# Teleconferencing: Cost Optimization of Satellite and Ground Systems for Continuing Professional Education and Medical Services

## May 1972

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Teleconferencing: Cost Optimization of Satellite

and

Ground Systems for Continuing Professional Education

and

Medical Services

May, 1972

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# Chapter I

## Introduction and Summary

The study just completed developed a set of analytical capabilities that are needed to assess the role satellite communications technology will play in public and other services. It is user oriented in that it starts from descriptions of user demand and develops the ability to estimate the cost of satisfying that demand with the lowest cost communications system. To ensure that the analysis could cope with the complexities of the real users, two services were chosen as examples, continuing professional education and medical services.

Telecommunications costs are effected greatly by demographic factors, e.g., distribution of users in urban areas and distances between towns in rural regions. For this reason the analytical tools were "exercised" on sample locations. San Jose, California and Denver, Colorado were used to represent an urban area and the Rocky Mountain states were used to represent a rural region. In assessing the range of satellite system costs, two example coverage areas were considered, one appropriate to cover the contiguous forty-eight states, a second appropriate to cover about one-third that area.

It is important to note that this six-month study was not meant to make specific proposals for complete systems to satisfy a given demand. Even if user demand information and additional time were available, it is beyond the responsibility of this group to make many of the decisions implied by recommendation of any specific service. For example, the states to be served, management responsibility for the system, the method of financing, and the relationships between different services, all involve decisions of different government agencies and of other public and private institutions. It was felt to be a more useful first step to develop a "catalog of capabilities" and methodology for determining demand rather than to propose a specific service. (The next logical step is to use these results to compare the costs of alternative organization of different services.)

In Chapter II the characteristics of the users are developed, the prime emphasis being on continuing professional education and medical services. In both these areas it is apparent that while travel will never be replaced by teleconferencing, partial substitution of communications for travel should occur. Just how much, depends strongly on the

quality and convenience of the medium. In continuing professional education the market is large, important, and relatively affluent. In general, the principal role of teleconferencing would be to keep the professionals abreast of the developments in their fields, a need poorly satisfied by today's array of journals, conventions and occasional seminars. To provide better service, it is essential that the medium be convenient both in location (in the office or professional building seems necessary) and in the form of material (retrieval of specific information is more important than courses to some professionals). The services simply will not be used if they take an inordinate amount of travel or searching through material. Since each professional group has different educational requirements, this implies a variety of media requirements.

In medical telecommunications services, central hospitals, smaller hospitals, doctors in private practice, rural communities and ghetto areas all have different needs. The typical problem is to use teleconferencing to distribute the centralized capabilities of larger hospitals to other communities. In most medical service systems there will be tiers of service. Rural clinics will receive aid from referral hospitals, which in turn will contact central hospitals on matters for which specialists are needed. The teleconferencing can provide consultation both in direct patient care and in emergency diagnosis before evacuation. In addition to consultation, the telecommunications can play an important role in community health education and in general coordination of information such as patient records, blood inventories, scheduling of specialized equipment, and general management information.

While the study met with success in defining important characteristics of telecommunications services, it was not able to determine with any precision quantitative demand for these services. Bounds, such as money presently spent on information handling and numbers of professionals in any category were available. However, true demand information (how many would use the service at any given price) was just unobtainable. A major difficulty is that some information services are provided as a part of other services, and individual users often do not make a decision to use the information service based on its price. The demand picture is further clouded by heavy government subsidization of many of the

types of services being considered. In lieu of obtaining specific demand information, a demand analysis model was developed. This model can be used to guide a subsequent data effort and more importantly perhaps to guide the planning of evaluation phases of upcoming satellite experiments and demonstrations. The model includes subsegmentation of each target population into functionally different subgroups, estimates of maximum penetration rates, finite adoption times, and the demand for substitute services.

The demographic characteristics of the users, in addition to setting some bounds on user demand, are very important to the technical design of the system. The choice of alternative technologies depends greatly on the clustering tendencies of the different users. For some services the system can be designed around a professional group, for others it can be designed around an industry, which may contain several professional groups. Data for each strategy must be gathered separately and the quality of data varies markedly among professional or industrial categories.

In the categories studied it was found that professional groups tend to cluster differently, reducing the possiblity of having a joint receiving location serving several groups. Doctors tend to cluster in larger cities, especially downtown and near hospitals. In San Jose for example, when there was at least one doctor on a block there were on the average 3.3 doctors on the block. In rural communities and large suburban communities, the doctor to population ratio tends to be low. Most towns with less than 2,000 people have no doctors at all and many large residential suburban communities also have no doctors (hence the demise of the house call?). While engineers and lawyers also tend to cluster in the cities they do so in different parts of the city, lawyers generally around the central business district and engineers near research centers. Teachers on the other hand are distributed much more along general population lines. These results are not particularly surprising. Nevertheless, in assessing alternative communications schemes, it is of major importance that these details be properly accounted for.

The remaining Chapters III through VII are concerned with the specifics of the communications systems that can deliver the services to the users. It is the purpose of these chapters to develop cost information on the various components of the alternative systems and then to develop the methodology for comparing the alternatives. In configuring the alternative systems, care was taken to develop the methodology that can cope with the actual characteristics of users described in Chapter II.

Chapter III develops the cost information on the ground systems used to process the signals transmitted to and from the satellites. Some cost information was obtained from previous studies but most was obtained directly from commercial suppliers of the equipment. The three main components on which information was gathered and summarized are antennas of varying diameters, pre-amplifiers of varying noise figures, and transmitters of varying power levels. Component costs were obtained for different numbers of these items to account for "learning curves," or decrease in per/unit costs as the number of ground stations grows. Costs were also obtained for the typical installation and maintenance of such stations.

In the case of stations that only receive signals from the satellite, an optimum cost combination of antenna and preamplifier is found for any given station sensitivity (G/T). In the case of stations that transmit as well as receive, the optimum combination depends on the characteristics of the satellite and master ground station and therefore cannot be treated in an isolated manner. The overall combination is the subject of Chapter V. Although the temptation was great to use cost information of equipment being designed and built at Stanford, the temptation was resisted. However, it should be noted that there is a range of costs from suppliers, the more recently designed components being the least expensive. It is also apparent that should the users develop as expected, there will be significant gains to be made by optimizing ground-transceiver design to meet the specific needs of the communications satellites. If this is done, the costs derived here and used in subsequent chapters may be somewhat high. The most important information in this chapter is that ground station costs vary from about $2000 to $500,000 each as

satellite signal power varies over the available ranges. This is not particularly new but it is often not properly accounted for in designing services for low-density, dispersed user groups which can benefit greatly from use of the lower cost stations.

Chapter VI considers the costs of the space segment. Costs and specifications were accumulated on satellites from Intelsat I to the present, from domestic filings for future satellites, and from three unfiled satellite proposals. It was felt that the earlier satellites were mainly of historical interest and therefore they were not used to derive costs for future operational systems. The remaining satellites display a wide range of costs and performances. And since some costs are based on satellites already being built while others are more generalized projection costs, the credibility of the figures also varies. Rather than engage in a detailed costing debate it was decided to use the figures supplied to develop a methodology for comparison of satellites with different capabilities and then use this methodology to establish a range of satellite costs to be included in subsequent chapters. The range of costs can be used to establish general system feasibility and the methodology can be used to compare specific bids for an actual operational system.

The satellite costs have been described from two points of view: costs to the satellite supplier (in terms of the present value of his total launch-stream outlay); and costs to the satellite user (in terms of his annual lease payments to the supplier to assure recovery of the supplier's investment). Since the time-value of money can strongly influence large investment decisions, and since a credible analysis must consider satellites as part of a larger system existing (and probably growing) during the foreseeable future, supply and demand have been examined as functions to time; and continuous costs have been considered rather than just the cost of a single satellite. These supply streams have been tailored to satisfy three classes of demand functions: constant (no growth), linear growth, and a constant/linear composite. Large and small satellites are compared on the basis of the same demand (requiring, of course, multiple small satellites to meet the same demand as one large one).

For the basic cost data, three candidate satellites were chosen as representative of those either now in service or proposed for service by 1975. The candidates span the entire range of satellite sizes (in terms of total RF power) available within this time period: small (Hughes HS-336), medium (Intelsat IV), and large MCI-Lockheed Domestic Filing). This choice has allowed the examination of the cost tradeoffs between economies of scale and the time-value of money for each of the supply/demand profiles.

In addition to the active satellites, the costs of spare satellites are included to provide insurance against sudden failure. Two spare strategies are considered, one with the spare kept on the ground the second with the spare in orbit.

Throughout the analysis, it is assumed that total satellite RF power is the prime measure of satellite capacity. For teleconferencing applications (i.e., for a system with a large number of remote ground stations), this assumption is not unwarranted: the minimum-cost system is expected to be power-limited. Within this context, satellite power is the scarce resource that must be allocated to minimize total system cost. Hence, the user-costs are expressed on a per-RF Watt basis. These results are subsequently used to establish transponder powers and to derive costs on a per-channel basis.

Major findings for the satellite segment are as follows:

- Costs to the satellite customer, with a 10% discount factor, varying from $30K to $71K per RF Watt • year with an in-orbit backup satellite; $21K to $47K per RF Watt • year with the backup satellite on the ground.

- The present value of the space segment with a 10% discount factor, for the various demand profiles ranged from $42M for continuous demand suitable for one small satellite with ground spare to $268M with in-orbit spares and demand growing linearly at a rate appropriate for addition of a large satellite each decade.

- For constant demand, a large satellite tends to be slightly less expensive than a small one for all discount rates.

- When demand changes with time, however, economies of scale tend to be offset by the time-value of money so that small satellites are preferred, especially for high discount rates.

Investment in multiple small satellites can be made over time as demand grows while large satellites entail an initial large investment.

• One (small) spare can insure many small service satellites, whereas one large service satellite must be insured with a minimum of one (large) spare. Hence, spare costs are a much higher percentage of total satellite segment costs when large satellites are used--especially if the spares are in-orbit. An in-orbit spare strategy almost always negates whatever advantage the large satellite may have over the small.

• For the examples given, the "medium" satellite is more expensive than either the large or small satellite: it has diseconomies of scale--mainly because the Intelsat IV is underweight as regards to its launch vehicle. Other medium satellite configurations may not suffer such diseconomies.

Many of these conclusions are strongly dependent upon the cost data and the demand functions used in the analysis. But, as tendencies, they can be considered robust.

In Chapter V methodology is described to combine satellite cost and capability with ground station cost and capability to determine the least cost system for any user need. A computer program was written to specify the antenna diameter, pre-amplifier noise temperature, and transmitter power of each ground station in the system and to determine the per-channel transmitter power, bandwidth, gain and transmitter back-off level of the satellite, recognizing that different transponders may be needed to handle different systems. Using cost information of Chapter III and IV the program adjusts noise contributions from the ground transmitter to satellite-link, from intermodulation noise within the satellite and from the satellite to the ground receiver link for optimum overall cost. The devision is a function of the number of originating and receiving stations. When ground stations transpond (use the same antenna for transmitting and receiving), the interaction is accounted for in the optimization. The program also can account for a mix of ground-station-performance needs, useful for example if some stations only receive while others receive and rebroadcast. The results are calculated for a range of satellite radio power costs, area of signal coverage, and different modulation schemes.

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To exercise the methodology a system configuration was chosen that is pertinent to many of the user services discussed in Chapter II. One master station is equipped to transmit signals with television bandwidths and receive a multiplicity of signals with audio bandwidths from a number of remote stations. The remote stations are equipped to receive the television signals and transmit an audio bandwidth signal, either voice or data, back to the master station. The stations are scattered over an area corresponding to a third of the United States or to the forty-eight contiguous states and the number of remote stations was varied from 10 to 10,000. Computer runs evaluating these alternatives resulted in a multitude of useful results, some of which are plotted and summarized in Chapter V. Some of the highlights of the results are:

- The costs of the selected systems are quite low in comparison with probable software and programming costs. For example, for eight TV-channel systems it would cost about $1,500/year for each of a 1000 stations spread over 1/3 of the United States. This annual cost includes satellite and master station cost as well as the cost of the remote transceivers. If the same number of stations were spread over the forty-eight states the cost would be $3,000/year. For 10,000 stations over the forty-eight states it is $800/year. For 250 over 1/3 of the United States it is about $4,000/year.

- Given that the system is distributing TV, the marginal cost of adding return audio or digital channels is quite small, only about 15% of the TV-only system.

- Since relatively little effort has been spent on the development of the smaller stations there should be a high priority to support such development. However, because there is a range of optimum configurations it is probable that a "catalog" of small stations should be assembled rather than focusing on one specific type.

- The low total costs result from use of high signal strength from the satellite. The characteristics of the various domestic satellite filings appear to be distinctly suboptimal from the standpoint of the small user of teleconferencing.

It is important to note that these results do not include factors concerned with frequency space utilization. Thus while results reflect the actual costs of providing given services with the least-cost system, they may not reflect the "price" that could result from other users bidding for the limited frequency bands and satellite orbit positions. Power limited satellites (those that use up their radio power while using only part of the available frequency bands) do not directly under use the frequency bands since additional satellites using the remaining bands can be placed in the same orbit position without technical difficulty. However, the higher-power satellites do work with ground stations with smaller antennas which may require greater spacing between satellites (less satellites per orbit) to avoid interference. An analysis of this must consider competing uses, prices of alternative ground systems, cost of achieving isolation in low-cost antennas, required protection ratios and regulatory factors. Such an analysis is part of proposed future work. From initial work, it seems probable that the above conclusion may not be greatly modified.

In addition to the capabilities described above a modified program has the capability of optimizing ground-station selection for a fixed satellite transponder which must be used on an all or nothing basis. This capability is useful for designing a system to use an experimental no-cost (at least to the user) satellite.

The above results should be of interest to teleconferencing users; however, they treat only a few specific cases. The program ideally should be used to evaluate systems specific to each potential user.

Chapter VI presents the costs of ground-based communications systems and techniques for determining the best mix of satellite and ground systems for getting the services to the user. The systems considered were a network of microwave repeater stations for long-distance transmissions, a cable network or "tree" for local distribution, and an ITFS (Instructional Television Fixed Service) transmitter/receiver with associated receivers and audio transmitters for local distribution. As in the case of satellite equipment, costs were obtained from commercial suppliers of the equipment.

Five functions were generated to describe the costs of the various systems. The first describes cables for area coverage in terms of the number of subscribers, the radius of the cable grid and the number of channels. The second describes area coverage of the ITFS system, essentially a TV broadcast, in terms of the number of channels and subscribers. The third describes the costs of cables necessary to connect different distribution systems together, a function of the number of channels and distance. Both the ITFS and cable distribution systems are limited to an area coverage of about 40 miles in radius. The remaining two functions described long haul systems, a microwave system and a repeater ITFS system. Technically these systems are very similar and are a function of the number of channels and the number of repeater stations determined by the terrain.

In Chapter VII the ground system cost functions and the satellite cost functions are combined to determine the lowest cost system. For this comparison a service with video out and audio return is used. The comparisons are separated into long distance transmission and local relay. In the long distance comparison, densities appropriate to the Rocky Mountain States are used; and the distributions of professionals in the San Jose area are used for local relay comparisons.

The prime purpose of the sample comparisons is to develop and illustrate the methodology; for each actual system the detailed comparison would have to be made anew. However, from the present comparison some general observations can be made:

- The comparison between regional long-distance transmission by terrestrial microwave or by satellite shows that for more than about 100 receive points in the Rocky Mountain area the satellite system is dramatically less expensive. For fewer receive points the microwave system begins to be competitive only if the points are not widely dispersed.

- Within clusters of a local distribution system, comparison indicates that cable is the least cost method.

- In areas where no community cable television system is available:
    a) within clusters special cable systems is the least costly way of local distribution.

b)  between clusters in an urban area, e.g., from one pocket
    of doctors to another, satellites are cheapest.  In most
    such cities, there would most likely be several non-con-
    nected cable grids, the headends of which would be fed
    by satellite.

• Where communities are already wired for cable television the
  price of providing special services through the cable depends
  on the cable operators policy.  In most situations the cost
  should be less by the satellite feeding the cable head end
  than by direct service from satellite to user or user cluster.

• In a few very large metropolitan centers for some services,
  ITFS is cost effective for distribution of the signals to
  the clusters or to existing cable head ends.

The present study has developed the techniques necessary to assess
the feasibility of satellites bringing telecommunications services to
a variety of different user groups.  In the examples analyzed, it was
clear that satellites will play a major role in future services.

## DEMAND FOR TELECONFERENCING

A. Introduction

As an industry expands into areas not previously explored, one of the pieces of information most needed is an analysis of demand. This is vital in answering questions regarding the slant of the industry's efforts in the future.

With regard to teleconferencing services, a good demand analysis should reflect the need for a coordinated effort among the suppliers of system services in satisfying user needs. On the technical side, one needs to know the types of system design needed, i.e., what technical capabilities are needed in each teleconferencing application. Associated with this, there is a quality constraint that each user group, such as the medical profession, will require to be satisfied.

Furthermore, a successful teleconferencing system will require a coordination of program planning with the systems which are developed. In the endeavor, the demand analysis would prove most vital.

Perhaps the most important use of the demand analysis is to provide information for economic decisions. The number of users of a system will be primarily determinant of the cost per user. This is essentially the feasibility aspect of the study. In this, as well as in each of the aspects described above, there is a strong need for the analysis to be time varying.

Background

Several previous efforts have been directed at various facets of the demand for teleconferencing services. These have been too general in their treatment to be of any significant benefit to the actual procedure of demand estimation. Some of the work has dealt with continuing professional learning and some with communication in the medical profession. Still other studies have been concerned with government subsidies in the information exchange effort of certain professional groups. Also, there has been a limited attempt to describe the overhead which is associated with teleconferencing services.

But examination of the literature has yielded little which is significant to the estimate of demand. A good description of the market is not to be found. The annual expendidures by profession for information

services is not well known. Moreover, since a description of the services that teleconferencing might provide has not previously been compiled, there was not even a vague idea as to the amount of expenditures per year that various user groups spend on services that would be suited to teleconferencing.

Our Analysis

Faced with so many difficulties, the project group first set forth to obtain at least a general description of the market. The total size of the market, according to the various potential professional user groups, is displayed in Table I. These figures are according to the latest data available.

The next step taken was an attempt to determine the amount of expenditures for information services, broken down by professional groups. Because of limited resources, this proved too large a task. However, a great deal of valuable experience and insight into the market structure was gained. It gradually became apparent that a methodology could most likely be designed to capture the essence of the market behavior as it adapts to the teleconferencing services. Several possible market segmentations were considered, and finally a set of suitable descriptive categories was settled upon. These categories are proposed as the basis by which potential demand can be estimated. With a logical procedure, the methodology proceeds to whittle down the potential demand to an estimated actual demand. Additionally, it would lead to estimates of the demand elasticities of price and substitution. The methodology has been constructed to allow design factors, such as system technical capabilities and the quality of service, to be fully realized in their interaction with the tariff policy, alternatives of service, and the acceptance of the teleconferencing innovation by society.

The analysis of demand which follows is divided into three parts. Part B describes teleconferencing markets and services as they might evolve. Part C presents demographic data and discusses the use of such data in assessing demand. Finally, part D presents a methodology for modeling teleconferencing demand and demand growth.

Table 1

Major Professional Occupational Groups

| CATEGORY | DATE | REFERENCE | NUMBER |
|---|---|---|---|
| MANAGERS, OFFICIALS AND PROPRIETORS | 1969 | 3 | 7,801,000 |
| ELEMENTARY AND SECONDARY TEACHERS | 1969 | 3 | 2,275,000 |
| ENGINEERS | 1967 | 8 | 905,213 |
| NURSES (R.N.) | 1969 | 4 | 680,000 |
| COLLEGE INSTRUCTORS | 1969 | 3 | 593,000 |
| ACCOUNTANTS | 1968 | 5 | 500,000 |
| LAWYERS AND JUDGES | 1966 | 8 | 316,586 |
| PHYSICIANS (M.D., D.O) | 1969 | 4 | 313,000 |
| CLERGY (PASTORS IN CHARGE) | 1969 | 8 | 209,913 |
| PHYSICAL SCIENTISTS | 1969 | 8 | 171,700 |
| PHARMACISTS | 1969 | 4 | 124,500 |
| DENTISTS | 1968 | 4 | 113,636 |
| TECHNICIANS | 1966 | 11 | 885,000 |

B.  Teleconferencing Markets and Services

1.  Service Categories

Teleconferencing, which we have defined as real time interaction between two or more parties, has many dimensions.  The interaction can be video, audio, digital, or a combination of the three.  Transmission bandwidths between the parties can be symmetrical or asymmetrical, and the parties involved can be people or computers.  All of these parameters are determined by the services needed by the parties involved, so it is logical to begin a study of teleconferencing with a breakdown of the total market into user groups, in order to determine what types of delivery system each will need.  In addition, the political, economic, and social constraints on system choice tend to be different for each user category.

Several potentially large markets exist for teleconferencing.  Major areas are:

1.  Education

   School-based Education
   General Adult Education
   Vocational Training
   Continuing Professional Education

2.  Remote Medical Services

3.  Business Teleconferencing

4.  Interactive Computer Services

Because of the project's limited duration, we did not attempt to consider all markets.  In selecting appropriate markets for study, we decided to eliminate commercial services such as business teleconferencing and commercial computer services.  It was felt that research in private sector services would be initiated by the private sector.  At the same time, the satellite filings now pending before the FCC illustrate what can happen if development is relegated to private sector interests.  Those filings which appear to be most economically viable are suited to the needs of large commercial markets, and do not provide the flexibility needed for several crucial public sector services.[*]  If promising public teleconferencing services are to be realized, steps will be needed to guide the course of various technologies or to produce dedicated communication services for these markets.

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[*] See Reference 2, Chapter 10

Of the remaining service categories, school-based and adult educational services were taken up by the Wisconsin group, with Stanford focusing on continuing professional education and remote medical services. This apportionment seemed logical in view of Stanford's experience with scientific communication, telecast professional courses, remote medical services, information retrieval and computer assisted instruction; and of the University of Wisconsin's experience with medical and educational teleconferencing systems.

Although our subfocus on specific markets narrowed the choice of services, it did not limit the number of technical delivery systems which could be considered. In continuing professional education, one-way video with two-way voice is used in remote telecasting of courses and professional society meetings. Digital feedback from students is also desirable for courses. Two-way voice, with or without two-way video, is desirable for teleconferences between researchers. Two-way digital is required for computer assisted instruction, bibliographic search and retrieval, and interactive computation. In medical services, symmetrical voice and visual signals are needed for consultation, as are digital channels for medical record transfer and the monitoring of physiological data. In addition, remote villages may require one-way video from the village to the doctor (which is opposite the video direction used in classroom telecasts). The quality (and cost) of services can be expected to vary as well as bandwidth. In many of these application, teletype, facsimile or or slow-scan television might be substituted for television or voice links. Hence, the services needed for these markets are sufficiently diverse to allow us to investigate the full range of technological alternatives.

In the following sections, we will discuss the markets for continuing professional education and for remote medical services and will comment briefly on the market for business teleconferencing, which (along with commercial computer services) will probably provide the bulk of the teleconferencing market over the long term.

2. Continuing Professional Education

In the United States today, there are between fifteen and twenty five million professional workers. Table I summarized the sizes of the largest professional categories. These professionals are one of America's

largest resources; they are responsible for America's leadership in most technical fields. Information and problem solving ability have always been the main tools of professionals. Yet the communication of scientific and technical information today is a haphazard and inefficient process. Teleconferencing services are badly needed to improve most communication channels. An improved knowledge transfer system would have a profound impact on the productivity of professionals.

The average professional must learn a great deal of information to accomplish his work tasks. Until he graduates from college, or receives a higher terminal degree, the professional is led through this information by the organized school system. With varying degrees of success, his schools have attempted to identify and develop the operational skills he will need in his working life. Then he graduates, begins his career, and is cast into a chaos of inaccessible information.

This is not to say the information does not exist or that no channels are open to bring it to him. The information supply is staggeringly large. It has been estimated that the technical information base is about $10^{13}$ characters.[1] Moreover, the formal information channels - i.e., the journal, professional society meeting and the library - are large and heavily funded institutions.

Yet in the middle of this abundance, most professionals have effective access to very little of the information they need. One writier estimated that missed information is responsible for wasting 30% of the professionals' time through poor solutions to problems or the needless duplication of work.[2] The problem is that most information channels fail to perform the two essential functions performed, at least in the ideal, by the school system. First, they fail to provide the professional with information tailored to his needs. They literally inundate him with material, most of which is marginal or completely irrelevant to his needs. In addition, retrieval of information is very tedious, and scientists often miss relevant information. Second, they fail to present the material in an organized, integrated manner. They fail to come to the professional, and when he comes to them, they prove to be fragmented and difficult to use.

a.  Problems With Traditional Systems

The lore of science holds that an integrated communication system already exists.  In theory, information is published in journals or presented orally in professional society meetings.  It is then abstracted and indexed, for later retrieval.  Finally, information analysis centers selectively disseminate information or perform searches for the scientists on materials collected in libraries.

This picture is almost completely erroneous.  The journal system is hampered by extensive lags in publication of articles.  A study by the American Psychological Association[3] indicated that a year and a half normally elapses from the time an article is submitted until it is printed.  Abstracting delays further slow the flow of information.  Thus, the journal system is presenting information which may be as much as three years old.  In fast growing fields, which are the crucial areas of science and health care, this bottleneck would almost destroy the research effort if scientists depended on the system.  To reduce the harm caused by these lags, scientists engage in a vigorous exchange of preprints.  Unrefereed and out of the reach of many researchers, these preprints serve to tie major researchers and many of their colleagues, but they hardly pose a solution to the basic problem.  In vertical dissemination of information between researchers and practitioners, preprints are virtually useless.  Some steps are being taken to overcome the time lags in the formal information system.  Computerized typesetting will speed journal publication and provide machine-readable data bases for literature searches.  In addition, preprint services have attempted to formalize the informal preprint flow to some extent, (for example, Preprints in Particles and Fields, produced by Stanford's Linear Accelerator Center).

Another problem with primary sources is the prevalence of "journal scatter."  Scientists and other professionals normally scan only a few "core" journals for articles of interest.  Yet a substantial amount of relevant information is published in non-core journals and in foreign languages.  This tends to result in the missing of much information, especially in problem areas with broad foci.

Professional society meetings have many failings.  First, about half of the information presented is lost from the system, through lack of

publication.[4]  Second, many feel that the amount which is subsequently published is actually too high, given its quality.  Third, Paisley and Paisley[5] have shown that "national" meetings tend to be local in the composition of attendants.  In one national meeting, they found that two-thirds of the attendants were within a one day drive of home.  Several studies have shown that attendants place a high value on invited symposia and corridor conversations with colleagues, and little value on the bulk of contributed papers.[6]  Clearly, much of the content of professional society meetings is tangential to their formal function of presenting new information to their members.  As in the case of the journal system, active experimentation is taking place on the format of meetings.  The American Psychological Association, for example, has begun to publish 1800 word "briefs" of papers.[7]  Available before the meetings, the briefs present a permanent record of the information and allow attendants to screen the list of talks for promising papers.  In addition, the publication of briefs should ease the publication burden of journals.  In the initial American Psychological Association briefs experiment ( a randomized block design), it was found that authors whose work was published in brief form substituted their work to journals at a rate 22% lower than did authors in other groups.  This finding held for meetings in subsequent years.

There is some hard information to indicate how poorly the formal system is functioning.  In one study, in which exhaustive literature searches were performed for professionals, the users reported that they had been familiar with only 39% of the material which they judged "highly relevant" to their work.[8]  Although many scientists feel that scanning a few journals and talking to colleagues will keep them abreast of their field, such findings make this belief appear to be illusory.  In addition, many studies (e.g., Parker[9]) have shown that professionals are usually unaware of information systems available to them.  Also, when asked to design blue sky systems which they would like to have, they tended to select information systems similar to those with which they were familiar.[10]

Teleconferencing holds the promise of alleviating many of the problems facing current information systems.  For example, remote broadcasting of professional society symposia could enfranchise most members in a meaning-

ful way. With larger numbers of effective participants, the symposia could be more detailed and cater to more segmented groups. It would probably be necessary to hold symposia throughout the year, since there would be more of them. This would not be undesirable, since it would free meeting dates for more interpersonal contact, both among people physically present and among distant members, through teleconferencing.

In the area of information retrieval, teleconferencing can be valuable in two ways. First, it can interconnect groups of researchers, who could discuss their work and alert one another to significant findings. This would essentially be a formalization of the "invisible college" notion of Derek Price.[11] Second, it could be used to allow the professional to interactively search the information base of his fields, to find items of interest and retrieve them rapidly. The growing availability of machine-readable data bases makes interactive searching attractive. Findings such as those of Lancaster[12] indicate that scientists tend to be poor at phrasing their requests; interactive search negotiations would allow more precise tailoring of the Boolean search to the professional's needs. Precision in document retrieval is very important. Behavioral studies have indicated that scientists have little patience with systems that inundate them with irrelevant material.[13]

Literature searches, in the exhaustive sense, are not really the staple of professionals' information diet. For one thing, professionals have indicated that they prefer to relegate the tedium of doing searches.[14] In information systems of the future, the basic searches will probably be done on the basis of previously acquired user profiles. In the extreme form, the professional would be sent a mini-journal tailored to him or to a small special interest group of which he is a member. Interactive searching of a pre-screened document base, however, with an opportunity to examine key words, abstracts or even whole text, would allow the user to determine the information he would finally receive in hard copy.

Another reason for the inadequacy of literature searches alone is that information serves multiple purposes. Orr[15] distinguishes between regular needs, such as professional news or attention to current journal contents, and _episodic_ needs, such as exhaustive literature searches or tutorial readings on developments in related fields. These functions are undoubtedly

related to a professional's current research phase. At the beginning of a project, an exhaustive search might be needed. In later stages, scanning current contents, discussions with colleagues and news items would be desired. During the final writeup, a search through personal files (hopefully aided by the computer) would be important. All during the project, of course, the professional would be gathering information for long-range usage.

In summary, teleconferencing can be used to ease lags in the current communication channels of professionals, and allow more precise searching of the total information base of the profession. Such systems must be designed on an integrated basis, in order to satisfy the multiple functions of knowledge services. It would be beneficial if the same system could provide interactive literature searches, display full document text, be used in computation and text editing, and keep track of the professional's personal files. The advantage of the integrated approach is that many terminals would be available to scientists close to their place of work. The importance of accessibility will be underscored in the following section. The real problem today is not the availability of high-quality systems. Many services are available but most are seldom used. The real problem is the inability of system designers to understand the sizable and growing base of research data on professionals' information seeking behavior, and to design systems with these findings in mind.

> b. Behavioral Considerations

Despite twenty years of behavioral research into scientific communication, most systems are still designed by engineers or administrators according to their ideas about how scientists do or should act. As a result, such massive communication programs as the Defense Documentation Center remain totally outside the experience of most scientists.

In Paisley's 1965 review[16] or research into information seeking behavior, he discussed many themes of interest to system designers. We will consider only two - the importance of accessibility and the relationship between information and productivity.

Allen and Gerstberger[17] attempted to test the proposition that professionals' behavior could be explained in terms of a desire to maximize

benefit relative to the financial and psychological costs of using various services. It was postulated that they would first turn to the channel with the highest benefit/cost ration, then work through less profitable channels. Instead, Allen and Gerstberger found that scientists went to the most accessible source of information first, regardless of quality. Ease of use was the next most important factor in channel selection. Scientists were found to filter material more critically in channels which they perceived to have poorer quality, but the fact remained that accessibility, and not perceived quality, determined channel selection. Rosenberg[18] and others have replicated this basic result. The implications of this finding for system designers are tremendous; it indicates that a high quality service which is not accessible will be ignored by professionals. And other behavioral barriers to acceptance exist as well. Rubenstein[19] conducted a series of operational experiments, in which researchers were given free access to various services which seemed, a priori, attractive. He found that the researchers failed to adopt the services, even two years after their initiation.

Channel entry restrictions, difficulty of use, and physical distance are three key elements of accessibility. Allen and his associates have studied the importance of physical distance (propinquity) in some detail, and have produced interesting results. O'Gara[20] found that interpersonal communication between professionals working in the same building falls off rapidly as the distance between their working stations increases. In fact, the probability of communication is essentially zero after only 25 yards. In a later article, Allen[21] discussed the fact that a professional will tend to have pockets of communication beyond this asymptote, but that these relationships tended to be task-specific and to decay with time, after the task is finished. Panko[22] found similar decays in task-specific groups. Frohman[23] found that propinquity effects could also be demonstrated with other information sources, such as libraries. These studies argue strongly for decentralization of system access ports, in order to bring them closer to professional's desks.

Several studies have documented the importance of information to productivity. It has been estimated that a professional spends about 33% of his working time in information gathering.[24] Because information

has an impact on how well a professional can solve a problem, it seems reasonable that information should correlate highly with productivity. Shaw,[25] Meltzer,[26] Pelz and Andrews,[27] Schilling, Bernard and Tyson,[28] Allen, Adrien and Gerstenfeld,[29] and Parker and Paisley[30] have all found good correlation between information gathering and productivity measures. Schilling and Bernard used multiple measures of productivity and found good correlations between these measures and information input measures. Parker and Paisley found that some information inputs were more important than others, and that informal communication was especially important. Although the situation is complicated, it appears that information and productivity are closely intertwined.

Improved delivery systems can also reduce the time a professional must spend seeking information, thus freeing him for operational tasks. The American Chemical Society[31] found that chemists spend 11.8 hours per week, on the average, gathering information - 7.5 hours on current awareness, and 4.3 hours on literature searching. The use of a computerized information retrieval service was found to reduce current awareness searching by 3.1 hours for every hour of computer searching, and literature searching by 4.8 hours for every hour of computer search. Time savings also exist if a professional can take courses or seminars at his place of work, rather than drive to a distant school to take a class.

c.  The Establishment of a National Information Network

There is a growing need for networks in many delivery services. Individual libraries, for example, are becoming increasingly unable to meet the needs of researchers, who require access to the totality of available knowledge.[32] The number of abstracting services is rapidly becoming unmanageable (there are at least 1300 different services[33]). The number of selective dissemination of information (SDI) services is in excess of 200[34]. Economics and time pressures to reduce duplication of effort are strong forces for the integration of resources, and the cost of tape bases - from $1,700 to $10,000 per year[35] - militates strongly against the haphazard reproduction of data bases. Once abstracts are produced from data bases, there are additional incentives for network distribution to avoid duplication of effort. One study found that the average cost of

producing an abstract was $18.40 over the group of services studied.[36]
The wide variance of reported costs - from $8.70 to $33.30 - reflects
the fact that abstracts are not a standardized product. A final economic
reason for the establishment of joint efforts is the rising costs of
books and journals. The costs of ink, paper, labor and other printing
expenses have combined to produce large and continuing inflation in print-
ing costs.

Several developments have allowed more sanguine estimates of network-
ing's potential for success than were possible in the past - the standard-
ization of the Library of Congress' MARC (Machine Readable Catalogue)
tapes, the establishment of ASIDIC (American Society of Information Dis-
semination Centers), National Science Foundation's (NSF) responsible
agent concept, the existence of large agencies such as the Defense Docu-
mentation Center, the growth of computer networks, and regional networks
of library automation, such as the proposed SPIRES/BALLOTS area service.

The NSF has funded leadership in the intergration of communication
channels. NSF has designated existing groups as "responsible agents" for
specific fields of inquiry. The responsible agent channels funds into
communication research projects and into improvement of current informa-
tion systems. In some cases, professional societies are used, for example,
the American Chemical Society in chemistry. Above these responsible a-
gents, NSF has designated some groups as "capping agents," whose jobs
are to allocate funds between the responsible agents.

Despite these developments, many problems remain. America really
has no national library. The Library of Congress, the National Library
of Medicine, and the National Agricultural Library all have national
scope, but their influence over local libraries has been limited mainly
to the distribution of catalogue cards and the standardization of MARC
tapes for other data bases. In addition, there are innumerable policy
constraints, such as goal conflicts, the danger of antitrust litigation,
traditional definitions of service and autonomy, the fact that no agency
has a mandate for creating networks, and problems with the development of
compatible hardware and data formats.

There would also be substantial software development problems for
proposed national systems. Airline ticket reservation systems, which are

less complex than national information networks would be, have taken years to develop. United Airlines, after heavy investment in Univac equipment, abandoned its effort and started over from scratch.

d. Probable Architecture of Future Networks

The concept of a national data base which users could search from their place of work is intellectually appealing. One of the more interesting considerations in the design of such networks, and one which is critically important when considering teleconferencing, is whether the system should consist of a single data base which users access by long-distance lines, many computers intimately linked, or complete localization of the information base near the professional's place of work.

Reproducing the entire data base at each user station was suggested shortly after World War II by Bannevar Bush.[37] Although the idea became less attractive with the advent of time sharing, newer developments such as laser and holographic technologies make this a long-term possibility. Local reproduction of data bases is particularly attractive in light of the fact that computer mainframe, memory and terminal costs have fallen dramatically in recent years, especially the minicomputer, while the cost of long-distance telephony has remained virtually static. The use of a single national center which would be accessed over long distance links will remain unattractive unless newer services, such as satellites or special-carrier microwave reduce communication costs substantially.

It seems probably that multi-access, multi-computer schemes will be used in the future, hopefully with a single user interface to disguise the heterogeneity of the system. On the local level, most computational problems and much of the terminal logical switching could be handled by low-cost, easily accessed minicomputers. These local computers could also access nearby data bases. But minicomputers tend to have a limited number of subroutines and limited memories. For access to larger data bases, special languages, subroutine libraries, and lines to regional computer networks would be necessary. Interconnected cable systems, perhaps using television sets as the final output display, should prove attractive in information retrieval and the remote viewing of classes or pre-prepared tapes. It is also likely that there will be several hierarchies of computational systems, much as there are switching hierarchies in the tele-

phone network.

There are several classes of service, however, which would require direct national access. The most prominent are specialized limited-interest systems (much like special library collections), very large systems (such as natural language processors are likely to be when they are introduced), and systems which are in development. The last class is very important. Services such as CAI are seldom well-defined. Rather, there is a hierarchy of progressively more powerful and more sophisticated techniques, which are continually being developed and refined. The development will take place at local research centers. During the initial stages of design and until the systems attract large enough audiences to justify distribution to regional centers, users will have to be connected to them remotely. A similar condition will exist with regard to automated abstracting and indexing systems, which are being developed gradually as as content analysis tools become available. Note that these software-based systems would be structured differently than would a single national depository of information: the research centers will probably have only one or two data bases of interest.

The problem is obviously one of optimization. Special collections, developing bases and extremely complex programs represent "corner point solutions" to the networking problem, guessed at intuitively. For the actual analysis, Chu[38] has developed a methodology for resource allocation in a computer network. His parameters are storage cost, transmission cost, file size, request rates, update rates, maximum allowable access time, and the storage of the central processor.

It should be pointed out that the sporadic nature of computer and user interaction tends to couple the optimization of the computer and communication lines. Communication is least expensive when the peak to average factor is low. This requires more expensive computer and terminal hardware, however.

One major problem of current computer systems is allocation of the central processing unit (CPU). Systems must be designed to handle peak loads, and the ratio of peak to average usage is a good statistic for measuring the efficiency of use. If there are many computers in a network, then computers can be interconnected to route temporary spill-over activity to underused systems.

In summary, the structure of computer networks will be determined by a number of parameters. It is likely that future networks will consist of mixtures of local and regional processors, with an undetermined number of large national data bases or software packages and small specialized collections. Long distance communication should prove necessary in connecting the user to regional, national and specialized centers, and in routing activity between systems to improve utilization. Satellite flexibility in connecting nodes could alleviate the major peak/average problems that dedicated terrestrial links would face with such networks.

e. The Economics of Integration

The integration of communication services, even on a partial basis, would have profound effects upon all services now in existence. Obviously, the services actually integrated into the system would be the most deeply affected. Some would be canceled entirely, while others would grow rapidly.

Other services would be influenced indirectly, because they serve to complement the services to be integrated. For example, the American Psychological Association's practice of publishing "briefs" (discussed above) of papers presented at its national meeting has reduced attendant's rates of submission to journals. This helped reduce publication pressures on journals. As journals begin to reduce publication lags through computerized typesetting, the desirability of preprint services should be increased, and the resultant computerized tapes can be used in retrieval systems. In the design of new systems, it is essential that responsible parties consider effects upon other services. Besides

influencing the economics of other services new information services may also place undo burdens upon them. For example, a preprint service simply places the burden of refereeing upon the journals which subsequently publish the papers.

At the present time, information services are funded by many groups, including the Federal Government, professional societies, and private groups. It can be expected that the implementation of systems will face substantial opposition from groups whose systems are being harmed by the new entry.

f. The Desirability of Teleconferencing

Two-directional real time services are badly needed for professional education. In professional societies, the local composition of national meetings argues strongly for remote teleconferencing of special symposia and discussions. With teleconferencing it can be expected that organized courses on advanced topics will proliferate. Live classes on special topics of current interest or seminars between the major researchers on critical fronts will also gain increased acceptance. In addition to live courses, computer assisted instruction (CAI) could provide rapid instruction in technical fields in which a professional wants to familiarize himself. In particular, a computer would be able to teach the use of a computerized information system, thus making use easier. CAI's proven ability to decrease learning time would be exceptionally valuable to busy researchers.

In bibliographic searches, an interactive system is necessary. In text retrieval, the same system could also be used to present abstracts, portions of text, or even full text, so the professional could determine

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whether he wanted to order hardcopies of the report.  It is even

possible that an online system could produce the hardcopy at less than

the cost of conventional printing and mail.[39]  Interaction would allow

greater precision in text retrieval, expecially if the system were able

to learn a user's preferences through analysis of past transactions.

Textual search could reduce the cost of sending wasted hardcopy and also

provide rapid retrieval, which would undoubtedly be important in system

adoption.

One of the prime advantages of teleconferencing would be synergism

with other interactive services, provided these also become popular.

Using CRT displays or television with "frame grabber" technology,

professional education could be enhanced by interactive programming and

computation (such as the Stanford INTERSTAT project) to perform text

editing of documents and simple calculator functions.  If enough demand

develops for these services collectively, the increased number of terminals

will allow ports to be located nearer to professionals, thus increasing

accessibility (and hence usage).

g.  A Scenario of Professional Education Systems

The purpose of this section is not to develop a definitive

picture of teleconferencing systems of the future.  Rather, system develop-

ment which is currently promising will be described in overview, to help

orient the reader in interpreting the results of technical sections of this

report.

Several delivery systems are possible.  When cable television channels

become ample and widely distributed, it is likely that textual and motion

picture information will be sent over these channels, directly to profes-

sionals' offices or homes.  Cable systems may either be

dedicated to one professional group or a few groups, or professional education may be carried over leased channels of commercial systems. Other distribution systems which may be more attractive in the very near future include the ITFS telecasting medium, the direct dial telephone system, wide area telephone service (WATS) lines, dedicated telephone lines, special carrier microwave, computer networks, and direct broadcast from satellites. Over the long term, the high bit rates and low switching costs of cables will probably tip the balance in favor of "piggy back" cable arrangements, for local distribution. In the short run, political constraints, the unavailability of two-way capability in many cable systems and the lack of interconnection between cables may tip the balance in favor of other systems, especially if AT&T offers more services with higher quality and lower cost, in response to competition from other carriers. It is also likely that for low density services, such as special symposia, professionals will have to travel to special communication centers interconnected by satellite.

Remote broadcasting of society symposia or discussion sessions, courses offered by schools or societies, and group meetings will be possible. These techniques, in connection with CAI, will allow packaging of information as well as the advantages of feedback between the learner and lecturer. In addition to these fully teleconferenced services, there will be non-real time presentations, wether through videotape and voice tape (the former exemplified by the Medical Media Network's services,[40] the latter by Wisconsin's various dial access information retrieval program[41]). In addition, it may prove valuable to create hybrid services, in which professionals watch videotaped lectures, then engage in voice teleconferences with the authors. This approach was used by Texas

Instruments in a recent private course in MOS/LSI, which was telecast over closed circuit television to 18 cities in the United States.

Such services have already become available to some extent. Remote telecasting of professional meetings has been done for some years in Europe, and a European medical conference in Davos, Switzerland, was recently telecast to Houston by satellite. Remote telecasting of courses has been done by several schools, including Stanford's Electrical Engineering Department, by means of ITFS, to students at remote work locations. The economics and effectiveness of these services might be enhanced if digital, rather than voice, feedback were used. Active participation would be possible for the student, as well as more accurate feedback to the teacher on his effectiveness. Since voice participation is more of an ideal than a reality in large classes, digital feedback could be used to increase class size by a factor of ten or more over these already bulky classes, without loss of student participation.

In information retrieval, it is useful to distinguish between bibliographical searches, in which a desired articles are identified and the retrieval of desired texts. Most current systems, such as SPIRES/BALLOTS at Stanford, only identify documents. Difficulties in acquiring these documents from a library or documentation center may still make these services useless. Computerized text retrieval would provide material rapidly and conveniently, especially if it could be done online. In future systems, searching and retrieval will become more intertwined, as users become able to examine portions of the text remotely before printing the entire text. Finally, as noted above, the cost of transmission and remote printing of text may prove cheaper than the expensive publication and transportation which exist today.

It is likely that every two weeks or month, the professional would be presented a pre-distilled information base including the current contents of journals and news items. He would use an online negotiation to browse through this collection and further refine the search, add marginal comments, and finally have a small journal printed online (which would be indexed for future retrieval). The contents of the pre-distilled data base would become more relevant to the user's needs as the system "learns" the preferences of the user on the basis of previous searches. The system would also provide exhaustive searches on episodic needs, as well as retrieve review articles (or film clips) when the professional wants to increase his competence in a given area. CAI courses would also be available online.

Hopefully, many terminals would be available, so that each could be located near a professional's desk. Through this single input/output port, the professional would be in contact with local mini-computers, regional information utilities, special collections located at remote points, and even other professionals working in other parts of the country. Hopefully, an integrated software system would control the networking so that a user in San Francisco would be unaware that he had just retrieved a document from Seattle, Washington after searching a special data base in Tampa, Florida. His local minicomputer could arrange the packaging of his responses, index the article, and place it in him permanent document collection.

Future delivery systems will do more than put existing services online; they will provide some entirely new services. The Science Citation Index is a good example of a novel service which allows new types of searches to be performed. Parker[42] suggests that successful

systems are not those which "work harder," but rather those which "work smarter" through new approaches to problem solving. Computerizing data bases will allow multiple entry and correlation of files in ways impossible with current services. Natural language man-machine communication and non-Boolean searches - both still far off - would allow searches to be tied more closely with the logical structure of the problem. In the very distant future, systems may use dialogue to help the user determine his problem's structure, and subsequently search the literature with the user's problem in mind, suggest relevant material and give reasons for their selection. Such a system would require the computer to have access to many data bases as well as to user interaction. The large size of its software program would probably allow implementation at only a few facilities, and would therefore require flexible, long distance communication links.

3. Remote Medical Services

Like education, medicine is a major industry, and faces an inflationary cost squeeze which is simultaneously threatening traditional services and preventing desirable new services from being implemented. In 1950, Americans spent $12.1 billion on all medical services.[43] By 1970, this figure had jumped to $67.2 billion.[44] Also like education, medicine is a labor-intensive industry which could benefit from new technology.

A large part of medical costs is the cost of information. It has been estimated by several sources that record keeping and other information handling in hospitals costs about $20 per patient, per day.[45] This is roughly a third of the total patient cost. Through automation, this figure should be reduced by faster input devices, less duplication of effort and less manual processing.

Other services, such as patient record keeping and accounting by private doctors, consultation between doctors, computer assisted diagnosis and various educational services are also amenable to communication and computer technology. These services could reduce costs by freeing of doctors' time from routine and delays in data transfer.

a. Medical Applications of Teleconferencing

Three needs of doctors might be met through teleconferencing: 1) remote medical diagnosis, 2) consultation with other physicians or non-medical personnel, and 3) continuing education for doctors.

Remote Diagnosis

Medical practitioners tend to be concentrated in urban areas, -- usually in the more prosperous areas of cities. In rural and ghetto areas, medical services tend to be substandard. In addition to such deprived areas, there are many places which require only occasional health services

(such as airport terminals), and do not require a full-time doctor. In both cases, remote medical diagnosis could be used to extend health care to these areas.

Remote diagnosis has actually been practiced successfully in operational situations. Logan Airport, near Boston, contains a room with diagnostic equipment, a paramedic, and a television link to a nearby hospital.[46] In case of emergency, the remote doctor makes an initial diagnosis and directs the paramedic in emergency treatment. In addition, two hospitals in the Boston area, linked by closed circuit television, have successfully conducted remote psychiatric interviews.[47]

In diagnosis, a video camera is usually at the patient end, and the doctor usually has only a voice return link. This is the reverse of the assymetry occuring in telecasting courses remotely. In the case of the two Boston area hospitals, the links were symmetrical.

Remote diagnosis poses problems with regard to doctor acceptance and cost of services, but the legal problems may prove to be the most restrictive. Doctors are subject to heavy financial liabilities if the patient is harmed during care. Civil suits might result if some ailment which cannot be detected with remote equipment is not treated. Unless legal responsibility is clarified and rendered consistent with the limitations of remote diagnosis (as was done for emergency treatment through the "Good Samaritan" laws of many states), the technique will probably not be adopted.

Continuing Education

Doctors' needs for continuing education differ somewhat from those of other professionals. First, doctors need mostly state-of-the-art information rather than degree programs. Origination at universities, which are

currently geared to degree education, would require institutional changes. Second, medical personnel must schedule their time according to patient needs. They will therefore prefer information-on-demand services. At the very least, sessions would have to be recorded for doctors called away to emergencies.

One service, the Medical Media Network,[48] offeres a series of recorded lectures on new medical developments. Many sessions are offered in which doctors are assembled to watch the programs and afterward ask questions of a travelling specialist. Since the specialist's time is extremely expensive, a teleconference might be used in place of a live visit.

Since many doctors are not stationed in hospitals, it would be desirable for systems to be inexpensive enough for use in private offices, or at least in clinics or professional buildings.

Consultation

In addition to diagnosis and education, teleconferencing can be used by doctors for consultation. Consultation on patient care is the most obvious requirement, but doctors also need advice on legal and educational matters, and such information is most frequently held by professionals in large hospitals. Teleconferencing would allow the community practitioners to use the resources of hospitals and larger clinics. A study was recently proposed by Dr. William J. Paisley, of the Stanford Communication Department, to examine the demand for such services.

Both diagnostic and consultation functions might be implemented as parts of general information services for doctors, such as computer assisted diagnosis or automated information retrieval. Synergistic effects might make several services cost effective, even if individually uneconomical.

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b. Classes of Users

The needs of a doctor at the Mayo Clinic are obviously different from those of a community health aide in a remote Alaskan village. For the purpose of analysis, it seems fruitful to discuss three classes of users separately: doctors in hospitals, doctors in private practice, and the needs of rural and ghetto areas.

Doctors in Hospitals

In this section, general hospital information systems for accounting and patient records will not be considered. It is important to recognize their existence, however, because many information services for doctors will develop around the hardware purchased for these systems, especially terminals, and minicomputers (which can be used as interfaces with external systems).

In a hospital, the doctor has a large variety of services close at hand. Administration and accounting are taken care of by the hospital staff. He has rapid and easy access to equipment, laboratories and specialists. Many educational services, including libraries and commercial services (e.g. the Medical Media Network), are easily accessible.

Hospitals will probably be the first users of most new technologies. A recent Canadian study, using the DELPHI technique, indicated that acute general hospitals would begin to use computer assisted diagnosis between 1976 and 1985, and remote library searching between 1976 and 1980.[49]

Doctors in hospitals, however, do have many needs which could be served through teleconferencing. To a doctor, time is extremely valuable, and new services could make his information gathering easier and free him from routine work. Computer assisted diagnosis and remote library searching

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will probably yield the most direct benefits. The software for computer assisted diagnosis is still in preliminary development, but the ability to search data bases such as AIM-TWX (Abridged Index Medicus - TWX) already exists. In addition, remotely televised lectures and symposia will save valuable time, as will teleconferenced discussions between members of a medical specialty.

Private and Group Practitioners

Community physicians tend to be isolated practitioners, far from a hospital or other cluster of doctors; or they are engaged in group practice, usually in a downtown area or very near a hospital. The needs of physicians in medical clinics or professional buildings are closer to those of doctors in hospitals than they are to those of isolated practitioners. But, although they share a building, and so can use common telecommunications equipment, they lack the financial sharing "umbrellas" (such as overhead) which hospitals afford.

Doctors in private and small group practice are more difficult to serve than clustered doctors, because they are farther from major facilities and cannot share the costs of receiving terminals. Yet these doctors are important, because they provide care where patients are located. Many health care policy alternatives, such as tarrifs for professional services, revolve around the importance of community doctors.

Private doctors have many service needs. Most could be implemented synergistically with accounting and medical records retrieval services. Much of the doctor's routine diagnosis work could be performed by the patient completing a health questionnaire with the aid of a time-shared computer. A diagnostic system could also perform initial screening

at this time, providing the doctor with a summary of significant or non-standard aspects of the patient's past history. In time, preliminary computer assisted diagnosis could be performed while the patient's recent history was being recorded. Further diagnostic information could be gleaned from significant changes in physiological data between visits: for this service, medical records retrieval would be necessary. Finally, by teleconferencing with the patient and local doctor, and through the transfer of physiological monitoring data, a specialist could examine the patient from a remote location.

Many educational services would be possible through medical teleconferencing. During patient treatment, the doctor must frequently look up references material or familiarize himself with the treatment of infrequently seen diseases. An online system could provide such information selectively and rapidly. Online systems would allow updating of stored information as new care techniques are developed. Telecommunicated journals could be browsed during off-hours times, and doctors could even take CAI courses to develop or update skill. In addition, live lectures or symposia at hospitals could be brought to the remote practitioner. Drug detail men could describe new drugs over the system. Current news could be brought to the doctor quickly through regular telecasts. Finally, teleconferencing could be used to put the community practitioners in touch with legal or financial resources of major hospitals.

The goal of these services would be to decentralize the use of hospital facilities, while maintaining the cost advantages of their concentration.

The value of teleconferencing lies in its ability to provide timely information, interconnect with regional medical records banks, reduce patient travel, and reduce tedious and expensive manual manipulation of data. In addition, as in the case of computer managed instruction, a teleconferencing system could be used to control non real-time services. For example, selective dissemination of information and the routing of voice and video tapes could be governed by an online system. In between services - such as dial-access voice tapes also involve teleconferencing.

The needs of doctors differ from those of other professions. Generally, the doctor faces severe time constraints. Since he cannot schedule free time easily, information on demand is essential. In addition, because the doctors's time is so expensive, a more sophisticated system could be justified than in other professions. Finally, the doctor must develop special competences as he broadens his scope or keeps up with changes in his specialty, although he does not necessarily require further degrees as might an engineer or accountant.

c.  Rural and Ghetto Services

In both rural and central city areas, there tends to be few doctors and little access to other medical services. While these two areas share a common lack of medical services, they are quite different demographically.

The ghetto is characterized by a high density of population and low level of income. Telecommunicate medical services needed in such areas include automated patient sorting (triage) and yearly checkup screening, remote access to medical records, the training of health aides, general health education for the community, and distant supervision over

paramedics. Medical records privacy is a sensitive matter, because many ghetto patients are concerned--sometimes justifiably-- that such records might incriminate them. In ghetto clinics, most of the patient care could be carried out by paramedical personnel. Doctors at hospitals could monitor and direct the process, occasionally calling upon specialists who, ideally, could tie in to the tele-consultation from any point in the country. Besides routine medical care, remote services could be used to perform initial patient screening to determine where he should go for treatment.

With the help of teleconferencing most ghetto medical case will eventually take place at local clinics. Major hospitals will treat special problems and emergencies, but even these patients will return to the clinics or to their homes as soon as they no longer require intensive care.

In rural areas, as in Alaska, people tend to live in small, widely dispersed communities. Many of these communities are too small to a fulltime doctor. There is a need in such areas for local clinics, staffed by part-time community aides, whose training would be comparable to that of a nurse. Under the telecommunicated direction of a doctor, the aide could care for minor illnesses or injuries, acting as a doctor's hands during the examination. Such centers could also be used for health education, both for the aides and for the community in general. As in the ghetto, the center could be used for yearly screening checkups for the local citizens.

Unlike ghettos, however, the very large separation of villages makes the allocation of critical equipment and labor resources more difficult: regional planning will be required. In ghettos, hospitals

are relatively close by and ambulances are available. In remote villages, however, especially in Alaska, evacuation must usually be done by airplane or helicopter, and is highly expensive. The higher cost of transportation in rural areas argues for more extensive equipment and for more intensive use of teleconferencing.

Three levels of service will probably evolve: village clinics, district hospitals where most of the consultation will be performed, and a central referrel hospital, where specialists will reside and to which evacuated patients can be transported.

Equipment

Teleconferencing for medical services will require computer terminals for data transfer, two-way voice service for consultation, physiological monitoring equipment (EKG, chest sounds), and low-rate visual transmission, such as slow-scan TV or facsimile. Visual transmission is desirable for transmitting patient records to remote sites, and a computer terminal is desirable for entering data remotely. In addition, television service (preferably color) is required: during examinations, the doctor must be able to see injuries. Remote hardware will have to be simple, reliable, and maintenance-free.

d. Regional Networks

For many of the services described above, regional networks will be required especially in rural areas. Regional networking will relieve the patient of the need to fill out histories whenever he changes doctors. Computer-assisted diagnosis would require the development of software too expensive for use by one hospital. Scarce resources, especially blood, need regional control. For epidemiology, accurate and comprehensive

willing to replace travel by communication. Although travel is expensive, the amount of executive travel attests to the high regard managers have for interpersonal communication. Although much business is transacted over the telephone and other media, important decision making usually take place in live conferences.

If teleconferencing can be done with audio and visual channels, and if prices are reasonable, then teleconferences will probably occupy a niche intermediate between telephones and travel. Hence, some travel would be replaced by communication. For teleconferences to compete seriously with travel, however, larger screens, clearer pictures and multiparty capability will be needed. Executives place great confidence in personal contact, so teleconferencing will have to match both the the status and the presence of a personal visit. In particular, the system will have to be capable of transmitting the nonverbal cues which are important in face-to-face conversations. The present slow rate of PICTUREPHONE ®adoption is probably due to its marginal quality relative to its high cost.

Different business applications call for different amounts of channel symmetry. An executive teleconference would require total symmetry. An address of upper management to lower echelons might require video service only in the downward direction. A status report from a branch manager to a corporate headquarters executive, on the other hand, might require visual transmission only in the upward direction (on the other hand, this might give the lower manager too much "control" over the communication channel). In addition, different levels of visual quality might be desirable, with lower managers using less

sophisticated (and less expensive) systems. In general, symmetry in decision-making requires symmetry in telecommunication.

In addition to person-to-person contact, many companies will require management information systems to be teleconferenced over long distances, at reasonable rates. Beyond MIS, transactions between corporations may be recorded and transferred automatically through interconnections between corporate computing systems. This would require inexpensive communications, and would also require tight system security and sophisticated switching. Such networks might originate with decided systems, then evolve into special carriers, as in the case of private microwave links.

e. The Need for Teleconferencing

Most of the services described above require fast 2-way (or n-way) interaction over long distances. Rapid information retrieval is needed for doctors to successfully treat unfamiliar diseases. Laboratory test results should be routed quickly to the physician. In education, the need for question answering must be served through a feedback link. All of these needs argue strongly for medical teleconferencing.

In Alaska, the expense of mailing documents and maintaining tape libraries is very high, and telecommunicated information retrieval and dissemination may be less expensive than mailed services. In general, the lack of terrestrial services and the geographical separation of users makes teleconferencing especially attractive for rural areas.

4. Business Teleconferencing

If businessmen could conduct multiparty teleconferences with high quality and reasonable cost, much of the expensive and time-consuming travel of corporate executives could be eliminated. Sales meetings with remotely located salesmen and the inclusion of branch managers in corporate office meetings could allow physical decentralization to co-exist with improved corporate coordination. Even board meetings could be teleconferenced, if legal barriers in some states could be overcome.

The present AT&T conference call system is expensive, and voice quality is poor. Yet corporate executives will probably require high quality voice, plus video capability before they will be willing to replace travel by communication. Although travel is expensive, the amount of executive travel attests to the high regard managers have for interpersonal communi-

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cation.  Although much business is transacted over the telephone and other media, important decision making usually takes place in live conferences.

If teleconferencing can be done with audio and visual channels, and if prices are reasonable, the teleconferences will probably occupy a niche intermediate between telephones and travel.  Hence, some travel would be replaced by communication.   For teleconferences to compete seriously with travel, however, larger screens, clearer pictures and multiparty capability will be needed.  Executives place great confidence in personal contact, so teleconferencing will have to match both the status and the presence of a personal visit.  In particular, the system will have to be capable of transmitting the nonverbal cues which are important in face-to-face conversations.

Different business applications call for different amounts of channel symmetry.  An executive teleconference would require total symmetry.  An address of upper management to lower echelons might require video service only in the downward direction.  A status report from a branch manager to a corporate headquarters executive, on the other hand, might require visual transmission only in the upward direction (on the other hand, this might give the lower manager too much "control" over the communication channel).  In addition, different levels of visual quality might be desirable, with lower managers using less sophisticated (and less expensive) systems.  In general, symmetry in decision-making requires symmetry in telecommunications.

In addition to person-to-person contact, many companies will require management information systems to be teleconferenced over long distances, at reasonable rates.  Beyond MIS, transactions between corporations may be recorded and transferred automatically through interconnections between corporate computing systems.  This would require inexpensive communications, and would also require tight system security and sophisticated switching.  Such networks might originate with dedicated systems, then evolve into special carriers, as in the case of private microwave links.

## C. Demography

Demography is defined as "the statistical study of Characteristics of human populations especially with reference to size and density, growth, distribution, migration, and vital statistics and the effect of all these on social and economic condition." (Webster's, 1970).

In the design of teleconferencing systems, demography is important for both demand projection and the design of system parameters. An estimate of the total number of users, for example, gives an upper bound for possible demand. More specific information, such as the average schooling of professionals, helps identify the demand for specific services more exactly.

In system design, the geographical distribution and growth of target populations is critical for selecting the appropriate communication medium. For scattered, low density markets, ITFS and direct satellite delivery become attractive, while in densely populated areas, cables provide more cost effective delivery. Growth is important because it argues against "hard wiring" a delivery system--which would make the absorption of additional subscribers difficult.

In following sections, the use of demography in assessing demand and system parameters will be explored in somewhat more detail for the markets of interest in this study. Then case studies examined for this report will be presented, followed by a general discussion of demography's use in the design of specific systems.

1. Demand Assessment

   a. Medical Services

Two of the most important sources of health care information are Health Manpower and Health Statistics, published yearly by the Federal Government, and Hospitals, a journal which each year publishes a summary of health care institutions. The American Medical Association publishes a yearly directory, which lists all doctors, together with their business mailing addresses, by state and city. Information on nurses tends to be more scattered and to vary in quality from state to state.

As shown in Table 2, there are about 7,000 hospitals in the United States. Table 3 presents a functional breakdown of the 31,000 health care facilities in this country. In this latter table, three points are interesting. The first is the enumeration of hospitals at 8,000, in contrast to the statistic in Table 2. This anomaly in probably due to difference in definition. Another interesting point is that the bulk of hospitals are general medical and surgical hospitals, although approximately a fifth are devoted to special care and will require special services from a teleconferencing system. The last point is the large number of nursing care and related homes. Remote medical diagnosis could yield substantial benefits in these homes, which normally do not have a doctor on duty. In another portion of this

## Table 2
### Trends in Hospitals

| Category | 1960 | 1965 | 1967 | 1968 |
|---|---|---|---|---|
| Hospitals | 6,876 | 7,123 | 7,172 | 7,137 |
| Beds (1000's) | 1,658 | 1,704 | 1,671 | 1,663 |

Source: Statistical Abstract of the United States, (1970 edition)
p. XIV

Table 3

Inpatient Health Facilities

| Facility | 1967 | 1968 |
|---|---|---|
| Total Facilities | 30,586 | 30,911 |
| | | |
| Hospitals | 8,147 | 7,991 |
|    General Medical & Surgical | 6,685 | 6,539 |
|    Specialty | 1,462 | 1,452 |
|     Psychiatric | 573 | 494 |
|     Geriatric | 333 | 291 |
|     Tuberculosis | 169 | 129 |
|     Other | 387 | 538 |
| | | |
| Nursing Care & Related Homes | 19,141 | 19,500 est. |
|    Nursing Care | 10,636 | (NA) |
|    Personal Care, With Nursing Care | 3,853 | (NA) |
|    Personal Care, Without Nursing Care | 4,396 | (NA) |
| Domiciliary Care | 256 | (NA) |
| | | |
| Other | 3,298 | 3,500 |

Source:  Health Manpower and Health Facilities, 1969, p. 242, Table 169

section, the distribution of hospitals by bed size will be discussed.

Turning to the rural case, the number of remote villages in Alaska has been estimated at 360 (Reference 9). Thus, Alaska will need a substantial communication system if teleconferenced medical care is to be provided for these villages. As will be discussed in the case studies, about 75% of places under 2,500 in population, in Colorado, do not have a single doctor. Although this study has only been able to scratch the surface of the need for remote medical services, such figures indicate that a substantial effort in this direction is warranted.

There are about 300,000 doctors in America. If the results of the San Jose, Denver and Salt Lake City case studies are indicative of a general trend, then most doctors are located in metropolital areas, although the bulk of them practice alone and a substantial number are located relatively far from main clusters.

b.  Continuing Professional Education

As shown previously in Table 1, there are between fifteen and twenty five million "professional" workers in the United States.  It is difficult to provide a more exact figure, because the definition of "professional" is somewhat ambigious.  For example, 8 million workers are listed as "managers, proprietors and other officials," but how many of these workers are truly professional can only be conjectured.  From Table 4, the fact that only 22% of these managers have completed 4 or more years of college indicates that most of these managers are only semiprofessional--at least in the sense that they would probably not be interested in obtaining advanced intensive training (such as an M.B.A.).  On the other hand, Table 4 illustrates that other labor categories are fairly large.  In such categories as "craftsmen," a substantial number of workers might be included who could benefit from vocational training that could best be categorized as "professional."

In addition to the absolute number of professionals in each category listed in Table 1, it is also necessary to determine how fast employment in these fields is growing.  A high growth rate indicates a dynamic field and a younger population of workers.  In Table 5, projected growth rates are given for elementary and secondary school teachers.  In Table 6 this information is given for teachers in higher education.  Growth rates for other selected fields are given in Table 7.  Note especially the large growth rates in nursing and teaching which are two of the largest professional fields.

## Table 4

### Occupations of Employed Persons
### 18 Years Old and Older (May 1969)

| Category | Number | Average* Years of Schooling | Some* College | 4 or More* Years of College |
|---|---|---|---|---|
| Professional, Technical & Kindred | 10,700,000 | 16.5 | 78% | 60% |
| Managers, Officials & Proprietors, Except Farm | 8,000,000 | 12.8 | 41% | 22% |
| Clerical & Kindred | 12,400,000 | 12.6 | 30% | 8% |
| Salesworkers | 4,800,000 | 12.8 | 42% | 17% |
| Craftsmen, Foremen & Kindred | 11,100,000 | 12.1 | 11% | 2% |
| Operatives & Kindred | 11,200,000 | 11.4 | 7% | 1% |
| Service Workers, Including Private Households | 8,900,000 | 12.1 | 15% | 2% |
| Farmers, Farm Managers, Laborers & Foremen | 2,900,000 | 9.4 | 9% | 3% |
| Laborers, Except Farm & Mine | 4,400,000 | 10.5 | 8% | 1% |

*Figures for White Males Only

Source: Digest of Educational Statistics, 1970, p. 14, Table 17

Table 5

Demand for Classroom Teachers in Elementary
and Secondary Schools, to 1979

| Year | K-12 | Elementary | Secondary |
|------|------|-----------|-----------|
| 1960 | 1,600,000 | 991,000 | 609,000 |
| 1965 | 1,951,000 | 1,122,000 | 828,000 |
| 1970* | 2,275,000 | 1,261,000 | 1,014,000 |
| 1975* | 2,305,000 | 1,180,000 | 1,126,000 |
| 1979* | 2,320,000 | 1,217,000 | 1,104,000 |

*Projected

Source: Projections of Educational Statistics to 1979-80, pp. 57-58, Table 26

## Table 6

### Demand For Instructional Staff
### In Higher Education

#### Instructor or Above

| Year | Total | Total | Full-Time | Part-Time | Jr. Instr. |
|------|-------|-------|-----------|-----------|------------|
| 1964-65 | 391,000 | 332,000 | 222,000 | 110,000 | 59,000 |
| 1969-70 | 578,000 | 491,000 | 328,000 | 163,000 | 87,000 |
| 1971-72* | 592,000 | 603,000 | 336,000 | 167,000 | 89,000 |
| 1979-80* | 801,000 | 681,000 | 455,000 | 226,000 | 120,000 |

*estimated

Source: <u>Projections of Educational Statistics to 1979-80</u>, p. 66.

Table 7

Growth Rates In Selected Professions

| Occupation | Est. Empl. (1968) | Average Annual Openings | |
| | | Number | % 1968 Empl. |
|---|---|---|---|
| Elementary and Secondary Teachers | 2,200,000 | 200,000 | 9.1 |
| Engineers | 1,100,000 | 53,000 | 4.8 |
| Engineering and Science Tech. | 620,000 | 31,000 | 5.1 |
| Registered Nurses | 660,000 | 65,000 | 10.1 |
| Accountants | 500,000 | 33,000 | 6.6 |

Source: Information Please, Almanac Atlas and Year Book, 1971, p. 141

There are two types of continuing professional education, namely degree-oriented and general. All professionals need general education, which allows them to keep abreast of current developments, review past learning, and pick up new competences. Degree-oriented education is a more restricted market. For example, doctors, lawyers and other professionals who have reached terminal degrees (such as M.D., L.L.B., M.B.A.) have no need for degree-oriented education, unless they are changing fields or are planning to go into specialized work, such as research or teaching. For other groups, it is desirable to know the percentage of workers having non-terminal bachelors or masters degree. In Table 8, such information is presented for scientists in general. Note that 30% have only a bachelor's degree, and about an equal number have a masters's. Information on the number of employed persons who could benefit from degree education is difficult to estimate. The managerial category, for example, has need for M.B.A.'s bachelor's degrees and special certificate programs.

In the following sections on the use of demography for demand assessment, no attempt was made to develop complete profiles of the various categories. Time did not allow all of this information to be gathered, and much of it does not exist in convenient form. Rather the emphasis was upon presenting the important demographic variables which must be considered by system designers.

Table 8

Highest Degree Of Scientists, 1968

| Highest Degree | Number | Percent |
|---|---|---|
| Ph.D. | 111,206 | 37.3 |
| Professional Medical | 7,455 | 2.5 |
| Master's | 86,717 | 29.1 |
| Bachelor's | 89,141 | 29.2 |
| Less than Bachelor's | 353 | 0.1 |
| Not reported | 3,070 | 1.0 |

Source: Statistical Abstract United States, 1970, p. 525, Table 808; derived from National Register of Scientific and Technical Personnel, 1968.

## 2. System Design

Demography helps system designers determine such things as the number of channels they will need for a given application. System design is largely dependent upon the clustering of users. If users are located in the same building, for example, a single receiver could be used for satellite reception, and its cost spread over the number of people served. Or, if user population in the area is generally high, cables become more attractive relative to ITFS, than if user density is low.

The demographics of health services are relatively straightforward. The number of hospitals must be known, as must the number and location of physicians, the remote villages to be served, and the desired number of ghetto clinics. Adequate listings of doctors and hospitals are available, as is other information (although sometimes difficult to locate).

The demographics of continuing professional education are less well-defined. To start with, the designer must decide whether the system will serve individuals at their place of work, or whether it will serve all of the professionals who work in a given plant. The former might be called a people orientation and the latter an industry orientation. Ultimately, as the professional group vs. industry matrix becomes disaggregated, this distribution will become meaningless. In the near future, however, systems are likely to be established by professional societies or industries, and the distinction will be an important one. In addition to this difficulty, demographers will find that few professions are adequately described in standard data sources. Engineers, for example, are spread across manufacturing, civic services, government, and a host of other jobs. Designing a people-based system for engineers (as was essentially done with the Stanford ITFS system) might be attractive from the standpoint of an academic department of a university, but demographic information for such a system is virtually nonexistent.

a.    People-Based Systems

Groups such as professional societies would probably seek delivery systems which serve specific work groups, for example engineers.    In order to design systems like this, it is essential to know the geographical distribution of the target population.    At the first level, it would be desirable to know distributions by state.    Table 9, taken from the Statistical Abstract of the United States (1970 Edition), illustrates some of the pitfalls of loose reasoning on geographical distributions.    In the original table, the number of professional scientists in a large number of categories was given, by state.    In Table 9, only physicists, chemists and atmospheric and earth scientists are listed.    Suppose a system designer had only figures for physicists, and tried to extrapolate this information to other fields.    Then his estimates of the number of chemists in New Jersey, for example, would be off by a factor of three.    And the estimated number of atmospheric and earth scientists would be off by a factor of almost six.

Just as professionals cluster by state, they also cluster by regions within a state.    In our first demographic case study, electronic manufacturers in the San Francisco Bay Area were located on a map.    Because ITFS delivery was contemplated, only employers with 20 or more engineers were plotted.    Note in this figure the heavy concentration around Palo Alto (where Stanford is located), and the lack of plants in large areas like San Francisco and Oakland.    Such clustering makes systems like cable or ITFS relatively attractive, while dividing the number of engineers in

## Table 9

### Scientists, By Field and State

### 1968

| State/Field | Physics | Chemistry | Atmospheric and Earth Sciences |
|---|---|---|---|
| California | 5,160 | 8,150 | 3,406 |
| New York | 3,724 | 10,283 | 1,278 |
| Pennsylvania | 1,743 | 6,887 | 780 |
| New Jersey | 1,474 | 8,096 | 285 |
| Texas | 1,248 | 4,047 | 4,572 |

Source: Statical Abstract of the United States, 1970, p. 526

the state by the total area in the state would make direct satellite reception appear to be necessary.

On an even smaller scale, professionals have varying tendencies to cluster in sections of metropolitan areas. In the Denver and Salt Lake City cases, doctors and lawyers were found to cluster in the central cities, with suburban areas being poorly served. The Denver case, however, illustrates the danger of extrapolation between professions. While doctors and lawyers were found to cluster in central cities to a greater extent than general population, teachers seemed to be more evenly distributed (although the quality of the data was poor on this point). Thus, different professional groups tend to cluster differently relative to population, within a region.

Within a central city, one would expect to find further clustering of professionals. The San Jose case demonstrated that doctors tend to be clustered primarily in downtown areas and near hospitals. Lawyers were also concentrated downtown. Other pockets of both professional groups were also found (the pockets did not coincide), the causes of which could not be determined from the analysis. In the San Jose case, a cable run of approximately 55 miles would serve about 95% of the doctors, while 85 miles of cable would have been necessary to serve all. The figures on lawyers were similar. Concentration, then, is a two-edged sword. It makes systems like cable relatively attractive, buy the marginal cost of adding outlying professionals to such systems is inordinately high.

The last level of clustering is concentration within a building. Because teachers work within schools, a single terminal system can normally serve 5 to 150 teachers. This allows the cost of the receiver and other interface devices to be spread over many users. Similar economies of concentration would exist for engineers in a research organization. For doctors and lawyers, the amount of clustering is not a priori apparent. Both groups tend to work in professional buildings, which are shared by other professional groups. A preliminary indication on the clustering of doctors was found in the San Jose case study. The data were not accurate enough to determine concentration by building, they yielded the result that if there was any doctor on a block, the average number of doctors on that block was 3.3. This is a fair degree of clustering, but its significance should not be overestimated. Large clusters (on the order of 50 doctors) in major clinics tend to suppress the number of doctors in solo practice in the concentration statistic. The fact that some doctors work in group practive or near other doctors while others work alone poses questions for the pricing of services. If receivers are sold, then doctors in solo practive will probably not be able to afford them. A more desirable policy might be to base charges on the number of hours of system use.

For professions in which people are normally employed by organizations, it is necessary to know what portion of the professionals are employed in each type of industry. Tables 10,11, and 12 present such information

Table 10

Physicians, By Type of Practice (1967)*

| | | | |
|---|---|---|---|
| All Physicians | 322,045 | | |
| Active Physicians | 305,453 | | |
| | | | |
| Professional Activity | | | |
| Patient Care | 285,200 | | |
| Solo, Group or Other Practice | | 200,000 | |
| General Practice | | | 72,200 |
| Other Full-Time Specialty | | | 127,900 |
| Hospital-Based Practice | | 85,000 | |
| Federal | | | 60,100 |
| Nonfederal | | | 25,000 |
| Training Programs | | | 47,700 |
| Full-Time Hospital Staff | | | 37,400 |
| Other Professional Activity | 14,900 | | |
| Inactive | 14,200 | | |
| Other (Unreported) | 2,400 | | |

*Includes M.D.'s and D.O.'s

Source: <u>Health Manpower and Health Facilities</u>, p. 128, Table 82

Table 11

Fields of Employment of Registered Nurses (1967)

| Field of Employment | No. Nurses | % of Total |
|---|---|---|
| Total | 659,000 | 100.0% |
| Hospitals, Nursing Homes and Related Functions | 452,500 | 68.7 |
| Hospitals | 361,100* | 55% |
| Nursing Homes, etc. | 91,500' | 14% |
| Public Health & Schools | 47,100 | 7.1 |
| Occupational Health | 19,600 | 4.2 |
| Private Duty, Office & Other Fields | 112,200 | 17.0 |

*1966 Data (HM&HF, 1969, p. 22)

'By Calculation (452,500 - 361,100)

Source:  Health Manpower & Health Facilities (1969) p. 146, Table 93

## Table 12

### Scientists In Private Industry By Industry, 1967

| Industry | Total | Engineers | Mathematicians | Chemists | Physicists | Life Scientists | Technicians |
|---|---|---|---|---|---|---|---|
| All | 1,747,800 | 824,000 | 31,300 | 85,200 | 16,200 | 22,400 | 737,700 |
| Chemicals & Allied Products | 140,200 | 42,500 | 1,400 | 40,500 | 2,100 | 11,200 | 40,800 |
| Petroleum Refining | 20,000 | 10,700 | 200 | 3,300 | 100 | less than 50 | 6,200 |
| Primary & Fabricated Metal Products | 105,000 | 50,600 | 1,000 | 3,200 | 400 | 100 | 44,000 |
| Machinery | 166,400 | 81,500 | 3,200 | 1,800 | 600 | 200 | 77,800 |
| Communications & Equipment | 115,600 | 68,100 | 1,900 | 600 | 1,300 | 100 | 42,900 |
| Aircraft & Parts | 131,600 | 84,500 | 3,600 | 2,100 | 1,400 | 200 | 38,200 |
| Motor Vehicles & Equipment | 50,300 | 29,300 | 500 | 800 | 200 | less than 50 | 18,800 |
| Instruments & Related Products | 60,600 | 32,400 | 500 | 3,500 | 1,000 | 200 | 22,500 |
| Other Manufacturing | 115,600 | 52,200 | 1,300 | 13,400 | 500 | 3,900 | 42,300 |
| Trans., Public Utilities, Other Manufact. | 206,080 | 82,500 | 7,500 | 4,800 | 300 | 3,200 | 107,600 |
| Services | 298,500 | 103,500 | 4,400 | 6,800 | 4,000 | 2,800 | 173,200 |

Source:  Statiscal Abstract of the United States, 1970, p. 523

for doctors, nurses, and scientists. For these fields, data is available.

For other fields, information is seldom in manageable form. For

example, accountants are spread through corporations in functional roles.

Even in the case of scientists and engineers (Table 12), available

information is relatively coarse grained and of limited utility to system

designers.

**b.** Industry-Based Systems

Three types of information is necessary in the design of industry-based systems. First, the number of people and work locations in the industry should be known. Second, it is necessary to know what types of professionals work in the industry. Finally, it is necessary to know the distribution of sizes of the working locations, at which professionals will receive services.

There is a great deal of scattered information on the first topic. For example, if the military were selected, about 3.5 million people would be in the total population. Table 13 lists the number of people employed in Federal, state and local jobs. Table 14 lists the number of banking and other financial units in the United States. Tables 15 and 16 provide the number of school systems and institutions of higher education, respectively. The next matter is determining what professional groups work in a given industry. Table 17 presents the breakdown of professionals and other classes in hospitals. Table 18 presents similar information concerning nursing homes. For other industries, information is usually more difficult to obtain, because classifications vary from organization to organization. The data from which Table 12 (scientists, by profession and industry) provides somewhat crude information for scientists and engineers.

The last problem is to determine the distribution of sizes of basic working units. In Table 15, the size distribution of school systems is

Table 13

Government Employment 1969

| Work Category | Total | Federal Civilian | State and Local | | |
|---|---|---|---|---|---|
| | | | Total | State | Local |
| All | 12,691,000 | 2,975,000 | 9,716,000 | 2,614,000 | 7,102,000 |
| National Defense, International Relations | 1,322,000 | 1,322,000 | | | |
| Postal | 728,000 | 728,000 | | | |
| Education | 5,079,000 | 18,000 | 5,061,000 | 1,112,000 | 3,949,000 |
| Teachers | 2,865,000 | | 2,865,000 | 242,000 | 2,523,000 |
| Health & Hospitals | 1,168,000 | 195,000 | 973,000 | 488,000 | 484,000 |
| Financial Administration | 326,000 | 91,000 | 235,000 | 92,000 | 143,000 |

Source:   Stat. Abst. U.S., p. 428

## Table 14

### Financial Institutions

### 1969

| CATEGORY | PAGE | NUMBER |
|---|---|---|
| FEDERAL AND STATE-CHARTERED CREDIT UNIONS | 446 | 23,908 |
| COMMERCIAL BANK | 442 | 13,681 |
| SAVINGS AND LOAN ASSOCIATION | 446 | 5,898 |
| LIFE INSURANCE COMPANIES | 458 | 1,820 |
| MUTUAL SAVINGS BANK | 448 | 497 |

Table 15

Number of Public School Systems

by Size of System: 1966-67

| ENROLLMENT SIZE | SCHOOL SYSTEMS | | PUPILS ENROLLED | |
| | NUMBER | PERCENT | NUMBER (X 1000) | PERCENT |
|---|---|---|---|---|
| TOTAL | 23,390 | 100.0 | 43,842 | 100.0 |
| 25,000 or MORE | 170 | .7 | 12,590 | 28.7 |
| 12,000 to 23,999 | 350 | 1.5 | 5,730 | 13.1 |
| 6,000 to 11,999 | 880 | 3.8 | 7,293 | 16.6 |
| 3,000 to 5,999 | 1,726 | 7.4 | 7,178 | 16.4 |
| 1,800 to 2,999 | 1,819 | 7.8 | 4,251 | 9.7 |
| 1,200 to 1,799 | 1,636 | 7.0 | 2,416 | 5.5 |
| 600 to 1,199 | 2,838 | 12.1 | 2,437 | 5.6 |
| 300 to 599 | 2,723 | 11.6 | 1,185 | 2.7 |
| 150 to 299 | 2,091 | 8.9 | 459 | 1.0 |
| 50 to 149 | 2,230 | 9.5 | 209 | 0.5 |
| 15 to 49 | 2,673 | 11.4 | 71 | .2 |
| 1 to 14 | 2,386 | 10.2 | 22 | .1 |
| NONE (NOT OPERATING) | 1,868 | 8.0 | – | – |

SOURCE: Description of Educational Statistics, 1970, p. 44

## Table 16

### Number of Institutions of Higher Education, Fall 1969

| Size of Enrollment | All Institutions | | Universities | | All Other 4-Year Institutions | | 2-Year Institutions | |
|---|---|---|---|---|---|---|---|---|
| | Number | Enrollment | No. | E. | No. | E. | No. | E. |
| All | 2,525 | 7,916,991 | 159 | 2,879,847 | 1480 | 3,094,819 | 886 | 1,942,325 |
| Under 200 | 273 | 29,693 | | | 183 | 20,055 | 90 | 9,638 |
| 200 - 499 | 369 | 128,346 | | | 204 | 71,138 | 165 | 57,208 |
| 500 - 999 | 570 | 421,139 | | | 379 | 280,243 | 191 | 140,896 |
| 1,000 - 2,499 | 618 | 966,425 | 2 | 4,075 | 392 | 611,588 | 224 | 350,762 |
| 2,500 - 4,999 | 287 | 1,019,495 | 10 | 42,138 | 163 | 575,446 | 114 | 401,911 |
| 5,000 - 9,999 | 229 | 1,656,757 | 50 | 387,051 | 112 | 808,447 | 67 | 461,257 |
| 10,000 - 19,999 | 114 | 1,589,323 | 47 | 710,038 | 36 | 461,243 | 31 | 418,042 |
| 20,000 - 29,999 | 39 | 924,830 | 25 | 587,913 | 10 | 234,308 | 4 | 102,609 |
| 30,000 or more | 26 | 1,180,983 | 25 | 1,148,632 | 1 | 32,351 | | |

Source:  Digest of Educational Statistics, 1970, p. 85

Table 17

Employment in Hospitals, 1966

| Occupation | Medical Total | Hospitals |
|---|---|---|
| All | 3,672,000 | 2,363,000 |
| Profl. & Tchnl. | 1,487,100 | 860,000 |
|    Engr. & Nat. Sci. | 23,200 | 11,300 |
|    Dentists | 94,900 | 900 |
|    Dietitians & Nutritionists | 18,200 | 13,200 |
|    Reg. Nurses | 584,100 | 395,900 |
|    Optometrists | 13,900 | 500 |
|    Pharmacists | 10,600 | 9,200 |
|    Physicians (MD's &DO's) | 254,500 | 59,100 |
|    Chiropractors & Therapists | 54,900 | 18,900 |
|    Med & Dent Technicians | 203,600 | 140,100 |
|    Socl. & Welfare Wkers | 15,800 | 10,600 |
|    Other | 213,400 | 200,400 |
| Mgrs., Offcls., & Proprietors | 94,400 | |
| Clerical | 596,700 | 280,300 |
| Service | 1,310,200 | 1,022,000 |
|    Aides, Orderlies, Attendants | 637,900 | 516,500 |
|    Cooks | 50,700 | 37,100 |
|    Prac. Nurses | 254,800 | 150,100 |
|    Janitors & Cleaners | 79,400 | 49,900 |
|    Other | 287,400 | 268,400 |
| Other | 183,600 | 148,100 |

Source: Stat. Abst. U. S., p. 64, 1970

Table 18

Full-Time Personnel in Nursing and Personal Care Facilities: April-July 1968

| Category of Personnel | Total | Nursing Care | Personal Care |
|---|---|---|---|
| Total Professional and Technical | 279,288 | 229,937 | 49,351 |
| Nursing Services: | | | |
| Nurse - R.N. | 25,139 | 21,263 | 3,876 |
| Licensed practical nurse or vocational nurse | 35,725 | 29,561 | 6,164 |
| Aide, Orderly, Attendant | 186,411 | 155,315 | 31,096 |
| Therapeutic Services | | | |
| Physical Therapist | 944 | 846 | 98 |
| Physical Therapy Assistant | 1,411 | 1,238 | 173 |
| Recreational Therapist | 1,743 | 1,385 | 358 |
| Registered Occupational Therapist | 450 | 373 | 77 |
| Other occupational therapists and assistants | 1,269 | 1,058 | 211 |
| Social Worker | 722 | 571 | 151 |
| Speech Therapist | 86 | 77 | 9 |
| Medical Records | | | |
| Registered medical record librarian | 192 | 158 | 34 |
| Other medical records librarians & technicians | 948 | 818 | 130 |
| Dietary: | | | |
| Dietitian | 3.082 | 2,087 | 995 |
| All other professional and technical | 21,166 | 15,187 | 1,633 |

Source: Health Manpower and Health Facilities, 1969, p. 23, Table 12

given. This is important for administrative purposes, but a better statistic would be the number of teachers in each school. Such information is seldom available in closed form. The Denver case study presents such information for teachers, although the base data was not ideal. Table 19 lists the distribution of units under social security. For larger units, this data is insufficient, because it is necessary to know how many buildings the workers are staffed in, in order to determine the number of receivers necessary. Table 20 lists hospitals, by bed size.

Table 19

Reporting Units Under Social Security (1968)

| Industry | 1-3 | 4-7 | 8-17 | 20-49 | 50-99 | 100-249 | 250-499 | 500 or more |
|---|---|---|---|---|---|---|---|---|
| Reporting Units | 1,815,244 | 708,594 | 568,762 | 252,021 | 84,443 | 48,104 | 15,343 | 10,942 |
| % of Total | 51.8 | 20.2 | 16.2 | 7.2 | 2.4 | 1.4 | 0.4 | 0.3 |
| Employees (x1000) | 3,142 | 3,671 | 6,779 | 7.572 | 5,793 | 7,297 | 5,281 | 14,911 |
| % of Total | 5.8 | 6.7 | 12.5 | 13.9 | 10.6 | 13.4 | 9.7 | 27.4 |
| Agriculture, Forestry & Fisheries | 19,230 | 6,719 | 4,099 | 1,323 | 294 | 93 | 16 | 1 |
| Mining | 9,689 | 4,591 | 5,652 | 3,480 | 1,150 | 645 | 223 | 130 |
| Contract Const. | 160,065 | 66,107 | 51,344 | 21,562 | 6,735 | 2,970 | 562 | 195 |
| Manufacturing | 71,608 | 48,183 | 66,051 | 51,094 | 29,351 | 20,855 | 8,129 | 6,189 |
| Transportation & Other Public Utilities | 53,830 | 23,878 | 25,323 | 13,827 | 5,400 | 3,222 | 982 | 803 |
| Wholesale Trade | 115,582 | 68,283 | 71,246 | 32,637 | 8,409 | 3,147 | 552 | 221 |
| Retail Trade | 523,408 | 247,846 | 183,553 | 64,536 | 16,098 | 6,376 | 1,683 | 11,131 |
| Finance, Insurance and Real Estate | 213,156 | 53,102 | 37,192 | 16,335 | 5,146 | 2,864 | 814 | 557 |
| Services | 598,220 | 176,888 | 116,344 | 45,148 | 14,838 | 7,932 | 2,382 | 1,733 |
| Unclassified | 50,456 | 12,997 | 7,958 | 2,079 | 22 | - | - | - |

Source: Statistical Abstract of the United States, 1970, p. 472

Table 20

Bed Size of Hospitals, 1968

| Bed Size | Total Hospitals | General Med. And Surgical | Specialty |
|---|---|---|---|
| All | 7,991 | 6,539 | 1,452 |
| Under 25 | 803 | 633 | 170 |
| 25-49 | 1,826 | 1,597 | 229 |
| 50-74 | 1,085 | 908 | 177 |
| 75-99 | 801 | 652 | 149 |
| 100-199 | 1,546 | 1,282 | 264 |
| 200-299 | 704 | 608 | 96 |
| 300-499 | 653 | 571 | 82 |
| 500-999 | 318 | 236 | 82 |
| Over 1000 | 255 | 52 | 203* |

*188 are psychiatric hospitals

Source:  Health Manpower and Health Facilities, 1969, p. 247, Table 171

c.  Summary

The purposes of the preceeding sections have been to give the
reader an understanding of what types of demographic data are desirable,
a flavor of what information is available, and a feeling for the general
paucity of information in a form useful for system designers.

3.  Case Studies in Demography

To illustrate the principles described above, and to provide
approximate population characteristics for the technological case studies,
six minor studies were conducted.  They will be presented in the
remainder of this section, generally in order of increasing geographical
area (and correspondingly decreasing resolution).  The exception to
this trend will be the first case, which explores the demographics of
a people-based delivery system.

Demographic information, even when available, is expensive to
process and normally contains little of theoretical interest.  Because
the resources allocated to this study were limited, attempts were made
to focus on population groups for which information is readily available,
and to provide rough cuts at actual numbers.  Although subject to
errors of fifteen to twenty five percent, the numbers would prove
sufficient accuracy for the technical case studies and also provide a
general picture of demographic trends.

a.   Case 1:   Electronic Manufacturers in the San Francisco Bay Area.

Figure 1 shows the locations of selected electronics manufacturers in the San Francisco Bay Area.   The list was selected to be semi-representative of companies in the Bay Area that might benefit from graduate courses in Electrical Engineering, delivered through ITFS.

The overall intent was to model the user population for the Stanford ITFS system, but no attempt was made at through analysis.   In the actual Stanford system, most of the member companies do not appear on our list, either because they do not engage in manufacturing or because their product line is not electronics.   Our figures were taken from Reference 59, which lists electronics manufacturers.   For the figure, only companies with 20 or more engineering employees were plotted, because it was felt that smaller companies would not have enough engineers interested in graduate training to justify the expense of an ITFS receiver.

The degree of clustering evident in the figure is indicative of the general need to consider each target population carefully and pay close attention to their geographic distribution.   We have already seen that professional populations vary in a complicated way from state to state.   The figure illustrates that clustering within states is also important.   Note that 54% of the companies are within 5 miles of Stanford University, and that 67% are within 10 miles.   The clustering, of course,

RICHMOND
|

CONCORD
|

WALNUT
CREEK
|

BERKELEY
|

SAN
FRANCISCO
3

OAKLAND

SAN
LEANDRO
|

SAN
RAMON
|

BELMONT
|
SAN
CARLOS
5

MENLO
PARK
3

PALO
ALTO
15
MOUNTAIN
VIEW
10
SUNNYVALE
5
SANTA
CLARA
3
CUPERTINO
|
SAN JOSE
2
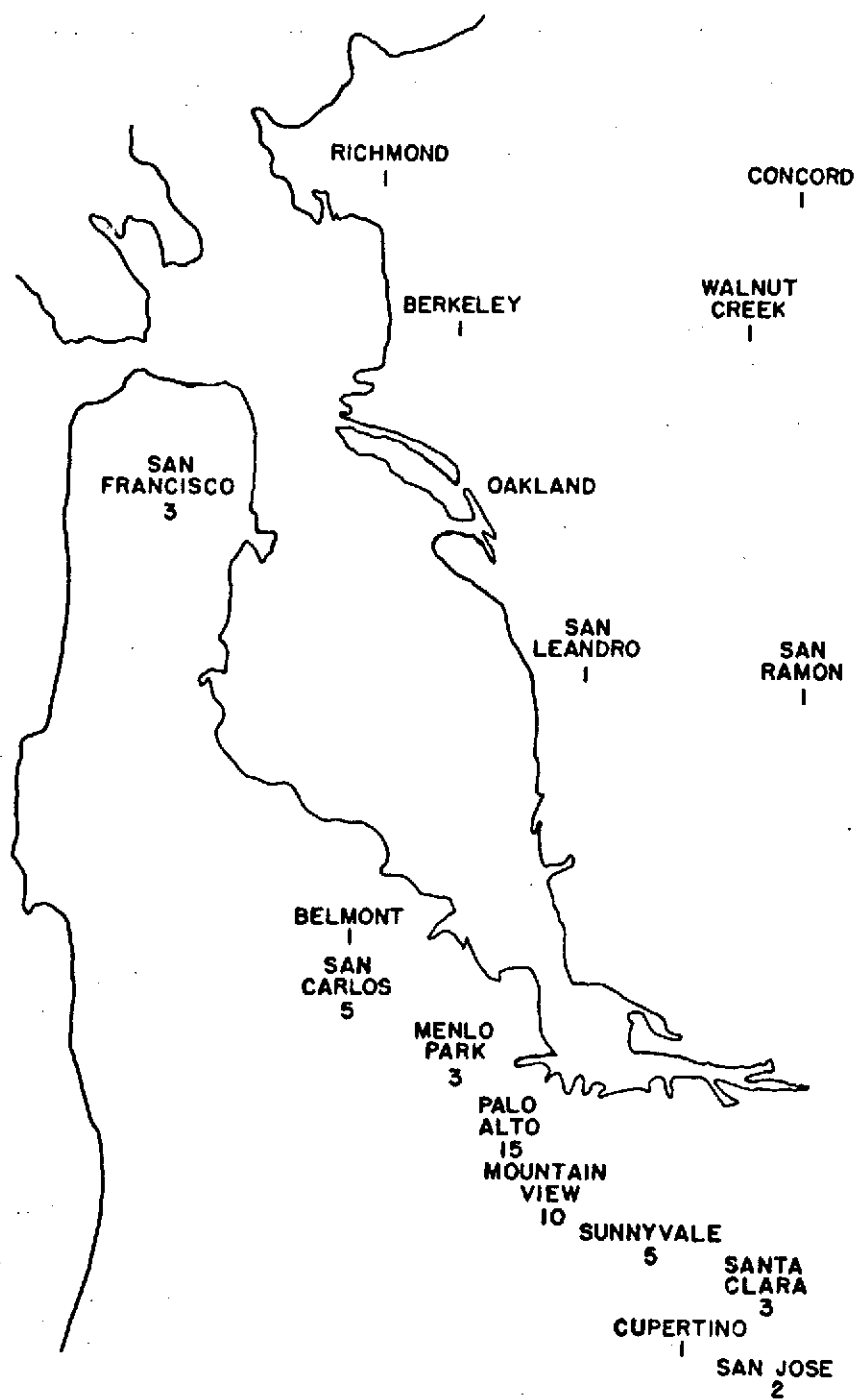
Figure 1:  Electronics Manufacturing Companies Having 20 or More
Engineering Employees

is mainly caused by the presence of Stanford Engineering "communities"
also exist in other regions.  In Santa Barbara, California, for instance,
there is a very large research and development concentration.

In Figure 2, the distribution of engineering employees by size of
firm is shown for electronics manufactureres in the Bay Area.  It is
interesting to note that 35% of the engineers work in companies with
between 1000 and 2000 engineering employees, while 15% are employed by
companies having fewer than 100 engineers.  About half of the engineers
are employed in companies with fewer than 400 engineers.
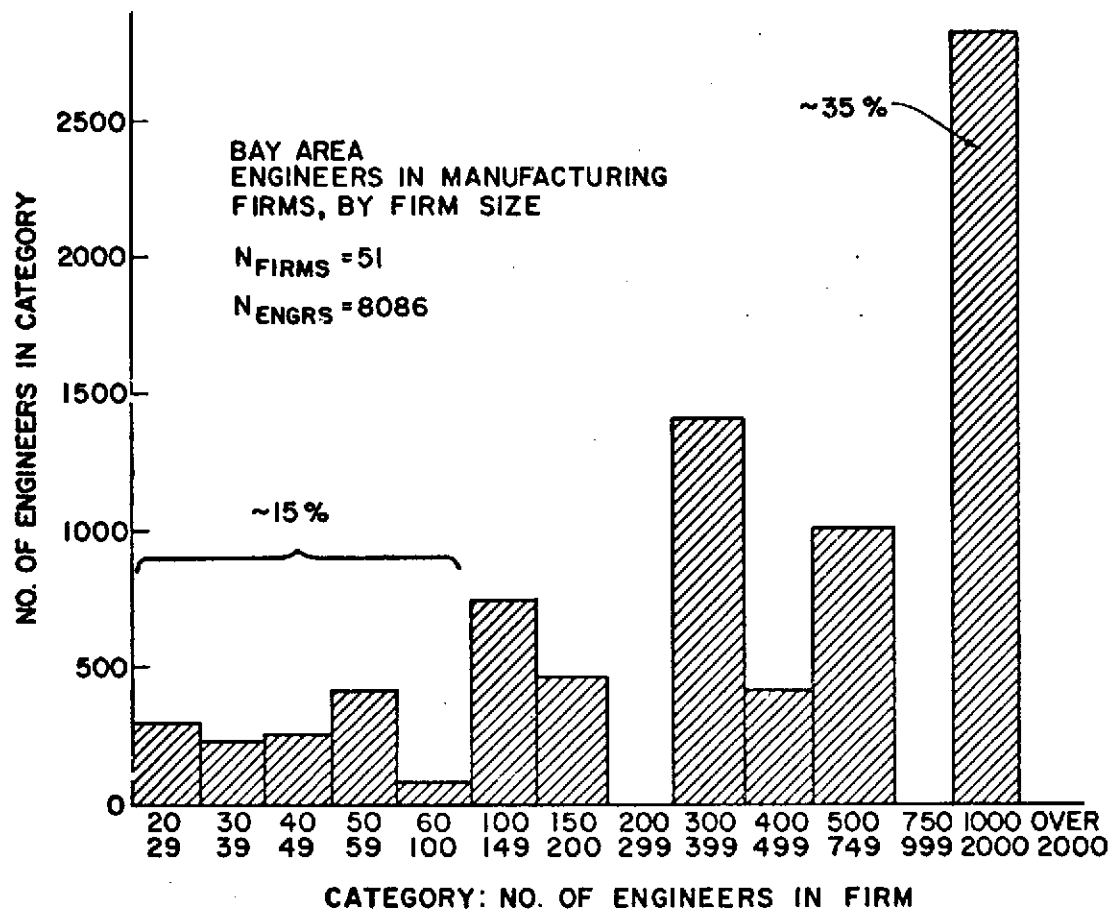
Figure 2: Distribution of Engineering Employees by Size
of Firm in Bay Area

b.    Case 2:  San Jose Detailed Analysis

To understand the detailed tradeoffs between cable, ITFS, direct
satellite broadcast and use of the telephone network, it was necessary
to analyze at least one city in detail.  Using information from
References 50 and 55, it was possible to find the mailing addresses
for doctors and lawyers in the City of San Jose.  (San Jose is a city of
about 400,000, located at the southern end of the San Francisco Bay Area --
see Figure 1).  Doctors and lawyers were then plotted on a city map.
This is a tedius and time consuming process, which should be automated
before designers attempt to analyze specific systems.

Data for doctors is plotted in Figures 3 and 4.  The total number of
doctors in the city is 700.  Note that doctors cluster by region within
the city.  The two main cluster types are the downtown area (in which
about a third of the doctors are located and in one three-block square
area of which, there are 118 doctors), and around the O'Connor and Santa
Clara County Hospitals.  Minor clusters are located in other parts of
the city.  These generally represent medical clinics, professional
buildings and streets with several professional office buildings.

In general, doctors are fairly clustered in San Jose.  Given that
there is at least one doctor on a block, there will be an average of
3.3 doctors on that block.  Of the 700 doctors, only 93% have solo
offices, and 48 are in buildings where only two doctors work.  The

Figure 3: Doctors in San Jose Area
Part I
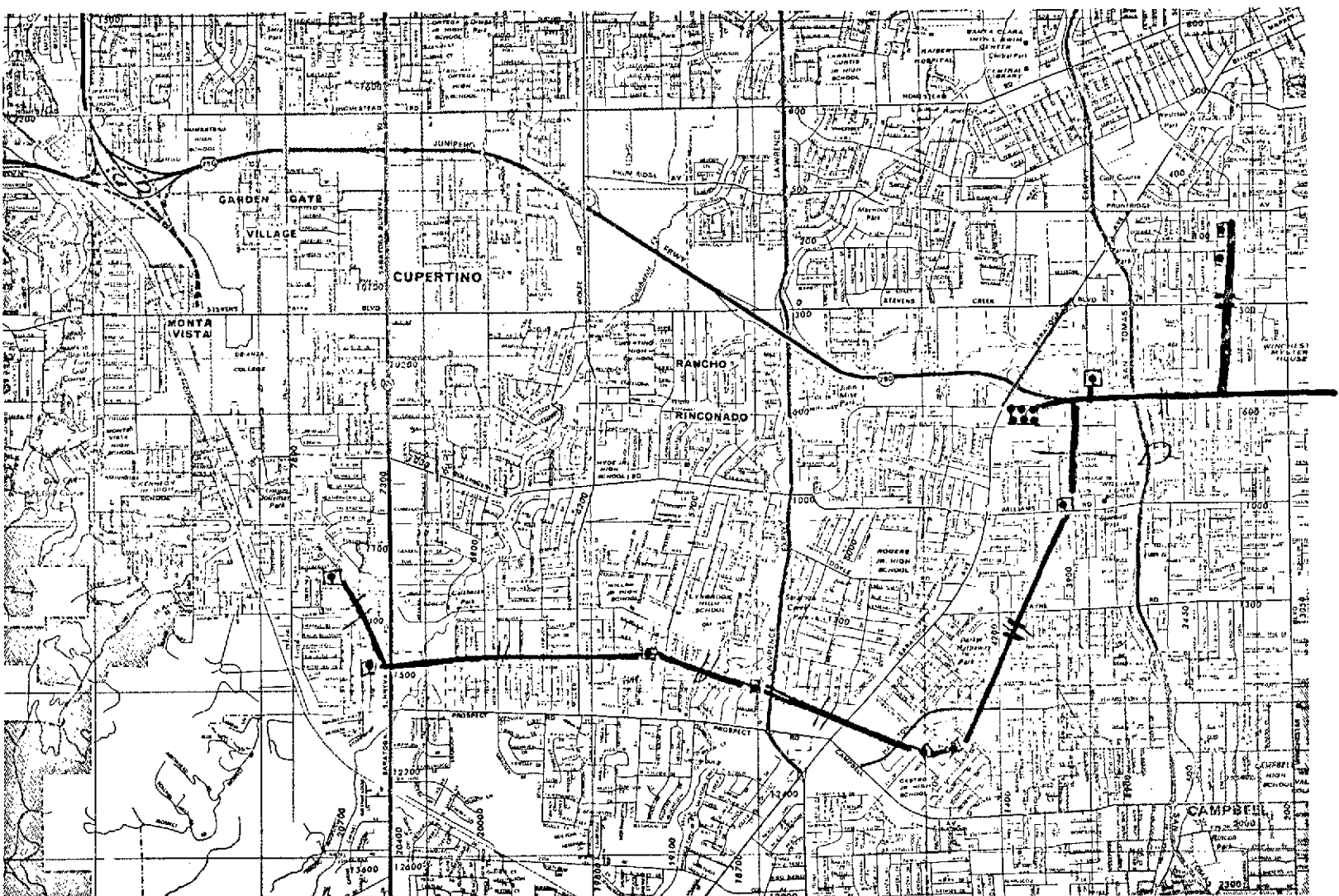
Figure 4: Doctors in San Jose Area
Part II

II-74

largest concentration, in the downtown area, is in a building with 59 doctors.

Because of the clustering, cable appears to be an attractive delivery system, relative to ITFS. A dedicated cable system to serve all 700 doctors would require 85 miles of cable, but all but 39 doctors (6%) could be served with a cable system of only 55 miles. (The actual configuration of cable and earth station facilities to serve San Jose is discussed in Chaper 7 as part of the local distribution systems comparison). Hence cable could serve the bulk of the doctors, but its use would further isolate community doctors, unless steps were taken to include them in the overall plan.

There are about 700 lawyers in San Jose. In general, the lawyers also cluster in the downtown area, to a slightly greater degree than doctors. There are other clusters, generally less than 15 lawyers, throughout the city. In general, the outlying clusters of doctors and lawyers do not overlap.

It seems reasonable that professional buildings will be important reception points, if only because potential users will be able to share receiver costs. As far as we could tell, no directory of professional buildings is currently available. One way to produce such a directory would be to correlate the addresses of doctors, lawyers, dentists and other professional groups.

c.    Case 3:   Doctors in the Salt Lake City Metropolitan Area

San Jose might be termed a "central city," relative to other communities near it.   It seems plausible that such cities will have different professional characteristics than surrounding urbanized areas of the same size.   To evaluate this conjecture, an analysis was made of doctors in the area defined in the 1970 census as the Salt Lake City Metropolitan Area.   Unlike standard metropolitan statistical areas (SMSA's), metropolitan areas are defined in terms of central cities, plus surrounding densely settled areas.   The Salt Lake City Metropolitan Area (SLCMA) is shown in Figure 5.

Table 21 lists the populations of cities within the SLCMA, the number of doctors in each, and the number of doctors per 1000 residents. Again, business mailing addresses were used.   The surprising result is the high clustering of doctors in the central city.   93% of the doctors are located in Salt Lake City, which contains less than half of the population of the region.   Note also that East Mill Creek, a city of 27,000 people, does not have a single doctor.
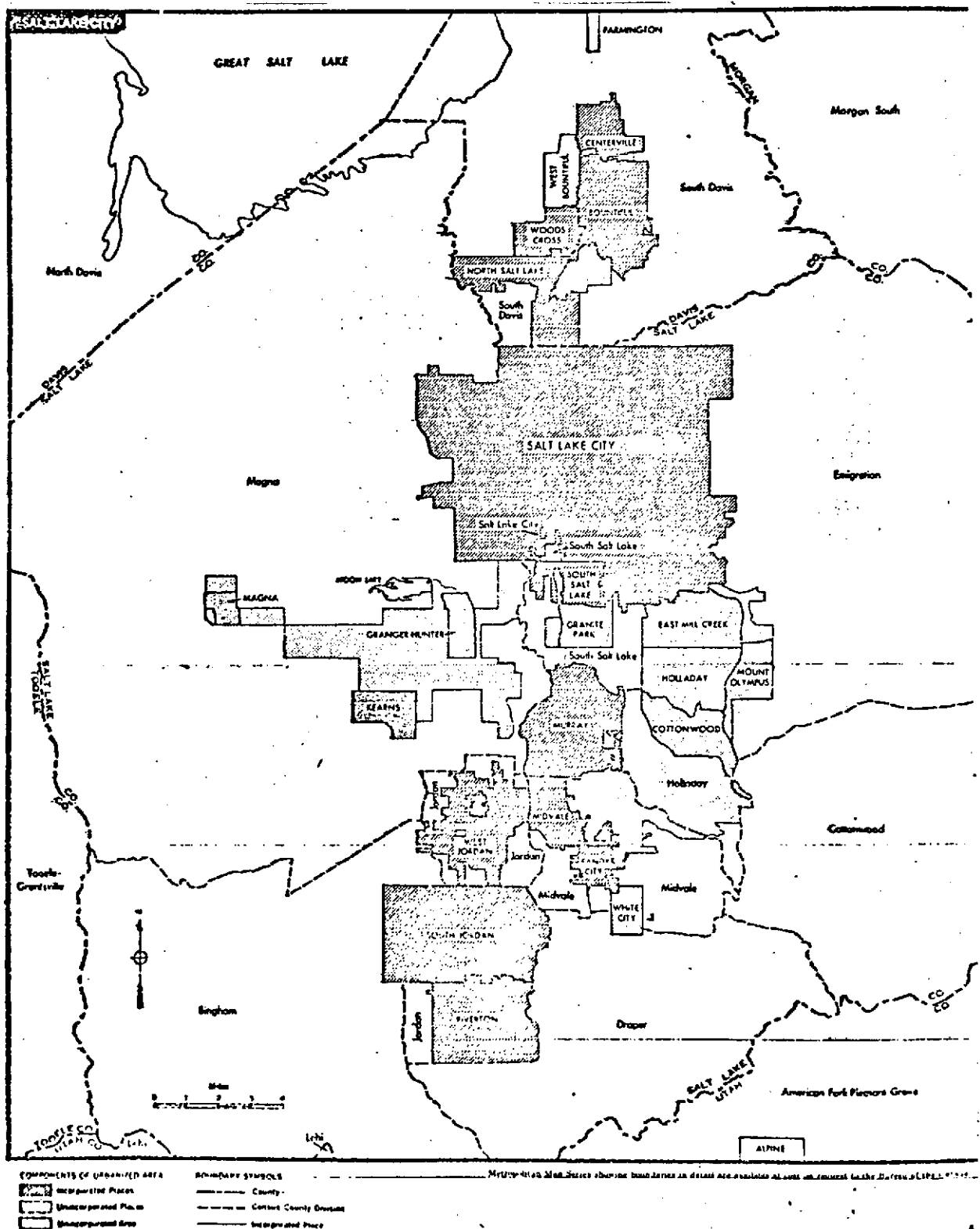
Figure 5:  The Salt Lake City Metropolitan Area

## Table 21

### Doctors in the Salt Lake City Metropolitan Area

| City | Population | MD/1000 | ≠ Doctors |
|---|---|---|---|
| Centerville | 3,268 | | 0 |
| West Bountiful | 1,240 | | 0 |
| Bountiful | 27,854 | 1.2 | 34 |
| Woods Cross | 3,124 | | 0 |
| N. Salt Lake | 2,143 | 0.4 | 1 |
| South Davis | - | | - |
| Salt Lake City | 175,885 | 5.3 | 939 |
| S. Salt Lake | 7,810 | | 0 |
| Magna | 5,509 | 0.7 | 4 |
| Granger-Hunter | 9,029 | 0.1 | 1 |
| Kearns | 17,071 | 0.1 | 2 |
| Granite Park | 9,573 | | 0 |
| E. Mill Creek | 26,579 | | 0 |
| Holladay | 23,014 | | 1 |
| Mt. Olympus | 5,909 | | 0 |
| Cottonwood | 8,431 | | 0 |
| Murray | 21,206 | 3.3 | 7 |
| Jordan | - | | 0 |
| W. Jordan | 4,221 | 0.2 | 1 |
| Midvale | 7,840 | 1.0 | 8 |
| Sandy City | 6,438 | 0.5 | 3 |
| White City | 6,402 | | 0 |
| S. Jordan | 2,942 | | 0 |
| Riverton | 2,820 | | 0 |
| Total (Count): | 378,308 | 2.6 | 1,001 |
| Census: | 479,342 | | - |

d.   Case 4:   Doctors, Lawyers and Teachers in the Denver Metropolitan Area

The Denver Metropolitan Area (DMA) is shown in Figure 6.   The populations of cities, number of doctors in each, and number of lawyers in each are shown in Table 22.   As in the case of the SLCMA, doctors cluster in the central city of Denver.   86% of the doctors are in Denver, which contains about half of the area's population.   Also as in the case of the SLCMA, there are several cities with populations over 10,000 which do not have any doctors.   Medical populations in the suburbs, however, are not uniform.   North Glen (27,937), for example, has only one doctor, while Littleton (26,466) has sixty.

Lawyers were also found to cluster in Denver (85%), and their populations in other cities closely paralleled those of doctors (with the exception of Golden, which has much legal activity).

Parallel data on schools could not be found, because school districts did not follow city boundaries, and there was not enough time to plot each school on maps.   The Denver school district, however, did cover only Denver, and the number of teachers there (4716) provide some comparison to doctors (2251) and lawyers (2726).   Nationally, there are almost 10 times as many teachers as doctors or lawyers, so these figures indicate that teachers are not as concentrated in the central area.   This is a common sense result, but one worth documenting.
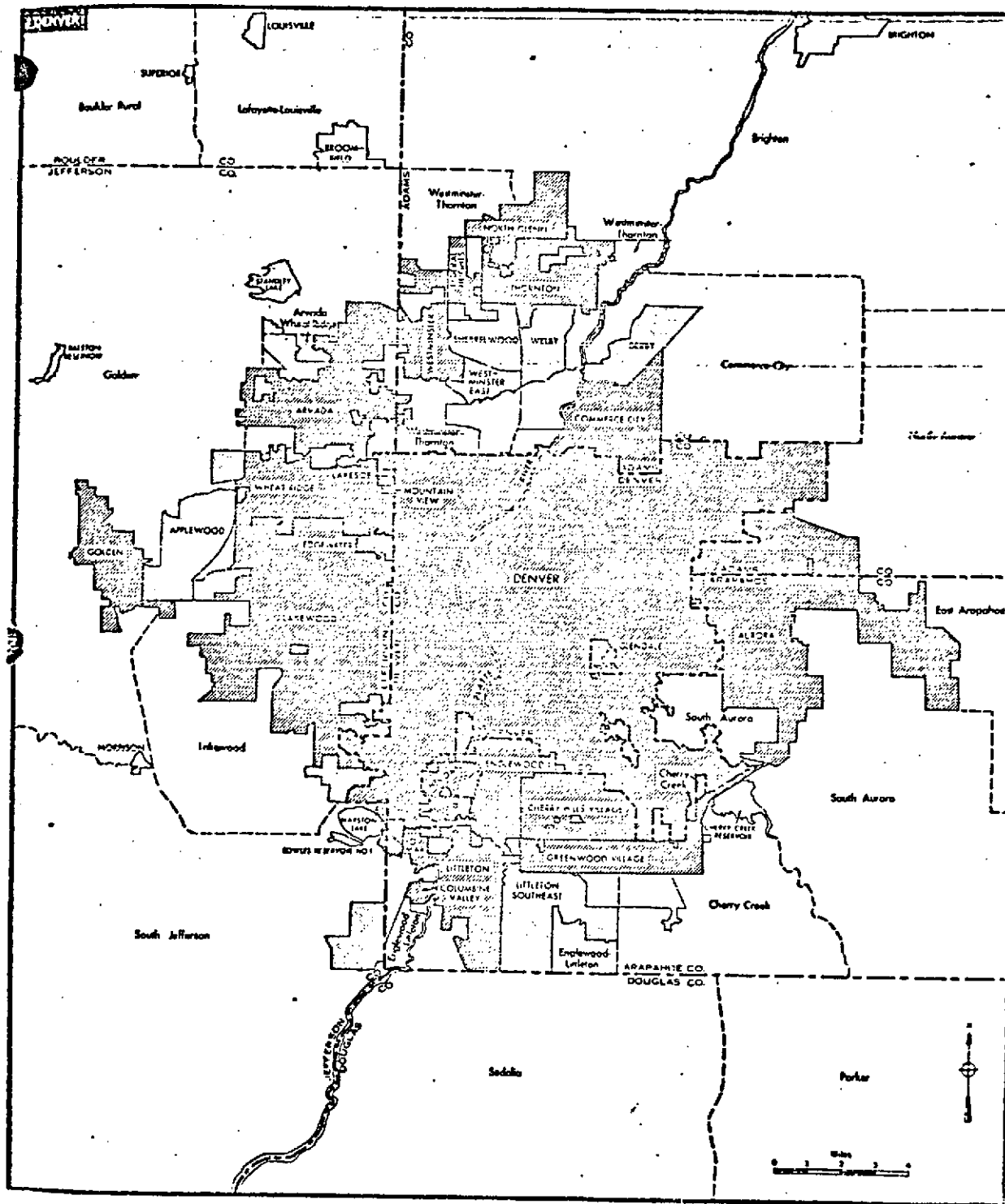
Figure 6:  The Denver Metropolitan Area

Table 22

Doctors and Lawyers in the

Denver Metropolitan Area

| City | Lawyers | Law/1000 | Population | MD/1000 | ≠ MD's |
|------|---------|----------|-----------|---------|--------|
| North Glen | 2 | .8 | 27,937 | .4 | 1 |
| Thornton | 2 | 1.5 | 13,326 | 1.5 | 2 |
| Federal Hts. | 0 | | 1,502 | | 0 |
| Arvada-Wheatridge | — | — | — | — | 0 |
| Westminster | 18 | .9 | 19,432 | .6 | 12 |
| Sherrelwood | 0 | | 18,868 | | 0 |
| Welby | 0 | | 6,875 | | 0 |
| Derby | 0 | | 10,206 | | 0 |
| Arvada | 38 | .8 | 48,814 | .5 | 22 |
| Westminster E. | 0 | | 7,576 | | 0 |
| Westminster – Thornton | 0 | | — | | 0 |
| Commerce City | 15 | .9 | 17,407 | .1 | 2 |
| Wheatridge | 44 | 1.5 | 29,795 | 1.8 | 54 |
| Lakeside | 0 | | 0 | — | 0 |
| Mtn. View | 0 | | 706 | | 0 |
| Denver | 2726 | 5.3 | 514,678 | 4.3 | 2251 |
| Aurora | 53 | .7 | 74,974 | .6 | 47 |
| Golden | 67 | 6.8 | 9,817 | 1.6 | 16 |
| Applewood | 0 | | 8,214 | | 0 |
| Edgewater | 1 | .2 | 4,866 | .4 | 2 |
| Lakewood | 75 | .8 | 92,787 | .6 | 59 |
| Glendale | 0 | | 765 | | 0 |
| S. Aurora | 0 | | — | | 0 |
| Cherry Crk. | 0 | | — | | 0 |
| Englewood | 98 | 2.9 | 33,695 | 2.5 | 84 |
| Sheridan | 0 | | 4,787 | | 0 |
| Cherry Hills Village | 0 | | 4,605 | | 0 |
| Bow Mar | 0 | | 945 | | 0 |
| Greenwood Village | 0 | | 2,578 | | 0 |
| Littleton | 75 | 2.8 | 26,466 | 2.3 | 60 |
| Columbine | 0 | | 481 | | 0 |
| Littleton S.E. | 0 | | 22,899 | | 0 |
| Englewood-Littleton | 0 | | | | 0 |
| | 3,214 | 3.2 | 1,005,001 | 2.6 | 2.612 |
| | | | 1,038,696 | | |

Pop. (Census)                 1,047,311

Table 23 indicates that teachers are more clustered than doctors or lawyers, as is to be expected. The wide variation in maximum and minimum school size in each district, however, is enlightening. Other general trends in the data were that the average size of schools in denser areas tend to be larger than in less dense areas, and that high schools tended to be much larger than elementary schools.

# Table 23

## Teachers in the
## Denver Metropolitan Area

| COUNTY | SCHOOL DISTRICT | #TEACHERS | AVERAGE # TCHRS IN SCHOOL | MAXIMUM | MINIMUM |
|--------|-----------------|-----------|---------------------------|---------|---------|
| ADAMS | MAPLETON | 287 | 23.2 | 45 | 12 |
| | EASTLAKE | 575 | 30.3 | 67 | 4 |
| | ADAMS CITY | 419 | 34.9 | 87 | 10 |
| | WESTMINSTER | 655 | 26.2 | 81 | 4 |
| ARAPAMOE | ENGLEWOOD | 322 | 26.8 | 83 | 4 |
| | SHERIDAN | 118 | 19.6 | 26 | 14 |
| | CHERRY CREEK | 341 | 31.0 | 76 | 14 |
| | LITTLETON | 775 | 43.1 | 94 | 24 |
| | ADAMS-ARAPAMOE | 768 | 29.5 | 88 | 26 |
| DENVER | DENVER | 4716 | 40.3 | 135 | 3 |
| JEFFERSON | JEFFERSON | 2798 | 32.9 | 81 | 2 |

Case 5: Doctors in the State of Colorado.

To extend and generalize our previous results, the number of doctors in each place was plotted (Fig. 7) against the population of the place, for the entire state of Colorado.

Several features of this figure are interesting. First, if a rough line were drawn through the data points, its slope would be greater than unity. This indicates a positive exponential relationship between doctors and city size; as population increases, the number of doctors per thousand people generally increases. At the bottom of the figure, however, major exceptions are shown to this rule. As noted, the cities of large size which have less than three doctors are all suburbs of central cities. Another interesting, although expected, characteristic is the large scatter of doctor populations for smaller places.

Table 24 amplifies the point that many cities, even of substantial size, do not have local doctors. For example, even in 25,000 to 50,000 category, only 6 of the 7 cities have doctors. As noted in the DMA case study, several large cities have only one or two doctors. For places with less than 1000 people, 75% do not have any doctors. The data indicate that few of these places are suburban regions of metropolitan areas, so the lack of service is real.

Figure 7:  Doctors In The State of Colorado
Against The Population
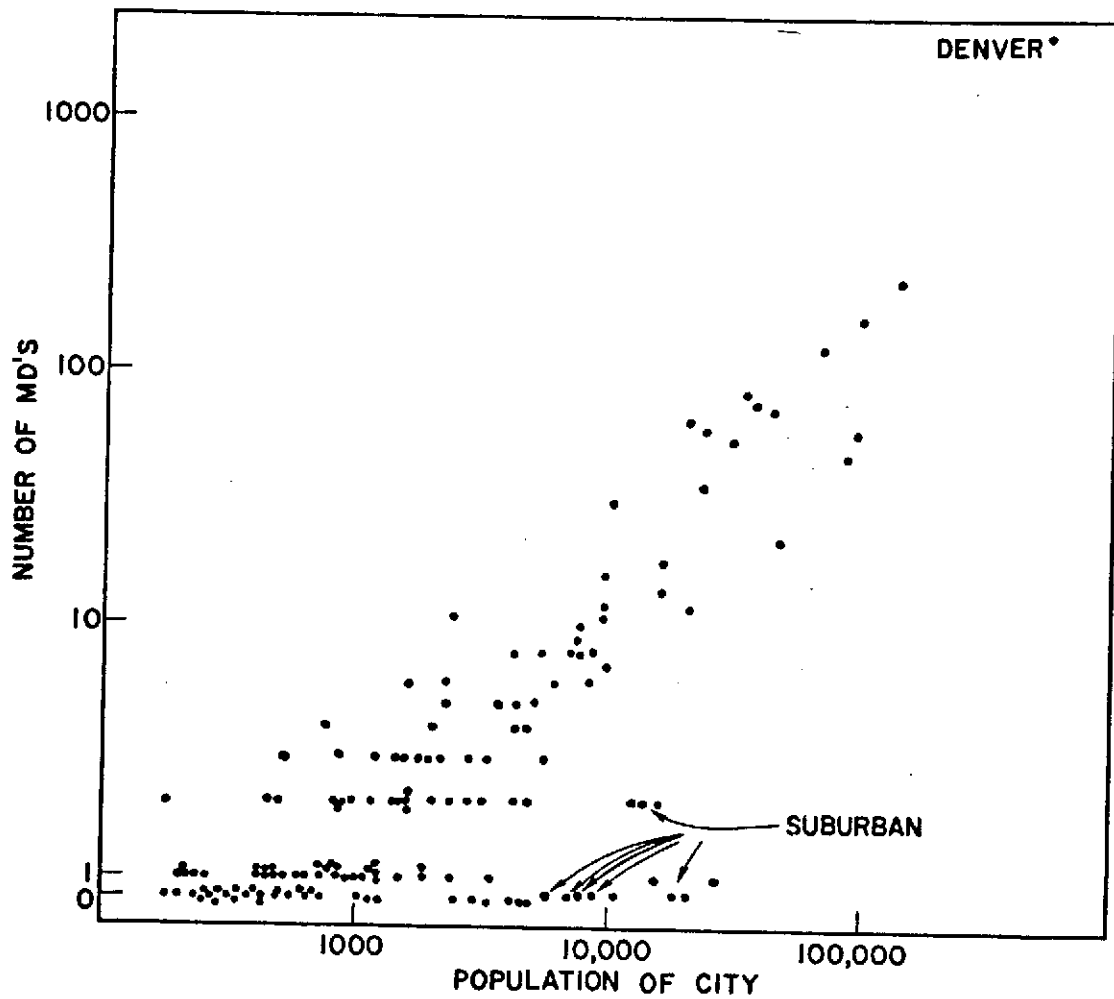
Table 24

Portion of Places in Colorado
Having No Doctors
by Size of Place

| RANGE | NUMBER OF PLACES | W MO'S | PERCENT HAVE NO MD'S |
|---|---|---|---|
| 500,000 to 1,000,000 | 1 | 1 | 0% |
| 250,000 to 500,000 | 0 | 0 | - |
| 100,000 to 250,000 | 1 | 1 | 0% |
| 50,000 to 100,000 | 4 | 4 | 0% |
| 25,000 to 50,000 | 7 | 6 | 14% |
| 10,000 to 25,000 | 13 | 11 | 15% |
| 5,000 to 10,000 | 16 | 11 | 31% |
| 2,500 to 5,000 | 22 | 15 | 32% |
| 2,000 to 2,500 | 8 | 8 | 0% |
| 1,500 to 2,000 | 18 | 14 | 22% |
| 1,000 to 1,500 | 15 | 10 | 33% |
| Less Than 1000 | 173 | 43 | 75% |

f.    Case 6:    The Rocky Mountain Area.

The Rocky Mountain Area, as defined for purposes of this study, is an eight-state region containing about a third of the land area in the United States, but only eight million residents.  Table 25 lists the distribution of city sizes for the eight states and for the area as a whole.  Note that the region does not contain any cities over a million in population, and contains only three cities whose populations exceed a quarter of a million.  There are 644 places, which are either incorporated or contain more than 1000 people, that have populations less than 250,000.  Extrapolating from the Colorado statistics, about 380 of these places do not have a single doctor.

Extrapolating again from the Colorado data, there are about 15,000 doctors in the region.  Using maximum clustering of receiving terminals, as estimated from the San Jose study, it would take about 15,000 receiving terminals to serve these doctors (this takes into account clustering within cities; in cities with less than ten doctors, one receiving terminal was assumed).  Given the cost of cable and other local distribution systems, the number of terminals, might be twice this high.

Table 25

Rocky Mountain Region  Number of Places, By Size

| Population Category | Colorado | Utah | Montana | Idaho | New Mexico | Arizona | Nevada | Wyoming | Total |
|---|---|---|---|---|---|---|---|---|---|
| Millon or more | | | | | | | | | 0 |
| 500,000 - 1,000,000 | 1 | | | | | 1 | | | 2 |
| 250,000 - 500,000 | | | | | | 1 | | | 1 |
| 100,000 - 250,000 | 1 | 1 | | | 1 | | 1 | | 4 |
| 50,000 - 100,000 | 4 | 2 | 2 | 1 | | 3 | 1 | | 13 |
| 25,000 - 50,000 | 7 | 3 | 1 | 3 | 6 | 3 | 1 | 2 | 13 |
| 10,000 - 25,000 | 13 | 9 | 5 | 5 | 7 | 5 | 6 | 3 | 53 |
| 5,000 - 10,000 | 16 | 21 | 9 | 5 | 11 | 16 | 5 | 6 | 89 |
| 2,500 - 5,000 | 22 | 17 | 15 | 22 | 15 | 6 | 4 | 9 | 110 |
| 2,000 - 2,500 | 8 | 7 | 1 | 4 | 6 | 12 | 3 | 4 | 45 |
| 1,500 - 2,000 | 18 | 12 | 5 | 5 | 8 | 7 | 5 | 6 | 66 |
| 1,000 - 1,500 | 15 | 28 | 8 | 5 | 9 | 14 | 4 | 6 | 89 |
| 1,000 or fewer | 173 | 127 | 15 | 22 | 41 | 7 | 2 | 57 | 444 |
| State Population | 2,207,259 | 1,059,273 | 694,409 | 712,567 | 1,016,000 | 1,770,900 | 488,738 | 332,416 | 8,281,562 |

g.   Summary

The demographic data gathered for this study documented some common sense notions about user distributions, but it also produced some surprises, which bear further study.  As expected, substantial and complex clustering of professionals was found.  The extent of the clustering, however, was somewhat higher than expected.  In addition, the distribution of doctors within metropolitan regions and within cities produces substantial surprises.  In general, these sections demonstrated the need for attention to demographic detail in the design and costing of telecommunication systems and for segmenting markets on the basis of demographic differences.

The demographic study also provided estimates for the number of receivers needed to serve given teleconferencing markets, focusing primarily on doctors.  More precisely, the geographical clustering was translated into number of terminals from preliminary estimates of cable and other costs.  In the future, such demographic information should be refined and automated, although elaborate demographic information cannot be justified until the actual design of systems, because of data processing costs.

D. A Methodology For Demand Assessment

While the above sections established some limits to the potential markets for teleconferencing, before embarking on large scale implementation of services a more complete analysis must be completed. The methodology proposed in this section is of the level of complexity that is appropriate for such an analysis. The information needs are identified and in most cases methods to acquire the information are described. Subsequent analyses of specific teleconferencing services should seek information of the detail indicated by the model. Furthermore, in reviewing upcoming experiments in teleconferencing, this or a similar model should be used to ensure that the experiments are designed to acquire the needed information.

1. Characteristics and Assumptions of the Study

There is a need to specify what we mean by the term "market." Within the teleconferencing industry, we will not deal with competition between firms in the supply of teleconferencing services. As far as the study is concerned, there may be only one agency operating to provide the services with teleconferencing.

However, the term market (and hence the system) incorporates more than just the teleconferencing industry. In this analysis, one way in which we segment the market is by dividing it into the various professional groups within the market (see Table 26). For each occupation in the market there will be various services which would be suited to the needs of that occupation. While the members of the occupational class could conceivably get these services with teleconferencing, there would also be other means of satisfying their needs, such as professional journals,

Table   26

Occupational Classifications (Bureau of Census)

| Classification | Symbol |
|---|---|
| Professional, Technical, and Kindred: | |
| Elementary and secondary teachers | $c_1$ |
| Engineers | $c_2$ |
| Nurses (R.N.) | $c_3$ |
| Accountants | $c_4$ |
| College instructors (higher education) | $c_5$ |
| Physicians (M.D., D.O.) | $c_6$ |
| Lawyers and judges | $c_7$ |
| Clergy · | $c_8$ |
| Physical scientists | $c_9$ |
| Pharmacists | $c_{10}$ |
| Dentists | $c_{11}$ |
| Designers and draftsmen | $c_{12}$ |
| Technicians | $c_{13}$ |
| Musicians and music teachers | $c_{14}$ |
| Managers, officials, and proprietors | $c_{15}$ |
| Clerical and kindred | $c_{16}$ |
| Salesworkers | $c_{17}$ |
| Craftsmen, foremen, and kindred | $c_{18}$ |
| Operatives and kindred | $c_{19}$ |
| Service workers including private households | $c_{20}$ |
| Farmers, farm managers, laborers and foremen | $c_{21}$ |
| Laborers, except farm and mine | $c_{22}$ |

professional meetings, and the telephone.

If we direct our efforts along the planes suggested in Table 26, then for each of the occupational classes we generally find it would be appropriate to view each market as being served by oligopolies with differentiated products. The teleconferencing service is one of different qualities than any of the other products in the market. Yet, there are not really innumerable service alternatives; rather, there are only a few serious alternatives in each case.

This assumed view has several implications:

The price of any service in the market depends to some extent on the price of other services in the market.

The demand for any service in the market depends to some extent on the demand for other services in the market.

There will be fairly modest price differentials in the market.

The price differential depends on the success of convincing the public as to the superiority of the product.

Competition is principally in the area of advertising and sales promotion (to create a service brand preference which will benefit much more than concentration on the price differential).

We note that with our description of the market, market share elasticity becomes synonymous with elasticity of substitution.

A final point about this study is that it will be designed to be time varying (dynamic).

2. Estimating Potential Demand

Table 26 suggests a breakdown of users by occupational classifications. A further useful breakdown is by geographical areas (see Table 27). Note that the geographical units are labeled $a_1$, $a_2$.... . The ranges are only suggested ranges and could be made more or less divisible as

## Table 27

### Geographical Area Classifications

| Unit Population | Near Large City | Not Near Large City |
|---|---|---|
| 1,000,000 and over | $a_1$ | $a_2$ |
| 500,000 - 1,000,000 | $a_3$ | $a_4$ |
| 100,000 - 500,000 | $a_5$ | $a_6$ |
| 50,000 - 100,000 | $a_7$ | $a_8$ |
| 10,000 - 50,000 | $a_9$ | $a_{10}$ |
| 2,500 - 10,000 | $a_{11}$ | $a_{12}$ |
| Rural | $a_{13}$ | $a_{14}$ |

resources of time and research are weighed against the additional benefits of more narrowly defined ranges.

The information desired for each unit is a number and distribution by work location, representative of the members of each occupational classification in Table 26. It is suggested that two or three cities described by each unit designation be studied to give an average impression for each case.

The motivation for the collection of this data now becomes clearer. Suppose we are studying a specific region, say either part or all of the United States. For that region, we find how many cities are $a_1$-type cities, how many are $a_2$-type, and so on. We can look at our average number of the members of each occupational classification in each city type, and arrive at a potential demand within the region.

We have additional data which estimates the average annual growth rate of each occupation classification over the next ten to fifteen years. We assume that the growth rate is nearly uniform over the region. Applying this information we can now systematically describe a time varying potential demand for teleconferencing services in the region under study.

First, let us construct a matrix, [A], whose rows $(c_1, c_2, \ldots, c_m)$ represent the occupational classifications of Table 26. The columns of [A] represent the geographical areas of Table 27 $(a_1, a_2, \ldots, a_n)$. The elements of the [A] matrix we donote as $A_{ij}$.

Further, let us describe the $A_{ij}$ as time varying quantities. For example, we may have data which show that the average annual growth rate of classification $c_1$ is 5 percent. We already will have $A_{ij}$ at the time of the study, $t_0$. Then the dynamic description of $A_{ij}$ would be

$$A_{ij}(t) = A_{ij}(t_0)\{1 + 0.05\}^{(t-t_0)}$$

where $(t-t_0)$ is the number of years after the time of the initial $A_{ij}$ values.

For the region under study, let us also count the number of cities (or areas) which correspond to each geographical area, $a_i$. Let this number be $b_i$. Further, let us arrange the $b_i$'s in a vector with n components (just as there are n geographical areas). So we have

$$b] = b_1, \ b_2, \ b_3, \ldots, b_n \quad t$$

Note that if we take the project $[A]b$] we get a new vector, d], whose components represent the total number of members of each occupational classification (each $c_i$) in the entire region. The elements of d] must be checked against the actual known aggregates for each occupation, and the elements of the $[A]$ matrix should be corrected so that a reasonable comparison is achieved. From the dynamic property of $[A]$, it follows that d] is time varying.

We have succeeded in describing the potential market with a time varying capability.

3. Converting Potential Demand to Actual Demand

Given that we have a time varying description of the potential market, we now attempt to determine what portion of the market will use the facilities. This is the step which separates potential demand from actual demand. Within this process we must reflect on both the willingness to pay as well as the ability to pay. The following factors seem to relate to the problem:

Technical capabilities, including technical performance, and system response time.

Quality of service, including technical quality and program service.

Availability of system, hours of week available.

Price (tariffs).

Alternatives of service (substitute services).

Anticipated future of system (users expectations).

Users income.

Acceptance of innovation (adoption by society).


The first three of these are really policy variables.  There is also a strong possibility that prices will be a policy variable, perhaps as the telephone company charges uniform rates throughtout a given area code.



4.  Plausibility of System to User

At this point we face one of the apparent impasses of this demand study.  It would be advantageous to know what the form of the teleconferencing system would be in order to nail down the forecast with any certainty.  On the other hand, the design of the system itself depends on the demand and the circle of dependence emerges.

There is an important principle we should follow in this study.  We

do not want to limit the policy making latitude with too narrow a study.

So we examine each $A_{ij}$ of the market to see what effects each system

type will have on demand.  It would be appropriate to examine each $A_{ij}$

and ask, "What decimal fraction of the people in the category would

plausibly employ the system under each of the two or three foremost

systems being considered?"  The system design includes technical c

capabilities, quality and availability of system service.  This leads

us to two types of eliminations that can be made on the grounds of

implausibility.  One is those people whose needs are not satisfied by

the technical capabilities of the system.  The other is for people who

are not likely to use the system for reasons of age (too old to retrain

or follow the state-or-the-art), or possibly for other similar reasons.

The rationale is that we are trying to determine the ultimate plausible

number of users.  Consider the number of people for a given $A_{ij}$ to be

1,000.  In evaluating a given system design perhaps it is determined for

the above reasons that only 800 could plausibly be served by the system

design.  So we would have a system plausibility factor of 0.8 associated

with $A_{ij}$.

For some alternatives we may find an extremely low factor (say, 0.05)

associated with $A_{ij}$ as $F_{ij}$.  For others we may find a very high factor,

perhpas approaching 1.0.

5. Tariffs (Pricing)*

For the purposes of the study, we are presently faced with two specific pricing policies. One is that the price will be uniform to all users in a given area. The second policy is that the prices depend on the actual distribution costs to each location. For example, in a given area a user far out from the receiving station (antenna) would have to absorb some of the higher costs of cable installation and maintenance to his location. Because the pricing policy is critical, it would seem necessary to carry out the study in two independent steps, one for each policy.

The import of the pricing policy has already been introduced in the section on characteristics of the study. To further illustrate this, let us suppose that a questionnaire were drafted and sent to samples of one of the $c_i$ classifications (say lawyers and judges) in a given area. In the questionnaire we inquired as follows:

1. What is the user's total expenditure per year on information services?

2. Then we describe the system and the services it would provide, noting primarily only the points interesting to the particular class of user.

3. How much does the user spend per year on services that our system could provide?

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*See also the section on "Limitations of the Methodology."

4.    What is the user's total income?


The next step would logically be to ask how many additional services
the system would provide beyond what they already receive, and to follow
this question by asking how much they would pay for the additional
services.   However, we encounter two problems here:

1.    We really don't know how many additional services the system
      will offer, and

2.    Even if we knew, the question is too abstract to receive mean-
      ingful response, especially on a questionnaire.


So we now rely on the attribute of they system as a differential
product.   Let the answer to question 3 above be $1,000.   We will take
this figure as a competitive price.   The next step is to view the
market in two parts, that which the system can supply and the second as
that which are satisfied by non-teleconferencing efforts.   This division
is presumably sound because it would take an aggregated effort by the
"other" services to match the services that the system could provide.


Consider the schedule (in Table 28) which is typical of the duopoly
with differentiated products that has now been described.


From the system designers and program costs, we should have a fairly
good idea of the cost of service to the different users of a given occupa-

Table 28

**Price-Market Share Schedule**

| Price/year (Expenditures per year on a given quantity) (teleconferencing services) | Market Share Factor (Decimal Fraction) (Range of Values) |
|---|---|
| $5,000. | 0.00 - 0.01 |
| $2,000. | 0.01 - 0.10 |
| $1,500. | 0.1 - 0.3 |
| $1,100. | 0.3 - 0.5 |
| $1,000.* | 0.4 - 0.6 |
| $ 900. | 0.5 - 0.8 |
| $ 600. | 0.8 - 1.0 |

*Competitive Price, i.e., the average amount spent in a given time period on similar services that teleconferencing could provide (for given $A_{ij}$).

Table 29

Market Share Factor for Nonuniform Tariff

| Percent of Potential Users | Tariff for That Group | Mean Market Share Factor |
|---|---|---|
| 10 (Distant) | $2,000. | 0.05 |
| 30 | $1,100. | 0.40 |
| 50 | $1,000. | 0.50 |
| 10 (Near) | $ 900. | 0.75 |

tion within each geographical area. For example, suppose that we have

a uniform tariff of $900. Then we would estimate that our market share

factor would be between 0.5 and 0.8 of those for whom the system is a

plausible one.

If we had a nonuniform tariff rate, then we would take a weighted

average of the users in that area. This is one reason why the distribu-

tion data on users in each $A_{ij}$ was mentioned as important early in this

discussion. For example, suppose that for a given occupation in a given

area, we had a user distribution as in Table 29. The table illustrates

that distant users would have higher tariffs, and that the market-share

factors for them would be expected to be lower. Then the market share

factor is:

$$M_{ij} = 0.1(0.05) + (0.3)(0.4) + (0.5)(0.5) + (0.1)(0.65) = 0.440.$$

A few additional comments seem proper about the importance of this

study. First, it may be desirable to place some type of limits on the

market share factors most likely at each price in the schedule. The

demand study is not necessarily deterministic, in the sense that an exact

demand must be forecast. The limits would be quite useful in describing

upper and lower bounds. This range of values might be more valuable

than exact numbers whose variation is not perceived.

Another reason not to try to nail down the price differentials with excessive accuracy is that the real effort should be directed toward advertising and sales promotion, rather than to the exact nature of the price differential.

The reader may recognize that this part of the analysis attempts to relate the user's expenditures on a certain class of services to his present expenditures. This is in recognition of the user's finite income However, it does not presuppose that the fraction of his income spent on these services will be necessarily constant. (The user who spend $1000 per year before may spend $1200 per year after the teleconferencing services are introduced.) Nor does this analysis presuppose a strictly substitute effect of the different services, for to some extent the services may actually be complementary. On the balance, however, it seems a priori that the substitute effect would reign predominant.

Finally, the schedule suggested would lead us to price and substitute elasticities of demand. For all these reasons, it is suggested that a rather intensive effort be made to determine a schedule similar to the one presented in this section, with well-reflected ranges on the market share factors.

6. Acceptance of Innovation*

Let us retrace our logic for a moment. First, we segmented the market by user occupation and geographic location. This gave an upper bound for the number of users, a base from which to work. Then we scaled the ultimate number down to a more realistic plateau by reducing the potential demand to only those for who the system was plausible. We further scaled this down by a market share factor, from a market share of demand schedule characteristic of oligopolies with differentiated products. So now we have an idea as to the demand after the teleconferencing systems are established and the market stabilizes.

We now turn our attention to the behavior of the market from the time at which the teleconferencing systems are introduced until the market stabilizes. Teleconferencing services are an innovation, and there has been significant work done in analyzing the acceptance of innovation in society. One such source, Diffusion of Innovations, by Everett M. Rogers, discusses the spread of a new idea from its source of invention to its ultimate users or adopters. This process called the adoption process has certain characteristic phases which determine what percentage of the ultimate user number subscribe to the innovation during the period following its introduction.

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*See also the section on "limitations of the Methodology".

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One empirically suggested pattern of acceptance of an innovation over time is an "S" shaped curve, as in Fig. 8. At first only a few pioneer users adopt the idea, then the majority decide that the new idea is desirable, and finally the adoption curve levels off as the influence of the product in the market stabilizes. In our case, the plateau is estimated to be the demand in the stabilized market. A similar pattern is followed in user awareness of the product over time.

The exact shape of the adoption curve, $G(t)$, is not known. For one thing, the curve could rise immediately, or it could stay low for some time rising faster at a much later time. Another unknown is the time until stabilization which is represented by T in Fig. 8. Likely estimates of T have run anywhere from an optimistic six years to a pessimistic fifteen years.

We require only that the curve satisfy three criteria:

(i)  $G(t_0) = 0$.

(ii)  It must have an S shape (suggested by empirical data).

(iii)  It must have an asymptote at $G = 1.0$ for large values of time.

The exact form of the adoption curve does not seem to be the most important thing. What would be more desirable would be to cover the range of probable shapes (immediate rise to delayed rise) with a set of calculations to get a feel for the impact of variation in shape of the adoption curve on the demand. The time until stabilization should also be varied in the model to see how it affects the demand. The experiences of other products can be used to see how the confidence and expectations
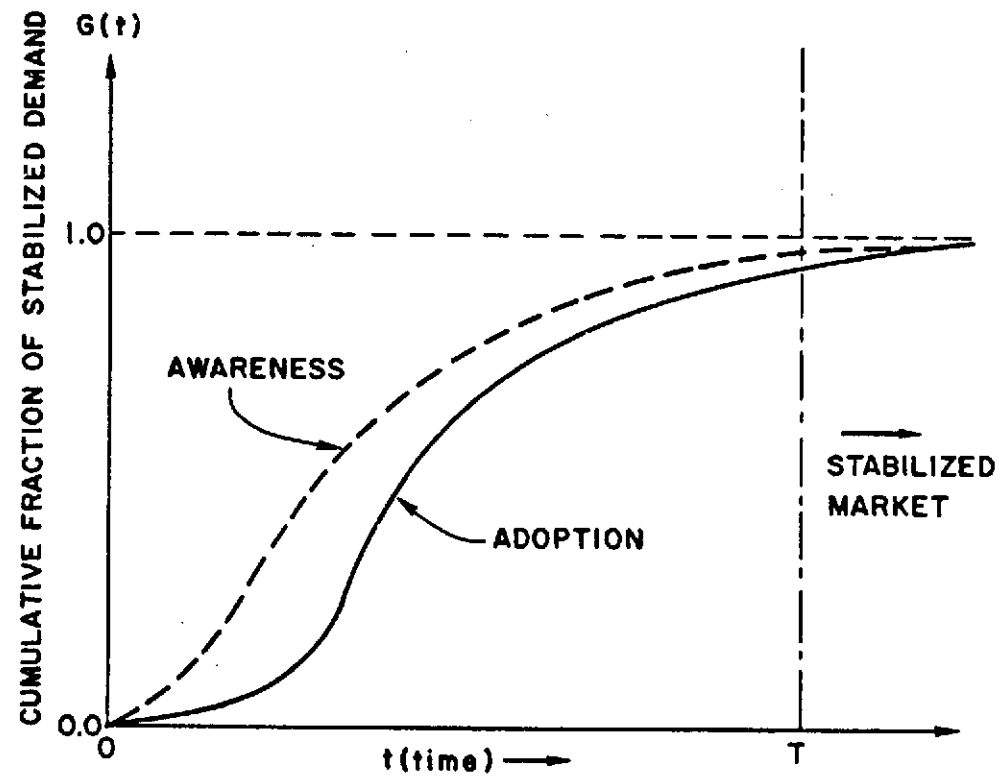
Figure 8: The Adoption Curve

calculations to get a feel for the impact of variation in shape of the adoption curve on the demand. The time until stabilization should also be varied in the model to see how it affects the demand. The experiences of other products can be used to see how the confidence and expectations of users have manifested themselves in the past.

Further thought is necessary regarding whether any particular adoption curve will be appropriate for all segments of the market, or whether individual curves will be needed for each row, column, or element of the [A].

7. Putting It All Together--Demand

For a given system design

For a given tariff policy

For a given region

Assuming one $G(t)$ (adoption curve) for the whole region.

The demand is described as

$$D(t)] = G(t) \begin{bmatrix} (M_{1,1})(F_{1,1})A_{1,1}(t) & \cdots\cdots & (M_{1,n})(F_{1,n})A_{1,n}(t) \\ (M_{2,1})(F_{2,1})A_{2,1}(t) & \cdots\cdots & (M_{2,n})(F_{2,n})A_{2,n}(t) \\ \cdot & & \cdot \\ \cdot & & \cdot \\ \cdot & & \cdot \\ \cdot & & \cdot \\ \cdot & & \cdot \\ (M_{m,1})(F_{m,1})A_{m,1}(t) & \cdots\cdots & (M_{m,n})(F_{m,n})A_{m,n}(t) \end{bmatrix} \begin{bmatrix} b_1 \\ b_2 \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ b_n \end{bmatrix}$$

where $D(t)]$ is the vector each of whose components represent the expected

actual demand by people in each occupation at time t.

$G(t)$ is the adoption curve.

$M_{ij}$ is the market share factor.

$F_{ij}$ is the plausibility factor.

$A_{ij}$ is the potential demand.

b] is the vector whose components represent the number of cities

of each type in the region.

If we had reason to have a different $G(t)$ for each occupation, then the matrix would be pre-multiplied by a row vector $G(t)$, each of whose $m$ elements would apply to the corresponding occupational classification (i.e., $G_i(t)$ corresponds to $c_i$, the $i^{th}$ row of the $[A]$ matrix).

Finally, although for conceptual reasons we have considered the $M_{ij}$ and the $F_{ij}$ factors separately, there is no reason why they cannot be combined into one factor in practice, as long as that one factor retains all the properties of the original factors.

8.  Example Calculation:  Determinations of Price and Substitute
    Elasticities of Demand

Using the price-market share schedule displayed in the description

of market share factors earlier, we proceed with the following example:

A particular $A_{ij}$ is being considered.

A uniform tariff policy is followed.

We assume that a 95% level of the adoption curve is to be reached

in four years.  (Other adoption curve characteristics previously

indicated are also to be followed.)

The occupational classification, $c_i$, grows at five percent

per year.

We assume a system palusibility factor of 0.8 associated with

$A_{ij}$.

We assume a uniform distribution on the $M_{ij}$ over the ranges

shown.

There are 1,000 people in $A_{ij}$ at $t_0$.

We have from the above the following time-varying description of $A_{ij}$:

$$A_{ij}(t) = 1,000(1.05)^{t-t_0}$$

We also construct an adoption curve which meets all the specifications

desired.  This could be done by a table of G(t) vs t in years, or by some

continuous function.  We opt for the latter:

$$G(t) = \frac{1 - e^{-t}}{1 + e^{-t}}, \quad t \quad 0,$$

whose characteristics are:

    (i)   $G(0) = 0$.

   (ii)  Asymptote at $G = 1.0$.

 (iii)  "S" shaped curve (see Fig. 9).

  (iv)  $G(4) = 0.96$, or in 4 years we achieve the 95% adoption rate.

We now make calculations for the values of $A_{ij}$ and $G_{ij}$ in years one through four, shown in Table 30, and follow with the demand calculations in Table 31.

Table 30

Example Values for $A_{ij}(t)$ and $G_{ij}(t)$

| t | $A_{ij}(t)$ | $G_{ij}(t)$ |
|---|---|---|
| 1 | 1,050 | 0.45 |
| 2 | 1,103 | 0.77 |
| 3 | 1,157 | 0.91 |
| 4 | 1,216 | 0.96 |

The graph shows a curve labeled $G(t) = \dfrac{1-e^{-t}}{1+e^{-t}}$

The y-axis is labeled CUMULATIVE FRACTION OF STABILIZED DEMAND with values 0.0, 0.2, 0.4, 0.6, 0.8, 1.0 and $G(t)$ at top.

The x-axis is labeled t (time, years) with values 0, 1, 2, 3, 4 (T).

A vertical dashed line at T marks the STABILIZED MARKET.
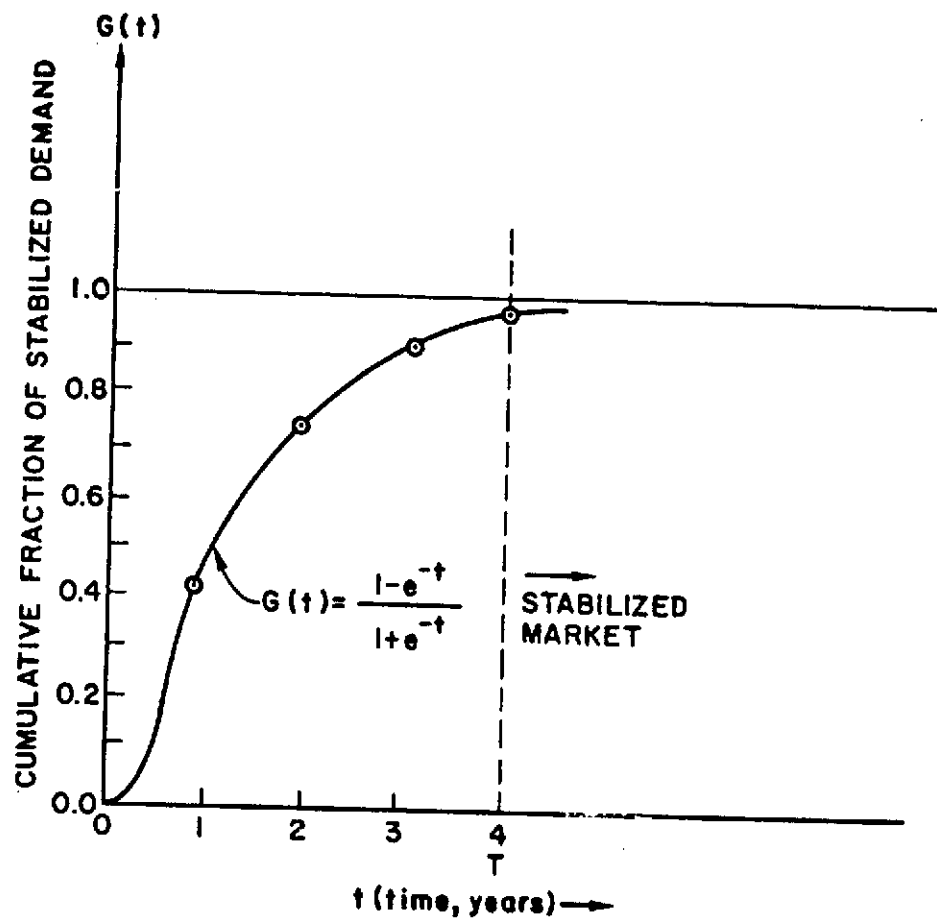
Figure 9:  Adoption Curve for Example Analysis
(from Rogers, Diffusion of Innovations)

# Table 31

## Demand Calculations and Results

| Price (Expenditures/yr on Teleconferencing) $P$ | Market Share Factors (Range) $M_{ij}$ | Time (yrs) $t$ | Product of Factors Year t $(F_{ij})(A_{ij})(G_{ij})$ | Demand Year t Range $D_{ij}(t)$ | Demand Year T Mean $\overline{D_{ij}(t)}$ | Market Share Factor Mean $\overline{M_{ij}}$ |
|---|---|---|---|---|---|---|
| $2,000. | 0.01-0.1 | 1 | 380 | 4- 38 | 21 | 0.05 |
|  |  | 2 | 680 | 7- 68 | 37 |  |
|  |  | 3 | 840 | 8- 84 | 46 |  |
|  |  | 4 | 930 | 9- 93 | 51 |  |
| $1,500. | 0.1 -0.3 | 1 | 380 | 38-114 | 76 | 0.1 |
|  |  | 2 | 680 | 68-204 | 136 |  |
|  |  | 3 | 840 | 84-252 | 168 |  |
|  |  | 4 | 930 | 93-279 | 186 |  |
| $1,100. | 0.3 -0.5 | 1 | 380 | 114-190 | 152 | 0.2 |
|  |  | 2 | 680 | 204-340 | 272 |  |
|  |  | 3 | 840 | 252-420 | 336 |  |
|  |  | 4 | 930 | 279-465 | 372 |  |
| $1,000.* | 0.4 -0.6 | 1 | 380 | 152-228 | 190 | 0.5 |
|  |  | 2 | 680 | 272-408 | 390 |  |
|  |  | 3 | 840 | 336-504 | 420 |  |
|  |  | 4 | 930 | 372-558 | 465 |  |
| $ 900. | 0.5 -0.8 | 1 | 380 | 190-304 | 247 | 0.65 |
|  |  | 2 | 680 | 340-544 | 442 |  |
|  |  | 3 | 840 | 420-672 | 546 |  |
|  |  | 4 | 930 | 465-754 | 610 |  |
| $ 600. | 0.8 -1.0 | 1 | 380 | 304-380 | 342 | 0.90 |
|  |  | 2 | 680 | 544-680 | 617 |  |
|  |  | 3 | 840 | 672-840 | 756 |  |
|  |  | 4 | 930 | 754-930 | 842 |  |

*Competitive price.

## 9. Elasticity Calculations

Suppose we wish to calculate the price and substitute elasticities of demand at $P = \$1,000$ in the third year for the example just presented.

At $t = 3$, we have:

$X$ = quantity of teleconferencing services demanded

$Y$ = quantity of other services in the market demanded

$P_x$ = price for teleconferencing services represented by X

$P_y$ = price for other market services represented by Y

$MRS$ = marginal rate of substitution of X for Y

Subscript 1 = values from Table 6 for $t = 3$, $P = \$900$.

Subscript 2 = values from Table 6 for $t = 3$, $P = \$1,100$.

Price Elasticity of Demand (Calculation with arc elasticity):

Point:

$$\epsilon = \frac{\dfrac{\Delta X}{X}}{\dfrac{P_x}{P_x}}$$

Arc:

$$E_p = \frac{\dfrac{X_2 - X_1}{X_2 + X_1}}{\dfrac{P_{x_2} - P_{x_1}}{P_{x_2} + P_{x_1}}}$$

$$E_p = \cfrac{=\ \cfrac{336\ -\ 546}{336\ +\ 546}}{\cfrac{1100\ -\ 900}{1100\ +\ 900}} = -2.4$$

Substitute Elasticity of Demand (Calculation with arc elasticity):

Point:

$$\epsilon_s = \cfrac{\cfrac{\Delta(X/Y)}{X/Y}}{\cfrac{\Delta MRS}{MRS}} = \cfrac{\cfrac{\Delta(X/Y)}{X/Y}}{\cfrac{\Delta(P_x/P_y)}{P_x/P_y}}$$

Arc:

$$E_s = \cfrac{\cfrac{(X/Y)_2\ -\ (X/Y)_1}{(X/Y)_2\ +\ (X/Y)_1}}{\cfrac{(P_x/P_y)_2\ -\ (P_x/P_y)_1}{(P_x/P_y)_2\ +\ (P_x/P_y)_1}}$$

$$E_s = \cfrac{=\ \cfrac{0.4\ -\ 0.65}{0.4\ +\ 0.65}}{\cfrac{1.1\ -\ 0.9}{1.1\ +\ 0.9}} = -2.4$$

Further work was done in an attempt to relate income elasticity of demand to the two elasticities already described; however, a realistic relationship would require data of a much more abstract nature. By this we refer to the fundamental equation of price theory, the Slutsky equation, which relates the three types of elasticity. However, in the case presented with this project, information regarding changes in the marginal rates of

substitution of the information services is required along iso-utility

lines (in the microeconomic sense).   This data is not easily obtained.


The result of the procedure above is that we would now have the

price and substitution elasticities associated with each $A_{ij}$.   With these

matrices, we can attempt to predict the impact on the change in demand

for teleconferencing services in any occupation/geographic area due to

changing the prices of the services or the demand for substitute services.

The extension of the impact to the entire region follows in the same way

the overall demand was projected from the information associated with the

elements of the [A] matrix.

10. Limitations of the Methodology

There are three general areas in which significant limitations of the methodology suggested are found. The first is in the adoption curve concept. It has been suggested frequently that the adoption curve rises in an "S" shaped curve to a plateau, an asymptote as time gets large. However, some sources contend that after the adoption curve reaches its peak and holds for some time, it declines exponentially to another plateau. For example, the telegraph reached a peak as it was adopted, but because of new services, its use actually has declined to some extent since it peaked.

This does not deal a fatal blow to the methodology which has here been proposed. In the section on adoption curves, it was mentioned that further thought on the shape of the curve is necessary. It is difficult to imagine what services would cause the adoption curve for teleconferencing services to decline as it did for the telegraph; however, it would have most likely been hard for those developing the telegraph to see how the adoption curve for that great innovation to peak out and then decline. In this fast moving age of technology, we should not blind ourselves to the idea that a smilar behavior is likely to befall the adoption curve for teleconferencing services.

The second area of concern is in the uncertainty associated with certain variables. In the price-market share schedule (see Table 3),

there was a range of market share factors associated with each price. The example assumed a uniform probability distribution of the values within the range used. However, the actual study suggested in this methodology might reveal a different distribution. The calculations would then be based on that distribution.

Similarly, the value of T in the adoption curve, representing the time until market stabilization, might be described by a probablilty distribution instead of straightforward case studies based on various values of T.

Another uncertainty is the location of the "S" in the adoption curve. This can be studied with probabilistic analysis, or in a case study given various locations of the curve.

This methodology has first suggested the case studies of these variables to see which ones are sensitive enough to warrant further investigation of the probabilistic nature just described. In any event, analysis with distributions represent extensions of this methodology, and would not deem any of the suggested output of the study invalid.

The third area of concern again deals directly with the price-market share factor schedule, such as that of Table 3. We have proceeded in this study under the assumption that the services provided by the

teleconferencing industry are introduced into a market which presently exhibits a high degree of stability among the already existent services (such as professional journals, telephone service, professional meetings, etc). The market share factors are based on the characteristics of the oligopoly with differential products, and the "competitive price" in the schedule, as well as the price of the services provided by the teleconferencing industry, are likely to vary. Let us consider these variations one at a time.

We arrived at the competitive price by determining how much the user of market services presently (before the teleconferencing services are introduced) spends with a given time period, say, a year. It is realized that after the teleconferencing services are introduced, the user may actually increase his total expenditure on services provided by the market, because of the introduction of the teleconferenicing services, the market share factors originally assigned will not change. All the demand and elasticity calculations will remian valid, for the effective competitive price will not change.

However, if one of the substitute services comes forth with a drastic price change, then two consequences emerge.

1. The "competitive price" is altered significantly, and the price-market share schedule must be adjusted accordingly.

2.  The impact of the price change on demand can no longer be accurately predicted since the elasticity is a concept dependent on changes "in the limit" (as the price change is fairly small). New elasticities based on the new price-market share schedule must be derived, using the same procedure described in the section on elasticities.

The second consideration is what happens when the price of teleconferencing services is changed. The pricing has been viewed as a policy variable, and if the price is changed, the study will simply use the same price-market share schedule with the new price being used instead of the old one to determine the market share. No modification in the model is required. The demand is described with one set of $M_{ij}$ before the change, and a new set of $M_{ij}$ afterwards.

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## A. Introduction

The purpose of this chapter is to discuss the economic characteristics of a satellite communication ground station. It presents the costs of the ground station antenna and pre-amplifier and derives the relation between G/T and minimum cost. Also the cost of the transmitter and of certain miscellaneous items are described. The results of this cost evaluation are used to obtain numerical approximations of a least-cost satellite system, including both ground segment and satellite segment, as described in Chapter V of this report.

## B. Antenna Gain

The most important characteristic of an antenna is its gain. The gain of a parabolic antenna is given by:

$$G = \eta(\frac{\pi d}{\lambda})^2$$

where

| | | |
|---|---|---|
| G | : | Antenna Gain |
| d | : | Antenna Diameter |
| $\lambda$ | : | Wave Length |
| $\eta$ | : | Antenna Aperture Efficiency |

or in dB, $\quad G = 9.96 + 20\log d - 20\log\lambda + 10\log\eta$

Today, 50 percent efficiency is common, and 55 percent has been realized. A 55 percent efficiency is assumed in this discussion.

The Cassegrain type antenna is usually employed for INTELSAT standard earth stations, while the parabolic antennas are commonly used for smaller gain requirements.

## C. Receiving System Noise Temperature

In a satellite communication system, noise generated in a circuit is expressed in terms of an equivalent input noise temperature for the circuit. The noise temperature and the noise figure, F, which is defined as the ratio of input S/N to output S/N, are related by the following expression:

$$T = (F-1)T_o$$

where

| | | |
|---|---|---|
| T | = | the noise temperature in $^{\circ}$Kelvin |
| F | = | the noise figure expressed as a numerical ratio |
| $T_o$ | = | 290 $^{\circ}$K |

In an earth terminal, the system noise temperature, $T_s$, is best used as a measure of sensitivity.

System noise temperature is defined as:

$$T_s = T_a + (L_f-1)T_o + L_f T_r$$

where

| | | |
|---|---|---|
| $T_a$ | = | the noise temperature of the antenna |
| $L_f$ | = | feeder loss between antenna and receiver |
| $T_r$ | = | the receiver noise temperature |

The noise temperature of the antenna depends on the antenna elevation angle. The following are the sources which contribute significantly to the noise temperature of the antenna.

1) Antenna spill over

2) Cosmic noise

3) Atmospheric absorption

The receiver noise temperature is the noise temperature of the entire receiver chain including the pre-amplifier.

## D.  G/T vs. Antenna Diameter

The ground receiving terminal is described primarily in terms of the receiving antenna gain, G, and the receiving system noise temperature, $T_s$. The ground station figure of merit is defined as a ratio of the receiving antenna gain to receiving system noise temperature, $G/T$.[*]

The implementation of a certain G/T is a cost trade-off between antenna size and pre-amplifier complexity. Because the cost of the antenna increases with increasing antenna diameter and the cost of the pre-amplifier increases with decreasing equivalent noise temperature, a trade-off between these parameters can be carried out to five the minimum cost combination of antenna and pre-amplifier to meet a particular sensitivity requirement. It will be helpful in the determination of the minimum cost combination to construct general curves of antenna diameter vs. G/T for various probable system noise temperatures. These curves are shown in Fig. 1. Combinations of antenna diameter and system noise temperature whose costs are obviously non-minimum have not been included. Thus, each curve extends over only a small range of antenna diameter.

As may be inferred from Fig. 1, each value of G/T corresponds to a unique combination of G and T in a minimum cost, receive-only system. In a two-way system, one must simultaneously satisfy constraints of one receiver sensitivity and uplink EIRP. The determination of G, T, and P is slightly more complicated and will be deferred to Chapter V.

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[*]Some people use the ratio of $A_e/T$ as a figure of merit. Where $A_e$ is the effective area of the parabolic antenna. This figure of merit does not contain the receiving frequency as a parameter, thus a flux density in watts/m$^2$ may be employed to represent the source of signal strength.
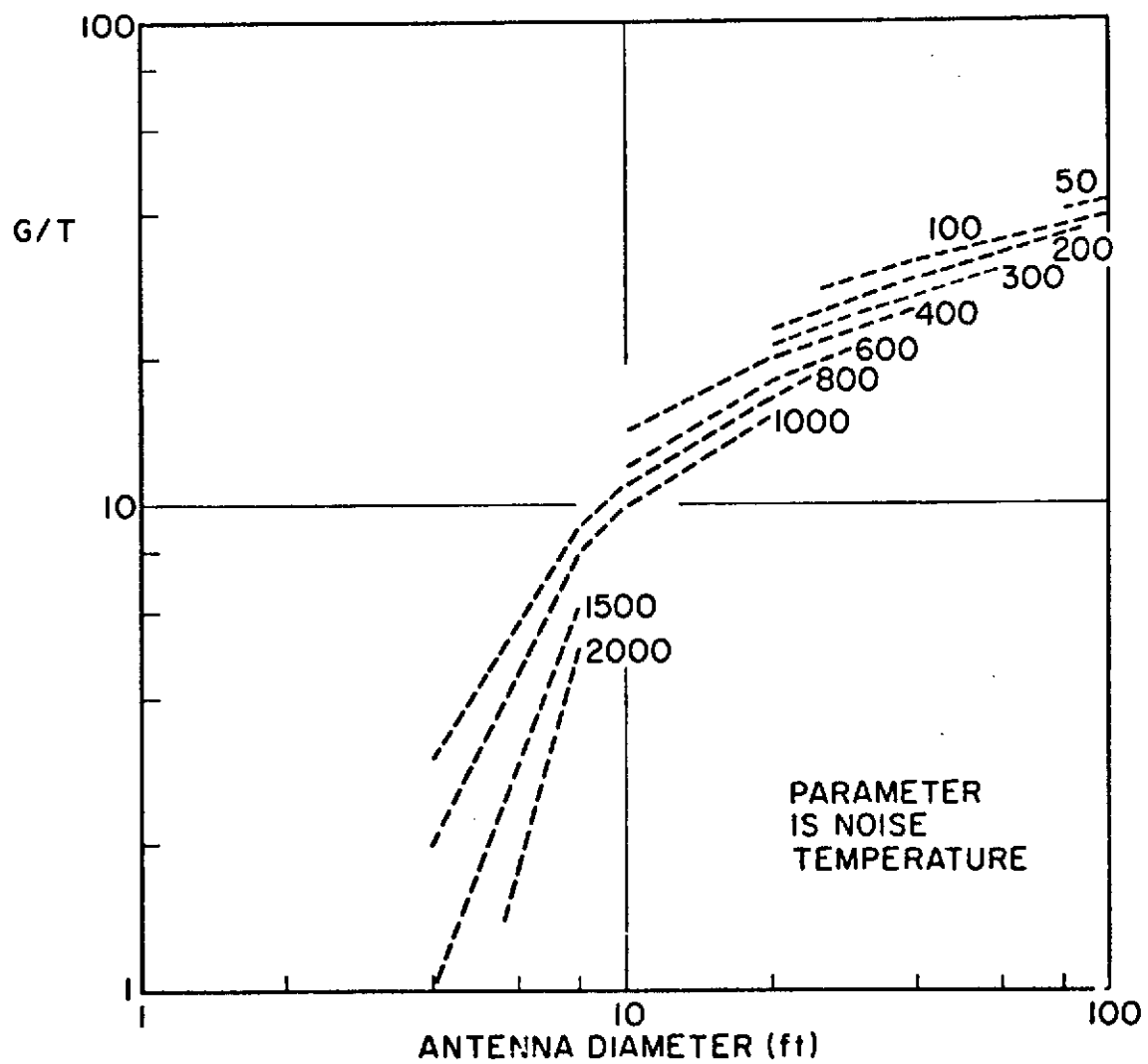
Figure 1: G/T vs. Antenna Diameter

E.  Cost vs. Antenna Diameter

The most significant variation in the cost of antennas is associated with the antenna diameter cost increases with increasing diameter.  Nevertheless, the cost also depends upon the type of antenna, the steering method, the mount to be adopted, the materials to be used and method of manufacturing, and the production quantity.  Following are the major alternatives of antenna design and construction which affect antenna cost.

Table 1:  Antenna Alternatives

1.  Antenna Type:                Direct Illuminate Parabola,
                                 Cassegrain,
                                 Casshorn

2.  Steering Method:             Fixed,
                                 Partially Steerable,
                                 Fully Steerable

3.  Mount:                       AZ-El,
                                 X-Y,
                                 HA-DEC*

4.  Material and Manufac-
        turing:                  Spun Aluminum,
                                 Flat Segmented Aluminum,
                                 Stamped Aluminum,
                                 Plastic

5.  Quantity:                    Single Unit,
                                 10 or more units

—————————————————
*

A survey of existing satellite communication antennas, sales catalogs and the literature was made to establish basic costs.  Fig. 2 is a plot of antenna cost as a function of antenna diameter for each antenna encountered in the survey.  Using this information, a smooth curve of antenna cost vs. antennna diameter was derived and is presented in Fig. 3. There are three segments to the curve:
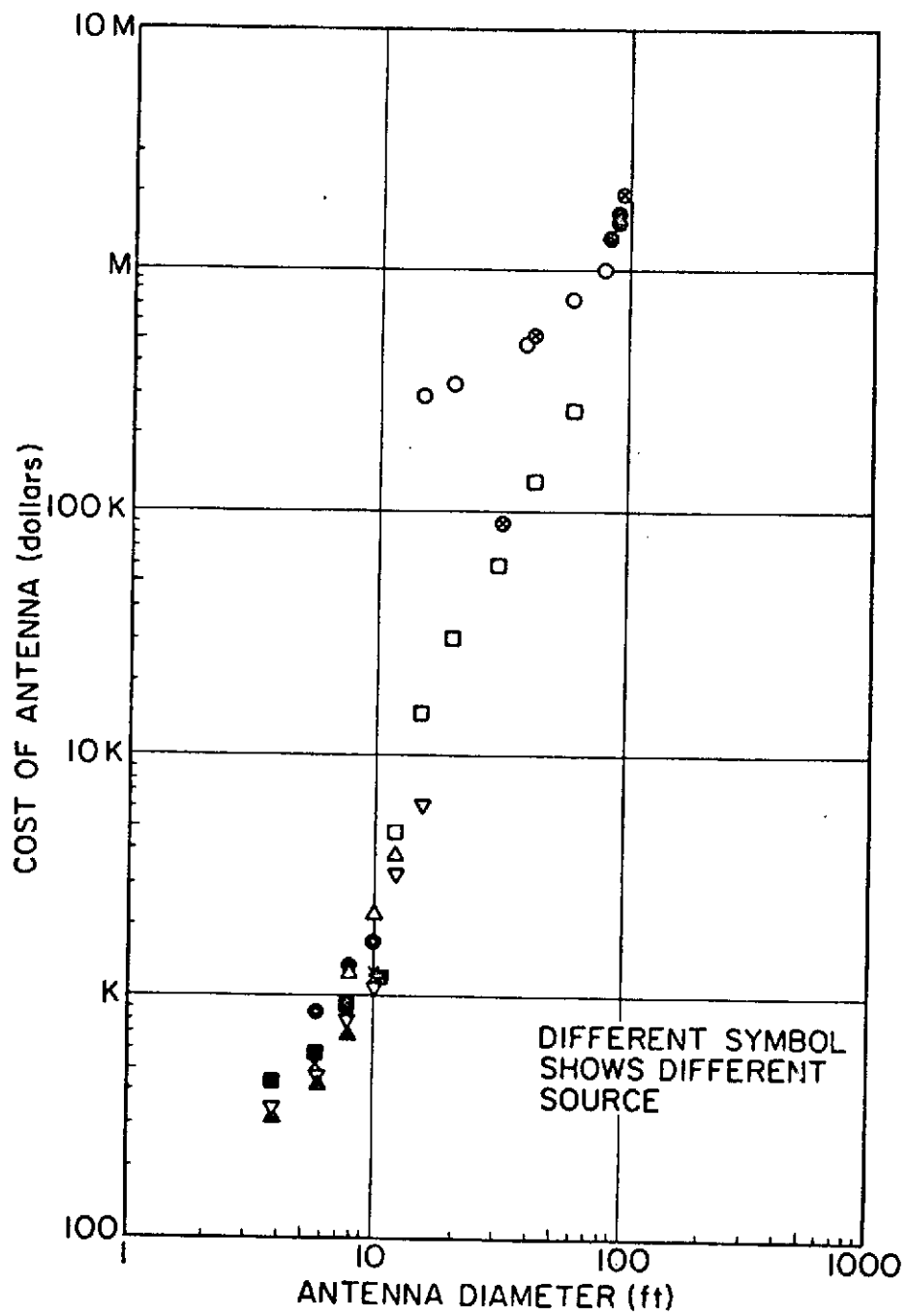
Figure 2: Cost vs. Antenna Diameter
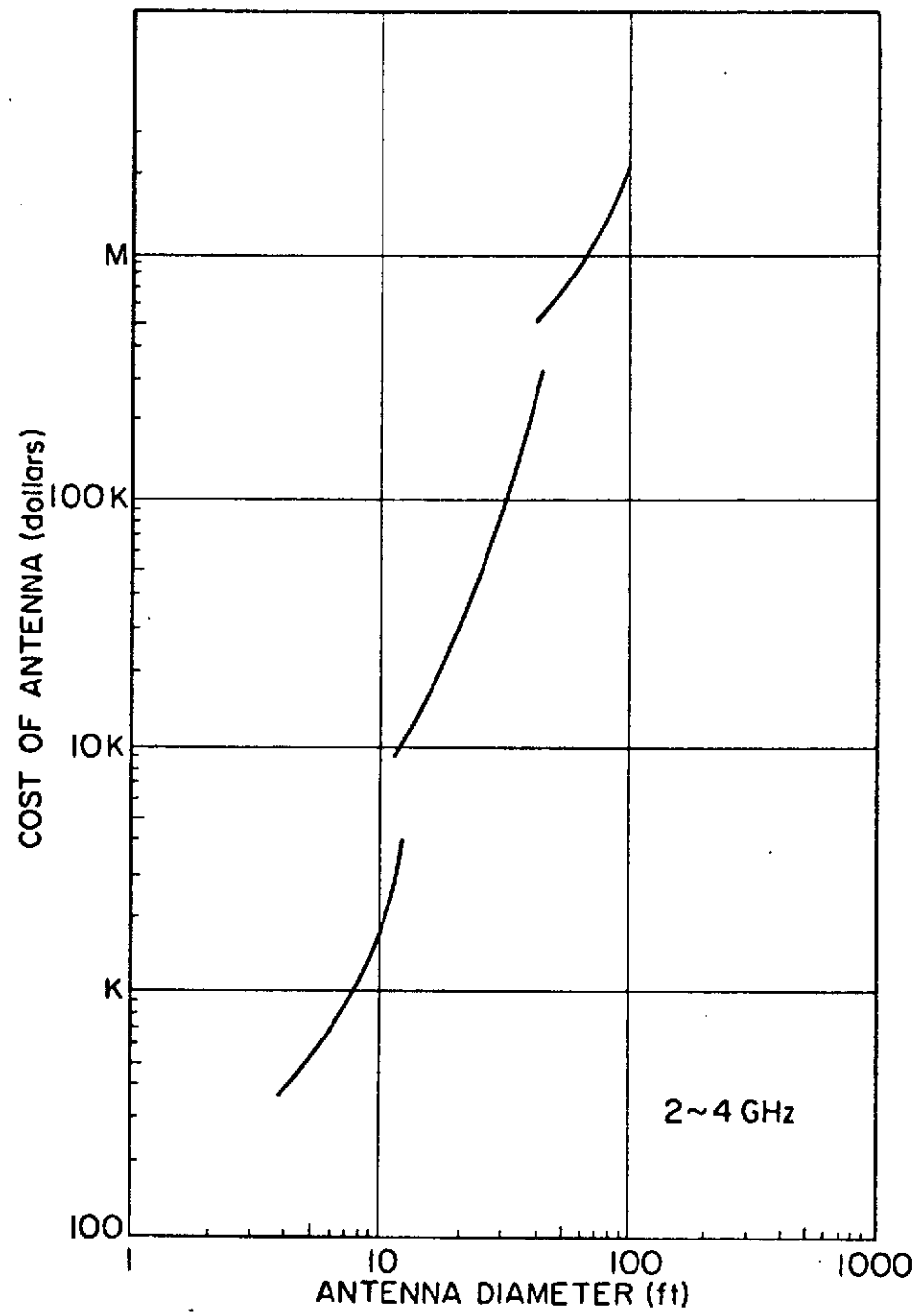
Figure 3: Cost vs. Antenna Diameter

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1)   The upper curve is associated with antennas larger than 40-feet diameter.  Generally speaking, these antennas will have tracking capability.  Therefore, a fully steerable capability is included in their cost.

2)   Antennas with diameters between 40-feet and 12-feet are associated with the middle curve.  They usually have a limited steering capability, which is included in their cost.

3)   The lower curve corresponds to antennas with diameters less than 12-feet.  This type of antenna is fixed and is commonly used for terrestrial microwave links.

The indicated costs are broadly applicable in the frequency range of 2 to 10 GHz.  The data show only slight distinction in cost between using the antenna for reception only or both reception and transmission. In fact, this cost difference is less than the cost difference for similar antennas made by different manufacturers.  It would appear that these costs are almost completely independent of the use of the antenna.

F.   Cost vs. Pre-amplifier Noise Temperature

In general, the cost of pre-amplifiers increases with decreasing equivalent input noise temperature.  Today in commercial satellite communication networks, cooled parametric amplifiers are commonly used.

Pre-amplifier alternatives are listed in Table 2.

Table 2:   Pre-amplifier Alternatives

| | Pre-amplifier Type | Noise Temperature ($^{\circ}$K) |
|---|---|---|
| 1. | Cooled Parametric Amplifier | 10- 80 |
| 2. | Uncooled Parametric Amplifier | 80- 250 |
| 3. | Transistor (or Tunnel Diode) | 300- 900 |
| 4. | Low Noise TWT | 900-1600 |
| 5. | Mixer Pre-amplifier | 1600-2000 |

Fig. 4 shows the data for cost of the pre-amplifier vs. noise temperature as obtained from the existing ground station pre-amplifiers, sales catalogs and the literature.  A smooth curve derived from this data is shown in Fig. 5.
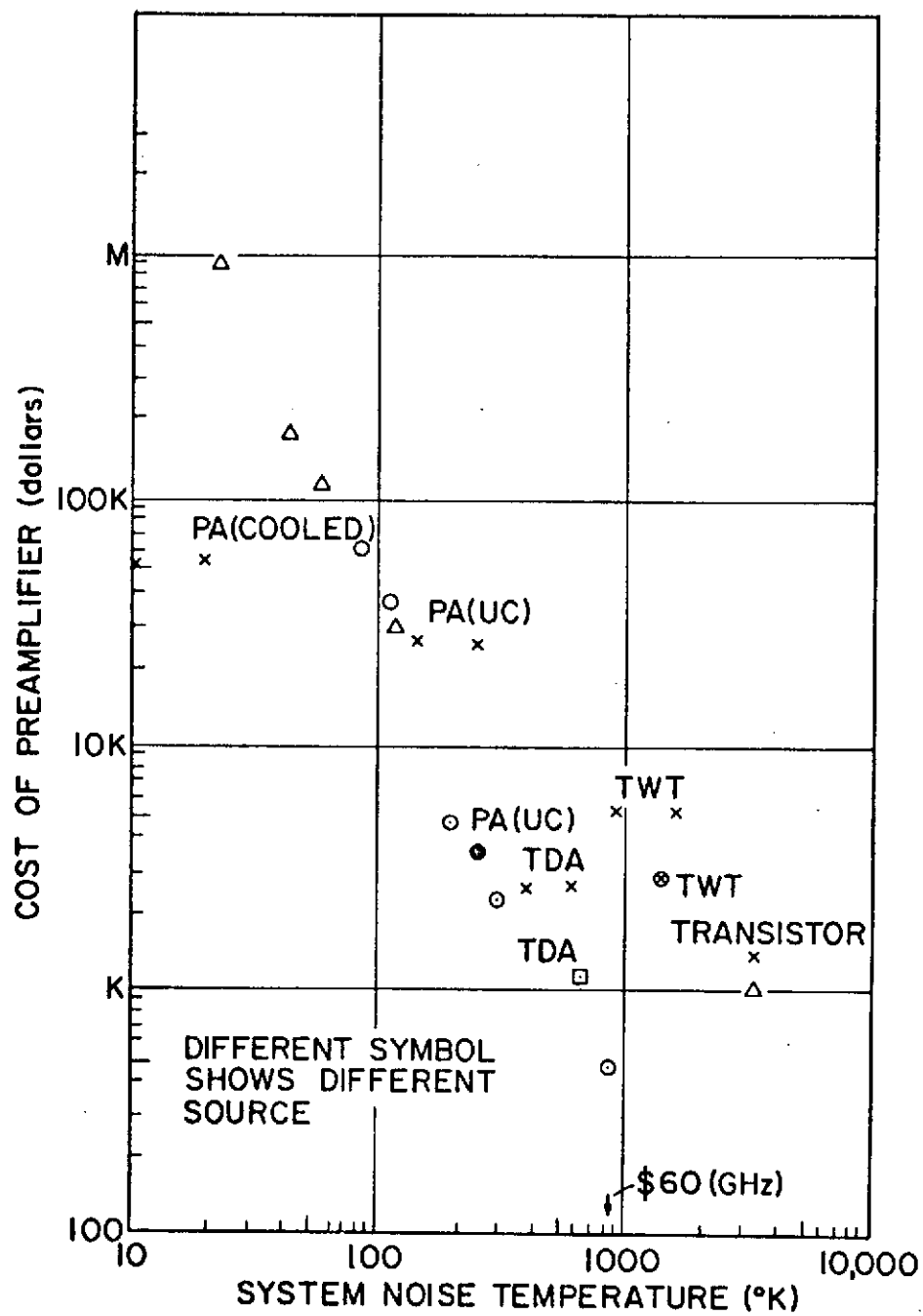
Figure 4:  Cost vs. System Noise Temperature
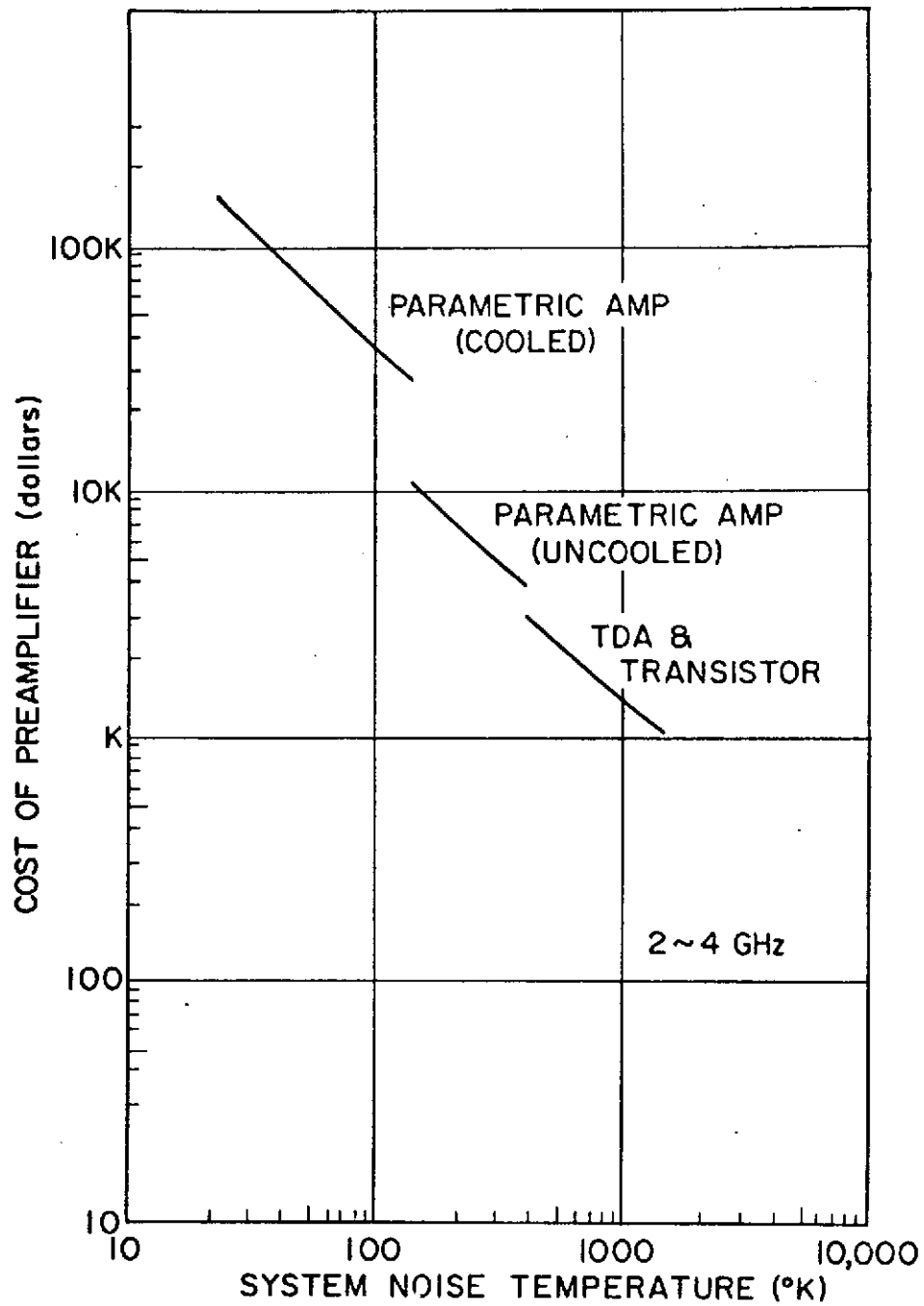
Figure 5:   Cost vs. System Noise Temperature

G.  Cost vs. G/T

The procedure for deriving the relation between cost and G/T is as follows:

1.  A G/T is selected.

2.  For this choice, there will be one or more curves on Fig. 1 which intersect the constant G/T lines.

3.  For each such point of intersection, there is a combination of $T_s$ and D.

4.  From Fig. 3 and Fig. 5 the cost of each combination is evaluated.

5.  The minimum cost combination is selected and $T_s$ and D plotted on Fig. 6.

Fig. 6 shows the least-cost combination of antenna and pre-amplifier vs. G/T as determined above. It will be noted that any G/T greater than 30 dB must use an antenna between 40-feet and 100-feet in diameter and a cooled parametric amplifier. For G/T between 30 dB and 5 dB, the antenna diameter may lie between 12-feet and 4-feet and should be combined with an uncooled parametric amplifier. G/T less than 15 dB may use an antenna of less than 12-feet in diameter with a mixer or transistor amplifier.


H.  Cost Savings for Mass Production

In order to estimate the cost savings resulting from mass production, learning curves have been introduced. The relation between the multi-unit cost and single-unit cost is given as follows:

$$\text{Cost} = \text{Single Unit Cost (Learning Curve \%)}^{\log_2 N}$$

A 90% learning curve is used to estimate the cost of both the antenna and the pre-amplifier. Fig. 7 and Fig. 8 show the cost of each with quantity produced appearing as a parameter.

Fig. 9 shows the relation between G/T and the cost of antenna and per-amplifier for the case of one and of 1000 units of production.


I.  EIRP vs. G/T

The ground station G/T can be reduced by choosing a larger satellite EIRP. This is an important economic trade-off and will be affected by
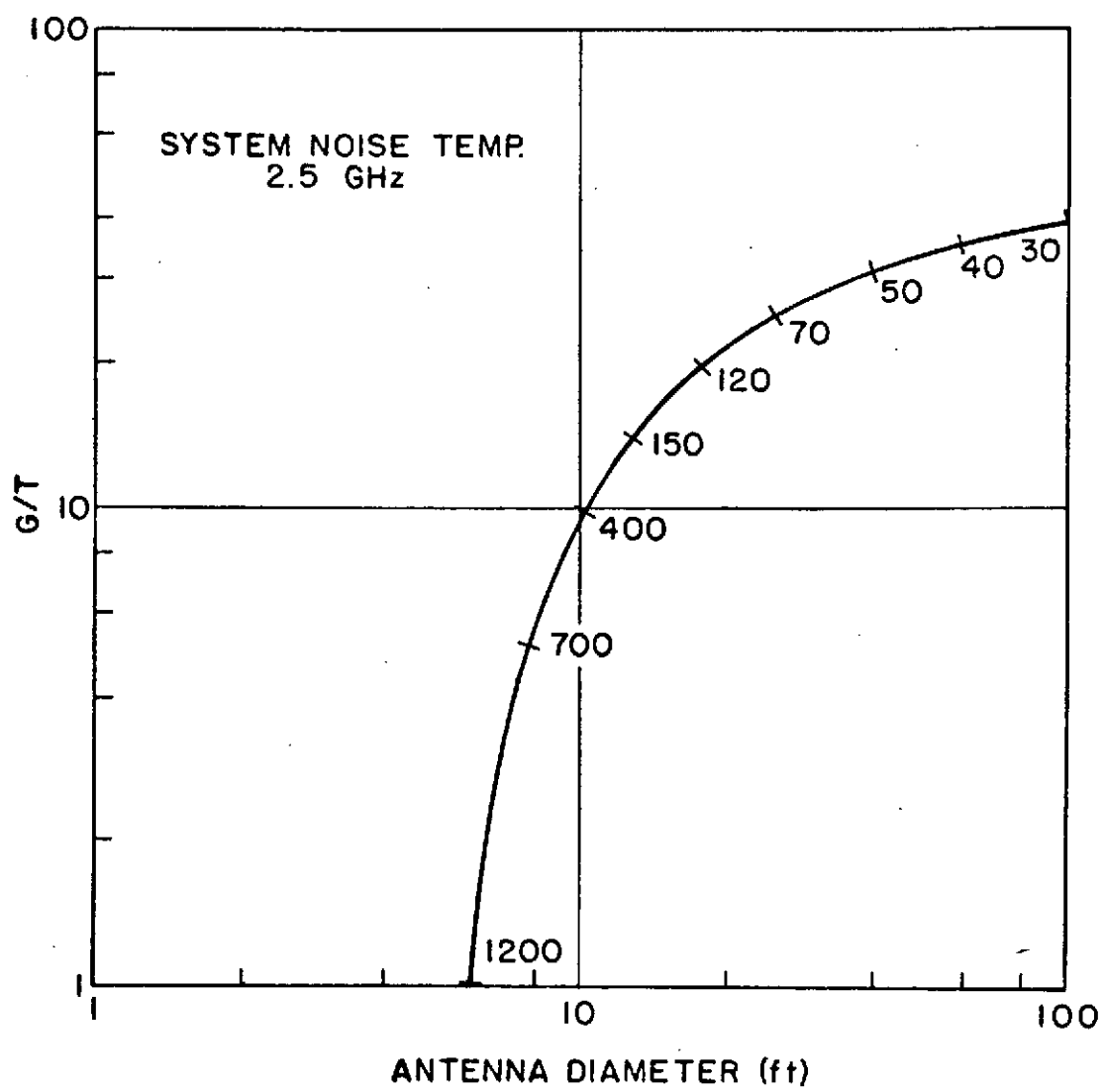
Figure 6: Antenna Diameter vs. G/T Which Gives A
Minimum Cost Combination of Antenna and Pre-Amp.
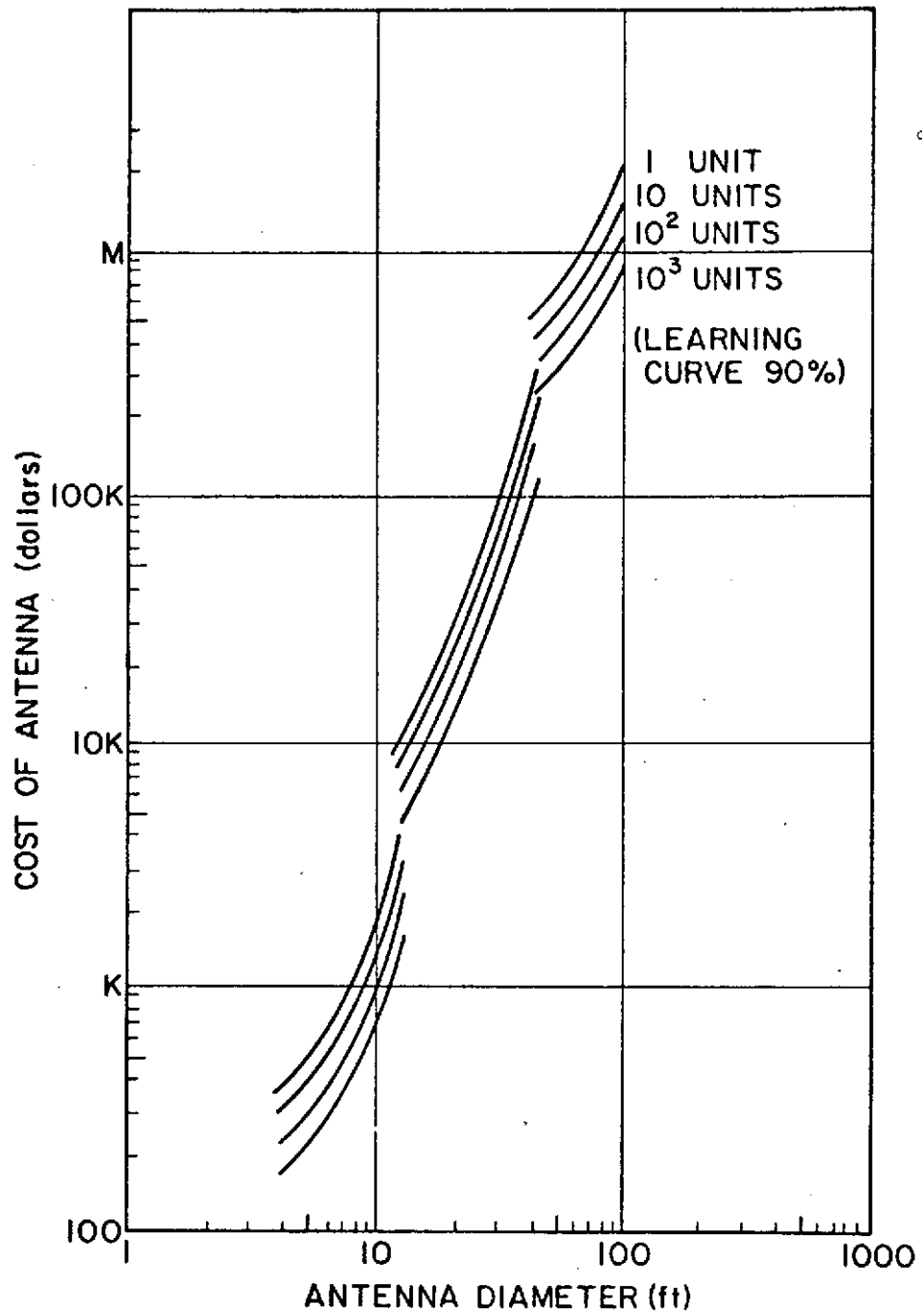
Figure 7: Cost vs. Antenna Diameter
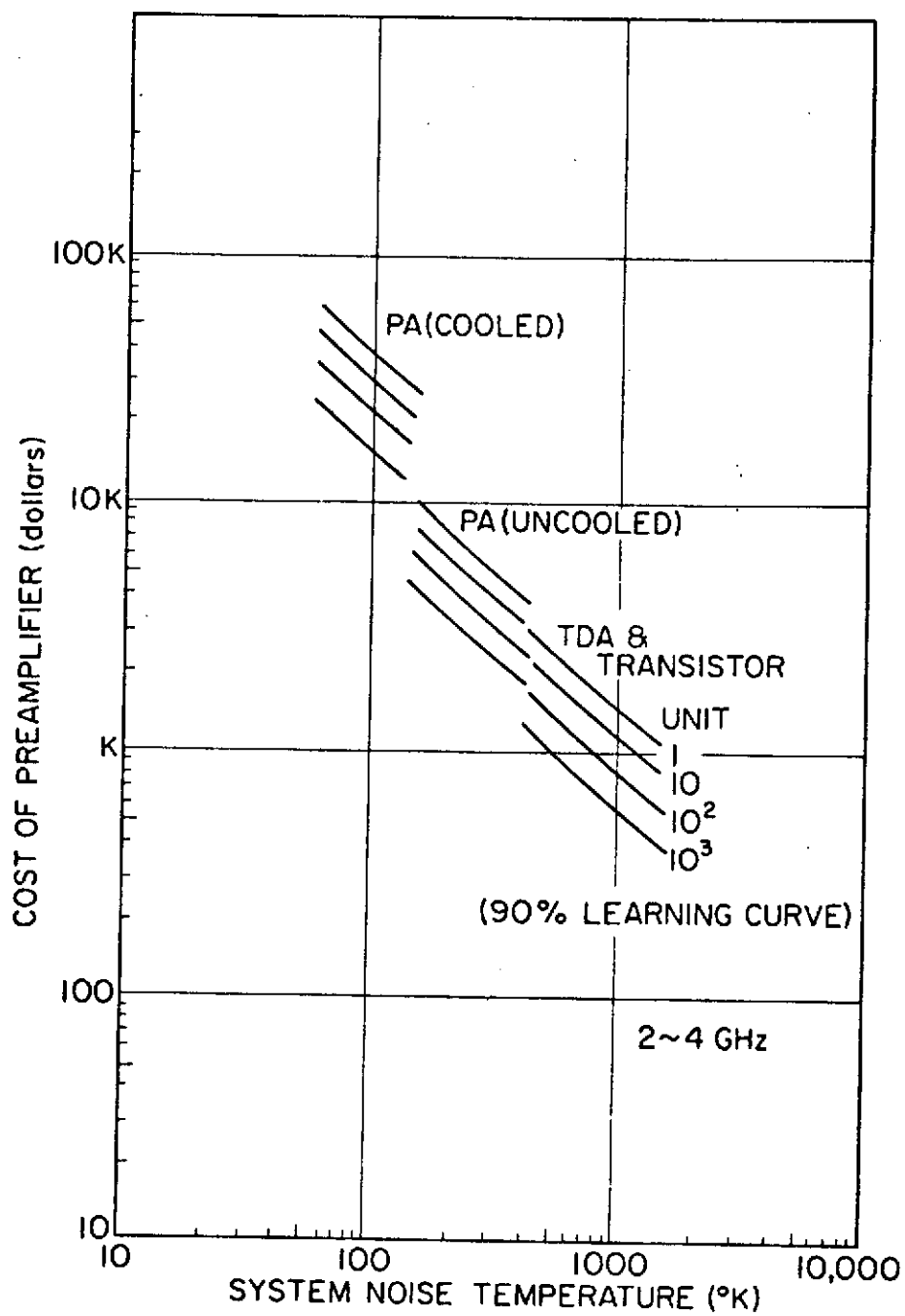
Figure 8: Cost vs. System Noise Temperature
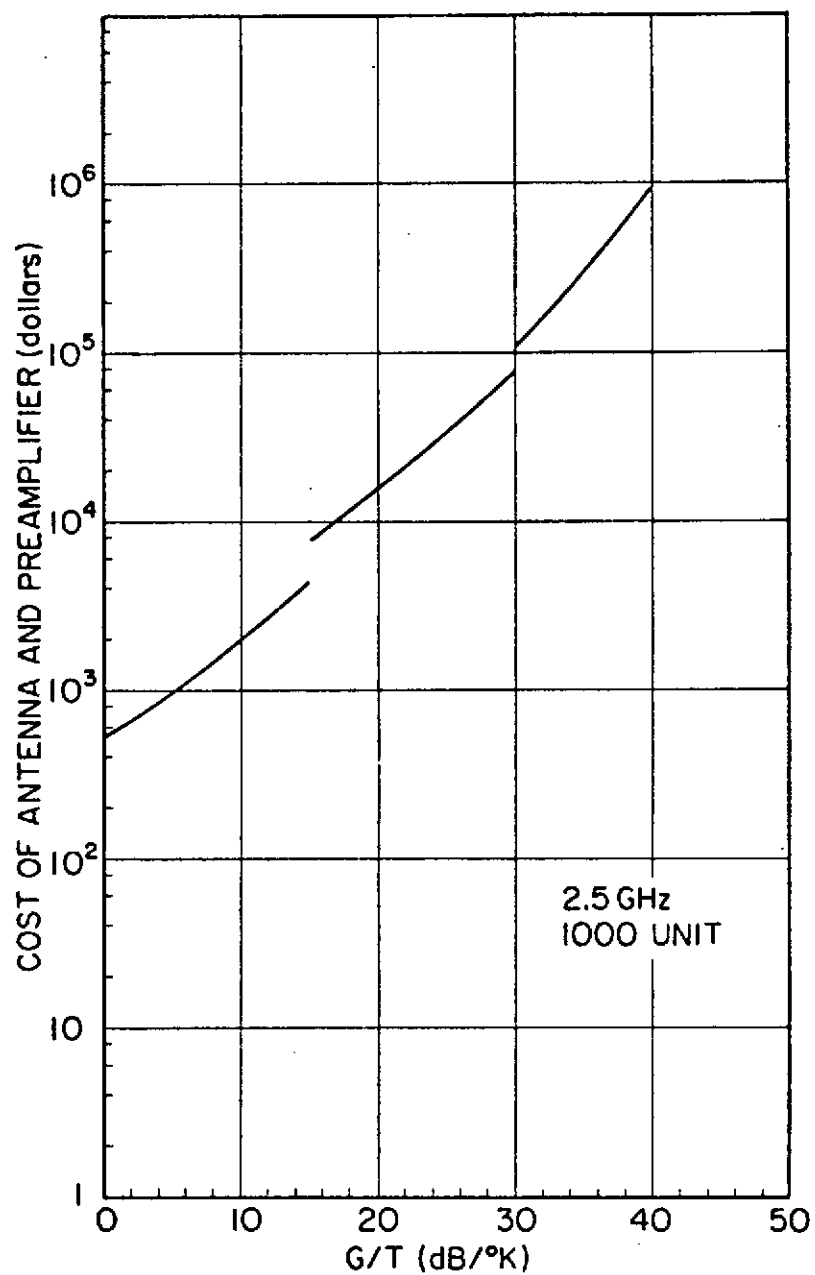
Figure 9: Cost of Antenna and Pre-Amplifier vs. G/T

the number of receiving stations and the relative importance attached to the complexity and cost of the space segment vs. the earth segment. Thus, the satellite communication system cost can be minimized by trade-offs between ground station antenna size and satellite EIRP for a given frequency.

It seems that the future trend will be toward the use of higher EIRP satellites with larger numbers of ground stations having correspondingly reduced cost.

The per-channel EIRP required for a link is given by:

$$EIRP = C/T + L_p + L_m + M - (G/T)_e$$

where

$\quad$ EIRP $\quad$ : $\quad$ Satellite effective isotropic radiated power

$\quad$ C/T $\quad$ : $\quad$ Carrier-power to system noise temperature ratio

$\quad$ $L_p$ $\quad$ : $\quad$ Path loss in the link

$\quad$ $L_m$ $\quad$ : $\quad$ Miscellaneous losses in the link

$\quad$ M $\quad$ : $\quad$ Desired operating margin

$\quad$ $(G/T)_e$ $\quad$ : $\quad$ Antenna gain to system noise temperature ratio at the earth-station receiver input

Fig. 10 shows a curve of EIRP vs. G/T with C/T as a parameter for a ground-station antenna elevation of 10 degrees at 2.5 GHz. It was assumed that $L_m$ = 1.5 dB, and M = 2.5 dB. The ratio C/T is determined by the nature and quality of the desired signal. Values of interest range from C/T = -190 dBW/°K for a low bit rate data channel to C/T = -140 dBW/°K for a high quality TV channel. This relation is important, essentially determining the satellite and earth terminal configuration.

## J. Cost vs. Transmitter Power

The cost of power amplifiers changes depending upon the output power and bandwidth, the type of amplifier, the number of carriers to be transmitted, etc. Generally speaking, the cost increases with increasing output power. The power amplifier alternatives are listed in Table 3.
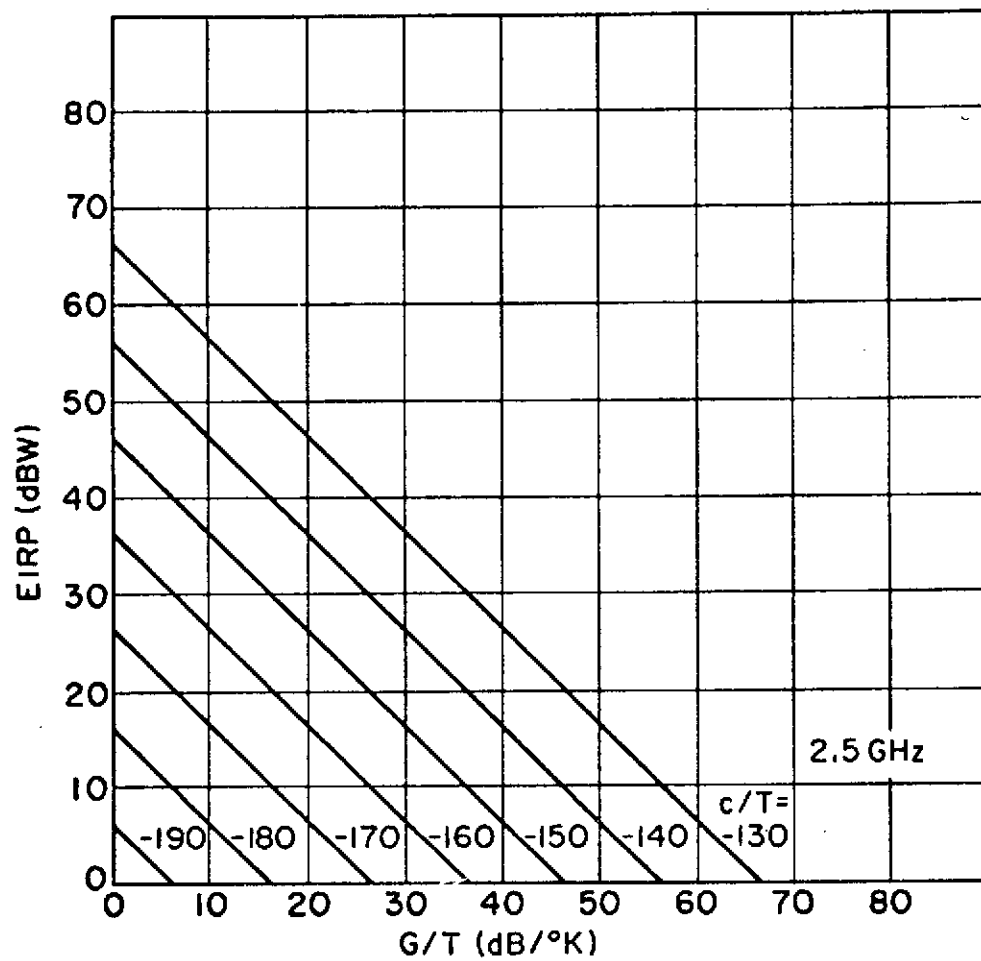
Figure 10: EIRP vs. G/T for given C/T

Table 3: Power Amplifier Alternatives

| Power Amp. Type | Output Power | Bandwidth |
|---|---|---|
| Klystron | High | Narrow |
| Traveling Wave Tube | Medium | Wide |
| Transistor | Low | Wide |

Fig. 11 is a plot of power amplifier cost encountered in the survey as a function of their out power. A smooth curve of cost vs. output power is presented in Fig. 12.

## K. Installation Cost

The installation costs consists of shipping charges and labor costs for equipment installation, a power plant, water supply facilities, grading road construction.

Installation, material, and labor range from 15 to 30 percent of the equipment cost depending on the size and importance of the station, the provision of standby equipment, and the availability of any existing power supply. Considering stations of small channel capacity, the maximum station demand will be 10 to 50 KVA, while medium and large traffic capacity station will demand in the range of 200 to 500 KVA. Main power is typically purchased from a commercial supplier with standby power provided by one or more diesel-generator sets.

Commercial power lines may cost from $10,000 to $20,000. Standby power supplies will range from 8 to 15 percent of total hardware cost.

When the system is installed in relatively inaccessible or remote locations, the installation cost, of course, increases. It is assumed that the installation cost, including only material and labor, is 15 percent of equipment cost for small antennas, 20 percent for medium size antennas, 30 percent for large antennas, and 15 percent for other equipment. Power provision, water supply facilities and their installation and road construction costs are assumed to be 15 percent of the initial capital investment.

The cost of power provision, water supply and road construction is shown in Fig. 13. Fig. 14 shows the cost vs. G/T including installation.
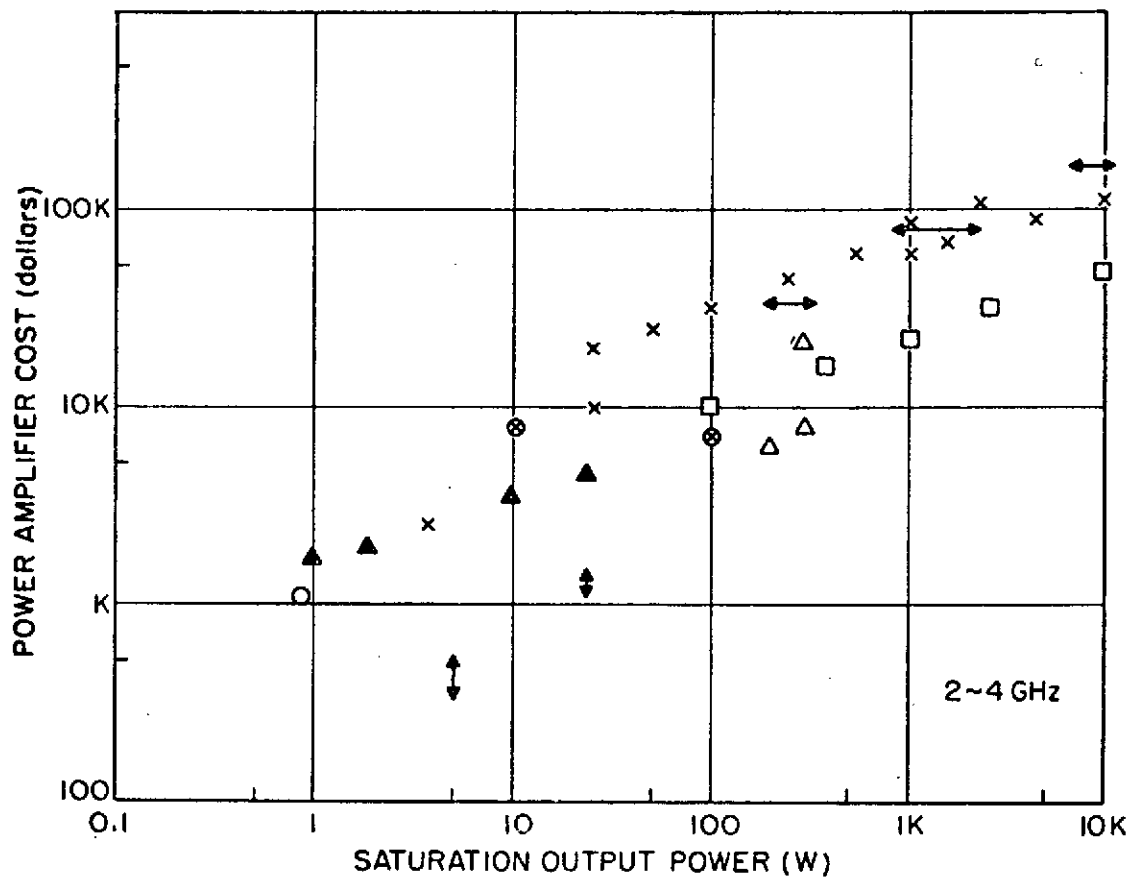
Figure 11: Power Amplifier Cost vs. Output Power
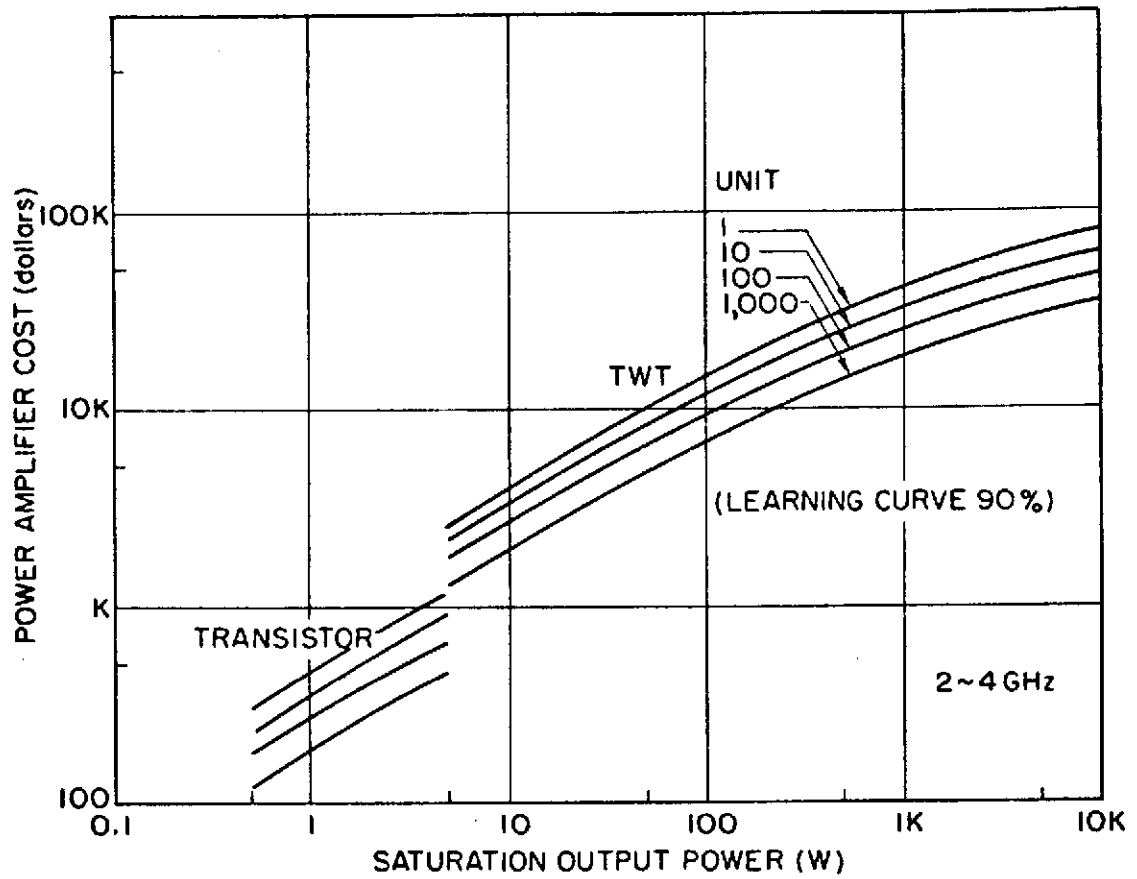
Figure 12: Power Amplifier Cost vs. Output Power
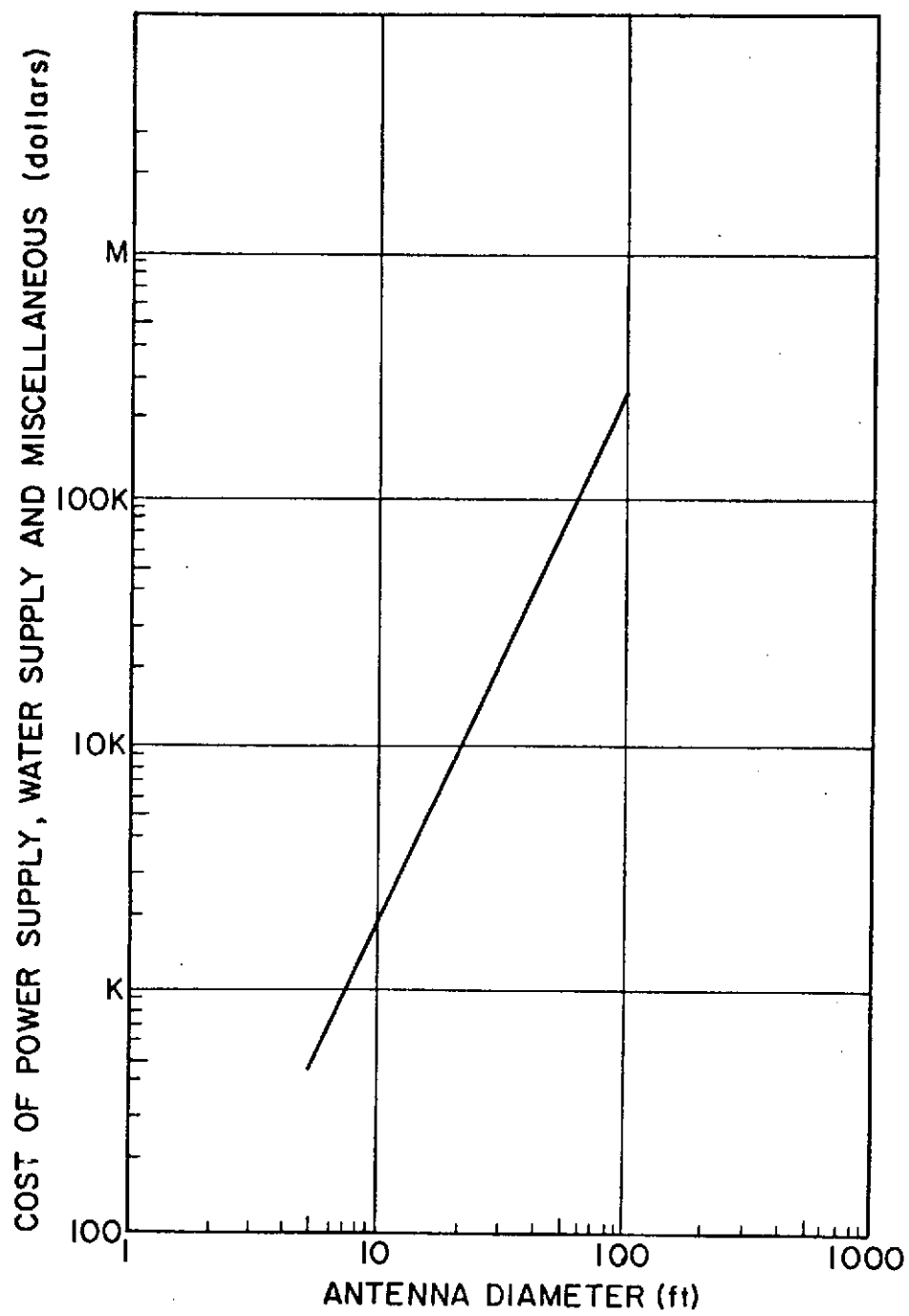
Figure 13:  Cost of Power Supply,
Water Supply and Miscellaneous

III-21
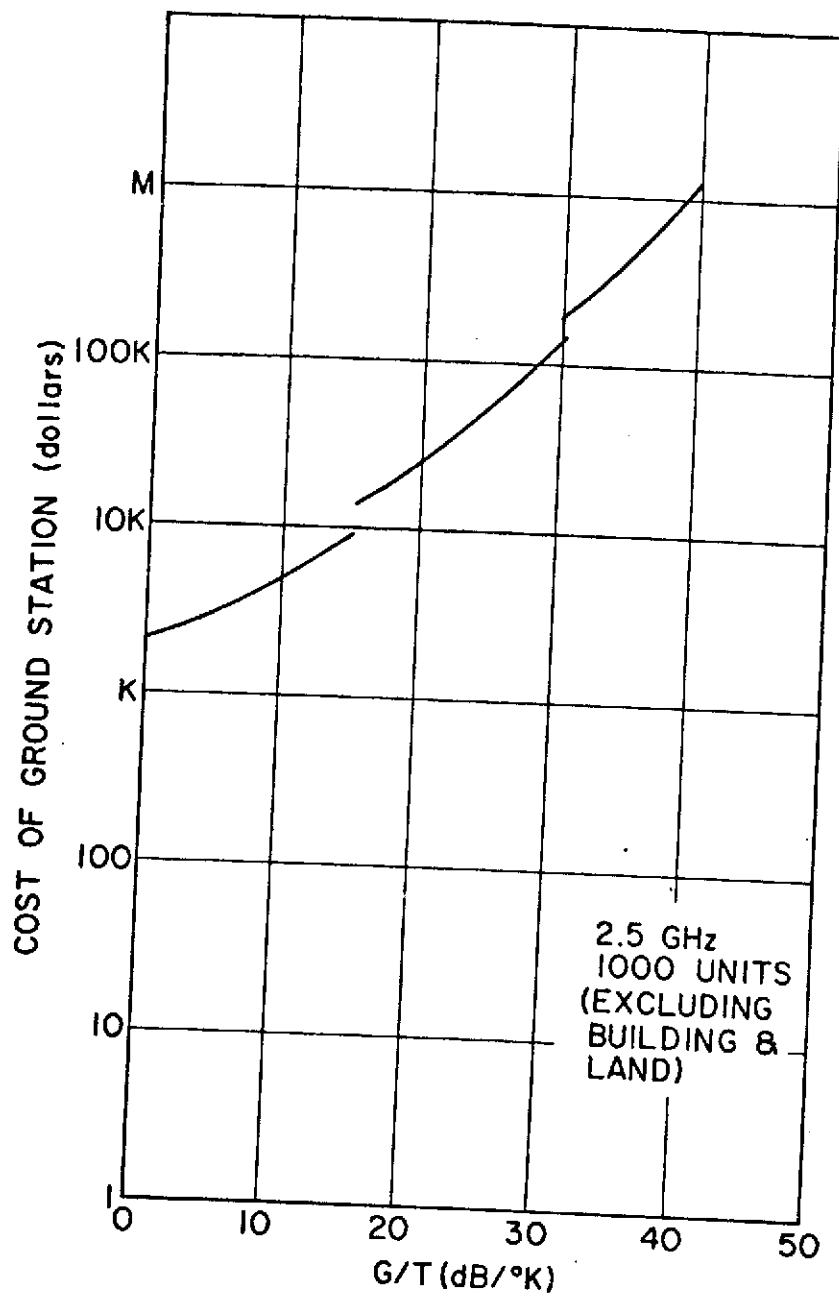
Figure 14:  Ground Station Cost vs. G/T

L. Maintenance and Operation Costs

Although equipment costs vary to some extent, greater variations are observed in maintenance and operation costs and in installation costs. These annual costs typically range from 5 to 15 percent of initial equipment cost. Maintenance and operation costs[*] as given in this section include expenditures for the following items:

1. Wages of operating and maintenance personnel.
2. Replacement parts
3. Test equipment
4. Power, water, utility, etc.
5. Taxes

The annual O and M costs of an antenna equal approximately 5 percent of its initial cost for small antennas, 7.5 percent for medium size antennas with partial steering capability, and 15 percent for large antenna with full steering capability. The O and M costs of pre-amplifiers vary depending on the type of pre-amplifiers. Although transistor amplifiers and tunnel diode amplifiers require little realignment, parametric amplifiers need frequent adjustment. Cooled parametric amplifiers need a high level of maintenance. The annual O and M cost of a cooled parametric amplifier is approximately 25 percent of its initial cost, at at least half of which is for maintenance. The O and M cost of an uncooled parametric amplifier is approximately 15 percent of initial cost. A tunnel diode amplifier and a transistor amplifier require O and M costs of less than 5 percent of initial cost.

The O and M costs of power amplifiers is 20 percent of initial cost for high-power tubes and 5 percent for small tubes. These costs include the costs of power consumption and (frequent) tube replacement.

It is assumed that the O and M costs of the other miscellaneous items of equipment are 10 percent of the initial cost.

Figures 15, 16, and 17 show the O and M costs of antennas as a function of antenna diameter, the O and M costs of pre-amplifiers as a function of system noise temperature, and the O and M cost of power amplifiers as a function of output power. These are reasonable estimates under easy maintenance conditions.

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[*] We will use abbreviation "O and M" in this report.
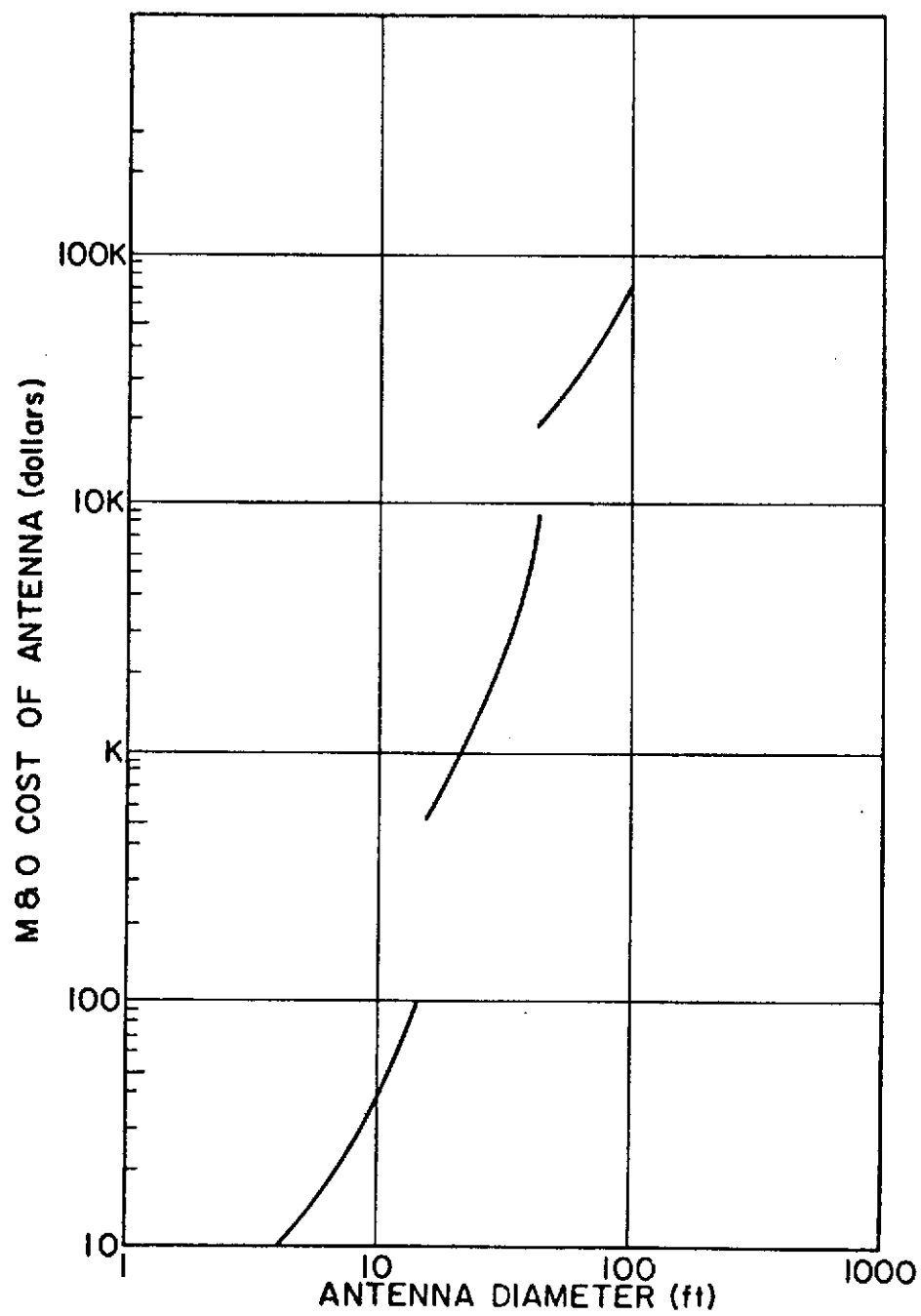
Figure 15: M & O Cost of Antenna
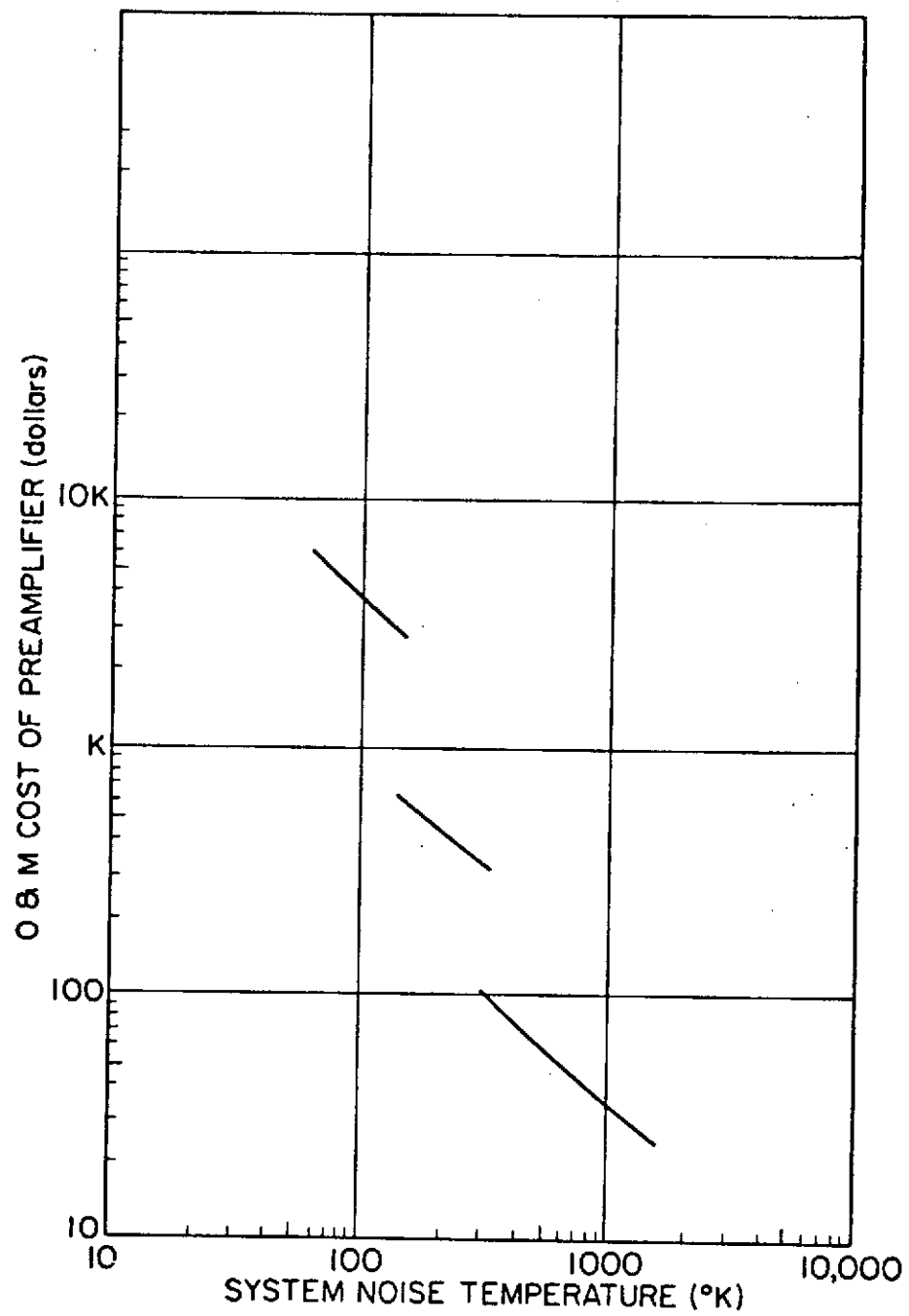
Figure 16:   O & M Cost of Pre-Amplifier
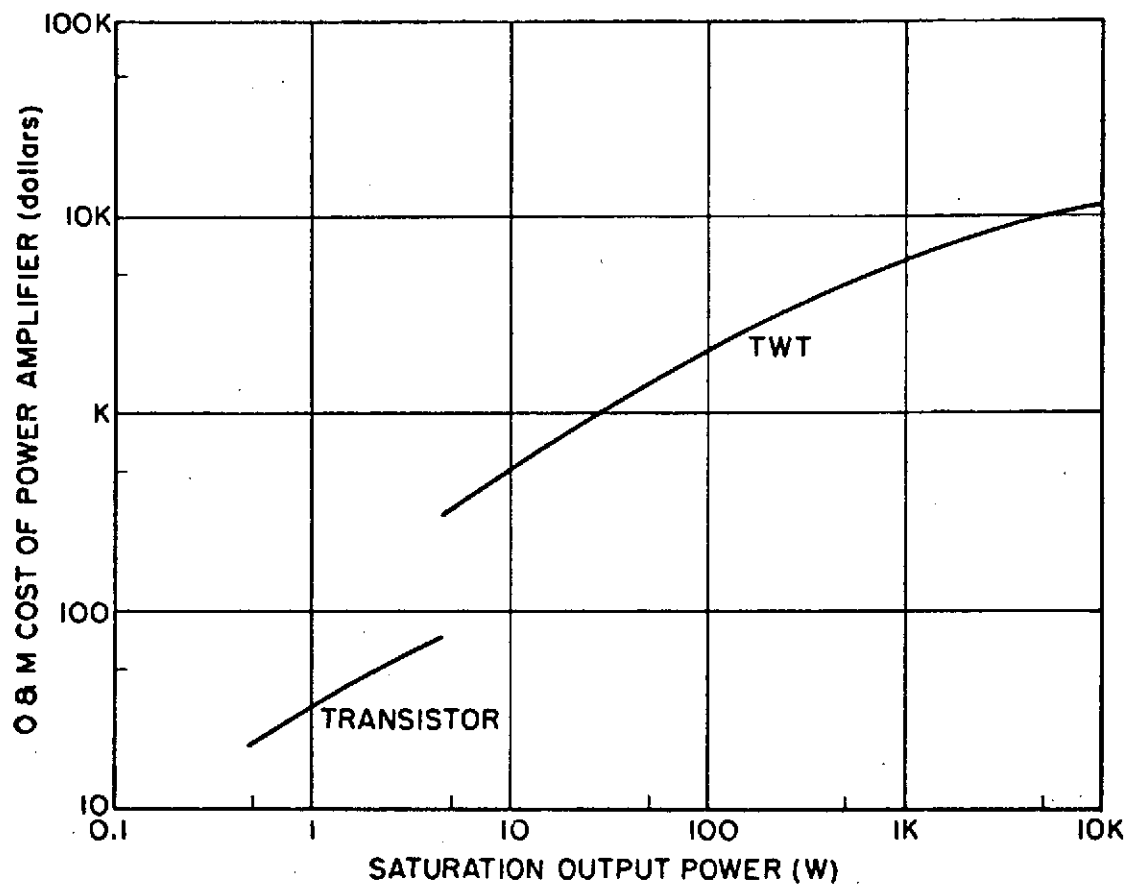
Figure 17:   O & M Cost of Power Amplifier

M.   Site and Building Costs

The site and building costs depend on the location and increase with increasing antenna diameter. A typical cost of buildings for tele-communications stations is approximately $20 per square foot. The cost of land ranges from $5,000 to $50,000 depending on the location.

It is estimated that a small station needs 100 to 500 square feet of building and 0.02 to 0.05 acres of land. Also, it is estimated that a large station needs 10,000 to 20,000 square feet of building and 2 to 5 acrea of land. Fig. 18 shows the cost of the building as a function of antenna diameter. Fig. 19 shows the site cost as a function of an-tenna diameter.
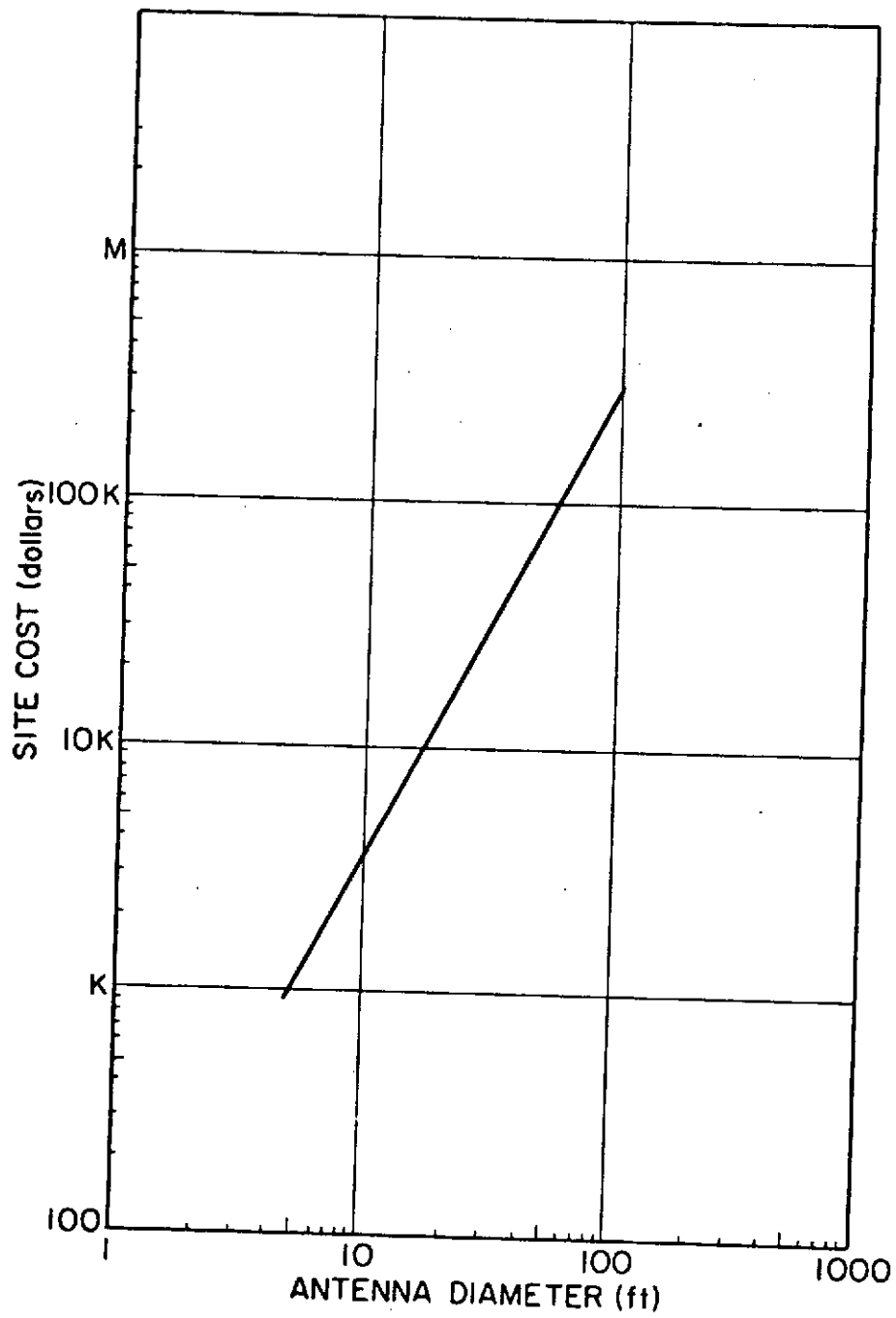
Figure 18:   Building Cost of Ground Station
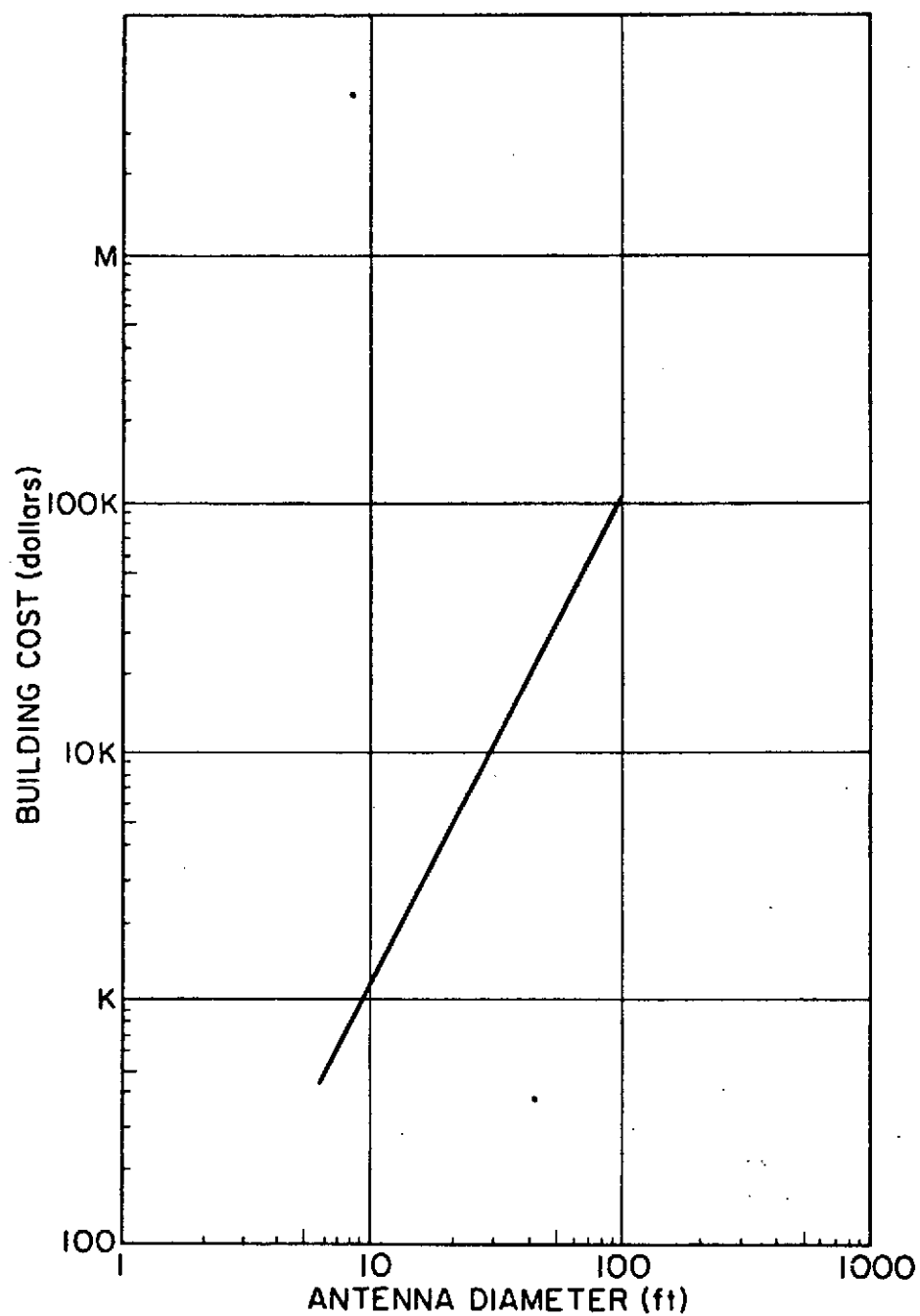
Figure 19: Site Cost of Ground Station

N. Conclusion

We have developed the satellite communication ground station costs from a survey of existing ground stations, sales catalogs, and literature. Using this basic cost information, smooth curves of cost vs. antenna diameter, cost vs. system noise temperature, and cost vs. transmitter output power were derived. The figures presented make no attempt to predict cost reductions that may occur in the future as a result of improved technology or novel mass-produced designs. Rather, they reflect the cost of presently available commercial equipment.

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12. Standard Industrial Survey Report, Jan. 1970.

CHAPTER IV

SATELLITE SEGMENT COSTS

A. Introduction

Since the teleconferencing systems we are considering have a large
number of remote ground stations, minimizing the total space-segment
cost implies that these stations be inexpensive - hence of low sensitivi-
ty. Under these conditions, the system is "power-limited" so that, for
a given area of coverage, total satellite RF power* is the scarce resource
of the space segment. We wish to estimate the lowest reasonable cost
of this resource: i.e., <u>the annual cost per RF Watt.</u>

One approach to this problem is to fit a curve to historical data.
Between the data points, a cost model can be employed to generate a con-
tinuous function of cost/watt vs. total watts. Such models are based on
the fact that the cost of a satellite in orbit is primarily determined by
its weight, which in turn is highly correlated with its total RF power.[1]

But such a trend approach is not realistic for our application since
we are interested only in contemporary (or near-future) system components.
Instead, we shall examine a contemporary "shopping list" of satellites;
and the launch stream of each needed to satisfy a given demand growth.
We posit three types of demand functions (constant, linear, and a com-
bination of both); and two spare-backup strategies (orbit spare and
ground spare). For each case, we then calculate the present value of the
required investment stream as a function of the discount rate. Finally,
we compute the annual cost (or price) which must be charged to recover
the invested capital. We will choose that launch stream which has the
lowest annual cost per RF Watt.

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*We assume that this total power can be partitioned into as many trans-
ponders as desired--bounded, of course, by FCC and CCIR bandwidth re-
straints. We determine the power per teleconferencing transponder by
minimizing total system cost for a given number of teleconferencing
transponders (say, 4). If the resulting total teleconferencing RF
power is less than the total satellite power, we assume that the sur-
plus will be channeled into additional transponders and sold to other
markets (i.e., non-dedicated use).

B. Methodology

Many of the satellites now in orbit or proposed for near-future launch are possible candidates for teleconferencing use - either as configured now, or as reconfigured appropriately vis-à-vis beam coverage and frequencies. Table 1[ω] is a representative listing of these candidates. Also given (see last column) is the per-watt investment, assuming one in-orbit satellite, for each case.

These data alone might suffice for a rudimentary analysis. But a more accurate assessment of space segment costs must include the effects of

(1) Supply and demand time-profiles

(2) Economies of scale

(3) The time value of money

(4) Gracefulness of system degradation

(5) Reliability (failure rate)

(6) Flexibility to changing demands and technology.

The analysis which follows treats (1), (2), (3), explicitly; and develops a general methodology for treating the effects of (4), (5), and (6). Three demand models are developed. Then the launch-stream investment necessary to meet these demands is calculated on a present-value basis. This is done for several discount rates and for two system "back-up" strategies. Finally, annual cost-per-watt is computed as the zero profit price an entity (presumably, the satellite owner) would charge to recover its invested capital for a given demand growth.

1. Three Candidate Satellites: Small, Medium and Large

To keep the analysis within bounds, our shopping list must be culled. We desire comtemporary satellite designs either already suited for teleconferencing use, or easily modified. Moreover, we would like to examine cases which span

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[ω]Data sources include References 2, 3, 4, 5, and 6.

# TABLE 1: SATELLITE ATTRIBUTES AND COSTS

| Satellite | Weight (lbs.) in-orbit | Weight (lbs.) pad | Launch Vehicle | Total RF Power | Frequency Bands [4] | Satellite Supplier [6] | Number of Transponders | Transponder Bandwidth (MHz) [7] | Total Bandwidth (MHz) [7] | Prime Power (D.C. watts) | Design Life (years) | Contemporary? | Launch Costs [8] First | Launch Costs Subsequent | Satellite Costs First | Satellite Costs Subsequent | Development Costs | TT&C Costs [9] | Total Investment Total [12] | Total Investment Per Watt |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| INTELSAT I | 85 | 150 | Thrust-Augmented Delta | – | C | Hughes | 2 | (15) | 30 | – | 1.5 | | 3.3 | 3.3 | 7.4 | 3.6 | n.a. | – | 10.7 | – |
| II | 160 | 357 | | 18 | C | Hughes | 1 | 130 | 130 | – | 3 | | 3.5 | 3.5 | 4.1 | 3.5 | n.a. | – | 7.6 | .423 |
| III | 290 | 647 | | 20 | C | TRW | 2 | 225 | 450 | – | 6 | | 5.1 | 5.1 | 4.0 | 4.5 | n.a. | – | 9.1 | .455 |
| HS-333: TELSAT | 510 | 1206 | Thor Delta MGT | 50 [10] | | | | | | | | ✓ | | | 8 | 8 | Included | – | 15.0 | .300 |
| TELSAT – Alaska | 510 | 1206 | | 50 [10] | {C} | {Hughes} | {12} | {36} | {432} | {220} | {7} | ✓ | {7} | {7} | 8 | 8 | 2 | – | 17.0 | .340 |
| Hughes [D] | 453 | 1120 | Thor Delta MGT | 60 | | | | | | | | ✓ | | | 8 [10] | 8 [10] | {Included} | | 13.0 | .216 |
| Western Union [D] | 510 | – | Thor Delta MGT | 60 | | | | | | | | ✓ | | | 8 [11] | 8 [11] | | | 13.0 | .216 |
| HS-336 | 598 | 1560 | Thor Delta Upgrade | 88 | S | Hughes | – | – | 190 | – | ~10 | ✓ | 7 | 7 | 6.3 | (6.3) | (8.4) | (.9) | 21.7 | .247 |
| RCA [D] [1] | 838 | 1412 | Thor Delta 904 | 60 | C | RCA | 12 | 36 | 432 | ~305 | 7 | ✓ | 7.3 | 7.3 | 3.6 | 3.6 | 14.8 | 1.2 | 25.7 | .429 |
| WTCI [D] | 663 | 1446 | Thor Delta 2914 | 60 | C,K | N.A.R. | 12 | 36 | 432 | – | 7 | ✓ | 7.5 | 7.5 | 8 | 8 | 15 | .6 | 28.5 | .475 |
| ATS – 1 | 775 | – | Atlas Agena D | 16 | {C} | {Hughes} | {3} | 2 | 25 | 50 | – | | { | | | | n.a. | | | |
| – 3 | 798 | – | | 32 | | | | 2 | 25 | 50 | – | | | | | | | | | |
| INTELSAT IV | 1223 | 3055 | Atlas Centaur | 120 | C | Hughes | 12 | 36 | 432 | – | 7 | ✓ | 16. | 16 | 12 | 10 | (9) | – | 37.0 | .309 |
| COMSAT [D] | 1650 | 3100 | Atlas Centaur | 89 | C | – | 24 | 36 | 816 | ~340 | 7.75 | ✓ | 17.9 | 17.9 | 13.5 | 13.5 | 13.9 | 2.7 | 45.3 | .509 |
| ATS – F [e] | ~1900 | 2600 | Titan IIIC | 15 | V,S,C,M | – | – | – | – | – | 2.5 | ✓ | { | | | | n.a. | | | |
| – G [e] | – | – | – | ~200 | | F-M | – | – | – | 750 [3] | 7 | | 25.7 | 25.7 | 14.7 | 14.7 | 16.6 | | | |
| Fairchild-Hiller [D] [e] | ~2600 | 2903 | Titan IIIC Uprate | 95 | S,C,K [5] | F-M | 120 | 36 | – | 750 | 7 | ✓ | 25.7 | 25.7 | 14.7 | 14.7 | 16.6 | 5.3 | 67.0 | .6 |
| MCI – Lockheed [D] [e] | 3900 | – | Titan IIID Agena | 672 | C,K | Lockheed | 48 | 36 | 1728 | 4400 | 10 | ✓ | 22.8 | 21.7 | 20.6 | 20.6 | 30.3 | 1.5 | 73.6 | .109 |

NOTES:
n.a. – not applicable
– – unknown
[D] – Domestic filings
[e] – 3-axis stabilized
[1] – Spin-stabilized option (similar to HS-333)
[2] – Approximate: same weights apply after apogee motor fire and are higher than final in-orbit weights
[3] – End-of-life total RF power

[4] – V = VHF; S = 2.5 GHz; C = 4/6 GHz; K = 12/13 GHz; M = millimeter
[5] – 7/13 GHz used instead of 12/13 GHz
[6] – F-M is Fairchild Hiller; N.A.R. is North American Rockwell
[7] – Useable (~ –1 dB) bandwidth
[8] – Includes range support

( ) – approximate (deduced)

[9] – For two or more active satellites
[10] – Assumed to be the same as Western Union
[11] – Western Union will pay Hughes $47.725 m for 5 satellites and 3 launches; or about $26.7 m for 5 Hughes satellites, including development and TT&C costs.
[12] – Includes development costs; excludes TT&C costs.

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extremes in total RF power. With these criteria in mind, the field can
be narrowed to three[1]:

| Size | Satellite | In-Orbit Weight (lbs) | Launch Vehicle | No. of 36 MHz Transponders | RF Total Power | D. C. Prime Power | Efficiency |
|------|-----------|----------------------|----------------|---------------------------|----------------|-------------------|------------|
| Small | HS-336 | 598 | Thor Delta (Upgrade) | 12 | 88W | 220W | .4 |
| Medium | Intelsat IV | 1225 | Atlas Centaur | 12 | 120W | 740W | .16 |
| Large | MCI-Lockheed Domestic Filing | 3900 | Titan IIID Agena | 48 | 672W | 4.4kW | .15 |

The satellites are quite similar in basic design although the MCI-Lockheed
satellite differs by being three-axis stabilized and by operating half of its
transponders at 12/13 GHz (the other two are spin stabilized and operate at 4/6
GHz or 2.5/6 GHz). Note that the Hughes design has a higher efficiency (ratio of
RF power to prime power). For our purposes, these differences are relatively
minor.

Approximate cost data are re-summarized as follows:[1]

| Satellite | First Launch ($M) | Launch Thereafter ($M) | First Satellite ($M) | Satellites Thereafter ($M) | Development Costs ($M) |
|-----------|-------------------|------------------------|----------------------|----------------------------|------------------------|
| Hughes HS-336 | 7 | 7 | 6.3 | 6.3 | 8.4 |
| Intelsat IV | 16 | 16 | 12 | 10 | 9 |
| MCI-Lockheed | 22.8 | 21.7 | 20.6 | 20.6 | 30.2 |

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[1] These data were obtained either from published figures (See References)
or from knowledgeable sources. Those from the latter are credible estimates
but cannot be considered hard quotes.

These cost data are estimates; and they will vary with time as well as with application. Our conclusions, therefore, although based on specifics, must be considered generic; and they are valid only for the data used. However, the methodology developed below can be applied in general.

## 2. Supply and Demand Functions

Consider three general types of demand growth over time: (1) constant demand, (2) linear growth over a specified span; constant demand thereafter, (3) linear demand growth forever. These three demand functions and the various launch streams necessary to satisfy them are summarized in Fig. 1. A ten-year lifetime is assumed for all three satellites.[1]

These supply and demand functions allow us to examine tradeoffs between scale economies and the time-value of money. Indeed, most of the demand curves have been shaped to facilitate an economic comparison of small, medium, and large satellites. We are assuming implicitly here that capacity is proportional to total RF power (power-limited operation). For teleconferencing applications (small ground stations),this is not an unwarranted assumption. Note that the large satellite has about six times the capacity of the medium one, and about eight times the capacity of the small one. (This comparison would be exact if MCI were 700 Watts; Intelsat IV, 116.7 Watts; and Hughes, 87.5 Watts.)

## 3. Economies of Scale

We can examine economies of scale explicitly by expressing the costs of the larger satellite in terms of the costs of the smaller:

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[1] Intelsat IV is quoted at 7 years, but we feel that a "medium" satellite of its characteristics will have at least a ten-year lifetime by 1975.
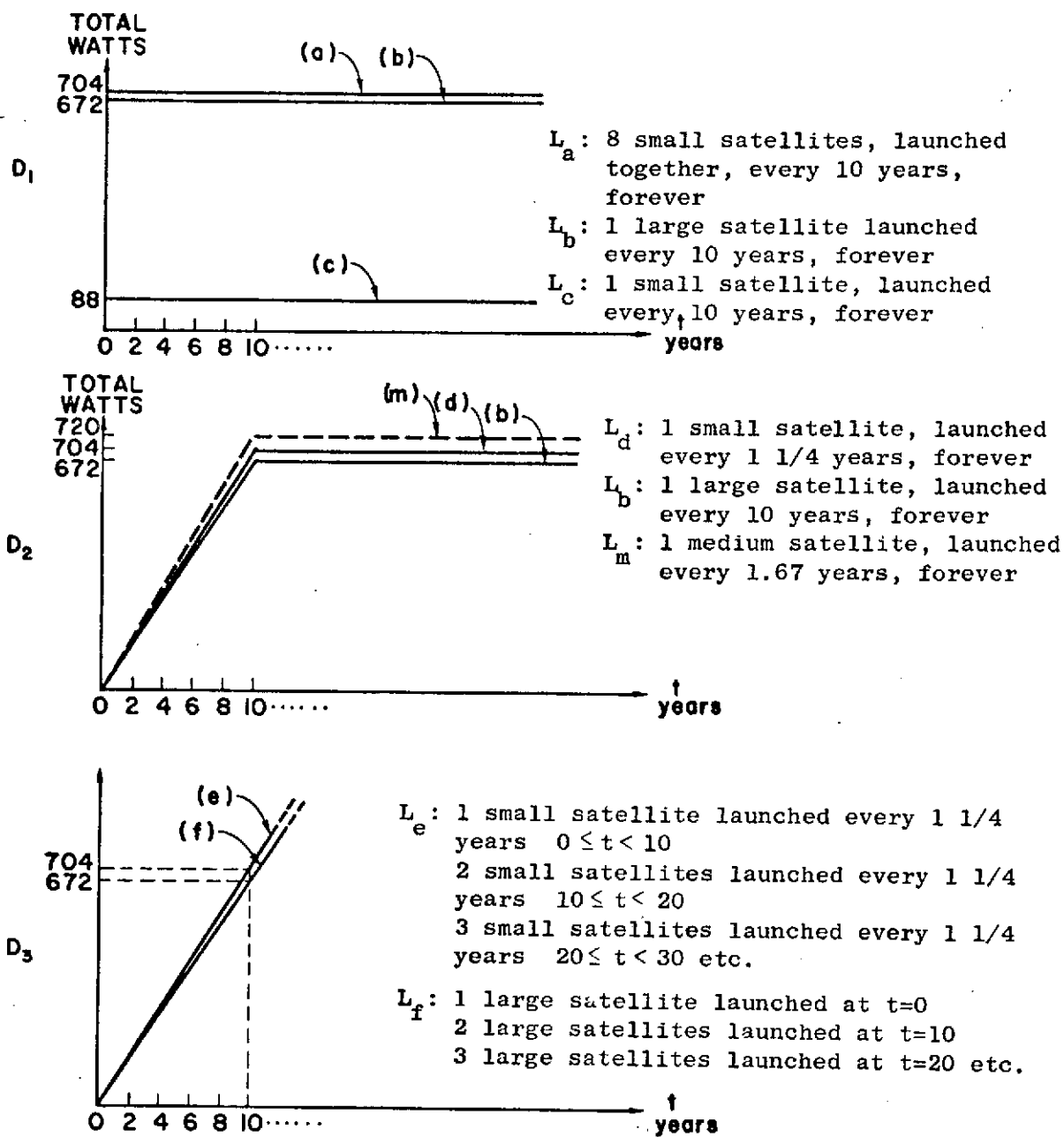
Figure 1: Supply and Demand Functions

In the figure:

$D_1$ (TOTAL WATTS axis, values 704, 672, 88; curves (a), (b), (c)):

$L_a$: 8 small satellites, launched together, every 10 years, forever

$L_b$: 1 large satellite launched every 10 years, forever

$L_c$: 1 small satellite, launched every 10 years, forever

$D_2$ (TOTAL WATTS axis, values 720, 704, 672; curves (m), (d), (b)):

$L_d$: 1 small satellite, launched every 1 1/4 years, forever

$L_b$: 1 large satellite, launched every 10 years, forever

$L_m$: 1 medium satellite, launched every 1.67 years, forever

$D_3$ (values 704, 672; curves (e), (f)):

$L_e$: 1 small satellite launched every 1 1/4 years $0 \leq t < 10$
2 small satellites launched every 1 1/4 years $10 \leq t < 20$
3 small satellites launched every 1 1/4 years $20 \leq t < 30$ etc.

$L_f$: 1 large satellite launched at t=0
2 large satellites launched at t=10
3 large satellites launched at t=20 etc.

|  | Larger | Smaller |
|---|---|---|
| Development Costs: | $D_s F_D x$ | $D_s$ |
| Satellite Costs: | $S_s F_s x$ | $S_s$ |
| Booster Costs: | $B_s F_B x$ | $B_s$ |

where x is the number of smaller satellites needed to produce the same total RF power (i.e. capacity) as the larger; and where the efficiencies F account for the fact that increasing satellite capacity by, say 8 times, does not (usually) increase its cost by as much as 8 times. If the F's are $\geq 1$, there are diseconomies of scale.

Using the data presented earlier above for the three satellite cases, we can deduce the economies of scale for each pairwise combination:

|  | x=8<br>Larger = MCI<br>Smaller=HS-336 | x=6<br>Larger=MCI<br>Smaller=Int.IV | x=1.365<br>Larger=Int.IV<br>Smaller= HS-336 |
|---|---|---|---|
| Development $F_D$ | .45 | .56 | .782 |
| Satellite $F_s$ | .41 | .286 | 1.4 |
| Booster $F_B$ | .407 | .238 | 1.68 |

We concluded that the large satellite enjoys considerable economies of scale over both the small and the medium satellite. The medium satellite has diseconomies for the data given mainly because its total power is low for the launch vehicle used. The time-value of money may alleviate these diseconomies, but will benefit the small satellite still more. We expect, therefore, that the medium satellite will be an uneconomical choice on the basis of cost per RF Watt. Because of this, we have relegated the economic analysis of the medium satellite case (launch stream $D_{2m}$ in Fig. 1) to Appendix D. The results of this appendix corroborate our tentative conclusion.

4. <u>Present Value Comparisons: Launch Stream Investments</u>

Consider two system alternatives:

    A. N + 1 satellites: N orbit active and 1 orbit spare

    B. N + 1 satellites: N orbit active and 1 ground spare

For these two cases, launch stream investments can be compared on a present-value basis in the following way. Let

    D = the non-recurring development costs.

    S = the recurring satellite costs.

    B = the recurring launch booster costs.

    L = the design lifetime (assumed ten-years for all cases)

    r = the      failure rates (assumed $= \frac{1}{4}$ for satellites and for all other system elements).

    i = discount rate $=$ (interest rate - inflation rate)

$\hat{N}_a(L,i)$ = equivalent number of active (service) satellites for a given launch stream and discount rate (i.e., the discounted total number of satellites launched during the interval $[0 \leq t < \infty]$).

$\hat{N}_{sp}(i)$ = equivalent number of orbit-spare satellites for a given discount rate: one launched every $t = 0, 10, 20 \ldots$ years.

Then total investment for each of the two alternatives becomes:

Alternative A:   $D + (1+r)\,[S+B]\,\hat{N}_{sp}(i) \;\; + \;\; (1+r)\,[S+B]\,\hat{N}_a(L,i)$
(in-orbit spare)

Alternative B:   $D + \qquad\qquad S \qquad\qquad + (1+r)\,[S+B]\,\hat{N}_a(L,i)$
(ground spare)

        Development Orbit-Spare   Service-Satellite
         Costs    Costs      Costs

or, with $r = \frac{1}{4}$ , and using the cost data presented earlier,

| Satellite | Alternative | Development Costs($M) | | Spare Costs ($M) | | Service Costs ($M) |
|---|---|---|---|---|---|---|
| Small | A | 8.4 | + | $16.6 \, \hat{N}_{sp}$ | + | $16.6 \, \hat{N}_a$ |
| Small | B | 8.4 | + | 6.3 | + | $16.6 \, \hat{N}_a$ |
| | | | | | | |
| Medium | A | 9 | + | $35 + 32.5\{\hat{N}_{sp}-1\}$ | + | $32.5 \, \hat{N}_a$ |
| Medium | B | 9 | + | 12 | + | $32.5 \, \hat{N}_a$ |
| | | | | | | |
| Large | A | 30.2 | + | $54.2 + 52.9\{\hat{N}_{sp}-1\}$ | + | $52.9 \, \hat{N}_a$ |
| Large | B | 30.2 | + | 22.8 | + | $52.9 \, \hat{N}_a$ |

Since the discounted orbit-spare total, $\hat{N}_{sp}(i)$, does not depend on the launch stream configuration, it can be computed directly (see Case 1, Appendix B): $\hat{N}_{sp}(10\%) = 1.627$, and $\hat{N}_{sp}(15\%) = 1.328$. The above table can therefore be simplified, for these two discount rates, to:

| Satellite | Backup Alternative | Discount Rate | ($M) Present Value of Total Investment |
|---|---|---|---|
| Small | { A: in-orbit spare } | 10% | $35.4 + 16.6 \, \hat{N}_a(L,10\%)$ |
| | | 15% | $30.5 + 16.6 \, \hat{N}_a(L,15\%)$ |
| | { B: ground spare } | general | $14.7 + 16.6 \, \hat{N}_a(L,i)$ |
| | | | |
| Large | { A: in-orbit spare } | 10% | $117.6 + 52.9 \, \hat{N}_a(L,10\%)$ |
| | | 15% | $101.9 + 52.9 \, \hat{N}_a(L,15\%)$ |
| | { B: ground spare } | general | $53.0 + 52.9 \, \hat{N}_a(L,i)$ |

where we have deleted the medium satellite case, which is treated in Appendix C. Values of $\hat{N}_a$ are calculated in Appendix A for discount rates of $i = 5\%, 10\%, 15\%,$ and $20\%$.

## 5. Annual Cost: Zero-profit pricing

We derive annual cost (or price) per watt for a given discount rate and investment stream by calculating the annual lease payments to the satellite-owner necessary to ensure recovery of his capital. We assume that the "owner" (who may be fictitious) will be satisfied with a zero profit. Then the present value of the lease payment stream must equal the present value of the capital outlay:

$$PV(\text{revenues}) = C_W \cdot \hat{W}(D,i) = PV(\text{investment})$$

where $C_W$ = annual cost (or lease price) per watt (dollars per watt per year)

$\hat{W}(D,i)$ = effective (discounted) total RF power sold.

The amount of sold power (or capacity) at a given time depends entirely upon assumed demands; while the discounted <u>total</u> sold capacity depends not only upon the demand function, but the interest rate as well. (We must discount the total sold capacity because payments far in the future are less valuable to the "owner" then payments he receives now). Values of the discounted total, $\hat{W}(D,i)$ are computed in Appendix B for $i = 5\%$, $10\%$, $15\%$ and $20\%$ and for all prescribed demand functions.

Note that annual operating and maintenance costs have been ignored: they are not crucial and will, in any event, be relatively invariant to changes in the launch stream strategies.

## C. Results and Conclusions

Table 2 summarizes the results from Appendices A and B for discount rates of 10% and 15%. As expected for non-zero interest rates, the discounted supply and demand totals are finite even though the supply and demand streams are infinite.

TABLE 2

## Discounted Capacity: Supply and Demand

| | TOTAL SUPPLY | | | | TOTAL DEMAND | | | |
|---|---|---|---|---|---|---|---|---|
| Case No. | Type of Launch Stream[1] | | Discounted Total Number of satellites Launched, $\hat{N}(L,i)$ | | Type of Demand Function[1] | | Discounted Total sold capacity (RF Watts) $\hat{W}(D,i)$ | |
| | L | Satellite Size | $i = 10\%$ | $L = 15\%$ | D | Function Shape | $i = 10\%$ | $i = 15\%$ |
| 1 | $L_a$ | small (lumped) | 13.020 | 10.627 | $D_{1a}$ | constant | 7040 | 4693 |
| 2 | $L_b$ | large | 1.627 | 1.328 | $D_{1b}$ | constant | 6720 | 4480 |
| 3 | $L_c$ | small | 1.627 | 1.328 | $D_{1c}$ | constant | 880.0 | 586.7 |
| 4 | $L_d$ | small | 8.610 | 5.948 | $D_{2d}$ | mixed | 4450 | 2431 |
| 5 | $L_b$ | large | 1.627 | 1.328 | $D_{2b}$ | mixed | 4248 | 2320 |
| 6 | $L_e$ | small | 14.012 | 7.901 | $D_{3e}$ | linear | 7040 | 3129 |
| 7 | $L_f$ | large | 2.649 | 1.764 | $D_{3f}$ | linear | 6720 | 2987 |

[1] Definitions (see, also, Fig. 1)

1 $(L_a, D_{1a})$: Demand of 704 Watts forever. Supply of 8 small satellites launched together at $t = 0$, 10, 20 ... years forever.

2 $(L_b, D_{1b})$: Demand of 672 Watts forever. Supply of 1 large satellite launched at $t = 0$, 10, 20 ... years forever.

3 $(L_c, D_{1c})$: Demand of 88 Watts forever. Supply of 1 small satellite launched at $t = 0$, 10, 20 ... years forever.

4 $(L_d, D_{2d})$: Demand growing linearly from 0 at $t = 0$ years to a maximum at $t = 10$ of 704 Watts; thence 704 Watts forever. Supply of 1 small satellite launched every 1 1/4 years, $t = 0$, 1 1/4, 2 1/2 ..... years, forever.

5 $(L_b, D_{2b})$: Demand growing linearly from 0 at $t = 0$ years to a maximum at $t = 10$ of 672 Watts; thence 672 Watts forever. Supply of 1 large satellite launched at $t = 0$, 10, 20 ... years, forever.

6 $(L_e, D_{3e})$: Demand growing linearly from 0 at $t = 0$ years with a slope of 70.4 Watts/year forever. Supply of 1 small satellite launched every 1 1/4 years, $0 \leq t < 10$; 2 small satellites every 1 1/4 years, $10 \leq t < 20$; 3 every 1 1/4 years $20 \leq t < 30$, etc. forever.

7 $(L_f, D_{3f})$: Demand growing linearly from 0 at $t = 0$ years with a slope of 67.2 Watts/year forever. Supply of 1 large satellite at $t = 0$; 2 large satellites at $t = 10$; 3 at $t = 20$, etc. forever.

Table 3 summarizes present values of investments and annual costs per watt for all prescribed launch strategies, supply and demand functions, and for discount rates of 10% and 15%.

Figures 2, 3, and 4 depict these results graphically and extend them for discount rates of 5% and 20%.

TABLE 3

Present Value of Investment; and Annual Cost per Watt

| Case No. | Present Value of I($M) | | | | Annual Cost Per Watt($K) | | | |
|---|---|---|---|---|---|---|---|---|
| | Strategy A | | Strategy B | | Strategy A | | Strategy B | |
| | i=10% | i=15% | i=10% | i=15% | i=10% | i=15% | i=10% | i=15% |
| 1  $(L_a, D_{1a})$ | 251.5 | 206.9 | 230.8 | 191.1 | 35.73 | 44.09 | 32.79 | 40.72 |
| 2  $(L_b, D_{1b})$ | 203.7 | 172.2 | 139.1 | 123.2 | 30.31 | 38.43 | 20.70 | 27.51 |
| 3  $(L_c, D_{1c})$ | 62.4 | 52.5 | 41.7 | 36.7 | 70.92 | 89.56 | 47.40 | 62.63 |
| 4  $(L_d, D_{2d})$ | 178.3 | 129.2 | 157.6 | 113.4 | 40.07 | 53.16 | 35.42 | 46.66 |
| 5  $(L_b, D_{2b})$ | 203.7 | 172.2 | 139.1 | 123.2 | 47.94 | 74.20 | 32.74 | 53.12 |
| 6  $(L_e, D_{3e})$ | 268.0 | 161.7 | 247.3 | 145.9 | 38.07 | 51.66 | 35.13 | 46.61 |
| 7  $(L_f, D_{3f})$ | 257.7 | 195.2 | 193.1 | 146.3 | 38.35 | 65.36 | 28.74 | 48.98 |
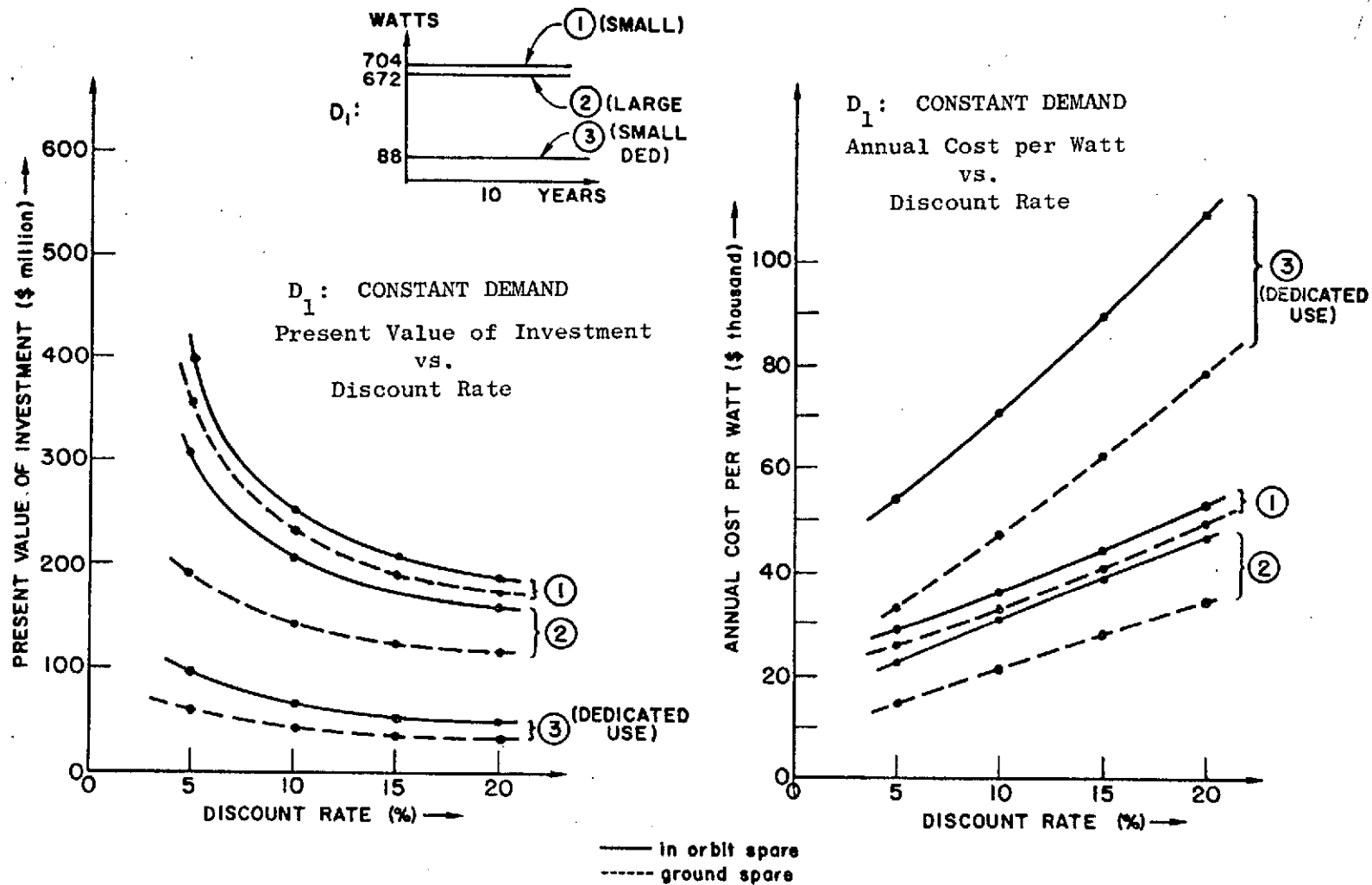
Figure 2: Costs For Constant Demand
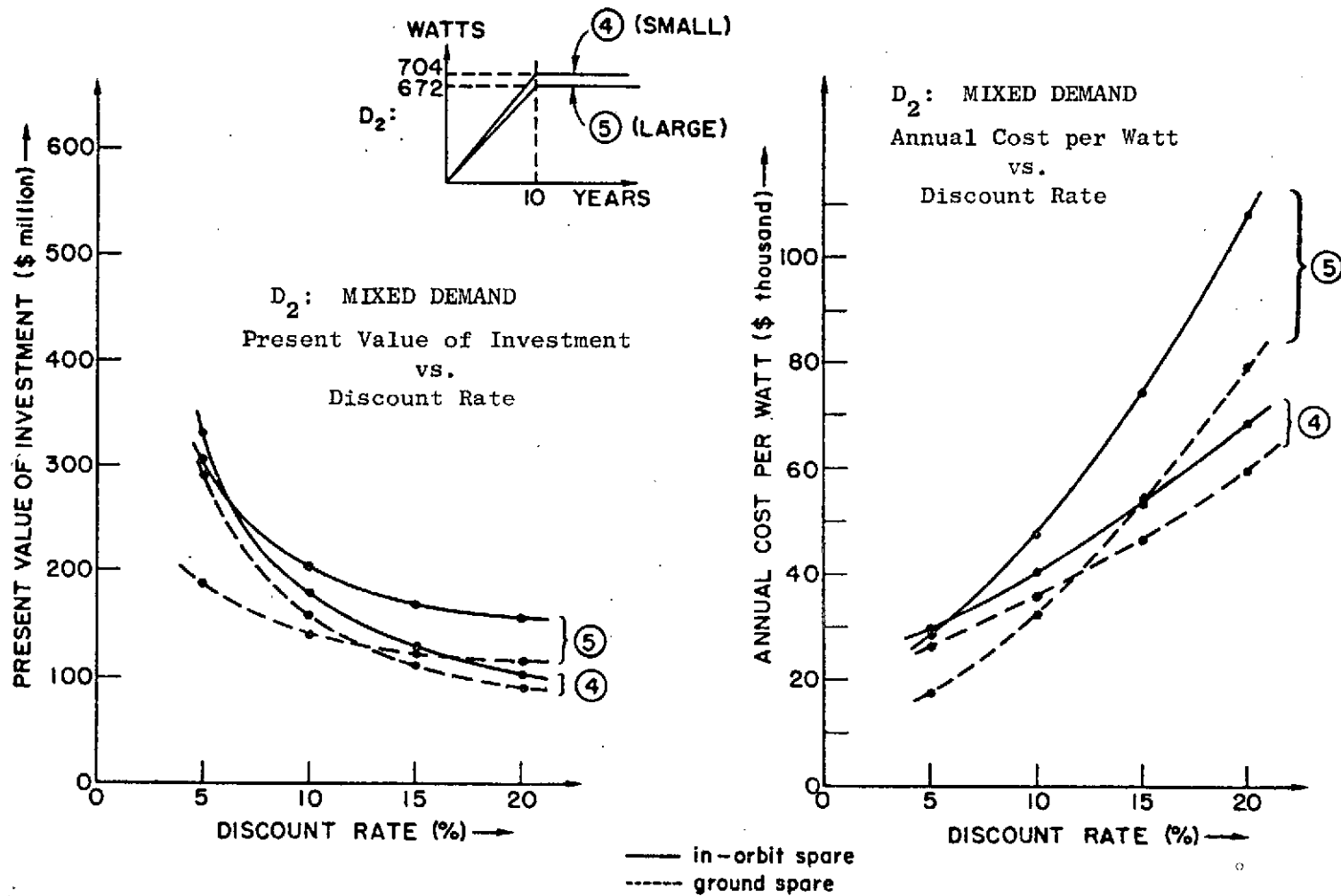
Figure 3:  Costs For Mixed Demand
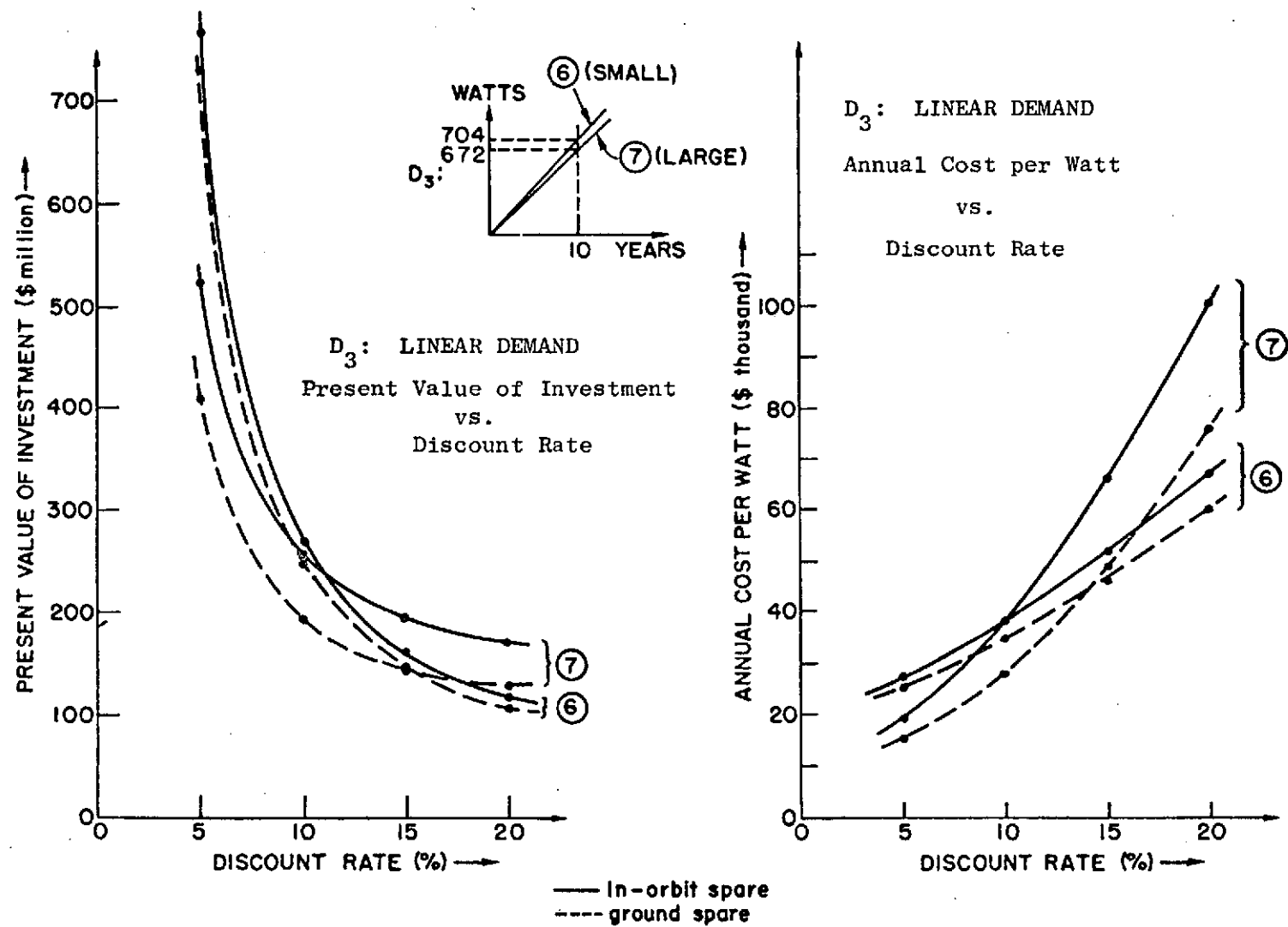
Figure 4: Cost For Linear Demand

For discount rates, ranging from 10-15%,[*] we conclude from Table 3 that

(a) Costs to the satellite-segment consumer, on an annual cost per Watt basis, vary for i = 10% (15%) from \$30K→\$71K (\$38K→\$90K) for a backup strategy of in-orbit spares; \$21K→\$47K (\$28K→\$63K) for a strategy of ground-spares. Specific cost values depend upon assumed demand growth.

(b) Costs to the satellite-segment supplier, on a present value basis, vary for i = 10% (15%) from \$62M→\$268M (\$52M→\$207M) for a backup strategy of in-orbit spares; \$42M→\$247M (\$37M→ \$191M) for a strategy of ground-spares. Specific cost values depend upon assumed supplied capacity.

(c) Higher discount rates decrease the costs (present value of investment) to the system supplier; but increase the costs (annual lease price per Watt) to the consumer.

(d) The lowest capacity system (Case 3), which corresponds to a satellite devoted exclusively to teleconferencing, requires the least investment but requires the most annual revenue per Watt. Hence, for power-limited operation, a dedicated satellite is most expensive alternative for the teleconferencing user.

[**]
(e) For constant demand (highest initial supplied capacity), the small satellite is somewhat (~20%) more expensive than the large satellite if in-orbit spares are used; considerably (~50%) more expensive if ground spares are used--in terms of total investment as well as annual cost per Watt. This result is not surprising: the large satellite is favored when there is a large initial traffic demand. The time-value of money does not offset economies of scale for this case.

[**]
(f) For linear demand growth (highest final supplied capacity), the annual cost per Watt of the large and small satellites are roughly equivalent at a discount rate of 10% if in-orbit spares are used. If ground spares are used, however, the large satellite is about 20% cheaper than the small satellite. These results are highly sensitive to charges in the discount rate: at i = 15%, the small satellite is cheaper for both spare backup strategies.

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[*] Discount rates from 8% to 12%, are commonly used, with 10% as the usual norm.

[**] Our comparisons of the large and small satellites are not exact, although they are accurate enough for our purposes. Annual costs per Watt are biased in favor of the small satellite by the ratio of 704 Watts/672 Watts, making it appear about 4.3% cheaper than it would be were the large and small satellite capacities perfectly divisible.

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The time-value of money largely offsets economies of
scale for this case: the small satellite can conform more
closely to changing demand, whereas the large satellite is
penalized heavily for its large initial unsold capacity.

**

(g)  For demand which grows linearly over the 10-year lifetime
of the first-generation of satellites, but remains constant
thereafter, the results are similar to those for linear demand
growth in (f) above:  the disparity in the two demand functions
for t > 10 years is clouded by the discount rate.  On an annual
cost per Watt basis, the small satellite is ~20% cheaper than
the large satellite for i = 10% (~30% cheaper for i = 15%), if
an orbit-spare is used.  If a ground spare is used, the small
satellite is slightly (~6%) more expensive at i = 10% but
becomes ~12% cheaper than the large satellite at i = 15%.

(h)  Since one backup spare insures many small service satellites
almost as well as it insures one large service satellite, the
spare strategy has a major impact upon the cost of the large-
satellite system.  In particular, in-orbit spare costs are a
much greater burden upon a system of large satellites than
they are upon a system of small satellites.  This is evident
from the above results: an in-orbit spare strategy almost
always negates whatever advantage the large satellite may have
over the small satellite.

(i)  For the data given, the medium satellite is the most expensive
alternative as viewed by either the space-segment supplier or
the consumer (see Appendix D). Other, more efficient,medium
satellite designs might not suffer this shortcoming,however.

Figures 2, 3, and 4 illustrate those results over a wider range of discount
rates.  In general, these figures show that the present value of total outlay
decreases with discount rate, whereas annual required revenue increases with
discount rate.  Note that the time-value of money influences the choice of large
vs. small satellite only when demand changes with time (Figs. 3 and 4): the small
satellite is always preferred if the  discount rate is high enough.  For constant
demand (Fig. 2), however, economies of scale prevail regardless of the discount
rate.  In particular,

(a)  Figure 2 shows that if demand is constant, the large satellite
is the cheapest alternative from the viewpoint of both supplier
and consumer, for all values of the discount rate.

(b) A dedicated satellite (Fig. 2, Case 3) costs the least to supply, but the most to consume. The teleconferencing user, therefore, will prefer to share a non-dedicated satellite.

(c) Figure 3 shows that if demand grows for 10 years but does not grow further thereafter, the small satellite requires the least outlay and revenues for discount rates exceeding ~6% ( ~ 12%) for in-orbit spares (ground spares) respectively. As expected, the in-orbit spare burdens the large satellite case more than the small.

(d) Figure 4 shows that if demand grows linearly forever, the small satellite requires the least outlay and revenues for discount rates exceeding 11% (15%) for in-orbit spares (ground spares) respectively. Meeting this demand requires the highest present value of capital outlay. But annual costs to the user remain about the same as they do for the other demand function shapes.

We conclude, for the specific examples given, that there are significant scale economies in large satellites which can be passed on as cost-savings to the satellite-segment user. However, for launch streams which are tailored to meet demand growth, these savings are offset by the time-value of money, so that large satellites may no longer be preferred, especially for discount rates exceeding 10%. Hence, although the large satellite has advantages, especially if a ground-spare is used, these advantages do not dominate in all cases. Indeed, unless the full capacity of a large satellite can be sold immediately after launch, small satellites will be slightly more economical.

These conclusions, of course, will change with varying cost data and under different demand growth assumptions. Two conclusions, however, can be considered robust: (1) Accelerating demand tends to favor small satellites, especially for high discount rates, whereas large initial demand tends to favor large satellites; (2) Dedicated use of a small satellite for teleconferencing is far more expensive to the user than non-dedicated sharing of a larger capacity system.

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CHAPTER V

MINIMUM COST SATELLITE TELECONFERENCING NETWORKS

A. Introduction

1. Statement of the Problem

This chapter assumes the viewpoint of the prospective supplier of tele-
ferencing services. The objective is to estimate the cost of that
satellite distribution network which would provide the desired grade of
service in such a way as to minimize the annual cost. The pure-satellite
system could then be compared with other alternatives to determine:

1. Whether the economies of satellite teleconferencing are
feasible; and

2. If so, the cost and technical specifications of the minimum-
cost delivery system.

Attention has been restricted to those services, primarily in the
health and educational sector, that require a one-way wideband capabili-
ty and a narrowband return capability, such as computer-assisted instruc-
tion, information retrieval, and certain forms of remote medical diagno-
sis and "open university" educational services. Most of the problems
that we shall analyze have the following generic form: One "master"
station is equipped to transmit video while N "slave" stations receive
the video and return narrowband information (either voice or data) to the
video-origination station-but not to each other. These N slave stations
may or may not be identical. It is conceivable that there may be a need
for a mix of performance characteristics, some stations being located at
the point of use and others serving as the "community antenna" of a
local distribution network. The "community antenna" stations are assu-
med to require commercial-grade video, which corresponds to an out-put
signal-to-noise ratio of 56 dB; and the "direct broadcast" stations are
configured to receive a 43 dB signal on the 3 dB beam edge, which is com-
parable to the highest-quality video now available to home users. We
consider both the case in which the performance characteristics of the
satellite transponders are fixed and when they may be tailored to meet
particular user requirements.

When the satellite parameters are variable, the annual cost of a
transponder is assumed to be a linear function of the time-value of
money, the total demand for satellite power as a function of time, and

the backup strategy used to provide insurance against launch failure. One selects that satellite which provides the most watts per dollar, in view of the aforementioned factors. The methodology used in making this selection is described in Chapter 4.

We also considered three network configurations having greater symmetry:

1. Two-way video (or two-way audio with no video). N identical stations.

2. One-way video with symmetrical, two-way audio. The N identical slave stations may now communicate with each other as well as with the video-origination station.

3. One-way voice plus symmetrical, two-way audio in a network for which the various slave stations have vastly different voice-circuit capacity requirements.

Quantitative methods have been developed for all but the last category of problems. Due to a lack of data concerning switching costs, we only have qualitative results for problem 3.

There is a tradeoff between earth-station performance and satellite performance that vitally affects the total system cost. The "standard" stations of the Intelsat network were designed to service high-volume, point-to-point traffic between a relatively small number of stations over great distances. Given the limited power of the commercial satellites of the 60's, extremely high performance was required on the ground to obtain the necessary voice-circuit capacity. Consequently, the capital cost of the Intelsat standard station is quite high (approximately $5,000,000).

Recent improvements in communication satellites have resulted in increased effective isotropic radiated power (EIRP) per dollar and better station keeping. The required sensitivity of the ground stations has been reduced and there is no longer a need for automatic tracking. The improved noise figures of transistor amplifiers, which can operate in the ITFS band* likely to be preferred by small users in the health and

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*
The ITFS (Instructional Television Fixed Services) band, which extends from 2500 to 2690 MHz was authorized for educational broadcasting from satellites by the World Administrative Radio Conference in August, 1971.

educational community, has further reduced the cost of the ground stations that would be compatible with the most recent communication satellites.

There can be significant savings when the satellite and ground stations are tailored to meet particular network requirements. The principles used to develop the Intelsat system are not entirely applicable to the "master/slave" network configurations that we have considered. We have attempted to quantify the numerous tradeoffs involved in building a communication-satellite network: Each parameter has been related to the required capacity, signal quality, and total annual cost.

Qualitatively speaking, as the capital cost of the ground segment declines, the cost of the space segment increases. The ratio of the capital cost of a slave station to the combined cost of the satellite and video uplink should decline as N, the number of slave stations in the network, increases. One must partition the noise budgets for the video and return links to minimize the combined cost of the ground and space segment.

The model proposed provides a convenient means of assessing possible economies of scale; the marginal cost of increasing the number of video channels; the marginal cost of a narrowband-return capability, given a receive-video capability; the marginal cost of extending the area of coverage; and the "robustness" of a proposed system configuration to possible changes in the demand for remote stations and/or video or narrowband channels. In summary, we feel the model is extremely flexible; and will be of particular value during the preliminary planning of a communication system.

We relate the annual cost to the number of slave stations in the network, the number of video and narrowband channels, $n_{TV}$ and $n_A$, and the specified signal-quality constraints for the video and narrowband-return traffic. Both time-division-multiple-access and frequency-division-multiple-access will be evaluated as a means of providing the return capability.

In the course of estimating the annual cost of the network, numerous other system parameters are specified, such as the "first cost" of the network; the antenna diameter, pre-amp noise temperature, and uplink transmitter power of each ground station in the network; and the power, gain, and bandwidth of the audio and video satellite transponders.

Several parameters are assumed to be known a priori:

1. The uplink and downlink frequencies of the TV and narrowband return traffic, $_1f_u$, $_1f_d$, $_2f_u$, and $_2f_d$;

2. The desired area of coverage. This information, in conjunction with knowledge of the frequencies, establishes the diameter of the satellite antenna, $D_{sat}$;*

3. The system-noise temperature of the satellite transponders, $T_{sat}$;

4. Single-unit cost data for the antennas, pre-amps, and uplink power transmitters; and knowledge of the volume discount as a function of the number of items purchased.

5. Estimates of the cost of installation, operations, and maintenance as a function of the capital cost of the ground-station components;

6. The cost-per-watt-per-year of the satellite, SS.

Slave stations receive a volume discount in purchasing capital equiptment; the master station pays single-unit prices unless it deploys components also used by the slave stations. The discount factor is computed as follows: If the per-unit cost of N items is one unit, the per-unit cost of 2N units is assumed to be .92 units. That is, the per-unit cost of N items is assumed to be $.92^{log_2 N}$ times the single unit cost.

Two coverage patterns have been considered, both of which are based on the assumption that $_1f_d$ = 2.5 GHz and that the master station lies within the cone of coverage of the return traffic. To cover the eight-state Rocky-Mountain region,** the site of a proposed educational-satellite experiment sponsored by NASA, HEW, and the Corporation for Public

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* In all probability, the desired "footprint" - referenced to the satellite - will not be circular, $D_{sat}$ may be thought of as the diameter of an equivalent parabolic reflector having the same effective area as the desired antenna.

** Montana, Idaho, Wyoming, Colorado, New Mexico, Utah, Arizona, and Nevada. This region, incidentally, covers approximately one third of the land area of the Continental U.S. and has approximately 3% of the population. It is a logical candidate for a satellite-communication network.

Broadcasting, a 2° by 2.5° beam is required. The effective area of the associated antenna on the satellite is approximately equal to that of a 10' parabolic dish. For Continental U.S. coverage, a 3° by 7° beam is required. The associated antenna is equivalent to a 6' dish.

The geostationary satellite is assumed to have station-keeping capability sufficient to maintain its nominal orbital position to within ± 1°. Consequently, automatic tracking is not required on the ground until the ground-station antenna is at least 34' in diameter, assuming that the uplink frequencies for the video and return traffic are less than or equal to 6 GHz, and it is desired to keep the pointing error less than 1 dB. A schematic diagram of the problems considered appears in Figure 1.

The principal conclusions which emerge from this study are as follows:

1.  The case for satellites as a means for networking video signals is overwhelming. A four-channel system appears to be less costly than common-carrier facilities for all but intra-urban traffic if there are at least 25 stations in the network. And the cost per station drops sharply as N increases.

2.  The antenna diameter of the minimum-cost slave station ranges from 20' to 8' and the master-station antenna diameter ranges from 14' to 40' as N ranges from 10 to 10000. Even in the case of two-way video, the antenna diamaters were never observed to exceed 30'. Small-antenna teleconferencing systems do appear to be cost effective.

3.  The per-transponder satellite power in the minimum-cost system is surprisingly modest, ranging from 1 to 10 watts for the video and much less for the return audio. Such power requirements are well within the range of state-of-the-art technology.

4.  A narrowband-return capability increases the annual cost of the (minimum cost) TV-only network by approximately 10%-30% when the return traffic is directed only to the video-origination station. When the N slave stations also serve as distribution centers of a long-haul telephone network, the marginal cost, of course, is a critical function of the internodal voice traffic. Satellites do not appear to offer possible savings for large-volume telephony at the present time. They are attractive for thin routes, particularly when there is also a need to distribute video.

5.  Decreasing the diameter of the satellite antenna from 10' to 6', thereby providing Continental U.S. coverage rather than regional coverage at 2.5 GHz, increases the cost by approximately 70%. Stated another way, increasing the coverage by approximately

Given: $_1f_u$, $_1f_d$, $_2f_u$, $_2f_d$, $D_{sat}$, $T_{sat}$, SNR[TV(1)], SNR[TV(2)], SNR(A),

R = distance of geostationary satellite from most distant ground
station on 3 dB contour, SS, Ground-Segment Cost Data

Decision Variables: $n_{TV}$, $n_A$, $N = n(1) + n(2)$

Determine: Annual Cost, Capital Cost, $A_s(i)$, $T_s(i)$, $P_s(i)$, $i = 1, 2$, $A_m$,
$T_m$, $P_m$, $P_{sat}^{(v)}$, $P_{sat}^{(A)}$, $g_1$, $g_2$, BO

I. Asymmetrical Teleconferencing



| Satellite (Fixed or Variable Transponder Parameters) | |
|---|---|
| Given: $D_{sat}$, $T_{sat}$, SS = $ W./yr. | |
| Video Trans. $P_{sat}^{(v)}$, $g_1$, $BW_1$ | Return Trans. $P_{sat}^{(A)}$, $g_2$, $BW_2$ |

$_1f_d$  $_1f_u$     $_2f_u$     $_2f_d$

| Slaves | Master |
|---|---|
| Given: i = 1 (56 dB) or i = 2 (43 dB), n(i), SNR[TV(i)]. Receives $n_{TV}$ video signals, returns a narrowband carrier to M. $A_s(i)$, $P_s(i)$, $T_s(i)$ unknown. | Originates $n_{TV}$ video signals. Receives $n_A$ narrowband signals from slaves. SNR(A) specified. $A_m$, $T_m$, $P_m$ unknown. |

II. Two-Way T.V.

N stations each have the capability to originate and receive $n_{TV}$
video signals. Determine $A_s$, $T_s$, $P_s$, $P_{sat}^{(v)}$, and $g_1$.

III. One-Way T.V. Plus Symmetrical Voice

N identical slave stations are also designed to receive the narrow-
band signals.

IV. Hybrid Satellite/Terrestrial Networks

Slave stations receive T.V. and route overflow voice traffic from
an existing terrestrial network.

Fig. 1:    Satellite Teleconferencing Networks

a factor of 3 increases the cost by roughly $\sqrt{3}$. This conclusion is based on the assumption that the total number of stations and the channel capacity are constant.

6. There are significant economies of scale. When there is one video-origination station and N slave stations which receive the video and return the narrowband information to the video-origination station, the total capital cost per station falls approximately as $\sqrt{N}$.

7. Until the spectrum must be reused[*], the marginal cost of adding video channels is constant when the satellite parameters are fixed and decreases when the satellite parameters are variable. When the spectrum must be reused, the ground-segment costs increase significantly, increasing the marginal cost.

8. The availability of directive antennas and larger amounts of RF power on a communication satellite – to the extent that they reduce the cost-per-watt-per-year of satellite power – will have a significant bearing on the configuration of the minimum-cost network. If SS is the annual cost per watt of satellite power, the annual cost of the network rises approximately as $\sqrt{SS}$.

9. The gross system parameters of the minimum-cost network, $A_s$, $T_s$, $P_s$, $A_m$, $T_m$, $P_m$, $P_{sat}^{(v)}$, and BO, are quite sensitive to variations in N, $n_{TV}$, and $n_A$. Because these demand indicators are unlikely to be known with precision, the supplier probably would seek a compromise solution rather than attempt to minimize his annual cost.

10. Frequency-division-multiple-access appears to be less costly than time-division-multiple-access for the master/slave network configurations that we have considered.

In sections C and D, we shall consider satellite teleconferencing under two settings: when the transponders are fixed and only the ground segment may be optimized and when both the ground and space segments are variable. We consider both digital feedback and voice feedback in the case studies. Two classes of slave stations are considered in Section C.2: otherwise the slave stations are assumed to be identical.

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[*] The channel capacity of the allocated frequency band may be increased by a factor of two by using orthogonally polarized beams. We have assumed that two antennas and two pre-amps will be used at each slave station in this event.

Network configurations having greater symmetry are considered in Section E. Numerical results are obtained for two-way video teleconferencing systems; and the case in which the N slave stations also serve as transit centers for a telephone distribution network is outlined. The analytical tools used throughout this report are developed in Section B.

## 2. Review of Literature

Low-cost communications are a common international concern. As would be expected, numerous authors have addressed themselves to the problem of determining the minimum-cost network for a particular set of requirements. We gratefully acknowledge the inspiration we derived from the previous contributions of Lutz[1], Chakraborty[2], McClure[3], Dickinson[4], and Talyzin, Kantor, Maryakin, and Payansky[5,6,7]. It perhaps would be appropriate at this time to indicate the point of departure of our work from these previous developments.

Lutz was the first to clarify the methodology required to quantify the ground/space tradeoffs in a satellite communications network. He simplified the complex relationship between the ground-station parameters, (D,T,P), the space-segment charges of the satellite, and the performance characteristics of the satellite transponder by expanding the cost equation into a Taylor series and restricting his attention to only the first-order terms. Unfortunately, he did not first attempt to optimize the satellite and the ground-stations as a function of the required area of coverage, channel capacity, and signal-quality constraints. That is, neither the satellite characteristics, space-segment charge, or ground-station parameters were allowed to vary. Consequently, the system as a whole generally was distinctly sub-optimal; and, not unexpectedly, Lutz came to the disappointing conclusion that small ground stations are "expensive bargains."

Previous attempts to optimize the ground and space segments often have been undermined by unduly restrictive assumptions.* In particular, the noise budget should not be partitioned a priori. This result should be an outcome, rather than a premise, of an optimization study. The determination of the least-cost allocation of the allowed noise in the system between the satellite, master station, and slave stations is the central issue in the optimization procedures to be described.

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*See for example, the conclusions of the Interim Meeting of Study Group W of the CCIR: "A Comparative Study of Possible Methods of Modulation and Multiple Access (for Multi-Channel Telephony)," Geneva, October 1968.

The richest source of literature pertaining to ground/space tradeoffs derives from studies of the Intelsat system. The usual problem considered in the Intelsat literature is to determine the satellite parameters which maximize the (voice) channel capacity to a link between two standard stations. References 2 and 3 provide excellent treatments of this problem.

Our problem is significantly different: the traffic pattern is inherently asymmetrical, and neither the space nor the ground-segment parameters have been fixed a priori. For a fixed traffic pattern, the problem is to specify these parameters so as to minimize the annual cost.

The two-way problem is more difficult to analyze than the one-way problem. In the receive-only case, to achieve a specified receiver sensitivity (as measured by the G/T ratio), there is usually a unique combination of G and T which minimizes the total cost.[4] Similarly, for a specified value of uplink EIRP (equal to the product of antenna gain and uplink RF power), generally there is a unique combination of G and P which minimizes the cost of providing this EIRP. When one antenna is to be used both to receive and to transmit, these problems must be considered jointly. We shall consider techniques to deal with the effects of coupling in the sections to follow.

The Russian papers[5,6,7] are similar in spirit to our own analysis: they too are concerned with providing economical telecommunications to the small user. It is conceivable that they used the same analytical tools, although this is not evident from the brief published excerpts of their work or from their references. Our thinking was shaped most prominently by the Comsat references.[2,3]

B. Analytical Framework

1. Cost Equation

Suppose that there are N identical slave stations in the network, each of which receives $n_{TV}$ video channels and require a total of $n_A$ return channels on the satellite. Define:

$C_t$ = total annual cost of the system;

$$C_t = \text{total annual cost of the system;}$$

$A_a, A_{pa}, A_{pt}$ = single-unit annual cost of the ground-station antenna, pre-amp, and power transmitter;

$C_{mp}(n_{TV})$ = annual cost of the multiplier used at the master station to combine the $n_{TV}$ video carriers;

$P_{sat}^{(v)}$ = watts per video channel required on the satellite(s);

$P_{sat}^{(A)}$ = watts per audio channel required on the satellite(s);

$g_1, g_2, BW_1, BW_2$ = gain and bandwidth of the video (audio) transponders;

$SS$ = space-segment charge = dollars/watt/year;

$d(N)$ = proportionately constant relating the capital cost of N identical components to the single-unit capital cost

$$= N(.92)^{\log_2 N}.$$

The object of the optimization procedure is to minimize the expression:

(1)
$$C_t = d(N) \cdot [A_a(A_S) + A_{pa}(T_S) + A_{pt}(P_S)] + A_a(A_m) + A_{pa}$$
$$+ C_{mp}(n_{TV}) + d(n_{TV} + 1) \cdot A_{pt}(P_m) + SS \cdot [n_{TV} \cdot P_{sat}^{(v)}$$
$$+ n_A \cdot P_{sat}^{(A)}],^*$$

subject to the signal-quality constraints.

We shall assume that the costs of installation, operations, and maintenance are proportional to the capital cost of the ground station and that the constant of proportionality is independent of the number of ground stations in the network. In equation (1) we have assumed for

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*If the master station deploys any of the components used by the slave stations, however, it receives the same volume discount on these items. Each slave station is equipped with one transmitter. The master station is equipped with $n_{TV}+1$ transmitters; i.e., there is one transmitter per video channel plus a spare. The cost of the multiplexer required to combine these $n_{TV}$ carriers at the master-station antenna represents a fixed cost which is independent of the system parameters to be optimized.

simplicity that these costs follow the same learning curve as the capital equipment.* In the course of the analysis, one should specify $D_s$ $(A_s)$, $T_s$, $P_s$, $D_m$ $(A_m)$, $T_m$, $P_m$, $P_{sat}^{(v)}$, $P_{sat}^{(A)}$, $g_1 = g_{sat}^{(v)}$, $g_2 = g_{sat}^{(A)}$, $BW_{sat}^{(v)}$, $BW_{sat}^{(A)}$, and the backoff of the return-link transponder. Having these values, of course, enables one to assess the annual cost of a per-station basis or on a per-station-per-video-channel basis. Note that our objective is to minimize the annual cost of the system rather than the capital cost of a slave station. It is conceivable that some users would exchange increased annual costs (arising primarily from less-efficient use of the satellite) for reduced capital costs. We shall describe this tradeoff graphically in Section D.

2. Noise Budget

The total received carrier-power-to-system-noise-temperature ratio in a satellite communications link is described by a "noise budget":

(2)     $(T/C)_t = (T/C)_u + (T/C)_{im} + (T/C)_d.$

The first term relates to noise contributed by the uplink, the second to noise contributed by the satellite (arising primarily from the combined effects of intermodulation distortion and AM-to-PM conversion in the satellite transponder), and the last to noise contributed by the downlink. $(T/C)_t$ is related to the required signal quality and channel capacity in the system and imposes an upper bound on the permissable noise level in the system.

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*This assumption is admittedly coarse. Capital equipment, installation, operations, and maintenance are subject in varying degrees to economies of scale; and should be treated as separate entries in equation (1) if more accurate information is available. Through centralized administration, the cost of installation and maintenance could be reduced by maintaining permanent crews of trained personnel and central warehouses. The cost of operations is difficult to predict. It most of the personnel were concentrated at the master station, there would be significant economies of scale. On the other hand, the cost of labor at each remote site (if required) would be quite insensitive to the total number of stations in the network.

The total system cost, $C_t$, is critically independent on how the noise budgets for the video and return links are allocated. This decision is not an arbitrary matter: for each alternative partitioning of the two noise budgets there is an associated cost, which we shall examine carefully in the sections to follow. Increasing the required signal quality or the channel capacity is tantamount to reducing the allowable noise level in the system, which entails an increase in the total cost.

We shall assume both for the uplink and the downlink that thermal noise dominates.* Define $(T/C)_q = (T/C)_t - (T/C)_{im}$. Then equation (2) becomes:

$$(3) \quad (T/C)_q = (T/C)_u + (T/C)_d.$$

Suppose $(C/T)_u = x \cdot (C/T)_d$. Then each of these terms may be related to quasi signal-quality constraint; $(C/T)_q = (C/T)_u = (1 + x) \cdot (C/T)_q$

$$(C/T)_d = (1 + x^{-1}) \cdot (C/T)_q$$

For each partitioning of the audio and video noise budgets [represented, say, by $(C/T)_u^{(v)} = x \cdot (C/T)_d^{(v)}$ and $(C/T)_u^{(A)} = y \cdot (C/T)_d^{(A)}$], a corresponding set of ground and space-segment parameters may be determined which minimizes the annual cost for the particular value of the couplet $(x,y)$. One then searches over a range of partitionings to obtain the global minimum. For TV-only operation, one need only search over $x$.

### 3. Cost Data

Only the capital cost of the antenna, pre-amp, power transmitter, and master-station multiplexer is considered explicitly in our analysis of ground-segment costs.** The cost of installation, operations, and maintenance is assumed to be proportional to these capital costs. Let $C_a [A(D)]$ be the capital cost of an antenna of effective area A feet$^2$

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*
The other sources of noise, such as earth-station, non-linearities, interference from terrestrial systems which share the spectrum, etc., have been lumped with thermal noise to obtain an estimated value of "total system noise."

**
Modem costs should have been considered, but insufficient data was available. A more complete description of the cost data obtained by the Stanford teleconferencing group may be found in Chapter 3.

(and diameter D feet), $C_{pa}(T)$ be the capital cost of a pre-amp having noise temperature T, and $C_{pt}(P)$ be the capital cost of a power transmitter having an RF output power of P watts. The cost of installation, which represents a capital investment, is assumed to consist of two components:

1. Installation and Alignment of Antenna

$$\text{Installation Cost} = \begin{cases} .15C_a[A(D)], & D \leq 12' \\ .20C_a[A(D)], & 12' < D \leq 40' \\ .30C_a[A(D)], & D > 40' \end{cases}$$

2. Water, Power, Roads, and Miscellaneous Equipment

$$\text{Cost} = .15[C_a(A) + C_{pa}(T) + C_{pt}(P)].$$

The cost of operations and maintenance, which are treated as annual costs, depends on the particular components employed. Our cost estimates are categorized below:

1. Antenna

$$\text{O\&M Cost} \cong \begin{cases} .05C_a[A(D)], & D \leq 12' \\ .075C_a[A(D)], & 12' < D \leq 40' \\ .15C_a[A(D)], & D > 40' \end{cases}$$

2. Pre-amp

$$\text{O\&M Cost} \cong \begin{cases} .25C_{pa}(T), & T \leq 70^{\circ} \text{ K (Cooled parametric amplifier} \\ .15C_{pa}(T) & 70^{\circ} \text{ K} < T < 300^{\circ} \text{ K (uncooled paramp)} \\ .05C_{pa}(T), & T \geq 300^{\circ} \text{ K (solid-state or mixer} \\ & \text{pre-amp)} \end{cases}$$

3. Power Transmitter

$$\text{O\&M Cost} \cong \begin{cases} .05C_{pt}(P), & P \leq 30 \text{ w (solid state)} \\ .20C_{pt}(P), & P > 30 \text{ w (klystron or TWT)} \end{cases}$$

4. Miscellaneous

$$\text{O\&M Cost} \cong .10[C_a(A) + C_{pa}(T) + C_{pt}(P)]$$

We have assumed that the ground stations are amortized over 10 years at
an interest rate of 10%. Thus, the annual payments on capital invest-
ments amount to approximately 16.2% of the first cost. To these interest
payments must be added the estimated cost of operations and maintenance.
The single-unit annual cost associated with use of the various components
by $A_a(A)$, $A_{pa}(T)$, and $A_{pt}(P)$.

The small ground stations under consideration tend to be power limi-
ted rather than bandwidth limited. Consequently, we have assumed their
space-segment charges are assessed on the basis of average power consump-
tion on the satellite and are not related to their consumption of band-
width.

The annual cost of a satellite transponder is assumed to be a linear
function of the RF output power of that transponder; it is assumed to
be independent of the power gain or the bandwidth. One selects that
satellite which provides the most watts per dollar as described in Chap-
ter IV.

Use of the geostationary orbit is assumed to be free of charge.
This assumption will have to be revised if the demand for low-cost
ground stations, which make relatively inefficient use of the geostation-
ary spectrum, overruns the supply of orbital slots. We do not feel that
this circumstance is likely in the foreseeable future; but steps not to
insure conservation of this scarce resource--without stiffling its
development--would not be unwarranted. A combination of political, legal,
and technical factors would have to be included in any meaningful analy-
sis of the economic value of this resource. If the cost could be expres-
sed in terms of $/degree of orbital arc/Hz of RF spectrum/year, this fac-
tor could easily be incorporated into equation (1), which we have used
as the figure of merit in comparing alternative system designs. Unfor-
tunately, the complex topic of orbital conservation is beyond the scope
of our present analysis.

The system noise temperature, T, and the uplink RF power, P, have
been restricted to a discrete range of values; the antenna diameter has
been allowed to range over a continuum. Were the diameter restricted
to a discrete set, it would be necessary to replace the differential-
calculus procedures to be described with exhaustive search techniques.

The required changes are straight-forward and are not included in this report.

The cost of antennas is a critical function of diameter. In a review of this subject that is summarized in Chapter III, Kinji Ono concluded that the cost of the antenna is:

1. Essentially independent of frequency for 2.0 GHz$<$f$\leq$6 GHz;

2. Essentially independent of whether the antenna is to be used for one-way or two-way operation; (That is, the marginal cost of the feed/diplexer for two-way operation is modest.)

3. Significantly different for

   a) $D \leq 12'$
   b) $12' < D \leq 40'$
   c) $D > 40'$

We approximated the single-unit annual cost of an antenna as an exponential function its effective area, $A_e$, using three families of curves in view of point 3:

$$(4) \quad A_a(A_e) = a_1(i) + a_2(i)A_e^{a_3(i)}, \quad i = 1, 2, 3.$$

By definition, $A_e$ = effective area = $\eta\pi D^2/4$. We shall assume that:

$$\eta = \text{efficiency} = \begin{cases} .50, & D\leq 12' \\ .55, & D>12'. \end{cases}$$

Finally, G = antenna gain = $(4\pi/\lambda^2)A_e$.

The coefficients of equation (4) were selected so that the capital cost (exclusive of installation) passed through the following points:

Table I:  Antenna Cost/Performance Data

| D | $\eta$ | Cost (single unit) |
|---|---|---|
| 7.0' | 50% | $ 435 |
| 10.0' | 50% | 1,050 |
| 12.0' | 50% | 2,610 |
| 13.0' | 55% | 9,000 |
| 20.0' | 55% | 30,000 |
| 32.0' | 55% | 90,000 |
| 42.0' | 55% | 510,000 |
| 85.0' | 55% | 1,420,000 |
| 97.0' | 55% | 2,180,000 |

Above 12', the manufacturing costs are much higher. Below 12', the techniques developed by Janky and Taggart of Stanford University are applicable.[8] These small antennas are now commercially available.

Six pre-amplifier configurations have been considered:

1. A parametric amplifier, the first stages of which are helium-vapor cooled. (Amplifier noise temperature, $T_n \cong 20^{\circ}$ K; system noise temperature, $T, \cong 45^{\circ}$ K).

2. A parametric amplifier, the first stages of which are liquid-nitrogen cooled; $T_n \cong 40^{\circ}$ K, $T \cong 68^{\circ}$ K.

3. Uncooled, two-stage parametric amplifier, $T_n \cong 90^{\circ}$ K, $T \cong 125^{\circ}$ K.

4. An uncooled, single-stage parametric amplifier, $T_n \cong 180^{\circ}$ K, $T \cong 228^{\circ}$ K.

5. A solid-state amplifier, $T_n \cong 320^{\circ}$ K, $T \cong 385^{\circ}$ K.

6. A mixer front end, $T_n \cong 1500^{\circ}$ K, $T \cong 1565$ K.

The losses arising from the antenna, feed, and wave guides have been assumed to range from $25^{\circ}$ K to $65^{\circ}$ K, depending on the cost of the antenna/feed design.

Eleven values of uplink RF power were considered, ranging from .1 watt to 10 kilowatts. A table of values and the associated single-unit costs follows. Included is the estimated site cost of the antenna and a column relating the per-unit cost of N identical items to the single-unit cost assuming that cost $= (.92)^{\log_2 N}$ units. $T_{sat}$ was fixed throughout at 1600 $K^{\circ}$ in the case studies.

4. State Equations

Let us now relate the terms of equations (2) to the space and ground-segment parameters. Define

$f_x$ = input flux density required to saturate the satellite transponder = watts/feet$^2$;

$f_{xr}$ = $4\pi R^2$, where R is the distance of the geostationary satellite from the most distant ground station on the 3 dB beam edge;

$P_{sat}$ = RF output power of the satellite transponder;

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Table II:  Ground Segment Cost/Performance Data

| Preamplifier | | Power Amplifier | | Antenna | | | | Volume Discount | |
|---|---|---|---|---|---|---|---|---|---|
| Pre-Amp(K°) | Cost(P.A.) | Trans(W.) | Cost(P.T.) | Diam(ft.) | Effic. | Cost(Ant.) | Site Cost | Number | Per-Unit Cost |
| 45 K° | $ 80,000 | 0.1 W | $ 200 | 7 ft. | .50 | $ 435 | 130 | 1 | 1.0000 |
| 68 | 40,000 | 0.5 | 500 | 8 | .50 | 530 | 160 | 10 | 0.7581 |
| 125 | 17,000 | 1.0 | 850 | 9 | .50 | 710 | 215 | 25 | 0.6790 |
| 228 | 7,000 | 5.0 | 2,000 | 10 | .50 | 1050 | 315 | 50 | 0.6246 |
| 385 | 1,000 | 10.0 | 3,500 | 11 | .50 | 1640 | 490 | 100 | 0.5747 |
| 1565 | 200 | 30.0 | 6,000 | 12 | .50 | 2610 | 780 | 250 | 0.5147 |
| | | 100.0 | 10,000 | 20 | .55 | 30,000 | 10,470 | 500 | 0.4735 |
| | | 350.0 | 17,000 | 32 | .55 | 90,000 | 31,400 | 1,000 | 0.4356 |
| | | 1000.0 | 28,000 | 42 | .55 | 510,000 | 229,400 | 2,500 | 0.3902 |
| | | 3000.0 | 34,000 | 85 | .55 | 1,420,000 | 637,000 | 5,000 | 0.3590 |
| | | 10000.0 | 60,000 | 37 | .55 | 2,180,000 | 978,000 | 10,000 | 0.3302 |

$(EIRP)_{sat}$ = effective isotropic radiated power of the satellite transponder on the 3 dB beam edge

= $P_{sat} \cdot_d G_{sat}$, where the latter term is the gain or the satellite antenna used on the downlink at the 3 dB beam edge;

$(A_e/T)_{sat}$ = effective-antenna-area-to-input-system-noise-temperature ratio of the satellite transponder at the 3 dB beam edge;

$(A_s/T_s)$, $(A_m/T_m)$ = corresponding quantity for the master and slave stations at beam center;

$P_s, \ell_s, P_m, \ell_m$ = power and loss of the transmitters at the master and slave stations.

Then[*]

$$
(5) \quad
\begin{cases}
(C/T)_u = (4\pi/\lambda_u^2)\ (A_e P)_u\ (A_e/T)_{sat}/f_{xr}\ \ell_u \\[2mm]
(C/T)_d = (4\pi/\lambda_d^2)\ (A_e P)_{sat}(A_e/T)_d/f_{xr}.
\end{cases}
$$

Consider first the case in which the satellite transponder is linear until the point of saturation. Letting g be the power gain of the transponder, the RF output power at beam center is given by the expression:

$$
P_{sat} =
\begin{cases}
g(4\pi/\lambda_u^2)\ (A_e P)_u\ (A_e)_{sat}/f_{xr}\ \ell_u, & (EIRP)_u \le f_x f_{xr}\ \ell_u \\[2mm]
g f_x (A_e)_{sat}, & (EIRP)_u > f_x f_{xr},
\end{cases}
$$

where

$$
(EIRP)_u = (4\pi/\lambda_u^2)\ (A_e \cdot P/\ell)_u.
$$

Recognizing that two classes of transponder are under consideration, we shall adopt the convention that transponder No. 1 pertains to the video link and transponder No. 2 to the return-audio (or data) link. After substituting equations (5) and (6) into equation (2) and recalling the definition, $(T/C)_q = (T/C)_t - (T/C)_{im}$, one obtains (after some algebra):

---
[*] For an introductory treatment of link-budget calculations, see G. M. Northrup: "Aids for the Gross Design of Satellite Communication Systems," IEEE Transactions on Communication Technology, Vol. Com-14, No. 1, pp. 46-56, February 1966.

$$
(7) \quad A_s T_s = \begin{cases} \dfrac{c_1}{g_1(A_m P_m - q_1)}, & q_1 < A_m P_m \le (_u\lambda_{TV}^2/4\pi)\,\ell_m\cdot {}_1 f_x\cdot f_{xr} \\[4mm] \dfrac{c_1' A_m P_m}{A_m P_m - q_1}, & A_m P_m > \max\left\{ q_1,\ (_u\lambda_{TV}^2/4\pi)\,\ell_m\ {}_1 f_x\ f_{xr}\right\} \end{cases}
$$

$$
(8) \quad q_1 = {}_1 f_{xr}\,(C/T)_q\,(_u\lambda_{TV}^2/4\pi)\,(A_e/T)_{sat}^{-1}\,\ell_m = \text{watts-feet}^2
$$

$$
(9) \quad c_1 = {}_1 f_{xr}^2\,(C/T)_q\,(_u\lambda_{TV}^2/4\pi)\,(_d\lambda_{TV}^2/f\pi)\,\ell_m\,(A_e)_{sat}^{-2} = \text{watt-feet}^4/{}^\circ K
$$

$$
(10) \quad c_1' = {}_1 f_{xr}\,(C/T)_q\,(_u\lambda_{TV}^2/4\pi)/P_{sat}(A_e)\ \text{sat} = \text{feet}^2/{}^\circ K,
$$

and $P_{sat}$ = maximum RF output power of satellite transponder.

Note that we have restricted our attention to those uplink powers for which $A_m P_m\ q_1$. The reader may verify that $A_m P_m/q_1 = (C/T)_u/(C/T)_q$. Were this ratio less than one, the required value of $(C/T)_d$ would be negative, as may be seen from equation (2).

The corresponding expression for the return link when the satellite is operated below saturation appears below:

$$
(11) \quad A_m/T_m = \dfrac{c_2}{g_2(A_s P_s - q_2)}, \quad q_2 < A_s P_s \le (_u\lambda_A^2/4\pi)\,\ell_s\ {}_2 f_x\ f_{xr},
$$

where

$$
(12) \quad c_2 = {}_2 f_{xr}^2\,(C/T)_q\,(_u\lambda_A^2/4\pi)\,(_d\lambda_A^2/4\pi)\,\ell_s\,(A_e)_{sat}^{-2}
$$

and

$$
(13) \quad q_2 = {}_2 f_{xr}\,(C/T)_q\,(_u\lambda_A^2/4\pi)\,(A_e/T)_{sat}^{-1}\,\ell_s.
$$

$\ell_m$, the power loss incurred in the video origination station, is a function of the number of video carriers multiplexed at the master station and is tabulated in Table III. $\ell_s$, the power loss of a slave station, is assumed to be 1.0 dB. Equations (7) through (13) establish the physical relationships between the ground and space-segment parameters which must be satisfied if the signal-quality constraints (which are related to $_1(C/T)_q$ and $_2(C/T)_q$ are to be met.

Consider now the case in which the satellite employs a hard limiter and/or automatic-gain control. Hard limiters have been employed extensively on communications satellites to insure that the limited available output power is fully utilized. The ideal hard limiter provides maximum output power however small the input power may be. Alternatively, automatic-gain control may be used to place the operating point at some specified value below the saturation point. This technique is attractive when multiple carriers are to access the transponder simultaneously, and it is necessary to reduce the intermodulation distortion generated in the transponder. Denote the nominal operating point, whether it be at saturation or some lesser value, by $P_{sat}$. We shall begin as before with equation (2). As defined, the numerator in the term $(C/T)_d$ pertains to that fraction of the satellite output power containing the signal. Denote this fraction by C and define $P_{sat} = C + N$ and let $L = C/P_{sat}$. It follows that $L^{-1} = 1 + N/C$. If B is the RF bandwidth of the transponder and k is Boltzmann's constant, then

$$N/C = kB[(T/C)_u + (T/C)_{im}].$$

By definition

$$L^{-1} \cdot (C/T)_d = (EIRP)_{sat} (A_e/T)_d/f_{xr}.$$

Substituting into equation (2), one ultimately obtains the expression:

$$(14) \quad A_s/T_s = \frac{c_{11}A_m P_m(c_{12} + c_{13}/A_m P_m)}{A_m P_m - q_1'}, \quad A_m P_m \geq q_1', \quad (_u\lambda^2_{TV}/4\pi) \ell_{ml} f_x f_{xr}$$

where

## Table III

### Cost/Performance of Master-Station Multiplexer

| No. Channels | Max. Loss | Cost |
|:---:|:---:|---:|
| 2 | 1.25 dB | $ 4,000 |
| 4 | 2.00 | 8,000 |
| 6 | 2.00 | 12,000 |
| 12 | 2.50 | 25,000 |

$$(15) \quad c_{11} = {}_1(C/T)_t\, f_{xr} / \left\{ [1 - {}_1\,(C/T)_t/(C/T)_{im}],\ (EIRP)_{sat} \right\},$$

$$(16) \quad c_{12} = 1 + kB(C/T)_{im}^{-1},$$

$$(17) \quad c_{13} = kBf_{xr}\, \ell_m ({}_u\lambda_{TV}^2/4\pi)\, (A_e/T)_{sat}^{-1}, \text{ and}$$

$$(18) \quad q_1' = {}_1(C/T)_t\, f_{xr} ({}_u\lambda_{TV}^2/4\pi)\, (A_e/T)_{sat}^{-1}/[1 - {}_1\,(C/T)_t/(C/T)_{im}].$$

Corresponding expressions may be written for the return link, where one replaces ${}_1(C/T)_t$ with ${}_2(C/T)_t$, $\ell_m$ with $\ell_s$, and $P_{sat}$ and $\lambda_{TV}$ with the expressions appropriate for the return link.

When only one carrier accesses the transponder, intermodulation distortion is negligible; and $c_{12} \simeq 1$, $c_{11} \simeq c_1'$, and $q_1' \simeq q_1$, where $c_1'$ and $q_1$ are defined by equations (9) and (7).

## 5. Signal-Quality Constraints

To complete the description of the coefficients defined above, it is necessary to relate ${}_1(C/T)_t$ and ${}_2(C/T)_q$ to the specified quality standards for the video and audio links.

Consider first the video link. Our design objective was to achieve at the receiver output a peak-to-peak-signal-to-weighted-noise-power ratio of either 43.0 dB or 56.0 at the 3 dB beam edge. From the FM equation,

$$(19) \quad (SNR) = 6[(B/2f_m) -1]^2 (C/N) (B/f_m)k_p, {}^*$$

---

[*]Equation (19) is based on the assumption that the RF bandwidth is given by Carson's rule, or $B = 2f_m(m+1)$. Recent experimental evidence suggests that the RF bandwidth allocated per video signal need not exceed the peak-to-peak frequency deviation, or a bandwidth of $2f_m \cdot m$ would suffice. Obviously these results, if confirmed, should be used in dimensioning future FM video systems. For details see "Breadboard Design and System Analysis for the ATS-F TRUST Experiment Small Ground Station," Communication R&D Branch, Goddard Space Flight Center, NASA, Greenbelt, Md., September 1971, pp. 2-48 through 2-68.

where

$B$ = RF video bandwidth,

$f_m$ = maximum baseband frequency for color TV = 4.8 MHz

$C/N$ = received carrier-to-noise ratio = threshold value
+ space-link margin = 10.0 + 3.0 = 13.0 dB

$k_p$ = noise-weighting-improvement factor = 10.8 dB,

$m$ = modulation index = $(B/2f_m)$ -1

Solving equation (19) for B (thereby obtaining threshold operation with a 3 dB space-link margin and an output SNR of 43 dB), one obtains $B = 25.1$ MHz.

Thus,

(20) $_1(C/T)_t$ = $(C/N)$ + B + k = 13.0 + 74.0 - 228.6 = 141.6 dBw/K,
where k = Boltzmann's constant = -228.6 dB watts/Hz-K.

If a 56 dB output SNR is required, one obtains $B = 56.2$ MHz. The corresponding value of $_1(C/T)_t$ = -140.8 dBw/K. However, if the RF band-width is constrained to be less than or equal to 40 MHz, as is now the case with most video transponders, one cannot operate at threshold. Solving for C/N in equation (19) with B = 40 MHz, one obtains C/N =18.2 dB, implying that $_1(C/T)_t$ = -134.3 dBw/K.

In Section C.2 we shall estimate the cost of a network to be composed of a mix of ground stations, some designed for direct reception (and threshold operation) and the remainder for terrestrial redistribution, requiring an output SNR or 56 dB. One searches over a range of RF bandwidths and modulation indices to obtain the minimum cost alternative. As the RF bandwidth increases, the performance (and cost) of the least-sensitive class of stations increases but the cost of the 56 dB stations decreases. Thus, the optimum RF bandwidth is a function of the ratio of direct broadcast to "community antenna" stations in the network.

We considered four modulation procedures for the return traffic, FM/FDMA, PCM/PSK/FDMA, PCM/PSK/TDMA, and Δ-MOD/PSK/TDMA.

The design goal was to achieve an output signal-to-noise ratio of 43 dB at the headend. From the FM equation,[9]

$$(21) \quad (SNR) = 3m^2 \ (C/N) \ (B/f_m) \ k_p',$$

where the terms are defined as before with the exception of the fact that we are concerned with rms signal power and that $k_p'$ is the peak-to-average factor for single-channel-per-carrier voice.[*] Choosing $k_p' = 13.0$ dB insures that the peak values will not be clipped more than 1% of the time.[10] Again using a threshold value of 10.0 dB with a 3.0 dB space-link margin, we have $C/N \geq 13.0$ dB. Solving equation (21) for m, one obtains m = 14.2, implying that $B \cong 2(14.2 + 1) \ (3400 \ Hz) \simeq 100$ kHz.
Thus,

$$(22) \quad _2(C/T)_t = 13.0 + 50.0 - 228.6 = 166.6 \ dBw/K$$

Consider now PCM/PSK. Operation is said to be <u>bandwidth limited</u> if the following inequality, expressed in dB, is satisfied:

$$(23) \quad B + \log_2 L_1 - R \leq (C/kT) - (E/N_o) \quad \ell \ M \ R$$

where $(C/kT)_t$ is the total carrier-power-to-noise-density ratio of the communications link, as given by equation (2). Otherwise, the system is said to be <u>power limited</u>. Prior to the advent of high-power TWT's and directive antennas, virtually all satellite communications networks tended to be power limited. Most stations in the Intelsat network are now bandwidth limited, and the tariff structure reflects the need to conserve bandwidth, which is relatively scarce. As mentioned previously, the small stations that we are considering tend to be power limited; and they are not charged for their use of bandwidth. The new terms introduced in inequality (23) are defined as follows:

---

[*] We have not assumed that syllabic companders or pre-emphasis will be used. These features would reduce $k_p'$ and should be studied. For a discussion of state-of-the art techniques, see P.M. Boudrean and N.G. Davies, "Modulation and Speech Processing for Single-Channel-per-Carrier Satellite Communications," 1971 International Conference on Communications.

R = required bit rate

L = number of levels in the PSK code

$E/N_0$ = received-energy-to-noise-power-density ratio

$\ell$ = implementation loss in the PSK modem

M = space-link margin

For voice, it is considered advisable to use 7-level PCM (with an eighth level for syncronization) and to sample at 8 kbps. Thus, R = 64.0 kbps = 48.1 dB-Hz. Typical numbers employed in a four-phase PSK system[4] are: = 2.3 dB, M = 3.0 dB, L = 4, and $E/N_0$ = 8.4 dB-Hz[2] (which provides a bit-error-rate of 1 in $10^4$). The required carrier-power-to-system-noise-temperature ratio is then:

$$(24) \qquad _2(C/T)_t = (E/N_0) + \ell + R + M + k = 8.4 + 2.3 + 58.1 + 3.0$$

$$- 228.6 = -166.8 \text{ dBw/K.}$$

On this basis, at least, there is little to distinguish between FM and PCM/PSK. At the present time, however, modem costs are much lower for FM. The picture may change in the future, which would be desirable in view of the flexibility offered by PCM/PSK in our case studies of digital feedback, although we would recommend using FM for voice-feedback systems comtemplated over the near term.

$\Delta$-MOD/PSK appears to offer significant power savings, although its merit relative to PCM/PSK remains controversial.[11] One may transmit at half the bit rate at a bit-error-rate of 1 in $10^3$ (rather than 1 in $10^4$), resulting in a power savings of approximately 4.0 dB.[12] That is, for $\Delta$-MOD/PSK, $_2(C/T)_t$ = 170.8 dBw/K for voice quality comparable to 43 dB in the FM case.

### 6. Intermodulation Distortion

As a satellite transponder is driven toward saturation, operation becomes increasingly nonlinear and intermodulation distortion increases. The extent to which a transponder is operated below saturation is known as input backoff, which in dB is defined by equation (25):

$$
(25) \quad BO = \begin{cases} 0, & (EIRP)_u - f_{xr} \le f_x \\ \\ f_x - (EIRP)_u + f_{xr}, & \text{otherwise} \end{cases}
$$

The output power, and hence the downlink carrier-power-to-noise-tempera-
ture-ratio, is also reduced by the factor BO. To maximize the channel
capacity of a particular satellite link, one must set BO to minimize the
quantity:

$$
(2) \quad (T/C)_t = (T/C)_u + (T/C)_{im} + (T/C)_d
$$

Unfortunately, we are unaware of an accurate, parametric relation-
ship between $(C/T)_{im}$ and BO. Given a satellite transponder, curves
may be obtained experimentally; but we do not wish to define the charac-
teristics of the transponder a priori. As a temporary expedient, we
shall employ curves provided by Chakraborty for Intelsat IV and assume
that they are generally applicable on a per-channel basis.[2] We do not
feel that our results pertaining to backoff are accurate. However, im-
proved accuracy could readily be obtained given a reasonable description
of $(C/T)_{im}$ as a function of input backoff, the transponder bandwidth,
and the number and spacing of the carriers which are to access this
transponder simultaneously.

We chose not to interpret Chakraborty's results quantitatively,
although we do assume that the shape of his curves is of general signi-
ficance. It is well known that when N FM voice channels are uniformly
spaced across a transponder, the (voice) channel capacity is maximized
when there is not backoff, at which time $(C/N)_{im} \cong 9$ dB.[13] Assuming
an RF bandwidth of 100 kHz per voice channel,

$$
(26) \quad (C/T)_{im}^o = 9.0 + 50.0 - 228.6 = -169.6 \text{ dBw/}^oK
$$

when the backoff, BO, equals 0 dB. $(C/T)_{im}^o$, as given by equation (26),
served as a reference point in our piecewise-linear approximation to
Chakraborty's Fig. 7. (Cf: ref. 2). Our approximation of the

per-channel value of $(C/T)_{im}$ as a function of BO appears below:[*]

$$(C/T)_{im} = dBw/^\circ K = \begin{cases} -169.6, & BO = 0 \text{ dB} \\ .643 \ BO - 169.6, & 0 < BO \leq 7 \text{ dB} \\ 1.12 \ BO - 172.9, & 7 < BO \leq 11 \text{ dB} \\ 1.78 \ BO - 180.2, & 11 < BO \end{cases}$$

The approximation given by equation (27) is compared with Chakraborty's empirical results in Fig. 2.

Curiously enough, when the ground-segment parameters are fixed and the space-sggment parameters are variable, the optimum backoff setting is a function only of the signal-quality constraint, $_2(C/T)_t$, and the uplink carrier-power-to-system-noise-temperature ratio, given by equation (5a). It is independent of the number of slave stations in the network, N, and the sensitivity of the master station, $A_m/T_m$.

To see this, define $P_{sat}^{(A)}$ to be the "useful" satellite power per audio channel required to achieve the required downlink carrier-power-to-noise-temperature ratio. If the backoff setting is BO, dB, the required peak satellite power, on which the space-segment is based, is BO dB above this value. That is, the per-channel space-segment charge is given by the expression: $SS \cdot 10^{BO/10} P_{sat}^{(A)}$. It will be shown in Section IV that $P_{sat}^{(A)}$ is related to the terms $A_s$, $P_s$, $A_m$, and $T_m$ in the following manner:

$$(27) \qquad P_{sat}^{(A)} = \frac{k_1 \ (A_m/T_m)^{-1}}{(1 - k_2/A_s P_s)}$$

where

$$k_1 = {}_2(C/T)_q \ ({}_d\lambda_A^2/4\pi) f_{xr} (A_e)_{sat}^{-1}$$

and

$$k_2 = {}_2(C/T)_q \ ({}_u\lambda_A^2/4\pi) \ \ell_s f_{xr} (A_e/T)_{sat}^{-1}.$$

---

[*] Equation (27) pertains to the value of $(C/T)_{im}$ per 100 kHz of RF bandwidth. If a multiplexed audio signal has an RF bandwidth of B kHz, the intermodulation term must be increased by the factor B/100 in equation (2).
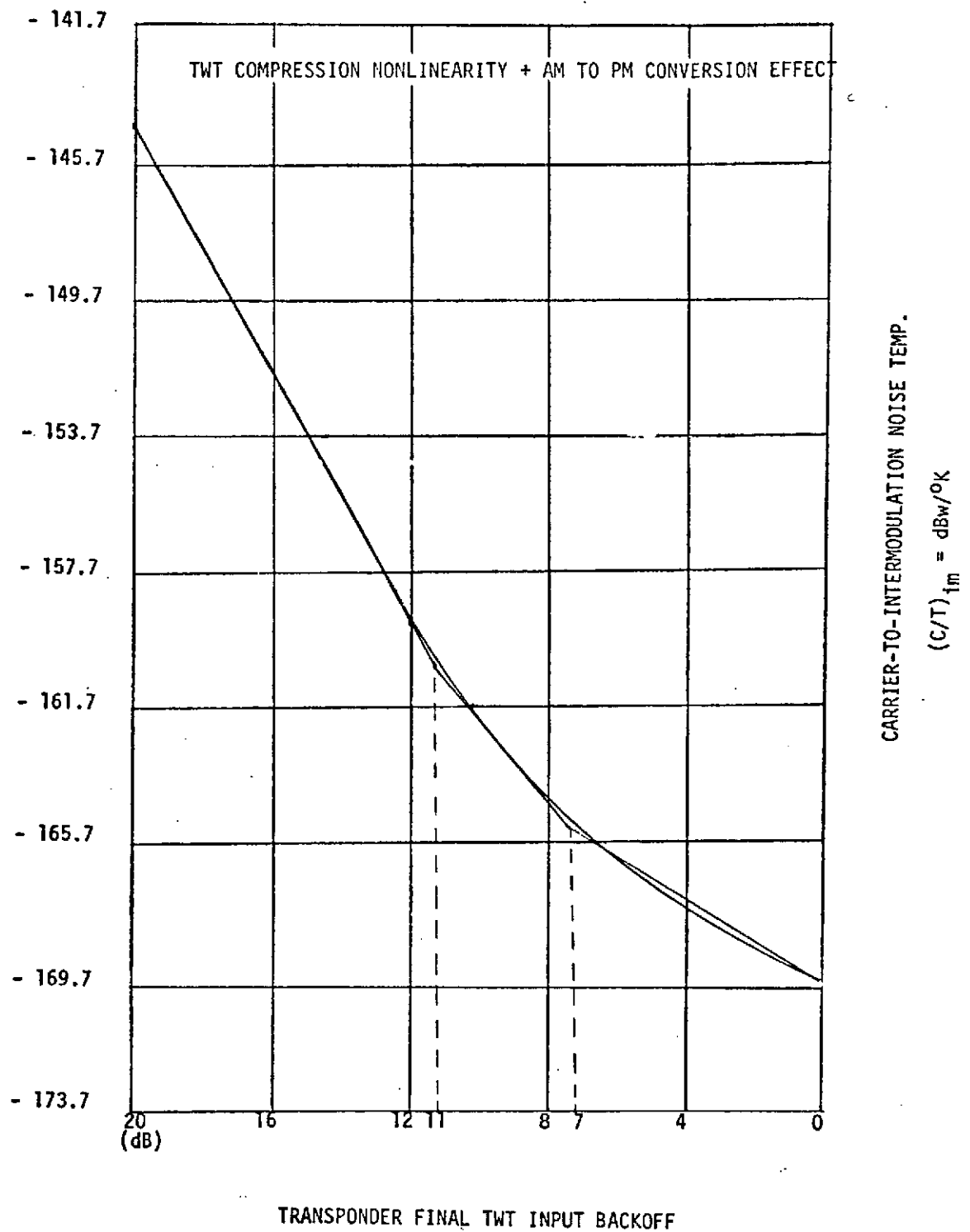
Fig. 2: $(C/T)_{im}$ vs. Backoff

$_2(C/T)_q$ may be related to BO using equation (27):

$$_2(C/T)_q = \frac{_2(C/T)_t}{1 - {_2(C/T)_t} \exp[-.2303(b_1 BO + b_2)]}$$

It follows that the space-segment charge is proportional to the expression:

(28) $\qquad P_{sat}^{(A)} = \dfrac{c_1 \exp(.2303BO)}{1 - c_2 - c_3 \exp(-.2303b_1 \cdot BO)}$

where

$$c_1 = {_2(C/T)_t}(A_m/T_m)^{-1}({_d}\lambda_A^2/4\pi)f_{xr}(A_e)_{sat}^{-1},$$

$$c_2 = {_2(C/T)_t}(A_s P_s)^{-1}({_u}\lambda_A^2/4\pi)\, \ell_s f_{xr}(A_e/T)_{sat}^{-1}$$

$$= {_2(C/T)_t}/(C/T)_u < 1,$$

and

$$c_3 = {_2(C/T)_t}\exp[-.2303\, b_2]$$

Differentiating (28) to minimize the space-segment charge, one obtains:

(29) $\quad BO(dB) = {_2(C/T)_t} -b_2 + 10\log_{10}\left[\dfrac{1+b_1}{1-c_2}\right]$

For the asymmetrical links under consideration, the ratio of total noise to uplink noise ranges from 4 to 18 dB. To obtain a 43 dB output signal-to-noise ratio for the return voice, $_2(C/T)_t = -166.6$ dBw/K$^O$. (Cf: equation (22).) Substituting the values of $b_1$ and $b_2$ given by equation (27), one may infer from the above expression that the optimum backoff setting ranges from 9.5 to 11.0 dB, depending only on the quantity $c_2 = {_2(C/T)_t}/(C/T)_u$. This result greatly simplifies a numerical evaluation of the optimum system configuration. In the case studies that appear in Section IV, we restricted the set of "admissible" backoff settings to 10 or 11 dB.

7. Modulation Procedures:

   a. Multiple Access

     There are many modulation techniques that can provide multiple access, each of which has advantages and disadvantages. In a time-division-multiple-access (TDMA) system, transmissions from different slave stations do not overlap in the satellite repeater. Each station is assigned exclusive use of the satellite transponder (which is effectively memoryless) during specified time slots; there is virturally no interaction between signals (i.e., intermodulation distortion is insignificant). The master station receives a single, wideband signal which must be demultiplexed at the master station to sort out the responses from the individual remote stations. This procedure makes very efficient use of the available bandwidth and power of the transponder, but the ground-segment costs are relatively high. In addition to the need for expensive demand-assignment control apparatus and digital modems, the uplink power transmitters required at each slave station tends to be larger in a TDMA system. An access channel, in the context of TDMA, designates a particular sequence of time slots.

     In a frequency-division-multiple-access (FDMA), system the bandwidth of the transponder is divided into a number of non-overlapping frequency slots, which define the access channels. Thus, the power of the satellite is continuously shared by many users. Conceptually, FDMA and TDMA are very similar in that both utilize non-overlapping signals. The practical implications of the two approaches, however, are quite different. Two other common techniques are spread-spectrum multiple access and pulse-address multiple access. These approaches are used primarily to provide secure communications, in the sense of privacy and resistance to jamming. Both are relatively expensive. For commercial applications, cost, capacity, and resistance to interference are the important considerations. At the present time, the choice is thought to be between TDMA and FDMA.[14]

     There are two major differences between TDMA and FDMA. In an FDMA system, a narrow band signal is returned from each slave station, which significantly reduces the required peak power of the uplink transmitter. Secondly, while the voice channel is active, the carrier accesses the transponder continuously, rather than in bursts. Unlike TDMA, many

carriers may be accessing the transponder simultaneously. Due to non-linearities in the transfer characteristics of this transponder, these different carriers interact, giving rise to intermodulation distortion. To combat this problem, one generally does not operate the transponder at saturation; that is, one "backs off" the (uplink) input signal and does not use all of the available power of the transponder--even though he pays for it. Thus, one must tradeoff the objectionable characteristics of intermodulation distortion against increased space-segment charges. The optimum value of the input backoff is a function of the ratio of the total allowable noise to that fraction contributed by the uplink. This value ranges from 9.5 to 11.0 dB, as indicated in Section B.6.

Suppose that $n_A$ narrowband channels are to share the return-link transponder. In a TDMA system, each slave station must transmit at the system bit rate, which in the case of audio channels is $R = n_A \cdot 64$ kbps. Referring to equation (24), it follows that the carrier-power-to-noise-temperature ratio required for this broadband signal is $n_A \cdot 2(C/T)_t$. Because intermodulation distortion is negligible in a TDMA system, $2(C/T)_q = n_A \cdot 2(C/T)_t$. In an FDMA system, $2(C/T)_q \cong 2(C/T)_t$ for BO > 9.5 dB.

For reasons that will be explained in Chapter III, the required EIRP at each slave station is higher in a TDMA system, although the product of satellite power and master-station sensitivity is reduced. For the networks under consideration, in which one is concerned with the combined cost of part of one satellite, one master station, and N slave stations, the cost comparisons increasingly favor FDMA systems for large values of N.

In our case studies of voice feedback, we compared the cost of FM/FDMA with Δ-MOD/PSK/TDMA. We restricted our attention to single-channel-per-carrier-operation. The carriers were assumed to be voice activated and the channels on the satellite were to be assigned on demand.

We compared PCM/PSK/FDMA with PCM/PSK/TDMA in our studies of digital feedback. To obtain a conservative estimate of the power requirements of the return-link transponders, each slave station was assumed to have a single carrier which was continuously active. The bandwidth require-

ments of such an approach rapidly become excessive, however. A minimum of 100 kHz of bandwidth would have to be allocated for each slave station in the network. Consequently, it probably would be necessary to employ a disciplined pulling procedure or even demand-assigned satellite circuits to service a large number of slave stations.

b.  Demand Assignment

As the number of return channels increases, the space-segment charges become more significant. Despite the increased ground-segment costs, demand assignment could prove to be cost effective. Demand-assignment circuits are well suited to the needs of users having light and diffuse traffic patterns. Such users would prefer to be charged per-minute-of-use rather than to lease pre-assigned satellite circuits-- which they would seldom use--for an extended period of time. Demand assignment uses the available bandwidth and power of the satellite far more efficiently when small users are accessing the transponder.

Communication networks are designed to accommodate an anticipated load (as described by the statistics of traffic origination) at a satisfactory grade of service (a function both of the desired signal-to-noise ratio and the loss probability--i.e., the probability that a circuit in the trunk will be found busy during the busiest hour). Traffic-handling efficiency (the ratio of traffic carried to the number of circuits in the trunk) tends to increase with the size of the trunk. To illustrate, suppose that a single-voice-circuit trunk is designed to have a 1% loss probability. The traffic statistics must be such that this circuit is used less than 1% of the time (on the average) during the busiest hour: the loss probability will be exceeded if the circuit is offered more than .01 erlangs[*] of traffic. A two-circuit trunk could be offered over

_____

[*] The erland is a unit of traffic flow. A simplex circuit which carries a one-way telephone conversation continuously for one hour has carried an average "load" of one erlang of-traffic. Quantitatively, erlangs equal call-hours-per-hour. Thus, in a physical sense, the erlang is a dimensionless quantity; in the context of traffic engineering, it has the dimensions of "calls".

15 times as much traffic (.153 erlangs) with this same loss probability, while with 12 circuits 5.88 erlangs could be offered--giving rise to a traffic efficiency of almost 50% without violating the constraint that a random call originated during the busiest hour should locate an open line with a probability of at least .99. The pooling arrangement of demand assignment dramatically increases the trunking efficiency of a communications satellite.

In a system having only pre-assigned circuits, the large trunks generally would be used more efficiently than the small ones, which typically would be very inefficiently employed. If all the circuits were members of a single demand-assignment pool, the circuits of the satellite transponder would constitute a single trunk to which all of the traffic would be offered, resulting in the maximum traffic-handling efficiency. For a given traffic profile with fixed loss, the number of circuits required on the satellite would be a minimum; any circuit taken from the pool (i.e., pre-assigned) would necessarily have a lower traffic efficiency for a loss equal to that of the previous configuration.

The foregoing observations do not necessarily imply that a policy of pooling all of the circuits of the voice transponder into a single demand-assignment pool is necessarily most satisfactory; the mechanics of allocating these circuits on demand are not trivial. Despite the increased satellite-utilization efficiency that would accrue through use of demand-assigned circuits, Intelsat did not introduce them until 1971, in part because of the complexity of the required control apparatus on the ground.

We have not explicitly considered modem costs in this anlaysis. The only commercially-available demand-assigment modem of which we are aware is SPADE, which was developed at COMSAT.[15] The capital cost of a SPADE terminal, designed to permit each ground station in the network to monitor satellite loading and to initiate a request for service independently, is approximately $100,000. Additionally, there is a per-channel cost of approximately $5,000.[15] These cost figures completely eliminate SPADE from consideration in a network to be composed of many low-cost ground stations. Of course, the control functions could be

handled primarily by the master station; the STAR network is one previous-
ly-developed alternative that is based on this concept.[16]

The flexible routing permitted by a communication satellite may prove
to be its most useful feature; but this promise will not be realized un-
til economical demand-assignment equipment becomes available. Unless
major technological breakthroughs occur, it is quite conceivable that
the cost of switching will dominate. (Switching equipment is estimated
to represent 70-80% of the cost of the long-haul apparatus in the Bell
System, for example.[17] Over the nearer term, the most attractive ser-
vices for satellite teleconferencing are those which do not involve sub-
stantial switching.

It would appear that the design of a low-cost control mechanism will
present more of a problem for TDMA than FDMA. If bandwidth is not
scarce, for example, each station (or group of stations) could be assig-
ned permanent frequency slots in an FDMA system. If their carriers were
voice actuated, the satellite transponder would have to be designed to
accomodate the peak composite demand for power (where, again, the pooling
arrangement would significantly reduce the ratio of peak-to-average
power consumption). Nonetheless, because the multiple-access efficiency
of TDMA is much higher than that of FDMA, TDMA is potentially the more
attractive alternative.[14]

### c.   Video Link

The video is transmitted using single-channel-per-carrier-
per-transponder FM. Consequently, one power transmitter per video chan-
nel is needed at the master station. Additionally, we have provided one
spare transmitter at the video uplink.

The carriers from the various transmitters are combined and radiated
through a single antenna. We have assumed that circulator multiplexers
having the cost and performance described in reference 19 will be employ-
ed. The power loss and cost is a function of the number of video chan-
nels to be transmitted. The alternative configurations and cost data
are tabulated in Fig. 3.

A video baseband bandwidth of 4.8 MHz has been assumed. This allot-
ment would permit transmission of color video with up to 8 audio channels

$n_{TV} = 2$

$n_{TV} = 4$

$n_{TV} = 6$



⊗ = Switch $\cong$ $500

F = bandpass filter $\cong$ $1000;   Loss $\cong$ .75 dB

Cir. = four-port circulator $\cong$ $1000; max loss $\cong$ .75 dB
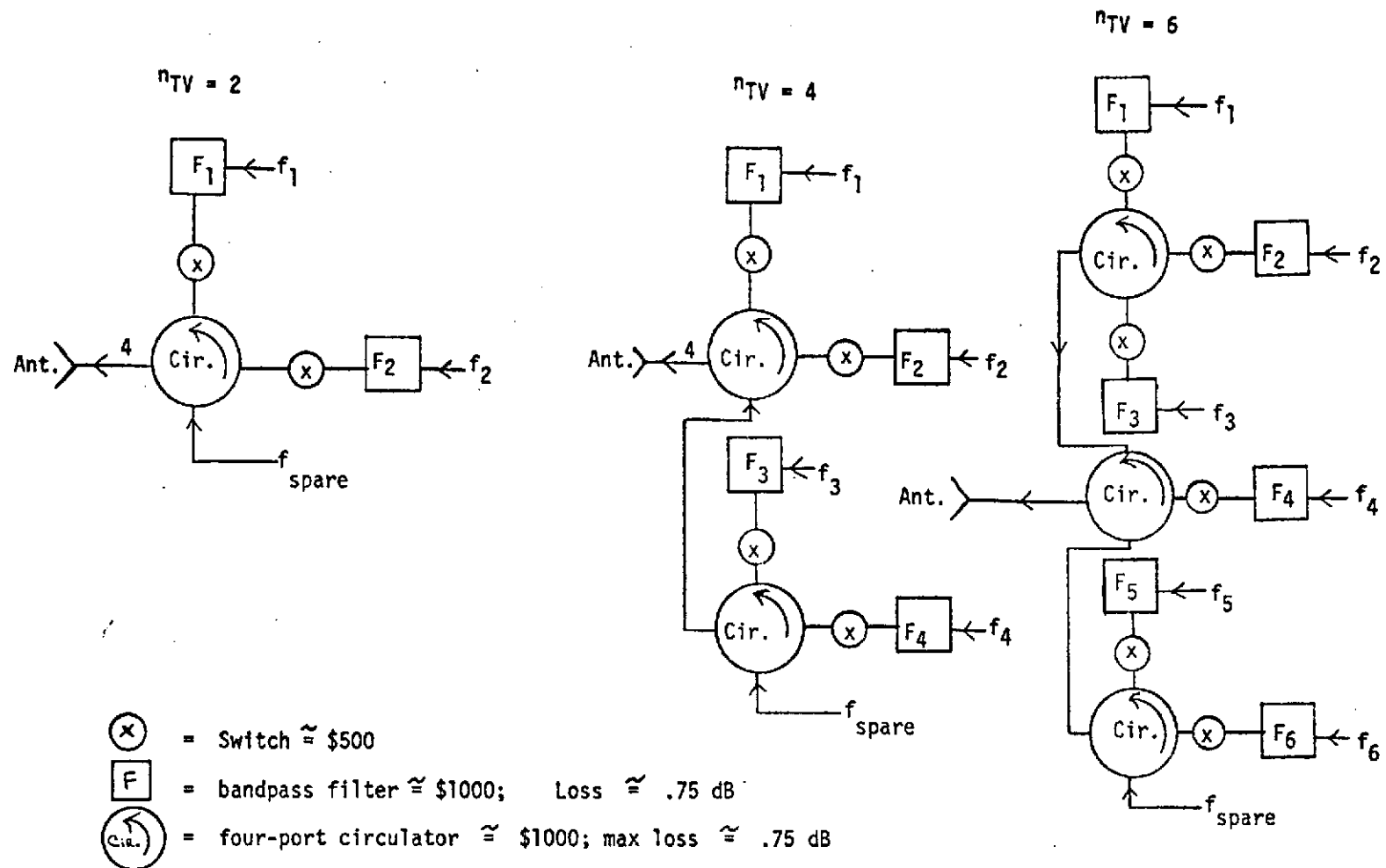
Table III:  Cost/Performance of Master-Station Multiplexer

| # Channels | Max. Loss | Cost |
|---|---|---|
| 2 | 1.25 dB | $ 4,000 |
| 4 | 2.00 | 8,000 |
| 6 | 2.00 | 12,000 |
| 12 | 2.50 | 25,000 |

Fig. 3:  Video Multiplexer Configurations

V-36

multiplexed on a subcarrier.[19] An output signal-to-noise ratio of 43 dB
or 56 dB at the 3 dB beam edge was the assumed signal-quality constraint.

Having no knowledge of available uplink frequencies, we have assumed
that both the TV and return audio would go up at 6 GHz. The downlink
frequencies have been set at 2.5 GHz and 2.2 GHz, respectively. The
ITFS band, which extends from 2500 MHz to 2690 MHz, is particularly well
suited for the distribution of educational and health materials via
satellite in view of the allocations granted at the 1971 session of the
World Administrative Radio Conference.[20] Nonetheless, the number of
video channels which may be distributed in this band is limited. We have
used an RF bandwidth of 25 MHz in our calculations, implying that if more
than 7 video channels are to be distributed the band must be reused.*
For $7 < n_{TV} < 15$, we have assumed that orthogonal polarization would be em-
ployed; and that two pre-amps and two antennas would be used at each
slave station.

Due to the fact that the channel capacity of the ITFS band is limited,
it would appear to be attractive to multiplex several video channels
per carrier. If high-power tubes could be made available economically,
it might be more efficient to use a single transponder, having 190 MHz
of bandwidth. One could achieve multiple access in the usual way by back-
ing off from the point of saturation. Unfortunately, the present video-
baseband format leads to significant practical difficulties. The goal,
of course, is to reduce the peak-to-average factor by combining many
channels on a single carrier--the principal reason large voice trunks
are multiplexed. However, the sync pulse and the color coding at 3.54 MHz
represent distinctly non-random features, meaning that a great many video
channels must be multiplexed before the law of large numbers begins to
take effect.[21] And when more than three conventional video channels are
multiplexed, it is difficult to obtain the required phase linearity in a
low-cost receiver.[22]

It might be possible, however, to modify the baseband format prior
to transmitting the video signals to the satellite. It would be necessary

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*
Threshold operation with a 3 dB space-link margin has been assumed, the
objective being to obtain an output signal-to-noise ratio of 43 dB. Cf:
equation (19).

to transform the multiplexed signals into a format compatible with exis-
ting TV receivers at the receiving ground station, but the increased
equipment costs on the ground might be justified by reductions in the
space-segment charges. We recommend that this notion be pursued further.

## C. Fixed Satellite Parameters: Optimization of the Ground Segment

### 1. Identical Slave Stations

We shall assume that one pays for the use of a TV or audio trans-
ponder on an "all or nothing" basis, the alternative being to use a ter-
restrial distribution system - or to write off the project as being econ-
omically unfeasible. A consequence of this assumption is that the para-
meters of the nimumum-cost ground stations are relatively insensitive to
the number of received video channels, $n_{TV}$.[*] Thus, once the system is
installed, the marginal cost of expanding the channel capacity is essen-
tially constant (equal to the incremental space-segment charge) until the
available bandwidth is consumed. Then one must reuse the allotted spec-
trum, increasing the ground-segment costs as well. (When both the ground
and space-segment parameters are variable, the marginal cost is a decrea-
sing function of $n_{TV}$ for $1 \leq n_{TV} \leq 7$, as will be seen in Fig. 6.20 of Chap-
ter VI.

The problem of determining the minimum-cost ground-station parameters
is relatively straight-forward when the transponder parameters are fixed.
One requires knowledge of the maximum output power of the two classes of
transponder, $_iP^o_{sat}$; the input flux density in watts/feet$^2$ which saturates
the transponders, $_if_x$, where $i = 1, 2$; curves relating $(C/T)_{im}$ to input
backoff; the effective area of the satellite antenna, $(A_e)_{sat}$; and the
noise temperature of the receive subsystems of the transponders, $T_{sat}$.
We shall assume that the power transfer functions of the transponders are
linear, although the equations easily could be modified for hard limiting
or automatic-gain control.

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[*] At most 190 MHz is available in the ITFS band, which extends from 2500
MHz to 2690 MHz. Assuming a 25 MHz RF bandwidth for the video signals,
at most 7 channels can be distributed before the spectrum must be roused.
We have assumed that two antennas and two pre-amplifiers would be used
at each slave station in this event.

The algorithm to be described is designed for rapid numerical analysis. To reduce the execution time, it is helpful to decouple the analysis of the slave stations from that of the master. We consider six different pre-amplifiers and 11 transmitter alternatives in our case studies. Thus, there are a maximum of 66 cases to be evaluated per station. If the stations were decoupled, at most $66 + 66 = 132$ cases would need to be considered; if the parameters of the master and slave stations were coupled, the figure would rise to $66 \times 66 = 3356$ cases. For this reason, we introduce two subsidiary parameters, which are the independent variables in the algorithm to be described.

Suppose that the video noise budget is partitioned so that $(C/T)_u = {}^x(C/T)_d$. It follows that:

$$(30) \qquad (C/T)_u = (1 + x)_1(C/T)_t = (4\pi/_u\lambda_{TV}^2)(A_m P_m/\ell_m f_{xr})(A_e/T)_{sat}*$$

and that

$$(31) \qquad (C/T)_d = (1 + x^{-1})_1(C/T)_t = [(EIRP)_{sat}/BO \cdot f_{xr}](A_s/T_s)$$

where
$(EIRP)_{sat} =/$ 1/2 the maximum effective isotropic radiated power of the satellite transponder**

and

$$(32) \qquad BO = \begin{cases} 1, & (A_m P_m/\ell_m f_{xr}) > 1^f x \\ 1^f x/(A_m P_m/\ell_m f_{xr}), & \text{otherwise.} \end{cases}$$

Thus, given a value of x, the following relations may be inferred:

---

* x must be greater than 0 to insure that $(C/T)_u >_1 (C/T)_t$. Otherwise, the required value of $(C/T) = [(T/C) - (T/C)]^{-1}$ would be negative.

**The objective is to meet the signal-quality constraint for those stations 3 dB or less from beam center. If the transponder uses automatic-gain control or a hard limiter, $(EIRP)_{sat}/BO$ is defined to be that fraction of the satellite output power containing the signal. There are minor modifications to equations (33) and (34) that are discussed in the derivation of equations (14) through (18).

$$(33) \qquad A_m P_m = (1 + x)_1 (C/T)_u \left(_u\lambda^2_{TV}/4\pi\right) \ell_m f_{xr} (A_e/T)^{-1}_{sat} = (1 + x)k_1$$

$$(34) \qquad A_s/T_s = \begin{cases} \dfrac{(1 + x^{-1})_1 (C/T)_t f_{xr} BO}{(EIRP)_{sat}}, & x \leq \dfrac{_1 f_x (A/T)_{sat}}{_1 (C/T)_t} - 1 \\[4ex] \dfrac{(1 + x^{-1})_1 (C/T)_t}{(EIRP)_{sat}}, & x \geq \dfrac{_1 f_x (A_e/T)_{sat}}{_1 (C/T)_t} - 1 \end{cases}$$

$$= (1 + x^{-1}) k_4(x)$$

The video-link equations are the same whether TDMA or FDMA is used to provide multiple access for the return traffic. In most cases it proves to be cost effective to drive the TV transponder into saturation. Even though the required uplink EIRP of the master station would be reduced by backing off, the cost of the N slave stations would be minimized by using all of the available transponder power – which one pays for in any case.

It is essential not to saturate the return-audio transponder when FDMA is used for the return traffic, however. As indicated in Section B.6. it is physically impossible to meet the signal-quality constraint unless at least 4.7 dB of input backoff is provided. (Equation (27), on which this statement is based, was derived from empirical data pertaining to Intelsat IV.) Even in the case of TDMA, for which intermodulation distortion is negligible, it sometimes proves to be cost effective to conserve uplink power from the N slave stations in exchange for increased master-station sensitivity.

Suppose that $n_A$ audio carriers must access the return-link transponder. In the case of FDMA, these carriers continuously occupy the transponder in non-overlapping frequency slots; they each receive $1/n_A$ of the available power. The information is modulated in bursts in the case of TDMA, each carrier receiving the full power of the transponder in non-overlapping time slots.

The total flux density required to saturate the audio transponder has been defined to be $_2f_x$ watts/feet$^2$. Thus, for a specified input backoff, the uplink EIRP for an FDMA carrier satisfies the equation:

$$(A_s P_s / \ell_s)(4\pi / _u\lambda_A^2)/f_{xr} = {_2f_x}/(n_A BO).$$

implying

$$(35) \qquad A_s P_s = ({_2f_x}/n_A BO) x_s ({_u}\lambda_A^2/4\pi) f_{xr} = k_3/(n_A BO).$$

Given BO, $(C/T)_{im}$ --and hence $_2(C/T)_q$ --may be determined from equation (27). The uplink EIRP must be sufficient to insure that $(C/T)_u = ({_2f_x}/n_A BO)(A/T)_{sat} > _2(C/T)_q$. Hence, BO must lie in the range:

$$(36) \qquad 4.7 < BO \ (dB) < {_2f_x} + {_2(A_e/T)_{sat}} - {_2(C/T)_q} - n_A$$

When $n_A$ becomes too large, a second transponder must be used.

The uplink carrier-power-to-noise-temperature ratio associated with a particular backoff setting, BO, is simply:

$$(C/T)_u = ({_2f_x}/n_A \cdot BO)(A_e/T)_{sat}.$$

To precisely meet the signal-quality constraint for the narrowband return signal, $(C/T)_d$ must satisfy the equation:

$$(37) \qquad (C/T)_d = \frac{1}{(T/C)_q - (T/C)_u}$$

$$= \frac{(EIRP)_{sat}}{n_A \cdot BO \cdot f_{xr}} \cdot (A_m/T_m)$$

Consequently, the required master-station sensitivity in an FDMA system is given by the equation:

$$(38) \quad A_m/T_m = \frac{BO \cdot f_{xr}}{(EIRP)_{sat}} \cdot \frac{1}{(T/C)_q/n_A - BO/[_2f_x \cdot (A_e/T)_{sat}]}$$

The quantity $_2(C/T)_q = \dfrac{1}{(T/C)_t - (T/C)_{im}}$ is bounded below by $(C/T)_t$, approaching the lower bound asympototically as BO and $(C/T)_{im}$ approach infinity. The optimum value of BO is generally in the neighborhood of 10 dB, however; so that for FDMA $_2(C/T)_q \cong {_2(C/T)_t}$.

When TDMA is used to provide multiple access, each slave station must transmit at the <u>system</u> bit rate and $_2(C/T)_q = n_A \cdot {_2(C/T)_t}$. The equations corresponding to (35) and (38) are:

$$(35') \quad A_s P_s = (_2f_x/BO) \,_s(_u\lambda_A^2/4\pi)f_{xr} = k_3'/BO$$

and

$$(38') \quad A_m/T_m = \frac{BO \cdot f_{xr}}{(EIRP)_{sat}} \left[ \frac{1}{(T/C)_t/n_A - \dfrac{BO}{_2f_x (A_e/T)_{sat}}} \right] = k_2(n_A, BO)$$

For the same backoff setting, the uplink EIRP is higher by a factor of $n_A$ for TDMA; and the master-station sensitivity is approximately the same. Of course, BO is not constrained to be greater than 4.7 dB in a TDMA system; in fact the transponder is often driven into saturation, in which case BO≤0 dB. As a result, the master-station sensitivity is generally less in a TDMA system, but the slave-station EIRP is significantly higher. Consequently, the cost comparisons increasingly favor FDMA as N becomes large. This conclusion is reinforced by the fact that modem costs, which presently are higher for TDMA systems, have not been included in the analysis.

Equations (33), (34), (35) and (38) are summarized below:

$$A_m P_m = (1 + x)k_1$$

$$(39) \quad A_m/T_m = k_2(n_A, BO)$$

$$A_s P_s = k_3/(n_A BO)$$

$$A_s/T_s = (1 + x^{-1})k_4(x)$$

Thus, given x and BO, the analysis of the master and slave stations is decoupled.

In most cases it is impossible to obtain combinations of parameters which simultaneously satisfy equations (33), (34), (35), and (38). The right-hand side of these equations serve as lower bounds which insure that the signal-quality constraints will be met. One searches over T and P to obtain the least-cost combination of parameters satisfying these inequalities. The optimum combination generally provides a slightly higher video and/or audio signal-to-noise ratio than required. A search over x and BO completes the analysis. For TV-only operation, one need only search over x.

Prior knowledge which enables one to restrict the range over which one must search for the minimum-cost values of x, BO, $T_s$, $P_s$, $T_m$, and $P_m$ greatly reduces execution time. For example, the peak power of the slave station transmitter is unlikely to exceed one watt for FDMA operation; and the video uplink is likely to require at least 10 watts of transmitter power. The pre-amp noise temperature of the slave stations is a monotonically increasing function of N, the number of slave stations in the network; while $T_m$ is a monotonically decreasing function of N. The range of x may be increasingly restricted in similar fashion. A flow chart of the procedure appears in Fig. 4.

$SS_v$ = \$/video transponder/year ($n_{TV}$ in all)

$SS_A$ = \$/return transponder/year ($n_{AT}$ in all)

START

Enter $D_{sat}$, $T_{sat}$, $u^\lambda_{TV}$, $d^\lambda_{TV}$, $u^\lambda_A$, $d^\lambda_A$, $_1(C/T)_t$, $_2(C/T)_t$, $SS_v$, $SS_A$, Ground-Segment Costs

Do 1 N ← 10, 25, ..., 1,000
Set discount factor:
$d(N) = N(.92)^{\log_2 N}$. Set
$C_t = N10^6$. Specify range of
x ← $X(N)$, B0 ← $B(N)$, $T_s$ ← $T_s(N)$,
$P_s$ ← $P_s(N)$, $T_m$ ← $T_m(N)$, $P_m$ ← $P_m(N)$.

Do 2 x ← $X(N)$
Compute $c_1 = (1+x)k_1$,
$c_4 = (1+x^{-1})k_4$.

Do 3 B0 ← $B(N)$
Compute $_2(C/T)_q$. Determine
required number of return-link
transponders, $n_{AT}$. Set
$c_2 = k_2(n_A, B0)$, $c_3 = k_3/(n_A B0)$
Analysis of master and slave
stations essentially decoupled
at this point.

Set $C_s = N10^6$
Do 4 $T_s$ ← $T_s(N)$
Do 5 $P_s$ ← $P_s(N)$
Set $A_s = \max\{c_3/P_s, c_4 T_s\}$
Compute $A_a(A_s)$ (eq'n (4))
$z = d(N)[A_a \cdot (A_s) + A_{pa}(T_s) + A_{pt}(P_s)]$
If (z ·GE· $C_s$) go to 5
$C_s = z$, $A^o_s = A_s$, $T^o_s = T_s$, $P^o_s = P_s$

5 continue
4 continue

Set $C_m = N10^6$

Do 6 $T_m$ ← $T_m(N)$

Set $d_T = \begin{cases} 1, & T_m \neq T^o_s \\ d(N)/N, & T_m = T^o_s \end{cases}$

Do 7 $P_m$ ← $P_m(N)$

Set $d_P = \begin{cases} \bar{n}_{TV} + 1, & P_m \neq P^o_s \\ (n_{TV}+1)d(N)/N, & P_m = P^o_s \end{cases}$

Set $A_m = \max\{c_1/P_m, c_2 T_m\}$

Compute $A_a(A_m)$

$z = A_a(A_m) + d_T A_{pa}(T_m) + d_P A_{pt}(P_m)$

If (z ·GE· $C_m$) go to 7

$C_m = z$, $T^o_m = T_m$, $P^o_m = P_m$, $A^o_m = A_m$
7 continue
6 continue

Set $z = C_s + C_m + n_{TV} SS_v + n_{AT} SS_A$
If (z ·GE· $C_t$) go to 3
$C_t = z$, $A'_s = A^o_s$, $T'_s = T^o_s$, $P'_s = P^o_s$
$A'_m = A^o_m$, $T'_m = T^o_m$, $P'_m = P^o_m$, $B0^o = B0$
$x^o = x$
3 continue
2 continue

Store the minimum-cost results for
the choice of $(n_{TV}, N, n_A)$ under
consideration.
1 continue

Print results for N ← [10, ..., 1,000]

STOP

## 2. Classes of Slave Stations

Suppose that there are k classes of slave stations and that
$N = n(1) + n(2) + \ldots + n(k)$. Each station is assumed to return a single,
narrowband carrier to the master station; but the video signal-quality
constraints for the various classes of stations are different. Denote
the required carrier-power-to-noise-temperature ratios by $_1(C/T)_t^{(i)}$,
$i = 1, 2, \ldots k$. As before, the configuration of the minimum-cost
ground segment is independent of the number of received video channels,
$n_{TV}(i)$, $i = 1, \ldots k$, until the spectrum must be reused. The different
stations do not necessarily pay the space-segment charge required to re-
ceive all of the available channels; but we shall assume that the TV
transponders have identical performance characteristics.

Fortunately, the analysis of the $k + 1$ different categories of sta-
tions may be decoupled. For simplicity, we shall let $k = 2$. This is
a case which would arise, for example, if $n(2)$ of the stations were lo-
cated at the point of use and $n(1)$ of the stations were the headend of
a terrestrial redistribution system, each of which required signal-to-
noise ratio at the point of use would rest with the owners of the terres-
trial systems. We have assumed that class 1 stations require a 56 dB
video signal and that class 2 stations require a 43 dB signal on the
3 dB contour.

The optimum modulation index for the video is a compromise between
that value which results in threshold operation for the 43 dB or 56 dB
stations; it edges ever close to that required by the class 1 stations
as the quantity $n(1)/n(2)$ increases. In configuring the two classes of
stations, it is important to consider the larger discounts which accrue
when they use identical components. This situation occurs with increasing
frequency as the quantity $n(1)/n(2)$ increases.

Suppose that the video noise budgets are partitioned so that

$$(C/T)_u^{(1)} = x_1 \cdot (C/T)_d^{(1)}$$

and (40)

$$(C/T)_u^{(2)} = x_2 \cdot (C/T)_d^{(2)}.$$

One may conclude from equation (33) that:

$$(33') \quad A_m P_m = (1 + x_1)_1 (C/T)_t^{(1)} (_u\lambda_{TV}^2/4\pi) \ell_m f_{xr} (A_e/T)_{sat}^{-1} = (1 + x_1)$$

$$k_1^{(1)}$$

and that

$$(1 + x_1) \cdot {}_1(C/T)_t^{(1)} = (1 + x_2) \cdot {}_1(C/T)_t^{(2)},$$

implying

$$(41) \quad x_2 = \frac{(1 + x_1)_1(C/T)_t^{(1)}}{{}_1(C/T)_t^{(2)}} \quad -1.$$

Thus,

$$A_s(1)/T_s(1) = (1 + x_1^{-1})k_4^{(1)} (x_1)$$

and (42)

$$A_s(2)/T_s(2) = (1 + x_2^{-1}) k_4^{(2)}(x_2)$$

where $k_4$ is defined by equation (34).

Both classes are designed to return a 43 dB audio signal to the master station. We shall constrain each station to provide the same uplink EIRP in order to insure that the transponder does not see two different values of "backoff". This constraint is unfortunate because the antenna of a class 1 station tends to be larger, meaning that a class 2 station requires more transmitter power to compensate. Given BO, the transmitter powers satisfy the expressions:

$$(43) \quad A_s(1)P_s(1) = A_s(2)P_s(2) = k_3/(n_A BO);$$

and the required master-station sensitivity is:

$$(44) \quad A_m/T_m = k_2(n_A, BO),$$

where $k_1$, $k_2$, $k_3$, and $k_4$ are defined by equations (33) through (38).

The analysis proceeds exactly as before with the exception that there are now two discount factors to consider, corresponding to n(1) and n(2). A single discount factor based on N = n(1) + n(2) is used if the stations choose to use the same pre-amplifier, transmitter, or antenna.

D.    Optimization of Both Ground and Space Segments

   1.    Analysis

   A primary goal of our study of teleconferencing at Stanford has been to estimate what the cost of satellite teleconferencing could be. To make this assessment, it is important to have the freedom to vary the transponder parameters as well. In this section, the RF power and gain of the video and return-link transponders are optimized to minimize the annual cost of service as a function of the desired area of coverage, the signal-quality constraints, the uplink and downlink frequencies, the required channel capacity, the total number of stations, and the relative cost of the ground and space segment.

   The space segment no longer is a fixed cost. It becomes economical to use large amounts of satellite power and a high-performance master station only when a large number of remote stations share the cost. For small numbers of stations, our results are substantially in agreement with those domestic satellite filings designed to provide comparable service, such as the Hughes/TelePrompter proposal.

   Unlike the case in which the performance characteristics of the transponders are fixed, it is possible to satisfy both the video and return-audio signal-quality constraints exactly. We begin as before with an arbitrary partitioning of the two noise budgets. Suppose that $_1(C/T)_u = x \cdot _1(C/T)_d = (1 + x)_1 (C/T)$ and $_2(C/T)_u = y \cdot _2(C/T)_d = (1 + y)_2 (C/T)_q$,

where

$$(45) \quad _2(C/T)_q = \begin{cases} (_2(T/C)_t - (T/C)_{im})^{-1}, & \text{FDMA} \\ n_A \cdot _2(C/T)_t, & \text{TDMA} \end{cases}$$

V-47

Reasoning as in the derivation of equations (33) and (34), one may conclude that:

(46)
$$A_m P_m = (1 + x)k_1$$
$$A_m/T_m = (1 + y^{-1}) k_2/P_{sat}^{(A)}$$
$$A_s P_s = (1 + y)k_3$$
$$A_s/T_s = (1 + x^{-1})k_4/P_{sat}^{(v)},$$

where

$$k_1 = {}_1(C/T)_t ({}_u\lambda_{TV}^2/4\pi) \ell_m f_{xr} (A_e/T)_{sat}^{-1}$$
$$k_2 = {}_2(C/T)_q ({}_d\lambda_A^2/4\pi) f_{xr} (A_e)_{sat}^{-1}$$
$$k_3 = {}_2(C/T)_q ({}_u\lambda_A^2/4\pi) \ell_s f_{xr} (A_e/T)_{sat}^{-1}$$
$$k_4 = {}_1(C/T)_t ({}_d\lambda_{TV}^2/4\pi) f_{xr} (A_e)_{sat}^{-1}$$

$P_{sat}^{(A)}$ = RF satellite power per video channel

$P_{sat}^{(A)}$ = $\begin{cases} \text{"Useful" RF satellite power per audio chan-} \\ \text{nel}^*, \text{ FDMA} \\ \text{Total RF satellite power for the return} \\ \text{traffic, TDMA} \end{cases}$

To determine $(C/T)_{im}$, which is needed to compute ${}_2(C/T)_q$ in the case of FDMA, the input backoff must be specified. Unlike the fixed transponder case, y and BO may be varied independently. The range over which one must search for the optimum value of BO is modest, as indicated in section B.6.; but unfortunately there is no way of determining the appropriate range of x and y a priori. We determined the optimum values through a method of trial and error. x and y were allowed to range over a span of 10 dB in increments of one dB. If the minimum did not occur at an interior point, the range was appropriately modified. A plot of the optimum values of x and y for one of the cases analyzed appears in Fig. 6.15.

---

*The "useful" satellite power is defined to be the required satellite power per channel divided by the input backoff, BO. The space-segment charges are proportional to $BO \cdot P_{sat}^{(A)}$.

Having specified x, y, and BO, the analysis of the ground-segment parameters for the master and slave stations is decoupled. Referring to equation (4), the objective is to minimize the expressions:

$$(48) \quad C_s(x,y,BO) = k(N,n_{TV}) \left[ a_1(i) + a_2(i)A_s^{a_3(i)} + A_{pa}(T_s) \right] + d(N)$$
$$A_{pt}(P_s) \, n_{TV} \cdot SS \cdot (1 + x^{-1})k_4 T_s/A_s$$

and

$$(49) \quad C_m(x,y,BO) = a_1(j) + a_2(j)A_m^{a_3(i)} + A_{pa}(T_m) + d(n_{TV}+1)A_{pt}$$
$$(P_m) + C_{mp}(n_{TV}) + SS \cdot (1 + y^{-1}) \cdot k_2 \cdot \begin{cases} n_A BO, & FDMA \\ 1, & TDMA \end{cases}$$

subject to:

$$(50) \quad A_s P_s \geq (1 + y)k_3$$
$$A_m P_m \geq (1 + x)k_1$$

where $C_{mp}(n_{TV})$ is the annual cost of the multiplexer required at the master station to combine the $n_{TV}$ video carriers; and

$$(51) \quad k(N,n_{TV}) = \begin{cases} N \cdot (.92)^{\log_2 N}, & 1 \leq n_{TV} \leq 7 \\ 2N \cdot (.92)^{\log_2(2N)}, & 8 \leq n_{TV} \leq 14; \end{cases}$$

$$(52) \quad d(N) = N \cdot (.92)^{\log_2 N};$$

$i, j \in \{1,2,3\}$; $T_s \in T_s(N)$; $P_s \in P_s(N)$; $T_m \in T_m(N)$, and $P_m \in P_m(N)$.

Consider the problem of minimizing $C_s(x,y,BO)$. For the moment, neglect the influence of $P_s$ and inequality (50a). Then for fixed i and $T_s$, the optimum value of $A_s$ may be obtained by differentiating equation (48), giving rise to the expression:

$$(53) \quad A_s'(x,T_s,i) = n_{TV} \cdot SS \cdot (1 + x^{-1})k_4 T_s / \left[ k(N,n_{TV})a_2(i)a_3(i) \right]^{1/[a_3(i)+1]}$$

where i=1, 2, 3. Initially, one sets i=1, assuming implicitly that

$D_s[A_s'(x,T_s,1)] \leq 12'$. Should this assumption prove to be incorrect, one may conclude that $D_s[A_s'(x,T_s,1)] = 12'$, a consequence of the fact that $C_s$ is a convex function of $A_s$ for fixed $i$; $T_s$, and $P_s^*$. If the solution lies on the boundary, one evaluates equation (53) for i=2. For this case, the extremal value is constrained to lie in the interval 12' $D_s[A_s'(x,T_s,2)]$ 40'. (Cf: equation (4).) Should the solution lie on the outer boundary, one must evaluate (51) for i=3. One selects that value of i which minimizes (48) for fixed $T_s$ and $P_s$, Denote this quantity by:

$$(54) \qquad A_s''(x,T_s) = \min_{i=1,2,3} \left\{ A_s''(x,T_s,i) \right\} .$$

In view of inequality (50a), the optimum value of $A_s$ for fixed $T_s$ and $P_s$ satisfies the equation:

$$(55) \qquad A_s^O(x,y,BO,T_s,P_s) = \max \left\{ (1 + y)k_3/P_s, \ A_s''(x,T_s) \right\}.$$

Finally, one searches over $T_s \in T_s(N)$ and $P_s \in P_s(N)$ to obtain the global minimum of $C_s(x,y,BO)$. Denote the associated parameters by $T_s^O$ and $P_s^O$.

$C_m(x,y,BO)$ is minimized in similar fashion, giving rise to the parameters $A_m$, $T_m^O$, and $P_m$. In general, (50a) and/or (50b) are strict inequalities at this juncture. Consequently, $P_{sat}^{(v)}$ and/or $P_{sat}^{(A)}$ may be slightly reduced from the values given by equations (46b) and (46d), which were based on the assumption that (50a) and (50b) would be exactly satisfied. Reasoning directly from the definition of the noise budgets, as given by equation (2), it may be shown that:

---

$^*C_s$ is convex in $A_s$ for fixed $T_s$, $P_s$, and i if the antenna cost rises at least as rapidly as the effective area. Indeed, if this were not the case, the cost data would be suspect.

$$(56) \quad P_{sat}^{(v)}(x,y,BO) = \frac{k_4 (A_s^O/T_s^O)^{-1}}{1 - \dfrac{k_1}{A_m^O P_m^O}}$$

$$(57)$$

$$P_{sat}^{(A)}(x,y,BO) = \frac{k_2 (A_m^O/T_m^O)^{-1}}{1 - \dfrac{k_3}{A_s^O P_s^O}} \quad ,$$

where $k_1$, $k_2$, $k_3$, and $k_4$ are defined by equations (47). The annual cost of the system, for the particular triplet $(x,y,BO)$ under consideration, is given by the expression:

$$(57) \quad C_t(x,y,BO) = k(N,n_{TV}) \left[ A_a(A_s^O) + A_{pa}(T_s^O) \right] + d(N)A_{pt}(P_s^O) +$$

$$A_a(A_m^O) + A_{pa}(T_m^O) + d(n_{TV} + 1) A_{pt}(P_m^O) + SS \left\{ n_{TV} P_{sat}^{(v)} \right.$$

$$\left. \begin{bmatrix} n_A BO, & FDMA \\ 1, & TDMA \end{bmatrix} \right\} + C_{mp}(n_{TV}).$$

A search over $x$, $y$, and BO completes the analysis. The required power gain of the video and return-audio transponders is computed in the last step.

It is essential to incorporate any prior knowledge that is available to restrict the range of alternatives in $x$, $y$, BO, $T_s$, $P_s$, $T_m$, and $P_m$ that must be considered. The alternatives may be increasingly refined as the optimum is approached. A flow chart of the algorithm that we have developed to estimate the cost of a satellite teleconferencing system when both the ground and space segment are variable appears in Fig. 5.

2. Summary of Results

We have analyzed a total of 48 different problems in an effort to gain quantitative knowledge of the impact on the annual cost of certain system parameters known to the decision maker a priori. $D_{sat}$ was

START

Enter $D_{sat}$, $T_{sat}$, $u^{\lambda}_{TV}$, $d^{\lambda}_{TV}$, $u^{\lambda}_A$, $d^{\lambda}_A$, $_1(C/T)_t$, $_2(C/T)_t$, SS, Ground-Segment Cost Data

Do 1 $n_{TV} \leftarrow \{2, 4, 6, 12\}$

Do 2 $N \leftarrow \{10, \ldots, 10,000\}$
Set $d(N)$, $K(N, n_{TV})$, $C_t = N10^6$.
Specify range of $x \leftarrow \chi(N)$, $y \leftarrow \mathcal{Y}(N)$, $BO \leftarrow B(N)$, $T_s \leftarrow T_s(N)$, $P_s \leftarrow P_s(N)$, $T_m \leftarrow T_m(N)$, $P_m \leftarrow P_m(N)$

Do 3 $x \leftarrow \chi(N)$
Compute $c_1 = (1+x)k_1$
$c_4 = (1 + x^{-1})k_4$

Do 4 $BO \leftarrow B(N)$
Compute $_2(C/T)_q$
Do 5 $y \leftarrow \mathcal{Y}(N)$
Compute $c_3 = (1 + y)k_3$
$c_2 = (1 + y^{-1})k_2 \begin{cases} n_A - BO, & FDMA \\ 1, & TDMA \end{cases}$

Set $C_s = N10^6$
Do 6 $T_s \leftarrow T_s(N)$
Compute $A_s''(x, T_s)$
Do 7 $P_s \leftarrow P_s(N)$
Compute $A_s'(x, y, BO, T_s, P_s)$
Compute $A_a(A_s')$, $u = SSc_4T_s/A_s'$
$z = k(N, n_{TV})[A_a(A_s') + A_{pa}(T_s)] + d(N)A_{pt}(P_s) + u$
If $(z \cdot GE \cdot C_s)$ go to 7
$C_s = z$, $T_s^o = T_s$, $P_s^o = P_s$, $A_s^o = A_s'$
$C_s^o = C_s - u$
7 continue
6 continue

Set $C_m = N10^6$
Do 8 $T_m \leftarrow T_m(N)$
Compute $A_m''(y, BO, T_m)$
Set $d_T \begin{cases} 1, & T_m \neq T_s \\ d(N)/N, & T_m = T_s^o \end{cases}$
Do 9 $P_m \leftarrow P_m(N)$
Compute $A_m'(x, y, BO, T_m, P_m)$
Compute $A_a(A_m')$, $u = SSc_2T_m/A_m$
Set $d_P = \begin{cases} n_{TV}+1, & P_m \neq P_s \\ (n_{TV}+1)d(N)/N, & P_m = P_s^o \end{cases}$
$z = A_a(A_m) + d_TA_{pa}(T_m + d_PA_{pt}(P_m) + u$
If $(z \cdot GE \cdot C_m)$ go to 9
$C_m = z$, $A_m^o = A_m'$, $T_m^o = T_m$, $P_m^o = P_m$
$C_m^o = C_m - u$
9 continue
8 continue

Compute $P_{sat}^{(v)}$, $P_{sat}^{(A)}$. Set
$z = C_s^o + C_m^o + SS[n_{TV}P_{sat}^{(v)} + P_{sat}^{(A)} \begin{cases} n_A BO, & FDMA \\ 1, & TDMA \end{cases}]$
If $(z \cdot GE \cdot C_t)$ go to 5
$C_t = z$, $\tilde{A}_s = A_s^o$, $\tilde{T}_s = T_s^o$, $\tilde{P}_s = P_s^o$
$\tilde{A}_m = A_m^o$, $\tilde{T}_m = T_m^o$, $\tilde{P}_m = P_m^o$, $\tilde{BO} = BO$,
$\tilde{P}_{sat}^{(v)} = P_{sat}^{(v)}$, $\tilde{P}_{sat}^{(A)} = P_{sat}^{(A)}$
5 continue
4 continue
3 continue

Store minimum-cost results for particular choice of $(N, n_{TV}, n_A)$ under consideration.
2 continue
1 continue

Print results for $N = 10, \ldots, 10,000$;
$n_{TV} = 2, 4, 6, 12$

STOP

Fig. 5: Variable Satellite Parameters
N Identical Slave Stations

set at 6' or 10', values which correspond to continental U.S. coverage or regional coverage at 2.5 GHz; SS, the annual cost per watt of RF satellite power, assumed values of \$15,000, \$30,000, or \$50,000[*]; voice or digital feedback was assumed; and either FDMA or TDMA was used to provide multiple access to the return-link transponder, the uplink frequencies for the video and return traffic were assumed to be 6.0 and 2.25 GHz respectively. The stations were assumed to be located at the point of use, and a 43 dB video signal for those stations located along the 3 dB beam edge was the assumed signal-quality constraint. For each case, 2, 4, 6, or 12 video signals were to be received by each of the N slave stations. N was allowed to assume values of 10, 25, 50, 100, 250, 500, 1000, 2500, 500, or 10,000.

The voice-feedback systems were configured for continuing professional education. Having no knowledge of return-traffic statistics, we made some arbitrary assumptions. A minimum of one return channel per video channel was allocated on the satellite. Additionally, one channel was allocated per 50 remote classrooms.

Class size would be extremely limited if all questions were rebroadcast. Consequently, we have assumed that multiple voice channels would accompany the video. Additional personnel would assist the instructor at the video-origination center by fielding questions from remote students and informing the instructor of their general drift. As many of the return channels as possible would be designed for duplex operation.

One of the forward channels would transmit data, intended in part to indicate which of the return channels were presently available. There is no provision for avoiding multiple seizure of these vacant channels, however. Sufficient return channels must be available to reduce the probability of such occurences to an acceptable level.

In the case of digital feedback, each station was assumed to continuously access the satellite with a single audio carrier. Thus, $n_A = N$. As will be seen (cf: Fig. 6.21), the cost of return-link power is dwarfed by the remaining components of the annual cost. This scheme, which easily could be implemented, is only 5% to 25% more expensive than the voice-feedback procedure discussed previously.

Some of the significant results of these case studies appear in Fig. 6. Figures 6.1 through 6.16 compare FDMA with TDMA. For each of

Audio F.B.,    SS = $30K, $D_{sat}$ = 10'
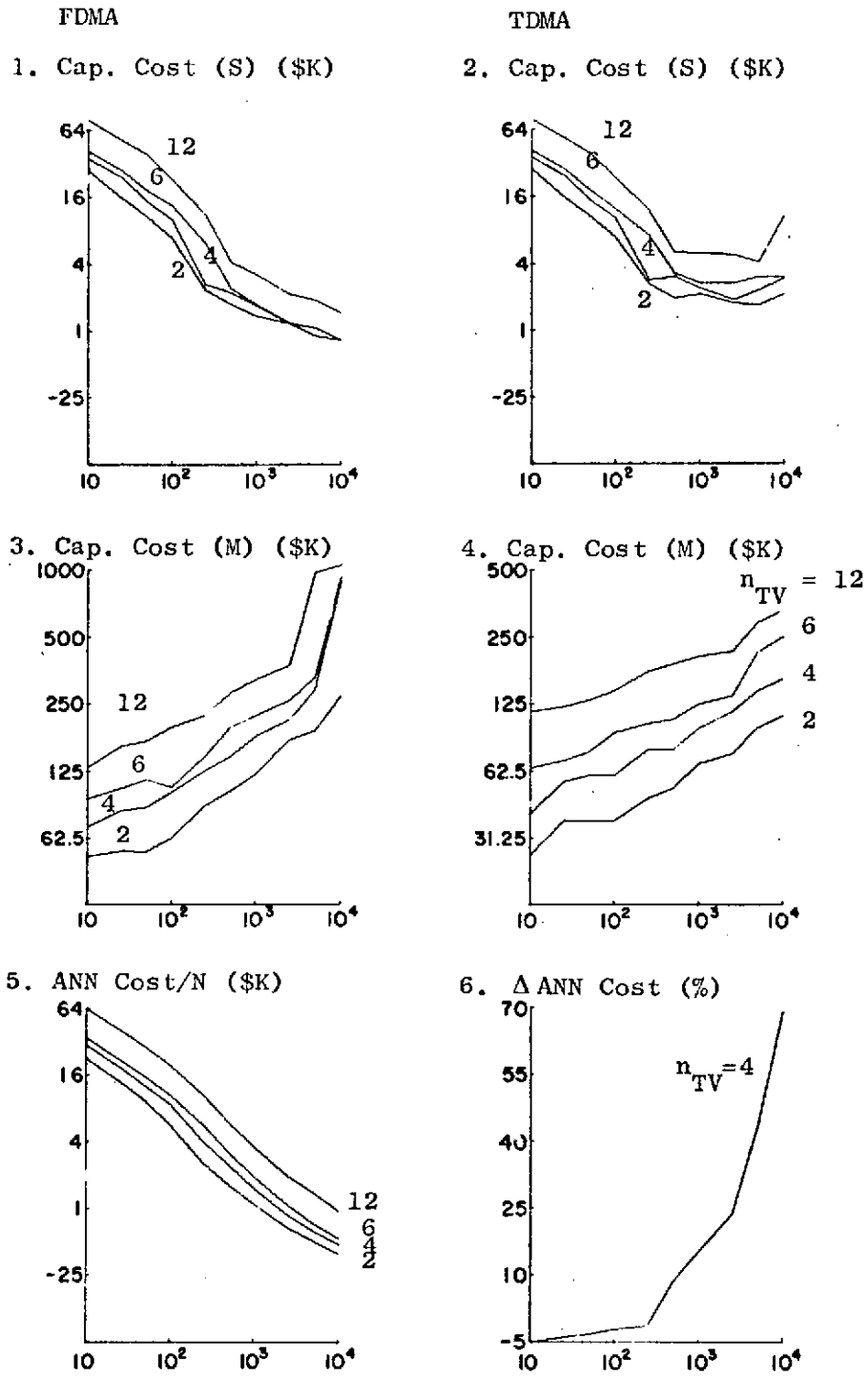


Figure 6:   Variable Satellite Parameters

FDMA                TDMA

7. Sat. Cost (\$K)       8. Sat. Cost (\$K)

9. Diam. (S) (ft.)      10. Diam. (S) (ft.)

11. Diam. (M) (ft.)     12. Diam. (M) (ft.)
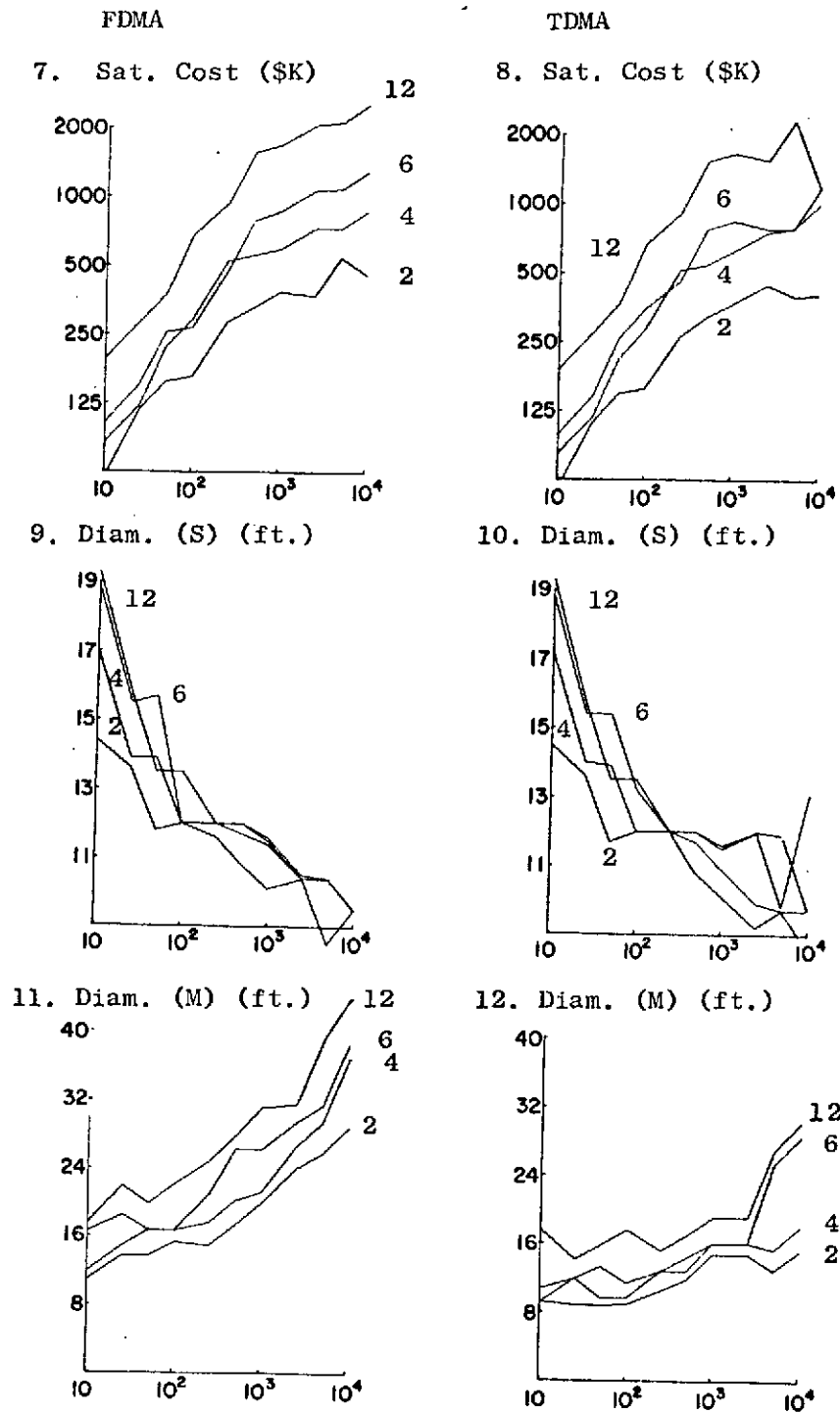
Figure 6:   FDMA vs. TDMA (cont.)

FDMA                                    TDMA
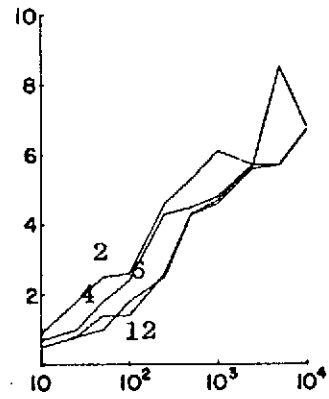
13. $P_{sat}^{(v)}$ (Watts)              14. $P_{sat}^{(A)}$ (Watts)
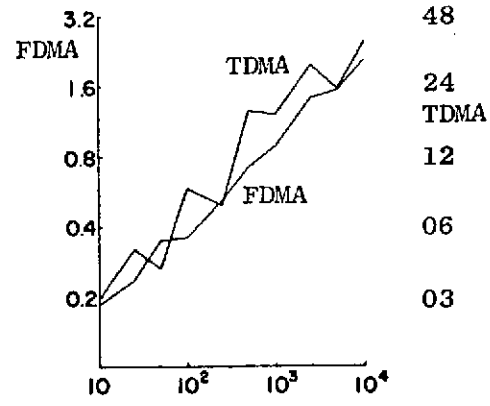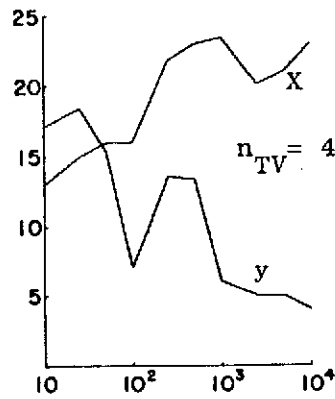


15. Noise Budgets (dB)                   16. Noise Budgets (dB)
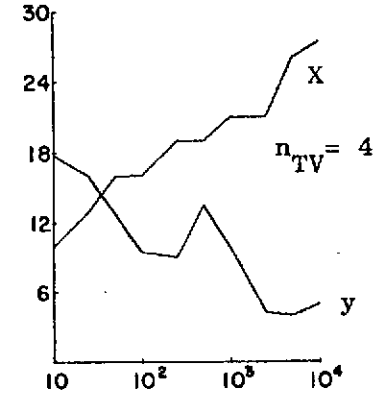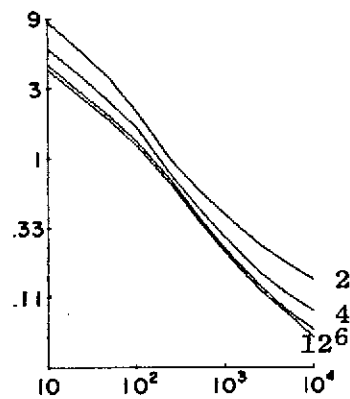


17. ANN Cost/$(N + n_{TV})$ ($K)         18. First Lost/N ($\propto 1/\sqrt{(N)}$)
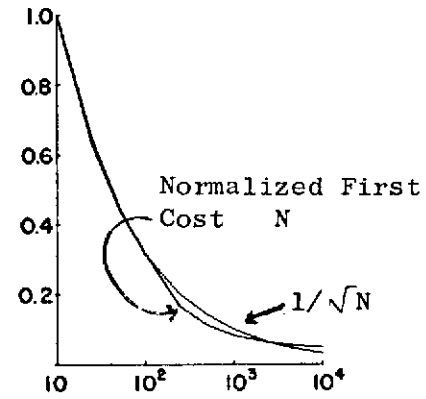
FDMA ONLY



Figure 6.13 - 6.16:  FDMA vs. TDMA ( cont.)

these figures, $D_{sat} = 10'$, $SS = \$30,000$, and $n_A = n_{TV} \cdot [1 + (N + 25)/50]$. The capital cost of the slave stations is displayed in Figs. 6.1 and 6.2; and the capital cost of the master stations appears in Figs. 6.3 and 6.4. The total space-segment charges are plotted in Figs. 6.7 and 6.8. The slave stations are much less expensive, the master station is much more expensive, and the space-segment charges are slightly higher in an FDMA system. Consequently, the cost comparisons favor FDMA for large values of N. This point is made explicitly in Fig. 6.6, which displays on a percentage basis the relative cost of the two systems. Note that for small values of N, TDMA is slightly less expensive--assuming that the modem costs are comparable. The basis for these relative costs is explained in equations (35) through (38') of Section C.1: The slave-station EIRP may be reduced in exchange for increased satellite power and master-station sensitivity when FDMA is used. Note that the capital cost of a TDMA station actually increases for large values of N, despite the reduction in the per-unit cost of the components. The cost of providing the necessary EIRP begins to dominate.

The annual cost per slave station is plotted in Fig. 6.5; and the annual cost per station per video channel appears in Fig. 6.17. It would appear that the annual cost of a satellite teleconferencing network could be quite modest. By contrast, the cost of leasing common-carrier facilities to distribute a single video channel is approximately \$30 per mile per month.[20] Thus, if there were at least 25 stations in the network, a satellite distribution system would be cost effective if the average internodal distance were at least 10 miles. Note that the cost drops sharply as N increases and that these cost-estimates include provision for return audio. We would anticipate a decline in the rate structure of common-carrier facilities when competition from dedicated satellite networks begins to materialize.

The slave station and master station antenna diameter for a TDMA or an FDMA system is plotted in Figs. 6.9-6.12. Note that the slave stations would be sufficiently compact to locate on a small building and that the diameter of the master-station antenna never exceeds 40'. Small-antenna systems do appear to be cost effective.

The required RF satellite power per video channel is plotted in Fig. 6.13. These modest powers per 25 MHz transponder are available with state-of-the-art technology. For example, the Hughes HS-336 is being designed to provide a total of 100 watts of RF power under a weight constraint that would permit insertion with a Thor-Delta launch vehicle.

The required RF power for the return-audio transponder is plotted in Fig. 7.14 for TDMA and FDMA with $n_{TV} = 4$. The minimum-cost TDMA system requires significantly less satellite power; for the networks under consideration, the space-segment cost for the return audio is but a small fraction of the total cost.

Note from Figs. 6.9-6.14 that the parameters of the minimum-cost system are sensitive to changes in N and $n_{TV}$. (They are also sensitive, but to a lesser extent, to changes in $N_A$.) The minimum-cost values of $T_s$, $P_s$, $T_m$, $P_m$, and BO, which are not as volatile as the antenna diameters and transponder powers, have not been plotted. Neither the traffic statistics or the total demand for slave stations are likely to be known with precision. Rather than attempt to minimize the annual cost of the network, the supplier probably would seek a configuration which would provide a satisfactory return on investment in the face of extreme, but not improbable, fluctuations in demand.

x and y, the subsidiary variables which partition the video and return-audio noise budgets in the optimization procedure, appear in Figs. 6.15 and 6.16. For the asymmetrical links under consideration, the uplink noise in the video link is usually much more than 10 dB above the downlink noise, a figure which is sometimes assumed to be optimum.

There are significant economies of scale in an asymmetrical satellite teleconferencing network. A normalized value of the "first cost" of the network on a per-station basis is plotted against $1/\sqrt{N}$ in Fig. 6.18. The curves are virtually indistinguishable. That is, the capital cost of the network rises approximately as $\sqrt{N}$.

The percent increase in the annual cost incurred by adding a return capability to the minimum-cost, TV-only network is plotted in Fig. 6.19. The figure ranges from 8% to 28% becoming increasingly large as N increases. When there are less than 1000 stations in the network, the increase is less than 20%.

Audio F.B., SS = \$30K, $D_{sat} = 10'$, $n_{TV} = 4$ — unless otherwise specified

19. Δ ANN Cost (2-way) (%)    20. Marg. Cost of Video Channel
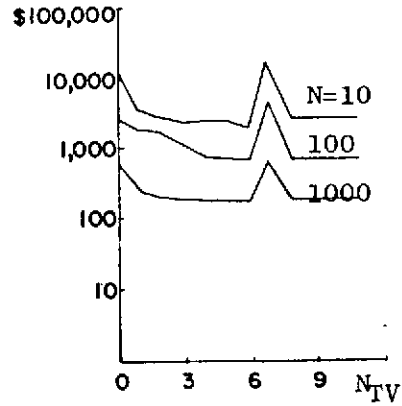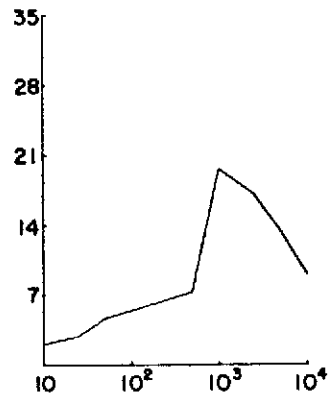


21. Δ ANN Cost (D.F.) (%)    22. Cap. Cost (S) vs. ANN Cost.
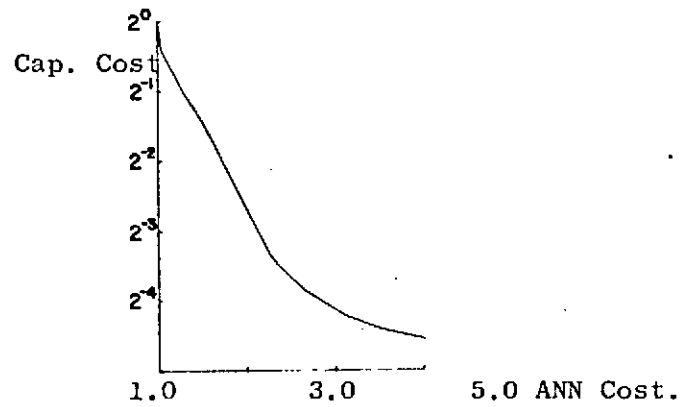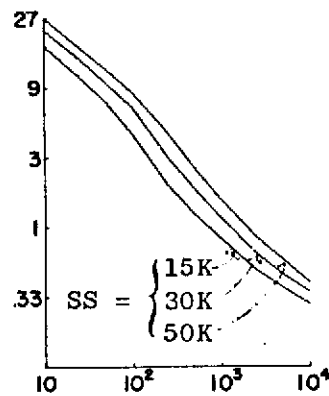


23. ANN Cost. /N (\$K)    24. ANN Cost. /N (\$K)
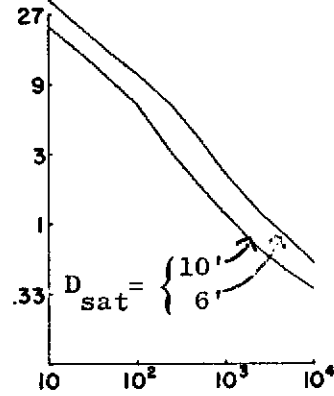


Figure 6:  Misc. Cost Comparisons (FDMA)

E.   Symmetrical Satellite Teleconferencing Networks

We have restricted our attention thus far to networks in which there is a one-way wideband capability and a narrowband-return capability.  We shall now consider three network configurations having greater symmetry:

1.   Two-way video (or two-way audio with no video).  N identical stations.

2.   One-way video with symmetrical two-way audio.  The N identical slave stations may now communicate with each other as well as with the video-origination center.

3.   One-way video plus two-way audio in a network for which the various stations have vastly different voice-circuit capacity requirements.  (For example, the ground stations may also be intended to serve as distribution centers for a long-haul telephony network.)

Once again, the traffic requirements are assumed to be known.  The objective is to determine the parameters of that satellite communication network which provides the desired grade of service in such a way as to minimize the annual cost.  Single-channel-per-carrier-per-transponder video is assumed and FM/FDMA is used to modulate the audio information. Two classes of transponder are available, one of which is optimized to carry video traffic and the other to carry the voice (or data) traffic. The transponders are modeled as linear repeaters.

We have obtained quantitative results for question 1, and the formulation of question 2 is complete.  The results for question 3 are qualitative, and will remain so until further cost information becomes available.

1.   Two-Way Video

Suppose that all N stations in the network are to receive and transmit $n_{TV}$ video channels.  Assume also that the signal-quality constraint is the same for each station.  Letting $(C/T)_t$ be the required carrier-power-to-noise-temperature ratio for each link and assuming that the noise budget is partitioned so the $(C/T)_u = x \cdot (C/T)_d$, one may conclude from equation (2) that:

$$(C/T)_u = (1 + x) \, (C/T)_t$$

and

$$(C/T)_d = (1 + x^{-1}) \, (C/T)_t .$$

The preceding equations may be expressed in terms of the system parameters, giving rise to the following relations:

$$(58) \quad A_s/T_s = (1 + x^{-1}) \; (C/T)_t f_{xr} (_d\lambda_{TV}^2/4\pi)/[(A_e)_{sat} P_{sat}^{(v)}] = (1 + x^{-1})/P_{sat}^{(v)}$$

$$(59) \quad A_s P_s = (1 + x) \; (C/T)_t f_{xr} \; \ell_s (_u\lambda_{TV}^2/4\pi)(A_e/T)_{sat}^{-1} = (1 + x)k_1.$$

Suppose that there is one spare uplink transmitter at each station. Then a total of $N(n_{TV} + 1)$ transmitters will be needed in all. The annual cost of the network may be approximated by the expression:

$$(60) \quad C_t = d[N(n_{TV} + 1)] \; A_{pt}(P_s) + k(N, \; n_{TV})[A_a(A_s) + A_{pa}(T_s)]$$

$$+ \; SSn_{TV} \cdot (1 + x^{-1})k_2 T_s/A_s + C_{mp} (n_{TV}).$$

where $d(\cdot)$ and $k(.,.)$ are defined by equations (51) and (52).

For each value of $x$, $C_t$ may be minimized in the manner outlined in equations (48) through (55). One then searches over a range of $x$ (which through previous experience contains the optimum for the particular settings of SS, N, and $n_{TV}$ under consideration) to obtain the global minimum of $C_t$. In the process, the optimum values of $A_s$, $T_s$, $P_s$, $P_{sat}^{(v)}$, and the power-gain of the transponder are determined.

Numerical results have been obtained for a network consisting of N two-way video stations, for N= 2, 4, 8, 16, 32, and 64. $n_{TV}$ assumed values of 2, 4, 6, and 12; SS was set at \$30,000/watt/year; and $D_{sat}$ at 10'. The output signal-to-noise ratio was constrained to be at least 43 dB within the 3 dB cone of coverage.

The annual cost per station is plotted in Fig. 7.1. While much higher than before, it is intriguing. If expensive new communications services become a substitute for transportation, two-way video may be among the first to be successfully marketed. Large cities could be equipped with studios in which individuals could participate in small tele-conferences. The cost of periodic board meetings or sales meetings

$$SS = \$30K, \quad D_{sat} = 10'$$

1. Cap. Cost (S) ($K)
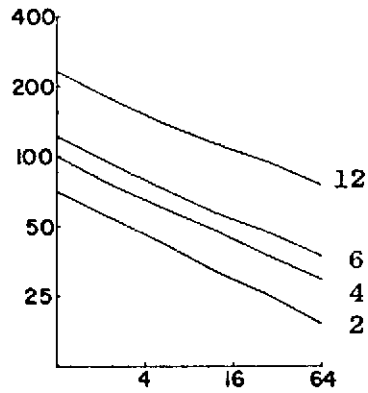
2. ANN Cost/N ($K)
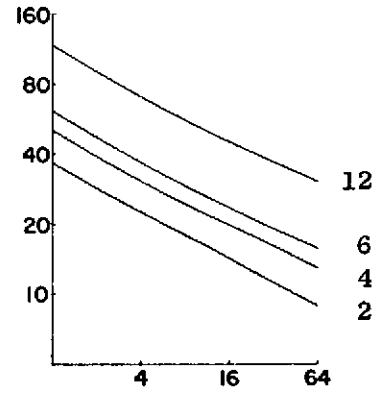


3. Diam. (ft.)
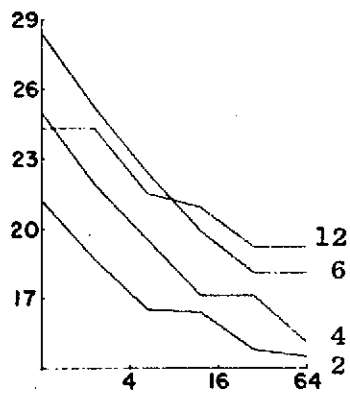
4. $P_{sat}^{(v)}$ (Watts)
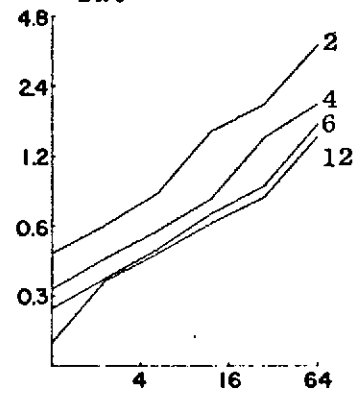


Figure 7:  Two-Way T.V.

could be significantly reduced—if the substitute proves to be acceptable.

The capital cost of the ground stations is plotted in Fig. 7.2. Again, the figures provide a preliminary indication of economic feasibility.

Finally, the antenna diameter of the minimum-cost stations and the required RF power per satellite transponder for transmission in the ITFS band appears in Figs. 7.3 and 7.4. For this symmetrical network, considerably more of the cost burden is placed on the ground.

## 2. One-Way Video Plus Symmetrical Voice

Suppose now that the network is designed for one-way video plus symmetrical voice. Support that the video noise budget is partitioned so that $(C/T)_u = x \cdot (C/T)_d$ and that the audio noise budget is partitioned so that $(C/T)_u = y \cdot (C/T)_d$. Letting $_1(C/T)_t$ and $_2(C/T)_q$ be the signal-quality constraints for the video and audio links, respectively, the sensitivity of each station must be such that:

$$(61) \qquad A_s/T_s \geq \max \left\{ (1 + x^{-1})_1 (C/T)_t f_{xr}(_d\lambda_{TV}^2/4\pi)/[(A_e)_{sat}P_{sat}^{(v)}] \right.$$
$$\left. (1 + y^{-1})_2 (C/T)_q f_{xr}(_d\lambda_A^2/4\pi)/[(A_e)_{sat}P_{sat}^{(A)}] \right\},$$

where $P_{sat}^{(A)}$ and $P_{sat}^{(v)}$, is the "useful" RF satellite power allocated per audio channel and per video channel, respectively. If the signal-quality constraints are exactly satisfied, as will be the case in the minimum-cost network when both the ground and space-segment parameters are variable, one may conclude that:

$$(62) \qquad P_{sat}^{(A)} = \frac{(1 + y^{-1})_2(C/T)_q(_d\lambda_A^2/4\pi)}{(1 + x^{-1})_1(C/T)_t(_d\lambda_{TV}^2/4\pi)} \qquad P_{sat}^{(v)} = \frac{(1 + y^{-1})k_5}{(1 + x^{-1})} \cdot P_{sat}^{(v)}.$$

Thus, the annual cost of the network is approximately:

$$(63) \quad C_t = d(n_{TV} + 1)A_{pt}(P_m) + A_{pa}(T_m) + A_a(A_m) + d(N)A_{pt}(P_s)$$

$$+ k(N,n_{TV})\left[A_a(A_s) + A_{pa}(T_s)\right] + C_{mp}(n_{TV})$$

$$SS \cdot \left[n_{TV} \cdot (1 + x^{-1})k_4 + n_A\, BO(1 + y^{-1})k_4 k_5\right] T_s/A_s,$$

where $k_4$ and $k_5$ are defined by equations (47d) and (62). Additionally, the following constraints must be satisfied:

$$A_s P_s \geq (1 + y^{-1})_2(C/T)_q\, f_{xr}\ \ell_s(_u\lambda_A^2/4\pi)\ (A_e/T)_{sat}^{-1} = (1 + y^{-1})k_3$$

$$(64) \quad A_m P_m \geq (1 + x^{-1})_1(C/T)_t\, f_{xr}\ \ell_m(_u\lambda_{TV}^2/4\pi)\ (A_e/T)_{sat}^{-1} = (1 + x^{-1})k_1$$

$$A_m/T_m \geq A_s/T_s$$

The analysis is similar to the procedure outlined in equations (45) through (57). A flow chart of the procedure appears in Fig. 8.

### 3. Hybrid Satellite/Terrestrial Networks

Communication satellites have been used primarily to route high volume, point-to-point traffic over great distances. However, as the EIRP-per-dollar has increased and the station-keeping capability of satellites has improved, the economics of low-cost, multi-purpose ground stations have become more persuasive. Particularly in networks for which there is also a requirement for networking video signals, the cost of point-to-point, small-user service via satellite may be competitive with the best terrestrial alternatives. Given the existence of a satellite distribution network for video, the marginal cost of point-to-point traffic among the various ground stations declines significantly.

Three categories of service for which a satellite distribution network may be cost effective are the following:

START

Enter $D_{sat}$, $T_{sat}$, $u^{\lambda}_{TV}$, $d^{\lambda}_{TV}$, $u^{\lambda}_{A}$, $d^{\lambda}_{A}$, $_1(C/T)_t$, $_2(C/T)_t$, SS, Ground-Segment Cost Data

---

Do 1 $n_{TV} \leftarrow \{2,4,6,12\}$
Do 2 $N \leftarrow \{10,25, \ldots, 10,000\}$
Set discount factors, $d(N)$, $k(N,n_{TV})$.
Set $C_t = 10^6 N$. Specify range of $x \leftarrow \chi(N)$, $y \leftarrow \mathcal{Y}(N)$, $BO \leftarrow B(N)$, $T_s \leftarrow T_s(N)$, $P_s \leftarrow P_s(N)$, $T_m \leftarrow T_m(N)$, $P_m \leftarrow P_m(N)$.

---

Do 3 $x \leftarrow \chi(N)$
Compute $c_1 = (1+x)k_1$
$c_4 = (1 + x^{-1})k_4$
Do 4 $BO \leftarrow B(N)$
Compute $_2(C/T)_q$
Do 5 $y \leftarrow \mathcal{Y}(N)$
Compute $c_3 = (1+y)k_3$
$c_2 = (1 + y^{-1})k_2$

---

$C_s = 10^6 N$
Do 6 $T_s \leftarrow T_s(N)$
Compute $A''_s(x,T_s)$ [cf: (48)-(54)]
Do 7 $P_s \leftarrow P_s(N)$
Compute $A'_s(x,y,BO,T_s,P_s)$ [cf: (54)]
Compute $A_a(A'_s)$, $u = SSc_4 T_s/A_s$
$z = k(N,n_{TV})\cdot[A_a(A'_s)+A_{pa}(T_s)]+d(N)A_{pt}(P_s)+u$
If $(z \cdot GE \cdot C_s)$ go to 7
$C_s = z$, $C_s^o = C_s-u$, $A_s^o = A_s$, $T_s^o = T_s$, $P_s^o = P_s$
7 continue
6 continue

---

$C_m = 10^6 N$
$u^o = A_s^o/T_s^o$
Do 8 $T_m \leftarrow {}_m(N)$
$d_T = \begin{cases} 1, & T_m \neq T_s^o \\ d(N)/N, & T_m = T_s^o \end{cases}$

---

$u = T_m \cdot u^o$
Do 9 $P_m \leftarrow P_m(N)$
$d_P = \begin{cases} 1, & P_m \neq P_s^o \\ d(N)/N, & P_m = P_s^o \end{cases}$
Set $A_m = \max \{c_1/P_m, u\}$
$z = A_a(A_m)+d_T A_{pa}(T_m)+d_P A_{pt}(P_m)(n_{TV}+1)$
If $(z \cdot GE \cdot C)$ go to 9
$C_m = z$, $T_m^o = T_m$, $A_m^o = A_m$, $P_m^o = P_m$
9 continue
8 continue

---

$$P_{sat}^{(v)} = \frac{k_4(A_s^o/T_s^o)^{-1}}{1 - k_1/(A_m^o P_m^o)}$$

$$P_{sat}^{(A)} = \frac{k_2(A_s^o/T_s^o)^{-1}}{1 - k_3/(A_s^o P_s^o)}$$

$z = C_s^o+C_m+SS(n_{TV}\cdot P_{sat}^{(v)}+n_A \cdot BO \cdot P_{sat}^{(A)})$
If $(z \cdot GE \cdot C)$ go to 5
$C_t = z$, $\tilde{A}_s = A_s^o$, $\tilde{T}_s = T_s^o$, $\tilde{P}_s = P_s^o$,
$\tilde{A}_m = A_m^o$, $\tilde{T}_m = T_m^o$, $\tilde{P}_m = P_m^o$, $\tilde{P}_{sat}^{(v)} = P_{sat}^{(v)}$, $\tilde{P}_{sat}^{(A)} = P_{sat}^{(A)}$, $\tilde{BO} = BO$
5 continue
4 continue
3 continue

---

Store minimum-cost parameters for the choice of $(n_{TV},N,n_A)$ under consideration.
2 continue
1 continue

---

Print results for $N \leftarrow \{10,\ldots,10,000\}$; $n_{TV} \leftarrow \{2,4,6,12\}$.

STOP

Fig. 8:   One-Way TV Plus Symmetrical Voice

1. Multi-purpose service to remote users in regions where the population density is low;

2. Predictable point-to-point service (which periodically could be re-routed according to a predetermined schedule) for which the cost of terrestrial facilities, due to the inordinate amount of required switching, may be relatively high. Candidates for services include numerous business functions, such as inventory control, check clearing, and the general problem of periodically transferring data from one memory bank to another.

3. Switched point-to-point service in conjunction with existing terrestrial facilities. Satellites could provide a convenient "toe in the water", useful in assessing traffic patterns prior to investing in high capacity terrestrial links.

We shall discuss some preliminary findings regarding how a communication satellite could be used to complement existing terrestrial facilities. These results are rudimentary because we lack information concerning switching costs, which vitally affect the cost of point-to-point service. Some observers estimate that the cost of switching represents approximately 75%-85% of the cost of AT&T in establishing a typical long-distance phone circuit.[17]

Qualitative descriptions of switching costs are available from Bell System publications--although quantitative information is conspicuously absent. A "switching machine" performs two basic functions: it routes all calls which enter the network to the intended destination and concentrates the traffic so that calls are not carried on small, inefficient circuit groups. The switching mechanism also performs those ancilliary functions essential to any complex communications network, such as translation, signaling, and billing.

Weber[23] discusses quite succinctly the implications of switching costs on the configuration of a terrestrial network. There are two basic structures, the star and the mesh, which are depicted schematically in Fig. 9. In a mesh network, all traffic between a pair of nodes is carried over a single trunk (when no alternate routing is allowed). In a star network, the majority of calls are switched at a central node. No intermediate switching is required in a mesh network; but due to the lighter loading of the individual links, the trunks of a mesh network

typically are used less efficiently. Inevitably, one must strike a balance between switching cost and trunking efficiency. Generally speaking, for low traffic levels, star networks tend to be cost-effective; but as the volume of traffic increases, mesh networks become more economical.



Fig. 9: The Star and the Mesh

The problem is to determine that mixture of satellite and terrestrial facilities which minimizes the annual cost of servicing the forecast traffic. Because the cost of establishing a link within the cone of coverage of the satellite is distance independent, demand-assigned circuits are an attractive means of routing the overflow traffic from a terrestrial network. To gain some appreciation for the increased circuit-utilization efficiency which results from concentrating the overflow traffic into one trunk (the pool of demand-assigned satellite circuits), Table V is presented below. A ten-node network having equal internodal traffic which is constant throughout the day has been assumed. That is, $a_{ij}(T) = a$, i, j = 1, 2,....., 10; T = 1, 2,...., 24.

We shall dimension the system to have an overall loss of 3%. The demand-assigend traffic will suffer a multiple loss arising from three potential bottlenecks in the journey: existing from the origin station (all of the available modulators may be occupied), gaining a demand-assignment circuit on the satellite, and entering the destination station (where, again, the available demodulators may be occupied). To determine the best partitioning of the allowed 3% loss, one must perform an economic tradeoff between the cost of modulators and uplink transmitters, voice channels on the satellite, and the cost of demodulators. We do not have sufficient cost data to perform this tradeoff at the present time. Quite arbitrarily, we shall permit a 2% loss on the satellite and a .5% loss at each end. The terrestrial trunks are configured for a 3% loss.

A total of 180 terrestrial trunks are required to provide the necessary interconnections, assuming a mesh configuration is used. A 100% increase in voice traffic is forecast, which may be serviced either by increasing the size of the terrestrial trunks or by routing the overflow traffic to the satellite. Displayed are the number of simplex circuits per trunk required to route the present load; the increase in the capacity of each trunk required to route the forecast load; the total required increase (180 times $\Delta M_{ij}$); the number of satellite circuits required to carry the forecast overflow traffic[*]; and the ratio of the total required increase in terrestrial circuits to the number of satellite circuits.

---

[*] We used Wilkinson's methods to make this calculation.[24] Given the mean and variance of the overflow traffic from the terrestrial trunks, one may compute the "equivalent random traffic" having the same mean and variance as that of the graded multiple. It is then a simple matter to compute the number of satellite circuits required to service the overflow traffic from the graded multiple at a loss less than or equal to 2%.

Table IV: The Relative Efficiency of D.A. Satellite Circuits

| $a_{ij}$ (erl.) | $\Delta a_{ij}$ | $M_{ij}$ | $\Delta M_{ij}$ | Tot. $\neq$ T. Ckts. | $\neq$ Sat. Ckts. | Ratio |
|---|---|---|---|---|---|---|
| 0.25 | 0.25 | 2 | 1 | 180 | 15 | 12.00 |
| 0.50 | 0.50 | 3 | 1 | 180 | 20 | 9.00 |
| 1.00 | 1.00 | 4 | 2 | 360 | 48 | 7.50 |
| 2.50 | 2.50 | 7 | 3 | 540 | 134 | 4.03 |
| 5.00 | 5.00 | 10 | 6 | 1080 | 435 | 2.48 |
| 10.00 | 10.00 | 16 | 12 | 2160 | 1138 | 1.90 |
| 25.00 | 25.00 | 33 | 27 | 4860 | 3553 | 1.37 |
| 50.00 | 50.00 | 60 | 53 | 9540 | 7563 | 1.26 |
| 100.00 | 100.00 | 113 | 103 | 18540 | 16686 | 1.11 |

Even if there is an existing network of satellite ground stations used for networking video, the cost of demand-assigned voice circuits is likely to be high. It is doubtful that satellites will be competitive with terrestrial facilities over the near term for services which require a fully-variable switching unless the internodal traffic is light and/or the nodes are widely separated. The analysis must be considerably refined, however, before firm conclusions are possible.

F. Conclusion

1. Summary of Results

The principal conclusions which have emerged from this study are as follows:

a. The case for satellites as a means for networking video signals is overwhelming. A four-channel system appears to be less costly than common-carrier facilities for all but intra-urban traffic if there are at least 25 stations in the network. And the cost per station drops sharply as N increases.

b. The antenna diameter of the minimum-cost slave station ranges from 20' to 8' and the master-station antenna diameter ranges from 14' to 40' as N ranges from 10 to 10000. Even in the case of two-way video, the antenna diameters were never observed to exceed 30'. Small-antenna systems do appear to be cost effective.

c. The per-transponder satellite power in the minimum-cost system is surprisingly modest, ranging from 1 to 10 watts for the video and much less for the return audio. Such power requirements are well within the range of state-of-the-art technology.

d.  A narrowband-return capability increases the annual cost
    of the (minimum-cost) TV-only network by approximately
    10%-30% when the return traffic is directed only to the
    video-origination station.  When the N slave stations
    also serve as distribution centers of a long-haul tele-
    phone network, the marginal cost, of course, is a criti-
    cal function of the internodal voice traffic.  Satellites
    do <u>not</u> appear to offer possible savings for large-volume
    telephony at the present time.  They are attractive for
    thin routes, particularly when there is also a need to
    distribute video.

e.  Decreasing the diameter of the satellite antenna from 10'
    to 6', thereby providing continental U.S. coverage rather
    than regional coverage at 2.5 GHz, increases the cost by
    approximately 70%.  Stated another way, increasing the
    coverage by roughly a factor of 3 increases the cost by
    roughly a factor of $\sqrt{3}$.  This conclusion is based on the
    assumption that the total number of stations and the
    channel capacity is constant.

f.  There are significant economies of scale.  When there is
    one video-origination station and N slave stations which
    receive the video and return narrowband information to
    the video-origination station, the total capital cost per
    station falls approximately as $\sqrt{N}$.

g.  Until the spectrum must be reused, the marginal cost of
    adding video channels is constant when the satellite
    parameters are fixed and decreases when the satellite
    parameters are variable.  When the spectrum must be
    resued, ground-segment costs increase significantly,
    increasing the marginal cost.

h.  The availability of directive antennas and larger amounts
    of RF power on a communication satellite--to the extent
    that they reduce the cost per watt of satellite power--
    will have a significant bearing on the configuration of
    the minimum-cost network.  If SS is the annual cost per
    watt of satellite power, the annual cost of the network
    rises approximately as $\sqrt{SS}$.

i.  The gross system parameters of the minimum-cost network,
    $A_s$, $T_s$, $P_s$, $A_m$, $T_m$, $P_m$, $P_{sat}^{(v)}$, $P_{sat}^{(A)}$, and BO are quite sensitive
    to variations in N, $n_{TV}$, and $n_A$.  Because these "demand
    indicators" are unlikely to be known with precision, the
    supplier probably would seek a compromise solution rather
    than attempt to minimize his annual cost.

j.  Frequency-division-multiple-access appears to be less
    costly than time-division multiple access for the "master/
    slave" network configuration considered.

The numerical solutions obtained are summarized in sections D.2 and E.1. Due to a lack of data concerning switching costs, we do not have quantitative results for teleconferencing in a network for which the various ground stations have vastly different voice-circuit capacity requirements. For the same reason, our formulation of the minimum-cost hybrid satellite/terrestrial network is rudimentary. The indications of our results, however, provide support for the hypothesis that satellite teleconferencing may be economically feasible in the near future. We feel there is ample justification to support more intensive studies of this subject.

2. Suggestions for Future Research

Our recommendations for future technical research in the area of satellite teleconferencing fall into three categories: antenna development, modulation theory, and modem development. The communication satellite itself already appears to have reached a state of development that would permit economical teleconferencing among small users.

The two most critical technical impediments to the development of satellite teleconferencing appear to be:

1.  The objectionable sidelobe characteristics of small-diameter antennas. Despite their apparent cost-effectiveness, small-antenna ground stations will not become feasible until it can be demonstrated that they will not interfere unduly with other users of the spectrum, principally terrestrial microwave systems. Positive results in this area would also reduce the required orbital spacing of communication satellites which share the spectrum used by small-antenna networks.

2.  Economical demand-assignment apparatus. Perhaps the most significant feature of a communication satellite is the flexible routing that is potentially available. Satellites could provide a convenient "toe in the water", useful in assessing traffic patterns prior to investing in high-capacity terrestrial links. Demand-assigned satellite circuits would also be useful as a means of routing momentary overflow traffic from terrestrial facilities. Neither of these functions now appear feasible, however, due to the lack of adequate switching mechanisms.

When many users wish to access a communications channel simultaneously, the question of the cost and performance of alternative multiple-access

procedures arises. Presumably, the issues which pertain to accessing a communications channel are also relevant to the question of accessing a central processor. Remote feedback will not become economically attractive until a great many users can share the cost of the software, computers, and communications apparatus. Efforts to increase the number of users who may simultaneously access a computer or a satellite transponder should be intensified.

It is not clear how processing capability should be allocated in a large teleconferencing system. Should there be mini-computers in each remote CAI installation? At the cable-TV headend or other concentration points? Or only at the origination center? What demand-assignment capability should be installed at each slave station? Should the single master station shoulder most of the burden, if technically feasible?

In Section B.7.c. we discuss the need for cost-effectiveness studies of alternative procedures for modulating video signals through a satellite. Because the ITFS band is limited, techniques to increase the channel capacity of this frequency band in an economical manner should be refined. The multiplexing of video signals on an FM carrier is one alternative. It might be possible to employ a single transponder having 190 MHz of bandwidth and to use FDMA or TDMA to achieve multiple access. Essentially, the objective should be to explore techniques which would exchange increased ground-segment charges (the baseband signal exiting from the receive station would have to be compatible with an ordinary TV set) for reduced space-segment charges.

A problem which always arises in considering satellite-communication systems is the determination of an acceptable signal-quality standard for video, voice, or data. The international standard for voice is an output signal-to-noise ratio of 50 dB (psophometrically weighted). This figure takes into account the long terrestrial tails which frequently precede and follow the ground stations which route international traffic. (They may be as long as 2500 miles at each end.) In a regional system, of course, the terrestrial tails are much shorter—particularly in the case of direct broadcast. Consequently, the required signal-to-noise ratios should be appropriately reduced. Comsat recommended a value of 43 dB for voice in their proposed rural-Alaskan network[21]: but the need remains

for experimentally-determined standards for regional networks.

The development of modems for use in the home, school, community center, or place of work is a very critical area. A coordinated development effort will require further research on the psychology of learning and, in general, more refined information concerning user needs.

The appropriate blend of media for use in primary and secondary schools, for example, is not well established. Should CAI employ only two-way audio channels or are the incremental benefits of one-way video in conjunction with return data significant? These and other objectives will be pursued in the proposed ATS-F/Rocky Mountain educational-satellite experiment scheduled for 1973. Hopefully, the experiments will provide meaningful data useful in establishing terminal-development objectives.

3. Possible Implications

Hopefully, these preliminary results will serve to stimulate more refined studies elsewhere. Decision-makers should have quantitative knowledge of the price that is paid by the users of a satellite teleconferencing network designed to maximize, for example, the "bits per second per degree of geostationary orbit arc" within a specified bandwidth--irrespective of the demand for channels. It hardly makes sense to impose a system on the user that is optimized to an irrelevant set of constraints. One hopes that the minimum-cost alternative will be given due consideration. In our opinion, the current situation is analogous to what life might have been like had full attention in the television industry been devoted to the central broadcast studies and the transmitters of the local affiliates. And so what if the cost of a TV receiver were $5,000,000?

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Carlson writes the FM equation in the form $(SNR)_o = 3m^2(C/N) (B/f_m)^2 = x^{-2}$, where by definition $|x(t)| \leq 1$. To relate this expression to equation (15), define $|x(t)| = a(t)/k$, where $a(t)$ is the amplitude of the incoming signal. We define $k$ such that $\text{Prob}\{|x(t)|>|\} = \text{Prob}\{|s(t)| > k\} \leq .01$. It follows that $x^{-2} = s^{-2}/k^2 = $ (average signal power)/(peak signal power) $= 1/k'_p$, where $k'_p$ is the (99%) peak-to-average factor.

10. S.G. Lutz, "Transmission Calculations for Satellite Communication," Internal Memorandum, Hughes Aircraft Company, El Segundo, California, April 1963.

11. D. Slepian, Bell Telephone Laboratories, Murray Hill, New Jersey, private conversation. There are a number of papers that discuss the PCM/Δ-MOD controversy which have appeared in the Bell System Technical Journal between 1969 and 1971.

CHAPTER VI

## ELECTRONIC COMMUNICATIONS EQUIPMENT COSTS
## FOR TERRESTRIAL SYSTEMS

A.  Introduction

The report thus far has presented cost data and a minimum-cost opti-
mization procedure for a satellite-system alternative for long-distance transmis-
sion of teleconferencing signals.  The next two chapters treat terrestrial trans-
mission and distribution systems.  Their purpose is three-fold.  First, they in-
troduce cost information for a network of microwave relay stations -- presently
the only viable alternative to long-distance transmission by satellite -- and for
ITFS (Instructional Television Fixed Service) and cable systems, two local distri-
bution systems whose capabilities match the needs of a teleconferencing service.
Second, they present a cost comparison between the two alternative long-distance
transmission systems.  And, third, local distribution system alternatives are dis-
cussed and compared.

This chapter presents the results of work done in developing capital cost
formulas for various terrestrial communications systems both for local, wide-area
distribution and for long-distance, point-to-point transmission.  Only first costs of
electronic equipment and its installation are considered.  Other costs will, of course,
be encountered in the design and construction of a complete system.  These cannot,
however, be known beforehand with the same degree of accuracy as can capital equip-
ment costs, and are not included in this chapter.  It is known that in large communi-
cations systems approximately equal amounts of money are allocated for electronic
equipment; engineering, installation and testing; and, land and construction. [1]  Thus,
the costs given here may be expected to comprise from one-third to one-half of the
initial cost of an actual system.

To determine equipment costs, prices were solicited from a few local equip-
ment manufacturers.  Each manufacturer contacted was very helpful and their key
role in this effort is gratefully acknowledged.*  Results of similar studies, as re-
ported in the literature, were also used.

The system under consideration provides point-to-points transmission of a
TV program signal plus return, or points-to-point, audio signal transmission from

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* Although special thanks are due and have been offered to the various company
representatives who made this note possible, because of the competitive nature of
the microwave communications field, neither their names nor the names of their
companies shall be mentioned.

each receiving site (subscriber terminal). Although the cost equations given here are for this specific system, the underlying cost information is general enough that costs for systems with various other transmission capabilities could easily be derived therefrom.

In any system that provides feedback channels, questions arise as to the number of channels to be provided, how requests in those channels are to be made, and in what order the requests are to be served. Although they must, of course, be answered before an actual system can be designed, the answers will depend upon the exact services being offered. In any event, queueing discipline procedure and hardware is here taken to be of comparable cost in alternative configurations of the transmission system. Therefore, only transmission costs are included in the cost equations.

One return voice channel is provided per television channel on long-distance systems. However, each subscriber terminal will have the capability to provide talkback on only one of these return voice channels at a time, because only one channel can be viewed at a time. Thus, for intermediate distribution points, such as ITFS receive stations that supply the signal to cable headends, the return voice channel capability will be the smaller of $c$, the number of video channels transmitted by the system, and $s_j$, the number of subscribers served by the point.

## B. Local Distribution Systems Equipment

The capital equipment and installation costs (i.e., not including land, buildings, engineering, access roads, power connection, or operation and maintenance costs) of two wide-area transmission technologies, ITFS and cable, are as follows.

### 1. Cable[2]

| | |
|---|---|
| Headend electronics per microwave channel (studio and off-the-air channel costs are not included) | $2,300 |
| Distribution system (including cable and electronics, pole rearranging, and installation; not including engineering or utility company inspection of poles) | |
| pole mounted, per mile | 4,300 |
| below ground, per mile | 15,000 |
| Spare parts | 5 percent of headend cost plus $100 per mile |
| Tools and test equipment | 2 percent of headend cost plus $80 per mile (not to exceed $40,000) |

One must now include the cost of a talk-back capability. Using figures from a paper by Dr. Don Dunn delivered at the IEEE Eascon Conference in October, 1970, [3] the cost of return voice communication is between \$100 and \$200 per subscriber terminal (\$165 will be used in this paper), plus 10 percent of the cost of the distribution plant without talk-back. Consistent with the assumption that the queueing discipline hardware will be of comparable cost for alternative systems, the cost of a central computer that was included in the paper by Dr. Dunn has not been included here.

The above costs lend themselves to a cost formula of the form

$$C_{ca}(s_j, c, m_j) = \beta s_j + am_j + \phi c$$

where $s_j$ represents the number of subscribers
$\beta$ is the marginal cost per subscriber
$m_j$ is the number of route-miles of cable
$a$ is the cost associated with each mile of cable in the plant
$c$ is the number of video channels being provided
$\phi$ is the headend marginal cost per channel

Assuming that 5 percent of the distribution system is underground, the following values obtain for the cost parameters:

$$\beta = \$35 + \$165 = \$200$$
$$a = (\$4,000 \times 0.95 + \$15,000 \times 0.05 + \$180) \times )1 + 0.10) \cong \$5,500$$
$$\phi = \$2,300 \times (1 + 0.05 + 0.02) \cong \$2,500$$

Thus,

(1)     $$C_{ca}(s_j, c, m_j) = \$200s_j + \$5,500m_j + \$2,500c$$

It is important to note that there is a limit on the size of an area that can be served from one cable headend. As a signal propagates through a cable, its strength is diminished in direct proportion to the distance it travels. This attenuation is described as a loss per foot of cable and is inversely dependent on the cable diameter. On long cable runs an amplifier must be inserted in the cable every so often to increase the signal strength before the signal is attenuated beyond recovery. In so doing, the amplifier also adds noise to the signal (there are no perfect, noiseless amplifiers). The noise contributed by several amplifiers in succession, each from 300 to 800 yards further down the cable, is cumulative with regard to its effect on the quality of the video signal. Since, for an acceptable

quality picture, the noise must be kept below a specified level, only a limited number of amplifiers may be used, and thus only a limited distance may be attained.

The spacing between amplifiers is determined in large measure by the loss per foot of cable and the dynamic range of the amplifiers. The higher the loss per foot or the smaller the dynamic range, the shorter must be the distance between amplifiers. It is easy to see that larger, more expensive cable or better quality, more expensive amplifiers will permit longer cable runs.

Cable loss per foot is also a function of frequency. Signals carried at high frequencies are attenuated more severely than those carried at low frequencies. As more channels are transmitted, higher frequencies must be used, and amplifiers must be more closely spaced. In general, then, the amplifier spacing, and thus the total permissible length of cable run, is dependent on the diameter of the cable, the number of channels carried and the quality of the amplifers being used. With present cables and amplifiers, and a 30-channel system, a distance of about 20 to 25 route miles may be attained. For 12-channel systems, 35 to 45 miles can be expected. Because the route- to air-mile factor is about 1.33,[4] a nominal run, in air-miles, for a 12-channel system is 25 to 30 miles. For comparisons made in this note, a coverage radius of 25 miles per headend is used.

One other consideration should be mentioned. If cable systems have already been installed in the area where service is desired, it may be possible to lease unused channel capacity from the existing cable company. In the case of educational programming, the lease cost may be very small. One cable company contacted in the San Francisco Bay Area, suggesting that its attitude was not atypical, said it was anxious to be helpful to the educational television effort, and would be willing to run some of this type of programming as a public service.

2. ITFS

Video broadcast facility
| | |
|---|---|
| transmitter (4 channels) | $46,000 |
| (a single channel transmitter costs about $13,000) | |
| feeder (150' of Heliax at $9.10 per foot) | 1,360 |
| antenna (custom built for the particular situation) | 7,000 |
| tower (150' guyed, installed) | 6,000 |
| installation and alignment (10 percent plus $225 for feeder) | 5,540 |

These costs may be modeled by:

$$C_b = \$15,300 + \$50,600 \left[ c/4 \right]$$

where $\left[ c/4 \right]$ indicates that the channel capacity is obtained in increments of four.

Voice feedback receive facility
| | |
|---|---|
| receiver (4 channels) | $10,000 |
| antenna (custom built for the particular situation) | 7,000 |
| feeder (150' of Heliax) | 1,360 |
| installation and alignment (10 percent plus $225 for feeder) | 1,940 |

$$C_{fr} = \$9,300 + \$11,000 \left[ c/4 \right]$$

Video receive subscriber facility
| | |
|---|---|
| 2' antenna, 10' mast and power supply | $470 |
| down converter (4 channels) | 800 |
| cable (275') | 275 |
| installation and alignment | |
| mast | 85 |
| cable | 275 |
| antenna | 125 |
| 10 percent of other equipment | 100 |

$$C_r = \$1,250 + \$880 \left[ c_i/4 \right]$$

where $c_i$ represents the number of channels receiver by a subscriber.

Voice feedback subscriber transmit facility
| | |
|---|---|
| transmitter (4 channels, time shared) | $4,000 |
| feeder (100' Heliax plus other wiring and connectors) | 1,400 |
| antenna (4', use same mast as for receive antenna) | 350 |
| installation and alignment | |
| antenna | 125 |
| feeder | 200 |
| 10 percent of other equipment | 400 |

$$C_{ft} = \$2,075 + \$4,400 \left[ c_i/4 \right]$$

The total cost of this equipment for $s_j$ subscribers is obtained by sombining the previous four equations.

$$(2) \quad C_{itfs}(s_j, c, c_i) = \$24,600 + \$61,600 \left[ c/4 \right] + \sum_{i=1}^{s_j} \left( \$3,325 + \$5,280 \left[ c_i/4 \right] \right)$$

As was the case for cable, the area of coverage with ITFS from a single transmitter is limited. A typical radius of coverage may be calculated. Before doing so, the terms involved in the calculation are introduced and defined.

The quality of the received signal is generally described in terms of the ratio of the signal power to the total available noise power at the receiver, the latter being given by:

$$P_n = kTB$$

where $P_n$ is the received available noise power
   $k$ is Boltzmann's constant
   $T$ is the effective receiver input noise temperature ($^{\circ}$K)
   $B$ is the receiver bandwidth

Signal transmission by radio waves between aligned antennas may be described by the following equation:

$$P_r = P_t G_t G_r / (4\pi d / \lambda)^2$$

where $P_r$ is the received signal power, in watts

   $P_t$ is the transmitted signal power, in watts

   $G_t$ is the gain of the transmit antenna (a number ratio)

   $G_r$ is the gain of the receive antenna (a number ratio)

   d is the distance between the transmitting antenna and the receive antenna, in feet

   $\lambda$ is the wavelength of the transmitted signal carrier, in feet

With power and gain parameters now given in dB, the signal-to-noise ratio (SNR) at the receiver input is:

$$SNR = 10 \left[ \log(P_r / P_n) \right]$$
$$= P_t + G_t + G_r - 20 \left[ \log(4\pi d / \lambda) \right] - P_n$$

Using the maximum transmitter power allowed by the FCC of 10 watts per channel, a broadcast antenna with 15 dB gain, and assuming a typical receiver noise figure, F, of 10 and a receiver bandwidth of 6 MHz, we have:

   $P_t$ = 40 dBm  (dBm is decibels with respect to 1 milliwatt)

   $G_t$ = 15 dB

   $\lambda$ = 0.38 ft.  (2.6 GHz)

   $T$ = $(F - 1) T_0$ = $(10 - 1) \times 290\ ^{\circ}$K = 2610 $^{\circ}$K

   $P_n$ = -198.6 dBm + 101.9 dB = -96.7 dBm

   $G_r$ = 27.5 dB (using a 4' receive antenna at 2.6 GHz with 48 percent efficiency)

Then by substituting these values into the SNR formula,

$$SNR = 40 + 15 + 27.5 - 20\ \log(4\pi/\lambda) - 20\ \log(d) + 96.7$$

Combining and rearranging terms,

$$20\ \log(d) = 148.8 - SNR$$

In addition to the terms making up this last equation, we must include a term to account for the random (statistical) occurrence of signal fading that accompanies any signal transmission through the atmosphere. Viewer surveys have shown that if the no-fade nominal received SNR is 40 dB then satisfactory pictures

will be received if the fades, when they do occur, reduce the signal-to-noise ratio below 30 dB no more than 1 percent of the time. The fade term, at 2.6 GHz, may then be approximated by a 0.75 dB per mile loss for the first 20 miles and a 0.5 dB per mile loss for the next ten miles, with no loss after 30 miles. [5]

Let $d' = d/5280$. Then, with the fade terms in the equation, and using the 30 dB SNR figure,

$$20 \log(5280d') = 148.5 - 30 - 0.75d' \Big|_{d' \leq 20} \quad -0.5(d'-20) \Big|_{20 < d' \leq 30}$$

or

$$\log(d') = 2.202 - 0.375d' \Big|_{d' \leq 20} \quad -0.025(d'-20) \Big|_{20 < d' \leq 30}$$

This equation can be solved by trial and error to give

$$d' = 23.35 \text{ miles}$$

If a 10' (50 percent efficiency) receive antenna is used in place of the 4' antenna, the distance is increased to 39.5 miles. The cost difference between a 4' and a 10' antenna is $910.

If a 10' spot beam transmit antenna is used in conjunction with the 10' receive antenna and a 1 watt tap on the total transmitter power is used, then the spot coverage distance is,

$$SNR = 30 + 2 \times 35.4 - 20 \log(4\pi/\lambda) + \log(5280d') - P_n - 0.75d' \Big|_{d' \leq 20} \quad -0.5(d'-20) \Big|_{20 < d' \leq 30}$$

Since it is evident that $d' > 30$ miles, we may simplify the above to:

$$30 = 30 + 70.8 - 30.4 - 20 \log(d') - 74.46 - P_n - 20$$

or

$$20 \log(d') = 70.8 - 104.86 - 20 - P_n$$

$$= 42.64$$

$$\log(d') = 2.13$$

$$d' = 135 \text{ miles}$$

Notwithstanding the above calculation, no such transmission distance is possible. Transmission distance determination must also include path clearance criteria based on Fresnel zone and equivalent earth radius (K) calculations. Equation [2'] gives the required path clearance for recommended clearance criteria on light-route, or medium reliability systems. [6]

(2')    Required Path Clearance $\geq 0.6F_1 + 0.67(D/2)^2 + 10$ feet
         (with $K = 1.0$)

where K is the earth radius factor

F$_1$ is the radius of the first Fresnel zone, in feet, and is given by:

$$F_1 = 72.1 \times (d_1 d_2 / fD)^{1/2}$$

where d$_1$ = the distance from one end of the path to the
point of reflection

D = the total path length

d$_2$= D - d$_1$

f = the frequency in GHz

In Figure 1, the mid-path clearance as given by equation [2] is plotted against the path length in miles. This path clearance is not the height at which the radio path must be maintained above ground. Rather, as the name implies, it is a distance which must be maintained above the top of any ground structures such as buildings or trees. Even without allowing for the required increases in path clearance that would account for ground structures, the clearance height places prohibitive requirements on antenna heights for distances beyond 40 miles, unless the transmitting antenna can be located on a nearby mountain. In this case, of course, extra expense will be incurred in transmitting the signal to the mountain. It has been assumed in this report that the coverage area for ITFS will be limited to 25 miles from any one transmitter, with possible special beams reaching subscribers up to 40 miles away.

C.  Point-To-Point Systems Equipment

1. Cable

The cost of a point-to-point cable system is obtained in a manner quite similar to that for a wide-area cable system. The difference is that no costs per subscriber need be included. The result is:

(3)  $C_{ca}(c, m) = \$5,200m + \$1,600c$   (assuming only 5 percent is underground)

where m is the number of cable-miles in a point-to-point run.

2. ITFS

Video transmit terminal with audio receive

The cost of a video point-to-point transmit terminal with audio receive will be the same as for the wide-area broadcast terminal if we replace the two wide-area antennas with directional antennas (assume 6' antennas are used at a cost of $420 each). Thus, using previously established nomenclature, with a prime to indicate point-to-point costs:

$$C_b' = \$8.060 + \$50,600[c/4] \qquad \text{and} \qquad C_{fr}' = \$2,060 + \$11,000[c/4]$$

Figure 1. Microwave Mid-path Clearance versus Path Length, for $K = 1$ and $f = 2.6$ GHz.

Mid-path Clearance $= 0.6F_1 + 0.67(D/2)^2 + 10$ feet

where D is the total path length in miles
and $F_1$ is the first Fresnel zone radius in feet

D, the Path Length, in miles
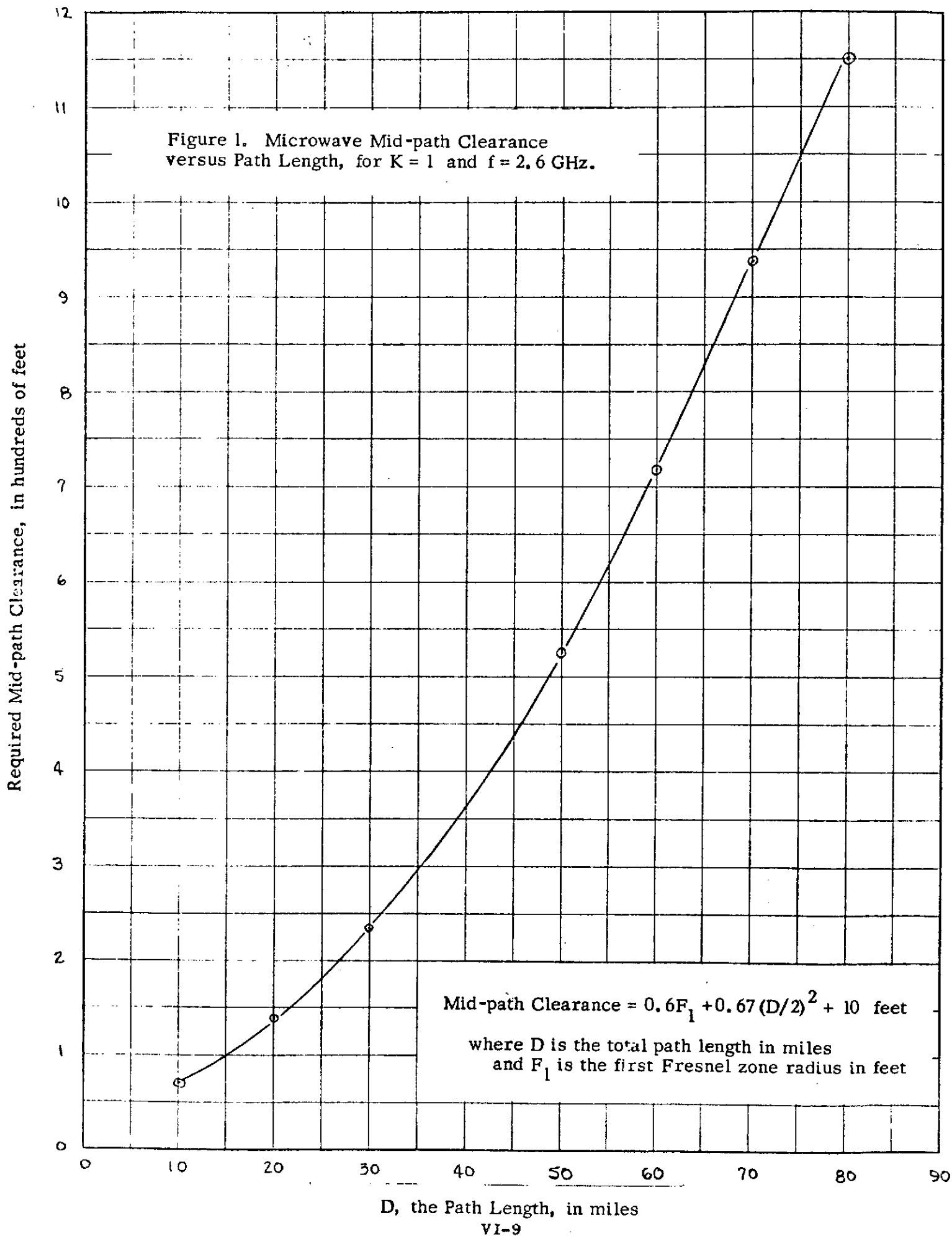
Repeater station

| | |
|---|---|
| tower (150' guyed, installed) | $6,000 |
| four 6' parabolic antennas | 1,700 |
| receiver and transmitter (4 channels) | 41,000 |
| estimate of voice talk-back receiver/transmitter | 7,000 |
| feeder (400' of Heliax) | 3,650 |
| batteries and chargers | 1,000 plus 200 / channel |
| installation and alignment (10 percent plus $1,300 for Heliax) | 6,050 |

$$C_{rep} = \$21,300 + \$45,300 \left[c/4\right]$$

Video receive terminal with audio transmit

| | |
|---|---|
| voice feedback transmitter (4 channel, time shared) | $4,000 |
| receive antenna and transmit antenna (two, 6') | 840 |
| transmit feeder (150' of Heliax) | 1,360 |
| receive feeder (150' of Heliax) | 1,360 |
| tower (not necessary if ITFS wide-area transmission is the next step -- the same tower may be used) | 6,000 |
| down converter (4 channels) | 800 |
| installation and alignment | |
| antennas | 500 |
| feeder | 450 |
| 10 percent of other equipment | 480 |

$$C'_r = \$1,360 + \$420 + \$225 + \$250 + \$880 \left[c/4\right]$$
$$= \$2,255 + \$880 \left[c/4\right]$$

$$C'_{ft} = \$2,255 + \$4,400 \left[c/4\right] + \$6,000$$

The total cost formula for ITFS point-to-point transmission is obtained by combining the above.

$$C_{itfs}(c, R) = \$14,630 + \$66,880 \left[c/4\right] + \$6,000 + (\$21,300 + \$45,300 \left[c/4\right]) \times R$$

where R is the number of repeaters.

2. Microwave

Transmit or receive terminal

| | |
|---|---|
| radio (per channel) | $4,500 |
| antenna and feed | 1,900 |
| batteries and charger - first channel | 1,600 |
| each additional channel | 200 |
| tower (150' guyed) | 6,000 |
| installation and alignment - first channel | 1,000 |
| each additional channel | 500 |

voice feedback

| | |
|---|---|
| radio | 4,500 |
| antenna and feed | 1,900 |
| batteries and charger | 200 |
| multiplex: heavy route - per channel | 2,000 |
| light route - per channel | 1,000 |
| installation and alignment - first channel | 900 |
| each additional channel | 200 |

$$C_{mt} = \$24,500 + \$7,400(c - 1) \qquad \text{heavy route voice system}$$

$$C_{mt} = \$23,500 + \$6,400(c - 1) \qquad \text{light route voice system}$$

Repeater

| | |
|---|---|
| radio - first channel | $7,000 |
| each additional channel | 7,000 |
| antennas and feed | 3,800 |
| batteries and charger - first channel | 2,000 |
| each additional channel | 200 |
| tower (150' guyed) | 6,000 |
| installation and alignment - first channel | 1,300 |
| each additional channel | 500 |
| voice feedback | |
| radio | 7,000 |
| antennas and feed | 3,800 |
| batteries and charger | 200 |
| installation and alignment | 1,100 |

$$C_{mr} = \$32,200 + \$7,700(c - 1)$$

The total cost formula for microwave point-to-point transmission is:

$$C_m(c, R) = \$49,000 + \$14,800(c - 1) + \$32,200 + \$7,700(c - 1) \times R$$

where R is the number of repeaters.

D. Summary of Cost Equations for Terrestrial Transmission

For convenience, cost equations [1] through [5] are repeated here.

[1] Wide-area Cable (for 5 percent underground)

$$C_{ca}(s_j, c, m_j) = \$200s_j + \$5,500m_j + \$2,500c$$

[2] Wide-area ITFS (for $c \leq 12$)

$$C_{itfs}(s_j, c, c_i) = \$24,600 + \$61,600[c/4] + \sum_{i=1}^{s_j}(\$3,325 + \$5,280[c_i/4])$$

[3] Point-to-point Cable (for 5 percent underground and a maximum distance of between 35 and 50 miles)

$$C_{ca}(c, m) = \$5,500m + \$1,600c$$

[4] Point-to-point ITFS (probably limited to 10 to 15 hops)

$$C_{itfs}(c, R) = \$14,630 + \$66,880[c/4] + \$6,000 + (\$21,300 + \$45,300[c/4]) \times R$$

[5] Point-to-point Microwave

$$C_m(c, R) = \$49,000 + \$14,800(c - 1) + \$32,200 + \$7,700(c - 1) \times R$$

where $s_j$ = the number of subscribers served by the jth local distribution center

$m_j$ = the number of cable-miles in the jth cable grid

$m$ = the number of cable-miles in a point-to-point run

$c$ = the number of channels carried on the long distance system

$c_i$ = the number of channels being received by the ith subscriber

$[c_i/4]$ or $[c/4]$ = the cost is given for channel increments of four at a time

$R$ = the number of repeater stations

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# CHAPTER VII

## LEAST-COST COMPARISON
## OF
## ALTERNATIVE TELECONFERENCING SYSTEMS

### A.  Introduction

The teleconferencing system envisioned in this report may be modeled in ..
terms of the natural division between long-distance transmission and local dis-
tribution.  Happily, these two subsystems are almost completely decoupled in the
sense that the least expensive total system may be determined by separate analyses
for each subsystem.  Drawing on material presented in chapters five and six, this
chapter develops the models used for each subsystem, outlines the methods used
in the comparisons, and gives the results obtained.

### B.  Long-Distance Transmission Subsystems

The long-distance subsystem consists of the means by which the teleconfer-
encing signals are transmitted from the origination station or stations to the local
distribution centers.  Two types of long-distance subsystem are considered: a sat-
ellite with earth stations at or near each local distribution center and a terrestrial
microwave network.  The following analysis accounts for only the first order costs
of both systems.  Nevertheless, the results obtained seem so favorable to the use
of a satellite for regional teleconferencing that a more exhaustive analysis at this
juncture was not indicated.

#### 1.  Models and Cost Equations

##### a. The Terrestrial Microwave Network

For the moment, suppose there is only one origination station.  A micro-
wave network would then consist of a chain of repeater stations connecting each
city to be served.  Each repeater would transmit TV program signals away from
the origination point and audio signals towards the origination point.  A very high
quality TV signal would have to be maintained at each repeater inasmuch as the
signal received by the local distribution center at the ends of the chain would pass
through several repeaters.

A microwave terminal station (no retransmission of the video signal is
required) would only be used in the network at the ends of the chain.  Nevertheless,
each terminal station will have its video transmit counterpart somewhere upstream

towards the origination station. This is significant in that it allows the costs of the microwave system to be modeled as the total number of stations used, whether terminal or repeater, times the cost of a repeater station; or, in equation form,

(1) $$C_{ldm}(c, N) = \left[1 + \eta(N)\right] NC_r(c)$$

where $C_{ldm}(c, N)$ is the cost of the long-distance microwave network

$\underline{c}$ is the video channel capacity of the network

$\underline{N}$ is the number of cities being served by the network

$\eta(N)$ is the ratio of the number of microwave repeater stations between cities to the number of cities connected by the network

$C_r(c)$ is the cost of a microwave repeater station

While the values for both N and $C_r$ may readily be determined, $\eta$ can be known accurately only after a preliminary route survey with topographic maps and path porfiles has been completed. It is sufficient for present purposes, how-ever, to derive a rough estimate of the functional dependence of $\eta$ on N. A uniform distribution of cities throughout the entire area to be served is assumed. Although not a very likely distribution for an actual system, it might be argued that the num-ber of repeaters required to serve such a distribution could be considered as an upper bound since any departure from uniformity would allow advantage to be taken of the clustering that would appear. If it is further assumed that the origination station will be located at one of the N cities to be served, the straight-forward deri-vation of $\eta(N)$ is as follows.

Consider a region of rectangular shape L miles long by W miles wide. For a uniform distribution, each city will be at the center of a smaller rectangle that is $L/N^{1/2}$ miles long by $W/N^{1/2}$ miles wide (see Figure 1). The intercity separation distance is thus either $L/N^{1/2}$ miles (long link) or $W/N^{1/2}$ miles (short link) depend-ing on whether the direction of travel is parallel to the length or the width of the rec-tangle. If, insofar as possible, cities are connected to their neighbors using short links fewer intercity repeaters will be required than with any other link pattern. With this pattern, the network will consist of $(N^{1/2} - 1)N^{1/2}$ short links and $(N^{1/2} - 1)$ long links.

In calculating the total number of intercity repeaters implied by this pattern, let $\underline{h}$ represent the average inter-repeater (hop) distance and $\underline{D}$ represent the dis-tance between cities, or the link length. Because $\underline{h}$ is the average hop distance and
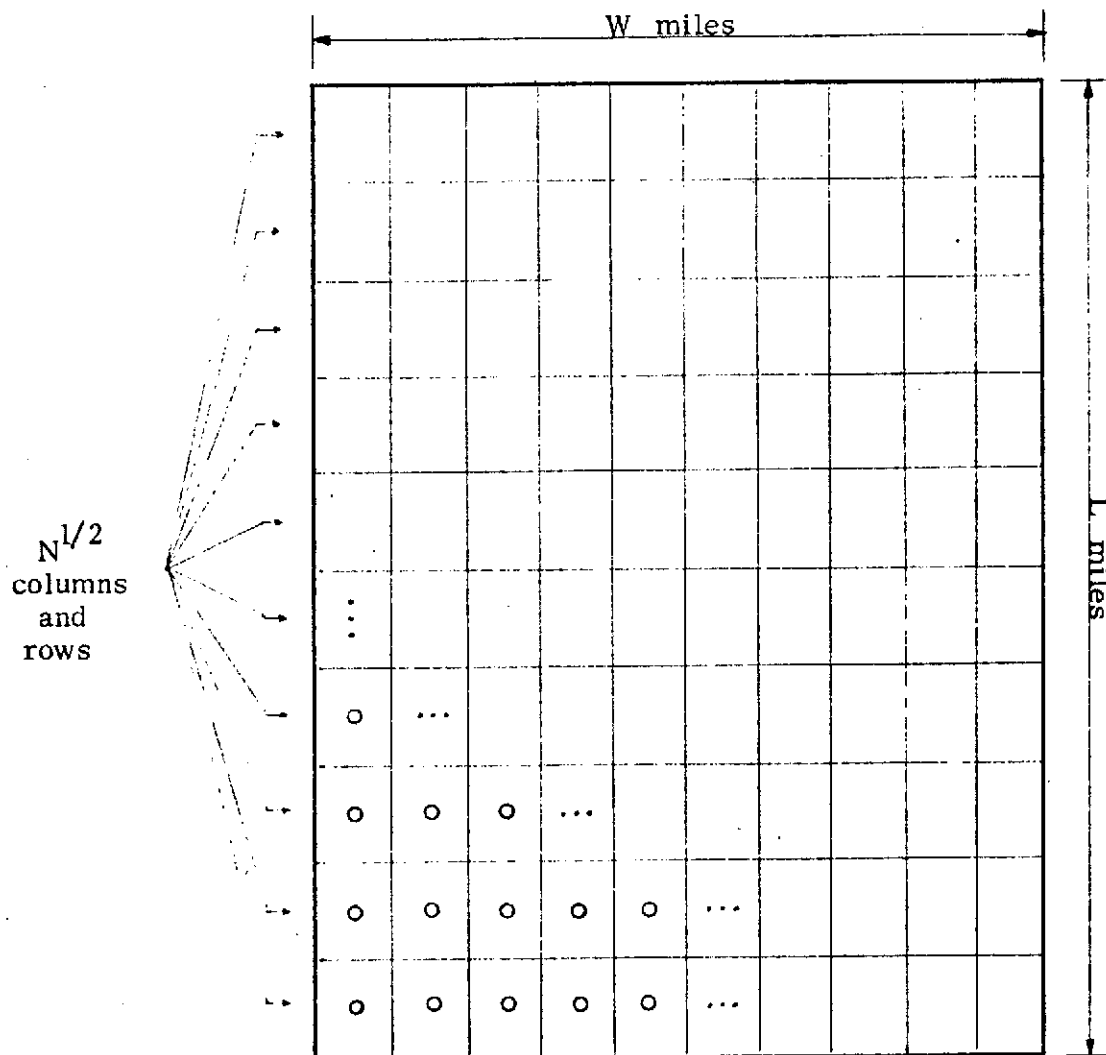
Figure 1. A Rectangular Teleconferencing Region
Containing N Uniformly Distributed Cities.

not the maximum, and because of the large numbers of equal length links involved, a reasonable approximation for the average number of repeaters per intercity link as a function of link length is taken to be $n = (D/h - 1)$. This average number will generally not be an integer.

An equation for the total number of intercity repeaters, $N\eta$, may now be written.

$$N\eta = N^{1/2}(N^{1/2} - 1) \times \text{(the average number of repeaters in a short link)}$$

$$+ (N^{1/2} - 1) \times \text{(the average number of repeaters in a long link)}$$

$$= N^{1/2}(N^{1/2} - 1)(W/hN^{1/2} - 1) + (N^{1/2} - 1)(L/hN^{1/2} - 1)$$

or

$$\eta = (N^{1/2} - 1)(W/h - N^{1/2})/N + (N^{1/2} - 1)(L/hN^{1/2} - 1)/N$$

For N very large, this equation would yield a negative value for $\eta$. To prevent this, $\eta$ will be defined as the larger of the value given by the above equation and zero. For $L = 1,500$ miles, $W = 1,000$ miles and $h = 30$ miles,[1]

$$\eta = (N^{1/2} - 1)(32.3 + 50/N^{1/2} - N^{1/2})/N$$

Table 1 gives some representative values of N and the corresponding $\eta$.

TABLE 1

. (N) for representative values of N

| N | $\eta$ |
|---|---|
| 100 | 2.46 |
| 250 | 1.16 |
| 500 | .52 |
| 1,000 | .07 |
| 1,140 | 0 |
| 10,000 | 0 |

b. The Satellite/Earth Station Network

A satellite long-distance transmission subsystem consists of the following components: 1) a video-transmit, audio-receive up-link earth station at each origination point, 2) a satellite, and 3) a video-receive, audio-transmit earth station at each local receive point. (The number of local receive points will generally be greater than the number of cities being served. In any event, it can not be less.)

Two types of video-receive earth stations might be distinguished according to their output signal-to-noise ratio. Earth stations that feed local distribution subsystems would need a higher output signal-to-noise ratio than would earth stations that serve isolated subscribers (no further distribution is necessary). For simplicity, the following analysis assumes that all earth stations provide the same higher quality signal as that required for redistribution. A slight cost savings could be realized in any actual implementation by limiting use of the higher quality station to receiving points that actually require the higher quality signal. In the comparison of local subsystems later in this chapter, allowance will be made for this savings.

The cost of the long-distance transmission subsystem by satellite may be expressed as:

$$(2) \qquad C_{lds}(c, N) = C_s(c, N) + C_b(c, N) + NC_e(c, N)$$

where $C_{lds}(c, N)$ = the cost of the long-distance satellite subsystem

$\underline{c}$ = the number of video channels carried by the satellite

$\underline{N}$ = the minimum number of video-receive earth stations in the network

$C_s(c, N)$ = the cost of that part of the space segment of the satellite subsystem actually used by the teleconferencing system

$C_b(c, N)$ = the cost of the master video-transmit, audio-receive station(s)

$C_e(c, N)$ = the cost of a video-receive, audio-transmit earth station

2. Cost Summaries

The costs for long-distance subsystems are given in detail in chapters five and six. The pertinent results of these chapters are summarized and placed here for convenient reference together with additional explanatory material relating to their use.

a. Satellite Cost Summary

The earth station costs that are presented in chapter five are based on the assumption that the cost per watt per year of satellite power is known. Earth station costs are then calculated using the criterion of minimum overall satellite system cost. Thus, if the cost per watt-of-space-segment-use increases, minimizing

total system cost would require that the earth stations be made more sensitive, and consequently more costly, so that less satellite power need be used. Similarly, if only a few earth stations are to be constructed, their unit cost should be much higher than if many are needed.

The range of per-watt space-segment charges that is used in chapter five is developed in chapter four. It is based on matching in-orbit satellite capacity with various assumed demand curves over time for that capacity. The present worths of the costs that would be incurred in providing suffieient satellite capacity to just meet these demands are calculated using the costs of currently proposed satellites. Then the amount that must be charged for a watt-year of satellite capacity is determined such that the present worths of the revenue streams associated with each demand curve are equal to the present worths of the costs, respectively, of satisfying the demand. The range of charges runs from \$15,000 per watt-year to \$50,000 per watt-year. From chapter five, then, a satellite system capable of one-way video and return audio from any earth station in a region approximately 1,500 miles by 1,000 miles would incur costs as a function of N as shown in Tables 2 through 7 ($C_{w/y}$ is the cost to the teleconferencing system of one watt of satellite power for one year).

As explained in chapter five, the earth station costs include the following:

1) equipment costs

2) site costs (assumed to be 40 percent of the antenna costs)

3) installation costs (assumed to be 10 percent of the equipment costs)

4) the present worth of maintenance costs over an assumed 25-year lifetime using a discount rate of 10 percent. (Annual maintenance costs are assumed to be 15 percent of equipment costs.)

5) the cost of channel separation and demodulation to baseband for each video channel received. On a per-channel basis, this cost has been estimated to be near \$1,200, as follows. A lower bound may be estimated by looking at the function and cost of an ITFS down converter. The down converter, used with an ITFS receive-station, does no more than shift the frequency of the incoming rf signal down to the proper TV carrier frequency, using a double conversion process, and then amplifies the result. The cost of the down converter is \$800. Demodulation is not included (it, of course, is not necessary in ITFS transmissions). An upper bound may be taken to be \$1,500. This is the cost of the equipment needed at a cable headend site to prepare a TV signal, received from a microwave link, for transmission on the cable.[2] This \$1,500 does not include demodulation either, but does include AM modulation, frequency translation to the proper cable channel, and

## TABLE 2

**Satellite System Cost Parameters with $C_{w/y}$ = \$15,000 and c = 4**

| N | $C_e(c, N)$ | $C_b(c, N)$ | $C_s(c, N)$ | $C_{lds}(c, N)$ |
|---|---|---|---|---|
| 100 | 13,277 | 190,453 | 1,719,027 | 3,237,180 |
| 250 | 11,404 | 244,954 | 1,969,774 | 5,065,735 |
| 500 | 9,437 | 263,594 | 2,626,464 | 7,608,640 |
| 1,000 | 8,115 | 295,771 | 3,515,082 | 11,925,763 |
| 2,500 | 6,999 | 427,823 | 5,101,800 | 23,027,488 |
| 5,000 | 6,459 | 520,435 | 6,886,546 | 39,700,528 |
| 10,000 | 6,085 | 697,998 | 9,391,256 | 70,938,144 |

## TABLE 3

**Satellite System Cost Parameters with $C_{w/y}$ = \$30,000 and c = 4**

| N | $C_e(c, N)$ | $C_b(c, N)$ | $C_s(c, N)$ | $C_{lds}(c, N)$ |
|---|---|---|---|---|
| 100 | 21,118 | 244,623 | 2,025,320 | 4,318,709 |
| 250 | 12,392 | 264,884 | 3,407,118 | 6,770,074 |
| 500 | 11,101 | 293,152 | 3,828,800 | 9,672,456 |
| 1,000 | 9,218 | 400,766 | 5,044,458 | 14,663,023 |
| 2,500 | 7,638 | 492,540 | 7,430,076 | 27,016,832 |
| 5,000 | 6,881 | 623,697 | 10,014,704 | 45,045,536 |
| 10,000 | 6,365 | 860,615 | 13,600,203 | 78,108,272 |

## TABLE 4

**Satellite System Cost Parameters with $C_{w/y}$ = \$50,000 and c = 4**

| N | $C_e(c, N)$ | $C_b(c, N)$ | $C_s(c, N)$ | $C_{lds}(c, N)$ |
|---|---|---|---|---|
| 100 | 34,185 | 258,583 | 1,890,907 | 5,568,063 |
| 250 | 19,415 | 287,412 | 3,418,220 | 8,559,295 |
| 500 | 11,785 | 389,192 | 5,663,671 | 11,945,315 |
| 1,000 | 10,338 | 439,389 | 6,659,990 | 17,437,072 |
| 2,500 | 8,287 | 564,274 | 9,812,110 | 31,093,520 |
| 5,000 | 7,311 | 739,032 | 13,221,370 | 50,516,352 |
| 10,000 | 6,649 | 1,045,246 | 17,928,640 | 85,466,640 |

## TABLE 5

| | Satellite System Cost Parameters with $C_{w/y}$ = \$15,000 and c = 12 | | | |
|---|---|---|---|---|
| N | $C_e(c, N)$ | $C_b(c, N)$ | $C_s(c, N)$ | $C_{lds}(c, N)$ |
| 100 | 44,205 | 328,056 | 3,083,475 | 7,832,028 |
| 250 | 28,173 | 3541861 | 5,168,194 | 12,566,348 |
| 500 | 24,865 | 457,012 | 6,227,586 | 19,117,216 |
| 1,000 | 21,722 | 506,487 | 8,287,900 | 30,516,720 |
| 2,500 | 19,078 | 739,824 | 12,093,080 | 60,527,104 |
| 5,000 | 17,832 | 919,098 | 16,257,658 | 106,335,184 |
| 10,000 | 16,980 | 1,248,249 | 22,008,800 | 193,059,920 |

## TABLE 6

| | Satellite System Cost Parameters with $C_{w/y}$ = \$30,000 and c = 12 | | | |
|---|---|---|---|---|
| N | $C_e(c, N)$ | $C_b(c, N)$ | $C_s(c, N)$ | $C_{lds}(c, N)$ |
| 100 | 68,250 | 354,861 | 3,418,916 | 10,598,739 |
| 250 | 41,094 | 460,870 | 6,113,468 | 16,847,920 |
| 500 | 27,071 | 614,462 | 10,116,378 | 24,266,496 |
| 1,000 | 24,318 | 689,948 | 11,992,616 | 37,000,112 |
| 2,500 | 20,606 | 877,653 | 17,622,336 | 70,051,760 |
| 5,000 | 18,844 | 1,140,515 | 23,679,872 | 119,038,928 |
| 10,000 | 17,650 | 1,601,609 | 31,992,640 | 210,097,520 |

## TABLE 7

| | Satellite System Cost Parameters with $C_{w/y}$ = \$50,000 and c = 12 | | | |
|---|---|---|---|---|
| N | $C_e(c, N)$ | $C_b(c, N)$ | $C_s(c, N)$ | $C_{lds}(c, N)$ |
| 100 | 81,443 | 450,293 | 5,032,237 | 13,676,797 |
| 250 | 41,094 | 606,186 | 9,968,821 | 20,848,576 |
| 500 | 38,959 | 669,417 | 10,121,574 | 30,270,368 |
| 1,000 | 26,058 | 773,462 | 17,017,984 | 43,849,040 |
| 2,500 | 22,161 | 1,030,177 | 23,275,408 | 79,706,912 |
| 5,000 | 19,873 | 1,386,146 | 31,278,336 | 132,027,904 |
| 10,000 | 18,332 | 1,997,533 | 42,237,200 | 227,550,608 |

power amplification. Insofar as demodulation can be considered to require equipment of lower cost than does modulation, the compromise figure of $1,200 per TV channel is reasonable.

b. Terrestrial Microwave Cost Summary

From equation [5] of chapter six, the cost of microwave repeater equipment and its installation is:

$$C_r(c) = \$32,200 + \$7,700(c - 1)$$

Before a comparison can be made between microwave long-distance transmission costs and satellite long-distance transmission costs, these microwave costs must be adjusted so that they, also, include site and maintenance costs. Cosgrove and Chipp[3] use $14,000 as a typical site cost (land, grading, and roads). However, repeater locations within cities may not require the purchase or lease of land. Therefore, a site cost of $10,000 will be used here to reflect this occasional savings. Similarly, it should be possible in some cities to place the antennas on the tops of already existing buildings, and avoid the need for a large tower. Accordingly, $4,000 will be used as the average cost of a tower.

The maintenance cost over a 25-year lifetime, discounted to present value is:

$$C_{maint} = 0.15(\text{electronic equipment cost}) \times 9.077$$

where 9.077 is the present worth factor of a stream of year-end payments for 25 years at 10 percent interest

The electronic equipment cost for a repeater station is $23,800 + $7,700(c - 1). Thus a maintenance cost of

$$C_{maint} = 1.36 \left[ \$23,800 + \$7,200(c - 1) \right]$$
$$= \$32,400 + \$9,800(c - 1)$$

must be added to the microwave costs.

When these adjustments are made,

$$C_r(c) = \$32,200 + \$7,700(c - 1) - \$2,000 + \$10,000 + \$32,400 + \$9,800(c - 1)$$

or

$$C_r(c) = \$72,600 + \$17,500(c - 1)$$

This gives $C_r(4) = \$125,000$ and $C_r(12) = \$265,000$.

C.  Long-Distance Subsystem Comparison

The comparison is based on equations [1] and [2]. With the values of the cost parameters as given in the previous section, both equations have been plotted in Figures 2 and 3 as a function of N with $C_{w/y}$ as a parameter. Figure 2 gives the costs for systems that carry four video channels and figure 3 gives the costs for 12-channel systems. Each figure also includes a plot of what the microwave network would cost if $\eta(N) = 0$. This approximates the case where the cities involved are not spread throughout an entire region but are, in fact, so situated that very few intercity repeaters would be needed.
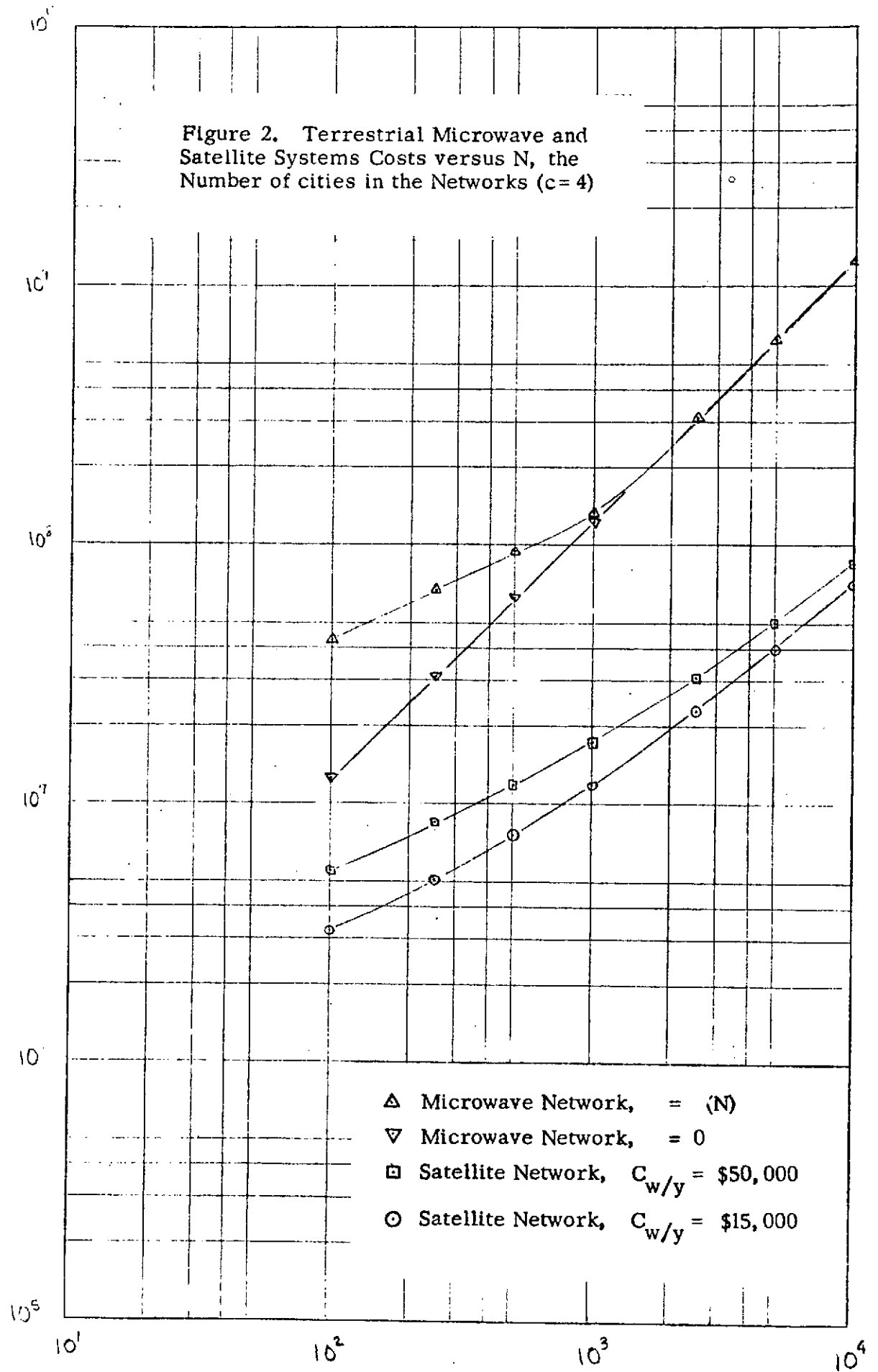
It may be seen that for any regional network serving even as few as 100 cities the satellite/earth station network is dramatically less expensive than the terrestrial microwave network. In fact, providing 12 channels via the satellite is less costly than providing 4 channels with the microwave network, even though to provide 12 channels through the satellite involves stacking the TV channels so close together in frequency that adjacent channels must be transmitted on carriers that are cross-polarized with respect to each other (permitting some overlapping occupancy of the available frequency spectrum) and the earth stations must then be equipped with two antennas and two preamplifiers. A microwave system would become less expensive for service to some number of cities less than 100 (about 30 to 50 if the curves are extrapolated) if they were not spread throughout several states as in the above case.

In view of this cost dependency on the number of cities involved, one is led to ask how many cities might require service in a typical regional system. An example of a region that might actually be served by a teleconferencing system is the Rocky Mountain region. In the eight states of this region there are 1168 cities. There are 361 cities of greater than 2,000 population and 100 cities of greater than 10,000 population. (The breakdown by states is given in Appendix F.) A teleconferencing system transmitting continuing professional education material, would be of most use in the smaller cities where large or specialized libraries and other research facilities are not available. Thus, most of the 361 cities of greater than 2,000 population would probably wish service. This is an obvious case, then, of where the satellite system would be less expensive.

Of course, one reason that a terrestrial microwave network is more expensive is that each receive-station in the network must also be a relay station (that is, a repeater), and only slight degredation of signal quality can be tolerated

Figure 2. Terrestrial Microwave and Satellite Systems Costs versus N, the Number of cities in the Networks (c = 4)

△ Microwave Network, = (N)

▽ Microwave Network, = 0

▣ Satellite Network, $C_{w/y}$ = $50,000

⊙ Satellite Network, $C_{w/y}$ = $15,000

Cost of the Networks, in dollars

N, the number of cities in the Networks

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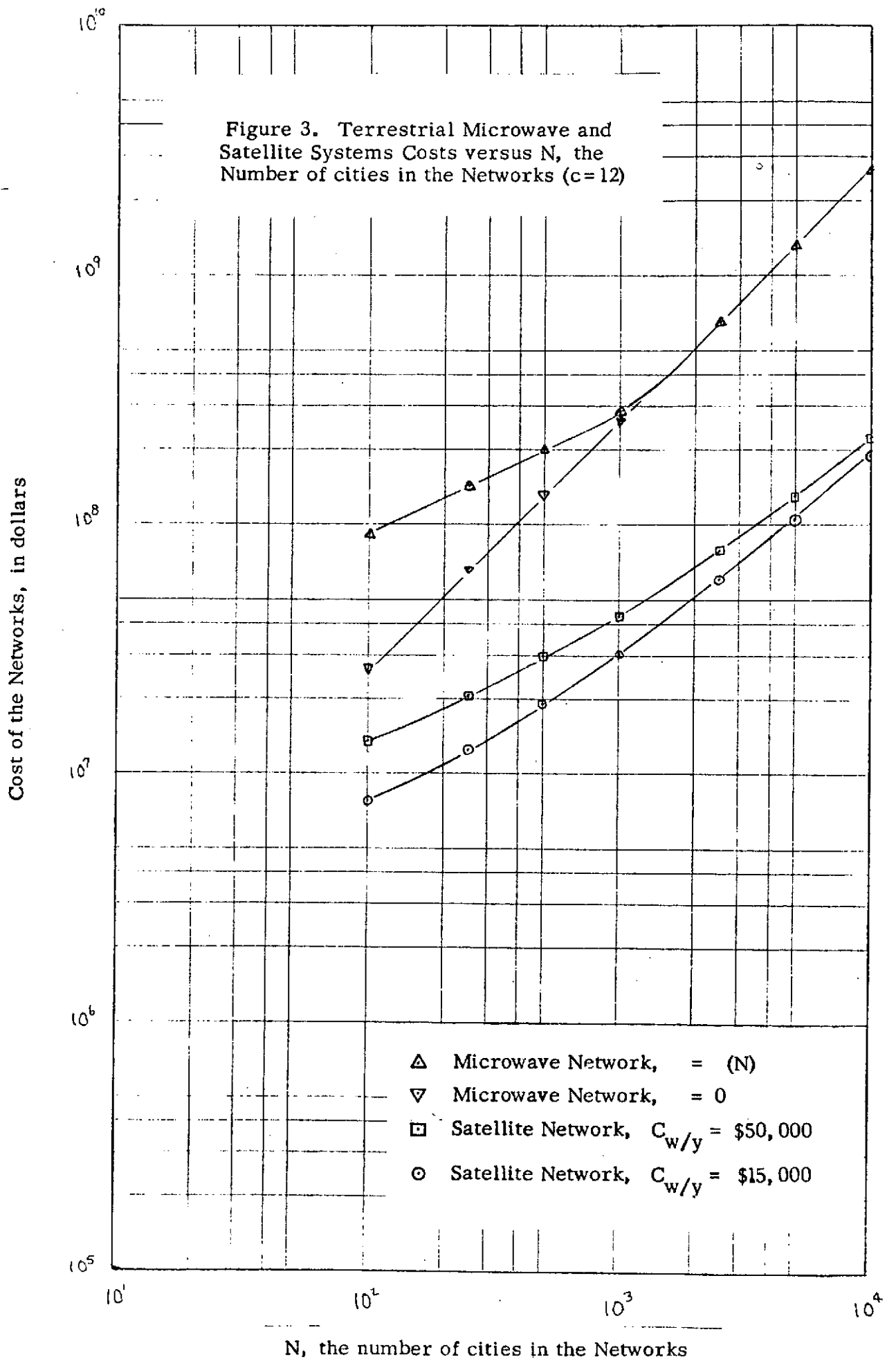Figure 3. Terrestrial Microwave and Satellite Systems Costs versus N, the Number of cities in the Networks (c = 12)

Cost of the Networks, in dollars

$\triangle$    Microwave Network,    =    (N)

$\triangledown$    Microwave Network,    = 0

$\boxdot$    Satellite Network,    $C_{w/y}$ = $50,000

$\odot$    Satellite Network,    $C_{w/y}$ = $15,000

N, the number of cities in the Networks

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at each repeater and still preserve an acceptable quality for subscribers at the extreme downstream ends of the network. By comparison, a satellite network has only one repeater in the whole network. An earth station need have only TV-receive capability plus audio transmit equipment and is, therefore, less costly than a repeater by at least the cost of the TV retransmit and the audio receive equipment. In addition, line-of-sight operation from the satellite is generally possible without the use of expensive towers.

It might also be argued that earth stations serving small cities need not be concerned about standby power. If the city power fails, no one could watch television anyway, and since the earth station is not one link in the chain of stations providing service to cities further on, the need for reserve power does not exist.

## D. Local Distribution Subsystems

With the acceptance of a satellite and an earth-station network as the least-cost method of long-distance transmission for a regional teleconferencing system, three presently available technologies may be considered in the synthesis of the local distribution subsystem: ITFS, cable, and signal reception at subscriber premises using a low-cost earth station. * Each is most appropriate for slightly different subscriber demographics. (Happily, however, cable and ITFS do have roughly the same range of coverage from one headend or transmitter, making direct comparison a bit less cumbersome.) Cable, because of the high cost per mile of installation, is best suited to fairly dense subscriber populations. For instance, most commercial cable ventures regard 40 potential subscribers per route-mile of cable as a minimum requirement for successful financial operation. If all subscribers

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*As mentioned above, in terms of teleconferencing programs for continuing professional education, the professionals in the smaller cities, without specialized libraries and dedicated research facilities, stand to benefit the most by their reception. In many of these smaller cities, or equivalently, in a large percentage of all the cities being served, there are fewer than 10 professionals in any one discipline who could be considered as potential subscribers. Having practically no need to redistribute the signal from the single long-distance earth station reception point, such cities would be in the market for a minimal G/T earth station at the lowest possible cost. The predominance in number of the small city is, then, a dominant consideration in earth-station cost determination. Consequently, this study assumes that reception by low-cost earth stations will be planned from the beginning.

were uniformly spaced over the local distribution area, 40 subscribers per route-mile would be equivalent to approximately 500 subscribers per square mile.**

ITFS, in contrast, because of the relatively high cost of subscriber terminals in comparison with cable subscriber drops, finds application where subscribers are widely dispersed. The ITFS system now in use by the Association for Continuing Education, with studio-classrooms at Stanford University, is a good example. This system serves about 21 subscriber receive-points scattered throughout the entire San Francisco Bay area.

Reception at a subscribers premises via a low-cost earth station has, of course, the same advantages as ITFS for dispersed subscriber populations without the need for an intermediate transmitter.

These technologies are not mutually exclusive and will most often be used to complement one another in providing signal distribution within any given community. An exception would be that ITFS and low-cost earth stations would only rarely be used simultaneously because of their very similar characteristics. Consequently, there are only two main local system configurations that could occur. Given their costs, which one is selected depends on the location of subscribers. They are:

A.  A single earth station for long-distance reception used in conjunction with an ITFS transmitter. The ITFS receivers would supply the signal both to cable headends and to isolated subscribers.

B.  One or more earth stations each serving either a cable headend or a single subscriber.

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** This number was obtained in the following manner. For a uniform subscriber population of P per square mile, subscribers are assumed to be at the intersection points of a cartesian grid, with $P^{1/2}$ lines per mile, that may be imagined to cover each square mile. The average subscriber drop-cable run is from 100 to 150 feet. Therefore, a distribution cable-run would be required along each line of the grid until the subscriber density is high enough that two adjacent grid lines are no more than 300 feet apart. When that occurs, two grid lines could be served by one distribution cable.

All such cable runs would be connected by one perpendicularly run trunk line. Thus, the total number of cable-miles per square mile of service area would be $(P^{1/2}/2 + 1)$ with each cable-run serving two grid lines. Although each cable run is one mile long and each would serve $2P^{1/2}$ subscribers, $2P^{1/2}$ must be slightly larger than 40 in order that the average number of subscribers per cable-mile, including the one mile of trunk-line cable, be 40. Thus, the minimum value for P such that $P/[(P^{1/2}/2) + 1] = 40$ and $P^{1/2}$ is an integer is P = 484.

## 1. Community Demographic Model

Similar to the way in which costs of the long-distance subsystem are a function of the number of receiving points (cities) in the network, the cost of the local distribution system is a function of the local community demography. The comparison of local subsystems is, therefore, most easily accomplished with the aid of a model of the dominant demographic characteristics of subscribers on a community level. In terms of the parameters of this model the costs of the local distribution alternatives can be expressed.

Figure 4 is a diagram of a demographic model of a community. The community boundaries must lie inside a radius of approximately 25 to 40 miles because of the distance limitation on cable and ITFS transmission. Within the community, , the tendency of professionals to locate adjacent to one-another is shown by the existence of $k$ clusters ($k = 0$, $1$, $2$, ...). Isolated subscribers may also exist. They are shown as dots within the community boundary and their total number is given by $\sigma$.

Based on the fact that subscribers who are "close enough" to each other will be connected by cable, a cluster is given the intuitive definition of "a group of subscribers who are close enough one to another that a cable distribution system is the least-cost method of serving them." Thus, in a community for which a configuration-A local subsystem is appropriate, the minimum distance, denoted by $d_A$, between a cluster boundary and a subscriber who is not served by the cluster's cable system is such that the cost of extending the cable system to include the subscriber would just equal the cost of an ITFS receive station. In terms of $a$, the cost of a route-mile of installed cable (including amplifiers, etc.) and $\mu$, the ratio of route-miles to air-miles,

$$d_A = \beta_{itfs}(c_i)/\mu a$$

where $\beta_{itfs}(c_i)$ is the cost of an ITFS receive station for $c_i$ video channels and $d_A$ is also the intercluster distance.

In a community for which a configuration-B local subsystem is appropriate, the intercluster and interisolated-subscriber distance, $d_B$, is

$$d_B = C_e(c_i, N)/\mu a$$

where $C_e(c_i, N)$ is the cost of an earth station.

Figure 4. A Demographic Model of a Community
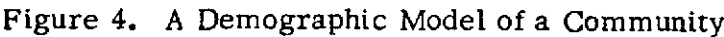
d = the intercluster and the intersubscriber distance
k = the number of clusters in the community
σ = the number of isolated subscribers in the community

If the number of channels carried by the satellite, $\underline{c}$, is not equal to the number of channels that each subscriber is prepared to receive, $c_i$ (that is, if $c > c_i$), then the situation is more complicated. For now, attention is restricted to the case where $c = c_i$. Afterwords, the more general case of $c > c_i$ will be considered.

From equation [2] of chapter six and the cost summary section of this chapter:

|  | N = 1,000 | N = 2,500 |  |
|---|---|---|---|
| $C_e(4) =$ | $8,100 | $7,000 | for $C_{w/y}$ = $15,000 |
|  | $9,200 | $7,600 | " = $30,000 |
|  | $10,300 | $8,300 | " = $50,000 |
| $C_e(12) =$ | $21,700 | $19,100 | " = $15,000 |
|  | $24,300 | $20,600 | " = $30,000 |
|  | $26,100 | $22,200 | " = $50,000 |

$$\beta_{itfs}(4) = \$3,325 + \$5,280$$
$$= \$8,600$$

$$\beta_{itfs}(12) = \$3,325 + \$15,840$$
$$= \$19,200$$

It will be noted that the costs are approximately the same: the earth station costs slightly less when the lowest charge for satellite power is used, the ITFS station costs less when the highest charge for satellite power is used. This is not surprising since the functions of the two stations are very similar. To a first approximation, then, we may say that whether a community uses a configuration-A or a configuration-B local distribution system, the number of clusters and the number of isolated subscribers in the community would be the same. Or, that $d_A$ is approximately the same as $d_B$.

2. Cost Equations for Configurations A and B

Based on the model, the costs of the two possible configurations are:

$$C_A = \sum_{j=1}^{k} C_{ca}(s_j, c, m_j) + f_{itfs}(c) + [x(k-1) + \sigma]\beta_{itfs}(c) + yC_e(c, N)$$

$$C_B = \sum_{j=1}^{k} C_{ca}(s_j, c, m_j) + (yk + \sigma)C_e(c, N)$$

where  k = the total number of clusters in the community
  $\sigma$ = the total number of isolated subscribers in the community

  $c_i$ = the number of channels received by each subscriber

$s_j$ = the number of subscribers in the $j^{th}$ cluster

$m_j$ = the average number of cable miles per customer that are needed to serve all customers in the $j^{th}$ cluster

$C_{ca}(s_j, c_i, m_j)$ = the cost of the cable system for the $j^{th}$ cluster

$C_e(c, N)$ = the cost of a subscriber earth station

$y$ = the ratio of the cost of a redistribution earth station to the cost of a subscriber earth station

$f_{itfs}(c)$ = the cost of the ITFS transmitter facility

$\beta_{itfs}(c_i)$ = the cost of an ITFS subscriber receive-station

$x$ = the ratio of the cost of a redistribution ITFS receive-station to the cost of an ITFS subscriber receive-station

The cost of the cable component of each configuration is portrayed as being independent of the number of channels received by the subscriber. This is because the cost of cable installation is a constant regardless of the number of channels being carried by the subscriber drop cables. Because of this, however, it may be possible in some cases to avoid the cost of a full-blown dedicated cable system.

Many commercial cable systems now in operation have excess channel capacity. Presumably this will also be the case for systems installed in the near future, especially if the current FCC proposal requiring 20-channel systems is adopted. It follows that a possibility exists of leasing idle channels from an existing cable system. Whether this could, in fact, be arranged and what the charges would be would depend on the particular situation. It is not inconceivable, however, that some time on idle channels would be made available for the teleconferencing programs as a public service for educational material. How much time would, again, depend on the particular situation. Nevertheless, the possibility that it exists suggests that some type of coordination and liaison between various groups that create educational programming and the cable companies would be worthwhile.

## 3. Cost Comparisons

The actual comparison must begin with accurate demographics for the community in question. Unless the number and location of subscribers are known fairly well the least-cost subsystem determination procedure, while still better than intuition, will only produce what could be described as an educated guess.

Assuming that this information is in hand, next look at the overall subscriber location pattern and select a possible site for the long-distance earth station. Then, with a charge per mile of installed cable, $\underline{a}$, that is appropriate to the community

(or the part of the community) under investigation, divide the community into clusters and isolated subscribers. These steps will have provided values for $\underline{k}$ and $\underline{\sigma}$.

All parameters of the cost equations are now known, and a determination of whether $C_A$ or $C_b$ is larger is straight forward. The comparison equation is:

$$C_A \overset{?}{\underset{>}{\lessgtr}} C_B$$

or

$$\sum_{j=1}^{k} C_{ca}(s_j, c, m_j) + f_{itfs}(c) + [x(k-1)+\sigma]\beta_{itfs}(c) + yC_e(c, N)$$
$$\overset{?}{\underset{<}{\gtrless}} \sum_{j=1}^{k} C_{ca}(s_j, c, m_j) + (yk+\sigma)C_e(c, N)$$

This reduces to

$$f_{itfs}(c) + [x(k-1)+\sigma]\beta_{itfs}(c) + yC_e(c, N) \overset{?}{\underset{<}{\gtrless}} (yk+\sigma)C_e(c, N)$$

From the facts that 1) an ITFS receive-station and an earth station of comparable signal quality and capacity perform approximately the same function and 2) $\beta_{itfs}(c) = C_e(c, N)$, as shown earlier, it follows that $x \equiv y$. Supposing this to be an exact relationship so that $y(k-1) + \sigma = x(k-1) + \sigma$, one may write:

$$f_{itfs}(c) + [y(k-1)+\sigma]\beta_{itfs}(c) \overset{?}{\underset{<}{\gtrless}} [y(k-1)+\sigma]C_e(c, N)$$

Or, for $C_A$ to be less than $C_B$, it is necessary that

$$0 < \frac{f_{itfs}(c)/[y(k-1)+\sigma]}{C_e(c, N) - \beta_{itfs}(c)} < 1$$

In words, ITFS will be the least-cost configuration whenever the cost of the ITFS transmitter per "weighted" receiver station is less than the difference in cost between a subscriber earth station and an ITFS subscriber station. (The number of weighted receiver stations is equal to $y(k-1) + \sigma$.)

It is now easy to see what was likely understood by the reader earlier. If $\beta_{itfs}(c) > C_e(c, N)$ then configuration A will not be used -- if least-cost is the only criterion. Where other considerations take precedent, such as the possibility of program origination and transmission at the local level, then ITFS would again enter the picture.

Another way to look at this comparison is in terms of a likely threshold value for the weighted number of receive stations. That is, a value of $y(k-1) + \sigma$, say $[y(k-1) + \sigma]_{th}$, such that if, in any particular community the actual value of $y(k-1) + \sigma$ does not exceed $[y(k-1) + \sigma]_{th}$ then one may, with certainty, choose configuration B as the least-cost local subsystem. What are typical values of $[y(k-1) + \sigma]_{th}$ for the cost figures generated in this study? From chapter six, $f_{itfs}(c) = \$24,600 + \$61,600[c/4]$. Thus, with

$$f_{itfs}(4) = \$86,000$$
$$\beta_{itfs}(4) = \$8,600$$

and
$$C_e(4,N) = \$9,200 \quad \text{choosing } C_{w/y} = \$30,000$$
$$\text{and } N = 1,000$$

then
$$[y(k-1) + \sigma]_{th} = \$86,000/(\$9,200 - \$8,600)$$
$$= 130$$

For a 12-channel subscriber reception system (not very likely),

$$f_{itfs}(12) = \$209,000$$
$$\beta_{itfs}(12) = \$19,200$$
$$C_e(12,N) = \$26,100 \quad \text{choosing } C_{w/y} = \$50,000$$
$$\text{and } N = 1,000$$

and
$$[y(k-1) + \sigma]_{th} = \$209,000/(\$26,100 - \$19,200)$$
$$= 30$$

This very large range in threshold value for the number of weighted receive stations means very simply, that no true threshold exists. That is, each case is unique. Nevertheless, certainly for any city where $y(k-1) + \sigma$ is less than about 30, the least-cost local subsystem will use configuration B.

The city of San Jose, California was analyzed with the method presented above. By actually plotting the locations of all doctors in San Jose on a city map, it was determined, using an intercluster distance, $d$, of 1 and 1/4 miles (corresponds approximately to overhead installation and c = 4), that k = 13 and $\sigma$ = 11. If $1 < y < 1.25$, then $23 < y(k-1) + \sigma < 26$. For d = 0.4 miles (corresponds to typical underground cable installation costs and c = 4), k = 22 and $\sigma$ = 38. Again, for $1 < y < 1.25$, then $59 < y(k-1) + \sigma < 64$.

If the 0.4 mile figure for $d$ is used in the downtown area and the 1.25 mile figure used for the residential parts of San Jose, k = 15 and $\sigma$ = 16. Thus, for $1 < y < 1.25$, $30 < y(k-1) + \sigma < 33$.

Can a generalization be made at this point? It seems reasonable to conclude that ITFS will find only limited application outside of the large metropolitan areas. With a present population of 445,709 San Jose is in the lower third of the thirty most highly populated urban places. If population alone were an indication of the likely number of weighted receive stations required in a given city, then certainly fewer than 50 cities could be expected to select ITFS on a least-cost basis.

Earlier, mention was made of the more general case where the satellite and local distribution clusters would carry more channels than each subscriber will receive. This would be needed, for instance, if two professional disciplines were to share the satellite and, to the extent possible, the local systems. Qualitatively, the changes that would be required in the above analysis to accommodate this situation are: 1) The intercluster distance, even though difficult to deal with quantitatively, will definitely increase. This, of course, is because of the increased cost of a cluster redistribution station caused by its increased channel capacity. Ths increased intercluster distance will have a tendency to decrease the number of clusters, $k$. (Because the interisolated-subscriber distance would remain the same as before, no significant change will occur in $\sigma$. 2) However, offsetting this will be an increase in $y$ since receive stations from which redistribution of the signal will occur must receive $c$ channels ($> c_i$). 3) $f_{itfs}(c)$ will increase by roughly the same factor as $y$.

Taken altogether, it appears that these changes will cause the ratio $f_{itfs}(c)/\left[y(k-1)+\sigma\right]$ to increase, not decrease. Therefore, the case for ITFS with $c > c_i$ seems even less favorable than with $c = c_i$.

E. Summary

On a least-cost basis, a satellite system has been shown to be clearly superior to terrestrial microwave for the transmission of teleconferencing signals throughout an entire region (several contiguous states). For a smaller area of coverage, terrestrial microwave will become less expensive as the number of cities in the teleconferencing network drops well below 100.

Local distribution will probably be accomplished with cable systems. In any given city, there will in all liklihood be several non-connected cable systems, the headends of which would be fed directly from their own earth station. Where local interconnection of the cable systems is desired, for instance so that local programming could occur, an ITFS system should be considered.

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## APPENDIX A

## Computer Assisted Instruction (CAI)

Introduction

Computer assisted instruction, along with its sister service, computer managed instruction, has been widely touted by educators and laymen as a means for improving education while reducing its costs. It has also been criticized as dehumanizing and deeply injurious to the total learning process. Much of the debate on CAI's cost and effectiveness has been clouded by a lack of understanding of what CAI and CMI really mean. The purpose of this appendix is to discuss the types of CAI which might be used in schools, their effectiveness and their costs.

Computers are already playing a major role in many school districts and private institutions. Accounting and administrative functions are being handled increasingly by machines. Students use the computer to solve homework problems. Writers use calculators to produce graphs and illustrations for their texts. In CAI and CMI, however, the computer is used to present material to the student directly, measure his progress and help the teacher select appropriate learning strategies.

Through individualization of material and pace, it is hoped, CAI can speed the learning process while reducing learning time. Evidence for this assertion will be discussed in following sections. Given certain caveats, there does seem to be justification for optimism with respect to CAI performance.

The other advantage of CAI is cost savings. If the cost of hardware and software can be reduced in the future -- and the trend is definitely in this direction -- then computers may be able to ease the cost squeeze which schools are now facing. In the discussion of costs in following sections, some of the complexities which confuse discussions of cost will be brought out. Although a general analytical framework will be developed, the only conclusion will be that there is as yet no good estimate of costs available.

## What are CAI and CMI?

One of the central problems in discussing CAI is that there are many types of computer assisted instruction. CAI is really a generic name for a variety of instructional techniques, whose performances vary widely and whose costs range from ten cents to a thousand dollars per student instruction hour. Although the diversity of CAI approaches is somewhat bewildering, it is possible to classify them along several dimensions for the purpose of further analysis.

In considering CAI, it is easy to fall into the error of the proverbial blind men who attempted to learn about elephants by examining parts of the animal. In computer assisted instruction, not even the name CAI is standard. Other terms meaning approximately the same are CBI (computer based instruction), CAL (computer augmented learning), and CAE (computer aided education). In large part, the differences in names reflect only historical usage by individual groups. For example, CAI was adopted by IBM for their early systems.[1] In part, however, the names were selected to reflect different philosophies in the use of computers for instruction.

Two issues should be noted somewhat parenthetically. First, CAI is not identical with programmed instruction (PI), which usually uses hardcopy texts. In addition, most CAI techniques are more sophisticated than traditional PI. Second, CMI must always be borne in mind as a substitute or supplement for CAI. In CMI, a computer is used to help teachers manage a student's progress through multiple media, such as books, videotapes, lectures and discussions. Many of the advantages claimed for CAI, in which material is presented directly by computer, have also been claimed for CMI.

There seem to be two general philosophies for the use of computers in instruction. Debate between the two schools has been active and occasionally bitter. The basic dimension under consideration is whether the student should control what he is to learn, or whether control should be left in the hands of teachers or a central instructional program. Much of the debate reflects a distinction in educational philosophies discussed by Kessen,[2] who believed that extreme forms of the opposing camps in education in general are

reflected in the writings of Locke and Rousseay. Locke believed that a child was primarily an unformed person, into which information could be poured by a teachter. Rousseau considered the child as a whole person, who would be capable of great gains if left to himself with sufficient resources. This, of course, is an overstatement of both Locke and Rousseau, and also of the positions advocated by CAI policy makers. Nevertheless, the distinction between tutorial and dialog techniques[3] reflects the Lockean and Rousseauian positions quite strongly. Within the basic categories of dialog and tutorial instruction, there is a wide variation in sophistication, and these ranges will be discussed in following sections.

## The Tutorial Mode

The tutorial mode can be described relatively well along the dimension of increasing sophistication in basining presentations on prior student responses.

The most elementary mode of CAI is to use the computer as a Skinnerian teaching machine. The student is presented a set of sequence of stimuli, to which he responds. Many PI texts resemble this approach. The first CAI program, in fact, was created in 1958 by using the computer to simulate a mechanical teaching machine.[4]

In the next level of sophistication, the student's response to presented material is used to "branch" him to an appropriate frame, instead of selecting the frame from a set sequence. This allows a student to move quickly through material which is easy for him and to receive more instruction in areas which he is having difficulties mastering. This is basically an online version of TUTOR-TEXT R type material. The advantages of the computer are the speed of branching, the potentially greater complexity of the branching, the ability to provide more levels of difficulty and spread software costs over more users, and the collection of data for student evaluation and program improvement.

Within the category of branching programs, there is considerable diversity. For example, most CAI systems present programs with several inherently different levels of difficulty, to reflect differences in

student learning abilities. In addition, the degree of branching within a given program will vary according to the author's discretion. These two considerations interact, because greater stratification by levels of difficulty will reduce the amount of branching required in each. In the end, it can be said that branching programs vary according to a hazy dimension which might be called "degree of complexity." This dimension is important because it profoundly influences programming costs and because greater complexity allows greater individualization and prevents the student from "running out of branches" in difficult areas.

Most systems now in operation depend upon branching logic. The student's response is usually limited to either a multiple choice response or a numerical entry. In the next level of sophistication, branching is done of the basis of unprogrammed responses. In such systems, the student's response to a question cannot be programmed, but a "judging routine"[5] is used to determine the appropriate branching. For example, the student may be asked to work a geometric proof. The computer program must analyze his progress to check for errors and to judge the suitability of his approach.

Just as there is a degree of complexity dimension in branching programs, there is a dimension in unprogrammed response techniques which might be called "range of judgeable responses." For example, in Albert and Bitzer's paper,[5] they describe a judging routine for determining whether the figure a student has drawn is really a triangle. Although this type of routine is not trivial, it is several orders of magnitude easier than a program for judging whether a student's approach to evaluating an integral is a good one. In a program being written as part of a doctoral thesis by Kimball,[6] the student is given integrals in order to evaluate the "priority list" he uses in applying evaluation techniques. The program then helps the student by suggesting different approaches and checking for logical errors. Such a program would undoubtedly teach the skill of integral evaluation more thoroughly than a simple branched logic technique, but it would also be orders of magnitude more expensive to create.

In the ultimate form of tutorial presentation, termed "Socratic dialogue," the computer program would use very sophisticated judging routines (including natural language input), and a vast store of information and teaching techniques to lead the student through material by means of a series of questions and unprogrammed responses.[7] This concept is largely an ideal, but progress is being made in this direction. For example, the program "ELIZA" has been used at MIT since 1967 to teach special relativity through Socratic dialog.[8] The program uses natural language input. Of course, the system is fairly crude; it must often ask the student to rephrase his response or to ignore the student's response and branch arbitrarily. The cost of running even ELIZA is very large, and the development of natural language processors of high flexibility will take several years. In time, however, CAI tutorial techniques should evolve closer to this ideal.

## The Dialogue or Response Mode

The Socratic dialogue approach runs closely to the ideal of the dialogue mode discussed above. Even in that case, however, the program is controlling the direction of the learning process. In the dialogue or response mode, the emphasis is placed on providing the student with resources to use on his own initiative. Unlike the tutorial mode, the response mode does not lend itself to discussion along a single dimension. There are several components of a responding system, and each will be discussed separately.

Perhaps the most straightforward component is the use of the computer for computation and display. In this mode, the student would come across an interesting problem and use the computer to calculate the magnitudes of certain variables or solve a numerical example. Through the use of simple languages such as BASIC and flexible display capabilities (including graphics), such a system could prove useful to students in quantitative subjects.

An adjunct to this capability is the use of computers for simulation or gaming. Simulation can be used to give the student a working feeling for various systems. Through graphic displays, he can see his solution

of a physics problem acted out, and see the sensitivity of his results to different variables. Physical and social systems have been modeled on computers by many organizations as teaching tools. Simulation can also be used to supplement experiments in the physical sciences. By eliminating set up time and "settling" delays, simulated experiments can be run more quickly. Added to laboratory experiences, this technique can provide more experience in a shorter time.

Another component of responding systems is information retrieval. Computers can be used in interactive modes to locate information, help the student search for relevant information and retrieve textual materials. In a CMI mode, the computer can also route voice or videotape material to the student. Information retrieval becomes increasingly important as the student solves more difficult problems. In continuing professional education, it might easily be the dominant mode of learning.

The final class of components has been termed "responding resources" by Nelson.[9] In responding resources, the student is presented with a textual or pictorial frame. By a typewritten input or pointing at a section of the picture with a light pen, the student indicates an interest he would like to pursue. The computer then provides some explanation of that section, provides a gaming or simulation exercise, or provides a motion picture illustration or a process. A "responding resource" is really a system of the components listed above. The purpose of a responding resource is simply to provide access to information when a student is interested in the subject.

In the sections above, a dichotomy was drawn between tutorial and dialogue modes. In practice, most well thought out systems would include both aspects. In too many proposals, however, researchers and administrators appear to be ignorant of this basic distinction and to the fact that there are levels of complexity within each. Too often, policy makers champion or debunk CAI on the basis of limited preconceptions. In doing so, they act very much like the blind men who argued heatedly about the nature of elephants.

## Performance

A good deal has been written about the performance of CAI, mostly from a theoretical viewpoint. Although some hard data is available, the situation seems far from clear. Rather than try to evaluate past systems, this section will focus on the issues which must be considered in the analysis.

First, it should be axiomatic from the preceeding section that questions on performance must be prefaced by the question, "What type of CAI is being considered?" General statements are of limited value in evaluation. Yet many general statements are available on how CAI should perform. These comments reflect the Locke/Rousseau distinction made above.

Lockean theorists tend to see CAI systems as uncomplaining tutors with unlimited patience. CAI appears as a road to uniform high quality instruction that can be tailored to each student's needs. Suppes (who is not a strict Lockean) stresses the value of individualization, listing five areas where individualization can be used: presentation of material, evaluation or progress, repetition of sections, level of difficulty, and review. These theorists feel that individualization will allow each student to learn at his maximum possible rate.

Rousseauian proponents have generally been reelgated to critics' roles, since most operational CAI experiments have centered around the tutorial presentation mode. A general warning is summed up by Theodore Nelson: "CAI in its conventional form enlarges and extends the faults of the American education system itself."[10] Nelson cites tendencies to boredom, lack of initiative, the tyranny of grades being renewed in terms of number of frames learned and narrowness of curricula.

Because most measurements of performance have been made in terms of a Lockean philosophy and have been further confused by the fact that they were specific to one form of CAI system. The results so far have been mixed but encouraging. Jamison, et al., were able to demonstrate[11] that CAI could provide remedial education in mathematics and reading better and more cheaply than additional classwork. Albert and Bitzer[12] discuss a medical science

course in which students learned the material in 1/3 to 1/2 the time of lectures and showed superior retention after 26 weeks. The time savings of 1/3 has come up in other studies, and while the number is undoubtedly tied to the level of sophistication of a program, it is indicative.

Several caveats are in order when discussing the efficacy of CAI. For example, CMI was used to teach a first-aid course for the American Red Cross, and improvements on the order of those found in CAI were obtained.[13] Since CMI is less expensive in general than CAI, performance/ cost ratios for CAI must be compared to those of CMI as well as to those of traditional instruction.

In addition, many of the advantages claimed of CAI can also be claimed of traditional methods. In his insightful review of CAI, Feldhusen describes a system called BOOK.

> All schools at all levels provide for much individualization of instruction. These activities include reading in BOOK (basic organization of knowledge)...

> "BOOK" is the best medium for individualized instruction so far devised. The student may enter at various places or levels, proceed at his own rate, branch by his own choice or under teacher direction, be actively engaged if he does the study exercises or problems, receive some feedback if the answers are given in the back of the book, and be reinforced if he performs well.[14]

In general, it seems fair to say that, even at the multiple choice branching level, CAI can provide time savings and be cost effective for some applications. Its performance at more sophisticated tutorial levels can only be conjectured. In addition, most of the measures used to date have been unacceptable from the viewpoint of theorists who favor exclusive or extensive student control of the learning process.

## The Cost of CAI

Although the development of evaluated instructional programs has been a major factor in CAI's slow acceptance in schools, it is generally conceded that the real stumbling block to adoption is current CAI's high cost.[15]

From the discussion above, the reader understands that it is impossible to speak of "the" cost of CAI, since different levels of sophistication in programming will be associated with different financial outlays. Nevertheless, even fairly simple drill and practice types of programming are still too expensive to be employed in the bulk of the school system.

The purpose of this section is not to produce a definitive survey of the costs of various CAI systems. At present, cost data is too confused and scattered to provide hard numbers. Instead, the various components of CAI will be discussed, and general considerations for comparing CAI to traditionally administered instruction (TAI) will be presented. Although the most useful cost figure is dollars per student contact hour, it is necessary to discuss component costs first. Placing costs on a per contact hour basis is a fairly subtle, and controversial, problem.

## Component Costs

CAI costs can be segregated into hardware, software, and operational costs. Hardware costs can be further subdivided into head-end, communication and terminal segments. Hardware costs will be considered first.

At the head end, most of the financial investment is tied up in the central processing unit (CPU), memory banks consisting of tapes and discs, and various peripheral devices such as card readers. In the past, the CPU mainframe has dominated the investment. With the growth of larger computers, however, which serve many more users, CPU cost per users has fallen rapidly, in comparison to the relatively constant per user investment in memory and peripherals. In his excellent review of future computer technologies,[16] Wallace Riley noted that:

> In 1955, for example, of every dollar spent on hardware, 20 cents went for peripherals; in 1965, the ratio was more nearly 50-50, and by 1975, if not sooner, it will be 80-20 -- the reverse of the 1955 figure.

> Much of this growth is due to increased interest in remote on-line computing, which requires communication channels and a multiplicity of terminal devices. Much of it is also due to the increased raw power of central processors, which require more and fancier peripheral devices to provide them with enough data to absorb their output.

Because of the growing importance of peripherals, costing of CAI systems must be done with careful attention to the types of input/output and communication devices needed by the system. Several CAI designers have made the mistake of extrapolating falling CPU costs directly into drops in CAI costs. In addition, it is not certain that large CPU's will be used extensively in CAI systems. Although Socratic dialogue techniques will require large software systems, most CAI systems can be handled by local minicomputers, accessing remote data bases. Because of mass production and comparative simplicity, four or five minicomputers may cost considerably less than a single CPU of comparable processing power.

Communication costs have been the main focus of this study so they will not be addressed here. It should be noted, however, that most current CAI systems use only local communication lines, although a few systems (such as the Stanford project) have used long distance communication. As a result, system designers have tended to ignore communication costs in the past. As CAI begins to use more advanced techniques, instructional bases will probably become more clustered, and the importance of long distance communication should grow accordingly.

Terminal costs are probably the most serious hardware limitation on CAI's acceptance. At the user's end of the system, there is a model (modulator-demodulator) to digitize the analog signals passing over the communication channel, a multiplexer/demultiplexer, if there are several users at the terminal location, and a display device. Modem and multiplexing costs will probably fall dramatically as LSI becomes more prevalent and the growing demand for time sharing brings them into mass production. The cost of adequate displays, however, is still very high.

An IBM model 333 teletype costs about $850. Although these displays are relatively inexpensive, they are very slow and suited only to relatively simple CAI techniques. A CRT (cathode ray tube) terminal, on the other hand, can display much information rapidly, but is very expensive. For literature searching, simulation and graphical displays, CRT capabilities are essential. Unfortunately, image quality is relatively poor on most systems and a flexible display which allows text editing and other needed functions costs between $5,000 and $20,000. A fairly simple system, using a commercial television set and "frame grabber" storage would be inexpensive,

but communication costs would be exhorbitant. In order to bring down communication costs, it is necessary for the display to have character generation and editing capability, both of which are currently very expensive. Display costs are fairly sensitive to such factors as number of characters displayed, amount of storage required, editing capabilities and character generation. The design of a reasonably priced system requires that the purchaser be familiar with the options available to him.

The importance of display costs can best be appreciated by the fact that half of the total per student contact hour costs estimated for the University of Illinois' proposed PLATO IV system (which includes software, instructional programming, CPU, memory and communications) arise from the display terminal.[17] Yet these terminals are projected $1800 devices, beyond the current state of technology. The reason that displays are so important in the overall cost picture is that other hardware and software can be spread over many users. The terminals, however, serve one user at a time.

Operating system software (excluding instructional programming) is another expensive factor in system design. It has been noted that while "the cost per hardware gate has dropped by two orders of magnitude since the middle 1950's, the cost per software instructions has remained just about constant, at around $10."[18] Rising labor costs in programming and the growing complexity of large CPU's are probably responsible for the bulk of this increase. Software creation is especially expensive if the system will provide the users with several computer languages, different information bases, and sophisticated accounting procedures.

Operating costs for the head-end system can be large because of maintenance, operation of the equipment and the management necessary to run large centers. At the terminal end, there is also a need for maintenance, and maintenance costs can run close to the yearly depreciation of some terminals, doubling their effective per/year cost. If the system is to be used in schools, there will be a need for a center proctor, to maintain

the equipment, teach use of the system, and keep discipline, if necessary. Although proctors will be paid less than teachers, their salaries will become significant if a center has only a half-dozen terminals or so.

The last component to be considered is instructional programming, which can usefully be subdivided into initial production and revision. The costs of initial production remain somewhat of a mystery. Published estimates[19,20] seem very crude, and private firms consider such information to be proprietary. Naturally, the initial cost is dependent upon the level of sophistication being used in programming strategy. One point of agreement appears to be that simple programming languages will be needed in the future, especially if teachers write their own programs. The TUDOR[21] language represents the direction in which languages will travel. After a program is written, it can be modified and updated, with the aid of statistics gathered from the online users. It is disturbing that estimates of CAI costs have tended to ignore the costs of updating programs. One of the principal advantages of using a computer for instruction is the feedback it can provide to the program designer on the performance of his product.

In the preceeding paragraphs, the author has given qualitative determinants of system costs. Although some quantitative estimates have been made,[22,23,24] all leave out one or more portions of the preceeding analysis, and their breakdown of costs on a per student contact hour basis seems to leave even more to be desired. All three were good efforts, approaching the problem through different hardware and instructionware directions. Although all are worth reading, none appears to provide a complete analysis. Clearly, a great deal more effort is necessary in this area.

## Per Student Contact Hour Costs

Two problems with placing costs on a per student contact hour basis are annualizing the costs and placing them on a per hour basis. The first is logically prior to the second, and also somewhat more straightforward.

Annual costs consist of amortizing capital costs and computing operating costs. As noted above, operating costs consist of maintenance, supervision, communications, and the operation of equipment. Major capital costs consist of hardware, software, and instructional programming.

To annualize hardware depreciation, it is necessary to know the equipment's lifetime in years $(n)$, the cost of capital for the user $(i)$, and the initial cost of the equipment, $(C_o)$. The annual cost $(C_a)$ for each piece of equipment is then given by:

$$C_a = \frac{C_o}{\sum\limits_{j=1}^{n} \frac{1}{(1+j)^i}}$$

The equipment's lifetime in years may be either its physical lifetime, or the time span over which it is not made obsolete by newer equipment. Leasing the equipment, rather than buying it, may be the best choice, especially if the user does not wish to maintain it himself, cannot use the capital equipment tax writeoff or feels that the equipment should soon be replaced by more modern devices. Previous estimates of system costs have tended to use straight line depreciation, which can be a poor estimate if the cost of capital is high, as it might be for a hospital or individual professional.

Software should also be amortized over time. As each piece of software is written, it should be capitalized, and its useful life estimated. If it is purchased from another system, this becomes its initial cost. Because identical hardware systems can use identical software, if there is cooperation between users, and because the cost of producing software is high, computer systems for CAI will benefit greatly if they exchange software or jointly pay for software design. The lifetime of software is difficult to estimate, and is determined almost exclusively by obsolescence. It is a matter of judgement whether major revisions are capitalized or treated as annual costs.

Instructional programming, like system software, benefits from cooperative production and use. If each teacher writes his own program, even using a simple language, instructional progeamming costs will be high. At the other extreme, if programs are produced nationally, their cost per user will become negligible (in larger fields). Socratic dialogue and other sophisticated techniques will probably require national origination. For

less advanced techniques, programs will probably be produced by individuals and sold competitively, much as textbooks are now. Also like textbooks, programs probably will be developed only in larger fields, with live lectures being used in small growing fields. One way to get around the "big brother" connotation of national origination would be to produce programs modularly, and let the teacher build programs (with the aid of the computer). Another approach to localizing instruction is illustrated by Kimball's[25] calculus tutor, in which the teacher's personal approaches and priorities in problem solving can be learned by the program and used as the basis for instruction of the students. Whatever approach is used to create programming, the advantages of cooperative usage should be realized and mechanisms should be provided for the feedback necessary in the revision of programs.

Once costs are annualized, it is necessary to place them on a per student contact hour basis. In a sense, this step has already been done for instructional programming. Once the number of students using the system per year is known, and the system lifetime is estimated, the per contact hour cost falls out immediately.

The cost of the CPU and head end software are determined by system utilization. Ideally, the system would be used 100%, 100% of the time. In practice, this is impossible and a false goal. It is impossible, because usage will vary with time of day, and because systems must be designed to accomodate growth in the number of users. The peak-to-average consideration can be alleviated somewhat by a tarrif structure that encourages users to use the system during off peak hours. To simply legislate that the system will be used evenly, however, would make it unattractive from the users' standpoint, and it would probably not be adopted. A 50% utilization rate of the CPU is considered almost extraordinaty for the most current systems. The problem of growth can be somewhat alleviated by designing the system to be able to grow by adding modular components, but this cannot always be done. Attention should be paid, however, to the comparative economics of modular growth versus major additions.

Alpert and Bitzer's cost estimates for PLATO IV illustrate just how important utilization really is to system efficiency.[26] Alpert and Bitzer project a per student contact hour cost of about $0.60 (including hardware and instruction ware) which would be competitive with current educational costs in schools. However, they assume 100% utilization of the CPU and student terminals. In addition, they assume that the system would be used 45 weeks per year, 44 hours per week, or 2000 hours per year. The regular school year, in contrast, is only 1050 (6 hours per day, 35 weeks per year). In another paper[27] the author recalculates the per student contact hour cost, using 60% CPU utilization, 60% terminal utilization, and a 1575 hour school year (allowing for night usage by adults and a slightly longer school day). The costs jumped by a factor of two, and were no longer attractive for school use.

On the college level, and in the military, longer student days could be used, bringing the effective system usage to something near 2000 hours per day. Problems of CPU utilization would still remain. In addition, the traditional costs of college and specialized instruction are much higher than they are on the elementary school level. It can be expected, then, that the first use of CAI may be on the college level. In fact, Florida State University offers a freshman physics course by CAI.

For professionals, high utilization rates for the terminals are impractical. Although some of the terminal costs may be taken by using the terminal for other computational functions, it is doubtful that professionals would adopt a system for which they had to wait in line for any length of time. Moreover, it would be best to bring terminals into professionals' offices, which would almost certainly mean low utilization rates. Although the problem should be eased as the cost of displays, modems and multiplexers decline, it appears that CAI will not be attractive for professionals in the near future unless teletype terminals are used. This in turn limits the sophistication possible in programming and will make literature searching tedious and slow, casting doubt on system acceptability.

## CAI vs. TAI

In a sense, comparing CAI to TAI is like comparing apples and oranges. Traditionally administered instruction is labor intensive, and ideally suited to short school days. CAI is hardware intensive, and therefore sensitive to utilization rates. In addition, instructional programming must be spread over many users, whereas live class instruction can be done effectively by individual teachers. In constraining CAI to normal school days and lock-step progress through grades, a distorted unfavorable view is presented of its economics. One of the main characteristics of CAI is its ability to teach material faster. Randall and Blashke[28] calculated that if students were allowed to progress through grades faster as a result of CAI, the number of years saved would make CAI look competitive with traditional costs. For the school system, the issues of teacher replacement, length of the school day and progress through grades are explosive issues, subject to considerable inertia and resistance -- much of it justified.

In less traditional areas, like vocational education, continuing professional education and, to some extent, the college system, the time savings of CAI could prove decisive. If a professional could learn without travelling to school and pick up competencies rapidly, the amount of time saved by his company might justify CAI costs in the range which producers now claim they can reach.

## Conclusion

The reader will probably find the absence of hard cost figures disconserting, especially in light of the communication costs derived in technical sections of this report. This discomfort is certainly justified, since communication costs cannot be used meaningfully until other system costs are known. Unfortunately, the area of CAI has proven to be particularly difficult to quantify. Studies references above, which attempted to determine CAI costs, all had methodological weaknesses, or used assumptions which do not seem reasonable or desirable. Moreover, many of the costs seem to be "off the top of the head" estimates, of doubtful value. In general, it seems that CAI costs for current systems range between $1 to $10 per hour

of student contact. The lower estimate is near the cost of textbooks in college and about double the total cost in elementary and secondary schools. As component prices continue to fall and software becomes available, the economic outlook for CAI should continue to improve. It is doubtful, however, whether educators or private groups will be willing to make major investments until instructionware packages are improved considerably and cost estimates become more reliable.

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Supply:  Discounted Launch Streams

The equivalent (discounted) number of satellites is derived for each case as follows:[1]

Case 1   One satellite launched at $t = 0, 10, 20 \ldots$ years, forever.

   Application:  $L_b$, $L_c$, and all orbit-spare streams

   Formula:

$$\hat{N}(i) = \lim_{n \to \infty} \sum_{k=0}^{n} (1+i)^{-10K} = \lim_{n \to \infty} \left[ \frac{1 - (1+i)^{-10n}}{1 - (1+i)^{-10}} \right] = \left[ \frac{1}{1 - (1+i)^{-10}} \right]$$

   Thus,  $\hat{N}(L_b, i) = \hat{N}(L_c, i) = $

| | |
|---|---|
| $\infty$ | for $i = 0\%$ |
| 2.5901 | 5% |
| 1.6274 | 10% |
| 1.3283 | 15% |
| 1.1926 | 20% |

Case 1'   8 satellites launched together at  $t = 0, 10, 20 \ldots$ years, forever

   Application:  $L_a$

   Formula:  Same as above, but answer is multiplied by 8

   Thus,  $\hat{N}(L_a, i) = $

| | |
|---|---|
| $\infty$ | for $i = 0\%$ |
| 20.7208 | 5% |
| 13.0195 | 10% |
| 10.6266 | 15% |
| 9.5409 | 20% |

---

[1] Discrete annual payment periods are assumed except for small-satellite linear buildups where quarterly payments must be used.  For the latter case, "equivalent" annual payments are computed.

Case 2    One satellite launched at $t = 0$, and every $1\frac{1}{4}$ years thereafter, forever

Application: $L_d$

Formula: $\hat{N}(i) = \lim\limits_{n \to \infty} \sum\limits_{k=0}^{n} (1 + i/4)^{-(4)\left(\frac{5}{4}\right)K} = \left[\dfrac{1}{1 - (1 + i/4)^{-5}}\right]$

Thus, $\hat{N}(L_d, i) =$

|  |  |
|---|---|
| $\infty$ | for $i$ = 0% |
| 16.6052 | 5% |
| 8.6096 | 10% |
| 5.9481 | 15% |
| 4.6195 | 20% |

Case 3    Infinite launch chains (one satellite every 10 years):
one chain initiated each at $t = 0$, 10, 20 ... years, forever.

Application: $L_f$

Formula: $\hat{N}(i) = \left[\hat{N}(\text{Case } 1, i)\right]^2 = \left[\dfrac{1}{1 - (1 + i)^{-10}}\right]^2$

Thus, $\hat{N}(L_f, i) =$

|  |  |
|---|---|
| $\infty$ | for $i$ = 0% |
| 6.7086 | 5% |
| 2.6486 | 10% |
| 1.7645 | 15% |
| 1.4223 | 20% |

Case 4    Infinite launch chains (one satellite every $1\frac{1}{4}$ years): one chain initiated each at $t = 0$, 10, 20 ... years, forever.

Application:  $L_e$

Formula:  $\hat{N}(i) = \hat{N}(\text{Case 2, i}) \cdot \hat{N}(\text{Case 1, i})$

Thus, $\hat{N}(L_e, i) = $

|  |  |
|---|---|
| $\infty$ | for i = 0% |
| 43.0091 | 5% |
| 14.0116 | 10% |
| 7.9010 | 15% |
| 5.5093 | 20% |

## Demand:  Discounted Sold Capacity

The equivalent (discounted) total capacity sold depends upon demand functions and the interest rate as follows:[1]

Case $D_1$    Constant demand

  Application:  $D_{1a}$, $D_{1b}$, $D_{1c}$

  Formula:

$$\hat{W}(D_1,\ i) = W \int_0^\infty e^{-it}\ dt = W\left[\frac{1}{i}\right] = \begin{cases} 20\ W & \text{for } i = 5\% \\ 10\ W & 10\% \\ 6.666\ W & 15\% \\ 5\ W & 20\% \end{cases}$$

| Thus, | $i$ | $\hat{W}(D_{1a},\ i)$ | $\hat{W}(D_{1b},\ i)$ | $\hat{W}(D_{1c},\ i)$ |
|---|---|---|---|---|
| | 5% | 14,080 | 13,440 | 1,760 |
| | 10% | 7,040 | 6,720 | 880.0 |
| | 15% | 4,693 | 4,480 | 586.7 |
| | 20% | 3,520 | 3,360 | 440.0 |

---

[1] Continuous lease payments are assumed. Satellite capacity may at times exceed demand, but we presume it cannot be sold. Since some of our posited demand functions grow continuously, continuous discounting (exponential) will be used. This is not unrealistic: several proposed satellite owners (e.g. COMSAT) expect to lease their transponders on a monthly basis.[2] This is a tentamount to continuous leasing.

Case $D_2$    Linear demand, $0 \leq t < 10$ years; constant demand thereafter.

Application:  $D_{2d}$, $D_{2b}$

Formula:

$$\hat{W}(D_2, i) = W\left[\frac{1}{10}\int_0^{10} t e^{-it}\, dt + \int_{10}^{\infty} e^{-it}\, dt\right]$$

$$= W\left[\frac{(1 - e^{-10i})}{10\, i^2}\right] = \begin{cases} 15.739\ W \text{ for } i = 5\% \\ 6.3212\ W \hspace{2.2em} 10\% \\ 3.4528\ W \hspace{2.2em} 15\% \\ 2.1617\ W \hspace{2.2em} 20\% \end{cases}$$

Thus,

| $i$ | $\hat{W}(D_{2d}, i)$ | $\hat{W}(D_{2b}, i)$ |
|-----|------|------|
| 5% | 11,080 | 10,577 |
| 10% | 4,450 | 4,248 |
| 15% | 2,431 | 2,320 |
| 20% | 1,522 | 1,453 |

Case $D_3$    Linear demand, $0 \leq t < \infty$ .

Application:  $D_{3e}$, $D_{3f}$

Formula:

$$\hat{W}(D_3, i) = W\left[\frac{1}{10}\int_0^{\infty} t e^{-it}\, dt\right] = W\left[\frac{1}{10i^2}\right] = \begin{cases} 40\ W \text{ for } i = 5\% \\ 10\ W \hspace{2.2em} 10\% \\ 4.444\ W \hspace{1.5em} 15\% \\ 2.5\ W \hspace{2.2em} 20\% \end{cases}$$

C-2

Thus,

| i | $\hat{W}(D_{3e}, i)$ | $\hat{W}(D_{3f}, i)$ |
|-----|-----|-----|
| 5% | 28,160 | 26,880 |
| 10% | 7,040 | 6,720 |
| 15% | 3,129 | 2,987 |
| 20% | 1,760 | 1,630 |

# APPENDIX D

## Comparative Evaluation of the Medium Satellite Case

The demand functions $D_{2b}$, $D_{2d}$, and $D_{2m}$, and their corresponding launch streams $L_b$, $L_d$, and $L_m$, are ideally suited for an economic comparison of all three satellite types: small, medium, and large (see Fig. 1 in the main body of the report). Unfortunately, the capacity of the medium satellite is not divisible with the capacities of the other two cases in a way which allows us to use the discrete present-value formulations developed in Appendix A. Since continuous compounding does not suffer this limitation, we will use the following present-value formula instead:

$$\hat{N}_a(L_{b,d,m}, i) = \lim_{n \to \infty} \sum_{k=0}^{n} e^{-k\left(\frac{10}{x}\right)d} = \left[\frac{1}{1 - e^{-10i/x}}\right]$$

where  x = (capacity of largest satellite/capacity of satellite in question); or, alternatively, the number of launches in 10 years necessary to satisfy demand $D_2$ at  t = 10 years:

$$x(\text{small}) = 8$$
$$x(\text{medium}) = 6$$
$$x(\text{large}) = 1$$

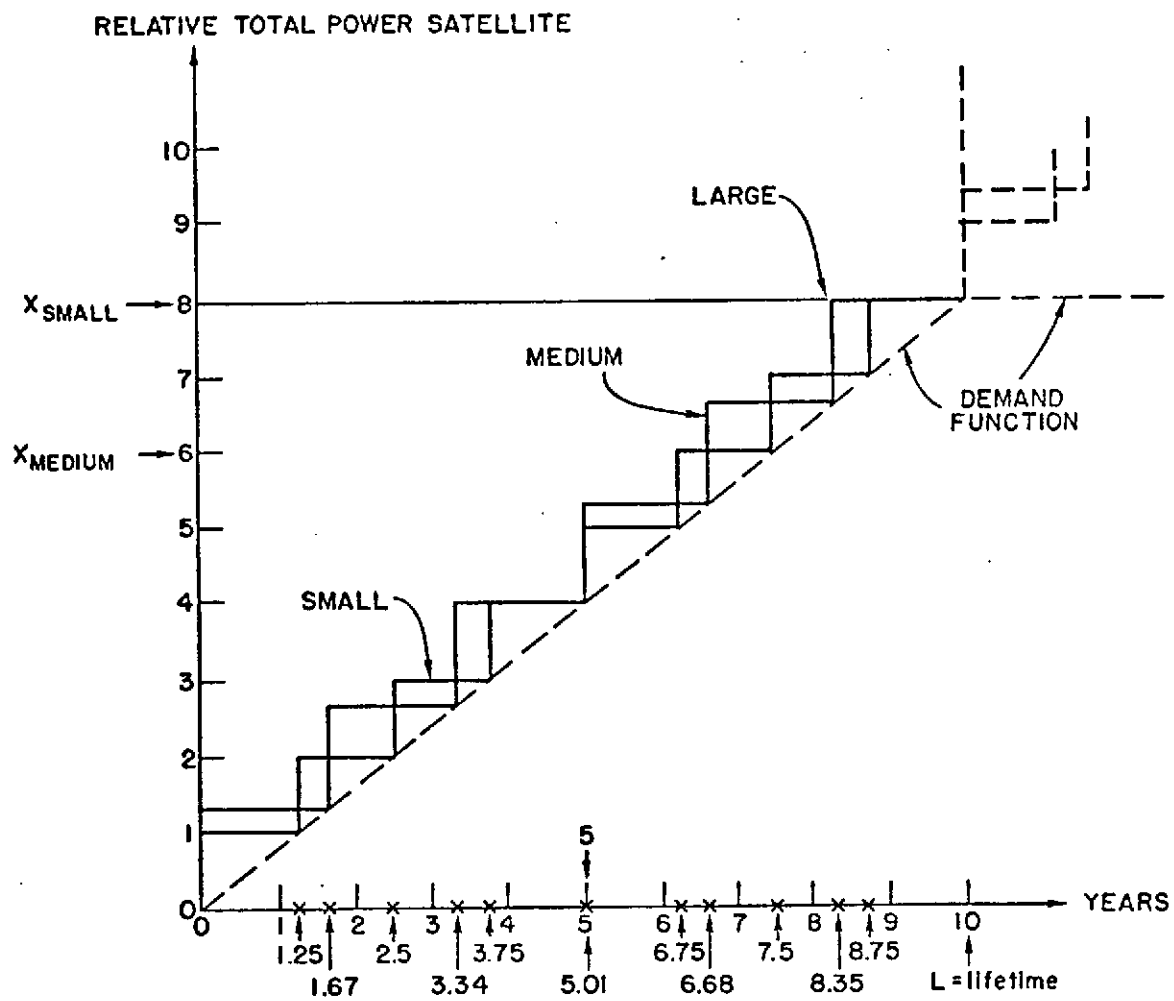Figure D-1 illustrates this definition and the relevant supply and demand functions.

Figure D-1:  Timing of Launches to Meet Linear Demand Growth

The actual demand functions $D_{2b}$, $D_{2d}$, and $D_{2m}$ have maximum values of 672 Watts (the largest satellite); 704 Watts (8 small satellites); and 720 Watts (6 medium satellites) respectively. The equation for discounted capacity, $\hat{W}(D, i)$ developed in Appendix B, Case $D_2$ applies here without modification. So do the earlier orbit-spare launch stream formulas, which yield the following discounted investments for spares and for R & D:

| Backup Strategy | Discount Rate $i$ | Discounted Investments in R & D and spares ($M) | | |
|---|---|---|---|---|
| | | Large | Small | Medium |
| A: in-orbit spare | 5% | 168.6 | 51.4 | 95.7 |
| | 10% | 117.6 | 35.4 | 64.4 |
| | 15% | 101.9 | 30.5 | 54.7 |
| | 20% | 94.6 | 28.2 | 50.3 |
| B: ground spare | general | 53.0 | 14.7 | 21.0 |

Our general methodology still applies: we add these investments to the service-satellite investments calculated from the formula for $\hat{N}_a$ developed above. This yields total discounted investment, which when divided by $\hat{W}$, yields annual cost per Watt. The results are as follows:

| Discount Rate $i$ | Discounted Supplied and Demanded Capacity | | | | | |
|---|---|---|---|---|---|---|
| | Supply, $\hat{N}$ | | | Demand, $\hat{W}$ | | |
| | Large | Small | Medium | Large | Small | Medium |
| 5% | 2.541 | 16.529 | 12.500 | 10,577 | 11,080 | 11,320 |
| 10% | 1.582 | 8.511 | 6.534 | 4,248 | 4,450 | 4,550 |
| 15% | 1.287 | 5.862 | 4.521 | 2,320 | 2,431 | 2,485 |
| 20% | 1.156 | 4.521 | 3.531 | 1,453 | 1,522 | 1,558 |

Figure D-2 summarizes the results for investment and annual cost per Watt. Results for the small and large satellites are virtually identical to those obtained for cases 4 and 5 respectively ( see Fig. 3 in the main report). The slightly lower ( $<3\%$ ) values obtained here differ slightly because of the continuous discounting formula used. Hence the same conclusions apply: for the orbit-spare strategy, the small satellite is the better choice for $i > 6\%$; for the ground-spare strategy, the large satellite is the better choice for $i < 11\%$. As expected, the medium satellite is the most expensive choice.[ω]

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[ω] Results are actually biased over 7% in favor of the medium case (i.e., by the ratio of 720 Watts/672 Watts). Without this bias, the medium satellite would have the highest annual cost per Watt, even at $i = 20\%$.
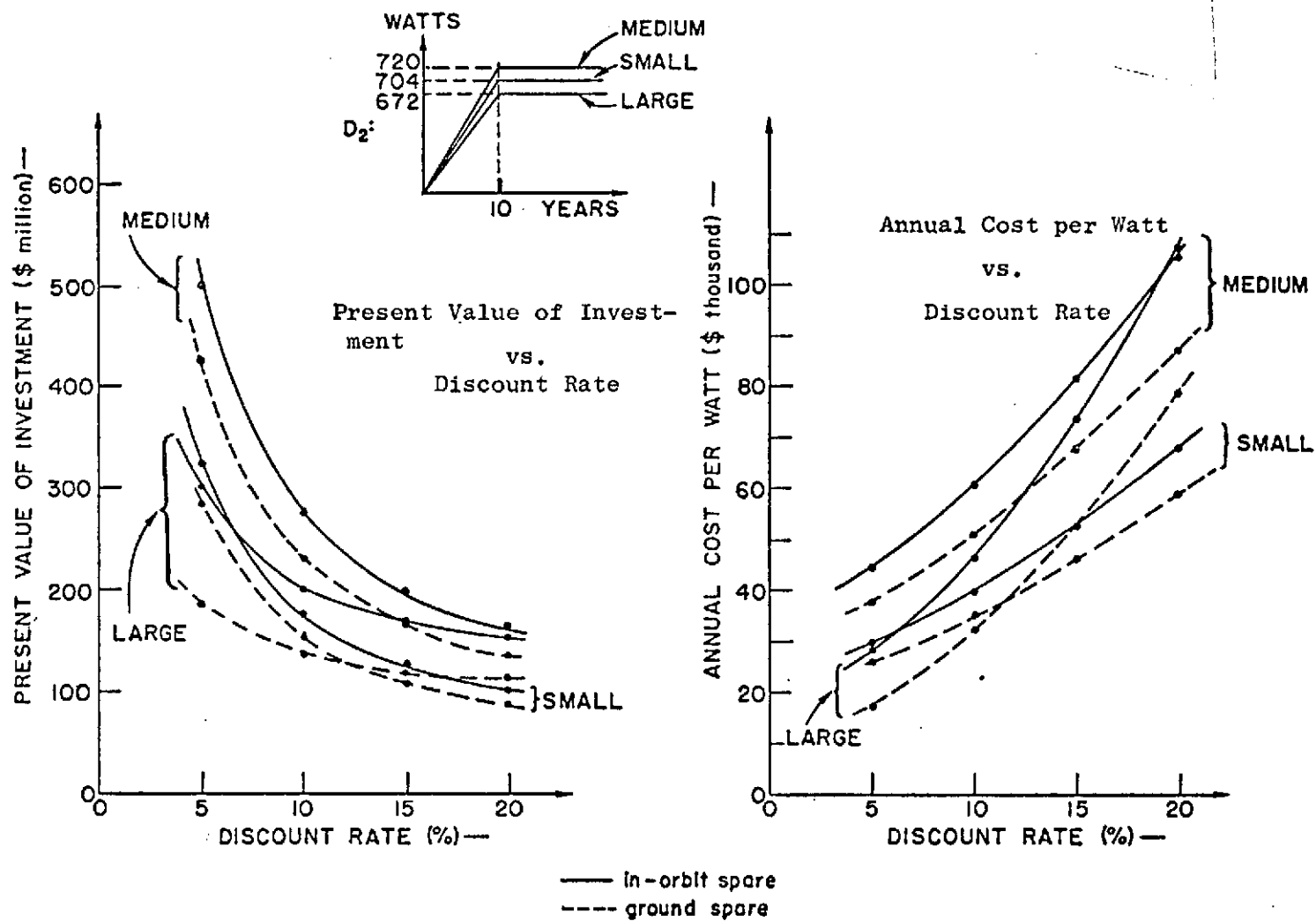
Figure D-2: Summary of Results for Investment and Annual Cost Per Watt

APPENDIX E

# The Number Of Cities In The Rocky Mountain Region In Three Size Categories*

## Total Region

| all cities | 1168 |
|---|---|
| greater than 2,000 | 361 |
| greater than 5,000 | 189 |
| greater than 10,000 | 100 |

| State | all cities | greater than 2,000 | greater than 5,000 | greater than 10,000 |
|---|---|---|---|---|
| Arizona | 87 | 59 | 29 | 13 |
| Colorado | 278 | 72 | 42 | 26 |
| Idaho | 200 | 41 | 14 | 9 |
| Montana | 135 | 38 | 17 | 8 |
| Nevada | 32 | 21 | 14 | 9 |
| New Mexico | 105 | 46 | 26 | 15 |
| Utah | 227 | 60 | 36 | 15 |
| Wyoming | 94 | 24 | 11 | 5 |

* U.S. Bureau of the Census, U.S. Census of Population. 1970 -- Number Of Inhabitants, Final Report PC(1)-A4, A7, A14, A28, A30, A33, A0, and A52.