUAL BENEFITS	475.00
ANNUAL COSTS	.00
LENGTH OF INTERVAL (YRS)	10.00

THE NET VALUE (K$) INCLUDING LAG TIME EQUALS --

533.5

LAUNCH SCENARIO FOR ADVANCED SOLAR CELLS INTRODUCTION INTO THE U.S. DOMSAT MARKET

TABLE 13.27a

**** US DOMSAT--1980 INTRODUCTION OF ADVANCED SOLAR CELLS ****

YEAR	SATELLITE LIFE (YEARS)	COST PER SATELLITE (M$)	SATELLITE CAPACITY (K CKT/2)	NO. OF LAUNCHES	DISCOUNTED US-US COST (M$)	DISCOUNTED US-FOR COST (M$)
1975	7	35.0	14.0	1.00	35.00	0.00
1976	7	37.6	15.4	.31	11.64	0.00
1977	7	40.4	16.9	.34	12.20	0.00
1978	7	43.5	18.6	.37	13.47	0.00
1979	7	46.7	20.5	.40	14.88	0.00
1980	7	50.0	22.5	.44	16.37	0.00
1981	7	53.3	24.8	.88	32.67	0.00
1982	7	57.9	27.3	1.04	38.17	0.00
1983	7	62.2	30.0	.73	26.81	0.00
1984	7	66.9	33.0	.80	29.10	0.00
1985	8	71.9	36.3	.87	31.57	0.00
1986	8	77.3	39.9	.95	34.24	0.00
1987	8	83.2	43.9	1.04	37.12	0.00
1988	8	89.4	48.3	1.34	47.58	0.00
1989	8	96.1	53.2	1.50	52.88	0.00
1990	8	103.4	58.5	1.43	50.08	0.00
1991	8	111.1	64.3	1.56	54.21	0.00
1992	8	119.5	70.8	1.25	43.22	0.00
1993	8	128.5	77.8	1.78	60.66	0.00
1994	8	138.1	85.6	1.94	65.57	0.00
1995	8	148.5	94.2	2.11	70.85	0.00
1996	8	159.6	103.6	2.40	79.73	0.00
1997	8	171.5	114.0	2.64	86.64	0.00
1998	8	184.5	125.4	2.78	90.36	0.00
1999	8	198.4	137.9	3.03	99.80	0.00
2000	8	213.2	151.7	3.10	103.27	0.00
2001	8	229.3	166.9	3.57	120.47	0.00
2002	8	246.5	183.5	3.90	133.06	0.00
2003	8	265.0	201.9	4.25	146.96	0.00
2004	8	284.8	222.1	4.68	163.89	0.00
2005	8	306.2	244.3	5.12	181.31	0.00

PROJECTED COST OF SATELLITES (INCLUDING LAUNCH) BETWEEN 1980 and 1984 FOR U. S. MANUFACTURE AND U. S. USE - $143.11 MILLION

TABLE 13.27b

**** US DOMSAT--1985 INTRODUCTION OF ADVANCED SOLAR CELLS ****

YEAR	SATELLITE LIFE (YEARS)	COST PER SATELLITE (M$)	SATELLITE CAPACITY (K CKT/2)	NO. OF LAUNCHES	DISCOUNTED US-US COST (M$)	DISCOUNTED US-FOR COST (M$)
1975	7	35.0	14.0	1.00	35.00	0.00
1976	7	37.6	15.4	.31	11.64	0.00
1977	7	40.4	16.9	.34	12.20	0.00
1978	7	43.5	18.6	.37	13.47	0.00
1979	7	46.7	20.5	.40	14.88	0.00
1980	7	50.2	22.5	.44	16.43	0.00
1981	7	54.0	24.8	.88	32.79	0.00
1982	7	58.3	27.3	1.04	38.30	0.00
1983	7	62.4	30.0	.73	26.90	0.00
1984	7	67.1	33.0	.80	29.19	0.00
1985	8	71.9	36.3	.87	31.57	0.00
1986	8	77.3	39.9	.95	34.24	0.00
1987	8	83.2	43.9	1.04	37.12	0.00
1988	8	89.4	48.3	1.34	47.58	0.00
1989	8	96.1	53.2	1.50	52.88	0.00
1990	8	103.4	58.5	1.43	50.08	0.00
1991	8	111.1	64.3	1.56	54.21	0.00
1992	8	119.5	70.8	1.25	43.22	0.00
1993	8	128.5	77.8	1.78	60.66	0.00
1994	8	138.1	85.6	1.94	65.57	0.00
1995	8	148.5	94.2	2.11	70.85	0.00
1996	8	159.6	103.6	2.40	79.73	0.00
1997	8	171.6	114.0	2.64	86.64	0.00
1998	8	184.5	125.4	2.78	90.36	0.00
1999	8	198.4	137.9	3.03	99.80	0.00
2000	8	213.2	151.7	3.10	103.27	0.00
2001	8	229.3	166.9	3.57	120.47	0.00
2002	8	246.5	183.5	3.90	133.06	0.00
2003	8	265.0	201.9	4.25	146.96	0.00
2004	8	284.8	222.1	4.68	163.89	0.00
2005	8	306.2	244.3	5.12	181.31	0.00

PROJECTED COST OF SATELLITES (INCLUDING LAUNCH) BETWEEN 1980 AND 1984 FOR U. S. MANUFACTURE AND U. S. USE - $143.61 MILLION

LAUNCH SCEANRIO FOR ADVANCED SOLAR CELLS INTRODUCTION INTO THE INTELSAT ATLANTIC AND PACIFIC MARKET

TABLE 13.28a

**** INTELSAT ATLANTIC AND PACIFIC--1980 INTRODUCTION OF ADVANCED SOLAR CELLS ****

YEAR	SATELLITE LIFE (YEARS)	COST PER SATELLITE (M$)	SATELLITE CAPACITY (K CKT/2)	NO. OF LAUNCHES	DISCOUNTED US-US COST (M$)	DISCOUNTED US-FOR COST (M$)
1975	7	35.0	10.0	1.00	17.50	17.50
1976	7	37.7	11.1	0.00	0.00	0.00
1977	7	40.5	12.3	.30	5.35	5.35
1978	7	43.6	13.7	.31	4.82	4.82
1979	7	46.9	15.2	.86	13.14	13.14
1980	7	50.3	16.9	.83	12.47	12.47
1981	7	54.1	18.7	.37	5.58	5.58
1982	7	58.2	20.8	.88	12.95	12.95
1983	7	62.6	23.0	.42	6.15	6.15
1984	7	67.4	25.6	.59	8.50	8.50
1985	8	72.5	28.4	.63	8.88	8.88
1986	8	78.1	31.5	.92	12.83	12.83
1987	8	84.0	35.0	.94	12.85	12.85
1988	8	90.4	38.8	.75	10.16	10.16
1989	8	97.3	43.1	1.03	13.68	13.68
1990	8	104.7	47.8	.85	11.07	11.07
1991	8	112.6	53.1	.98	12.41	12.41
1992	8	121.2	59.0	.73	9.13	9.13
1993	8	130.4	65.4	1.05	12.81	12.81
1994	8	140.3	72.6	1.23	14.61	14.61
1995	8	151.0	80.6	1.29	14.94	14.94
1996	8	162.5	89.5	1.26	14.27	14.27
1997	8	174.8	99.3	1.44	15.85	15.85
1998	8	188.1	110.3	1.43	15.21	15.21
1999	8	202.4	122.4	1.55	16.71	16.71
2000	8	217.8	135.9	1.51	16.56	16.56
2001	8	234.3	150.8	1.73	19.14	19.14
2002	8	252.1	167.4	1.89	21.16	21.16
2003	8	271.2	185.8	2.00	22.71	22.71
2004	8	291.8	206.2	2.08	23.93	23.93
2005	8	314.0	228.9	2.25	26.29	26.29

PROJECTED COST OF SATELLITES (INCLUDING LAUNCH) BETWEEN 1980 and 1984 FOR U. S. MANUFACTURE AND U. S. USE - $45.65 MILLION

TABLE 13.28b

**** INTELSAT ATLANTIC AND PACIFIC--1985 INTRODUCTION OF ADVANCED SOLAR CELLS ****

YEAR	SATELLITE LIFE (YEARS)	COST PER SATELLITE (M$)	SATELLITE CAPACITY (K CKT/2)	NO. OF LAUNCHES	DISCOUNTED US-US COST (M$)	DISCOUNTED US-FOR COST (M$)
1975	7	35.0	10.0	1.00	17.50	17.50
1976	7	37.7	11.1	0.00	0.00	0.30
1977	7	40.5	12.3	.30	5.35	5.35
1978	7	43.6	13.7	.31	4.82	4.42
1979	7	46.9	15.2	.86	13.14	13.14
1980	7	50.5	16.9	.83	12.52	12.52
1981	7	54.3	18.7	.37	5.60	5.60
1982	7	58.4	20.8	.89	13.00	13.00
1983	7	62.8	23.0	.42	6.17	6.17
1984	7	67.6	25.6	.59	8.53	8.53
1985	8	72.5	28.4	.63	8.88	8.88
1986	8	78.1	31.5	.92	12.83	12.83
1987	8	84.0	35.0	.94	12.85	12.85
1988	8	90.4	38.8	.75	10.16	10.16
1989	8	97.3	43.1	1.03	13.68	13.68
1990	8	104.7	47.8	.85	11.07	11.07
1991	8	112.6	53.1	.98	12.41	12.41
1992	8	121.2	59.0	.73	9.13	9.13
1993	8	130.4	65.4	1.05	12.81	12.81
1994	8	140.3	72.6	1.23	14.61	14.61
1995	8	151.0	80.6	1.29	14.94	14.94
1996	8	162.5	89.5	1.26	14.27	14.27
1997	8	174.8	99.3	1.44	15.85	15.85
1998	8	188.1	110.3	1.43	15.21	15.21
1999	8	202.4	122.4	1.55	16.71	16.71
2000	8	217.8	135.9	1.51	16.56	16.56
2001	8	234.3	150.8	1.73	19.14	19.14
2002	8	252.1	167.4	1.89	21.16	21.16
2003	8	271.2	185.8	2.00	22.71	22.71
2004	8	291.8	206.2	2.08	23.93	23.93
2005	8	314.0	228.9	2.25	26.29	26.29

PROJECTED COST OF SATELLITES (INCLUDING LAUNCH) BETWEEN 1980 and 1984 FOR U. S. MANUFACTURE AND U. S. USE - $45.81 MILLION

1980 through 1984. The difference in the values between the two tables represent the value of early introduction of the solar cell technology into the U.S. DOMSAT market. Tables 13.28a and 13.28b present corresponding data for advanced solar cell applications to the Atlantic and Pacific regions of the Intelsat system. The decrease in satellite construction and launch costs associated with the technology appearing early (1980 rather than 1985) is 0.5 million dollars for the DOMSAT application and 0.2 million dollars for the Intelsat Altantic-Pacific applications, for a total gross benefit of 0.7 million dollars, discounted to 1975. Application of the equation for equivalent annual benefits (EAB) yields an EAB of 0.43 million dollars per year for the assumed 10-year operating interval.

The resultant screening score for solar cell technology is 0.5 million dollars. Sensitivity plots which show the effect upon this screening score of variations in the assumed values of the input parameters are given in Appendix II. A tabulation of the sensitivity plot slopes is given in Table 13.29.

Application from assessment methodology requires specification of lower and upper bounds and a modal value for each of the input parameters utilized in screening, or mean and standard deviation. The analytic approximation used in assessment assumes a Gaussian distribution for each input and for the output NPV. Table 13.30 contains the input data used for assessment of the advanced solar cell technology.

The assessment, or risk analysis, for solar cells indicates that the assumed Gaussian distribution of the net present value of the technology development has a mean value of 530 thousand dollars and a standard deviation of 112 thousand dollars.

The relative ranking of the technology development programs being evaluated is based upon parameters taken from the cumualtive distribution function for the net present values of the technologies. These CDFs are established by a full Monte Carlo simulation using Beta distribution random number generators for the input parameters of the NPV equation. For solar cell technology, the input parameter ranges are the same as those presented in Table 13.30 of the assessment application. Figure 13.17 contains the histogram of the Monte Carlo simulation results. The height of each bar

TABLE 13.29

SLOPES OF ADVANCED SOLAR CELL NPV SENSITIVITY PLOTS

Variable	Slope
Time Delay	90 k$/year
Annual Costs for Basic R&D	-.5 k$/k$
Length of Basic R&D Interval	-94 k$/year
Probability that Industry will Implement the Technology	670 k$
Annual Costs During Applied R&D Interval	-.2 k$/k$
Length of Applied R&D Interval	-60 k$/year
Annual Costs in Industry Construction Interval	-.2 k$/k$
Length of Industry Construction Interval	-50 k$/year
Annual Benefits	1.4 k$/k$
Length of Operating Interval	50 k$/year

TABLE 13.30

ASSESSMENT PARAMETERS FOR ADVANCED SOLAR CELLS

QUICK RISK ANALYSIS FOR :ADVANCED SOLAR CELLS

****** INPUT PARAMETERS ARE AS FOLLOWS ******

DISCOUNT RATE .... .06

VARIABLE	INPUT BETA PARAMETERS MIN	MODAL	MAX	COMPUTED MEAN
TIME DELAY (YRS)	4.50	5.00	6.50	5.17
NASA R&D				
CONDITIONAL PROBABILITY	1.00	1.00	1.00	1.00
ANNUAL BENEFITS (K$)	0.00	0.00	0.00	0.00
ANNUAL COSTS (K$)	100.00	250.00	500.00	266.67
INTERVAL LENGTH (YRS)	2.00	2.00	2.00	2.00
INDUSTRY R&D				
CONDITIONAL PROBABILITY	.85	.95	1.00	.94
ANNUAL BENEFITS (K$)	0.00	0.00	0.00	0.00
ANNUAL COSTS (K$)	75.00	100.00	200.00	112.50
INTERVAL LENGTH (YRS)	1.00	1.00	1.00	1.00
INDUSTRY CONSTRUCTION				
CONDITIONAL PROBABILITY	1.00	1.00	1.00	1.00
ANNUAL BENEFITS (K$)	0.00	0.00	0.00	0.00
ANNUAL COSTS (K$)	50.00	75.00	150.00	83.33
INTERVAL LENGTH (YRS)	1.00	1.00	1.00	1.00
OPERATION TIME				
CONDITIONAL PROBABILITY	1.00	1.00	1.00	1.00
ANNUAL BENEFITS (K$)	300.00	475.00	650.00	475.00
ANNUAL COSTS (K$)	.00	.00	.00	.00
INTERVAL LENGTH (YRS)	7.00	10.00	13.00	10.00

THE EXPECTED NET VALUE (K$) EQUALS --

530.0

STANDARD DEVIATION EQUALS --

112.3

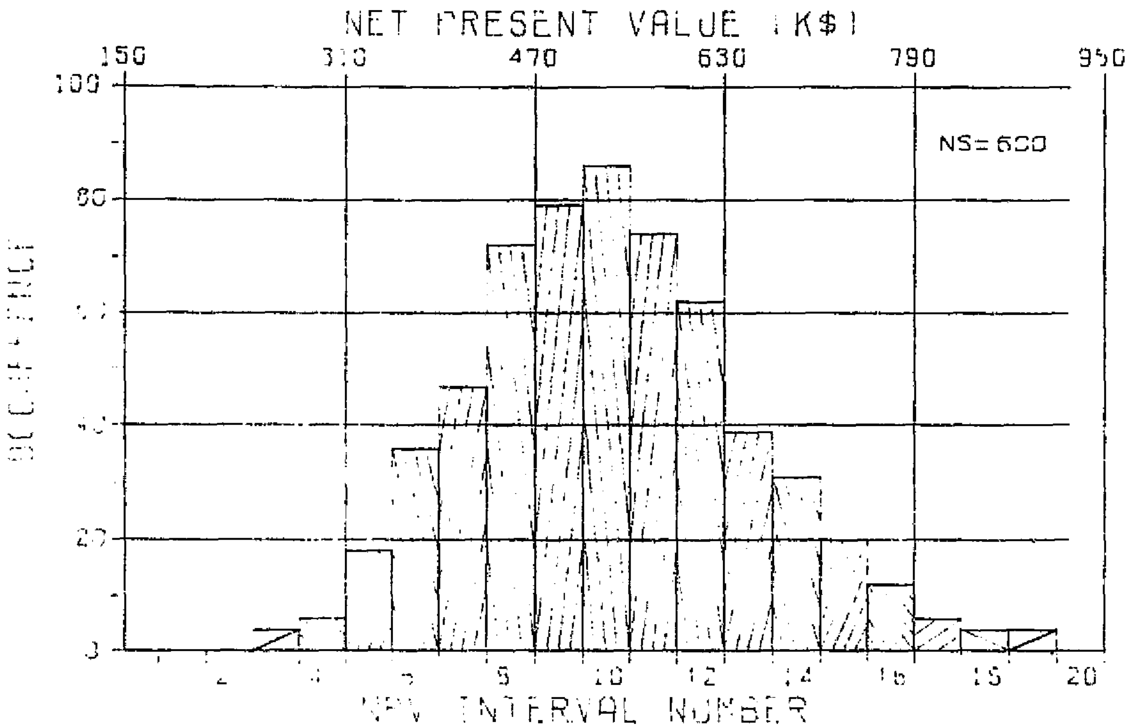


Figure 13.17. Advanced Solar Cell NPV Histogram.

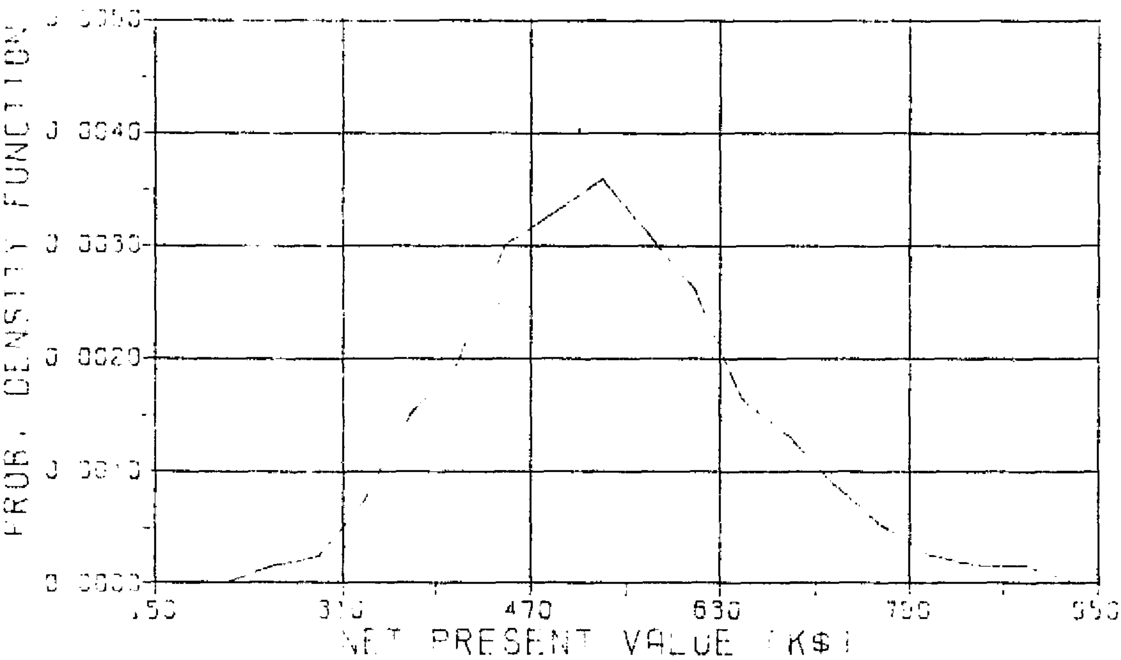


Figure 13.18. Advanced Solar Cell NPV Probability Density Function.

is proportional to the number of sample NPVs occurring within an interval of width 40 thousand dollars. The interval number is labeled at the bottom of the plot, and a scale indicating the actual NPV is at the top of the plot. The histogram indicates that the distribution is essentially unimodal and near-Gaussian in shape. Figure 13.18 displays the data of the histogram in a different form; here the data points have been normalized by dividing by the total number of occurrences and by the width of the NPV interval so that the resulting curve represents the probability density function (with unity enclosed area). Figure 13.19 shows a plot of the cumulative distribution function, the integral of the probability density function. It is this cumulative distribution function which supplies the parameters to be used in ranking this technology against other technologies being considered. For the advanced solar cell technology, it is seen that essentially all of the sample NPVs lie between about 200 thousand and 900 thousand dollars.

13.7 Adaptive Heat Pipes

Heat pipes are now being routinely used to transport heat from heat sources to radiators in satellite thermal control systems. Current developments in heat pipe technology include bent heat pipes and variable conductance heat pipes. The ATS-F satellite contains an advanced thermal control system experiment which utilizes a variable conductance heat pipe and a closed loop temperature control system. While valuable data has been gained from this experiment, the temperature of the controlled region has been significantly greater than the designed value, and the control loop is effective only a portion of the time. Additional effort is required to bring this technology to maturity.

One application area of interest for the closed loop thermal control system with variable conductant heat pipes is temperature control for the satellite battery system. The charging cycle of the battery pack requires a rather close temperature control, and application of a closed loop thermal control system for the batteries can result in increased effective lifetime of the battery system. This in turn allows a higher transmit power near the end of the effective life of the communication satellite. The proposed heat pipe technology program will utilize variable conductance heat pipes in the development of a stable closed loop thermal control system appropriate for use with satellite battery systems.

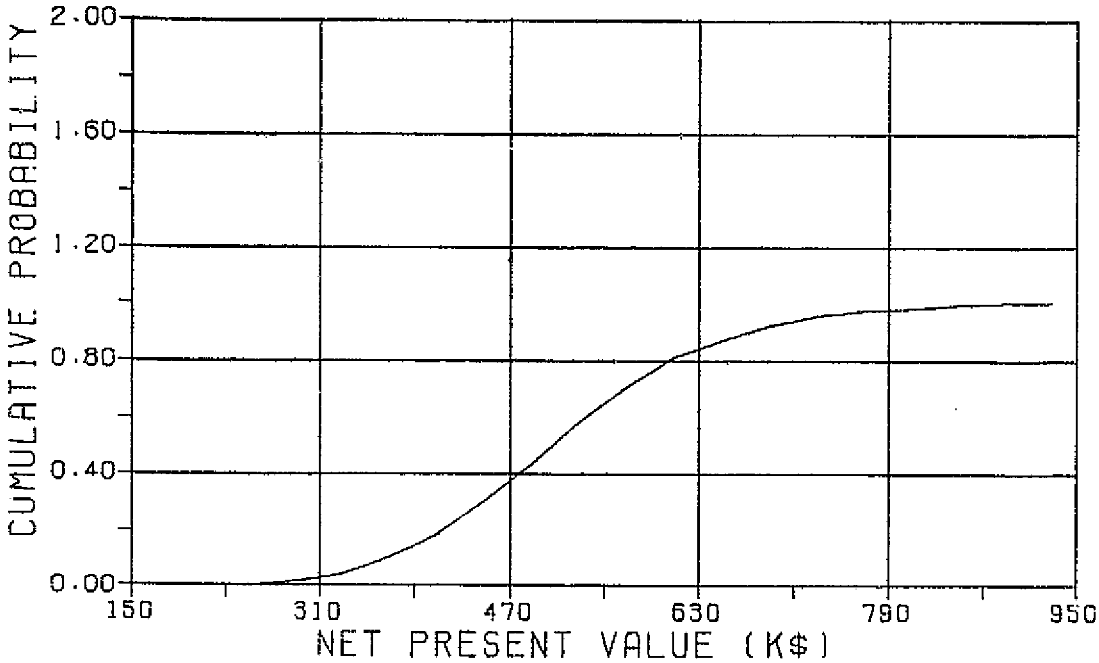


Figure 13.19. Advanced Solar Cell NPV Cumulative Distribution Function.

As a result of the impact and development costs of adaptive heat pipes with several industrial and governmental groups, the parameter values shown in Table 13.31 have been selected. The basic research and development program is estimated to require three years and cost 1.5 million dollars. The likelihood of U. S. industry implementing such heat pipes in commercial communication satellites after such a NASA R&D program is estimated at 80%. The application program is estimated to require an industrial expenditure of 450 thousand dollars over a two-year period for applied research and development and prototype development. It is assumed that adaptive heat pipe technology would continue to be incorporated in communication satellites for 12 years after its introduction without significant modifications to the basic technology. Since adaptive (variable conductance) heat pipe technology is in an early stage of development, it is estimated that the time delay in their availability resulting from NASA not pursing the development is six years.

A calculation of the equivalent annual benefit (EAB) for the NASA sponsored development of the technology is based on the fractional satellite launch schedules of Tables 13.32 and 13.33. Tables 13.32a and 13.32b correspond to the U. S. DOMSAT market for introduction in 1981 and 1987, respectively, of the technology. Both scenarios correspond to the demand, satellite cost, and satellite capacities of Figures 10.1-10.3 except that the satellite capacity is considered to increase by 2% and the satellite cost by 1% at the time of the introduction of the technology. The increase in average capacity is associated with improved battery performance from better temperature control. The sixth column of each table, discounted U.S.-U.S. cost, contains the annual expenditures for satellite purchase and launch, and are the same for Tables 13.32a and 13.32b except for the years 1981 through 1986. The difference in the values between the two tables represent the value of early introduction of adaptive heat pipe technology into the U.S. DOMSAT market. Tables 13.33a and 13.33b present corresponding data for applications to the Atlantic and Pacific regions of the Intelsat system. The decrease in satellite construction and launch costs associated with the technology appearing early (1981 rather than 1987) is 0.5 million dollars for the DOMSAT application and 2.2 million

TABLE 13.31

SCREENING PARAMETERS FOR ADVANCED ADAPTIVE HEAT PIPES

```
SCREENING FOR :ADVANCED ADAPTIVE HEAT PIPES


 ******  INPUT PARAMETERS ARE AS FOLLOWS  ******

   (COSTS AND BENEFITS IN THOUSANDS OF DOLLARS)

TIME DELAY (YRS) ......................        6.00
DISCOUNT RATE .........................         .06

NASA R&D
CONDITIONAL PROBABILITY ...............        1.00
ANNUAL BENEFITS .......................        0.00
ANNUAL COSTS ..........................      500.00
LENGTH OF INTERVAL (YRS) ..............        3.00

INDUSTRY R&D
CONDITIONAL PROBABILITY ...............         .80
ANNUAL BENEFITS .......................        0.00
ANNUAL COSTS ..........................      300.00
LENGTH OF INTERVAL (YRS) ..............        1.00

INDUSTRY CONSTRUCTION
CONDITIONAL PROBABILITY ...............        1.00
ANNUAL BENEFITS .......................        0.00
ANNUAL COSTS ..........................      150.00
LENGTH OF INTERVAL (YRS) ..............        1.00

OPERATION TIME
CONDITIONAL PROBABILITY ...............        1.00
ANNUAL BENEFITS .......................     1525.00
ANNUAL COSTS ..........................         .00
LENGTH OF INTERVAL (YRS) ..............       12.00




THE NET VALUE (K$) INCLUDING LAG TIME EQUALS --

             1835.8
```

LAUNCH SCENARIO FOR ADVANCED ADAPTIVE HEAT PIPES INTRODUCTION INTO THE U.S. DOMSAT MARKET

TABLE 13.32a

**** US DOMSAT--1981 INTRODUCTION OF ADVANCED ADAPTIVE HEAT PIPES ****

YEAR	SATELLITE LIFE (YEARS)	COST PER SATELLITE (M$)	SATELLITE CAPACITY (K CKT/2)	NO. OF LAUNCHES	DISCOUNTED US-US COST (M$)	DISCOUNTED US-FOR COST (M$)
1975	7	35.0	14.0	1.00	35.00	0.00
1976	7	37.6	15.4	.31	11.04	0.00
1977	7	40.4	16.9	.34	12.20	0.00
1978	7	43.5	18.6	.37	13.47	0.00
1979	7	46.7	20.5	.40	14.88	0.00
1980	7	50.2	22.5	.44	16.43	0.00
1981	7	54.5	25.4	.86	32.31	0.00
1982	7	58.6	27.9	1.02	37.90	0.00
1983	7	62.9	30.6	.72	25.58	0.00
1984	7	67.6	33.6	.79	28.98	0.00
1985	8	72.6	36.9	.86	31.36	0.00
1986	8	78.0	40.5	.94	34.64	0.00
1987	8	83.9	44.5	1.02	36.93	0.00
1988	8	90.1	48.9	1.32	47.37	0.00
1989	8	96.8	53.8	1.48	52.67	0.00
1990	8	104.1	59.1	1.42	49.90	0.00
1991	8	111.8	64.9	1.55	54.65	0.00
1992	8	120.2	71.4	1.24	43.11	0.00
1993	8	129.2	78.4	1.76	60.52	0.00
1994	8	138.8	86.2	1.92	65.45	0.00
1995	8	149.2	94.8	2.10	70.74	0.00
1996	8	160.3	104.2	2.39	79.61	0.00
1997	8	172.3	114.6	2.62	86.53	0.00
1998	8	185.2	126.0	2.77	90.27	0.00
1999	8	199.1	138.5	3.02	99.72	0.00
2000	8	213.9	152.3	3.09	103.20	0.00
2001	8	230.0	167.5	3.56	120.40	0.00
2002	8	247.2	184.1	3.98	133.00	0.00
2003	8	265.7	202.5	4.24	146.91	0.00
2004	8	295.5	222.7	4.67	163.85	0.00
2005	8	306.9	244.9	5.10	131.28	0.00

PROJECTED COST OF SATELLITES (INCLUDING LAUNCH) BETWEEN 1981 AND 1986 FOR U. S. MANUFACTURE AND U. S. USE - $190.97 MILLION

TABLE 13.32b

**** US DOMSAT--1987 INTRODUCTION OF ADVANCED ADAPTIVE HEAT PIPES ****

YEAR	SATELLITE LIFE (YEARS)	COST PER SATELLITE (M$)	SATELLITE CAPACITY (K CKT/2)	NO. OF LAUNCHES	DISCOUNTED US-US COST (M$)	DISCOUNTED US-FOR COST (M$)
1975	7	35.0	14.0	1.00	35.00	0.00
1976	7	37.6	15.4	.31	11.04	0.00
1977	7	40.4	16.9	.34	12.20	0.00
1978	7	43.5	18.6	.37	13.47	0.00
1979	7	46.7	20.5	.40	14.88	0.00
1980	7	50.2	22.5	.44	16.43	0.00
1981	7	54.0	24.8	.88	32.79	0.00
1982	7	58.1	27.3	1.04	38.30	0.00
1983	7	62.4	30.0	.73	26.90	0.00
1984	7	67.1	33.0	.80	29.19	0.00
1985	8	72.1	36.3	.87	31.66	0.00
1986	8	77.5	39.9	.95	34.33	0.00
1987	8	83.9	44.5	1.02	36.93	0.00
1988	8	90.1	48.9	1.32	47.37	0.00
1989	8	96.8	53.8	1.48	52.67	0.00
1990	8	104.1	59.1	1.42	49.90	0.00
1991	8	111.8	64.9	1.55	54.65	0.00
1992	8	120.2	71.4	1.24	43.11	0.00
1993	8	129.2	78.4	1.76	60.52	0.00
1994	8	138.8	86.2	1.92	65.45	0.00
1995	8	149.2	94.8	2.10	70.74	0.00
1996	8	160.3	104.2	2.39	79.61	0.00
1997	8	172.3	114.6	2.62	86.53	0.00
1998	8	185.2	126.0	2.77	90.27	0.00
1999	8	199.1	138.5	3.02	99.72	0.00
2000	8	213.9	152.3	3.09	103.20	0.00
2001	8	230.0	167.5	3.56	120.40	0.00
2002	8	247.2	184.1	3.98	133.00	0.00
2003	8	265.7	202.5	4.24	146.91	0.00
2004	8	285.5	222.7	4.67	163.65	0.00
2005	8	306.9	244.9	5.10	181.28	0.00

PROJECTED COST OF SATELLITES (INCLUDING LAUNCH) BETWEEN 1981 AND 1986 FOR U. S. MANUFACTURE AND U. S. USE - $193.16 MILLION

LAUNCH SCENARIO FOR ADVANCED ADAPTIVE HEAT PIPES INTRODUCTION
INTO THE INTELSAT ATLANTIC AND PACIFIC MARKET

TABLE 13.33a

**** INTELSAT ATLANTIC AND PACIFIC--1981 INTRODUCTION OF ADVANCED ADAPTIVE HEAT PIPES ****

YEAR	SATELLITE LIFE (YEARS)	COST PER SATELLITE (M$)	SATELLITE CAPACITY (K CKT/2)	NO. OF LAUNCHES	DISCOUNTED US-US COST (M$)	DISCOUNTED US-FOR COST (M$)
1975	7	35.0	10.0	1.00	17.50	17.50
1976	7	37.7	11.1	0.00	0.00	0.00
1977	7	40.5	12.3	.30	5.35	5.35
1978	7	43.6	13.7	.31	4.82	4.82
1979	7	46.9	15.2	.86	13.14	13.14
1980	7	50.5	16.9	.83	12.52	12.52
1981	7	54.8	19.1	.37	5.53	5.53
1982	7	58.9	21.2	.86	12.86	12.86
1983	7	63.3	23.4	.42	6.11	6.11
1984	7	68.1	26.0	.58	8.46	8.46
1985	8	73.2	28.8	.62	8.84	8.84
1986	8	78.8	31.9	.91	12.78	12.78
1987	8	84.7	35.4	.93	12.82	12.82
1988	8	91.1	39.2	.75	10.14	10.14
1989	8	98.0	43.5	1.02	13.65	13.65
1990	8	105.4	48.2	.85	11.05	11.05
1991	8	113.3	53.5	.97	12.40	12.40
1992	8	121.9	59.4	.73	9.13	9.13
1993	8	131.1	65.8	1.05	12.80	12.80
1994	8	141.0	73.0	1.22	14.60	14.60
1995	8	151.7	81.0	1.28	14.93	14.93
1996	8	163.2	89.9	1.26	14.27	14.27
1997	8	175.5	99.7	1.44	15.85	15.85
1998	8	188.8	110.7	1.42	15.21	15.21
1999	8	203.1	122.8	1.54	[illegible].71	16.71
2000	8	218.5	136.3	1.51	16.56	16.56
2001	8	235.0	151.2	1.72	19.15	19.15
2002	8	252.8	167.8	1.88	21.17	21.17
2003	8	271.9	186.2	1.99	22.71	22.71
2004	8	292.5	206.6	2.07	23.94	23.94
2005	8	314.7	229.3	2.25	26.30	26.30

PROJECTED COST OF SATELLITES (INCLUDING LAUNCH)
BETWEEN 1981 AND 1986 FOR U. S. MANUFACTURE AND
U. S. USE - $54.58 MILLION

TABLE 13.33b

**** INTELSAT ATLANTIC AND PACIFIC--1987 INTRODUCTION OF ADVANCED ADAPTIVE HEAT PIPES ****

YEAR	SATELLITE LIFE (YEARS)	COST PER SATELLITE (M$)	SATELLITE CAPACITY (K CKT/2)	NO. OF LAUNCHES	DISCOUNTED US-US COST (M$)	DISCOUNTED US-FOR COST (M$)
1975	7	35.0	10.0	1.00	17.50	17.50
1976	7	37.7	11.1	0.00	0.00	0.00
1977	7	40.5	12.3	.30	5.35	5.35
1978	7	43.6	13.7	.31	4.82	4.82
1979	7	46.9	15.2	.86	13.14	13.14
1980	7	50.5	16.9	.83	12.52	12.52
1981	7	54.3	18.7	.37	5.60	5.60
1982	7	58.4	20.8	.88	13.00	13.00
1983	7	62.8	23.0	.42	6.17	6.17
1984	7	67.6	25.6	.59	8.53	8.53
1985	8	72.7	28.4	.63	8.90	8.90
1986	8	78.3	31.5	.92	12.86	12.86
1987	8	84.7	35.4	.93	12.82	12.82
1988	8	91.1	39.2	.75	10.14	10.14
1989	8	98.0	43.5	1.02	13.65	13.65
1990	8	105.4	48.2	.85	11.05	11.05
1991	8	113.3	53.5	.97	12.40	12.40
1992	8	121.9	59.4	.73	9.13	9.13
1993	8	131.1	65.8	1.05	12.80	12.80
1994	8	141.0	73.0	1.22	14.60	14.60
1995	8	151.7	81.0	1.28	14.93	14.93
1996	8	163.2	89.9	1.26	14.27	14.27
1997	8	175.5	99.7	1.44	15.85	15.85
1998	8	188.8	110.7	1.42	15.21	15.21
1999	8	203.1	122.8	1.54	16.71	16.71
2000	8	218.5	136.3	1.51	16.56	16.56
2001	8	235.0	151.2	1.72	19.15	19.15
2002	8	252.8	167.8	1.88	21.17	21.17
2003	8	271.9	186.2	1.99	22.71	22.71
2004	8	292.5	206.6	2.07	23.94	23.94
2005	8	314.7	229.3	2.25	26.30	26.30

PROJECTED COST OF SATELLITES (INCLUDING LAUNCH)
BETWEEN 1981 and 1986 FOR U. S. MANUFACTURE AND
U. S. USE - $55.05 MILLION

dollars for the Intelsat Atlantic-Pacific applications, for a total gross benefit of 2.7 million dollars, discounted to 1975. Application of the equation for equivalent annual benefits yields an EAB of 1.5 million dollars per year for the assumed 12-year operating interval.

The resultant screening score for adaptive heat pipes is 1.8 million dollars. Sensitivity plots which show the effect upon this screening score of variations in the assumed values of the input parameters are in Appendix II. A tabulation of the slopes of the plots is given in Table 13.34.

Application of the assessment methodology requires specification of lower and upper bounds and a modal value for each of the input parameters utilized in screening, or the mean and standard deviation. Table 13.35 contains the input data used for assessment of adaptive heat pipes.

The assessment, or risk analysis, for the pipes indicates that the assumed Gaussian distribution of the net present value of the technology development has a mean value of 1.8 million dollars and a standard deviation of 0.5 million dollars.

The relative ranking of the technology development programs being evaluated is based upon parameters taken from the cumulative distribution function for the net present values of the technologies. These CDFs are established by a full Monte Carlo simulation using Beta distribution random number generators for the input parameters of the NPV equation. For the heat pipe technology, the input parameter ranges are the same as those presented in Table 13.35 of the assessment application. Figure 13.20 contains the histogram of the Monte Carlo simulation results. The height of each bar is proportional to the number of sample NPVs occurring within an interval of width 150 thousand dollars. The interval number is labeled at the bottom of the plot, and a scale indicating the actual NPV is at the top, of the plot. The histogram indicates that the distribution is essentially unimodal and near-Gaussian in shape. Figure 13.21 displays the data of the histogram in a different form; here the data points have been normalized by dividing by the total number of occurrences and by the width of the NPV interval so that the resulting

TABLE 13.34

SLOPES OF ADAPTIVE HEAT PIPE NPV SENSITIVITY PLOTS

Variable	Slope
Time Delay	250 k$/year
Annual Costs for Basic R&D	-.75 k$/k$
Length of Basic R&D Interval	-260 k$/year
Probability that Industry will Implement the Technology	2800 k$/year
Annual Costs During Applied R&D Interval	-.19 k$/k$
Length of Applied R&D Interval	-200 k$/year
Annual Costs in Industry Construction Interval	-.19 k$/k$
Length of Industry Construction Interval	-160 k$/year
Annual Benefits	1.5 k$/k$
Length of Operating Interval	140 k$/year

TABLE 13.35

ASSESSMENT PARAMETERS FOR ADVANCED ADOPTIVE HEAT PIPES

QUICK RISK ANALYSIS FOR :ADVANCED ADAPTIVE HEAT PIPES

****** INPUT PARAMETERS ARE AS FOLLOWS ******

DISCOUNT RATE .... .06

VARIABLE	INPUT BETA PARAMETERS MIN	MODAL	MAX	COMPUTED MEAN
TIME DELAY (YRS)	3.00	6.00	9.00	6.00
NASA R&D				
CONDITIONAL PROBABILITY	1.00	1.00	1.00	1.00
ANNUAL BENEFITS (K$)	0.00	0.00	0.00	0.00
ANNUAL COSTS (K$)	167.00	500.00	1000.00	527.83
INTERVAL LENGTH (YRS)	3.00	3.00	3.00	3.00
INDUSTRY R&D				
CONDITIONAL PROBABILITY	.70	.80	.95	.81
ANNUAL BENEFITS (K$)	0.00	0.00	0.00	0.00
ANNUAL COSTS (K$)	200.00	300.00	400.00	300.00
INTERVAL LENGTH (YRS)	1.00	1.00	1.00	1.00
INDUSTRY DEVELOPMENT				
CONDITIONAL PROBABILITY	1.00	1.00	1.00	1.00
ANNUAL BENEFITS (K$)	0.00	0.00	0.00	0.00
ANNUAL COSTS (K$)	100.00	150.00	250.00	158.33
INTERVAL LENGTH (YRS)	1.00	1.00	1.00	1.00
OPERATION TIME				
CONDITIONAL PROBABILITY	1.00	1.00	1.00	1.00
ANNUAL BENEFITS (K$)	760.00	1525.00	2300.00	1526.67
ANNUAL COSTS (K$)	.00	.00	.00	.00
INTERVAL LENGTH (YRS)	9.00	12.00	15.00	12.00

THE EXPECTED NET VALUE (K$) EQUALS --

1837.2

STANDARD DEVIATION EQUALS --

526.2

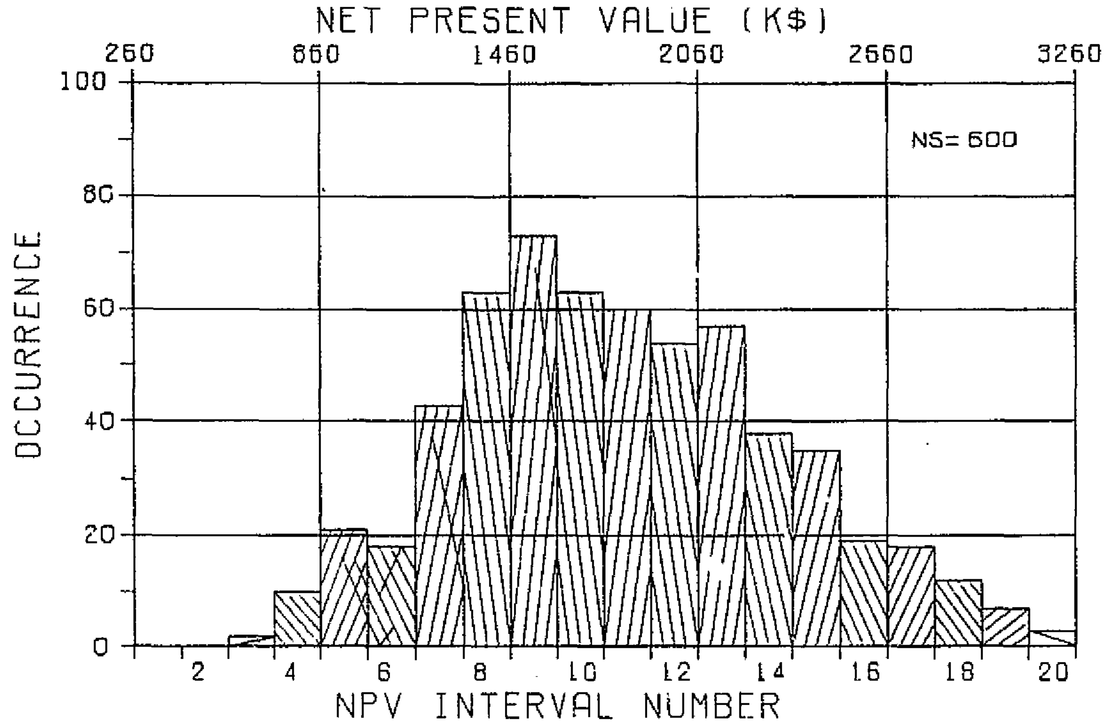


Figure 13.20. Heat Pipe NPV Histogram.

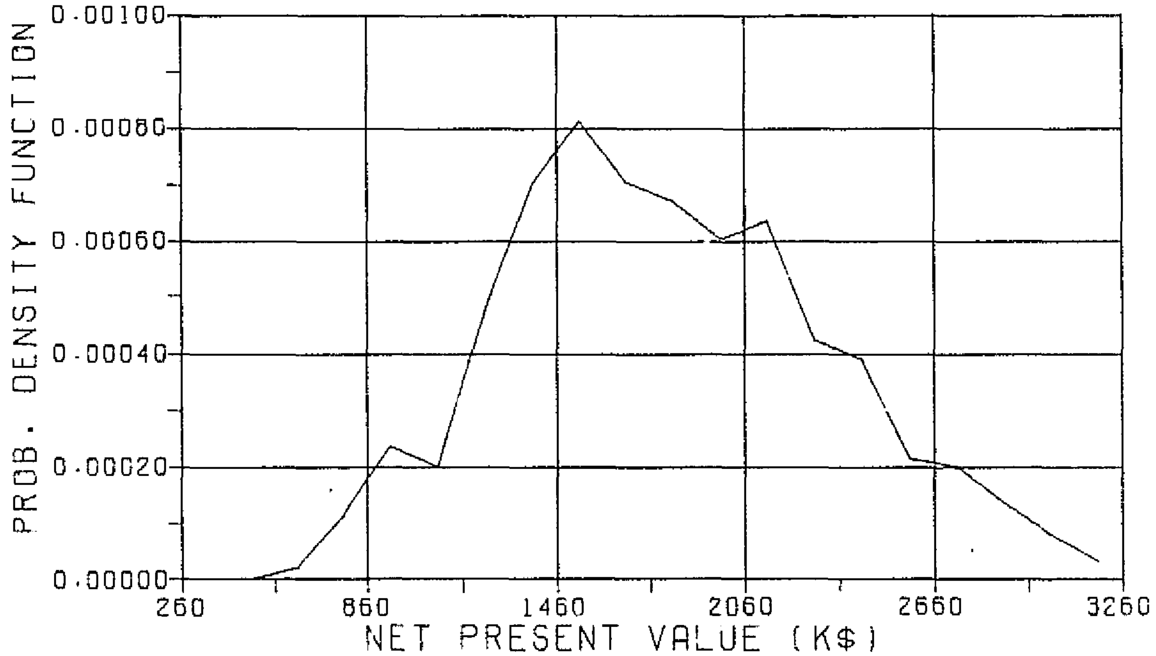


Figure 13.21. Heat Pipe NPV Probability Density Function.

curve represents the probability density function (with unity enclosed area). Figure 13.22 shows a plot of the cumulative distribution function, the integral of the probability density function. It is this cumulative distribution function which supplies the parameters to be used in ranking this technology against other technologies being considered. For the adaptive heat pipe technology, it is seen that essentially all of the sample NPVs lie between about 0.6 million dollars and 3.2 million dollars.

13.8 Summary of Screening and Assessment Results

Screening and assessment methodologies have been applied to nine space communication technologies in Sections 11, 12 and 13. The assessment methodology was applied to each example technology here in order to allow investigation of the consistency of screening and assessment; normal application would result in assessment of only a higher-scoring subset of the screened technologies.

The nine space communication technologies analyzed above are listed in Table 13.36, in decreasing order of screening scores, along with their screening scores (estimated NPV) and their NPV standard deviations as calculated by the approximate Gaussian technique of the assessment methodology. It can be seen from this table that the three top-scoring technologies (millimeter, solid state power amplifier, and low cost earth station) have expected NPVs approximately an order of magnitude greater than the lower-scoring technologies. The millimeter communications technology is estimated to have a 24 million dollar NPV as a result of (1) its significantly increased channel capacity and (2) its long delay time for non-NASA development. The latter factor follows from the very large investment required for development and flight demonstration of the millimeter technology. Solid state power amplifier (14 GHz) technology scored well as a result of the low estimated development cost and associated satellite useful-lifetime extension. The relatively high screening score for the direct demodulation receiver technology for low cost earth stations resulted from the anticipated large number of applications.

Midway in the screening score range are the satellite multibeam antenna and ion engine techologies. The multibeam antenna technology score was held down by the relatively large development cost, while the

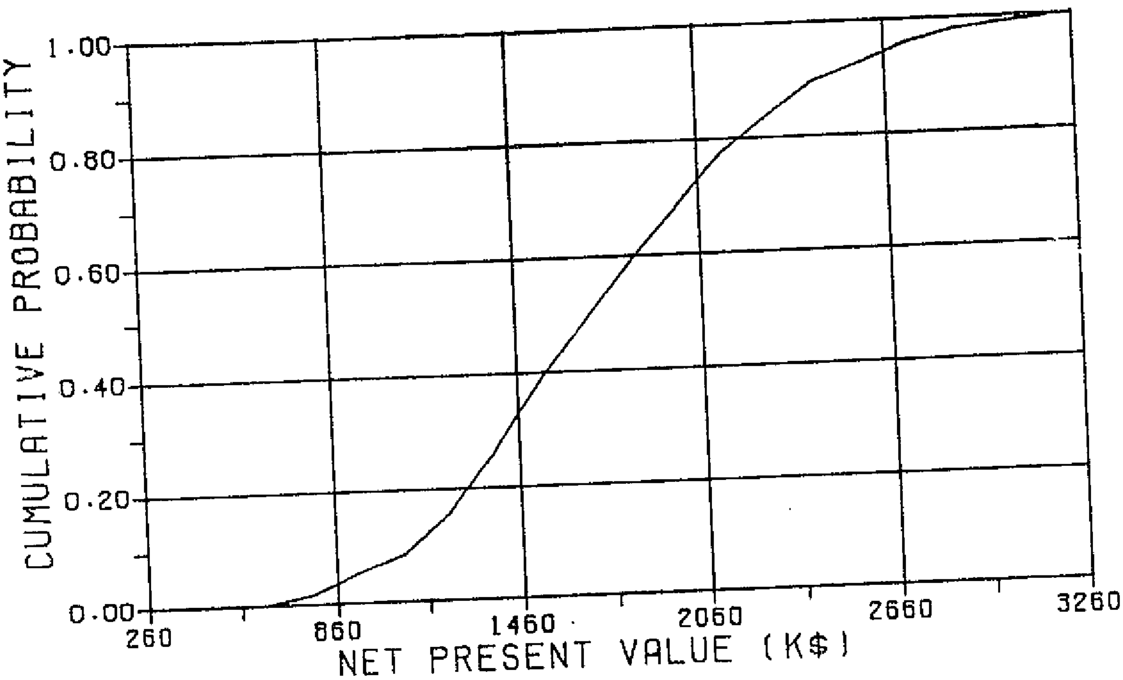


Figure 13.22. Heat Pipe NPV Cumulative Distribution Function.

TABLE 13.36

TECHNOLOGY SCREENING AND ASSESSMENT RESULTS

TECHNOLOGY	SCREENING SCORE NPV(M$)	ASSESSMENT STANDARD DEVIATION (M$)
1. Millimeter Communications System	23.8	11.5
2. Solid State Power Amplifier	22.5	5.6
3. Low Cost Earth Station	10.9	2.1
4. Multibeam Antenna	4.0	1.1
5. Ion Engine	3.2	0.8
6. Adaptive Heat Pipe	1.8	0.5
7. RF Attitude Sensor	1.7	0.4
8. Laser Communication System*	1.1	2.7
9. Advanced Solar Array	0.5	0.1

*Laser system data based upon use of approximate break-even benefits.

ion engine technology score was lowered by the small estimated delay time without NASA support. The score of the laser communication system is not particularly significant since it is based upon an equivalent annual benefit selected near the break-even value in the absence of quantified benefits. It should be noted that the sensitivity plots of Appendix II can be used to recompute the screening score for a change in estimated value of one or more screening input parameters.

In addition to the screening scores, Table 13.36 also contains the approximate (linearized, Gaussian) standard deviation of the technology project NPVs determined by the risk analyses in the assessment methodology. Figure 11. shows the Gaussian PDF and CDF curves as functions of mean (μ) and standard deviation (σ). By using the screening score and standard deviation (assessment) from Table 13.36, one can sketch the approximate NPV PDF and CDF for each of the technologies to gain additional insight into the likely outcomes of the technology development projects. A large standard deviation, relative to the mean, indicates a high degree of uncertainty or difference of opinion among the "experts" polled for the input parameters; it is inversely proportional to the confidence one has in the screening prediction of project value.

SECTION 14
RANKING OF TECHNOLOGIES

Our methodology to this point results in each technology being characterized by its NPV PDF. Ranking of the various technologies implies a ranking of those PDF's. As discussed in our presentation of ranking methodology, a PDF cannot be adequately summarized by a single statistic. Rather, each PDF exhibits a number of potentially equally interesting statistics, e.g., mean, mode, minimum, maximum, standard deviation, range, PROB NPV>K (K=constant), size of confidence intervals, etc. In general, it is one's attitude toward risk which influences which is the most useful ranking statistic.

14.1 Data Summary for Ranking

Table 14.1 presents the raw data for the ranking of the nine technologies. The data is drawn from the PDF and CDF generated by each technology's Monte Carlo simulation. Only the first five ranking criteria are used for ranking in the risk spectrum adopted. Other statistics are included in the table so readers may easily construct new criteria of interest and determine their effects.

14.2 Ranking the Nine Technologies

Following the concept of a risk spectrum developed in the ranking methodology discussion, the nine technologies can be ranked according to statistics which appear to capture the sense of the spectrum points. These points, their associated statistics, and the corresponding rankings are presented in Table 14.2. Needless to say, different statistics may be deemed appropriate for ranking in other circumstances.

Note the similarities in the rankings. For instance, C and E are ranked within the top 3 places under all statistics.

14.3 Relation to Screening

Five rankings of the nine technologies are presented above. An interesting question is the relation of the screening methodology to those rankings. A test of the screening methodology can be based on the degree of similarity between the ranking given by screening alone, and the rankings compiled after more detailed analysis. The screening methodology can be judged successful if its ranking is borne out by the later analysis.

TABLE 14.1

PARAMETERS FOR TECHNOLOGY RANKING

TECHNOLOGY RANKING STATISTICS	A	B	C	D	E	F	G	H	J
Minimum NPV (K$)	490	1600	7800	210	5100	890	-4400	-6100	600
Probability (NPV>0)	1	1	1	1	1	1	.98	.60	1
$\hat{\mu}-\hat{\sigma}$ (K$)	1300	2990	17500	416	8200	2430	12000	-1320	1300
Mean ($\hat{\mu}$) (K$)	1830	4080	23000	533	10400	3200	23100	1000	1690
Maximum NPV (K$)	3200	7200	39000	930	17000	6400	61000	9800	2800
Range (Max-Min) (K$)	2700	5600	31000	720	12000	5500	66000	16000	2200
Standard Deviation ($\hat{\sigma}$) (K$)	529	1080	5490	117	2160	776	11100	2320	390
$\hat{\mu}+\hat{\sigma}$ (K$)	2360	5180	28500	651	12500	3980	34300	3330	2080
Probability (NPV$\geq\hat{\mu}+\hat{\sigma}$)	.13	.02	.12	.12	.14	.09	.12	.10	.07
Mode (K$)	1630	3860	21200	531	10200	2880	19200	1500	1640
90% Confidence Interval:									
Upper Bound (K$)	2700	5900	32000	340	13000	4400	44000	4500	2300
Lower Bound (K$)	920	2300	14000	730	6900	1800	3900	-3500	1000

Letter	Technology
A	Adaptive Heat Pipes
B	Multibeam Satellite Antennas
C	Solid State Power Amplifiers
D	Advanced Solar Arrays
E	Low Cost Earth Station
F	Ion Engines
G	Millimeter Communication System
H	Laser Communication System
J	RF Attitude Sensor

TABLE 14.2

RANKING TECHNOLOGIES

RISK ATTITUDE	STATISTIC	RANKING*								
		1	2	3	4	5	6	7	8	9
Ultra Conservative	MIN NPV	C	E	B	F	J	A	D	G	H
Somewhat Conservative	PROB(NPV>0)	(A	B	C	D	E	F	J)**	G	H
Moderate	$\hat{\mu} - \hat{\sigma}$	C	G	E	B	F	J	A	D	H
Somewhat Risky	$\hat{\mu}$	G	C	E	B	F	A	J	H	D
Very Risky	MAX NPV	G	C	E	H	B	F	A	J	D

*Code letters identifying technologies are based on Table 14.1.

**All tied for first position.

Since the objective here is to compare ordinal rankings, a quantitative method is appropriate. For any two rankings of the same items, the quantitative method should assign a value indicating the degree to which the two rankings agree. Let 0 indicate the greatest possible disagreement, and 1 perfect agreement. Let R_k denote the ranking by criterion k, and r_i^k the rank of the ith technology in the ranking R_k. For example, suppose k=1 is MIN NPV, and k=2 is $\hat{\mu}$. For three technologies A, B, C, the results might be R_1 = B,C,A and R_2 = A,B,C; where the technologies are ranked in descending order of value. A quantitative measure of agreement between R_1 and R_2 is needed. Denote that measure by M, and let

$$M(R_1,R_2) = 1 - \frac{\sum_{i=A}^{C}(r_i^1 - r_i^2)^2}{Z}$$

where $Z = \text{MAXIMUM} \sum_{i=A}^{C}(r_i^1 - r_i^2)^2$

Z is the normalizing factor which scales the last term between 0 and 1. If there is perfect agreement the last term is 0 and $M(R_1,R_2)=1$. If complete disagreement prevails, the last term is 1 and $M(R_1,R_2)=0$. Since the ranking methodologies allow ties, Z must be calculated allowing the possibility of ties. In this case, Z=9 which occurs if R_1=A,B,C and R_2 has B and C tied for first, with A third. Table 14.3 illustrates the calculation. Note that if the rankings simply reversed each other, e.g., A,B,C and C,B,A; Z would equal 8. For the hypothetical rankings given above

$$M(R_1,R_2) = 1 - \frac{1+1+4}{9} = .33$$

indicating a low level of agreement between R_1 and R_2.

A quantitative assessment of the agreement between the screening ranking and final rankings can now be carried out. The calculation of Z for the 9 technology case is shown in Table 14.4. Table 14.5 details the calculations for the relation between screening ranking and MIN NPV ranking. Calculations for the other comparisons are done analogously. The results are summarized in Table 14.6. Note that screening was a

TABLE 14.3

CALCULATION OF Z FOR THE THREE TECHNOLOGY CASES

Technology	Rank under R_1	Rank under R_2	Difference^2
A	1	3	4
B	2	1	1
C	3	1	4
			9 = Z

$$Z = \text{MAX} \sum (r_i^k - r_i^{k'})^2 = (1-3)^2 + (2-1)^2 + (3-1)^2 = 9$$

TABLE 14.4

CALCULATION OF Z FOR THE NINE TECHNOLOGY CASES

Technology	Rank under R_1	Rank under R_2	Difference^2
A	1	9	64
B	1	8	49
C	1	7	36
D	1	6	25
E	5	1	16
F	6	1	25
G	7	1	36
H	8	1	49
J	9	1	64
			364 = Z

$$Z = \text{MAX} \sum (r_i^{k} - r_i^{k'})^2 = (1-9)^2 + \ldots + (9-1)^2 = 364$$

TABLE 14.5

CALCULATION OF M (SCREENING RANKING, MIN NPV RANKING)

Technology	Screening Ranking	MIN NPV Ranking	Difference^2
A	6	6	0
B	4	3	1
C	2	1	1
D	9	7	4
E	3	2	1
F	5	4	1
G	1	8	49
H	8	9	1
J	7	5	4
			TOTAL 62

$$M \text{ (Screening, MIN NPV)} = 1 - \frac{62}{364} = .83$$

TABLE 14.6

MEASURES OF AGREEMENT BETWEEN
THE SCREENING RANKING AND THE FINAL RANKINGS

	MIN NPV	PROB(NPV > 0)	$\hat{\mu} - \hat{\sigma}$	$\hat{\mu}$	MAX NPV
Screening	.83	.44	.99	1.00	.94

perfect predictor of the $\hat{\mu}$ ranking, almost perfect for $\hat{\mu}-\hat{\sigma}$, and quite good for MAX NPV and even MIN NPV. The poor relation between screening and PROB(NPV>0) can be explained by the large number of ties which the latter ranking resulted in.

14.4 Relation Among the Five Final Rankings

Just as the measure of agreement is calculated between pairings of the screening ranking with the final rankings, so can such measures of agreement be calculated among the possible pairings of the final rankings. This would be no mere acadmic exercise. Since the rankings represent points along a risk spectrum, we should expect rankings based on risk attitudes close to each other on the spectrum to show more agreement than rankings further removed from each other. Operationally, this would amount to demanding that the rankings not be too sensitive to small movements along the risk spectrum. It would be disconcerting indeed if the decision maker were equally disposed, in his risk attitude, to adopt either a $\hat{\mu}$ or $\hat{\mu}-\hat{\sigma}$ criterion for ranking, but the actual rankings based on those criteria differed substantially! A test of the rankings' sensitivity to risk is important. Such a test can be based on the expectation that the $M(R_k.R_j)$ between some criteria should be higher than for others. Letting the five identified points on ths risk spectrum (from MIN NPV to MAX NPV) be denoted as R_1 through R_5, we expect

$$M(R_1,R_2) \geq M(R_1,R_3),\ M(R_1,R_4),\ M(R_1,R_5)$$
$$M(R_2,R_3) \geq M(R_2,R_4),\ M(R_2,R_5),\ M(R_1,R_3)$$
$$M(R_3,R_4) \geq M(R_1,R_4),\ M(R_2,R_4),\ M(R_3,R_5)$$
$$M(R_4,R_5) \geq M(R_1,R_5),\ M(R_2,R_5),\ M(R_3,R_5)$$

In order to test these conditions, the matrix of M's must be available. This matrix is presented in Table 14.7. Reading from that Table, the conditions may be tested:

$$.75 \geq .52,\ .44,\ .26$$
$$.52 \geq .51,\ .46,\ .52$$
$$.99 \geq .44,\ .51,\ .90$$
$$.95 \geq .26,\ .46,\ .90$$

TABLE 14.7

MATRIX OF MEASURES OF AGREEMENT FOR THE FIVE RANKING CRITERIA

	MIN NPV	PROB(NPV > 0)	$\hat{\mu} - \hat{\sigma}$	$\hat{\mu}$	MAX NPV
MIN NPV	1	.75	.52	.44	.26
PROB(NPV > 0)		1	.52	.51	.46
$\hat{\mu} - \hat{\sigma}$			1	.99	.90
$\hat{\mu}$				1	.95
MAX NPV					1

Note that all the tests are passed. This establishes both the meaningfulness of the spectrum concept and the proper sensitivity of the actual rankings.

14.5 Ranking Summary

Five technology rankings have been presented. Which one is best? The Georgia Tech research team would opt for the ranking given by the moderate risk attitude, using the statistic $\hat{\mu}-\hat{\sigma}$. Table 14.7 shows a very substantial agreement between the $\hat{\mu}-\hat{\sigma}$ and the $\hat{\mu}$ and MAX NPV rankings. The only substantial difference between $\hat{\mu}-\hat{\sigma}$ and MIN NPV or PROB(NPV>0) is the placement of Technology G, Millimeter Communication Systems. These differences are easily explained. With regard to MIN NPV, G has a large possible range, which is expected from a technology with high mean value. Certainly a low MIN NPV should count against a technology. However, the probability of a negative NPV is only 2%. The technology is not as risky as the ordinal MIN NPV ranking might overtly suggest. With regard to the PROB(NPV>0) statistic, G ranks a poor 8th only because 7 technologies have a probability of unity that NPV>0. For G, its probability of a positive NPV is 98%. Again, this ranking seems to overplay the risk of G. Thus, the moderate attitude toward risk, corresponding the criterion $\hat{\mu}-\hat{\sigma}$, best represents the Tech team's assessment of the one best ranking.

SECTION 15

CONCLUSIONS

The questions of whether or not NASA should support the further development of space communications technology and which technologies, if any, should be given the highest priority have been attacked from a cost-benefit point of view. Both qualitative and quantitative methods for addressing the issues have been formulated and applied. The screening, assessment, and ranking methodologies have been applied to conceptual communications systems and subsystems which resulted from the user preference and technology state-of-the-art surveys. Baseline scenarios were defnied that included forecast demands for communications channels and forecast channel capacity per satellite as well as estimates of improvements in communication systems resulting from specific technology developments. Using these scenarios, estimates were made of the value to the nation of U.S. government support of the development of space communications technology.

A set of nine technologies have been carried through the screening, assessment, and ranking methodologies. Eight of the nine technologies (all except low cost direct demodulation earth station equipment) passed the qualification test based upon market failure (the failure of the private sector to provide adequate financial incentives to potential developers). The quantitative methodology application resulted in mean and standard deviation values for the net present value of each proposed technology development program. A ranking of the technologies according to several statistics of interest has been developed and is presented below for the means. The technologies are listed in order of decreasing value.

(1) Millimeter communications systems
(2) Solid state power amplifier (satellite)
(3) Low cost earth stations
(4) Multi-beam antenna
(5) Ion engine
(6) Adaptive heat pipe
(7) RF attitude sensor
(8) Laser communication system
(9) Advanced solar array

This ranking is according to economic considerations only, and is to be used as a design aide by the decision maker; it is not an end in itself.

The screening, assessment, and ranking methodologies developed within this program provide a consistent, tractable, defensable, and quantitative approach for evaluation of potential NASA research and development programs. The consistency was achieved by the use of similar criteria in the screening and assessment stages and was demonstrated by the high correlation between screening scores and final technology ranking. Tractability was assured by use of the appropriate level of detail in the quantitative analysis, and the defensability resulted from the use of a performance criteria accepted within the economic profession, net present value.

Economic evaluation of the technologies from this cost-benefit viewpoint has shown that certain technologies should be implemented with government support to accrue maximum benefits to the nation as a whole. That is, the value to the nation of government-supported early development of the higher-ranked technologies significantly exceeds the cost. NASA, as the appropriate government agency, should play an important role in advancing future communications technology since otherwise, the benefits described in this report would not be realized.

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APPENDICES

APPENDIX I

ANALYTICAL ASPECTS OF EXTERNALITIES AND INTERDEPENDENCY

A. Externality Considerations

In Section 2, Part I of the text, it was pointed out that when social or private costs or benefits diverge, public intervention can improve overall welfare. The following provides insight into the discussion from a mathematical viewpoint.

For simplicity, a very simple economic model can be used. The conclusions as will be seen, are simply thus: first, in presence of externalities, the pursuit of individual self-interest does not result in the best interests of society being observed (vis a vis Adam Smith's famous "invisible hand" doctrine which states that usually individuals, in pursuit of their own selfish interests are led, as if by an invisible hand, to do what's best for everyone) and second, it's possible for government action, directly or indirectly, to appropriately modify individual behavior to be in accord with social objectives. These conclusions are generalizable to more complex situations.

The model posits two individuals, A and B, each of whom consumes only two goods, x_1 and x_2. However, person A receives satisfaction; or utility, not only from his own consumption of x_1 and x_2, but from B's consumption of x_1. For example, x_1 may be landscaping and B's front yard dominates the view from A's front porch. The utility function of A can be represented as

$$U^A = U^A\ (x_{1A},\ x_{2A},\ x_{1B}) \tag{1}$$

where x_{1A} is the amount of x, consumed by A, and so on.

B's utility function is

$$U^B = U^B(x_{1B},\ x_{2B}). \tag{2}$$

We assume both A and B experience diminishing marginal utility in their consumption of x_1 and x_2. That is, the more units of a good consumed (per time period) the less satisfaction is gained from the marginal unit. Nonetheless, we also assume that an additional unit always confers some positive amount of utility. More concisely,

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$$\frac{\partial U^j}{\partial x_{ij}} > 0,\ j = A,B;\ \text{and}\ i = 1,2 \tag{3}$$

and

$$\frac{\partial}{\partial x_{ij}} [\frac{\partial U^j}{\partial x_{jk}} < 0,\ j = A,B;\ i = 1,2$$

Figure 1 illustrates the relevant concepts. Note the upper figures illustrates that more consumption always yields more utility, but at a diminishing rate. The lower figure, derived from the upper, shows that extra (or marginal) utility from another unit of consumption is always positive, but the increment increases with increasing consumption. Each figure (1a and 1b) reflects conditions (3).

Economic theory posits that each individual allocates his given income among the alternative goods available to him so that he maximizes his utility. Letting I_A and I_B represent the money incomes of A and B; P_1 and P_2 the unit prices of x_1 and x_2; the problem faced by A is

$$\underset{x_{1A},x_{2A}}{\text{MAX}} \quad U^A(x_{1A},\ x_{2A},\ x_{1B}) \tag{4}$$

$$\text{S.T.} \quad P_1x_{1A} + P_2x_{2A} = I_A$$

Note that A's control variables (written under "MAX") include x_{1B}; A has no control over the amount of x_1 and B purchases, even though A's welfare depends on it. Necessary conditions for the solution of (4) as derived from the associated Lagragian expression:

$$L = U^A(x_{1A},\ x_{2A},\ X_{1B}) + \lambda(I_A - P_1x_{1A} - P_2x_{2A})$$

These conditions are:

$$\frac{\partial L}{\partial x_{1A}} = \frac{\partial U^A}{\partial x_{1A}} - \lambda P_1 = 0 \tag{5}$$

$$\frac{\partial L}{\partial x_{2A}} = \frac{\partial U^A}{\partial x_{2A}} - \lambda P_2 = 0 \tag{6}$$

$$\frac{\partial L}{\partial \lambda} = I_A - P_1 x_{1A} - P_2 x_{2A} = 0 \tag{7}$$

Dividing (5) by (6), the Lagragian multiplier, λ, may be eliminated, as is done in (8). Conditions (7) and (8).

$$\frac{\dfrac{\partial U^A}{\partial x_{1A}}}{\dfrac{\partial U^A}{\partial x_{2A}}} = \frac{P_1}{P_2} \tag{8}$$

characterize the optimal solution to (4), A's self-interest problem. Assume the solution to (7) and (8) is $\bar{x}_{1A}$ and $\bar{x}_{2A}$.

In like manner, B's self-interest solution can be computed. It would be some values $\bar{x}_{1B}$, $\bar{x}_{2B}$ satisfying, in particular:

$$\frac{\dfrac{\partial U^B}{\partial x_{1B}}}{\dfrac{\partial U^B}{\partial x_{2B}}} = \frac{P_1}{P_2} \tag{9}$$

Now let us consider the problem from a social welfare point of view. We define the social welfare function $W = W(U^A, U^B)$. That is, society's level of well being depends on the well being on its members.

Let us investigate whether the solution to the overall social problem is consistent with $\bar{x} = \{\bar{x}_{1A}, \bar{x}_{2A}, \bar{x}_{1B}, \bar{x}_{2B}\}$.

The social welfare problem is

$$\max_{x_{1A},\, x_{2A},\, x_{1B},\, x_{2B}} W[U^A(x_{1A}, x_{2A}, x_{1B}),\, U^B(x_{1B}, x_{2B})]$$

$$\text{S.T.} \quad P_1(x_{1A} + x_{1B}) + P_2(x_{2A} + x_{2B}) = I_A + I_B$$

In words, find the amounts of x_{1A}, x_{2A} $+ x_{2B}$ which society can afford and which yield the greatest overall level of welfare. The first order conditions are

$$\frac{\partial W}{\partial U^A}\frac{\partial U^A}{\partial x_{1A}} - \lambda P_1 = 0$$

$$\frac{\partial W}{\partial U^A}\frac{\partial U^A}{\partial x_{2A}} - \lambda P_2 = 0$$

$$\frac{\partial W}{\partial U^A}\frac{\partial U^A}{\partial x_{1B}} + \frac{\partial W}{\partial U^B}\frac{\partial V^B}{\partial x_{1B}} - \lambda P_1 = 0 \qquad (10)$$

$$\frac{\partial W}{\partial U^B}\frac{\partial U^B}{\partial x_{2B}} - \lambda P_2 = 0 \qquad (11)$$

$$I_A + I_B - P_1(x_{1A} + x_{1B}) - P_2(x_{2A} + x_{2B}) = 0$$

Let the solution to these conditions be $x^* = (x_{1A}^*, x_{2A}, x_{1B}^*, x_{2B}^*)$.

Now let us investigate whether $\bar{x}$ is consistent with x, in particular focusing on x_{1B}, the externality inducing consumption of x_1, by person B. First, to eliminate the Lagrangian multiplier, divide (10) by (11), yielding:

$$\frac{\frac{\partial U^A}{\partial x_{1B}}}{\frac{\partial U^B}{\partial x_{2B}}} + \frac{\frac{\partial U^B}{\partial x_{1B}}}{\frac{\partial U^B}{\partial x_{2B}}} = \frac{P_1}{P_2} \qquad (11a)$$

Now, in comparing (11a) and (9), the RHS (right hand side) of each is identical, which means the solution to (9) must make the LHS of (9) identical to the LHS of (11a). That is

$$\left.\frac{\frac{\partial U^B}{\partial x_{1B}}}{\frac{\partial U^B}{\partial x_{2B}}}\right|_{\bar{x}} = \left.\frac{\frac{\partial U^A}{\partial x_{1B}}}{\frac{\partial U^B}{\partial x_{2B}}} + \frac{\frac{\partial U^B}{\partial x_{1B}}}{\frac{\partial U^B}{\partial x_{2B}}}\right|_{x^*} \qquad (12)$$

In order for (12) to hold, some reflection indicates that

$$x_{1B}^* > \bar{x}_{1B} \qquad (13)$$

This is because, as stipulated in (e), $\partial / \partial x_{ij} \left(\frac{\partial U^2}{\partial x_{ij}}\right) < 0$. Thus, to reduce the numerators on the RHS, x_{1B}^* must be increased beyond $\bar{x}_{1B}$. This is clear from Figure 16. The interpretation of (13) is simply that the socially optimal amount of x, for person B to consume is in excess of what his personal self interest dictates. This is intuitively quite reasonable: since B does not consider the benefit that A derives from x_{1B}, he provides less than would be provided if A's benefit was considered. The social welfare approach considers both A's and B's consumption of x_{1B}, whereas the self-interest approach of B does not.

The conclusion we must draw is that if B were directly or indirectly induced to increase his consumption of x_{1B} from $\bar{x}_{1B}$ to x_{1B}^*, the overall level of social well-being would be improved.

B. INTERDEPENDENCY OF PROJECTS

Interdependent Production or Consumption along with public goods, is perhaps the most significant class of externalities. Our initial discussion of externalities drew on a consumption interdependence; person A's utility depended on B's consumption of x_1. For completeness, we now briefly present a case of production interdependence based on pollution. Assume two firms located along a river, the upstream firm discharges an effluent into the river as a byproduct of its production process, and the downstream firm draws water from the river for use in its production. The downstream firm must treat the water, at some cost, to remove imporuties. The more impurities, the greater the cost. Each firm's goal is the maximization of its own profit. The overall social goal is the maximization of the value of production. Let firm A be upstream and B downstream. It will be convenient to introduce some notation.

- Q_i Output of Firm i
- C_i Total Costs of Production for Firm i
- P_i Selling Price of the Output of Firm i
- Π_i Profit of Firm i
- E_i Effluent of Firm i
- V Net Social Value (a market oriented measure of social welfare)

Firm A seeks to maximize

$$\Pi_A = P_A Q_A - C_A \qquad \text{where} \quad C_A = C^A(Q_A),$$

$$\frac{\partial C_A}{\partial Q_A} > 0, \qquad \frac{\partial}{\partial Q_A}\frac{\partial C_A}{\partial Q_A} > 0$$

The latter conditions state that marginal cost is positive and increasing over the relevant range. Finally, for firm A,

$$E_A = E^A(Q_A), \qquad \frac{\partial E_A}{\partial Q_A} > 0$$

i.e., its level of effluent depends positively on its level of output. Letting $\bar{Q}_A$ be A's profit-maximizing level of output, $\bar{Q}_A$ is such that

$$P_A = \frac{\partial C_A}{\partial Q_A} \qquad (14)$$

which is simply the first order necessary condition for a maximum of Π_A. Similarly, $\bar{Q}_B$ is such that $P_B = \frac{\partial C_B}{\partial Q_B}$. However, $C_B = C_B(Q_B, E_A)$. That is, B's costs depend on A's effluent, which B takes as given. The social objective is to maximize

$$V = (P_A Q_A + P_B Q_B) - (C_A + C_B)$$

i.e., the total willingness to pay for output less the total costs of producing it. Expanding V, we have

$$V = P_A Q_A + P_B Q_B - C^A(Q_A) - C^B[Q_B, E^A(Q_A)]$$

A relevant first order condition, which the socially optimal production of A_A, Q_A*, must satisfy is

$$P_A = \frac{\partial C^A}{\partial Q_A} + \frac{\partial C^B}{\partial E^A}\frac{\partial E^A}{\partial Q_A} \tag{15}$$

Now let us examine the difference between $\bar{Q}_A$ (the self-interest production level of firm A) as given by (14) and Q_A*, the socially optimal production level given by (15). Figure 2 illustrates the key aspects. The Intersection of P_A and $\frac{\partial C^A}{\partial Q_A}$ at x determines $\bar{Q}_A$ according to (14). Likewise, the intersection of P_A and $\frac{\partial C^A}{\partial Q_A} + \frac{\partial C^B}{\partial E^A}\frac{\partial E^A}{\partial Q_A}$ at Y determines Q_A* according to 15. Note that $Q_A* < \bar{Q}_A$ as long as $\frac{\partial C^B}{\partial E^A}\frac{\partial E^A}{\partial Q_A}$ 0. And this, of course, is indeed the case.

Thus, a production interdependence--one firm's cost function dependent on the output of another--gives rise to an externality. That is, it results in social and private costs diverging, leading to a non-optimal resource allocation: too much Q_A tends to be produced.

APPENDIX II

SCREENING SENSITIVITY PLOTS

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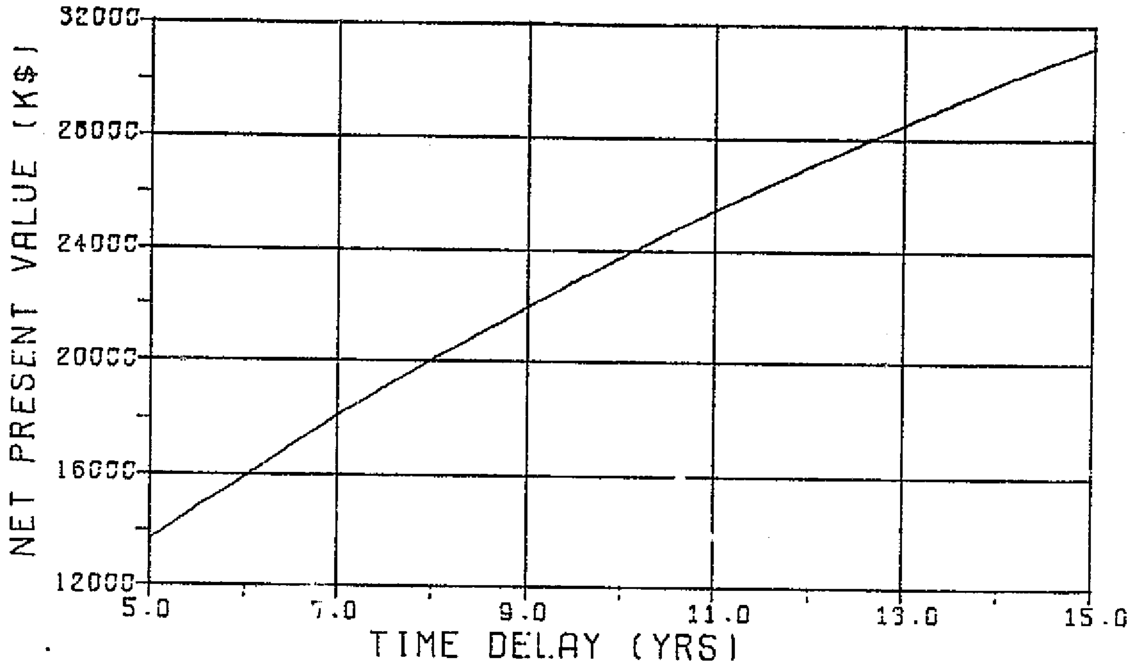

Figure II-1. Sensitivity of Millimeter NPV with Respect to Time Delay in Absence of NASA Support.

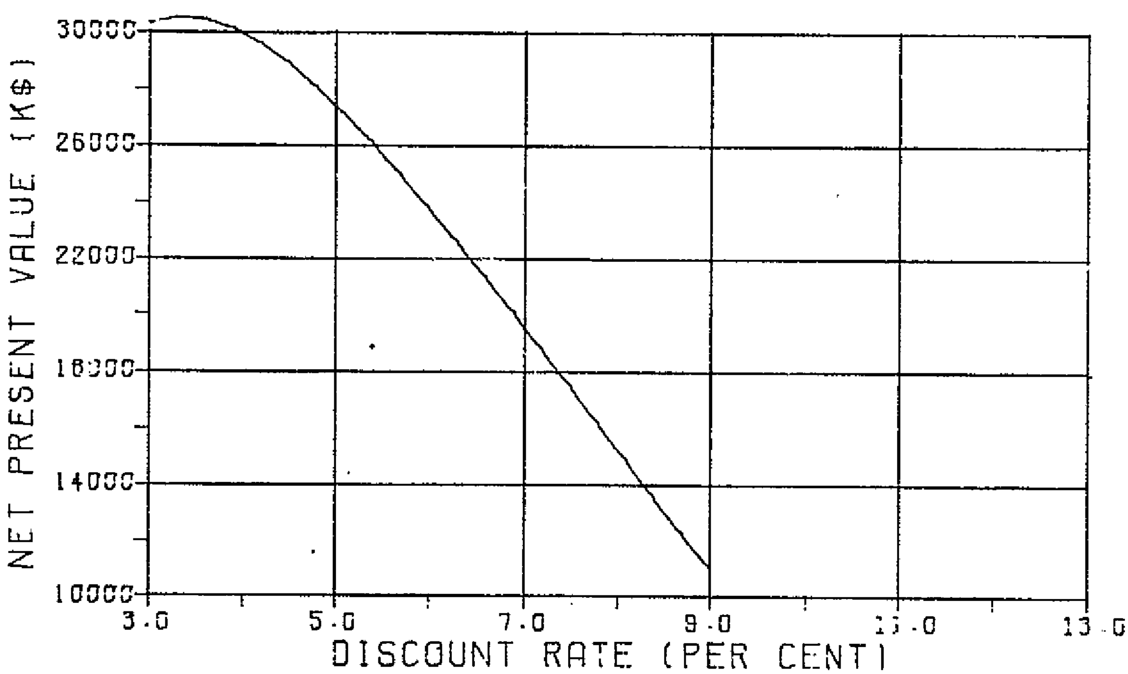

Figure II-2. Sensitivity of Millimeter NPV with Respect to Discount Rate.

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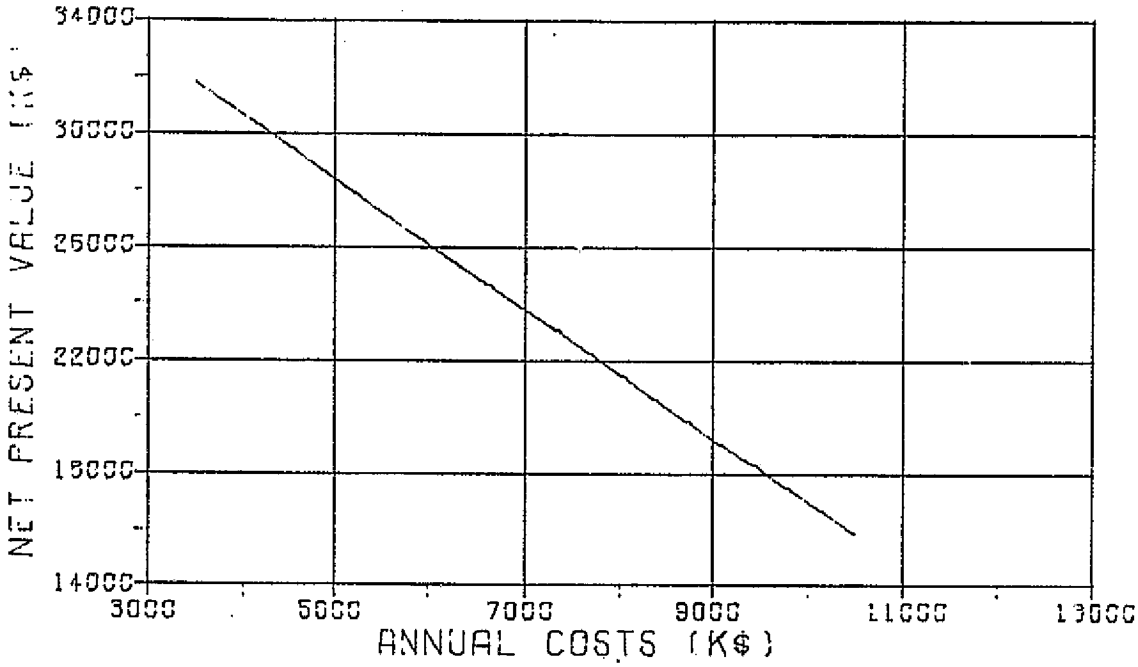
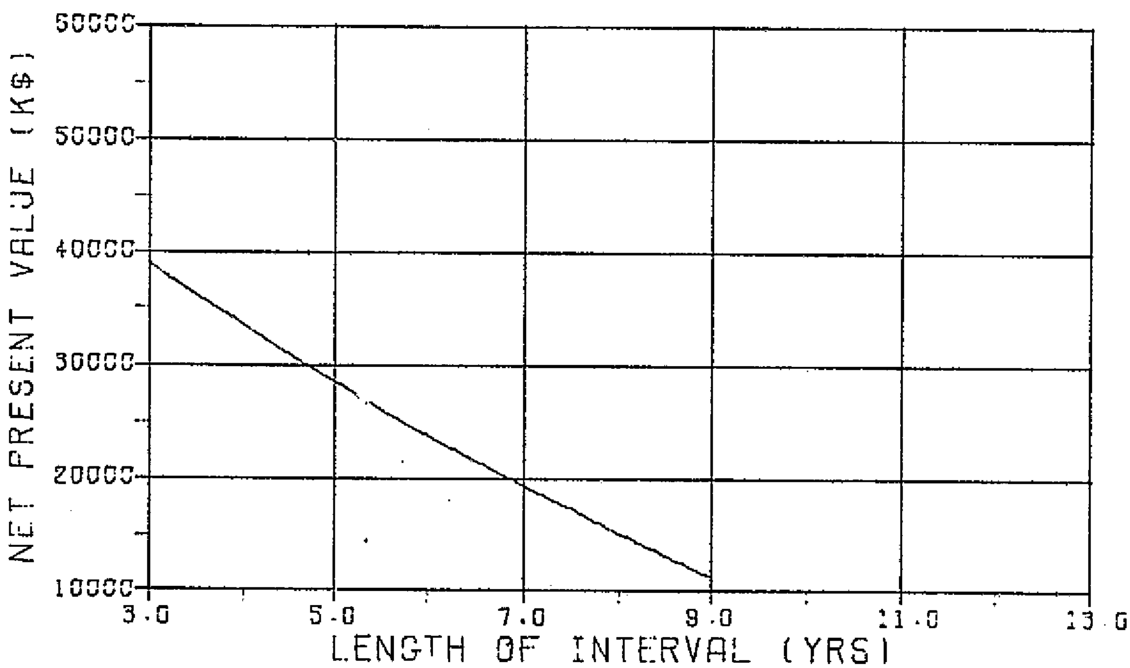


Figure II-3. Sensitivity of Millimeter NPV with Respect to Annual Costs for Basic R&D.



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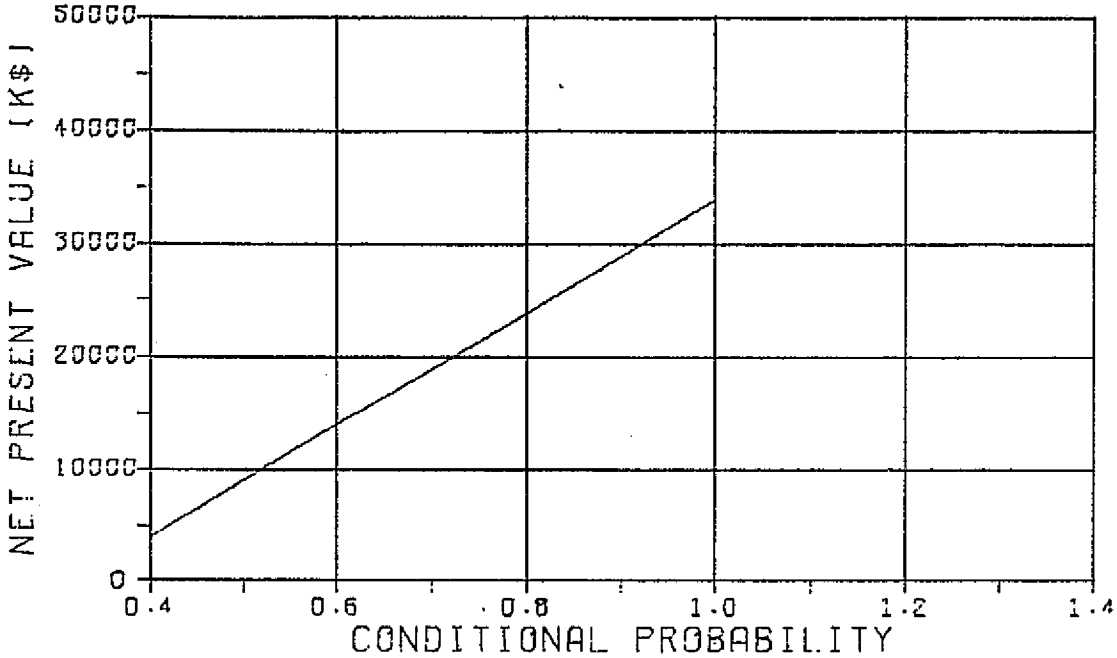


Figure II-5. Sensitivity of Millimeter NPV with Respect to Probability that Industry will Implement the Technology.

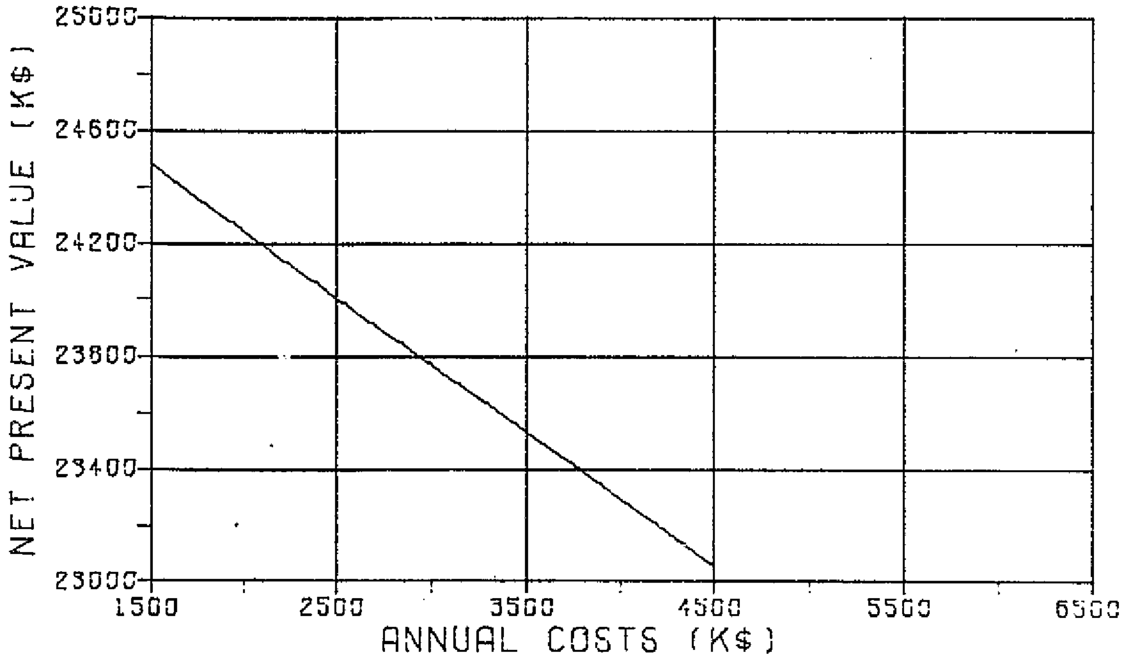


Figure II-6. Sensitivity of Millimeter NPV with Respect to Annual Costs During Applied R&D Interval.

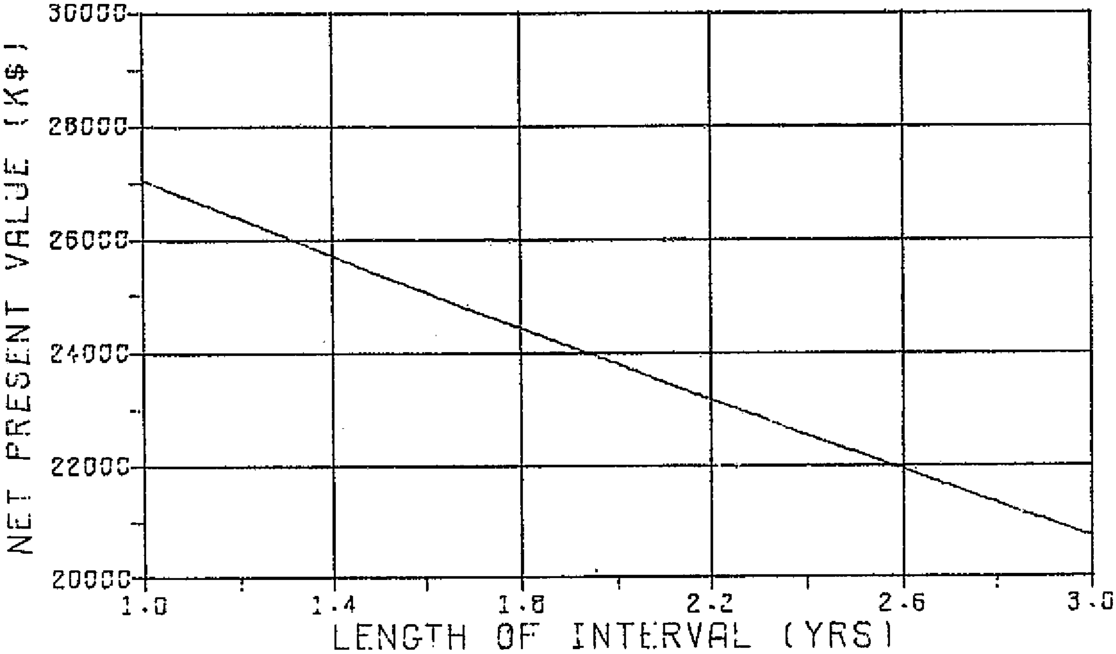


Figure II-7. Sensitivity of Millimeter NPV with Respect to Length of Applied R&D Interval.

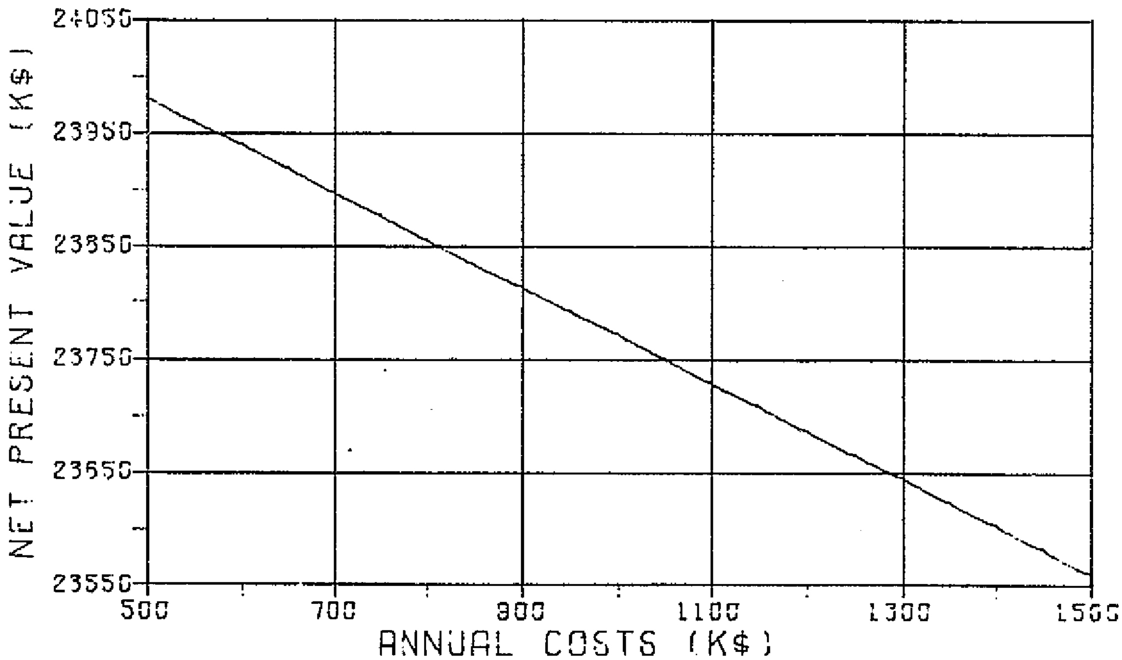


Figure II-8. Sensitivity of Millimeter NPV with Respect to Annual Costs in Industry Construction Interval.

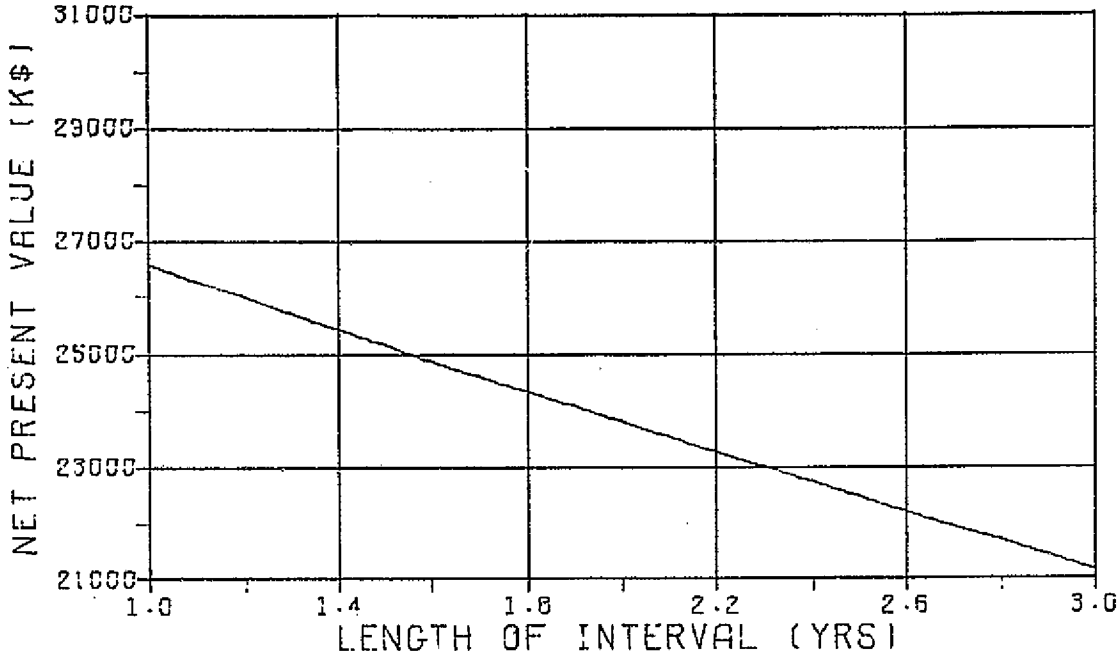


Figure II-9. Sensitivity of Millimeter NPV with Respect to Length of Industry Construction Interval.

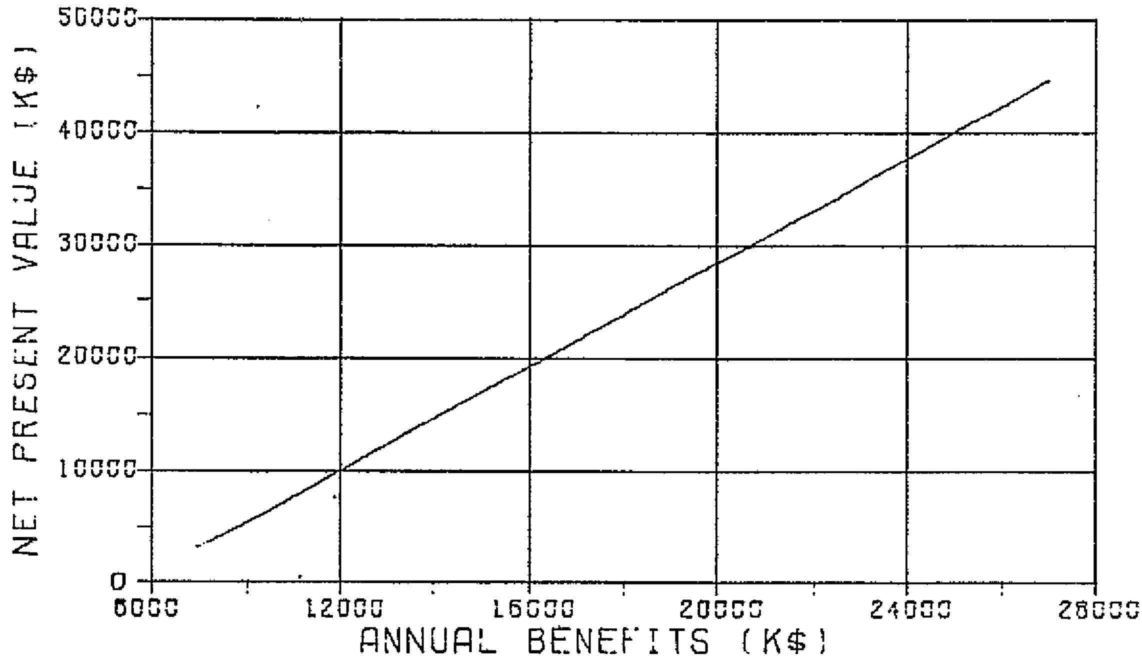


Figure II-10. Sensitivity of Millimeter NPV with Respect to Annual Benefits.

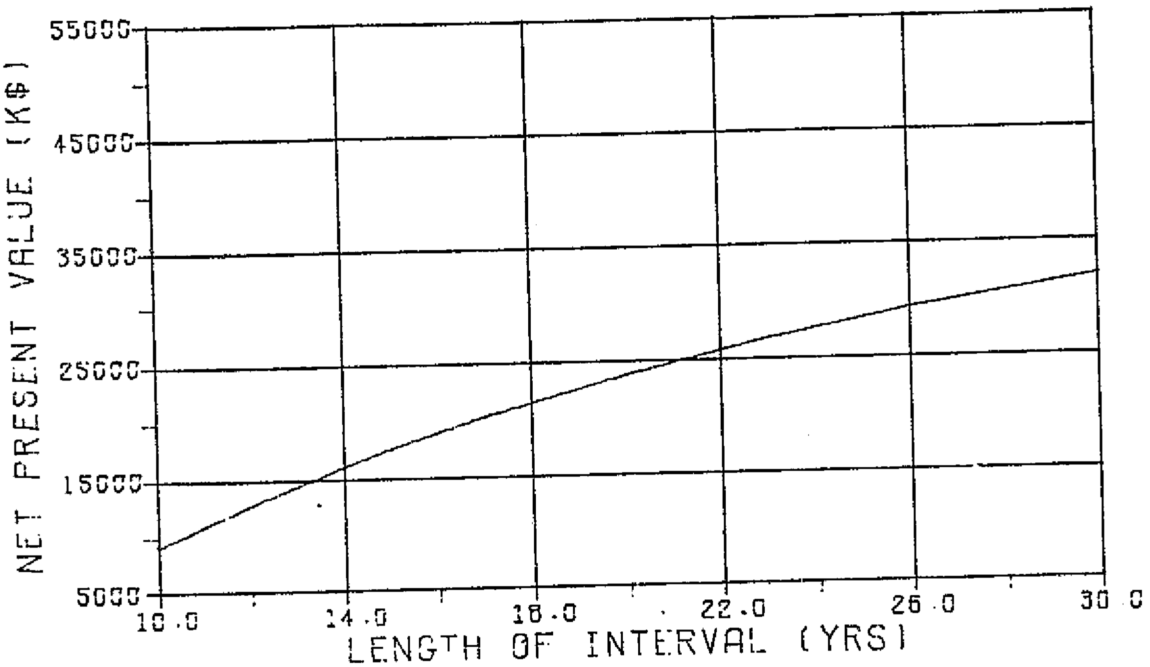


Figure II-11. Sensitivity of Millimeter NPV with Respect to Length of Operating Interval.

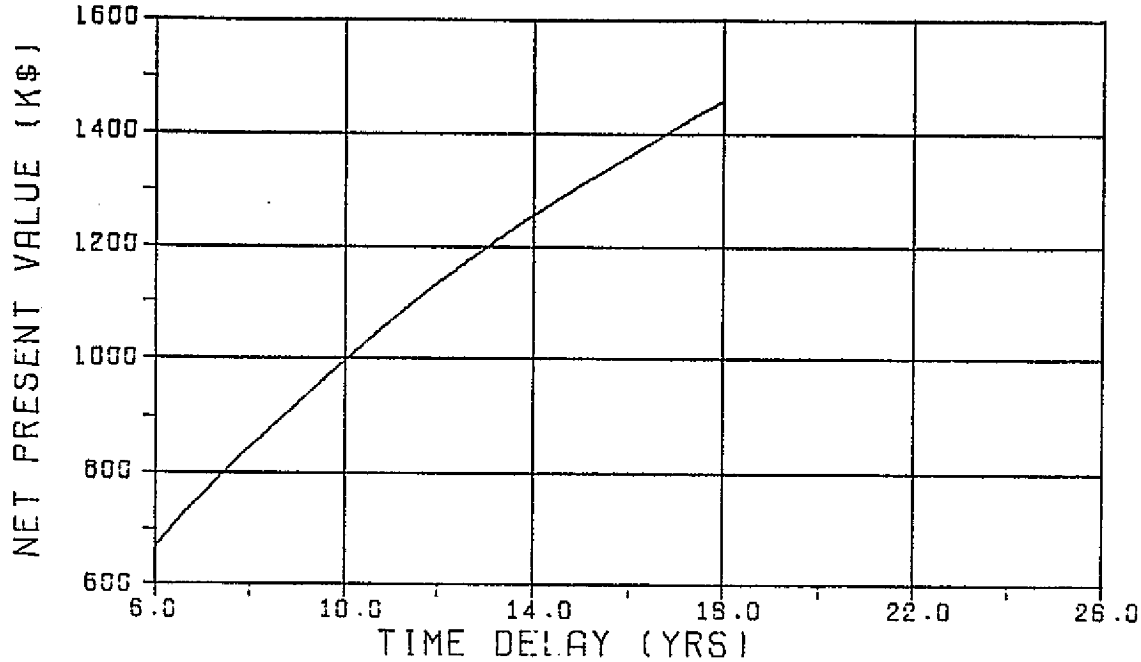


Figure II-12. Sensitivity of Laser NPV with Respect to Time Delay in Absence of NASA Support.

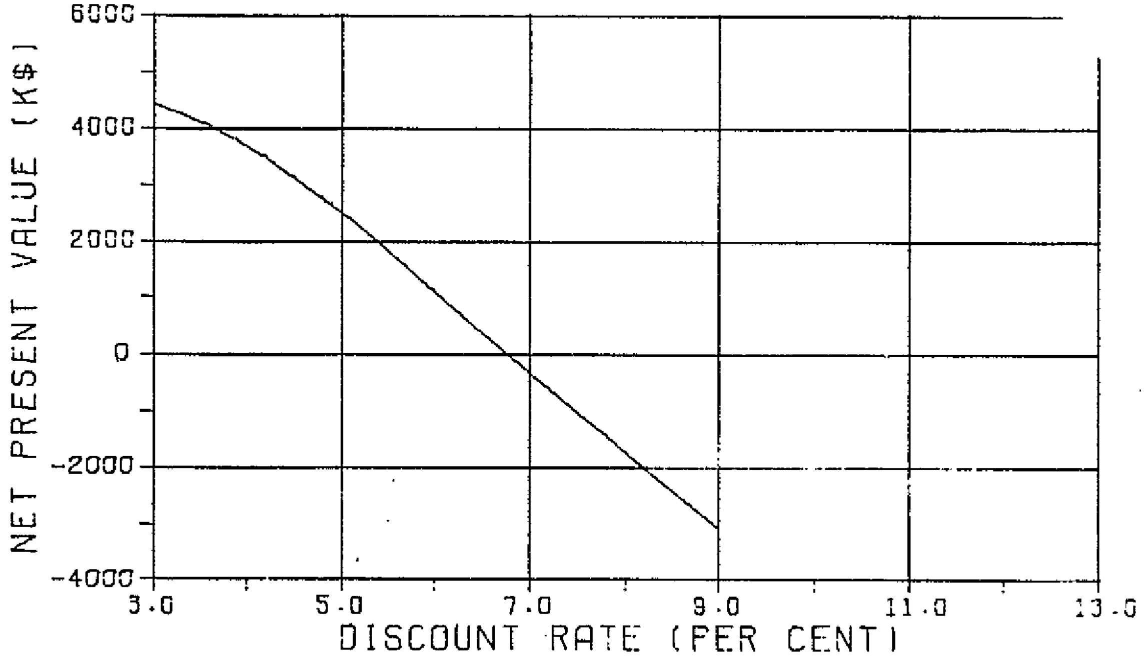


Figure II-13. Sensitivity of Laser NPV with Respect to Discount Rate.

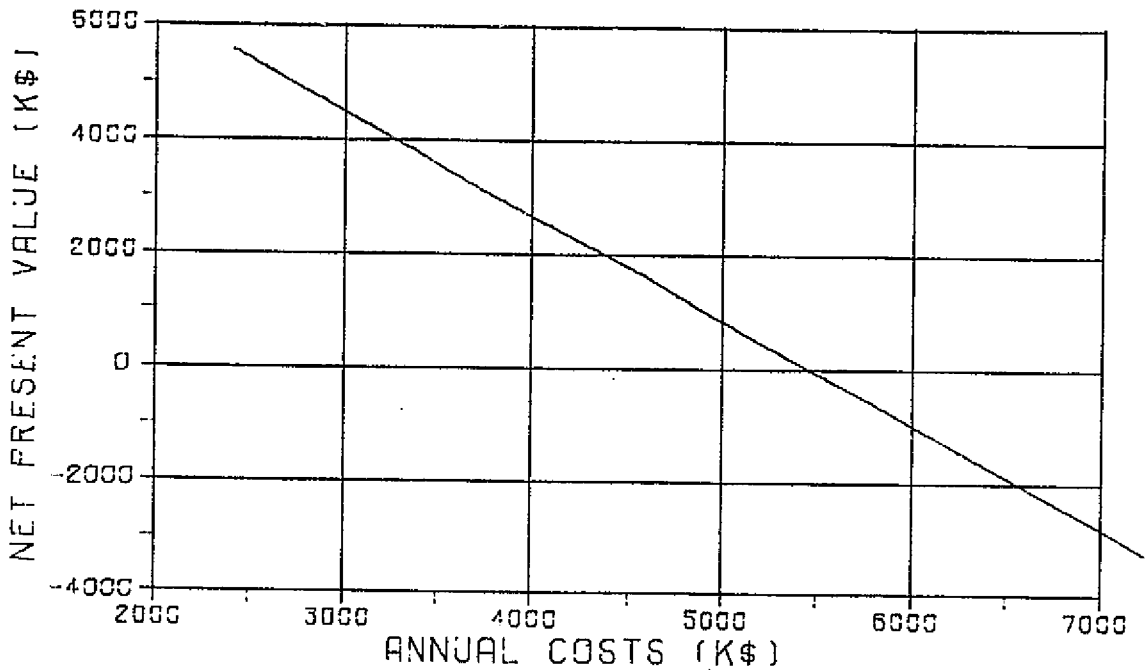


Figure II-14. Sensitivity of Laser NPV with Respect to Annual Costs for Basic R&D.

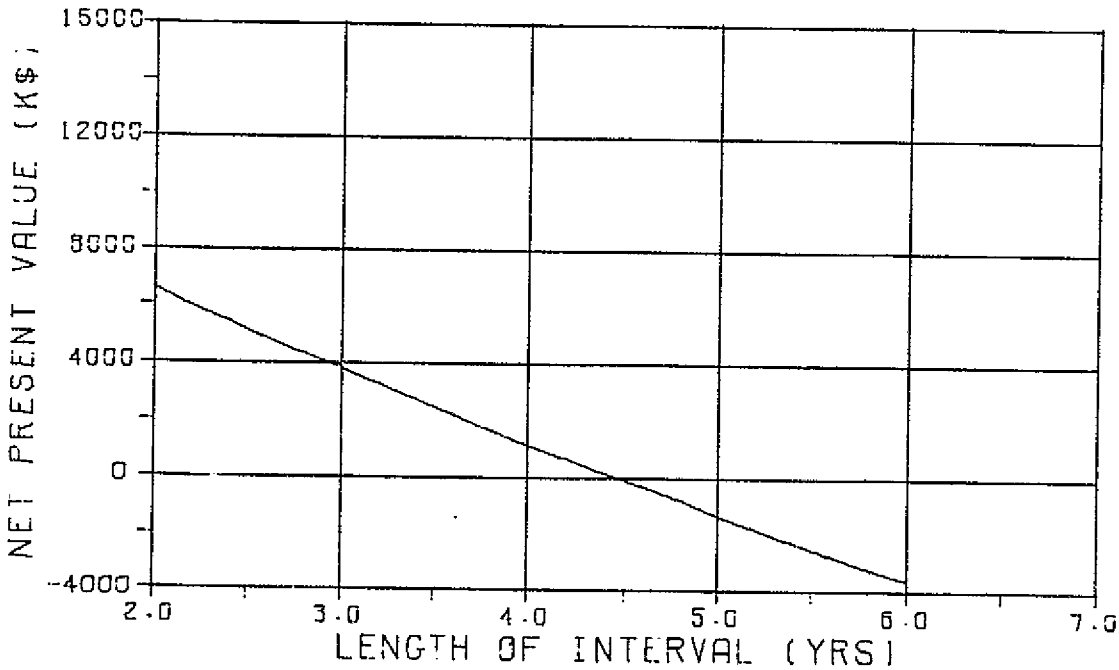


Figure II-15. Sensitivity of Laser NPV with Respect to Length of Basic R&D Interval.

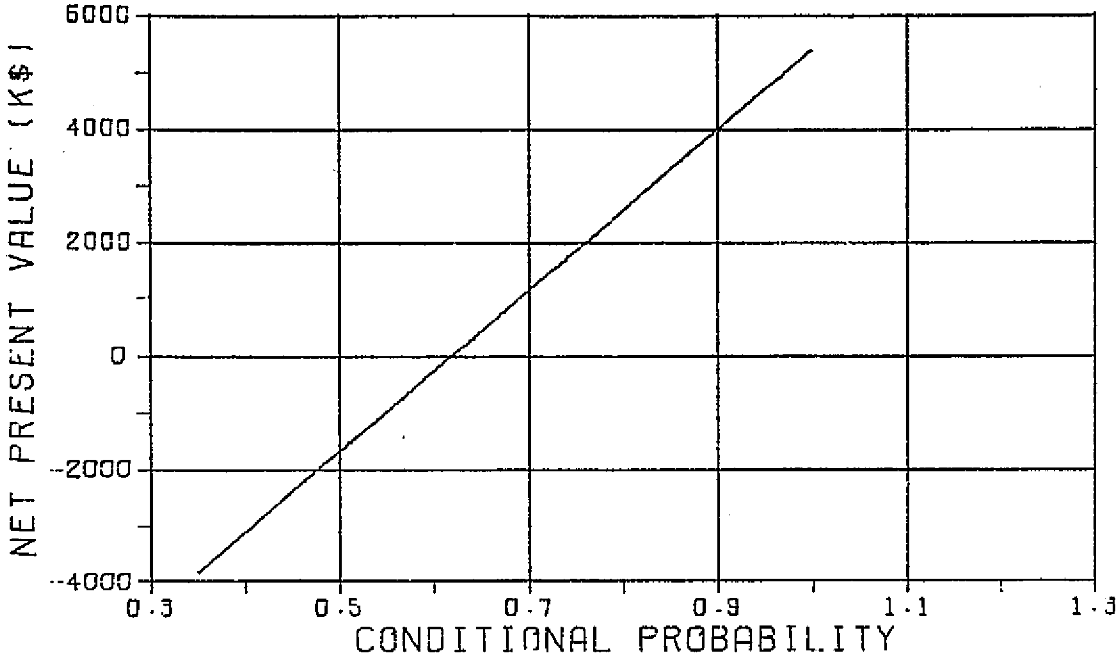


Figure II-16. Sensitivity of Laser NPV with Respect to Probability That Industry will Implement the Technology.

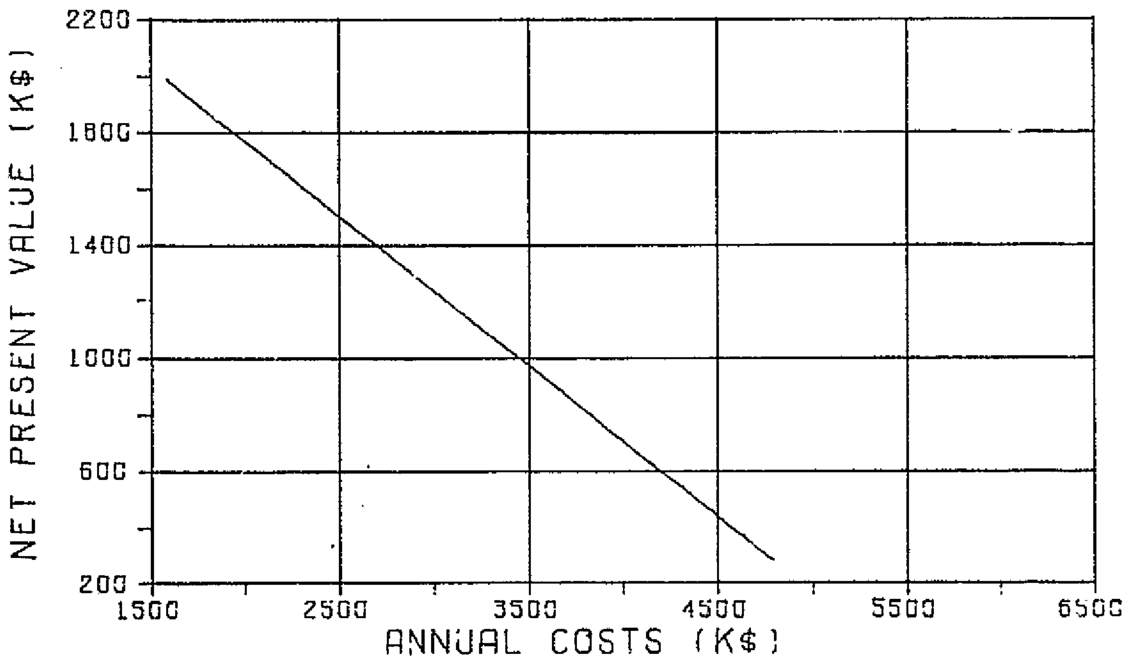


Figure II-17. Sensitivity of Laser NPV with Respect to Annual Costs During Applied R&D Interval.

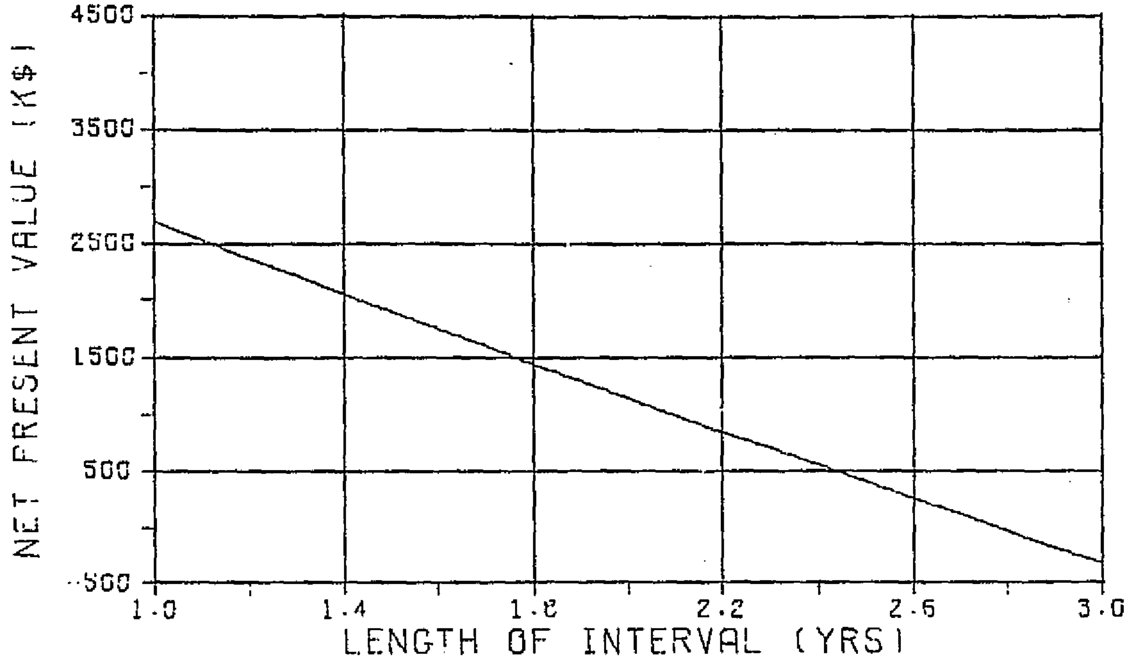


Figure II-18. Sensitivity of Laser NPV with Respect to Length of applied R&D Interval.

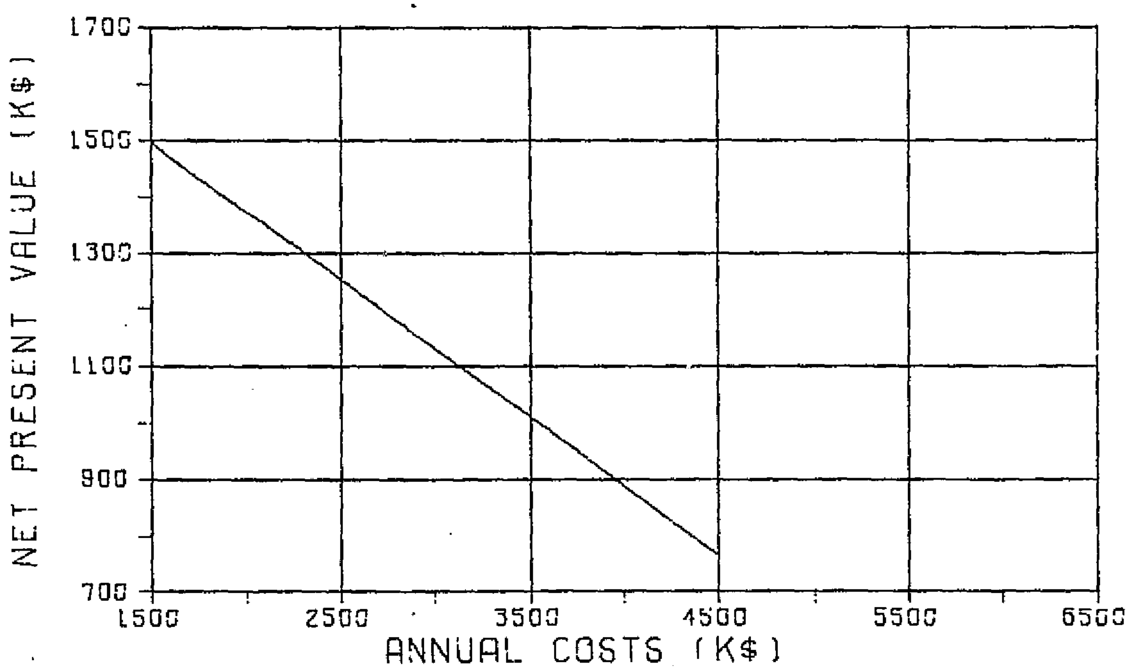


Figure II-19. Sensitivity of Laser NPV with Respect to Annual Costs in Industry Construction Interval.

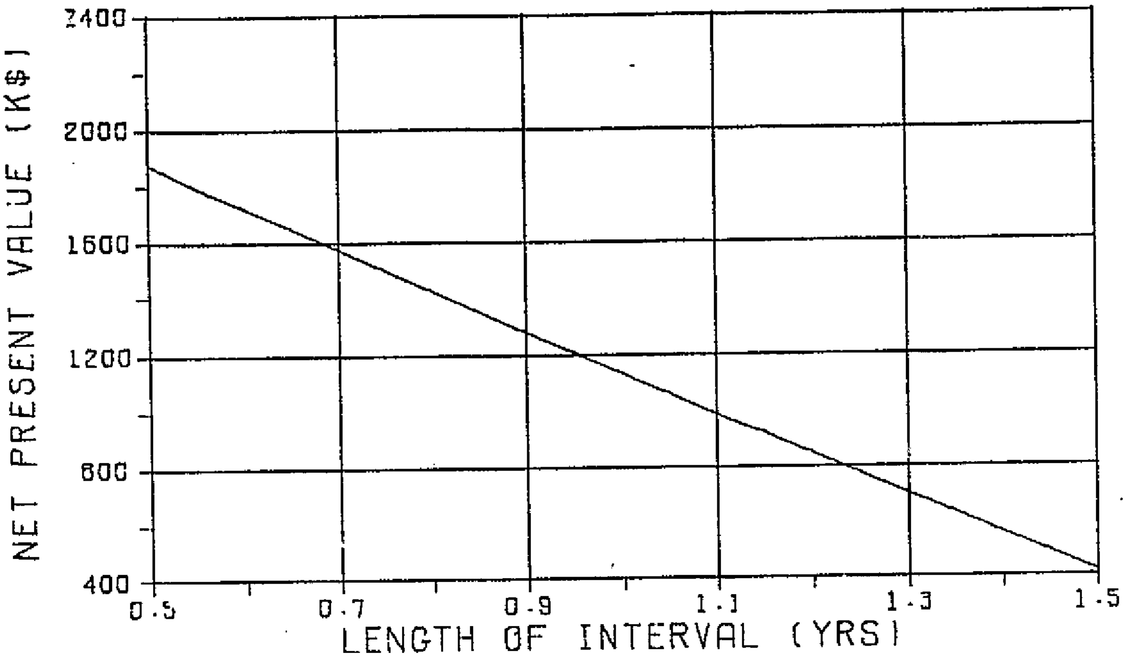


Figure II-20. Sensitivity of Laser NPV with Respect to Length of Industry Construction Interval.

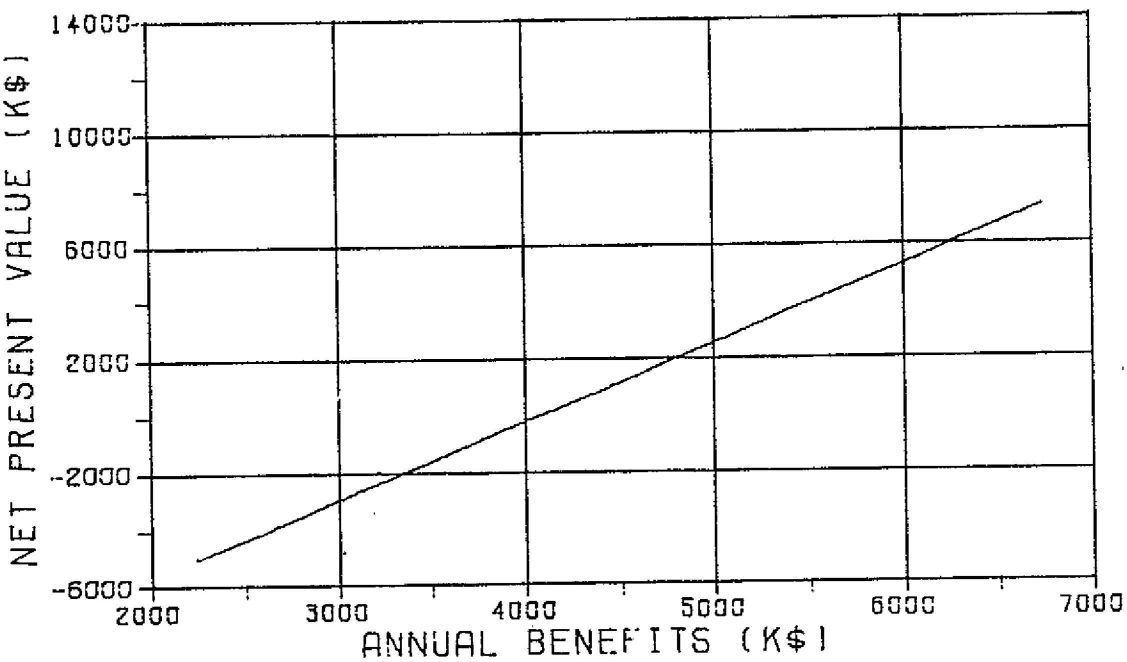


Figure II-21. Sensitivity of Laser NPV with Respect to Annual Benefits.

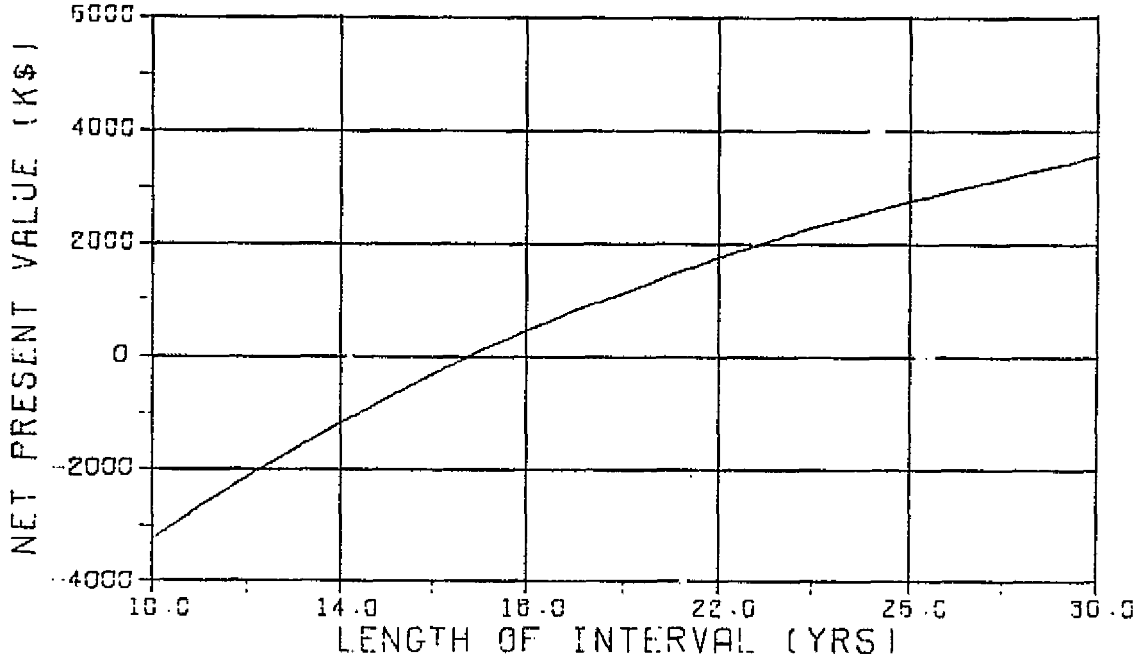


Figure II-22. Sensitivity of Laser NPV with Respect to Length of Operating Interval.

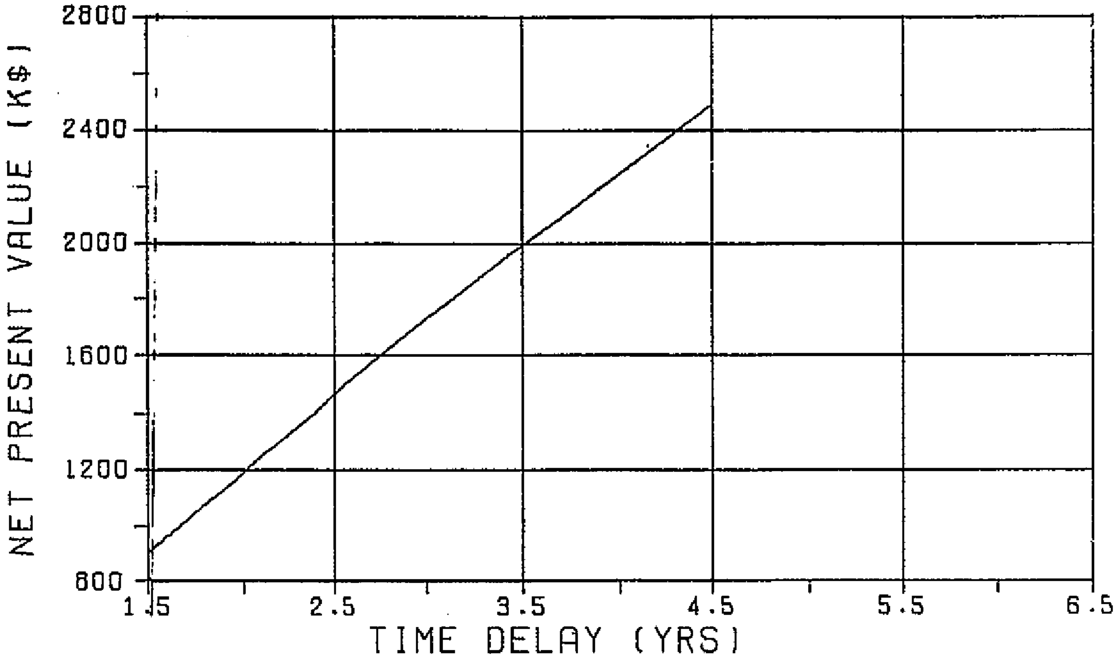


Figure II-23. Sensitivity of RF Attitude Sensor NPV with respect to Time Delay in Absence of NASA Support.

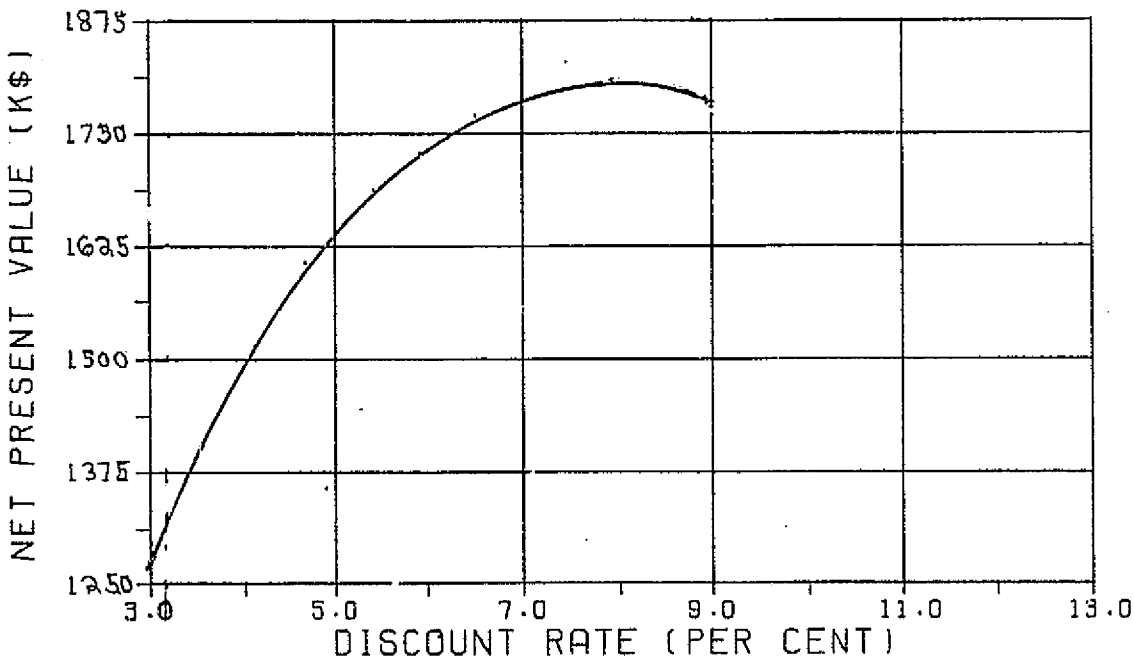


Figure II-24. Sensitivity of RF Attitude Sensor NPV with respect to Discount Rate.

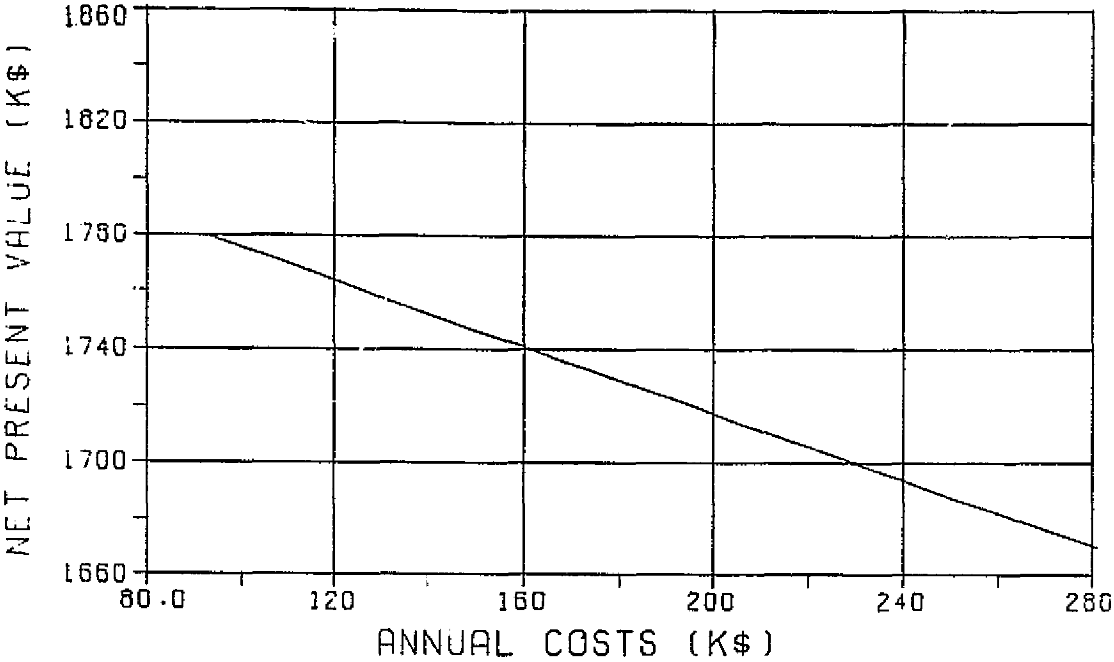


Figure II-25. Sensitivity of RF Attitude Sensor NPV with respect to Annual Costs for Basic R&D.

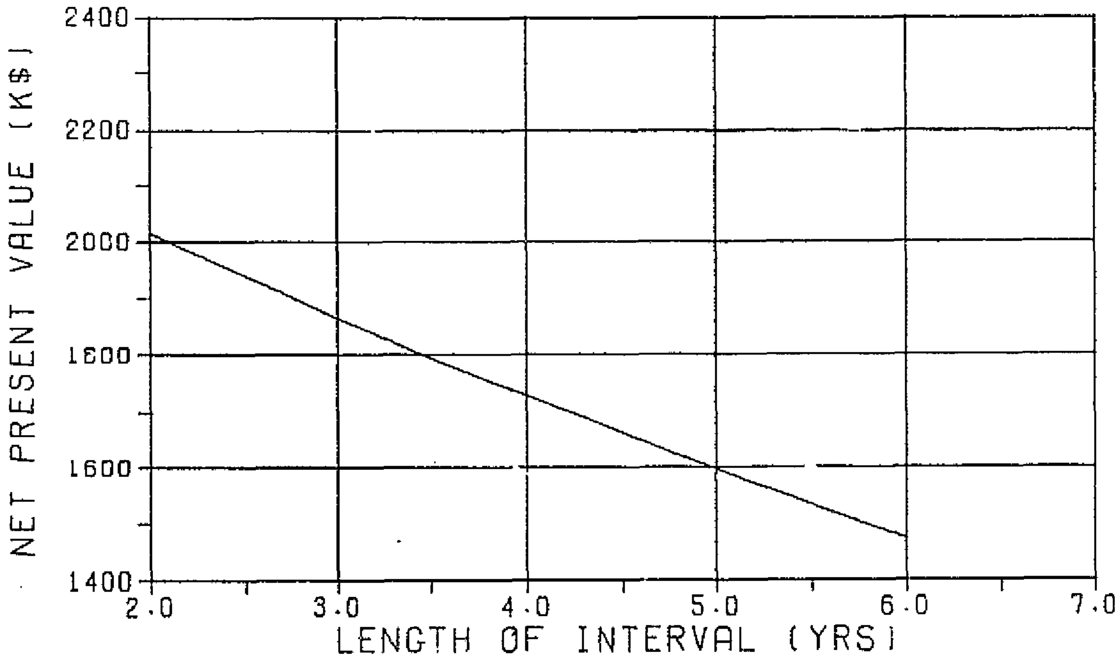


Figure II-26. Sensitivity of RF Attitude Sensor NPV with respect to Length of Basic R&D Interval.

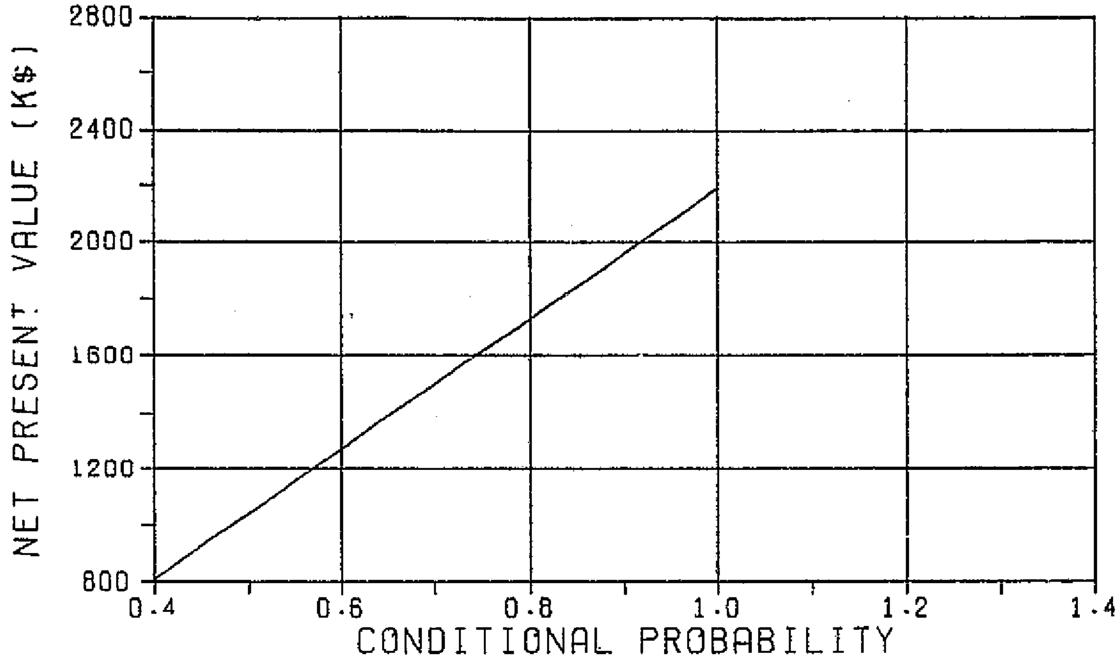


Figure II-27. Sensitivity of RF Attitude Sensor NPV with respect to Probability that Industry will Implement the Technology.

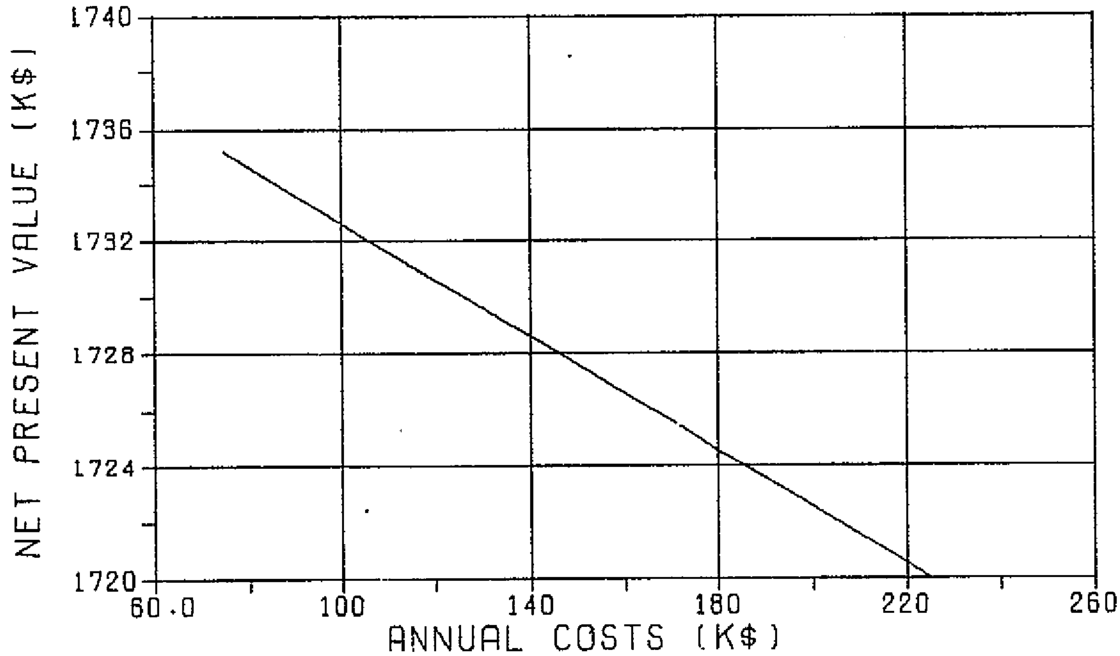


Figure II-28. Sensitivity of RF Attitude Sensor NPV with respect to Annual Costs During Applied R&D Interval.

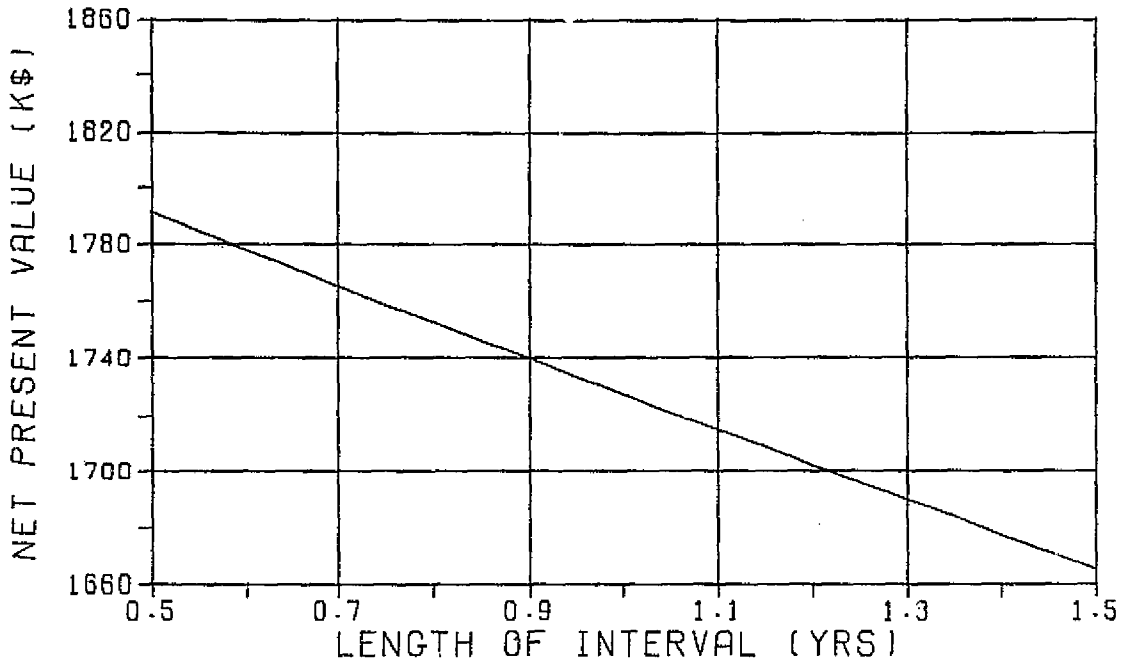


Figure II-29. Sensitivity of RF Attitude Sensor NPV with respect to Length of Applied R&D Interval.

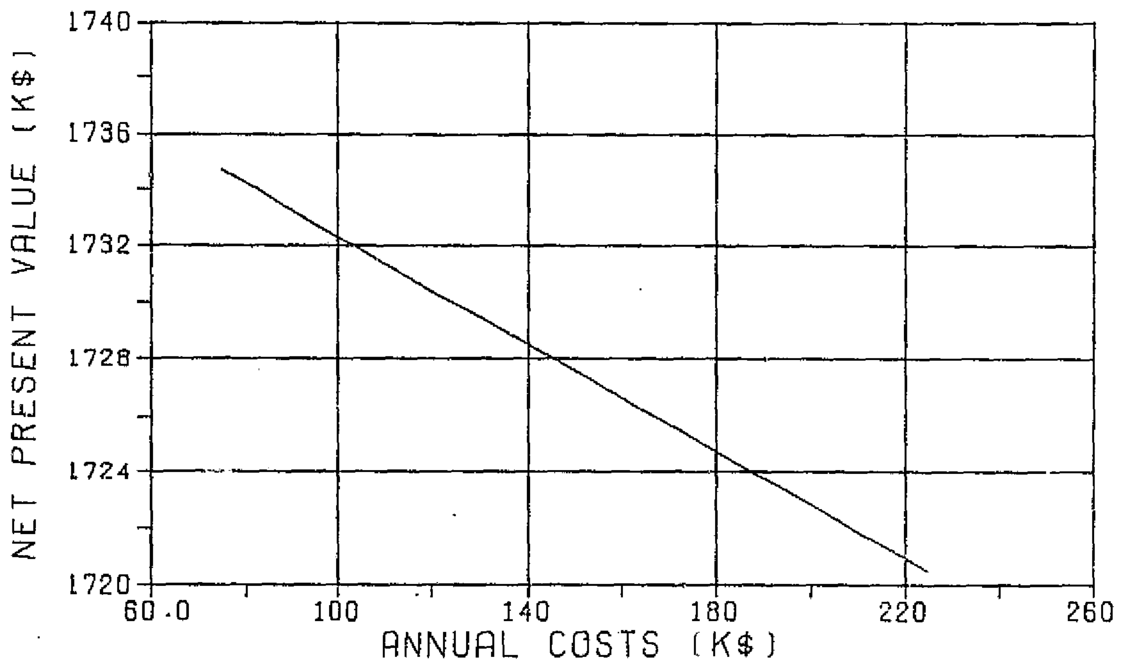


Figure II-30. Sensitivity of RF Attitude Sensor NPV with respect to Annual Costs in Industry Construction Interval.

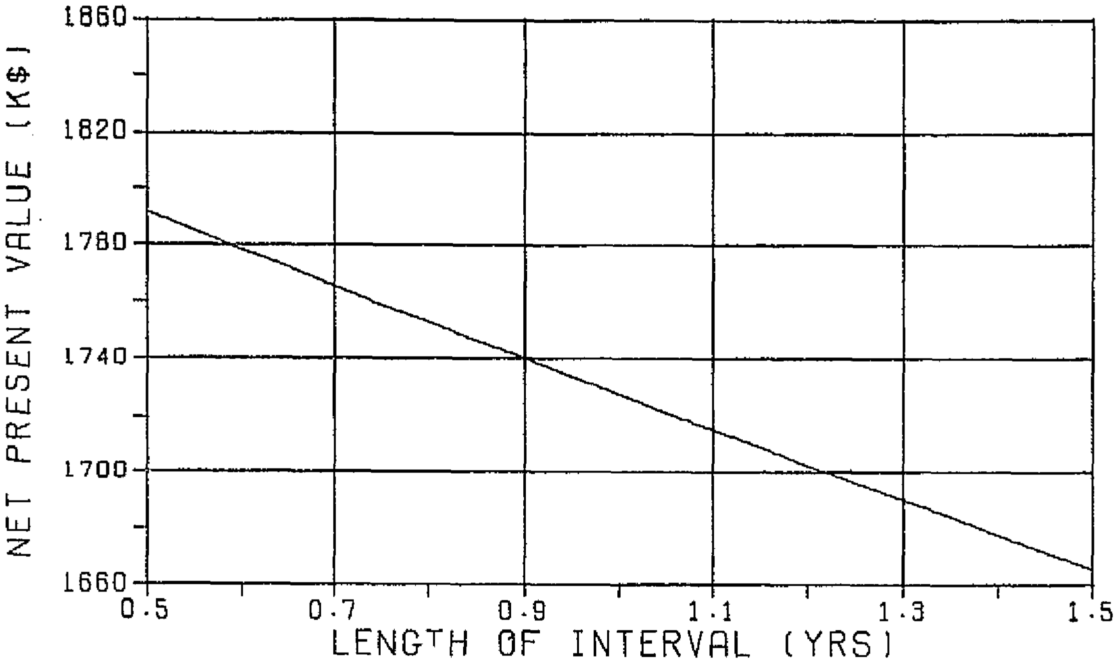


Figure II-31. Sensitivity of RF Attitude Sensor NPV with respect to Length of Industry Construction Interval.

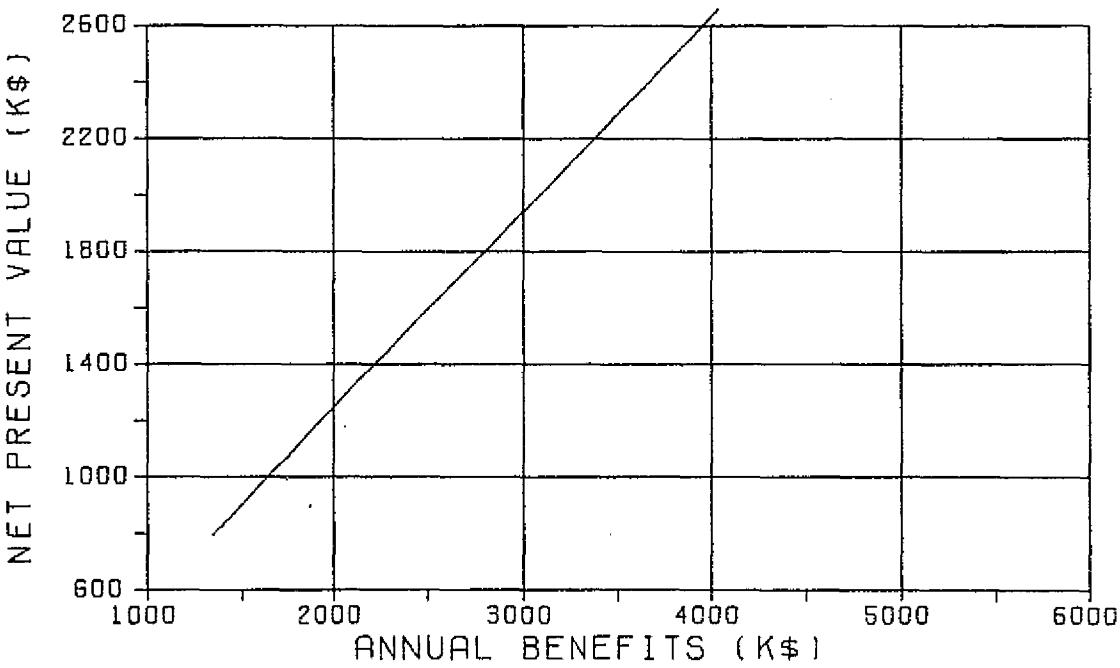


Figure II-32. Sensitivity of RF Attitude Sensor NPV with respect to Annual Benefits.

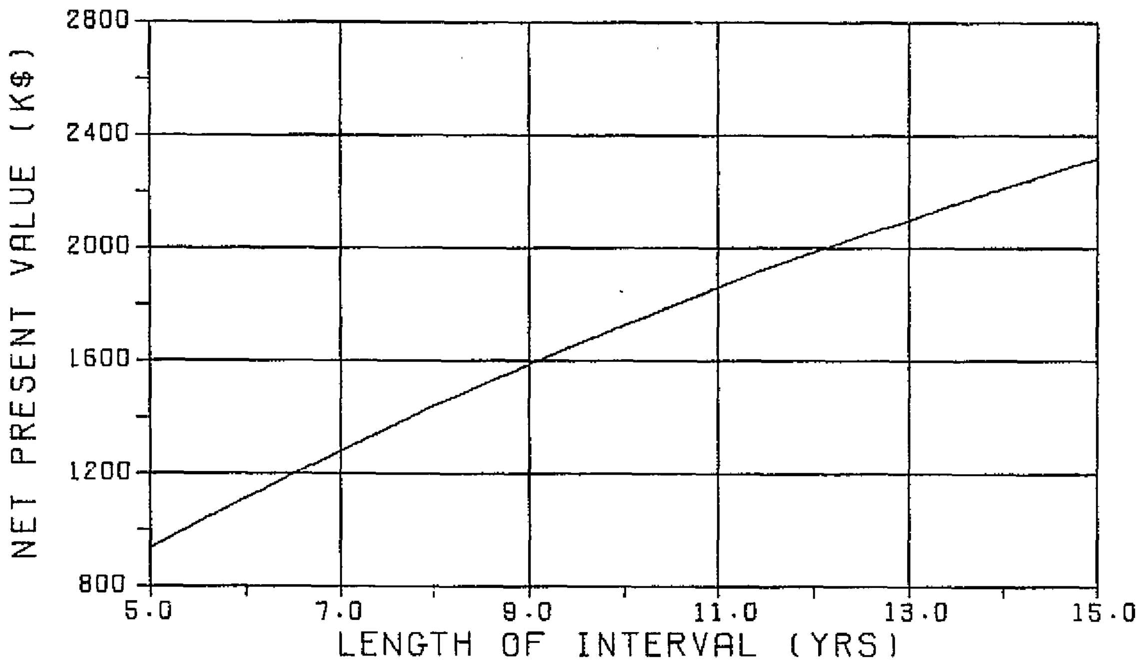


Figure II-33. Sensitivity of RF Attitude Sensor NPV with respect to length of Operating Interval.

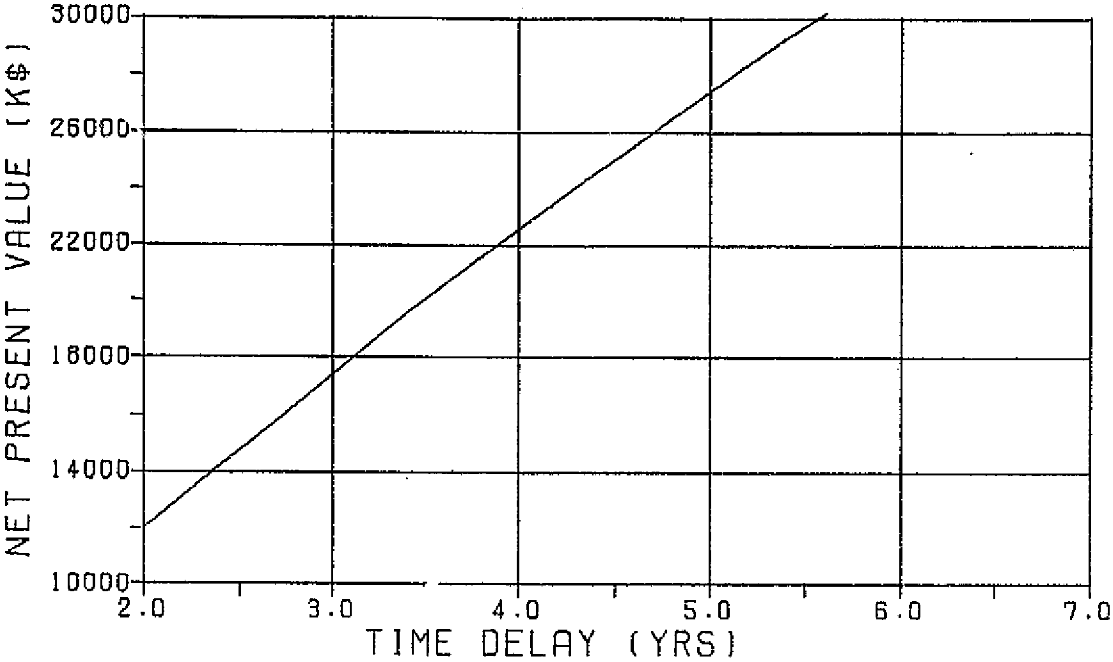


Figure II-34. Sensitivity of Solid State Power Amplifier NPV with respect to Time Delay in Absence of NASA Support.

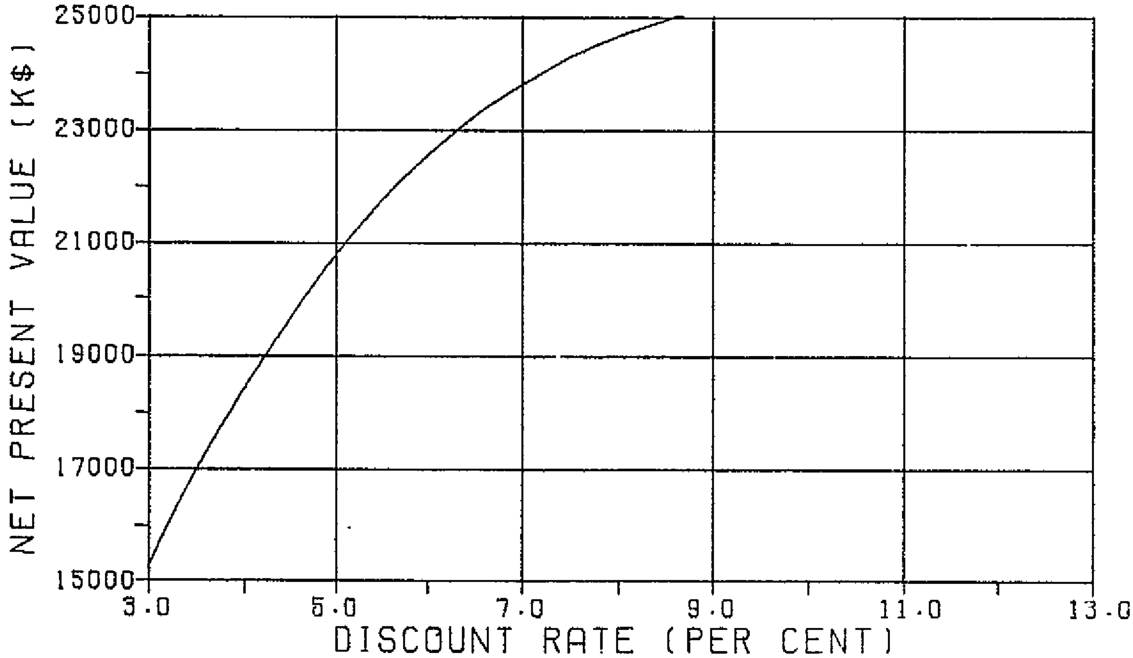


Figure II-35. Sensitivity of Solid State Power Amplifier NPV with respect to Discount Rate.

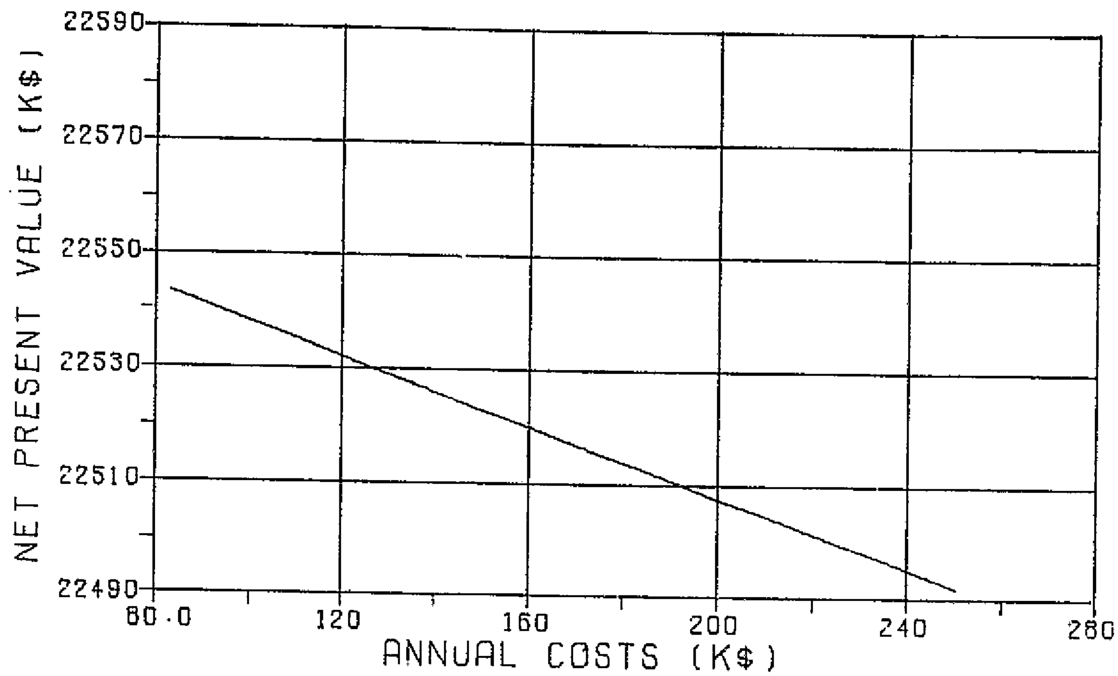


Figure II-36. Sensitivity of Solid State Power Amplifier NPV with respect to Annual Costs for Basic R&D.

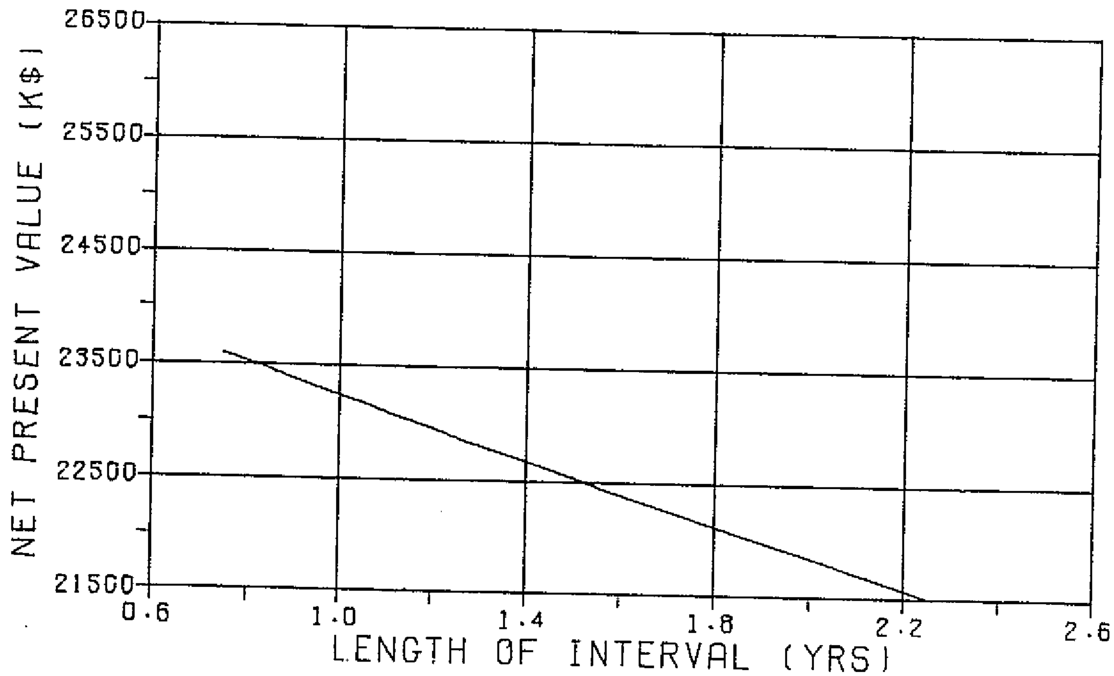


Figure II-37. Sensitivity of Solid State Power Amplifier NPV with respect to Length of Basic R&D Interval.

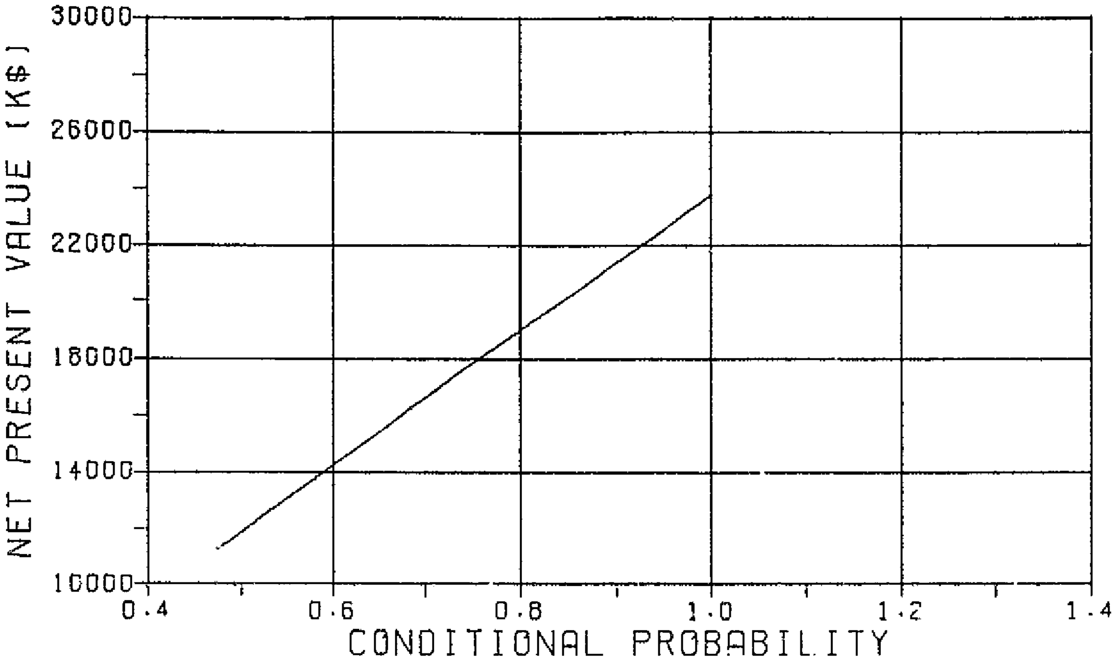


Figure II-38. Sensitivity of Solid State Power Amplifier NPV with respect to Probability that Industry will Implement the Technology.

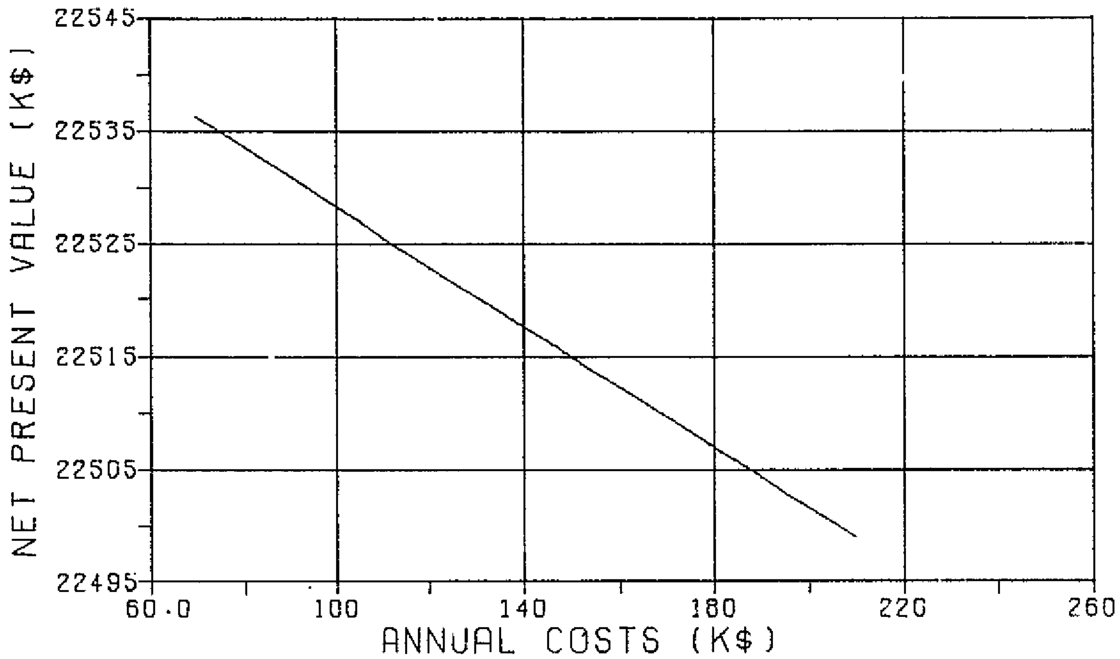
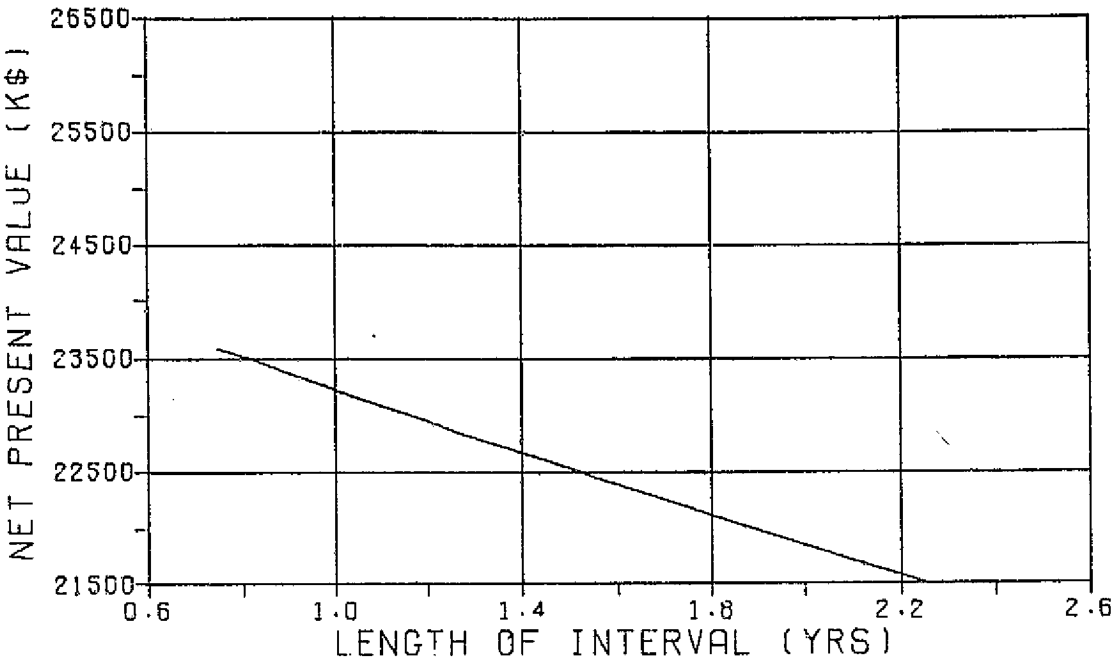


Figure II-39. Sensitivity of Solid State Power Amplifier NPV with respect to Annual Costs During R&D Interval.



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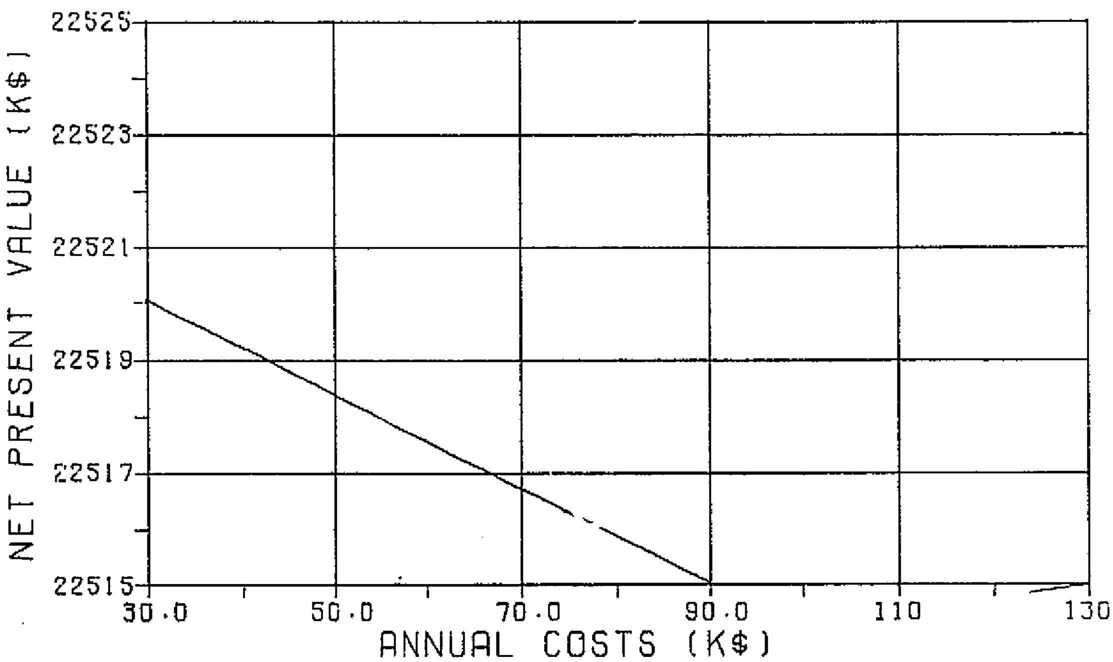

Figure II-41. Sensitivity of Solid State Power Amplifier NPV with respect to Annual Costs in Industry Construction Interval.

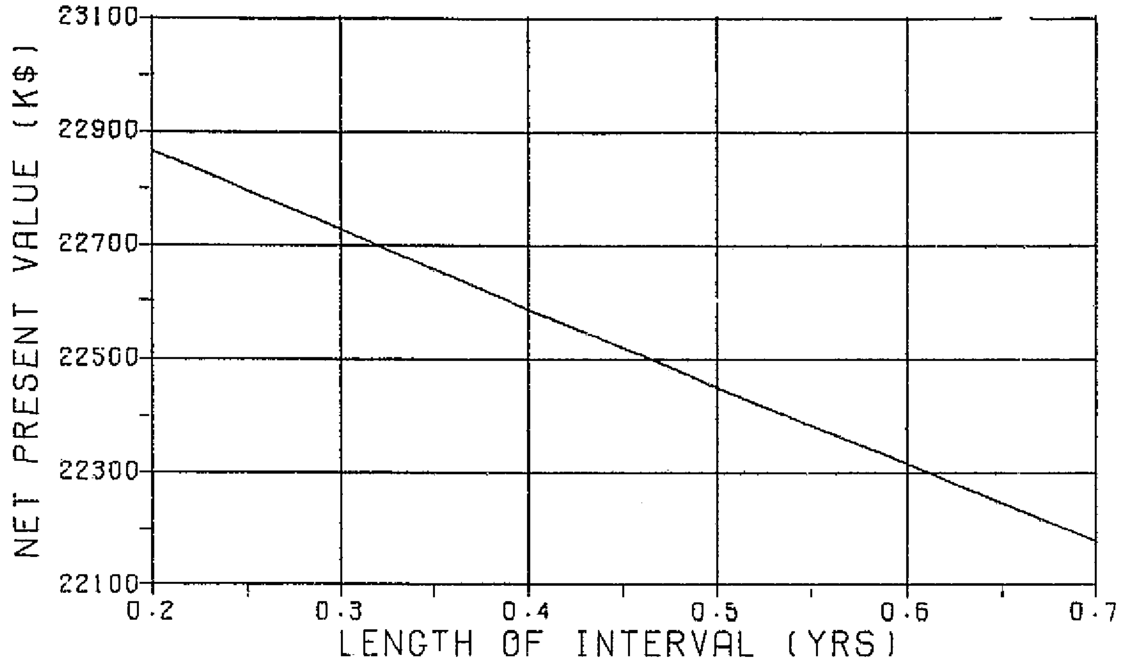

Figure II-42. Sensitivity of Solid State Power Amplifier NPV with respect to Length of Industry Construction Interval.

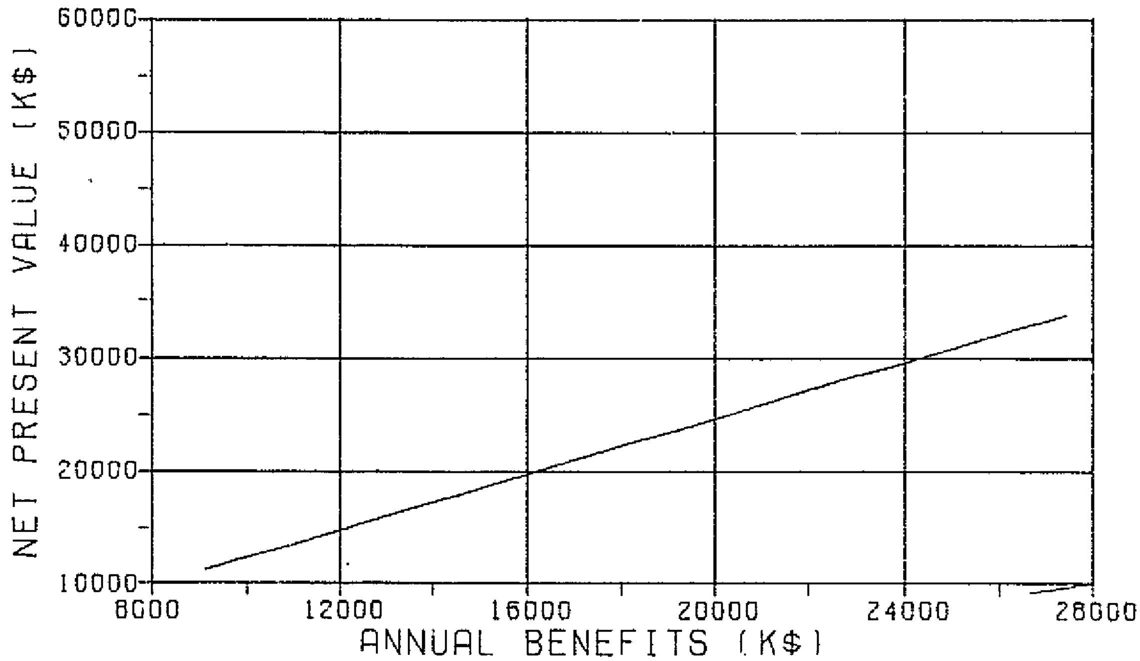

Figure II-43. Sensitivity of Solid State Power Amplifier NPV with respect to Annual Benefits.

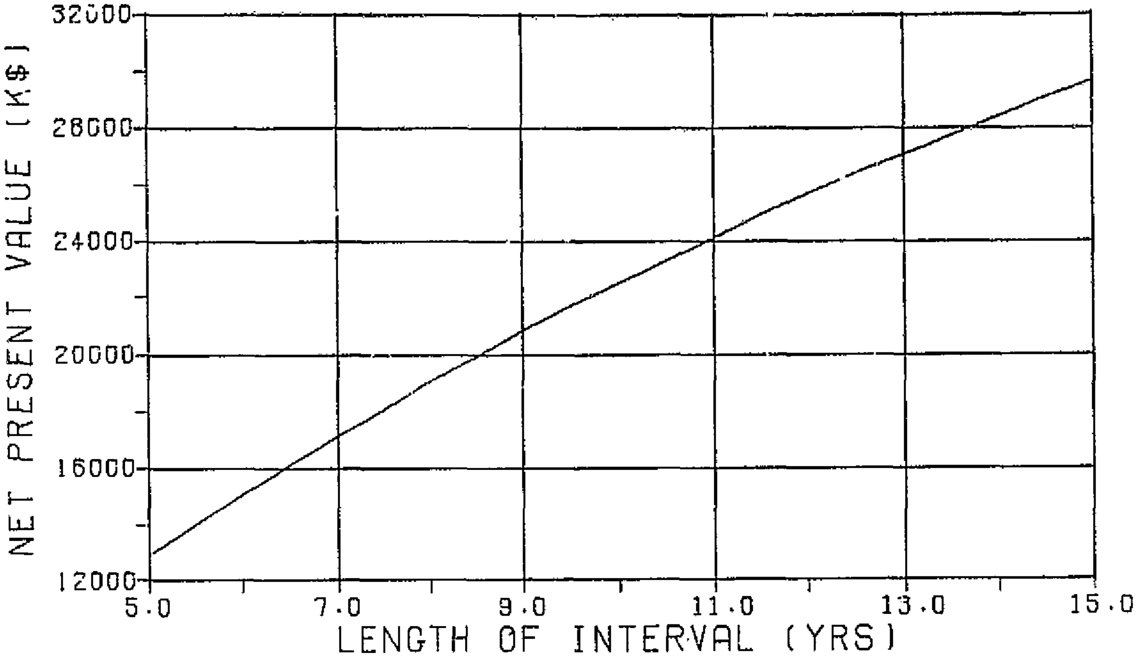

Figure II-44. Sensitivity of Solid State Power Amplifier NPV with respect to Length of Operating Interval.

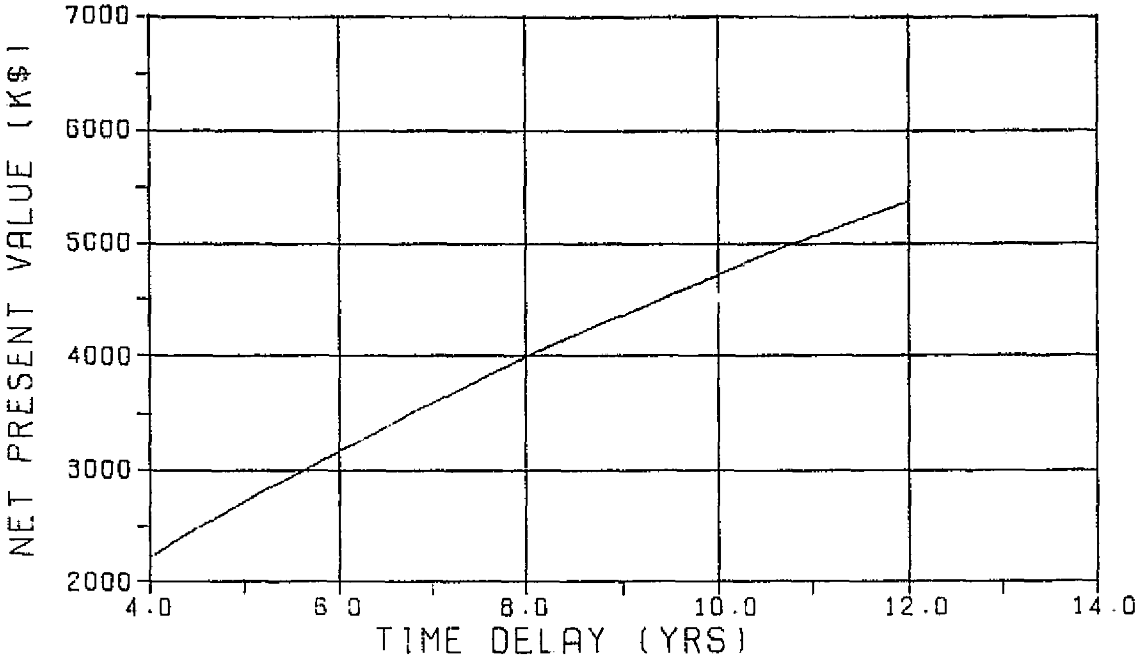

Figure II-45. Sensitivity of Multibeam Antenna NPV with respect to Time Delay in Absence of NASA Support.

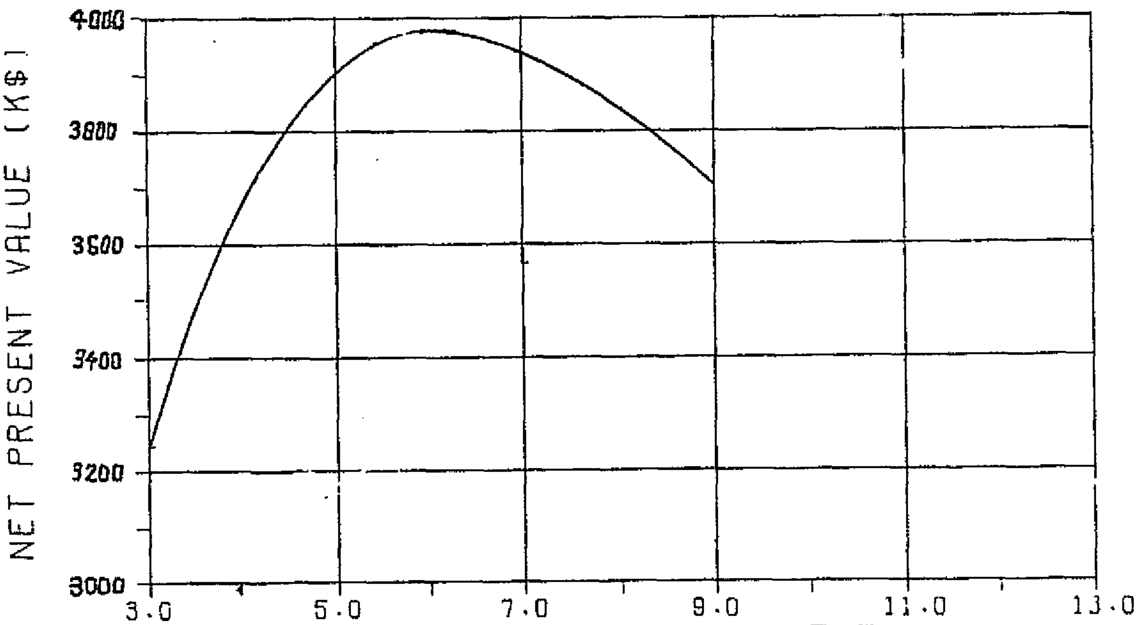

Figure II-46. Sensitivity of Multibeam Antenna NPV with respect to Discount Rate.

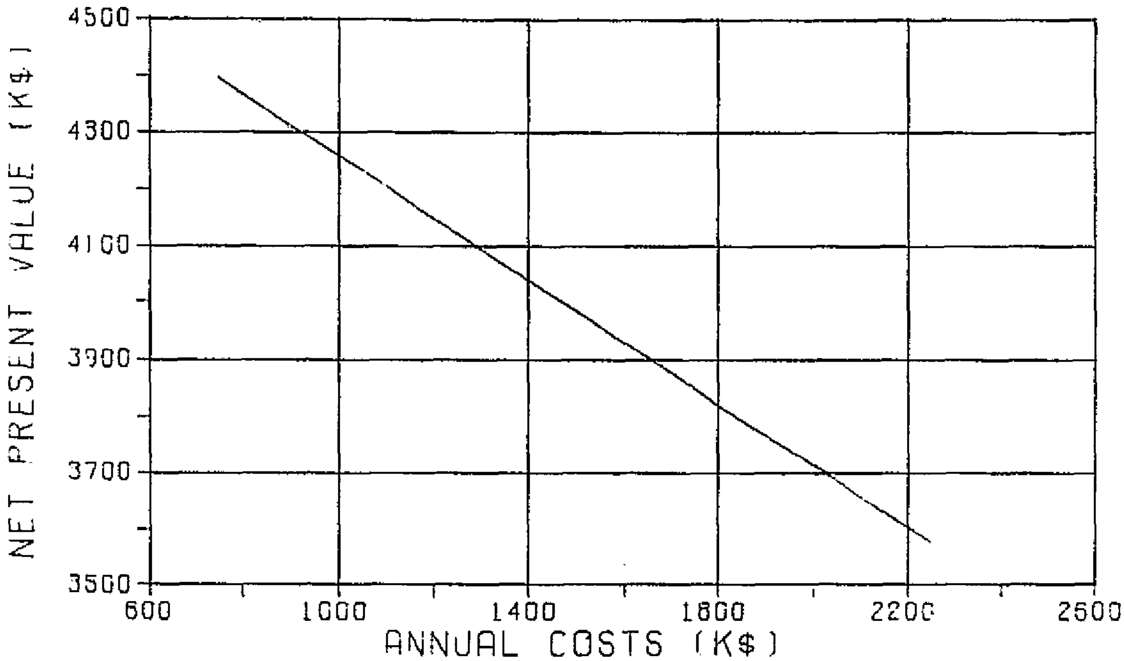

Figure II-47. Sensitivity of Multibeam Antenna NPV with respect to Annual Costs for Basic R&D.

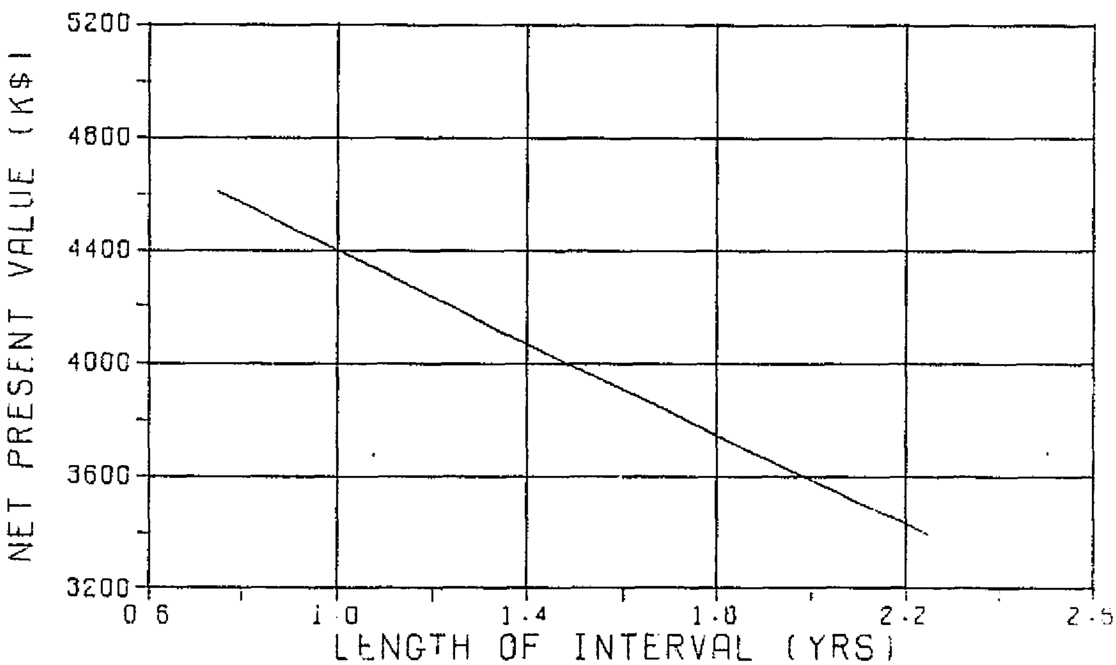

Figure II-48. Sensitivity of Multibeam Antenna NPV with respect to Length of Basic R&D Interval.

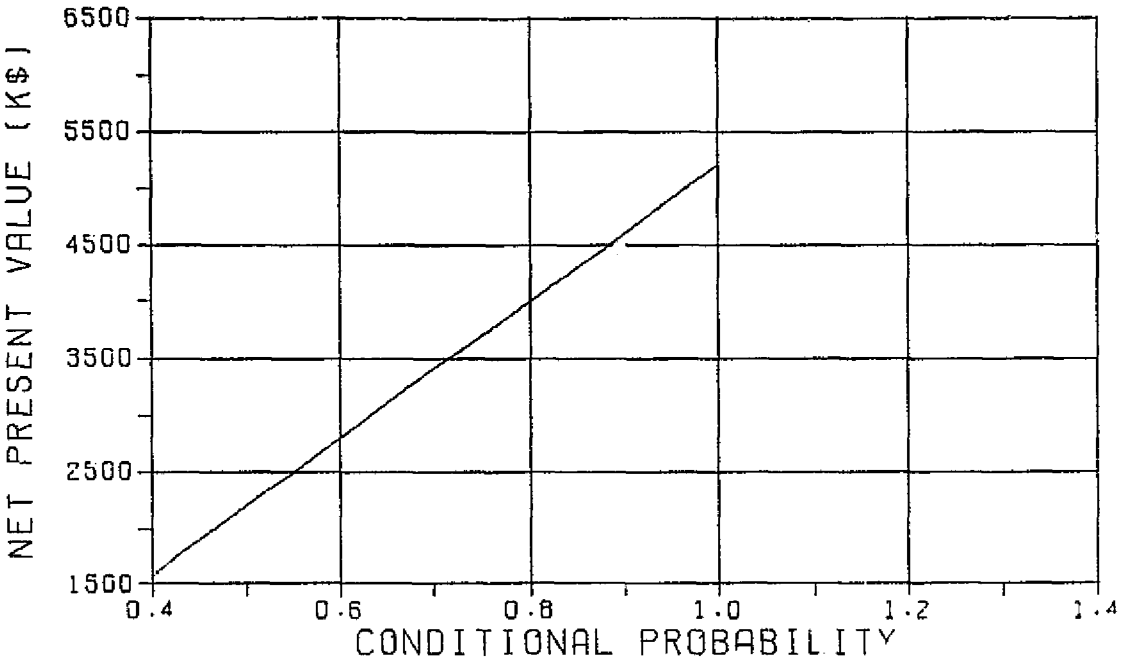

Figure II-49. Sensitivity of Multibeam Antenna NPV with respect to Probability that Industry will Implement th: Technology.

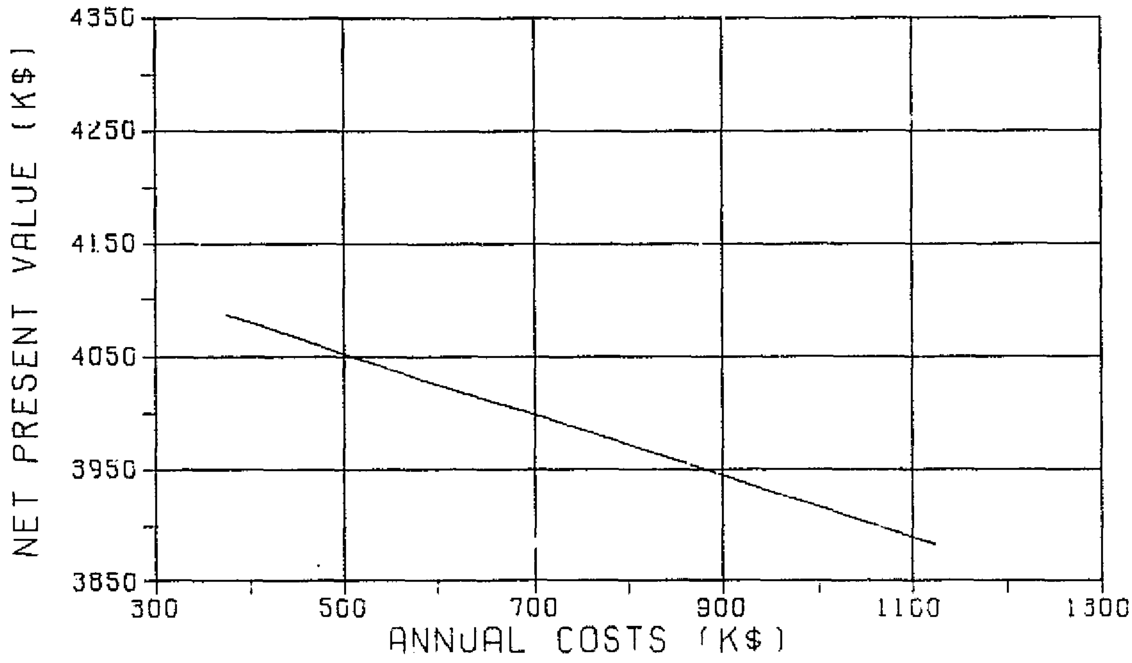

Figure II-50. Sensitivity of Multibeam Antenna NPV with respect to Annual Costs During Applied R&D Interval.

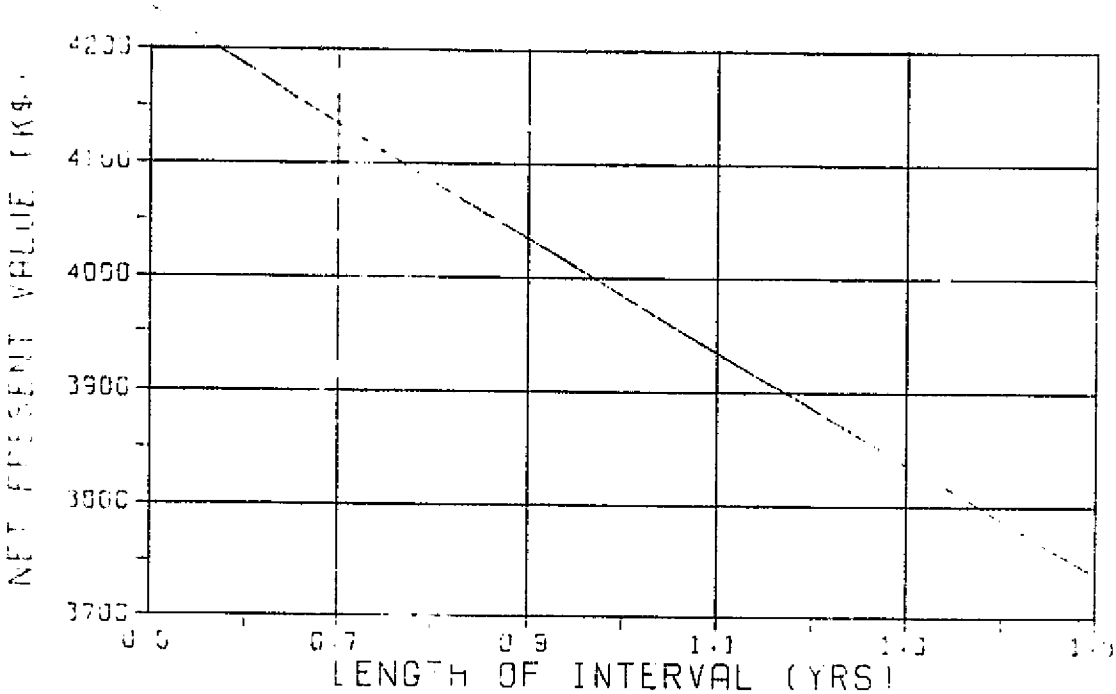

Figure II-51. Sensitivity of Multibeam Antenna NPV with respect to Length of Applied R&D Interval.

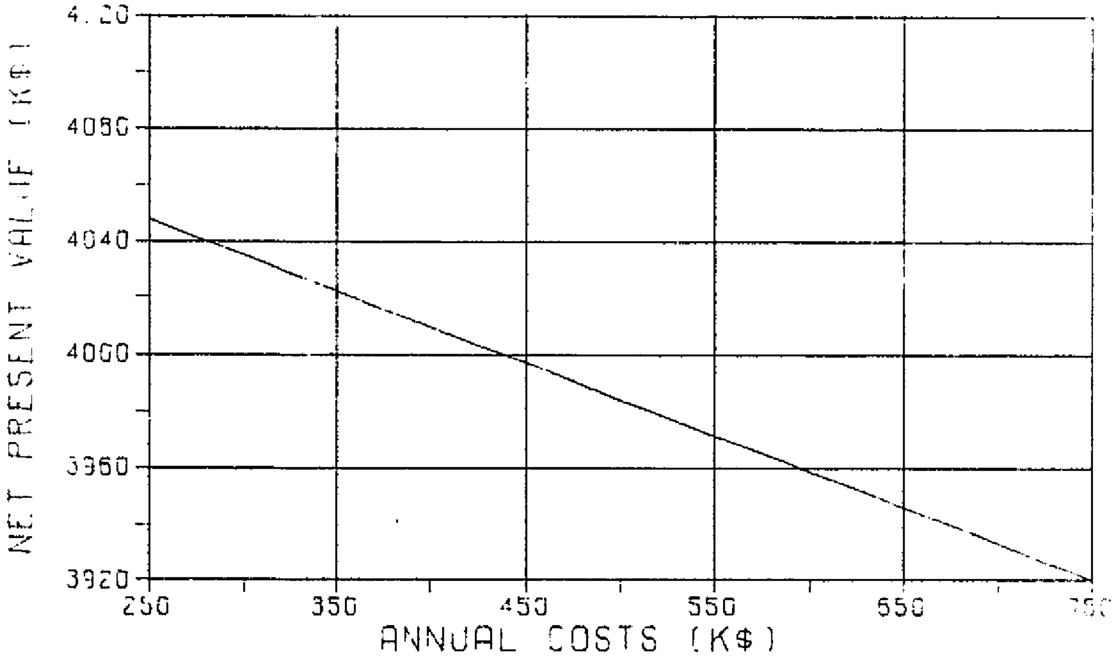

Figure II-52. Sensitivity of Multibeam Antenna NPV with respect to Annual Costs in Industry Construction Interval.

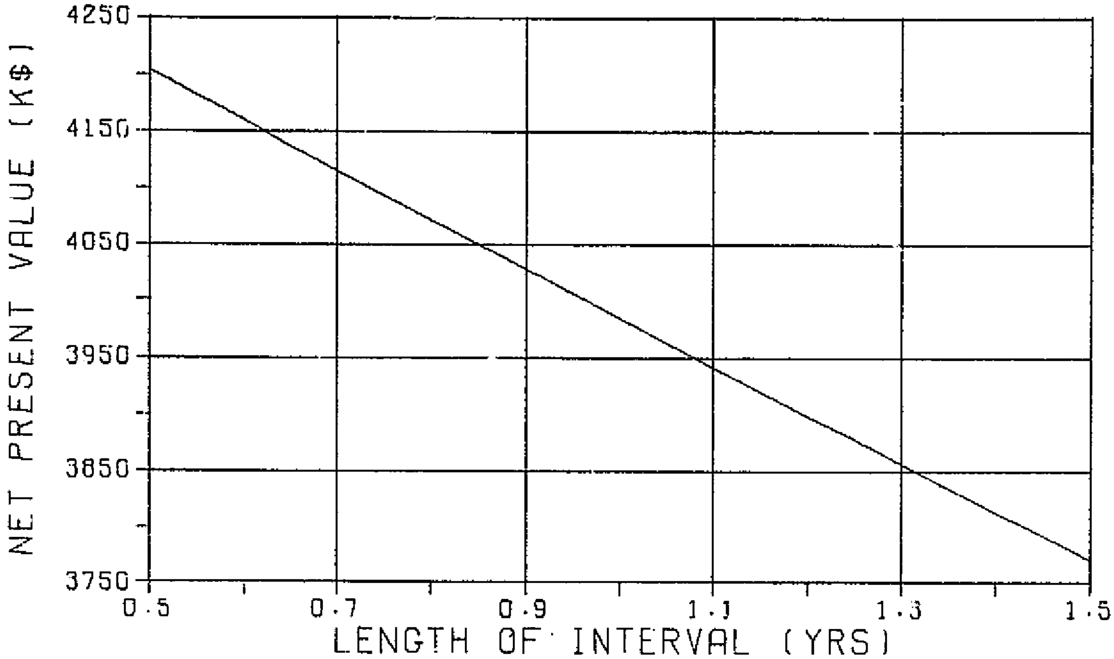

Figure II-53. Sensitivity of Multibeam Antenna NPV with respect to Length of Industry Construction Interval.

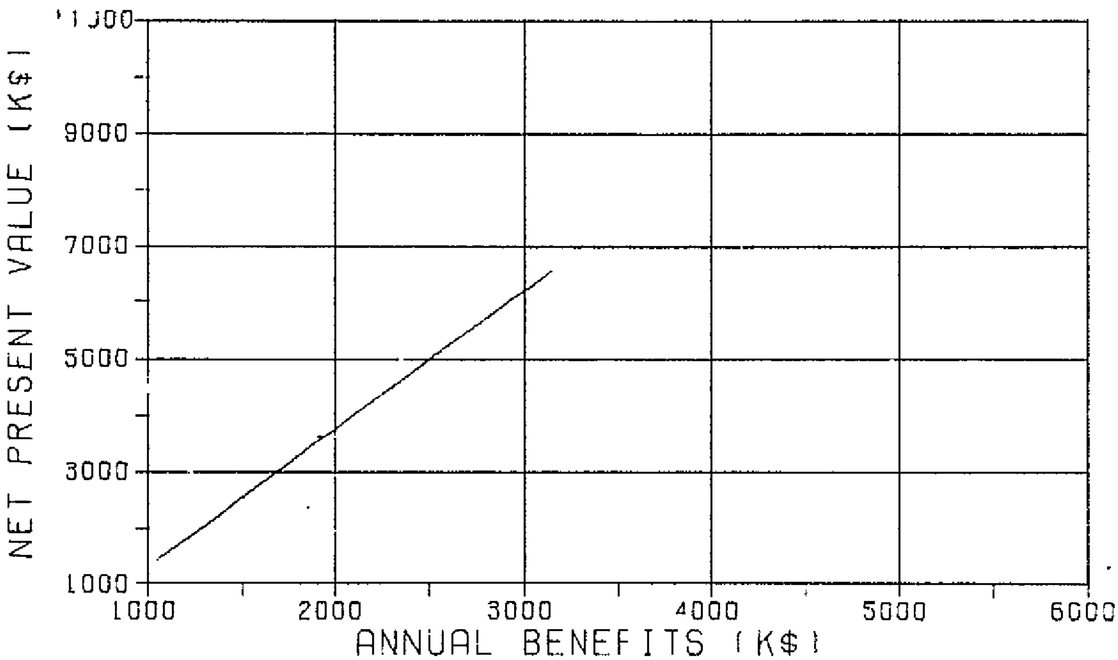

Figure II-54. Sensitivity of Multibeam Antenna NPV with respect to Annual Benefits.

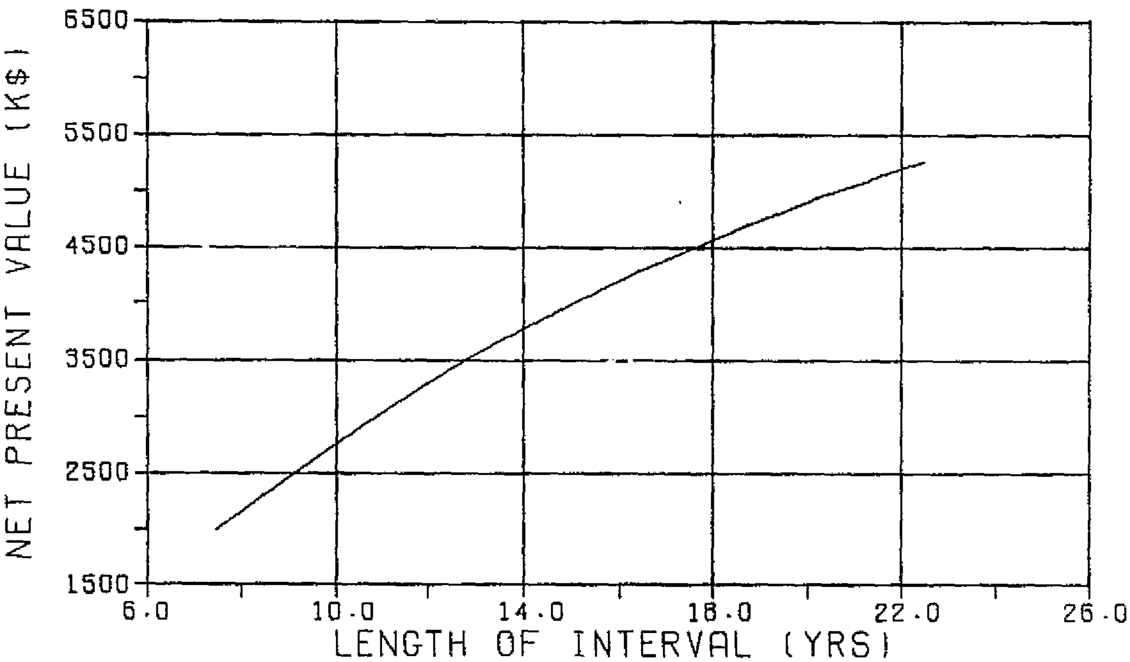

Figure LI-55. Sensitivity .f Multibeam Antenna NPV with respect to Length of Operating Interval

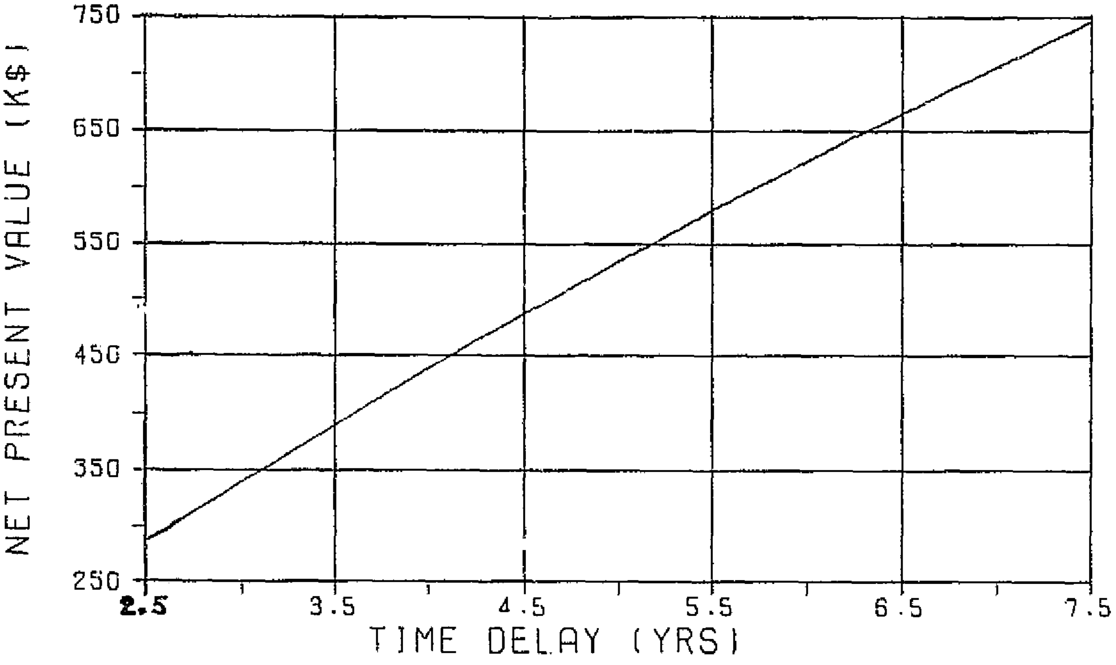

Figure II-56. Sensitivity of Advanced Solar Cells NPV with respect to Time Delay in Absence of NASA Support.

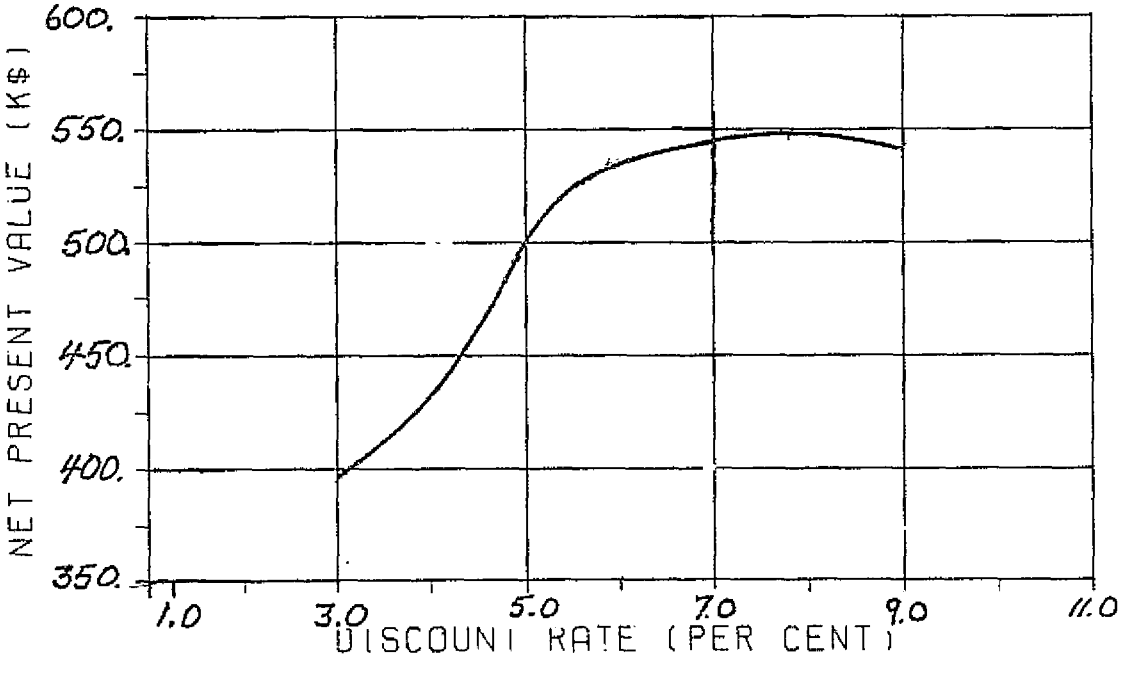

Figure II-57. Sensitivity of Advanced Solar Cells NPV with respect to Discount Rate.

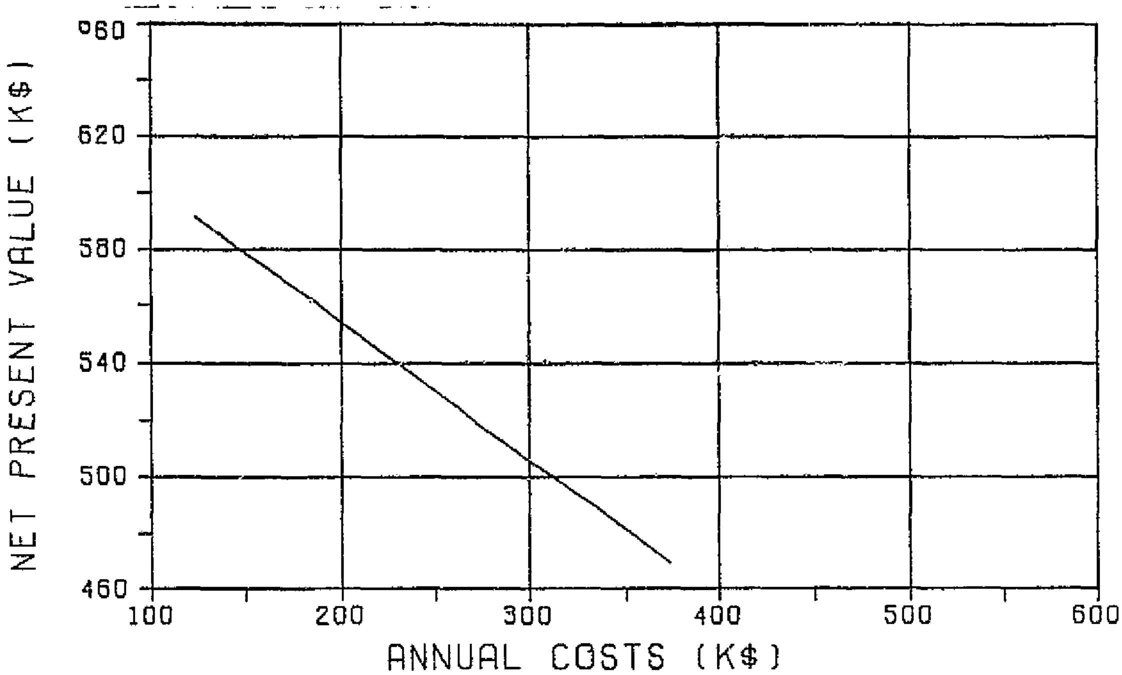

Figure II-58.. Sensitivity of Advanced Solar Cells NPV with respect to Annual Costs for Basic R&D.

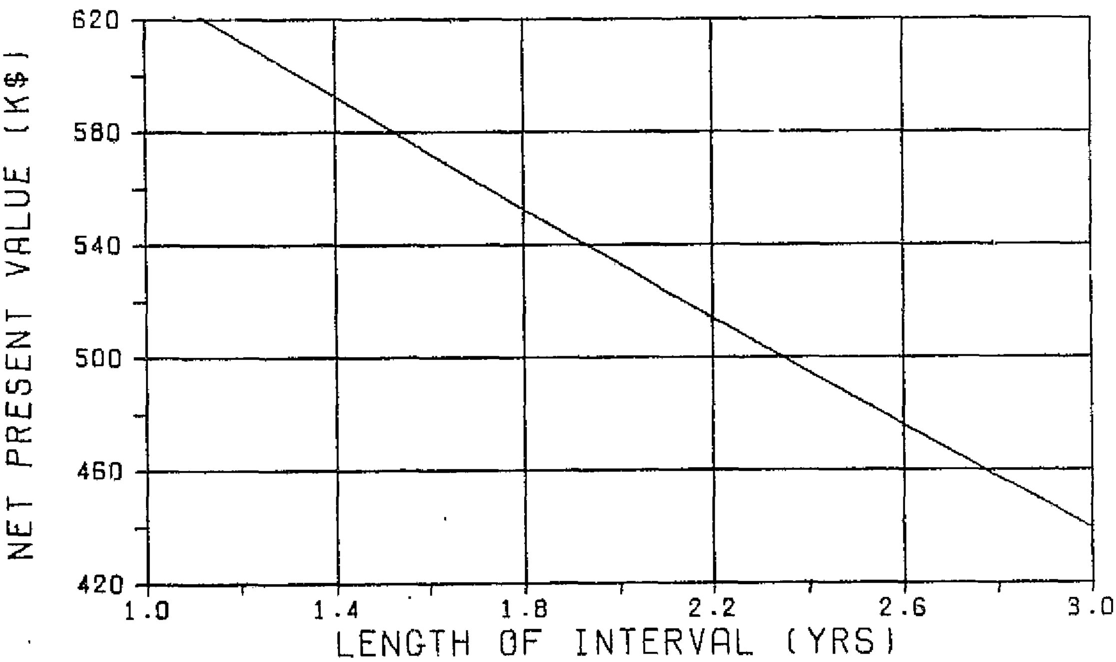

Figure II-59. Sensitivity of Advanced Solar Cells NPV with respect to Length of Basic R&D Interval.

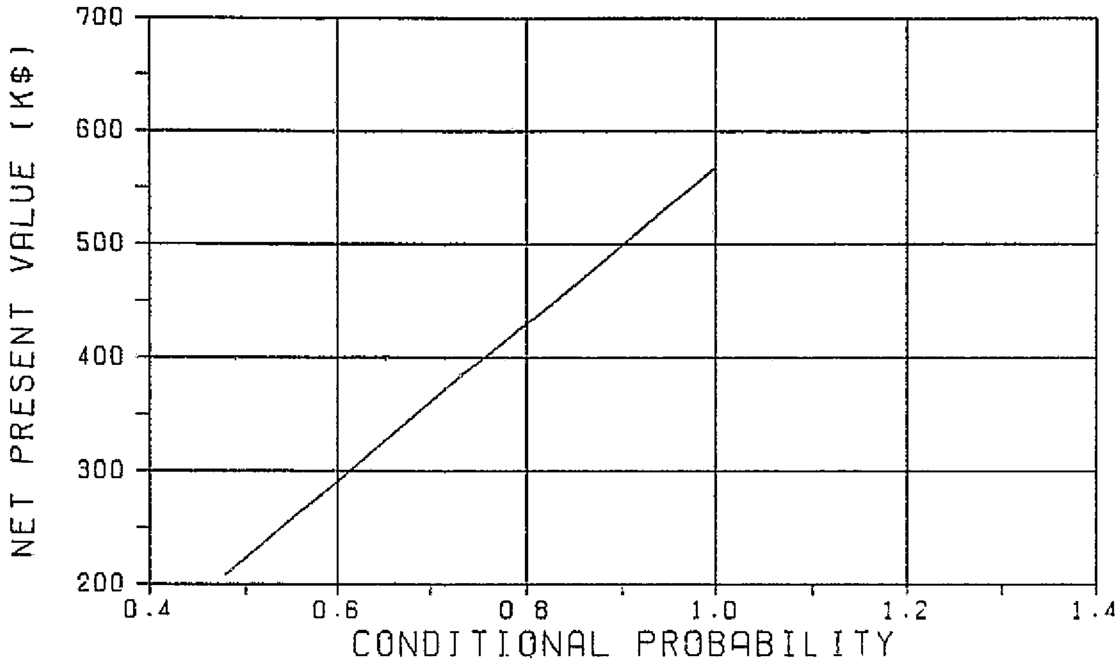

Figure II-60. Sensitivity of Advanced Solar Cells NPV with respect to Probability that Industry will Implement the Technology.

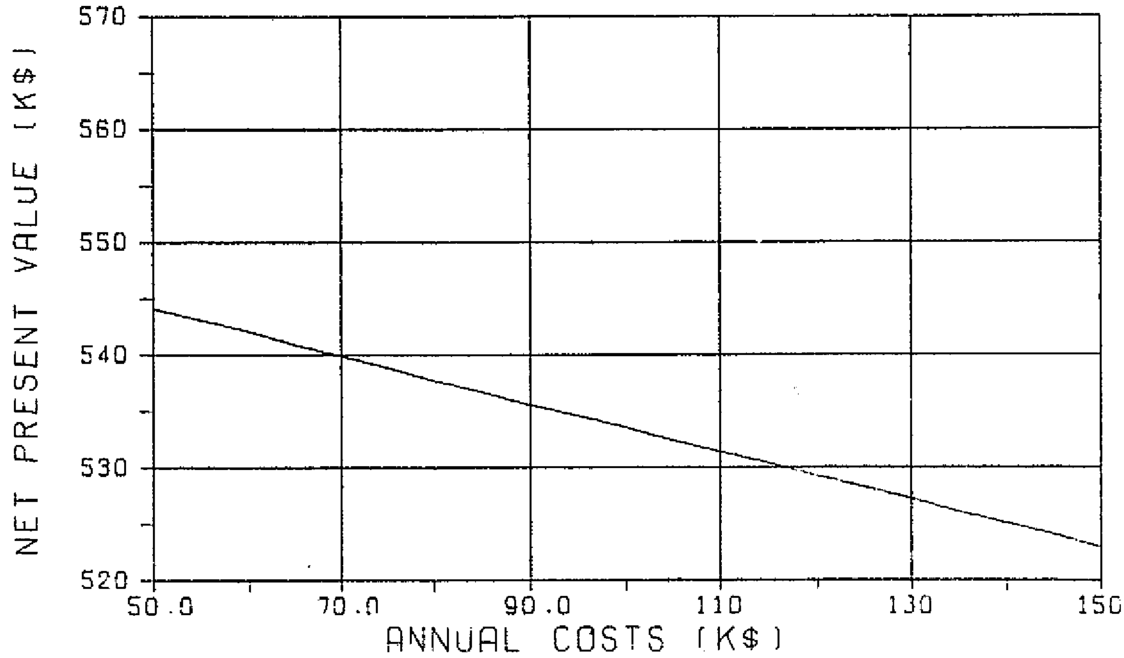

Figure II-61. Sensitivity of Advanced Solar Cells NPV with respect to Annual Costs during Applied R&D Interval.

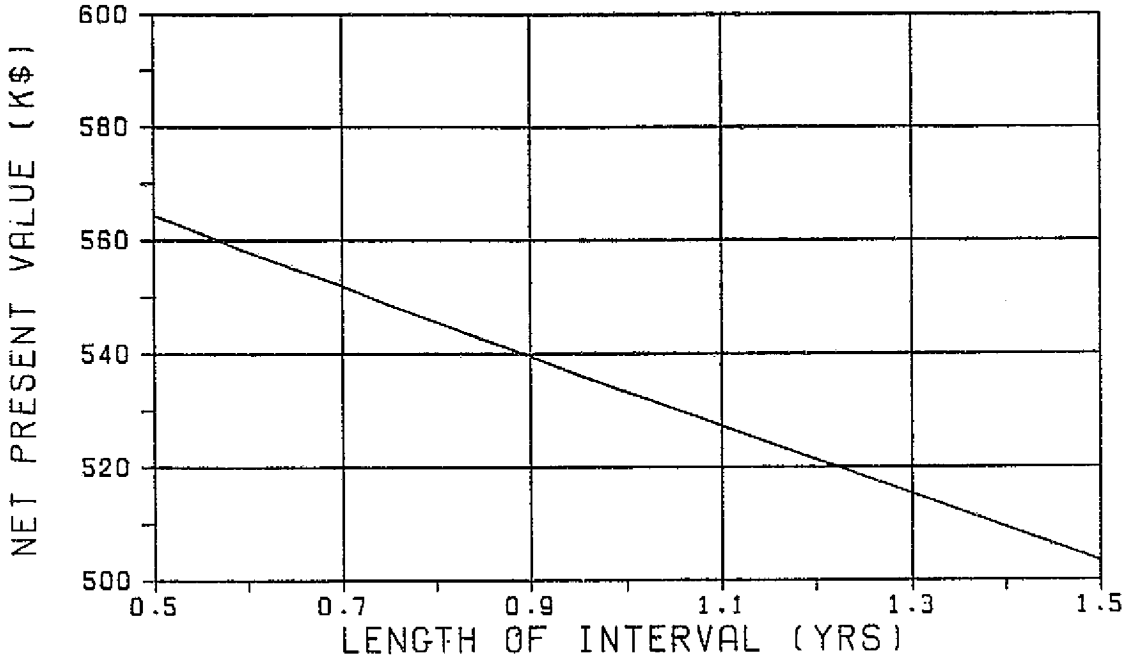

Figure II-62. Sensitivity of Advanced Solar Cells NPV with respect to Length of Applied R&D Interval.

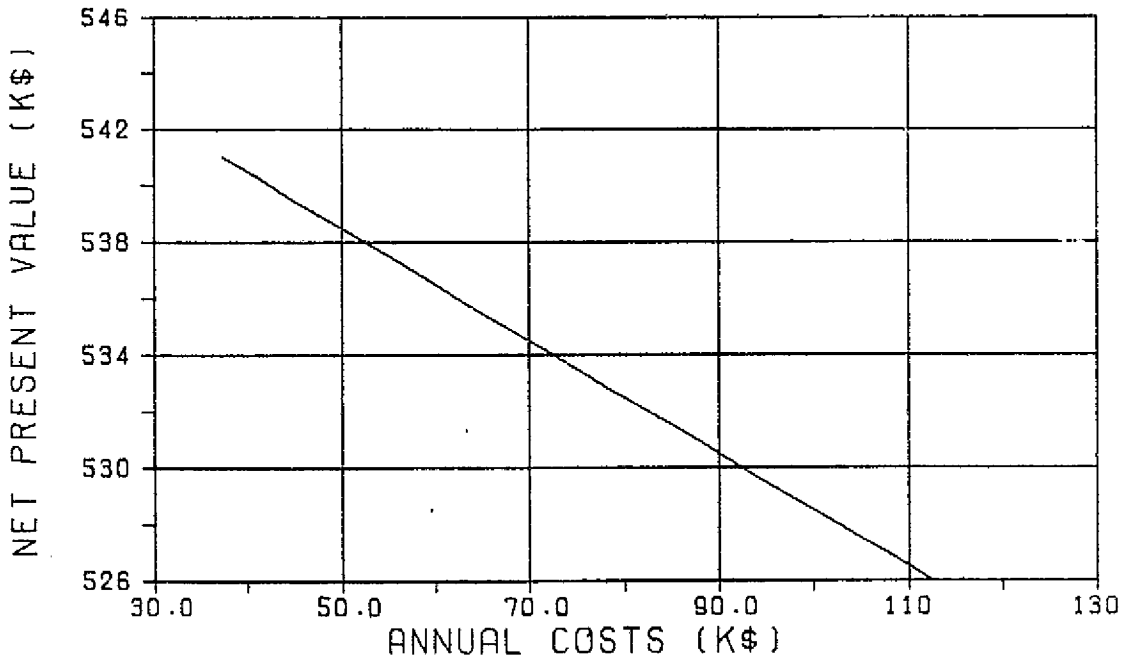

Figure II-63. Sensitivity of Advanced Solar Cells NPV with respect to Annual Costs in Industry Construction Interval.

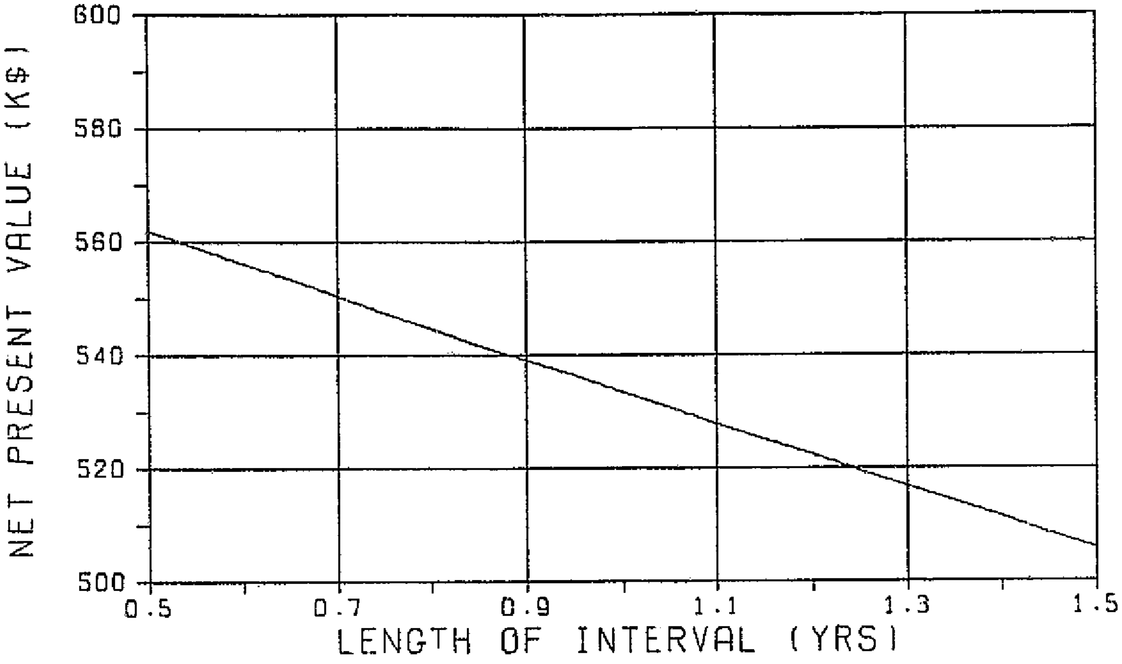

Figure II-64. Sensitivity of Advanced Solar Cells NPV with respect to Length of Industry Construction Interval.

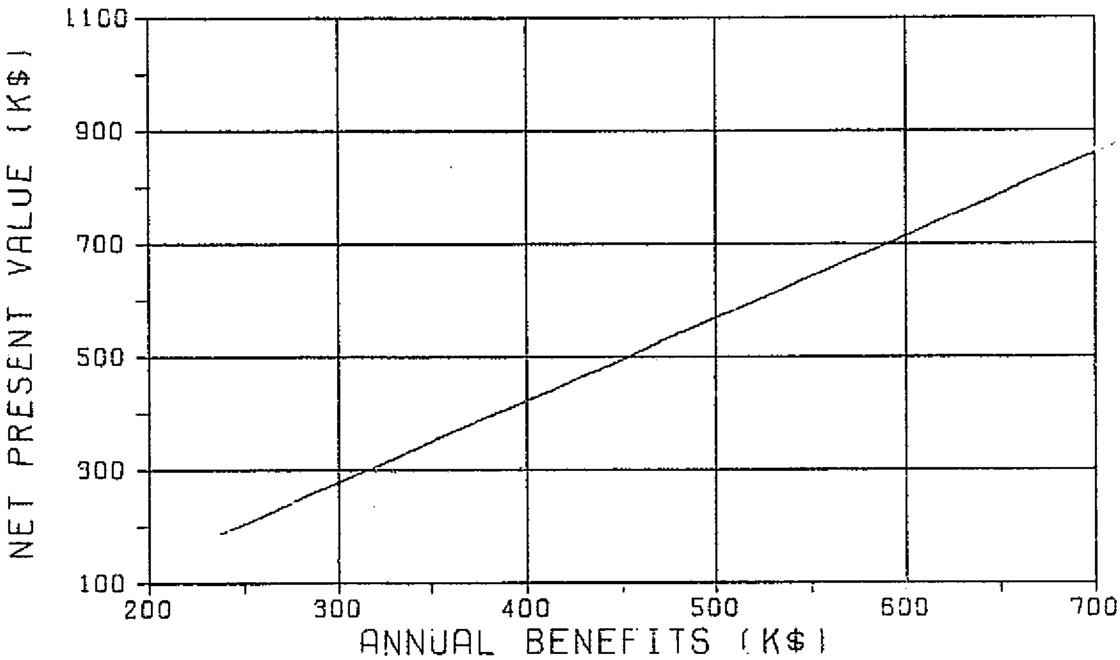

Figure II-65. Sensitivity of Advanced Solar Cells NPV with respect to Annual Benefits.

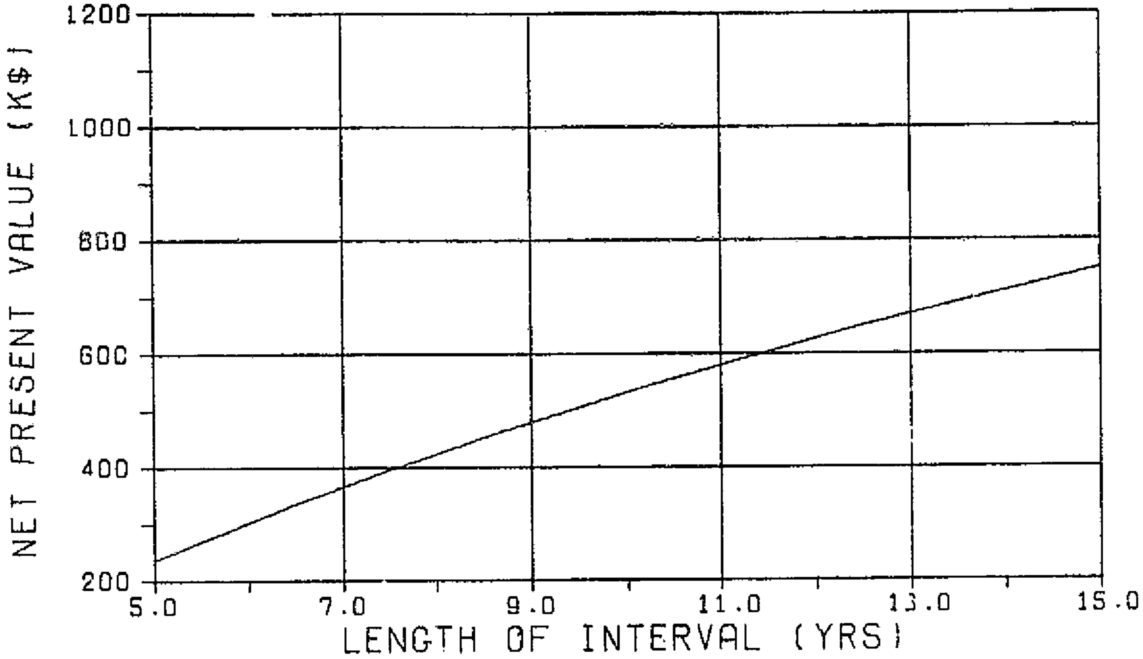

Figure II-66. Sensitivity of Advanced Solar Cells NPV with respect to Length of Operating Interval.

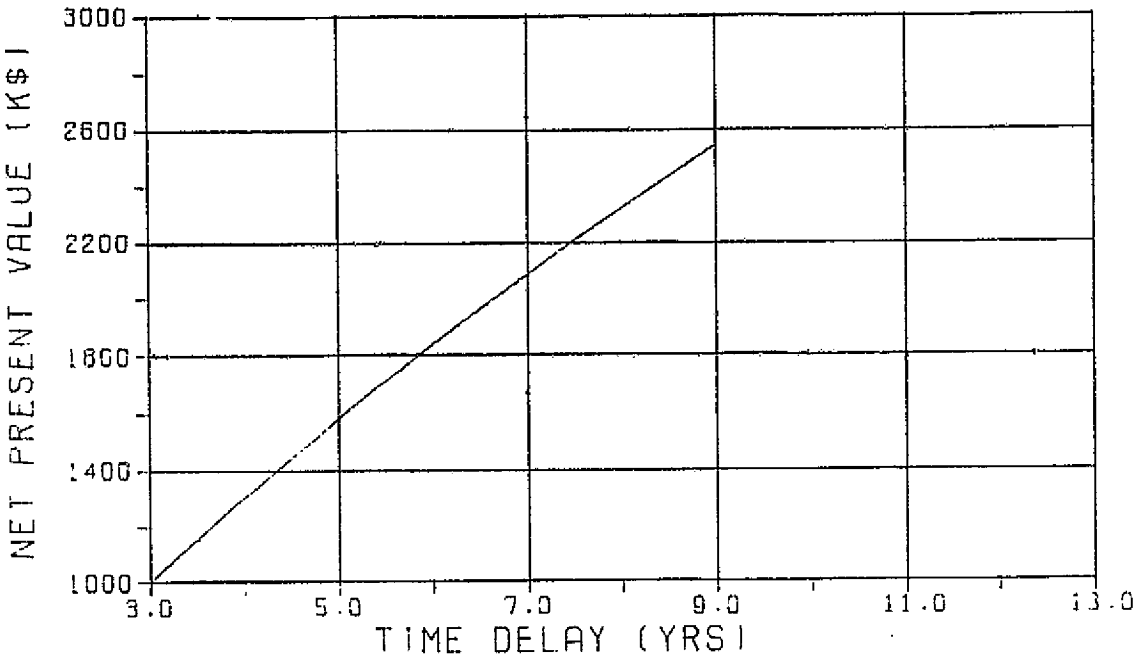

Figure II-67. Sensitivity of Heat Pipe NPV with respect to Time Delay in Absence of NASA Support.

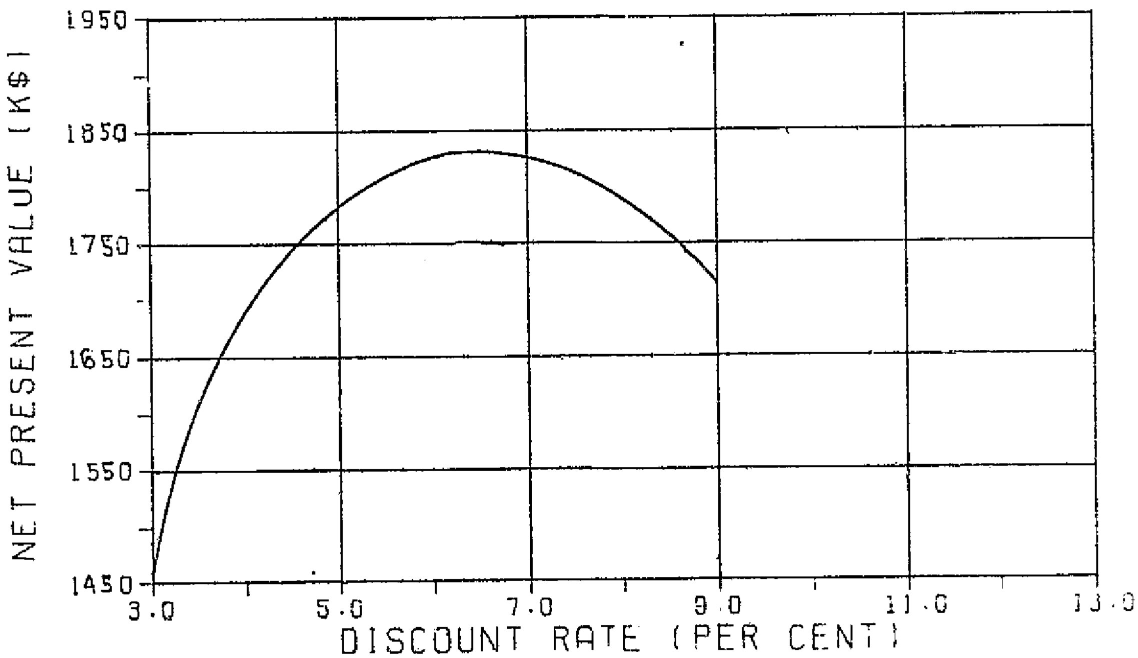

Figure II-68.Sensitivity of Heat Pipe NPV with respect to Discount Rate.

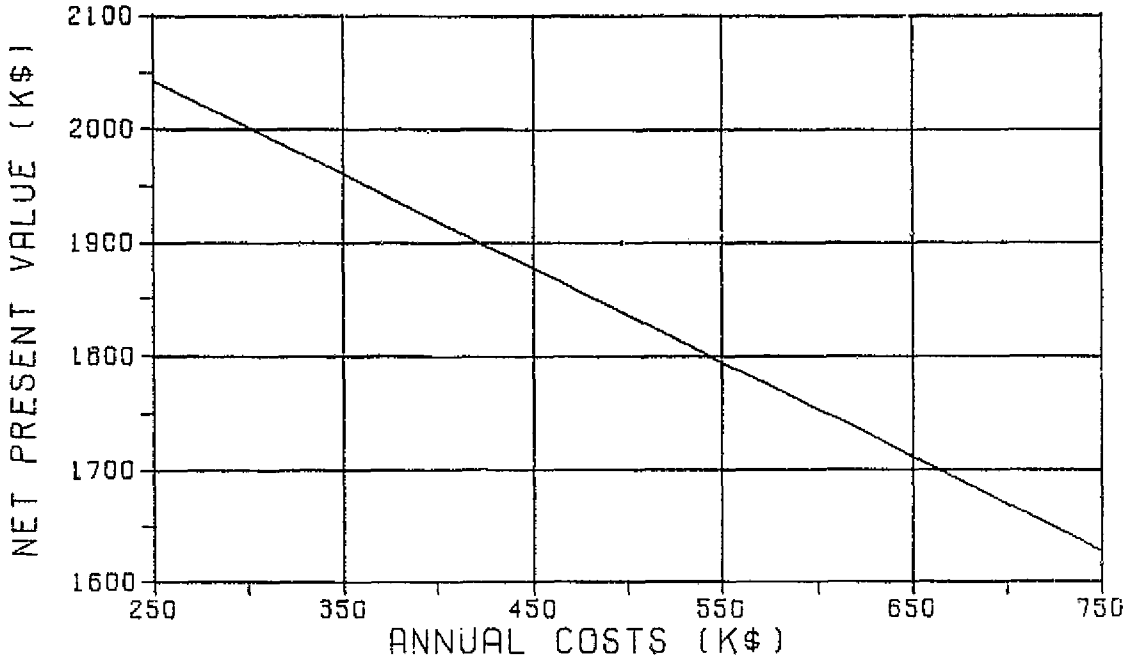

Figure II-69. Sensitivity of Heat Pipe NPV with respect to Annual Costs for Basic R&D.

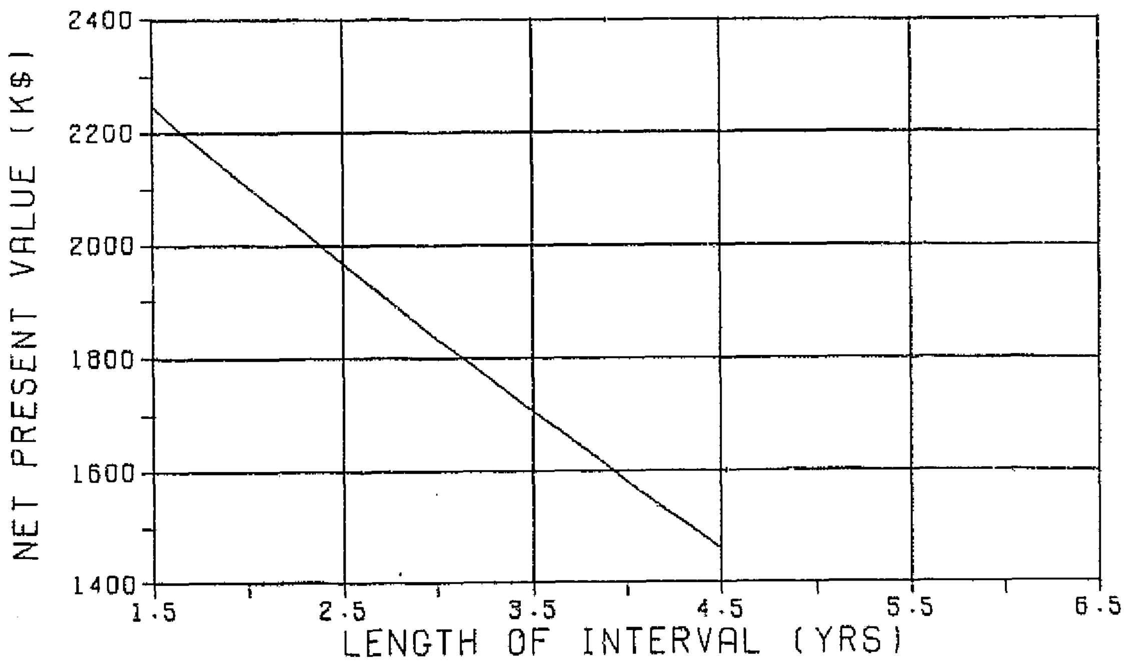

Figure II-70. Sensitivity of Heat Pipe NPV with respect to Length of Basic R&D Interval.

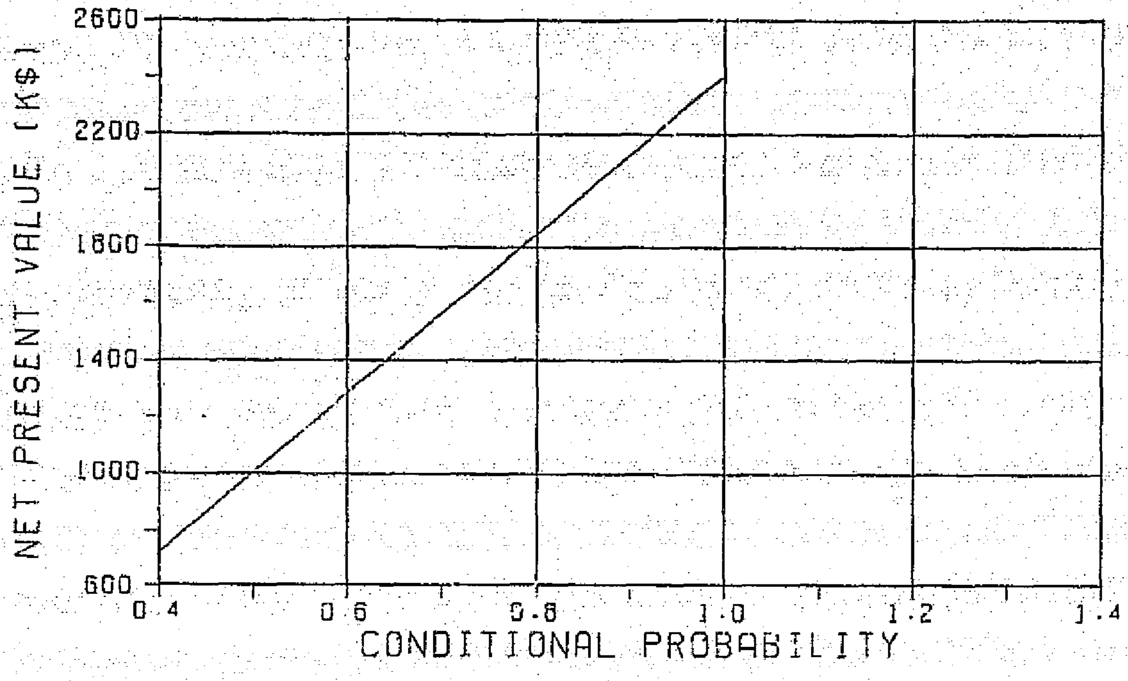

Figure II-71. Sensitivity of Heat Pipe NPV with respect to Probability that Industry Will Implement the Technology

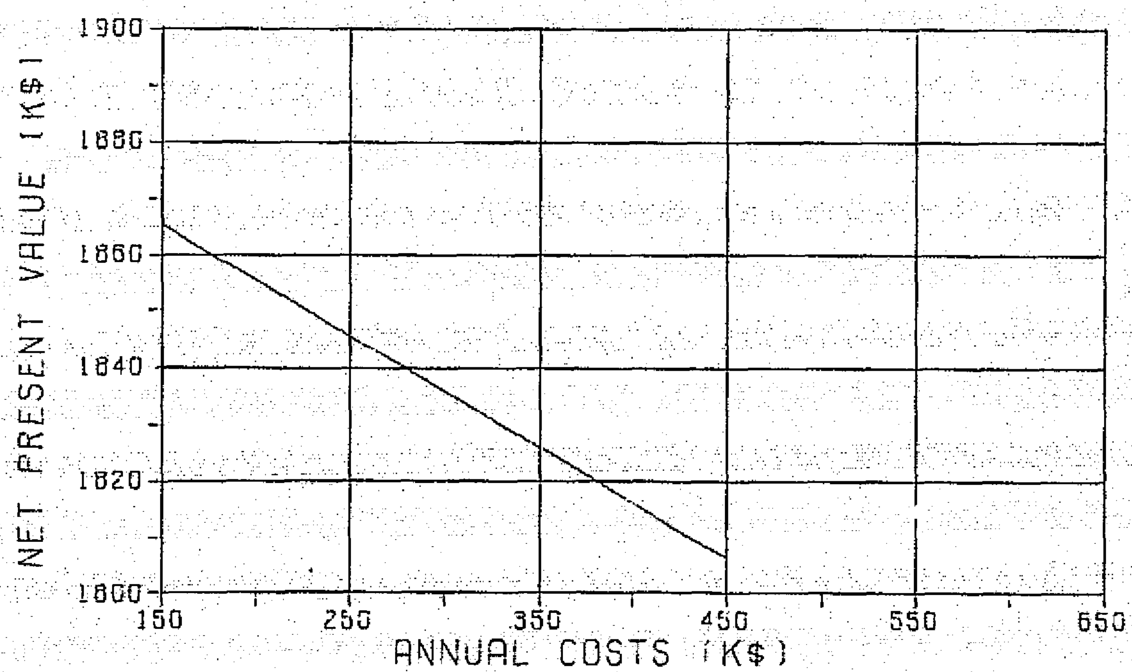

Figure II-72. Sensitivity of Heat Pipe NPV with respect to Annual Costs During Applied R&D Interval.

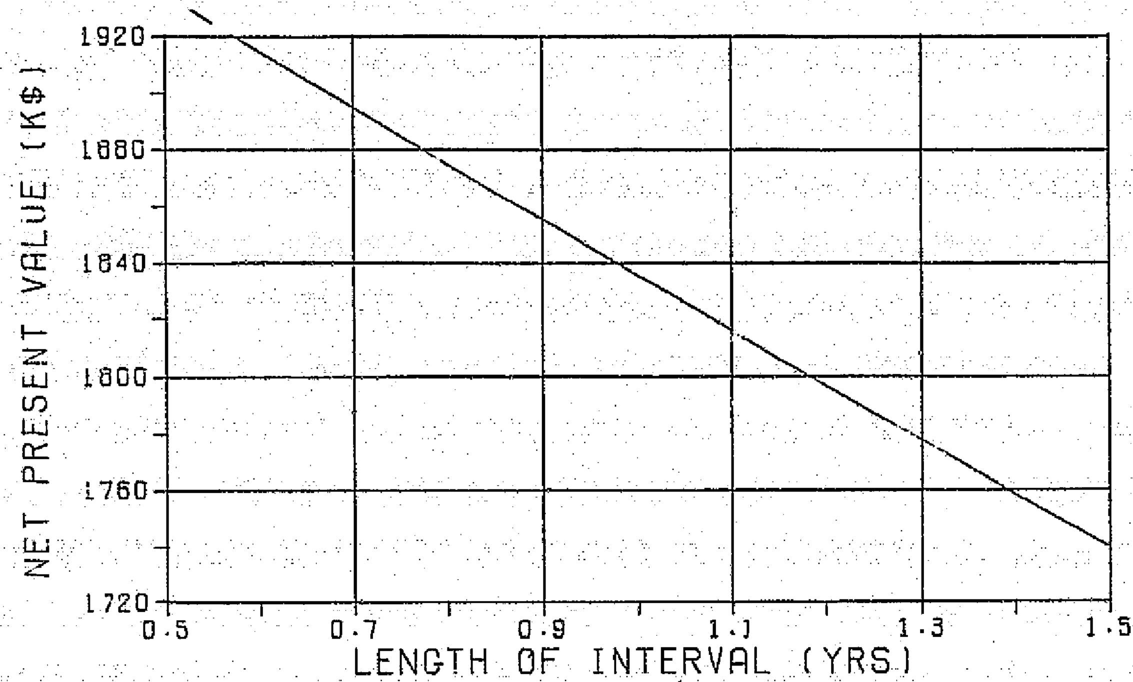

Figure II-73. Sensitivity of Heat Pipe NPV with respect to Length of Applied R&D Interval.

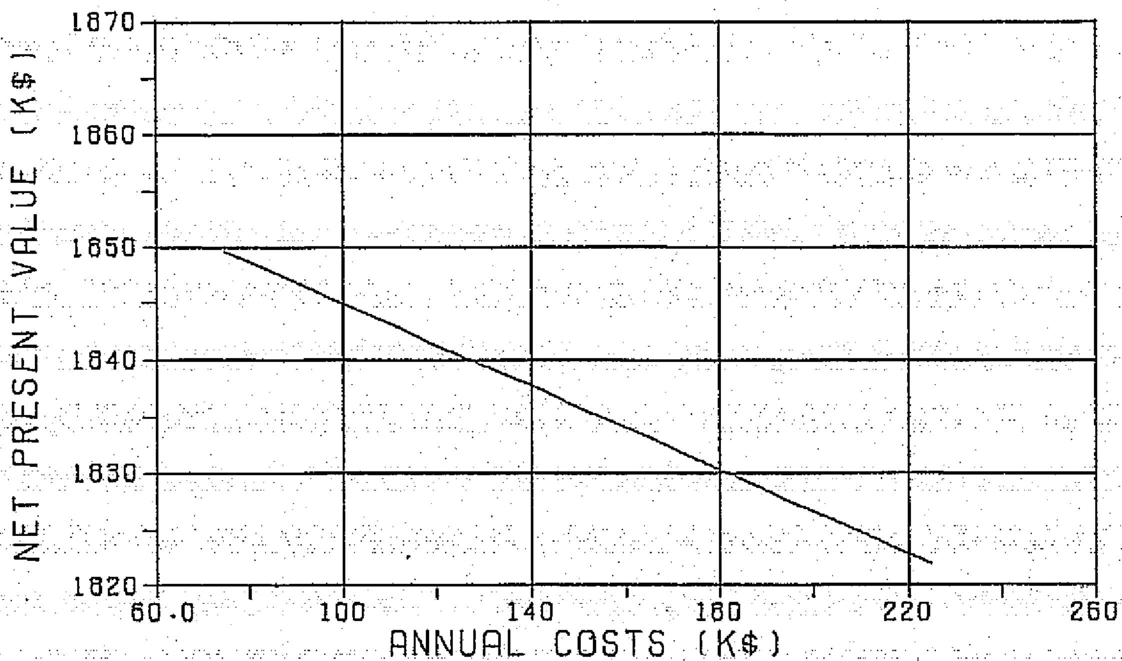

Figure II-74. Sensitivity of Heat Pipe NPV with respect to Annual Costs In Industry Construction Interval.

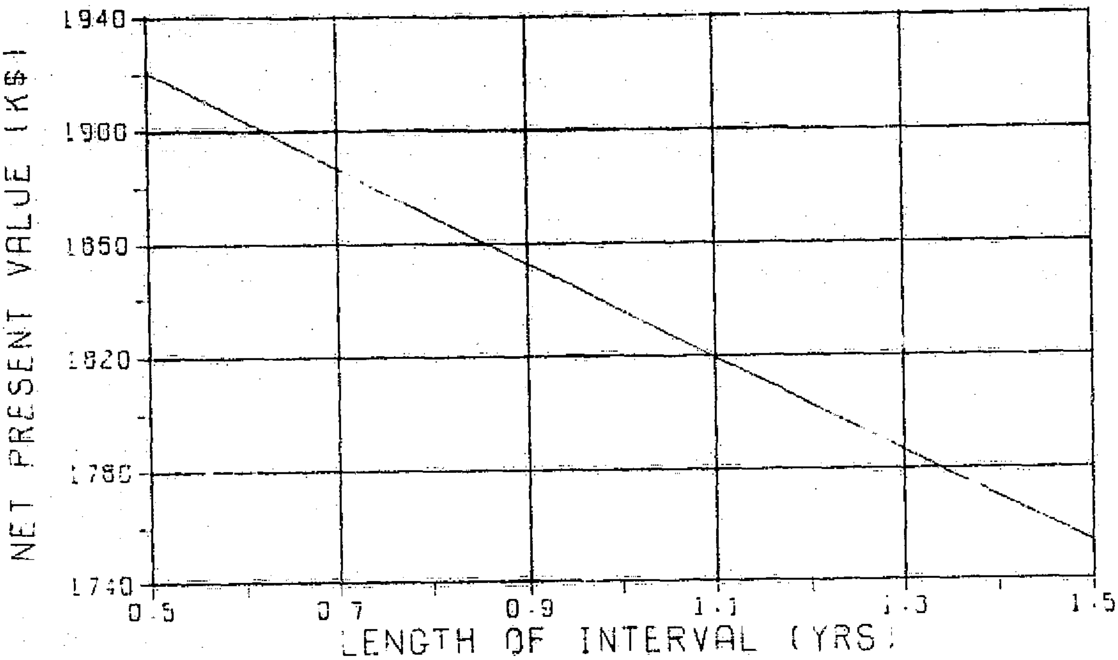

Figure II-75. Sensitivity of Heat Pipe NPV with respect to Length of Industry Construction Interval.

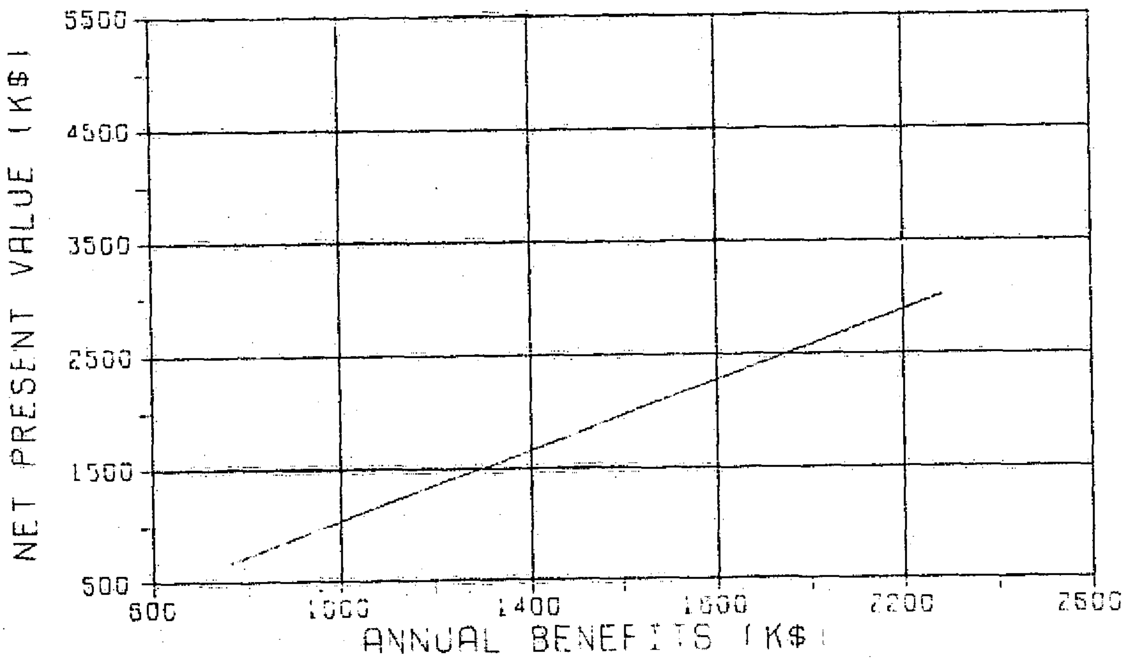

Figure II-76. Sensitivity of Heat Pipe NPV with respect to Annual Benefits.

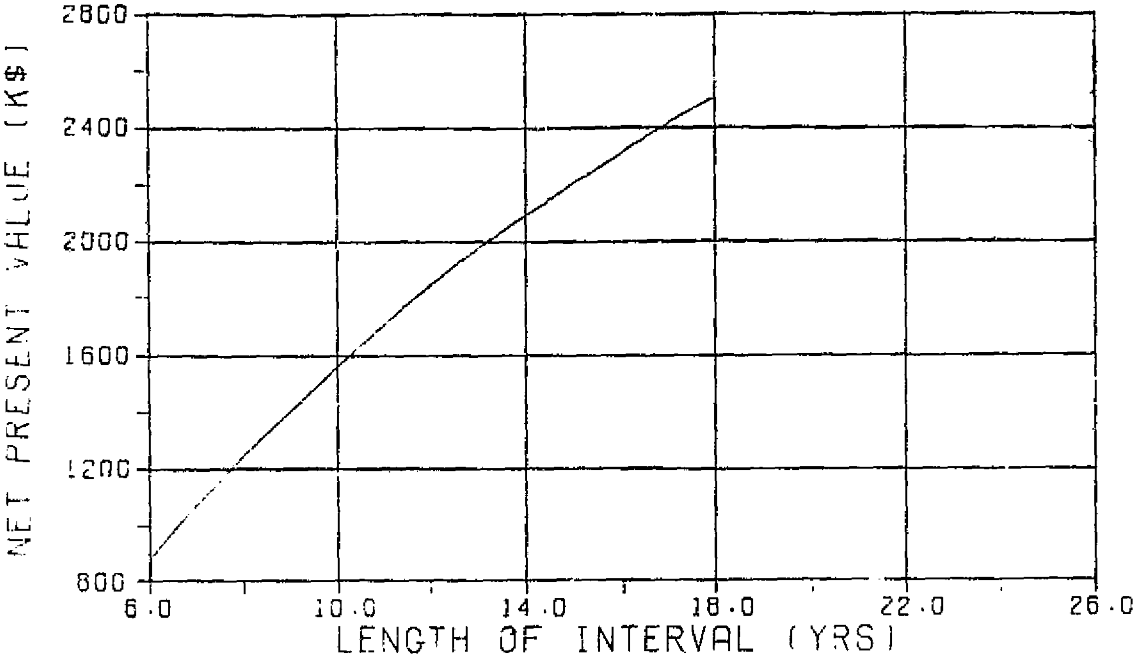

Figure II-77. Sensitivity of Heat Pipe NPV with respect to Length of Operating Interval.