POINT-TO-POINT COMMUNICATIONS 9

Useful Applications of Earth-Oriented Satellites

NATIONAL ACADEMY OF SCIENCES
NATIONAL RESEARCH COUNCIL

Useful Applications of Earth-Oriented Satellites

POINT-TO-POINT COMMUNICATIONS

Prepared by Panel 9 of the
SUMMER STUDY ON SPACE APPLICATIONS
Division of Engineering
National Research Council
for the
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NATIONAL ACADEMY OF SCIENCES
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PREFACE

In the fall of 1966, the National Aeronautics and Space Administration (NASA) asked the National Academy of Sciences to conduct a study on "the probable future usefulness of satellites in practical Earth-oriented applications." The study would obtain the recommendations of highly qualified scientists and engineers on the nature and scope of the research and development program needed to provide the technology required to exploit these applications. NASA subsequently asked that the study include an analysis of cost-benefit relationships.

Designated "The Summer Study on Space Applications," work began in January 1967, guided by a Central Review Committee (CRC) appointed by the Academy. The Study's Chairman was Dr. W. Deming Lewis, President of Lehigh University.

Technical panels were convened to study practical space applications and worked intensively for periods of two to three weeks during the summers of 1967 and 1968 at Little Harbor Farm in Woods Hole, Massachusetts. The work of each panel was then reported to the Central Review Committee, which produced an overall report. Panels were convened in the following fields:

Panel 1: Forestry-Agriculture-Geography
Panel 2: Geology
Panel 3: Hydrology
Panel 4: Meteorology
Panel 5: Oceanography
Panel 6: Sensors and Data Systems
Panel 7: Points-to-Point Communications
Panel 8: Systems for Remote Sensing Information and Distribution
Panel 9: Point-to-Point Communications
Panel 10: Broadcasting
Panel 11: Navigation and Traffic Control
Panel 12: Economic Analysis
Panel 13: Geodesy and Cartography

The Panel on Point-to-Point Communications compiled an interim report during the summer of 1967 under the chairmanship of Cole A. Armstrong. This final report was prepared under the direction of Dr. Samuel G. Lutz, who assumed responsibility for the Panel after the untimely death of Mr. Armstrong in the spring of 1968.

The major part of the Study was accomplished by the panels; the function of CRC was to review their work, to evaluate their findings, and, in the context of the total national picture, to derive certain conclusions and recommendations. The Committee was impressed by the quality of the panels' work and has asked that the panel reports be made available to specialized audiences. While the Committee is in general accord with the final panel reports, it does not necessarily endorse them in every detail. It chose to emphasize the major panel recommendations in its overall conclusions and recommendations, which have been presented in Useful Applications of Earth-Oriented Satellites: Report of the Central Review Committee.

In concluding this preface, it is emphasized that the conclusions and recommendations of this panel report should be considered within the context of the overall report of the Central Review Committee.

PANEL ON POINT-TO-POINT COMMUNICATIONS

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INTRODUCTION

Most studies of the peaceful uses of space involve potential applications to be evaluated in terms of benefits that may develop in the future. This presentation is somewhat different because obvious benefits already have been obtained from operational communications satellites, and projects even exist to extend these benefits to almost every country in the world. Moreover, in communications the space segment has progressed faster than the earth stations needed to connect the satellites to terrestrial networks.

The fact that terrestrial communications already exist and satellite usage through INTELSAT has begun indicated that, for this aspect of space application, [emphasis should center on worldwide commercial or common-carrier systems. The study of point-to-point communications reported in this volume was conducted generally under the following set of guidelines:

Examine point-to-point communication needs throughout the world.

Forecast, as far as possible, the likely role of satellite systems in filling these needs.

Determine the studies, experiments, and developments required to design satellite facilities to meet such needs in the most economical and effective way.

Compare these research and development requirements with NASA's existing program to determine the appropriateness of items in the program and to recommend any additional work needed.

While it did not appear necessary or desirable in this study to price out any complete system in detail, [economic factors were evaluated by comparing the costs of satellite facilities with the competing terrestrial technology for each type of application. The assumption was then made that, while there are a number of intangible factors at work, the economic factors would be the principal determinants of which system should be used. It was also assumed that there would be some demand for point-to-point TV circuits, such as camera-to-studio links, irrespective of the way actually chosen to handle TV broadcasting in the future.]

[Recognition of the fact that the frequency spectrum, the orbital slots, and the radiation patterns of communications satellites in geostationary orbit are of international interest and require international coordination was implicit throughout the study.]

The results of the study include general endorsement of the point-to-point communications items in NASA's present program and the recommendation of certain additional items required for effective development and utilization of satellite-transmission facilities throughout the world.

Two specific problems requiring further study and experimental work are:

1. For the small user, or low-traffic earth terminal, a substantial amount of system design and other work must be done to reduce costs. For the developing nations in particular, the provision of some form of demand-assignment of circuits is essential for more efficient use of circuits, to permit direct access to points where the demand is too low to justify even one circuit on a preassigned full-time basis, and to reduce costs per call. In addition, work done to reduce the costs of earth terminals while retaining the use of high-discrimination antennas for the efficient use of frequencies and orbital-space segments will certainly be profitable.

2. For any system serving the United States domestic market, there is an ultimate need for more bandwidth than the presently allocated 500 MHz. A study should be made to determine whether these should be reserved for microwave systems and area coverage down on satellite systems. To provide more spectrum space for narrow-beam nodal systems, frequency space above 11 GHz should be developed as rapidly as possible. The available data indicate that millimeter waves would be practical and that there is little likelihood of obtaining adequate allocations elsewhere in the spectrum.

A brief look into the probable course of future technology indicates that current work toward reduction of costs of terrestrial microwave systems, future possibilities of millimeter wave-guides, and laser beams in a pipe will provide heavy competition for systems in parts of the world such as the United States, where demand is great enough to permit using very large cross-section facilities. On the other hand, this reinforces the need for more spectrum bandwidth for satellites so that they may gain the economies of scale on a comparable basis.

This has not allowed investigation of longer-range technology such as the use of high-power laser beams for links between satellites and earth which, for all practical purposes, could solve the problems of basic limits on orbital arc/frequency bandwidth. Unfortunately, time also did not permit consideration of alternate possibilities such as passive satellites and the fundamental question of ultimate physical limits. Study of the future uses of very large satellites, for example, possibly manned during installation and/or maintenance phases, could lead to pronounced changes in systems concepts and operations. It is hoped that studies of such possibilities will be reported in a subsequent publication of this series.

For convenience, a summary of the report follows this introduction, preceding the main body of the report.

SUMMARY

Description of the Field

In terms of reference are point-to-point (fixed) applications of satellite communication, for voice and record traffic, program and data relaying (but not multipoint distribution). Excluded are points-to-point (data collection), point-to-points (broadcast, distribution), and mobile services (with aircraft, land vehicles and ships). Little attention was given to intersatellite relaying, and even less to space-research applications. Commercial systems have been assumed but with implicit recognition that most of the principles also will be applicable to noncommercial systems, except that the latter may have different requirements and value considerations.

State of the Art

Except for Russia's use of subsynchronous, highly elliptic orbits with high northern apogees (i. e., Molniyas), geostationary satellites have achieved clear preference.

Spin-stabilization is operational, although gravity-gradient and other three-axis attitude-control techniques are being developed and evaluated in NASA's Applications Technology Satellite (ATS) program.

Satellite antenna technology has entered the long-foreseen earth-subtending beam era via the ATS program and will become commercial with INTELSAT-III.

Preassigned multiple access (PMA) via the frequency modulation-frequency division multiplex (FM-FDM) multidestination carrier (MDC) technique started with INTELSAT-II, but the more versatile demand-assigned multiple access (DAMA), though badly needed by the developing nations for their lighter routes, is still being studied.

Studies of a domestic system, providing point-to-point and program-distribution services, have been filed with the Federal Communications Commission (FCC), and the state of the art appears to have become policy-limited rather than technology-limited. Meanwhile, Russia has started both these services, and other nations have established policies and are proceeding toward domestic and regional systems.

Except for certain temporary or noneconomic applications, the INTELSAT standard earth station, with a large (approximately 85-ft) antenna and helium-cooled low-noise amplifier has won acceptance. Fully steerable antennas with

automatic-tracking facilities suitable for use with TELSTAR or Relay still seem to constitute the state of the art for these standard stations.

Socioeconomic-Technologic Environment

The environment of commercial, international satellite communication is that of COMSAT-managed INTELSAT. NASA supports and conducts programs directed toward major technological advances in satellite communication, with such advances serving to maintain the U. S. position of technological leadership in satellite communication.

The basic economic principles of point-to-point communication, via satellite or via terrestrial systems, are relatively clear and firm. Consequently, if there were free and open competition, route by route, satellite communication would be chosen only for the most advantageous routes, those for which terrestrial communication of comparable quality would be more costly. Such determinations can be made readily by reference to break-even relations, which will be functions of the length and traffic volume of the route in question. The panel recognized that in general satellite communication acquired increasing leverage, relative to terrestrial systems, for longer distances and lighter routes (fewer circuits), assuming that such routes are between multiroute earth stations with reasonably heavy traffic loads and that the surface system could not use some less direct but more economic routing. The demand-assigned forms of multiple access will permit earth stations to build up economic traffic loads as the total from many routes, though the traffic from some may be very light.

The introduction and analysis of these break-even relations and the use of a simple graphic technique for clarifying them have been recent contributions to the work of this Panel. This break-even study also seems to permit clarification of the point-to-point goals and of potential practical benefits.

Unfortunately, the actual environment is not entirely one of free and open competition, route by route, as is well known. Although satellite communication cannot expand except when its costs are less than those of comparable terrestrial facilities, such expansion can be delayed by certain rate-making procedures, by protection of existing heavily capitalized terrestrial facilities, by established practices, and other forms of inertia. Nonetheless, improved knowledge of the potential advantages of satellite communication, via these break-even relations, may help to lessen such delays.

Goals of Point-to-Point Satellite Communication

Heretofore, the goal of this field, broadly stated, has been the improvement of international telecommunication capability throughout the world, making available, as needed, direct, high-quality circuits between any two earth stations that can use the same satellite. This still holds, but added is a somewhat simpler objective—that of improving the break-even relationship relative to terrestrial communication by lowering the cost and increasing the capacity and utility of satellite communication.

Studies of domestic systems show that the shorter routes account for much more total traffic. Shorter routes, moreover, lead to many more earth stations, closer together, hence to greater total traffic and therefore to more and larger satellites with lowering of space-segment rates and further improvement of break-evens. Qualitatively, neglecting policy, rate-making constraints, and less foreseeable socioeconomic constraints, the practical benefits from approaching this goal would be better telecommunication for more people to more places at greater distances with lower costs per call-minute. New or previously noneconomic services could be introduced, providing a great economic stimulus. To the developing nations, the realization of this objective should be even easier and bring greater benefits; their lack of heavy terrestrial communication routes should ease break-even decisions and permit rapid linking of major cities by satellite circuits with less investment. Analogies with the benefits from air transportation are obvious.

Needs for Further NASA Research and Development

Although point-to-point satellite communication is now an international commercial enterprise, with an assured future, it would be wrong to assume that NASA should transfer all R&D responsibilities in this area to INTELSAT or to other commercial interests. There are no alternatives to NASA's accepting responsibilities for further R&D because NASA has a statutory obligation, under the Communications Satellite Act of 1962, to provide the technological support for the pertinent policy-making agencies of the Government, such as the FCC and the Office of Telecommunications Management. Furthermore, continuation and strengthening of NASA's ATS program, along lines delineated below, seem essential for maintaining U. S. leadership in this international enterprise, and for fulfilling an important phase of U. S. space policy, i. e., making satellite communication more useful to all nations, including the less-developed ones.

Recommendations

Orbit-Utilization Principles

Thus far, there seems to have been little international recognition of the value of sectors of the geostationary orbit in relation to criteria for efficient use of the orbit. For example, orbital use can be measured in equivalent voice channels per degree of orbit, within a specified bandwidth and without harmful interference. This situation and its importance were recognized by this Panel, and Appendix D of Panel Report No. 9 is an exploratory study of the dependence of orbit-utilization efficiency upon modulation "hardness" (i. e., frequency-modulation index, pulse-code modulation "levels" or phase-states, error-correcting coding, etc.), and upon antenna beam widths. Further work is needed toward clarifying the effects of inequalities of signal strengths (effective isotopic radiated power EIRP) of adjacent satellites and of the use of higher EIRP for redistribution of the noise/interference budget. Another obviously important factor is the beam width and beam shape of the earth antennas. In addition, studies should be made of techniques for spectrum reuse, by means of independent multiple earthward beams, by use of orthogonal polarization, by supplementary use of nonequatorial orbits, etc.

The common objective of the studies recommended above is that of providing better knowledge of the various possible means of increasing the total traffic capacity and the relative cost-effectiveness of these means. This knowledge may, on one hand, show that exhaustion of certain orbital capabilities (such as orbit stations for certain kinds of satellites) is foreseeable and that efficient utilization practices are needed. On the other hand, this knowledge may show that the various spectrum reuse techniques can provide such enormous capacity that attention can be shifted from optimization problems to the making of intelligent trade-offs toward cost and reduction. Altogether, this field of knowledgeable orbit utilization offers important engineering opportunities.

Millimeter-Wave Technology

The allocation of at least two relatively broad bands in the vicinity of 15 GHz and 35 GHz for space communications should be achieved by the 1970 International Telecommunication Union Space Conference. This establishes the urgency for programs in support of millimeter-wave technology and frequency management. For the most effective use of these bands, more data on propagation through rain (and scattering by rain) are needed, along with the development of space-qualified millimeter-wave components. A logical application for this technology is the many relatively short and heavy routes, at lower latitudes, as in a U.S. domestic system, for which all stations would see their satellites at relatively high angles, with short paths through the atmosphere. A major question will be whether these new bands should be divided between or be shared with the foreseeable terrestrial services.

Multibeam Technology for Satellites

The future use of multiple earthward beams is attractive for achieving spectrum reuse and (with restrictions to point-coverage applications) for achieving higher EIRP in these beams.

However, the choice of methods for generating and controlling these very narrow multiple earthward beams is far from clear today. Recognizing that a satellite may need to direct dozens of such beams at terrestrial traffic nodes, can multiple feeds be used, with either parabolic or spherical reflectors? What about phased-array vs lens-imaging schemes? Development effort toward multibeam satellites needs prompt and strong NASA support. These multibeam satellites will be needed soon.

Intersatellite Relay Technology

A foreseeable solution to the problems of using multiple satellites in heavy-traffic systems, without requiring multiple beams from all or most earth stations, lies in the interconnection of a cluster of satellites via space-relay links. Thus, a call might go to satellite A from one of its stations, then across a short relay link to satellite B and then down to the called station, much as a metropolitan telephone call is completed by the interconnection of A and B exchanges. Except for the rather long arcs to far eastern or western satellites, the delay added by such intersatellite relays should not be troublesome. It is recommended that NASA explore this relay technology, because of its potential advantages.

Systemology Studies

The title "systemology studies" has been applied to a remaining class of problems which relate to overall point-to-point systems and their traffic aspects, break-even factors, frequency-sharing constraints, and cost-effectiveness of components such as the satellites, earth stations, etc. It is recommended that NASA pursue studies and essential developments in these and other system-type problems so as to maintain the expertise needed to advise when such problems or proposals involving these factors must be acted upon. A possibly too-familiar example of such problems is that of "cheapening" earth stations via small low-gain antennas, as contrasted to "improving" their cost-effectiveness by use of fixed reflectors, unattended operation, etc. DAMA may offer an even better example. Here, it seems important that NASA be able to advise the policy-making agencies concerning the needs, advantages, possible techniques, and cost-factors involved, recognizing that the selection and implementation of the specific system must be made by the satellite system operator.

1.0 PEACEFUL APPLICATIONS OF SPACE TO POINT-TO-POINT COMMUNICATIONS

1.1 Near-Term Applications Of Satellite Communications

Satellite-communications systems for peaceful uses will employ chiefly geostationary satellites for the foreseeable future. Satellites in other orbits will be used to meet specialized needs. However, the advantages of geostationary satellites in greatly simplifying tracking requirements of earth stations and in almost eliminating the problem of "handover" between satellites justify emphasis on geostationary satellites.

Additionally, emphasis in this study will be placed on relatively simple active satellites, ones that perform little more signal processing than their frequency translation from the "up" to "down" frequency bands or the signal interconnections between several earthward antenna beams. Since commercial applications over the next decade probably can be satisfied by these relatively simple satellites, the Panel considered it not to be worthwile at this time to speculate about complex forms of signal processing or about other such aspects of far-future satellites, except for pointing out that techniques which may seem too complex today may later become worthwhile and essential. We remember that only twenty years ago electronic digital computers seemed too complex for any hope of their widespread use!

In its point-to-point applications, satellite communication provides transmission links for terrestrial communication systems. This is to say that satellite service now is nation-to-nation and should become a city-to-city service, but not home-to-home except via the cities' earth stations and communication distribution systems. Such international and intercity links have thus far been provided (or could be) by terrestrial means such as cables, microwave relays, tropospheric scatter links, or by HF radio. Thus the competitive break-even aspects of satellite links assume obvious importance. However, a significantly novel aspect is that the satellite is a mode, through which must pass the links between all its earth stations, thus giving them multiple access. The demand assignment of circuits can enhance the usefulness of multiple access, especially by permitting temporary interconnections for light or too-light routes, as discussed in Appendix B.

Satellite links can transmit any of the various communications signals now transmitted via any other medium. System-design choices are likely to be made on the basis of economic considerations of total point-to-point traffic or total system traffic, with little attention given to the characteristics of particular applications. For this reason, there is little need to dwell at length on these.

Satellites already are in commercial and other operational use for the classical forms of telecommunication such as telephony, telegraphy, telex, facsimile transmission, and television program relaying. There is growing activity in the transmission of digital data at very low error rates for use with data-processing systems. The broad bandwidths available via satellite and the potentially low costs make visual telephony seem more attractive even for multiparty conferences in international scope; savings over travel costs become apparent. Many other applications of satellite communication are not of a point-to-point nature and therefore have not been treated in this portion of the report. Examples are audio and video broadcasting, or multipoint distribution of such programs for rebroadcasting, data collection and dissemination from and to multiple points, and navigation and position determination. The Panel also interpreted "point-to-point" as applying to relatively fixed points, thus excluding mobile applications such as air traffic control which were within the terms of reference of another Panel.

A somewhat gray area relates to the question of whether a spacecraft should itself be considered as a point, and whether it needs to be a fixed point. This Panel gave little or no consideration to telemetry, command, deep-space communication and similar forms of communication that are necessary to or normally associated with space research. These problems are of primary concern to NASA and are being solved with admirable competence. Intersatellite relaying of terrestrial information represents an area that comes closer to the interface with terrestrial communication. Such spacecraft applications are considered in Section 4. 0.

The terrestrial applications have been considered in the light of needs for: (1) international communications, (2) domestic communications in the developing countries, and (3) domestic communications in countries that already have well-developed systems of terrestrial links. Here, a unifying observation is that the volume of communication traffic is some inverse function of the distance, while the state of economic development chiefly provides a scale factor. Even primitive man communicated more (and better) with those in his own community than with members of distant communities. Countries, whether developed or developing, have a much greater volume-need for domestic communication and communication with neighboring nations (i. e., frontier circuits) than for long-haul global communication. The needs for satellite communication may appear greatest where terrestrial facilities have been least adequate, i. e., for intercontinental communication and toward accelerating domestic communications for developing countries, and these needs will be seen to match the strongest capabilities of satellite links.

Domestic satellite links may seem less necessary for countries in which well-developed terrestrial systems of large cross section already operate economically. One needs to consider the continuing growth of communication demand, hence the need for additional new facilities, and the possibility of realizing an economic advantage via an optimum mix of satellite and terrestrial facilities.

It is necessary to recognize the evolutionary nature of the requirements for satellite communications in the developing countries. Satellite links offer these countries a convenient and economical means of satisfying their need for long-distance domestic and international communications more rapidly than by extending terrestrial facilities to great distances over difficult terrain. Such considerations seem to have been important to Russia, for example, in its domestic use of Molniya satellites. Also, as discussed later, satellite links are most advantageous for long light-traffic routes. All nations, however, will come to need an adequate balance of terrestrial facilities in their domestic systems, for reasons that will become clear later.

Therefore, developing nations should not be led to regard a domestic satellite system as being a lasting substitute for adequate terrestrial facilities. Actually, the introduction of domestic satellite circuits via earth stations at major cities should encourage the extension of surface links to outlying cities and villages so that they too can gain access to these earth stations. Such an expansion of terrestrial facilities clearly does not imply any lessening in the total demand for satellite circuits. Rather, a growing demand is to be expected.

As worldwide needs for satellite communications develop, the demand for spectrum and orbital space will eventually become actual and intense. Management of these valuable resources and development of techniques to alleviate anticipated problems are discussed in Appendix D. From the discussion of the global system of international communications and its anticipated development over the next several years (Section 3.0), it is clear that sufficient spectrum and orbital space presently exist to meet the needs of the developing countries for satellite links; however, these considerations strongly suggest the need for prompt preliminary allocations of orbit locations for some specific interval of sufficient duration to permit long-range spectrum planning and economic use of capital investments. The idea of allocating spectrum and orbital space on an evolutionary basis might also be extended beneficially to areas other than satellite communications.

An immediate conclusion from these general considerations of worldwide needs for communications and the capabilities of satellite systems to meet them is the importance of developing techniques that will facilitate the integration of low-traffic users into the global system of satellite communications. This has been recognized in A Survey of Space Applications, prepared by NASA as a reference for the present study and in planning documents describing the current and future programs of NASA.

Much study and documentation have been devoted to the need for satellite links to serve the applications of telephone communications and broadcasting. Data on these requirements are available in the current INTELSAT plans and are summarized in Table 9.3.4. The needs for satellite links to serve facsimile, video conference, data transmission, and combined applications have developed very little. Some of the newer uses may prove to be quite important and will need attention in connection with traffic forecasts and the impact on overall design of satellite communication systems.

Historically, from telegraph to telephone and television, greater total bandwidth (or "cross section") has been used for previously unforeseen demands as rapidly as telecommunication technology could provide this greater capability. We should not take long-range forecasts too seriously!

Assuming that the domestic common carriers can provide adequate low-cost broad-band distribution circuits to offices and homes, much as is gradually being done for the broadcasters by the video cable and other community antenna television (CATV) systems, the future demand for video conference and other closed-circuit video applications may develop rapidly when rates are reduced substantially below present levels. Organizations with major offices spread over a large country or over the globe could use such circuits for many purposes including:

Video conference (two-way)

1. Management meetings
2. Engineering meetings

Closed-circuit TV (one-way with keyboard or audio feedback)

1. Video tours of major projects
2. Introduction of new products and services
3. Instruction of sales, system engineering, and maintenance personnel at field locations

As the use of video for such purposes spreads, the cost of travel between major offices of organizations will decrease, and more communication and more effective communication will be possible for the same total cost. In either case, the use of telecommunications in place of travel will be encouraged by management, and the traffic requirements for closed-circuit video can be expected to grow rapidly after the introductory phase. Such a possible chain of events will be of major significance to satellite system planning because of the large transmission capacity required for a video circuit as compared to an audio circuit and because of the predominance of group over individual needs in satellite-communications traffic. However, it is necessary to recognize that reduction in cost of intercity transmission facilities alone is not likely to produce major stimulation of demand because the terminal distribution, switching, and station equipment costs have become dominant in determining rates. For a 1500-mile telephone call, only 23 percent of the costs are in the intercity transmission, it has been reported.

Another unknown in forecasting future needs for satellite links is the rapidly growing field of data transmission. Long-distance interconnection of computers and other data-processing equipment, such as was developed in the 1950's by the military for command/control applications, has become common in the 1960's. The following are typical of such applications:

1. Information-retrieval systems
    - Travel reservations
    - Technical literature
    - Stock quotations
    - Medical information
2. Government administrative systems
    - Social Security system
    - Internal Revenue Service
    - Motor vehicle bureaus
3. Time-shared data-processing systems
    - Remote computing
    - Remote manipulation of text
4. Management information systems
    - Inventory control
    - Production control

The list of such applications is growing rapidly as many new companies enter the field and as established companies and government agencies develop new uses. Some more recent applications include:

1. Financial information systems
2. Consumer-data services
3. Remote typesetting
4. Traffic surveillance and control
    - Aircraft
    - Automobiles
    - Ships

In addition to the gross increase of satellite-communications traffic that applications of data transmission may require, it is important to note some of the peculiar characteristics of these applications. For example, a data circuit for remote time-shared computing in the conversational mode may require about the same bandwidth and connection delay as telephone, but the holding times and accuracy requirements are likely to be an order of magnitude larger and the duty ratio two orders of magnitude smaller than in telephony. Some data systems, such as reservations systems, tend to require the reverse: high-speed switching, very short holding times, and high call rates. Also, information-retrieval systems, particularly those involving replies in the form of images, require much more transmission capacity in the reply direction than in the query direction. Systems employing computer-controlled voice recordings or voice synthesizers to respond to inquiries from keyboards are current examples of systems involving large ratios of information output to input. It may thus be seen that systems such as the above lie somewhere between the classical extremes that provide either equal transmission capacities in both directions, as in telephony, or large capacities in a single direction, as with television.

Another problem that must be considered by satellite-communication system designers is that of providing economic combinations of service, e. g., voice and data service in the kilobits/second range. The first of these examples of combined service is represented in the present terrestrial system where circuits used for closed-circuit video during normal business hours might be used at off-peak hours to interconnect large computing centers to provide:

Transfer of jobs among centers

1. Load leveling
2. Back-up in case of center failure

Data freight

1. Posting of information banks
2. Revision of programs and operating systems
3. Publishing and updating manuals of operation, programming, and maintenance
4. Broadcast of responses to selected operation, programming, and maintenance queries

Combined applications may be of particular importance to developing nations in making economic use of the telecommunication facilities that they need to facilitate development.

Applications of satellite communications have been classified and tabulated in Table 9. 1. 1. In each case, the application is intended as a long-distance use, i. e., distances in excess of the break-even relative to the alternative terrestrial service (i. e., probably more than 100 miles).

TABLE 9. 1. 1

VALUE, NEED, AND FEASIBILITY OF APPLICATIONS OF SPACE TO POINT-TO-POINT COMMUNICATIONS

Application	International	Domestic	
		Developing Country	Developed Country
Telephony	1(b)*	1(b)*	2(a)
Video Conference	1(b)	2(a)	1(a)
Telegraphy Facsimile Transmission Data Transmission	1(a)	1(b)	2(a)

1. Clearly of value with present or predictable technology
   a. Now accomplished by other means
   b. New application
2. More study needed
   a. Technically feasible but value uncertain
   b. Valuable but technical feasibility uncertain

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*For a few of the possible countries or pairs of countries, this application is classified 1(a).

1. 2 Economic Benefits From Satellite Communications

The key economic arguments for satellite communications may be summarized as follows:

1. The relative cost advantage of satellites over other methods is demonstrable. Three comparisons, which are reviewed in Appendix A, include:

   a. Submarine cable

   b. Country with low-density traffic

   c. Country with high-density traffic (not as certain, but probable)

2. Cost advantages come from basic features of satellite systems:
   a. Costs are not a function of distance or of local terrain.
   b. Costs are more readily reduced by increased volume of traffic than are terrestrial costs.
   c. Costs are virtually independent of the number of circuits per route, being determined more by the total number of circuits per station.

3. Higher traffic volume benefits satellite communications in two ways:
   a. In space-segment costs, where higher total traffic benefits all multipoint users, not just two points of a fixed path as in terrestrial communications
   b. In earth-station costs, where higher traffic reduces unit circuit costs by larger cross-section similar to terrestrial costs

4. Other advantages of satellite communications cannot be measured quantitatively:
   a. Access on demand by a direct link with a point that could not be economically linked by other means (see Appendix B)
   b. Elimination of detours via transit points that are economically wasteful and politically distasteful

5. The objective of recommendations given in the following section is to exploit satellite advantages by suggesting studies that will improve:
   a. Costs of system components, which will benefit both high-density and low-density users
   b. Volume of traffic through expanding the spectrum available for high-density users
   c. Demand-access system for primary benefit of low-density users

2.0 SPECIFIC RECOMMENDATIONS

2.1 Principal Areas Covered

Recommendations are summarized in the form of a list of research and development projects and evaluations of their importance and priority. These recommendations emphasize the following major areas:

1. Need for and utilization of frequency bands above 11 GHz
2. Demand-assigned multiple-access systems of satellite communications
3. Fixed-reflector antennas with movable and/or multiple beams for earth stations and satellites
4. Long-life stabilization and station-keeping with adequate accuracy
5. Techniques and system designs for efficient utilization of spectrum and orbital space
6. Demonstration of low-cost, large-antenna earth stations
7. Measurement of the factors that contribute to the interference between satellite and terrestrial systems

2.2 Symbols Used on Summary Chart

The research and development projects listed in Table 9.2.1 were obtained from A Survey of Space Applications and Prospectus 1967 of NASA and from additional suggestions developed during this study. To facilitate brief descriptions for tabulation, the projects have been classified into the four types listed below in order of increasing magnitude:

1. Studies
   Designs, theory, economic trade-off, data collection and analysis
2. Measurements
   Experimental measurements in the laboratory, in the field, and/or in outer space as required
3. Components
   Development and testing of components and subsystems
4. Systems
   Development and operation of systems for applications of point-to-point communications on earth and in support of the exploration of outer space

It should be understood that the more involved projects often include tasks in categories other than that of the main project. Where necessary, evaluations of parts of the project are shown separately.

The cost figures given in Table 9.2.1 are rough estimates (± 50 percent) and are included only as an aid in description. More accurate estimates are needed for budget purposes and must await the preparation of project plans.

TABLE 9. 2. 1

RESEARCH AND DEVELOPMENT PROJECTS SUPPORTING SPACE APPLICATIONS IN POINT-TO-POINT COMMUNICATIONS

Project				References		Evaluation	
Paragraph Number	Title	Type	Recommended level of Funding in $1000	NAS Study	NASA Program	Value, Need & Feasibility	Priority
2.3.1	Demand-Assigned Multiple Access	Study	2,000	3,B,C		1	A
2.3.2	Systems for TV and and Telephone Distribution Separate vs Combined	Study	100	3		1	A
2.3.3	Fixed-Reflector Movable-Beam Antennas for Earth Stations	Components	500	3,E		1	A
2.3.4	Multiple-Beam Antennas for Earth Stations	Comp.	500	3,E		1	A
2.3.5	Multiple-Beam Antennas for Satellites	Study Comp.	200 2,000	3,E	I-19	1	A
2.3.6	Neutralization of Multiple Feeds	Comp.	300	E	$75K in Prog.	1	B
2.3.7	Retrodirective Array for Communication Satellites	Study Comp.	100 9,000	E	Active	1 2	B C
2.3.8	Satellite Stabilization and Antenna Pointing	Comp.	2,000	D	I-19 I-23	1	A
2.3.9	Ionic Thrusters for Stabilization	Comp.	1,000		I-22	1	A
2.3.10	Radio Interferometer for Satellite-Attitude Control	Comp.	500		I-19	1	A
2.3.11	Precise Long-Life Station-Keeping	Comp.			Active on ATS	1	B
2.3.12	Space-Qualified Low-Noise Amplifier	Comp.	300			1	A
2.3.13	Standarization of Launch Vehicles	Study			Always Active	1	B
2.3.14	Optimum Utilization of the Shared Bands	Study	100	D	$100K in Prog.	1	A
2.3.15	Spectrum and Orbit Utilization by Low-Traffic Earth Stations	Study	100	D		1	A

TABLE 9. 2. 1 (continued)

Project				References		Evaluation	
Paragraph Number	Title	Type	Recommended level of Funding in $1000	NAS Study	NASA Program	Value, Need & Feasibility	Priority
2.3.16	Design of Signals for Optimum Utilization of Orbit and Spectrum	Study	100	D	$50K in Prog.	1	A
2.3.17	Spectrum Allocations below 3.7 GHz	Study	300		TV Brdcst UHF etc A.T.C.	1	B
2.3.18	Spectrum Allocations above 11 GHz	Study Meas.	100 300	3-G	11 GHz in TV Study	1 1	A B
2.3.19	Narrow-Angle Forward Scatter through Rain	Meas.	200		$150K in Prog.	1	B
2.3.20	Subjective Effects of Terrestrial Interference with Satellite TV Distribution	Meas.	200	F		1	A
2.3.21	Precipitation Off-Path Scatter Interference	Meas.	500	F	POPSI	1	A
2.3.22	Terrestrial-Interference Contours	Study Meas.	100 200	F	ODTM	1 1	A B
2.3.23	Ducting Interference in the Shared Bands	Meas.	100	F		1	B
2.3.24	Aircraft Scatter Interference in the Shared Bands	Meas.	200	F	ODTM	1	A
2.3.25	Shielding of Earth Stations	Meas.	500			1	B
2.3.26	Interference with the Geostationary Orbit	Meas.			ATS-F ATS-G	1	A
2.3.27	Short-Range Inter-Satellite Communications	Study System		I	I-22	1 2	B C
2.3.28	Low-Cost Earth Stations	System	5,000	C	I-19	1	A
2.3.29	United States Domestic Service	Study	250	3,D		1	A
2.3.30	Forward-Acting Error Control	Study	100	D		1	B

The codes used in listing the evaluation of these projects are:

Value, Need, and Feasibility

1. Clearly valuable, needed, and feasible with present or predictable technology
2. More information needed to determine value, need, or feasibility
3. Clearly of little value, need, or feasibility with present or predictable technology

Priority

a. Results needed as soon as practicable
b. Substantial priority but can be delayed if it becomes necessary to delay some high-priority projects for any reason
c. Desirable projects of no particular urgency at present

Brief descriptions of the projects recommended in Table 9.2.1 are included in this section for convenience. Most of these projects are described and related to the requirements of point-to-point communications in other sections and appendixes of this report as indicated by the numbers and letters given in the column headed "NAS Study" in Table 9.2.1. Many of these projects are described in the NASA program documentation.

2.3 Brief Description of Recommendations

2.3.1 Demand-Assigned Multiple Access

Numerous studies are needed of various aspects of demand-assigned multiple-access systems, e.g., traffic statistics relating particularly to low-traffic users; various system-design approaches; modulation techniques; use of order-circuits and other switching-control schemes; economic trade-offs; spectrum and orbit utilization.

2.3.2 Systems for TV and Telephony Distribution—Separate versus Combined

Study the technical and economic advantages of providing telephony and TV distribution through various ways of sharing or using separate satellites and/or earth stations.

2.3.3 Fixed-Reflector Movable-Beam Antennas for Earth Stations

Develop and test economical movable-feed high-gain antennas capable of adjustment of earth-station beam over angles of the order of ± 15 degrees without moving the reflector. Give particular attention to beams that are narrower in longitude than in latitude.

2.3.4 Multiple-Beam Antennas for Earth Stations

Develop and test multiple-feed antennas capable of simultaneously producing several closely spaced beams from the same reflector to permit an earth station to communicate separate traffic with several geostationary satellites simultaneously.

2.3.5 Multiple-Beam Antennas for Satellites

Develop and test multi-feed antennas capable of permitting a geostationary satellite to communicate separate traffic with several earth stations simultaneously.

2.3.6 Neutralization of Multiple Feeds

Develop techniques for summing signals among the feeds in a multi-feed antenna to minimize interference between beams, particularly between adjacent beams.

2.3.7 Retrodirective Array for Communication Satellites

Study the applicability of a large retrodirective array in geostationary orbit for such uses as data collection from low-altitude satellites, sensors, aircraft, ships. If study results are favorable, develop and test such an array for the selected application(s).

2.3.8 Satellite Stabilization and Antenna Pointing

Continue a program of improvement in geostationary satellite stabilization and antenna pointing, with emphasis on obtaining accuracies of the order of ±0.1 degree and better over periods of several years.

2.3.9 Ionic Thrusters for Stabilization

Develop and test ionic thrusters for stabilizing (and station-keeping) a geostationary satellite over a period of 5 years or more.

2.3.10 Radio Interferometer for Satellite-Attitude Control

Develop radio-interferometric techniques for improving the accuracy of attitude control of geostationary satellites.

2.3.11 Precise Long-Life Station-Keeping

Continue development of techniques for station-keeping of geostationary satellites within 0.1 degree of longitude over periods of 5-10 years with minimum demand for total weight injected into orbit.

2.3.12 Space-Qualified Low-Noise Amplifier

Problems of interference between satellite earth stations and terrestrial microwave facilities (but not from radio relay transmitters to receivers in satellites) could be reduced if more sensitive receivers were developed for use in satellites. This project would develop such receivers.

2.3.13 Standardization of Launch Vehicles

Study various ways of reducing the number of types of launch vehicles by small changes in operational requirements of each of several applications. Determine how much could be saved in launch vehicles over a period of several years for each application and compare this with any increases in other costs or losses in capability. Determine which of the potentially available launch vehicles can deliver to geostationary orbit a satellite capable of completely and efficiently using an orbital slot.

2.3.14 Optimum Utilization of the Shared Bands

Determine the most efficient power budgets for terrestrial and satellite communications in the bands at 3.7-4.2 and 5.9-6.4 GHz. Determine whether it is better to share or to divide these bands between the two types of service.

2.3.15 Spectrum and Orbit Utilization by Low-Traffic Earth Stations

The idea of reducing earth station costs by using smaller antennas is superficial, as the analyses in Appendix D show, because small antennas lead to inefficient use of the geostationary orbit. This project is a definitive study of the economics of low-traffic earth stations capable of supplying both domestic and international communications through the global system of satellite communications.

2.3.16 Design of Signals for Optimum Utilization of Orbit and Spectrum

As shown in Appendix D, modulation and coding parameters interact with orbital spacing of geostationary orbits and must be considered in determining optimized utilization of orbital space as well as spectrum. This project is a definitive study of this problem.

2.3.17 Spectrum Allocations below 3.7 GHz

Small-antenna stations may be needed for mobile and other applications but cannot use the spectrum above 3.7 GHz effectively. This study will consider such applications and determine whether an allocation below 3.7 GHz is needed.

2.3.18 Spectrum Allocations above 11 GHz

To support exploitation of frequencies above 11 GHz that will be needed for North American regional communications, it will be necessary to accumulate geographically diverse data on the effects of rain on attenuation and noise by some or all of the following:

1. By extending NASA's ATS-E millimeter wave experiment to include more observations for longer periods
2. By supporting sun-tracker experiments
3. By diversity receiver experiments, either ATS-E or sun-tracker

4. By extrapolating weather-radar measurements made at lower frequencies

2.3.19 Narrow-Angle Forward Scatter through Rain

Because of the possibility of interference between closely spaced geostationary satellites due to narrow-angle forward scatter through rain, measurements of this effect are needed. This project would make such measurements in the shared bands and above 11 GHz over terrestrial paths several miles in length to simulate the up-link and down-link paths in satellite-communication systems.

2.3.20 Subjective Effects of Terrestrial Interference with Satellite TV Distribution

Measure the carrier-to-interference ratios required for various degrees of subjective quality, using laboratory equipment simulating the effect of a terrestrial carrier interfering with the down-link of a satellite TV distribution system, and vice versa. Consider the effect of using carrier dispersal in the satellite system.

2.3.21 Precipitation Off-Path Scatter Interference

Measure precipitation scatter interference between terrestrial and satellite systems in the shared bands.

2.3.22 Terrestrial Interference Contours

Determine the union of three-dimensional interference contours surrounding terrestrial microwave facilities in some metropolitan area, e.g., New York City. Consider the effects of terrain blocking of terrestrial beams. Conduct field measurements in selected elevated volumes to verify predicted contours relating to precipitation scatter. Determine whether an earth station can be located in the area for any assumed directions of its beam without causing excessive interference.

2.3.23 Ducting Interference in the Shared Bands

Determine the importance of ducting interference between terrestrial and satellite systems in the shared bands by measurement over many different paths and over a long period of time.

2.3.24 Aircraft Scatter Interference in the Shared Bands

Measure aircraft scattering cross section of the most common types of commercial aircraft for all scattering angles and attitudes. Study typical flight profiles and traffic patterns and predict the frequency of occurrence of aircraft scatter interference events for earth stations located properly with respect to air-traffic patterns. Verify predictions by measurements at a few selected locations.

2.3.25 Shielding of Earth Stations

Study results of previous work by Stanford Research Institute, Lincoln Laboratory, and others on the use of excavation, natural hollows, fences, tapered illumination of oversize reflectors, nulls in one (or a few) directions in the horizontal pattern, and other techniques for shielding earth stations to control interference between terrestrial and satellite communication systems. Extend these results by further measurements as required and determine the most practical approaches to earth-station shielding for various environmental situations.

2.3.26 Interference with the Geostationary Orbit

Measure the 6-GHz interference at several points in the geostationary orbit produced by terrestrial microwave facilities. This project needs to be done sooner than presently planned.

2.3.27 Short-Range Intersatellite Communications

Study the system organization and requirements for relatively short communication links between geostationary satellites. If the need and value of such links are established, develop and test techniques and systems for this application.

2.3.28 Low-Cost Earth Stations

Develop and demonstrate low-cost, large-antenna, earth stations for use by low-traffic users of the global system of satellite communications.

2.3.29 Frequency Bands for U.S. Domestic Service

Study the applicability and probable period of adequacy of the 4-GHz and 6-GHz bands for services which include U.S. domestic traffic. At some date, the volume of such traffic and other considerations probably will favor the use of much broader bands at frequencies above 12 GHz, but these frequencies may be less applicable to covering large areas than to spotlighting traffic nodes. Should service be started at these lower frequencies? How might this affect subsequent transition to the higher frequencies? Would the lower frequencies remain useful in the domestic system, and for what services?

2.3.30 Forward-Acting Error Control

Since it is likely that satellite transmission, like terrestrial facilities, will tend toward pulse-code modulation, a study is needed of the best way to handle needs for high-accuracy data transmission in the presence of the long time delay.

3.0 POSTULATED SYSTEM PLAN FOR COMMERCIAL COMMUNICATIONS-SATELLITE SYSTEM

3.1 Introduction

Considering the many political and financial problems involved in creating a commercial communications-satellite system capable of serving all parts of the world desiring to use it, development of such a system seems rapid in the period since the passage of the Communication Satellite Act of 1962. On the other hand, in comparison with technological possibilities, this progress has seemed lamentably slow, in the opinion of many people. This slowness has been disturbing when viewed from the standpoint of the importance of the services in contributing to world understanding and progress. At the present time, a substantial volume of traffic is being handled by satellite in both the Atlantic and Pacific areas. Before the end of 1968 additional capacity is expected to be added in both these areas and service will be started in the Indian Ocean area, thus completing a worldwide service capability. Earth terminals are finally being planned and implemented over much of the world, including many of the developing nations, as shown in Table 9. 3. 1.

Notwithstanding the existing degree of progress and the capabilities of available technology, numerous technical and economic areas still require additional study and investigative work. Further effort is needed to provide more service, improve the economics, and provide for more general application of the service potentials. Consequently, throughout this volume, emphasis is placed upon those areas in which more engineering and investigative work appears likely to yield substantial payoffs either in cost savings or in increased benefits to developing nations using satellite communications.

3.2 Near-Term INTELSAT Plans

Since one of the constraints on postulating a future system plan is that the existing system must be able to evolve into the postulated system, a review of how INTELSAT might develop during the next few years is needed.

The INTELSAT-III satellite, using a mechanical de-spun antenna, will provide 1200 full duplex voice circuits. To do so, it utilizes the full 500 MH once. The planned locations of these satellites are shown in Figure 9. 3. [illegible]. It may be noted that these three locations provide dual coverage of Europe and Africa by the Atlantic and Indian Ocean satellites, as well as dual coverage of much of Australia and the Orient by the Indian Ocean and Pacific satellites. Much of North America, however, will lack coverage from any of these satellites. Both the United States and southern Canada have terrestrial service to earth stations on both coasts. Moreover, the future can bring more such satellites at additional locations, over the Atlantic for example.

It has been forecast that there will be a traffic overload in the Atlantic by 1970, requiring a second INTELSAT-III. This raises interesting and important problems concerning how best to use this second satellite. One plan would be to put much of the heavy traffic between Europe and North America through one satellite and reserve the second for multiple-access use by all Atlantic earth stations. This plan would require that the few nations to use the heavy-traffic satellite would need second earth stations. An alternate plan, favored by some, would be to use one satellite primarily by stations in North and South America, plus a few in Europe, with the second satellite serving Africa, the Middle East, remaining stations in Western Europe, plus a second U.S. station. Proponents of this system point out that there is negligible traffic between Africa and Latin America, plus adequate surface communication over Western Europe, and that the United States could best afford the additional station with which to use both Atlantic satellites. This example may draw attention to some of the problems of trying to increase traffic capacity by the use of additional small satellites, instead of an adequately larger one. It now appears that the 6000-circuit INTELSAT-IV will meet this problem for the Atlantic, at least for a few years.

The INTELSAT-III satellites, the planned locations of which are shown in Figure 9.3.1, are scheduled for implementation in mid-1968 and will provide the first global service. The Atlantic congestion problem might possibly be relieved by providing a second satellite in a nearby location. There are multiple earth terminals both in Europe and in North America.

3.3 Factors Affecting Traffic Capacity

3.3.1 International Frequency Allocations

It commonly is considered that only two frequency bands, of 500 MHz each, are available for point-to-point satellite communication, these being 5925--6425 MHz from earth to satellite and 3700--4200 MHz from satellite to earth. Actually, the international frequency allocations for satellite communication are more extensive and much more complex, as can be seen by examining the Final Acts of the 1963 Extraordinary Administrative Radio Conference (Space EARC). This is further complicated by there being certain agreements or restrictions which would not be shown in an ITU document, such as the U.S. reservation of the 7250--7750 MHz and 7900--8400 MHz bands for governmental application of satellite communication. At lower frequencies, other bands appear to have been allocated for satellite communication but these have been contaminated by radar, tropo-scatter links, etc., so that they would not be usable.

These 4- and 6-GHz bands, as they are commonly referred to, are shared with domestic terrestrial radio-relay systems and, for this reason, certain restrictions have been imposed on both the sharing services by the ITU. Further restrictions have also been imposed by the Federal Communications Commission. These restrictions pertain to the minimum vertical antenna angles for earth terminals, the power used, etc.

3.3.2 Orbit Utilization vs Modulation Hardness

In terms of voice channels (one-way), the maximum capacity of a single radio path with 500-MHz bandwidth has been calculated for the FDM-

TABLE 9.3.1

EARTH STATION DATA BASE AS OF SPRING 1967

EARTH STATION DATA BASE (Implementation Schedule)

WORLD AREA		ANTENNA SIZE	1966	1967		1968		1969		1970		1971		1972	
			TOTAL ACTIVE AT END OF YEAR	NUMBER ACTIVATED DURING YEAR	TOTAL ACTIVE AT END OF YEAR	NUMBER ACTIVATED DURING YEAR	TOTAL ACTIVE AT END OF YEAR	NUMBER ACTIVATED DURING YEAR	TOTAL ACTIVE AT END OF YEAR	NUMBER ACTIVATED DURING YEAR	TOTAL ACTIVE AT END OF YEAR	NUMBER ACTIVATED DURING YEAR	TOTAL ACTIVE AT END OF YEAR	NUMBER ACTIVATED DURING YEAR	TOTAL ACTIVE AT END OF YEAR
AFRICA	Total Ant.	85'	-	-	-	1	1	2	3	2	5	2	7	2	9
	Total E.S.		-	-	-	1	1	2	3	2	5	2	7	2	9
ASIA		42'	-	2	2	-	1*	-	1	-	1	-	1	-	1
		72'	1	-	1	-	1	-	1	-	1	-	1	-	1
		85'	-	-	-	5	5	3	8	1	9	1	10	-	10
		90'	-	-	-	1	1	-	1	-	1	-	1	-	1
	Total Ant.		1	2	3	6	8	3	11	1	12	1	13	-	13
	Total E.S.		1	2	3	3	6	3	9	1	10	1	11	-	11
EUROPE		42'	2	-	2	-	2	-	2	-	2	-	2	-	2
		44'	1	-	1	-	1	-	1	-	1	-	1	-	1
		85'	3	-	3	2	5	-	5	2	7	1	8	-	8
		90'	-	1	1	-	1	-	1	-	1	-	1	-	1
	Total Ant.		6	1	7	2	9	-	9	2	11	1	12	-	12
	Total E.S.		6	1	7	-	7	-	7	2	9	1	10	-	10
CENTRAL & SOUTH AMERICA		85'	-	-	-	4	4	3	7	2	9	-	9	-	9
		95'	-	-	-	1	1	-	1	-	1	-	1	-	1
	Total Ant.		-	-	-	5	5	3	8	2	10	-	10	-	10
	Total E.S.		-	-	-	5	5	3	8	2	10	-	10	-	10
MIDDLE EAST		85'	-	-	-	2	2	5	7	2	9	-	9	-	9
		95'	-	-	-	-	-	1	1	-	1	-	1	-	1
	Total Ant.		-	-	-	2	2	6	8	2	10	-	10	-	10
	Total E.S.		-	-	-	2	2	6	8	2	10	-	10	-	10
NORTH AMERICA		30'	1	3	4	-	4	-	4	-	4	-	4	-	4
		42'	3	-	2*	-	2	-	2	-	2	-	2	-	2
		85'	4	-	4	5	9	-	9	-	9	-	9	-	9
	Total Ant.		8	3	10	5	15	-	15	-	15	-	15	-	15
	Total E.S.		5	3	8	4	12	-	12	-	12	-	12	-	12
OCEANIA		42'	-	1	1	-	1	-	1	-	1	-	1	-	1
		85'	-	-	-	-	-	1	1	1	2	-	2	-	2
		90'	-	1	1	-	1	-	1	-	1	-	1	-	1
	Total Ant.		-	2	2	-	2	1	3	1	4	-	4	-	4
	Total E.S.		-	2	2	-	2	1	3	1	4	-	4	-	4
WORLD SUMMARY		30'	1	3	4	-	4	-	4	-	4	-	4	-	4
		42'	5	3	7	-	6	-	6	-	6	-	6	-	6
		44'	1	-	1	-	1	-	1	-	1	-	1	-	1
		72'	1	-	1	-	1	-	1	-	1	-	1	-	1
		85'	7	-	7	19	26	14	40	10	50	4	54	2	56
		90'	-	2	2	1	3	1	4	-	4	-	4	-	4
		95'	-	-	-	1	1	-	1	-	1	-	1	-	1
	TOTAL ANT.		15	8	22	21	42	15	57	10	67	4	71	2	73
	TOTAL E.S.		12	8	20	15	35	15	50	10	60	4	64	2	66

* The 42' antenna at Brewster was moved to the Philippines in February 1967. The antenna installation in the Philippines is scheduled for April 1967, and will be operational through 1968.

Note: A standard earth station, as defined by the ICSC, generally employs an 85' or greater antenna size. It should be noted that there are other factors, as contained in the referenced paper, that determine whether or not a station is standard.

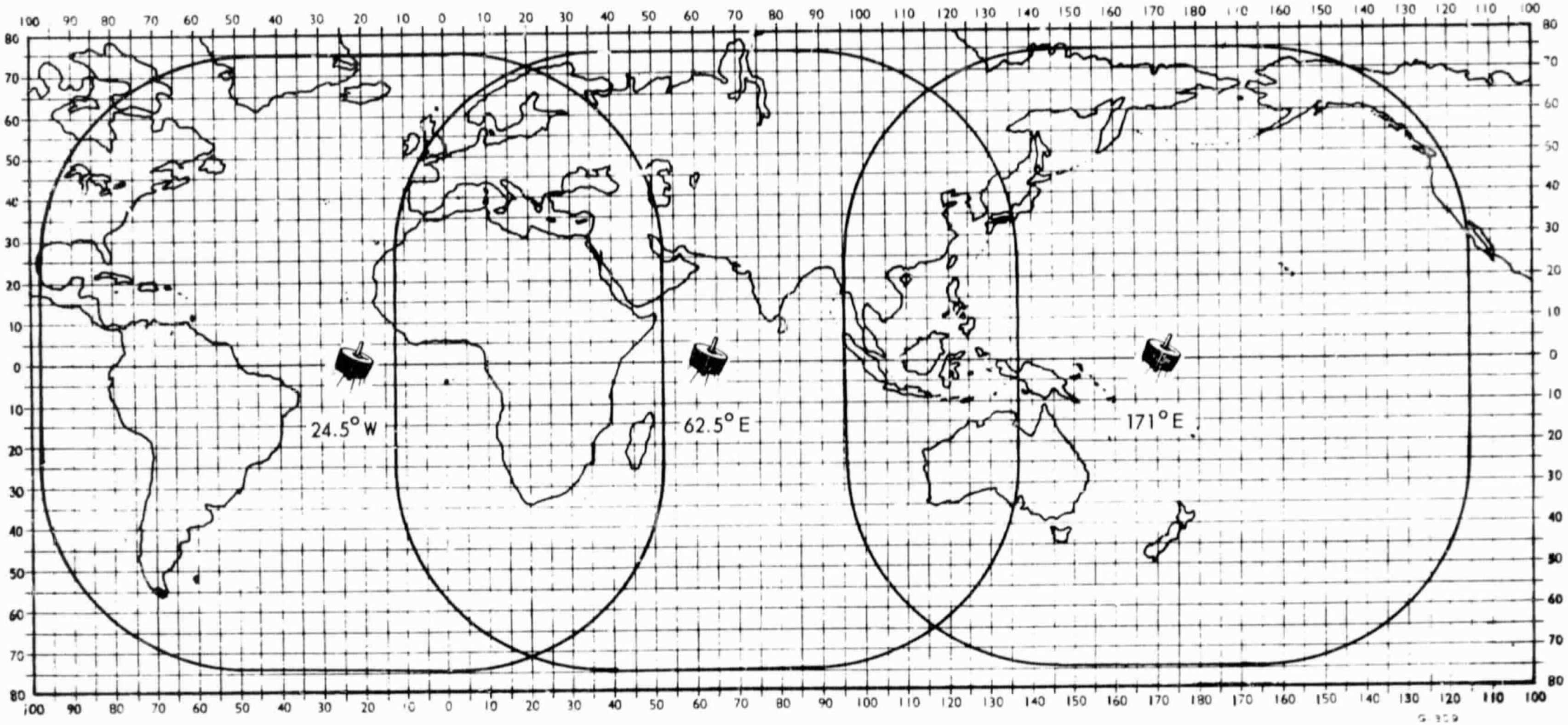

FIGURE 9. 3. 1 Proposed global system coverage–INTELSAT–III satellites (mid-1968).

FM (frequency division multiplex with frequency modulation) and for PCM-PSK (pulse code modulation with phase shift keying) in Appendix D. Although FDM-FM has been used by terrestrial radio-relay and satellite systems up to this time, PCM is rapidly coming into use for U. S. domestic wire communications and has several advantages for satellite systems, principally in its higher resistance to interference. The capacities computed in the appendix are summarized in Table 9. 3. 2.

TABLE 9. 3. 2

TELEPHONE CHANNEL CAPACITY OF A 500-MHz BAND

Modulation	Condition	Voice Channels
PCM-PSK	2-level	4, 500
	4-level	9, 120
	8-level	13, 680
	16-level	18, 240
FDM-FM	D=6. 2	6, 600
	D=2. 5	13, 600
	D=1	23, 800

Multilevel PCM-PSK and FDM-FM at low deviation ratios are considered to be "soft" modulations, in that they are relatively less resistant to interference, having achieved increased channel density in return for reduced noise-suppression or signal improvement. Thus, in a given noise or interference environment, the signal strength usually must be increased substantially as the modulation is softened to increase the channel density. For example, Appendix D shows (Figures 9. D. 4 and 9. D. 5) that a 137 times increase of in-power is required to achieve less than a fourfold increase in channel density by decreasing the peak-to-peak frequency deviation from D=6. 2 to D=1. 0. If this signal is much stronger than that from adjacent satellites it is correspondingly more likely to interfere with their signals unless the separation between satellites is increased. Even when many satellites are equally separated and operated identically, this "softening" would entail nearly a threefold reduction in orbit utilization (channels per degree) under the assumptions used in Appendix D. The D=6. 2 deviation ratio is that which simultaneously meets the noise and breaking margin requirements. Further hardening (higher deviation ratios) brings a diminishing increase in orbital channel density but with too many closely spaced satellites with too few channels each. Thus there appears to be an optimum deviation ratio, not sharply defined, but not so low as to require large orbital separations and excessive satellite powers.

In the use of PCM-PSK, the difference between four-level and eight-level modulation orbit-arc capacity appears relatively small, at least for the conditions which were assumed. It seems evident that orbit-utilization, in relation to choice and hardness of modulation, relative powers of adjacent satellites, spectrum-reuse techniques, earth antenna beamwidths, etc., constitutes an important field for further study. The results of such study would seem valuable toward policy guidance. It is to be hoped, however, that undue concern for efficient orbit utilization does not impede progress unnecessarily.

3. 3. 3 Antenna Directivity and Multibeam Satellites

Geostationary-satellite technology is entering the era of conical or two-dimensional earth-directed antenna beams, achieved by de-spinning techniques, or perhaps by means of three-axis stabilization of more conventional directive antennas. Antenna gains have increased from about unity, for the approximately isotropic antennas of TELSTAR and RELAY, to 6 to 9 dB for the spinning one-dimensional antennas of the SYNCOMS and prior INTELSATS, to about 19dB for an earth-subtending conical beam. This increase in gain has brought corresponding increase in the satellite's effective isotropically radiated power (EIRP) which has been fully as useful (up to this point) as corresponding increases in transmitter power.

Having achieved such earthward beams, it becomes relatively straightforward to make the antenna beam even narrower, with higher gain, letting it illuminate only some smaller portion of the earth that it is intended to serve. A 30-dB gain would be obtained from a five-degree beamwidth, for example, one which would about cover Brazil but not the rest of South America. Thus, further gain-increase brings reduction of earth coverage, making it less useful in some cases than a corresponding increase in transmitter power.

So long as a satellite has only one earthward beam, its channel capacity remains limited as previously discussed. If more circuits are needed than this single-beam satellite can provide, a second such satellite can be placed nearby at some minimum orbit separation from the first. Similarly, additional satellites can be added to the useful segment of the geostationary orbit up to the limit of this minimum separation. This method of increasing circuit capacity by adding satellites has complications, some as simple as those discussed in relation to a second Atlantic satellite. Nevertheless, satellite clusters are forseeable, as also is the use of intersatellite relay links (over short arcs) as a means for minimizing the need for multiple earth stations.

Another means of increasing the circuit capacity is through the use of two or more earthward beams from the same satellite. If two such beams could be used with accurately orthogonal polarization, both could reuse the same frequency band. Maintaining sufficient interference discrimination by this means alone could be difficult, however. Alternatively, if the two beams were used to illuminate sufficiently separated areas of the earth, both could reuse the same frequency band. In either case, this reuse would permit doubling the satellite capacity in terms of numbers of voice channels and a specified modulation. If additional narrow beams are used, all adequately separated, additional reuses of the same frequency band are feasible. In contrast, only two orthogonal polarizations are possible. These techniques can be combined, to some extent, using polarization orthogonality to enhance the isolation of certain pairs of beams whose angular separation would be inadequate. For example, one might have two beams, A and C, with adequate angular separation but wish to put a beam, B, between. Cross-polarizing B with respect to the polarization used for both A and C probably would provide the solution. As a 3-beam example in which polarization orthogonality would not save the day, let us start with beams A and B having been cross-polarized because of inadequate angular separation. Now it is desired to direct beam C at a point equidistant from A and B and with inadequate separation from either. C's polarization could be crossed with respect to that of either A or B but then would be the same as that of the remaining beam, from which its inadequate isolation would prevent reuse of the same frequencies.

The foregoing discussion may help clarify the beam-isolation problem when trying to place multiple beams for coverage of the major land areas visible from the satellite. Even with good use of orthogonal polarization, some beams having like polarization would still be much too closely spaced to permit them to reuse the full frequency band without excessive mutual interference.

There is another discouraging limitation to multibeam coverage of the earth's land areas, the technique often advocated because, "We shouldn't use costly satellite power to heat the oceans!" The implication is that multibeam coverage of the land areas should make substantially better use of the satellite power than if it all were radiated in an earth-covering (18°, 19 dB gain) beam. In a typical example, reasonably complete land coverage could be achieved with 9 beams, each of 5-degree width and 30-dB gain. Assuming that these each are fed with 10-watt transmitters, the EIRP at beam centers would be a nice 40 dBW. However, if all 90 watts had been put into the earth-covering antenna, the EIRP would have been a nearly-as-good 38 dBW. The use of the nine beams from nine transmitters aboard the satellite would seem a rather questionable way of saving only 2 dBW from the ocean!

Recognizing that there is some interest in similar use of multiple beams for the coverage of some one continent, or smaller region, and that these techniques have not yet been reduced to practice, the present conclusion would be that area-coverage applications of multiple beams offer little or no better use of the satellite power (compared with single-beam coverage of the same area), while offering partial reuse of the same frequency bands.

Going toward the other extreme, these earthward beams might be made sufficiently narrow and well separated for full reuse of the band, but each beam might then cover only one terminal city leaving intervening areas without coverage. In addition to full reuse of frequencies, these extremely narrow beams would have correspondingly higher gain, leading to a substantial increase in the EIRP of the individual beams, without any increase in the total satellite power. This latter aspect suggests the use of millimeter waves in multibeam point-coverage systems, both because of being better able to obtain these very narrow beams from satellite antennas of acceptable dimensions and because this EIRP improvement would help compensate for the higher propagation losses at these higher frequencies.

Going beyond these considerations the acceptability of point-coverage multibeam systems might depend heavily upon their system application. For example, studies have shown (see Appendix H) the probable applicability of such a system as a part of the U.S. domestic communication system, with the satellite beams directed toward each of some reasonable number of selected and well-established traffic nodes (at major cities, generally) and with the assumption of very close coordination between the operators of the satellite and terrestrial systems. Imperfect cooperation between these operators could lead to service impairments more easily than with an area-coverage system.

Such a nodes-only type system would not be an acceptable substitute for area coverage in the global system because suitable traffic nodes are not yet well enough established in many of the developing nations. These areas require a system that offers area service so that an earth terminal can be established in the future wherever needed. Similar reasoning indicates the need for area coverage in points-to-point systems, such as for data collection, and for point-to-points systems, such as for TV distribution.

It may be observed, however, that a future Atlantic satellite might well incorporate the combined use of area coverage of the four continents using the 4- and 6-GHz bands at least twice, with the addition of narrow, high-gain millimeter wave beams directed at known natural nodes or gateways of heavy international traffic. Although this traffic is heaviest between points in North America and Western Europe, there are significant and solidly fixed nodes at some of the large cities of South America, such as Buenos Aires. Such a satellite would use as small an orbital arc as other satellites contemplated but could have a total traffic capacity greatly exceeding that of satellites presently planned. Admittedly, such a satellite might become complex, as judged by today's standards, because it should provide flexible interconnectability between the stations having their own millimeter wave beams from the satellite and all similar stations, plus the many light-traffic stations covered at the lower frequencies, plus ones with heavier traffic but in locations (such as Scandinavia) where the millimeter waves might not be sufficiently useful.

3.4 General System Principles

In the development of system plans for the extension of communication-satellite service into all its many applications in worldwide telecommunications it is useful to choose a few general guides and principles for reference. These are:

1. Since there are alternative methods technically capable of filling any of the needs encountered throughout the world, the relative economics of the competing technologies will be a major determinant in the choice between satellite or the various surface technologies. Comparisons of service quality are an additional determining factor and measure of benefits. For example, HF radio circuits have thin-route advantages in low cost, ease of implementation, etc., but they are unreliable and too often unintelligible.

2. With the possible exception of HF radio circuits, the cost of any terrestrial circuit (exclusive of its terminal costs) is proportional to its length, so it can be obtained [illegible] a cost per circuit mile. Similarly, the corresponding annual costs can be expressed in dollars per circuit mile year.

3. A very significant characteristic of terrestrial systems is that progressively lower costs per circuit mile year are achieved by increasing the circuits per system and by introducing systems of greater cross section (i.e., circuit capacity). This trend is shown clearly by Figure 9.3.2, which came from AT&T, via ODTM. It is an updated and extended revision of a 1957 AT&T family of comparative annual cost curves for various systems, as filed with the FCC, Exhibit 2253 to Docket No. 11866 (1957 hearings). Note that these annual costs are comparative, and that the relation to dollar costs was not specified and remains uncertain. Various comparisons with costs reported elsewhere suggest that one dollar corresponds to a comparative cost of about 5, probably not more than 7, and surely less than 10. The trend line is especially significant in that the curves for the specific systems remain so close to it. Thus, when an actual system has not been specified, or its costs are not known, a cost obtained from this trend line provides a reasonable approximation. Additionally, this trend cost can be put in a functional form. In doing this, one notes that the circuits scale is not exactly logarithmic but has been slightly compressed at its high end, so as to preserve straightness of the trend line, even though the new higher capacity systems seem to be showing a slightly declining rate of cost reduction. Neglecting this, and for less than $N=5000$ circuits, the slope of this trend line agrees reasonably with that of $N^{-0.7}$. Then, using five comparative cost

units per dollar gives a cost trend relation, $380/N^{0.7}$ dollars per circuit mile year. This is in reasonable agreement with a similar relation, $300/N^{2/3}$, from the RAND Corp.

4. Surface routes are longer than the airline distance, D, between their ends. The factor 1.3 frequently is used in converting from airline to route miles. Using $1.3D \times 380/N^{0.7}$ and rounding off, leads to $500D/N^{0.7}$, dollars per circuit year, D being in miles. This permits plotting the trend costs for various distances (as a family of parallel lines which can be used as an underlay for satellite circuit costs curves - see Figure 9.3.3), for studying the break-even relations and trends, as will be explained later. Better cost curves of this general type should be used whenever available, ones applicable to the specific system and part of the world being considered.

5. The most significant aspect of satellite circuit costs is their complete independence of the distance between the two earth stations, one-hop satellite circuits being assumed. Since terrestrial circuit costs are distance proportional, there will be some break-even distance, beyond which a satellite circuit would be less costly. However, since terrestrial system costs also vary widely with the number of circuits, this break-even distance will also depend on the number of circuits, generally being less for the light traffic.

6. In an ideal INTELSAT-type system (one without compensatory payments), the earth stations contract and are charged for their use of the satellite by units of utilization of the space segment, S, multiplied by a penalty factor, P, which corrects for the less efficient utilization of the satellite by a substandard station. At present (prior to INTELSAT-III) the standard (85-ft antenna, 50°Kelvin) earth station pays S = \$20,000 per year per half-circuit (i.e., a channel pair, to and from the satellite). A 30-ft antenna station, operating at 200° Kelvin, would be charged P = 27 times this rate, or \$540,000 per year per half-circuit, on grounds that a circuit between two such stations uses as much of the satellite's power and bandwidth as 27 circuits between standard stations. Note that S is a rate, set by the satellite operator (INTELSAT), but it becomes a cost to the using earth stations.

7. Other than providing more circuits, if needed, or providing some new service such as demand-assigned multiple access, the earth stations' only economic interest in or benefit from the introduction of larger and better satellites, having much lower costs per circuit, depends on how much this space-segment rate, S, and/or their penalty factor, P, may be reduced. Thus, in a user-oriented economic analysis, improvements in the spacecraft need not be considered beyond their probable effect on S and (for substandard stations) P.

8. In a domestic-type system, with the satellite and all its earth stations owned and managed by the same entity, use costs may be more closely coupled to changes in cost and capability of the satellite. Hence, it is preferred to price out such systems completely.

9. The annual cost of an earth station can be considered as a function of its number of circuits, N, to and from the satellite. This functional relation may be approximated by the first two terms of a power series (see Appendix A),

$$T_o + T_1 N + \dots$$

T_o is the no-circuit coefficient and depends on the antenna, buildings, etc. T_1 is the per-circuit coefficient and depends on the modems, echo suppres-

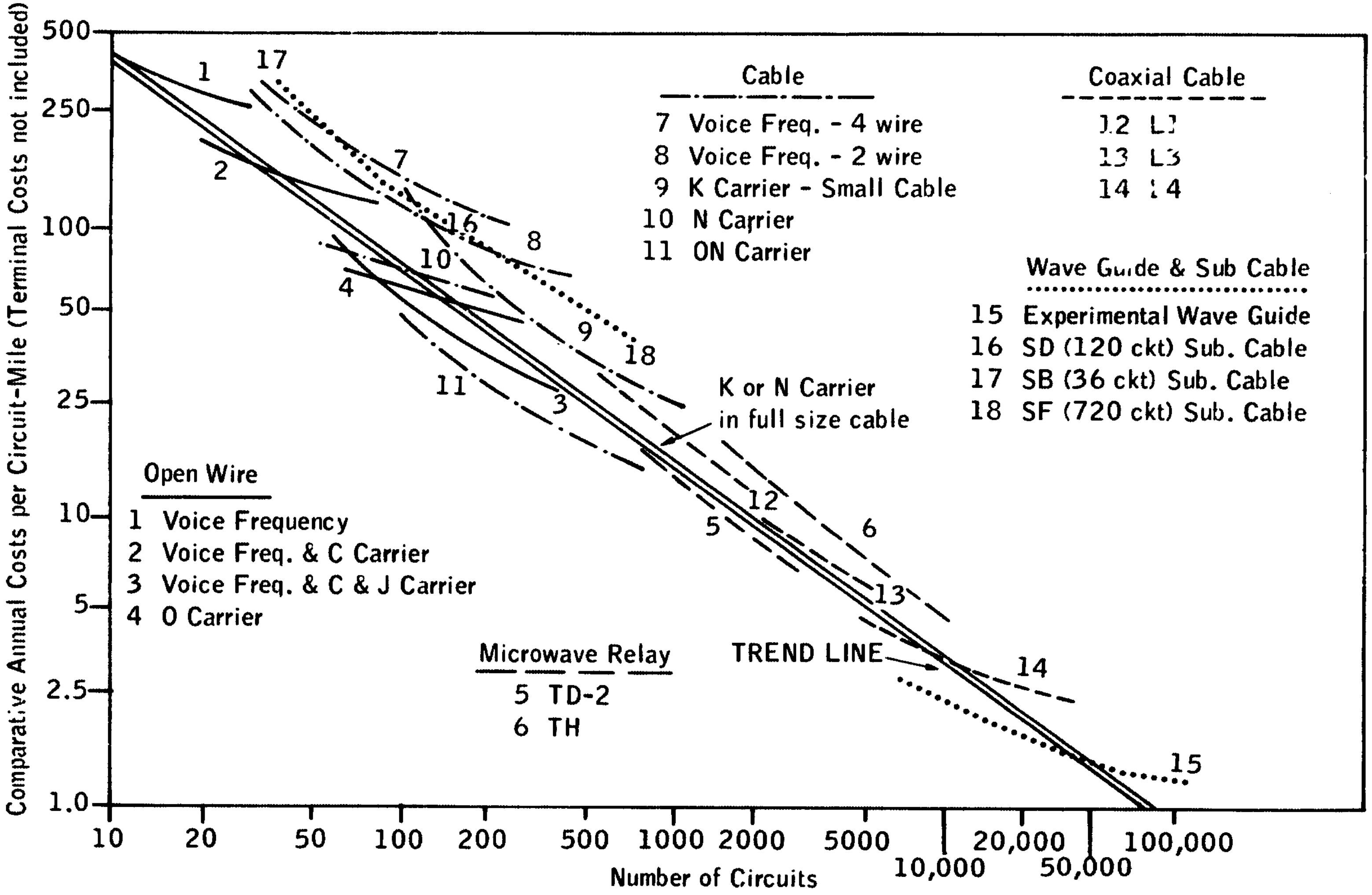

FIGURE 9. 3. 2 Comparative annual circuit costs (not in dollars) vs number of circuits. Curves for various systems are about optimum for their particular applications, and are closely spaced about trend line.

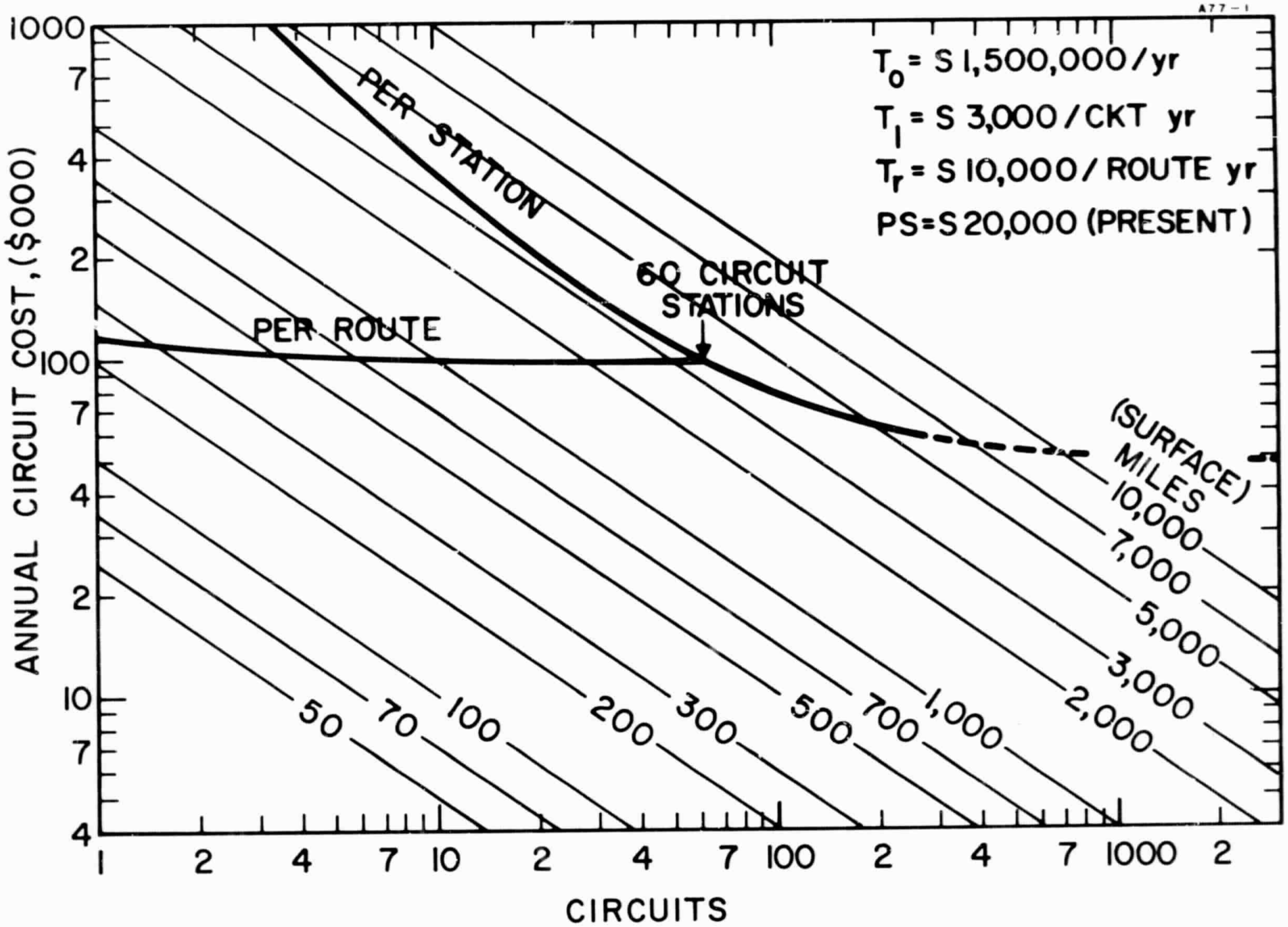

FIGURE 9.3.3 Illustrative break-even relations.

sors, etc. These coefficients account for labor and other operating costs as well as for amortization of the investment. Thus the annual cost per circuit is $T_o/N + T_1$, or each circuit's individual cost, plus its share of the no-circuit cost. The "economy of cross section" lies in the decrease of T_o/N as the circuits per station is increased, with T_1 being approached as the lower limit. Note that if all these stations were used for a single route to another station, (i.e., no multiple access) this economy of cross section would be similar to that with many forms of terrestrial communication. The significant difference is that N is the station's circuit total, from all its routes to other stations. Thus, even the light routes contribute to this total and to the reduction of T_o/N.

10. If a station adds a route (via preassigned multiple access) it may incur a slight additional annual cost, T_r, for processing the signal from and to this additional station and this must be spread over the N_r circuits of this route, as T_r/N_r. Typically, this incremental cost will be negligible except for very few circuits per route and will not be large even for a single-circuit route. Neglecting this incremental cost and neglecting the slight change in the station's circuit total, N, as the N_r circuits in one of its routes is changed one sees that the cost per circuit of a satellite route can be essentially independent of its number of circuits, N_r, as well as of the route distance between stations. Thus, multiple access satellite communication has its greatest leverage relative to terrestrial communication for long, light routes between multiroute stations.

11. The break-even conditions between the annual cost of a satellite circuit and the annual (trend) cost of an equivalent terrestrial circuit can be obtained readily from the above relations and applicable coefficient values, as explained in Appendix A.

12. The break-even conditions are poorest for a single route between a pair of stations $N = N_r$. Here, though the cost per circuit decreases with N, it may do so at a rate little different than that of the surface cost trend lines, $N^{-0.7}$. This leads to a minimum break-even distance which is broad, changing slowly with change in the number of circuits. See the "per station" curve of Figure 9.3.3.

13. The break-even conditions improve greatly when the stations have multiple routes, with few circuits per route, but totalling reasonably many circuits per station. Illustratively, the break-even distance may decrease from a few thousand miles for a single route station-pair, with 100 or less circuits, to a few hundred miles for light routes (12 circuits, more or less) between relatively large-capacity earth stations.

14. The above short and light break-even capability gives multiple-access satellite communication an attractiveness for intranational (domestic) use in developing nations which need light-traffic routes between relatively remote cities, each of which has enough total traffic (including international traffic) to justify an earth station. The balancing factor is that the potential traffic increases as the routes become shorter, so these short routes may not remain light. Thus the growth of traffic on these shorter intercity routes tends to increase the break-even distance and, perhaps, to favor the construction of higher-capacity terrestrial facilities.

15. Somewhat different problems enter in considering a domestic satellite system for a nation which already has heavily developed terrestrial facilities. The fact that there is a large investment in terrestrial facilities being used for services that could more economically be provided by satel-

lites can safely be ignored in planning for the introduction of satellite facilities into a situation of rapid expansion such as exists in the United States. The time required for a transitional period to reassign the services to satellite facilities and utilize the unloaded terrestrial facilities for shorter haul services is not long as compared with the time required to set up the satellite system. However, close coordination between the operators of the two types of facilities is required and might be much better accomplished by a single engineering-planning agency.

16. The transmission quality of satellite circuits for the various types of information exchange demanded of a telecommunications system can be considered as essentially equal to that of the competing terrestrial facilities. Each transmission-system technology presents its own unique set of technical constraints that must be observed in attaining a given level of quality. Except for HF radio, however, methods are available for accomplishing desired quality levels.

A characteristic of geostationary satellite circuits that needs to be considered in relation to transmission quality is the relatively great propagation time (or delay) for this long space path, approximately a quarter-second each way. This is of no concern for one-way services, such as television, but it may contribute to constraints on such two-way services as telephone and on data error-correcting systems of the ARQ type.

In respect to telephony, it is generally agreed that any quality impairment is apt to result from imperfectly suppressed delayed echoes, or from other degradations introduced by echo-suppressors. Thus, although a two-hop "four-wire" circuit (i. e., no echoes, no suppressors) might be acceptable to most users, the practical necessity of using available echo-suppressors dictates that two-hop circuits be avoided. This constraint need not be serious for even the longest intercontinental circuits which require only that a single long satellite hop be extended by terrestrial links of reasonable length and availability. The potential constraint may be more serious in relation to domestic or regional satellite systems being impeded in the use of a second hop through an international satellite and possibly then a third hop via another domestic satellite, to reach some desired station. As an interesting example, a Canadian domestic satellite system probably would not be bothered by this constraint. In southern Canada, as in the United States, the terrestrial facilities provide low-delay circuits to earth stations on both coasts. Points in northern Canada might be most dependent on their domestic satellite system, but probably would have little need for international circuits other than to Europe and Australia, which can be reached from southern Canada via submarine cable.

17. Satellites provide a means of establishing communications between any two nations without transiting the territory of a third nation. This ability has previously been available only with low-capacity and relatively poor-quality HF radio. This feature may lead, for reasons of national interest, to the acceptance of higher than minimum costs in a number of situations.

18. Although certain aspects of multiple access have been mentioned, this is such a unique and important aspect of satellite communication systems that further discussion will be found useful.

Multiple access refers to the important capability of satellite systems for simultaneous communication between three or more—usually many more—earth terminals using the same satellite. The duplex channels or circuits between pairs of terminals may be utilized by being preassigned (either permanently or according to some prearranged time schedule) or may be temporarily assigned upon demand for individual calls. With demand-assigned circuits, the up and down channels may be demand assignment, channels through the satellite may be variably assigned to earth stations at their transmitting ends, receiving ends or at both, the assignments being for the duration of a demand. With fully variable demand-assigned circuits, both channels are variably assigned at both ends. With semivariable demand assignment, the circuits are composed of channels which are preassigned at one end to a specific station and are variably assigned at their other end. This offers four possibilities, of which the use of preassigned transmitting channels, variably received, seems of interest because of its compatibility with the multidestination carrier (FDM-FM) form of preassigned multiple access now in use.

All these types of demand assignment permit earth stations to pool their traffic for more efficient use of their circuits. For good service there should be a low probability (P=1%, preferably) of finding all circuits busy. With only a single circuit available, by its preassignment to a light route, this circuit could not be used more than one percent of the time or the probability of its being found busy would exceed this same percentage. Moreover, if one were to "hold" until this busy condition ended, the average delay would be much greater than if one could use the first idle circuit from among several. This pooling of circuits for satisfying the fluctuating demands of a number of light routes has a significant economic effect in raising the efficiency of circuit utilization, as illustrated by Table 9. 3. 3.

TABLE 9. 3. 3

CIRCUIT CAPACITY

Probability of finding all circuits busy P = .01

No. of Circuits	Percent Usage	Avg. Delay on Delayed Calls in Holding Time
1	1.0	1.0
3	14.5	0.4
5	25.6	0.3
10	41.4	0.15
25	59.4	0.1
50	70.1	< 0.01
100	78.2	< 0.01

A major difference between the semivariable and fully variable forms of demand-assigned multiple access is that the former provides the circuit pooling at the station level whereas the latter pools the much greater number of satellite circuits, for use by any station, thus further increasing the traffic capacity of the satellite.* An important advantage of either form is that demand assignment permits each station of a satellite to have direct communication with any other station, even though the demand consists

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*Lutz, S. G., A Traffic Study of Multiple Access Satellite Communication based on an Atlantic System Model, Telecommunications, Part I, July 1968, pp. 27-32; Part II, August 1968, pp. 25-31.

simply of an occasional call—clearly not enough to justify even a single full-time preassigned circuit. There are, of course, some equipment costs associated with providing demand-access capability. The exact amount of these costs is determined by the method chosen and no meaningful cost estimates have thus far become available.

Because of these costs, whatever they may be, earth stations probably will use demand-assigned circuits for only lighter-traffic routes, while using preassigned circuits for heavier ones. Therefore, the compatibility of these two methods should be considered in selecting or improving a multiple-access system. (Appendixes B and C contain more detailed discussion of multiple access.)

3.5 Categories Of Services Considered

Point-to-point communications are categorized in different ways for convenient consideration of different aspects of the subject. For some purposes a differentiation is made between domestic, i.e., intranational, and international services. Such classification is useful for legal and organizational purposes but is not of much interest technically. It should be used with care in technical considerations because international traffic across a common border, such as between the United States and Canada, tends to be quite similar to domestic traffic in general characteristics. This is particularly evident in the short-haul portion that crosses the border for relatively short distances.

"Intercontinental traffic" is sometimes used as a separate classification but is becoming less and less useful as the technical capabilities of ocean-crossing facilities improve. It is one of the areas in which, at the present time, assignment of management responsibility on the basis of technology rather than on the basis of geography causes difficulty in determining requirements and choice of facilities to be used for particular applications.

Another common way of categorizing traffic and requirements is by types, or format, of the information flow to be handled. This gives the various categories such as telephone (whether analogue or digital is not significant), record, data, and TV. These distinctions are unhappily often used as a means of assigning management responsibility and are likely to cause difficulties since they are becoming less and less meaningful technically. Frequently it is impossible to distinguish between formats on the transmission facility.

In this report, these different categories are all considered to be in a single set unless specific modifiers indicate that only a particular subset is being considered.

The characteristic of transmission facilities of rapid unit-cost decrease as a facility cross section increases leads naturally to a desire to combine all categories of traffic on the same facility to the maximum possible extent. However, there are forces working in the contrary direction that should be recognized. First, there are always some limits on the maximum cross section that it is practical to attain on a given facility. For cables, the limit is usually due to the physical difficulty in handling excessively large cables; for radio systems such as terrestrial microwave and satellites, the limit is frequently due to limitations on the available frequency spectrum. A second force working in this direction is the desire for high reliability of communications between each pair of points. This leads to a spreading of requirements over two or more separate facilities where the penalty is not too large. In many instances, these forces can induce acceptance of higher-than-minimum possible costs.

In order to obtain a system that has good economic characteristics for postulation as a basis of this report, it is assumed that substantial weight is placed on the economic characteristics covered above and, to a reasonable extent, all categories of traffic are considered for combination on a single facility within a given area. Encouragement for such a procedure lies in the current INTELSAT, where 58 nations have been able to reach adequate levels of agreement to make progress toward a worldwide system engineered and implemented on a cooperative basis to serve the needs of all. While contrary forces are recognized, it is assumed, because of the great advantages to all, that it will be possible to continue such a form of international cooperation in telecommunications.

3.6 Projections of Communications Requirements

The demand for communications varies over an extremely wide range in different parts of the world. This fact produces very marked differences in the economics of transmission facilities. For example, in areas where needs can be filled by routes of approximately 50 voice circuits the annual costs per terrestrial circuit are around $20.00 per mile. In areas where the traffic is adequate to justify routes having 20,000 to 30,000 voice circuits, the annual costs drop to around 40 cents per circuit mile. Ratios such as this for the competing terrestrial facilities produce a situation in which satellite facilities are justified at widely different costs in various parts of the world. Clearly they are most attractive in the areas where demand is not highly developed. These areas include the developing nations particularly, and apply to the long haul needs most favorably. In areas, such as the United States, which have highly developed and still rapidly growing requirements, the cost competition encountered is such that the satellite system design needs to be changed to achieve break-even at much heavier traffic volumes but at not too great distances, and its routes must be selected with great care.

The most comprehensive worldwide traffic studies and forecasts have been made by the Regional and World Conferences of the ITU Plan Committee. Their forecasts, however, generally have not attempted to separate satellite and terrestrial traffic and have been constrained to an unknown extent by the forecasters' knowledge of terrestrial circuit economics and practices. World forecasts for the INTELSAT system are prepared from data supplied by its members and these data are processed and updated periodically by COMSAT. These data are available by routes in "units of utilization" (a "standard" station's voice circuit, to and from the satellite. A circuit between such stations represents a utilization unit from each). In effect, this practice assumes preassigned multiple access, showing zero traffic for most possible routes that might be demanded infrequently. A summary condensation of this COMSAT data, with the addition of AT&T estimation of U.S. domestic satellite traffic, is given in Table 9.3.4.

TABLE 9. 3. 4

END-OF-YEAR FORECAST IN UNITS OF UTILIZATION

Path	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976
N. America – Europe	560	924	1,214	1,496	1,820	2,078	2,336	2,608	2,880	3,266
N. America – Middle East	4	30	38	64	72	82	90	102	108	126
N. America – Africa	---	4	26	50	66	154	174	194	226	248
N. America – Puerto Rico	---	222	324	388	456	534	642	770	904	1,040
N. America – L. America	---	174	346	402	452	506	558	616	668	764
Europe – Middle East	---	---	74	232	270	312	340	386	426	498
Europe – Africa	---	22	108	124	176	320	358	388	424	460
Europe – L. America	8	162	256	330	348	396	420	482	510	588
L. America – L. America	---	16	78	112	136	158	190	222	240	270
Africa – Africa	---	---	12	30	130	172	192	216	240	260
Europe – Europe	---	---	92	102	106	116	124	130	138	160
Other Minor Paths	---	---	4	8	26	30	34	38	40	44
Total Atlantic	572	1,554	2,572	3,338	4,058	4,858	6,152	6,152	6,804	7,724
Total Pacific	506	754	926	1,240	1,442	1,620	1,822	2,004	2,212	2,502
Total Indian	---	86	308	616	836	1,016	1,202	1,396	1,568	1,950
NASA – Atlantic*	291	245	245	245	245	245	245	245	245	245
NASA – Pacific*	157	157	157	157	157	157	157	157	157	157
Total World	1,526	2,796	4,208	5,596	6,738	7,896	8,884	9,954	10,986	12,578
Average World	1,120	2,161	3,538	4,902	6,167	7,317	8,390	9,419	10,470	11,782
U.S. Domestic			12,800	38,400	38,400	78,400	87,600	101,200	160,000	182,400

*Reflects maximum utilization requirement and includes five units for order wires.

The validity of the international forecasts is seriously questionable for more than a few years in the future, but they are the best we can obtain at present. The data include only those requirements that the concerned administrations anticipate as calling for satellite service. For the most part, it should be anticipated that the figures are too low rather than too high.

The data contained in Table 9. 3. 4 suggest that illustrative consideration be given to two rather distinct systems, an INTELSAT-type global system having only international routes and a North American regional system. The Panel recognized, however, that there might be other regional or domestic systems elsewhere and that these might either be independent or a part of the INTELSAT system. Also, it appears probable that there will be separate Canadian and U. S. systems, possibly also a Mexican system, rather than the North American system which the Panel chose to study.

3. 6. 1 Global-International Aspects

For the Period of the forecast in Table 9. 3. 4 and according to its data, a 3-satellite (Atlantic, Pacific, and Indian Ocean) system appears adequate, with the satellites using earth-covering beams and the 4-GHz and 6-GHz bands. However, an advanced satellite such as INTELSAT-IV will be needed for the Atlantic region at an early date. An area-covering system seems essential, because it is not feasible to forecast where additional earth stations will be built. There might, however, be high-gain beams toward western Europe and the northeast coast of North America to aid in carrying the heaviest traffic. Frequencies above 12 GHz appear undesirable because of the low-angle paths.

It was recognized that the traffic estimates are very uncertain, with a possibility of very rapid growth due to the stimulation of better service. Rate of growth can turn out to be influenced in a major way by the provision of new features such as demand-access. Also, other satellite locations may become desirable, even within the time period of the forecast. For example, a Pacific satellite could be located somewhat farther east and provide a direct route from western South America to Japan. This route then could be extended throughout the Orient via terrestrial facilities and it is to be hoped that the construction of such facilities would enable the rest of South America to communicate with the Orient via this satellite.

3.6.2 North America

For the most part, North America is characterized by well-developed terrestrial facilities, large geographical extent leading to long circuit requirements for internal needs, comparatively very heavy traffic demands, a high rate of growth in demand, and relatively cheap competing transmission facilities due to large route cross sections. Conservative forecasts of potential demand for satellite circuits for internal use in this area indicate that the equivalent of over two million voice channels may be needed before the year 2000, a not unreasonable period to consider when planning the introduction of new technologies. Rough calculations indicate considerable doubt that it would be feasible to provide these quantities with multibeamed satellites using only the allocated 500 MHz of bandwidth; the order of magnitude actually required might be up to four or five satellites with multiple beams, each beam using 3 to 4 GHz of bandwidth.

A look ahead at technological development of terrestrial facilities such as millimeter wave guides or laser beams in a pipe indicates the possibility that the economic competitiveness of satellite facilities could be severely handicapped unless the wider frequency bands are available to permit the economics-of-scale factors to operate.

With these requirements for internal service, no significant economic handicap is imposed by the use of separate earth terminals for internal and intercontinental traffic. Hence the rest-of-the-world satellites can be used for intercontinental purposes but these are not in the correct positions to be visible from both coasts simultaneously as is required for internal traffic.

Because of the high development of investment in terrestrial microwave systems in this area and the extent of their use, the interference problems due to sharing the frequency band with satellites are much more serious than elsewhere in the world. It appears likely that the millimeter bands afford the only possibility for obtaining nonshared allocations. Hence the interference problem presents another reason for considering the use of higher frequencies.

3.7 Postulated Commercial Communications-Satellite System

In order to provide a basis for recommendations regarding NASA's program, it is desirable to postulate a reasonable system adequate to serve the entire area of the world and at least be plausible in the real world of conflicting interests of many types other than purely economic and technical. Hence the postulated system does not in any way constitute a forecast nor does it describe a system that will be adopted or evolve. In the technical and economic sense, it seems that this would provide a reasonably optimized system. Whether this is true or not may be determined by the outcome of the further studies that are recommended. No attempt has been made to describe the system in all details. Rather the intent has been to specify major characteristics to show the need for the studies recommended.

The following paragraphs contain this description of the postulated global and regional systems.

3. 7. 1 Need for Subsystem Design Coordination

The two subsystems to be considered will show the need for good design coordination and of correlation of their use of frequencies and the orbit.

Because of the provisions of the Space Treaty, the fact that area-covering antenna beams from satellites may not be accurately confined within the borders of a single nation, and other factors, it is mutually advantageous to all nations if the frequency spectrum involved and the geostationary orbital spaces used be considered as international resources. A degree of coordination of frequencies already exists through the mechanisms of the ITU. However, the function corresponding to that performed by the FCC within the United States for domestic commercial use of the spectrum is not fully provided for on any international basis at present. The International Frequency Registration Board, an ITU organization, does little more regarding these frequencies than its name implies. It registers station license information (frequencies, locations, calls, etc.) and informs applicants of all prior registrations for frequencies that they wish to use, but it does not attempt to evaluate the engineering and other considerations underlying the license. The FCC function involves the assignment of particular frequencies to particular users and the regulation of the power and radiation patterns used by the individual assignees. Moreover, there is no mechanism, except within INTELSAT, for administration of the geostationary orbital space slots. International competition for particular slots could easily develop into major proportions in some particular sectors where demand is high as it is in the overlapping arc of visibility of the United States and Canada.

Hence it is necessary that the two subsystems—global-international and North American—postulated below be engineered and designed in certain respects as if they constitute a global system. Some agency should perform this function, either INTELSAT or some new and stronger ITU agency. As a practical matter, however, the orbit coordination problems between the global and North American subsystems would seem minor, since the global satellites would be well removed.

3. 7. 2 Global-International Subsystem

1. This subsystem would consist of a minimum of three satellites using the presently allocated 4-GHz and 6-GHz frequency bands.

2. Service areas can be described as the Atlantic, Pacific, and Indian Ocean areas.

3. Initially, the antennas would provide for full coverage of the visible earth area with such gain as is compatible. Each satellite would utilize the full 500 MHz of the spectrum. As growth produces a demand greater than the capacity of a single 500-MHz beam in any one of the areas, the satellite involved would be replaced with a multiple-beam design or an additional satellite would be added depending upon the mix of demand that is encountered. Capabilities for demand assignment of part of the voice circuits would be provided, with the exact method and form of modulation subject to determination after further study. Preassigned circuits would be used for the heavier-traffic earth-station pairs, probably those requiring at least 12-channel group capacity.

4. Recognizing the much greater investment in earth stations than in satellites, especially for the stations serving the Atlantic satellites, it would seem economically attractive to shift this cost-burden somewhat, using satellites of higher power and better receiving sensitivity so as to lessen the cost of additional earth stations, or to gain other economies. Further system cost analyses are needed to guide such a decision.

3.7.3 North American Subsystem

This description of the North American subsystem is given on the assumption that no attempt will be made to go ahead with a fully operational subsystem confined to the 4-GHz and 6-GHz bands, for reasons previously discussed. This assumption presupposes the practicability of developing the technology for use of bands above 11 GHz and a worldwide agreement to allocate adequate bandwidths in that region for commercial satellite use. The state of the present technology makes such an assumption reasonable although not certain. The foregoing does not preclude the possibility of some sort of pilot system in the 4-GHz and 6-GHz bands in this area for purposes of operational trials and experience. In fact, the consensus is that such action is probably desirable on a temporary basis. Moreover, service at these lower bands seems desirable for lighter routes, where demand-assigned service would be desired, and especially where long, low-angle paths through rain-clouds might make use of the higher-frequency bands undesirable. These higher bands generally would be used to serve the heavy traffic nodes of the continental U. S. and southern Canada.

The North American subsystem can be characterized as follows:

1. Multiple satellites, each with multiple beams, located in geostationary orbit for visibility from all or most of North America.

2. The system would provide service for all general telephone, record, and data purposes plus point-to-point TV and, unless a different and more extensive form of satellite broadcasting develops, networking services for commercial broadcasting and such networking of ETV and ITV as is determined desirable by further developments. If TV networking is served by the subsystem, it seems probable that the 4-GHz band would be used for the down link in order to obtain the needed area coverage.

3. Multiple, narrow-beam antennas with coverage approaching the minimum area to provide diversity needed to handle rain attenuation, etc. Frequencies are in the bands above 11 GHz except as specifically noted for these beams.

4. This narrow-beam service to heavy-traffic nodes would be via preassigned circuits, probably on a full transponder basis, between most pairs of earth terminals, with the transponder capacity matching an integral number of master groups in the terrestrial systems, as well as matching TV needs. Some switching flexibility or beam-steering capability in the satellite would permit changing assignments.

5. Special provisions should be made for service to northern Canada, Alaska, Mexico and the Caribbean Islands, where lighter traffic and other problems would be apparent. Here, studies might show a need for demand-assigned circuits.

6. Earth stations should all have equally good angular discrimination ability, because of the use of equally spaced satellites.

3.8 Recommended Projects

In the global-international subsystem, an important problem is reducing costs for the many small users among the developing nations. Whatever can be done in this direction probably would assist also in cutting costs for small-user terminals within the heavier-traffic areas. It is not sufficient, however, to consider cheaper earth stations alone, especially if the less efficient use of the satellite by such stations leads to much higher space-segment costs (see Appendix C) or to the use of excessive segments of the orbit. A better objective would be the reduction of the annual cost per circuit, between stations having reasonably large numbers of circuits (say 24 or more). It is this cost per circuit which determines the terrestrial break-even, some short distance relative to light routes or longer for heavier routes.

3.8.1 System Studies and Developments

Numerous system studies and related developments should be conducted, toward improving this form of satellite communication and making it more useful, especially to the developing nations. The most significant items are as follows:

1. Study of the probable change in the space-segment rate, S, ($ per unit of utilization by standard stations) as the satellite power is increased. This should assume FDM-FM, with the deviation ratio being reduced (a) to unity, (b) to not less than D = 3, or other compromise value. Note that earth coverage should be maintained. If the satellite EIRP were increased by narrowing the earthward beam, this would correspondingly reduce earth-coverage and hence limit the usefulness of the utilization unit.

2. For a small (30-ft, 200°K) station, determine how the penalty factor, relative to the standard station, would change under the above conditions of increasing the satellite power, especially after the standard station reaches D = 3.

3. Make overall system optimization studies, directed broadly toward lowering the cost of satellite circuits and thus improving their break-even. This should account for heavier traffic over shorter routes, increased numbers of stations closer together, optimum balance between satellite costs and total earth station costs, etc.

4. Conduct demonstrations and initiate service trials of demand-assigned multiple access; the form of service which permits a station to obtain use of a direct circuit to any other station when needed, call-by-call rather than by the year. Demand assignment also improves circuit utilization efficiency by pooling many more circuits, from which any idle circuit may be temporarily assigned. A remaining uncertain factor is the determination of the best of many possible methods, determination of its equipment costs and, hence, determination of the minimum number of circuits per route for which preassigned circuits would break even. See Appendix B on Multiple Access.

5. Investigation of the best methods of using a single earth-station antenna with multiple beams allowing access to a second satellite, which may be a useful economy. The second satellite might be required relatively early in some situations--for example, where a decision has been made to use a large amount of capacity for TV distribution.

6. It would be worth investigating the desirability and possible difficulties of utilizing more than three satellites for the global service. On one hand, providing additional satellites would increase the overlap areas in which stations would have direct access to more of the earth by being able to use eastward and westward satellites. At present, none of South America and not even Mexico can see a westward satellite. On the other hand, proposed uses of a second Atlantic satellite would tend to divide the Atlantic Basin into two smaller regional systems and thus prevent direct communication between many of its stations.

7. Studies of the possibilities of lower-cost earth terminals, retaining the use of high-discrimination antennas. Several possibilities seem to offer some promise. One would be the use of fixed ("hole in the ground") spherical reflectors, with movable feeds for beam-steering. This approach is also a possibility for multiple beams. See Appendix E on Point-to-Point Communication Antennas.

8. Improved understanding of frequency-sharing, with more emphasis on techniques for avoiding interference with terrestrial microwave relay systems even when earth stations are to be located close to metropolitan areas. This interference coordination also would seem easier if more of the transmission burden were shifted to the satellite, so that earth stations would be less powerful and less sensitive, while keeping their antenna beamwidths narrow.

3.8.2 Special Requirements for a North American Subsystem

The requirements for a North American subsystem appear more difficult, especially in its heavy-traffic aspects, and if it is forced into a youthful marriage with TV program distribution. The problems of such a system also would depend upon whether it would need to combine light-traffic coverage of remote areas with the (eventually) very heavy traffic of the continental United States and southern Canada. In the latter case, the use of broader bands at frequencies above 11 GHz should be thoroughly considered. Thus, further investigation in the following areas seems needed:

1. Any extensive and long-lasting use of the 4-GHz and 6-GHz bands for the heavy domestic traffic would seem to require a more constructive approach to the problems of frequency-sharing (as discussed in item 8 of Section 3.8.1) plus careful consideration of orbit utilization. See Appendix D.

2. If, however, frequencies above 11 GHz are to be used it should be decided quickly whether such new bands are also to be shared or not. Sharing problems would be somewhat different and possibly more difficult, for example, if earth-station pairs are located at heavy-traffic nodes.

3. Improved knowledge of propagation, scattering, and absorption phenomena seems needed, for use of frequencies above 11 GHz. See Appendix G.

4. Spectrum reutilization, via multiple earthward beams, adequately separated, seems most feasible at frequencies above 11 GHz, partly because of spacecraft antenna problems at lower frequencies. The antenna technology for the formation, placement, control, and utilization of multiple beams seems inadequate and in need of prompt and strong effort.

5. The use of intersatellite relaying between the satellites of a heavy-traffic cluster should be investigated, both technically and from an economic aspect. The apparent alternative would be larger numbers of multibeam earth stations.

A third class of subsystems also should be considered more thoroughly, regional or national systems for less developed areas. A main concern with such system proposals should be with their confinement of coverage area and consequent curtailment of the distance-leverage. A related matter is that of retaining accessibility to intercontinental satellite systems and to the stations of other domestic systems, without multihop constraints.

4.0 POINT-TO-POINT ASPECTS OF OTHER SPACE PROGRAMS

4.1 Introduction

The main emphasis of this study is upon the more classical problems of communication between two or more earth terminals for voice, data, and television needs. This section briefly discusses some other types of point-to-point links and missions in support of development for point-to-point needs that do not fit the pattern of the more classical traffic. In particular, point-to-point in space (space-to-space links), passive reflector techniques, and the possibilities connected with manned orbital programs are the subjects of this section.

In general, the panel considered that NASA has a primary interest and a unique and well-demonstrated competence in providing the communication to and from its spacecraft and that it has a motivating interest in developing communication between spacecraft. Consequently, the topics in this section received less study by the panel and they appear here mainly for reference and for completeness. Nevertheless, some elements of these topics demand further study and coordination with other efforts. Recommendations concerning them should be considered in this light.

4.2 Space-to-Space Links

4.2.1 Low Earth-Orbiting Satellites

Every space vehicle depends upon a communication link to return data to the earth and to receive commands from earth. To date, this link has been established directly between the spacecraft and some appropriate earth terminal, and the distribution of signals to and from that earth terminal has been by various terrestrial means, with few exceptions. NASA has leased circuits from COMSAT to relay Apollo communications from s and shore-based terminals back to Houston. However, these circuits are alternates to HF radio or cable and in no way replace a space-to-space link from an orbiting Apollo capsule direct to a COMSAT satellite. The support given to the Apollo capsule comes from the links provided by NASA between the capsule and three ships or, alternatively, stations on Ascension Island, Canary Island, and Australia. Thus the actual contact with the astronauts depends on special tracking and communications sites maintained around the world by NASA. The same is true of other earth-orbiting satellites such as the TIROS or ESSA weather satellites and other experimental satellites. The number of stations is kept to a minimum in the latter case by storing information in these satellites and transmitting only when in view of an earth terminal.

The need for continuous communications with manned orbital operations is not currently satisfied over some areas of the earth, especially the ocean areas, and the provision of enough tracking ships to do so would represent a sizable investment. The future advent of high-resolution sensors for earth-resources-satellite applications may dictate the need for continuous read-out transmission in order to keep pace with the large amounts of data generated. NASA has begun the study of providing continuous contact with spacecraft in low earth orbit by using a synchronous satellite as a relay. The expected benefits will be the cost savings in the operation of sites around the world and the achievements of full-time coverage.

Results of work to date indicate the technical feasibility of establishing a satellite relay system using three satellites in geostationary orbit to provide continuous coverage for low-altitude earth-orbiting target satellites. So far, analyses have been confined to a specific set of requirement parameters; further study of probable system requirements is necessary before defining an actual system.

A highly desirable emerging technology is that of the phased-array antenna. Such an antenna consists of several hundred small transponders, each connected directly to its own antenna element. The phase of each transponder is controlled in such a manner that all signals add in an interference pattern to produce a beam in the desired direction. This has the advantage that several concentrated beams can be formed simultaneously by the geostationary relay satellite, each beam directed toward a specific low-altitude satellite. If a particular technique of transponder phasing, known as the retrodirective principle, is used, these beams will automatically follow the individual satellites. Changes in the attitude of the geostationary satellite are likewise automatically corrected in this approach.

The phased array has certain desirable features of redundancy and reliability. Since there are several hundred transponders, the failure of a few does not impair the overall operation significantly.

Appendix I contains some of the considerations that size the synchronous relay and determine the number of relays required. An early system using present component technology could be deployed, using launch vehicles based on an Atlas-Centaur for a minimum capability or the Titan-III-C series for greater capability. The transmissions assumed would provide a television (real-time) capability from a manned vehicle or a voice channel in an emergency mode if the manned craft should lose its attitude control for any reason. Other satellite needs for data transfer were not studied, and further study of system requirements is still required.

The frequency band preferred for this application (see Appendix I) was the S-Band region presently being used for satellite-data links. Recommendations dealing with further development efforts are included in Section 4.5.

4.2.2 Synchronous-to-Synchronous Relay

Two distinct applications are visua[illegible] or which a synchronous-to-synchronous relay in space might be des[illegible]ble. They differ primarily in the distance likely to be chosen between the satellites and the type of traffic.

The first application is the ultimate commercial use of such a link simply to provide connections among the various users of two separate satellites. Because of the time-delay problem inherent in the use of geostationary satellites for commercial telephony, the additional delay between two satellites on a space-to-space link should be kept to a minimum. Hence the satellite spacing is kept to a minimum.

In the second application, other types of data including control signals for satellites in a system would be transferred and the distances could become quite large. For instance, in the system discussed above in Section 4. 2. 1, the three geostationary satellites must be controlled and their data brought back to a control point in the United States. Two of these satellites could be visible from a single site in this country; the third would require an overseas site. A space-to-space link to this third satellite would save the cost of installing, operating, and maintaining such a site. The cost trade-off in the commercial application would involve quite different considerations than those relating to one single site, such as achieving the interconnections by terrestrial means. Further study of the merits of such space-to-space relays is required.

There are, however, certain common features in the two applications. As shown in Appendix I, there is a need for tracking antennas on either end of the synchronous-to-synchronous link. Generally speaking, with a tracking antenna at either end, the system will optimize at a higher antenna gain, which implies higher frequency. Propagation limitations are removed since these links do not intersect the atmosphere. Therefore, the use of millimeter waves is indicated. While frequencies near 60 GHz have the advantage that the atmosphere is relatively opaque and interference from earth is minimal, their use as discussed in Appendix I is illustrative and further study is recommended to arrive at a final choice.

Economic benefits are probably substantial savings in the cost of alternative earth-terminal sites for terrestrial distribution. Therefore further detailed study is recommended. Feasibility of achieving such links is based on the projected use of precision antenna mounts in space such as the LEM (lunar excursion module) rendezvous radar for Apollo, and the general status of component development in the millimeter-wave portion of the spectrum.

4. 2. 3 Lunar Communications

A considerable history exists on actual communications with various lunar mission spacecraft related to the Ranger, Surveyor, and Orbiter programs. Furthermore, an exhaustive study has been made of all phases of the Apollo program communications needs in the lunar environment as a part of the Apollo study.

With this background of history of experience and committed plans, one can quickly isolate what seems to be the sole remaining area for new development, communication with operations behind the moon. The urgency of any such development should be directly related to plans, if any, for operations behind the moon.

In Appendix I, the question of providing a communications link to the back of the moon is considered and two general approaches are suggested. One consists of a relay satellite in a quasi-stable orbit around the libration point behind the moon. The second system concept is based on three equally spaced relay satellites in lunar orbit at such an altitude that one is always visible at the lunar surface points of interest. Intersatellite space-to-space links provide connections to earth terminals at all times.

The first system requires long-term propulsion for orbit maintenance. High specific-impulse electrical propulsion systems appear useful for this purpose. Thus this application should be included in planning the development of such propulsion systems.

Similarly, the second system features space-to-space links, and that application or requirement should be included in the general rationale for developing such relay links.

A study to compare the relative merits of these two relay systems would be worthwhile, and no specific development other than such a study is recommended at this time. Should behind-the-moon missions be undertaken, the specifics of the communications-relay system should be immediately included as a part of such mission planning. Meanwhile, lunar communications, to the limited extent considered, merely support the general rationale for certain technique developments.

4.2.4 Deep-Space Communications

Communication with deep space probes such as the Mariners or Pioneers has developed historically along certain lines using microwave techniques for the most part. There seems little reason to believe that these will not satisfy future requirements. The three sites of the deep-space net on the earth seem to be the best means of maintaining links to such probes. While future requirements for wider bandwidths of data over longer distances will press developments severely--especially the equipment on the probes--there seems to be no a priori reason to separate such development from the general context of the using programs.

The question of using lasers for such links is often debated, but Appendix I concludes that there is no obvious merit to laser developments for this specific purpose.

Alternatively, it appears that the incorporation of deep-space links as a part of an earth-orbiting relay system may find some merit. Thus, such links do provide a collateral support for the rationale of recommending further study of earth-orbiting relay systems and development of space-to-space relay links at millimeter wavelength. Further effort in these areas should address the requirements of such deep-space links among all the other requirements included from other applications.

4.2.5 Relation to Data Collection and Air Traffic Control

The earth-orbiting data relay satellite system as visualized would maintain link connections between a site in the continental United States and most of the earth's surface. The satellites would be designed to work simultaneously with several different data sources. The retrodirective phased-array techniques previously described provide the full receiving capability of the relay satellite to a given data source independently of its concurrent preoccupation with other sources and links. Such a system has a significant capability, therefore, of addressing the many data-sensing packages envisioned for certain applications in hydrology, meteorology, and oceanography. A cursory examination of the hydrology section of this study (Panel 3) indicates that the total data-collection needs for hydrology application could be included within the scope of the system considered for satellite-to-satellite earth-orbiting relay systems.

An air traffic control system requires extension of communication links to aircraft in flight over ocean areas by use of geostationary satellites. Further consideration of integrating this requirement into the earth-orbiting data relay system is advisable, at least apparently. This becomes especially true for the time periods when, if at all, aircraft will move to frequencies near 1.5 GHz for such communications. The benefits of such integration of the total system requirements alone command further analysis.

Even if such requirements fail to coalesce in a final system, there is strong basis for suspecting that the development of retrodirective array antennas for geostationary satellites at appropriate frequencies will satisfy a broad range of requirements. Thus, basic development of principles and components may be of ultimate interest for many uses. The need to make an early determination of the usefulness of such developments leads to the recommendation that such broad requirements be included in a study of total earth-orbiting relay-system requirements at an early date.

4.3 Consideration of Manned Space Platforms

Because of the possibility of putting manned, resupplied space platforms into both medium-altitude and geostationary orbits, serious consideration was given to possible uses of such a platform for point-to-point communications.

However, there do not appear to be any attractive applications of such a facility to operational communications systems. It is unlikely that a platform placed so as to be useful for a multiplicity of purposes would be in the correct, limited position needed for commercial operational systems. The only useful function that man could perform in such systems would be for adjustment and maintenance. The cost of sending men up for that purpose is likely to be greater than the cost of replacing the satellite, however.

For collection of data and carrying out trials and experiments, the presence of men on the space platform could be very helpful. One specific example is collection of data on the interference from terrestrial microwave transmitters to satellite receivers. While this work could be done with or without men, it might be facilitated and expedited by men on the scene.

Such a manned capability might also be helpful in collecting data on the utilization of each portion of the frequency spectrum in various places on earth. Both the FCC and the Director of Telecommunications Management have a need for such data in connection with their problems of administering the spectrum. However, the needed data are rather fine-grained and possibly cannot be gathered from any satellite orbit. A relatively inexpensive study of the possibilities of this application would be desirable.

One observation pertaining to classical point-to-point communications and relative to manned operations is of interest. The Communications Satellite Act of 1962 specifies that the United States government will supply launch services, when requested, on a reimbursible basis. As manned flights to geostationary orbit become operational, they may provide an effective means of providing such launch services.

To the extent that large passive reflectors have an operational communications value, they may also be deployed by manned flight operations. Manned flights may also be an effective means of deploying certain experimental communications satellites or subsystems whenever the complication of such devices merits the attention of a man and success in a single mission is economically dictated. Conversely, the deployment of an earth-orbiting data-relay satellite system may provide continuous communications support for manned operations. Further study is required as the basis of evaluation of any of these possibilities.

4.4 Passive Communication Satellites

Early in the development of satellite communication there was considerable interest in passive satellites, such as the Echo spherical reflectors. The advantages often claimed for these passive satellites include: long life, lack of frequency dependence, response linearity, simple multiple access, etc. However, in drawing comparisons with active satellites, ones employing amplifying transponders, the disadvantages overwhelmingly outweigh the advantages. In essence, the active satellites provide quite large electronic amplification, in addition to the considerable gain attainable from both receiving and transmitting antennas, whereas the passive satellite provides only its reflection gain. Consequently, the passive satellite's lower gain must be offset by more powerful earth transmitters, use of fewer voice channels (typically one), and by the use of lower orbits.

Larger and more effective reflectors have been proposed and, in principle, it would be possible to achieve quite high reflection gains, to some relatively small area of the earth, for example, by using an accurately oriented reflecting plane. Nonetheless, the active amplification would be lacking.

4.5 Conclusions and Recommendations

With the disclaimer that, because of the limitations of time and the priority of other more central topics, the topics of this section have received inadequate consideration by the Panel, the following recommendations are offered:

A detailed study of the total requirements of earth-orbiting satellite relay systems should be undertaken as soon as possible. The earliest requirement, and therefore the pacing one, appears to be the low-altitude satellite to geostationary satellite-to-earth relay for data collected by such satellites and for command, control, and orbit determination of such satellites. This application appears essential to large-scale surveying of earth resources from satellites in near-earth orbits and clearly desirable for better communications support of manned missions in such orbits. The techniques for such applications should be the subject of an experiment in the ATS-F and G program.

Insofar as point-to-point communications is concerned, a quite different application of intersatellite relaying is foreseeable; that is, its use between the satellites of a domestic or regional cluster. Such relay links would generally be shorter and more stable, but their use could become complex by virtue of their numbers. The alternative to this application would be to require that each station receive channels from all satellites of its cluster, so the choice would appear to depend on the numbers of earth stations and satellites and on the results of extensive tradeoff studies.

Many additional applications are foreseeable in connection with future space-research programs. For example, a geostationary satellite as a terminal in space would permit communication with deep-space or other missions, at frequencies that might be absorbed by the atmosphere. Similarly, relaying may be needed for missions to the far side of the moon.

In connection with the obvious antenna-tracking problems in such relay applications, the applicability of retrodirective phased array antennas merits serious investigation and tests.

APPENDIX A

COMPARATIVE COSTS OF SATELLITE AND TERRESTRIAL COMMUNICATIONS

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A. 1 Economic Benefits

It would be extremely difficult, and of questionable significance, to attempt to calculate the economic benefits which the world can derive from point-to-point applications of satellite communication. On the other hand, it probably is simpler to understand how to achieve and measure such benefits in specific cases than for other applications of space technology, as will be seen. Specifically, it will be shown in this appendix that there are relatively simple relations which determine when satellite or terrestrial communications should be less costly between any two points and when these costs should break even. For the next few years at least, it appears that heavy routes (100 or more circuits) will break even at a few thousand miles whereas this may occur at only a few hundred miles for routes which need 12 or fewer circuits. The economic benefits will depend on the extent to which satellite communication is used in excess of its break-even relations and on the extent to which this economic advantage stimulates additional traffic. It seems of greater importance to observe that the improvement of point-to-point satellite communication systems can be measured by the improvement of these break-even relations. Thus a better satellite system or better use of a given system should break even at shorter distances, for a given number of circuits per route, or should break even for heavier routes at a given distance.

This appendix is intended to support, explain, and expand upon the General System Principles of Section 3. 4. As was explained in that section, the analysis can be applied to a domestic, regional, or global system. The assumption of an INTELSAT-type system means only that the earth stations obtain (and pay for) their satellite service from some satellite operating agency; perhaps a national or regional equivalent of INTELSAT. One recognizes that a national postal telephone telegraph (P. T. T.) administration or operating company may own and operate the satellite(s) and all earth stations, and that its routing decisions may be influenced by its existing terrestrial network and traffic patterns (as treated in Appendix H) but it could allocate its satellite and other space segment costs among its earth stations according to units of utilization, a la INTELSAT.

The following analysis will be in terms of annual costs for new or additional facilities; not in terms of marginal costs. Thus, the terrestrial system costs will be taken as explained in Section 3. 4, without considering the possible availability of idle or extra circuits between the points in question. Similarly, we neglect the possibility of the earth terminals being equipped for more circuits than they are using and we assume instead that each carries its share of the costs.

The numerical values of the cost factors to be introduced are uncertain, time-varying and often controversial but the meaning of the various factors seems most important and clear. Numbers will be assigned to these factors only for illustrative purposes and readers are invited to change these to whatever numbers they prefer. The method is more important than the numbers!

A. 2 Satellite Circuit Annual Costs

We will assume that earth terminals (or their operating agencies) are charged for satellite use in terms of units of utilization of the space segment, S, and a multiplying penalty factor, P, the latter being unity for standard terminals as defined by INTELSAT. This penalty rationale is that a substandard station will use a fraction of the satellite's capability per channel that could have provided P channels for a standard station.

Note carefully that S is a rate set by the satellite operator and becomes a cost to the users—the earth terminal operators. For simplicity, we assume that there are no compensatory assessments or dividends to the earth station operators who participate in owning and operating the satellite (i. e., nations that are members of INTELSAT). The important simplification thus introduced is that all economics (and mistakes!) that are made relative to the satellites and their operation appear only in the changing values assigned to S. If a bigger and better satellite is placed in orbit, and when its greater channel capacity is used adequately, its per unit cost to its operator may be greatly reduced, thus justifying some (generally lesser) reduction in his rate, S. For example, the space segment rate that was first established for Early Bird was $32, 000 per unit of utilization. This soon was reduced to the present (INTELSAT-II) rate of $20, 000 and there are prospects of a substantial further reduction, perhaps with INTELSAT-III.

It is clear that high-capacity earth stations will cost more than those equipped for few channels and that, consequently, there will be a functional relation between a station's annual cost, C, and the number of circuits, N, for which it is equipped. This relation can be approximated by the first two terms of a power series:

$$T_o + T_1 N + \ldots$$

Here, T_o is the no-circuit station cost coefficient and depends on the antenna, buildings, cryogenics, etc. T_1 is the per-circuit station cost coefficient and depends on the modems, etc. Thus, these two terms should be sufficient.

Additionally, if this station uses N satellite circuits with a penalty factor, P, this brings its cost per circuit year to

$$\frac{T_o}{N} + T_1 + PS$$

For N circuits between two identical stations, Fig. 9. A. 1, each has the above share and the total cost per circuit year to twice the above amount.

Introducing multiple access, we consider a route of N_{AB} circuits between stations A and B which have equal penalty factors and have N_A and N_B circuits respectively. Adding this route may entail additional equipment at each station, such as that needed to separate and demodulate this station's carrier. To allow for this we introduce an annual route cost coefficient, T_r, which each station distributes over the routes N_{AB} circuits and which thus results in the cost per circuit year becoming

$$C_y = \underbrace{\frac{T_o}{N_A} + \frac{T_r}{N_{AB}} + T_1 + PS}_{\text{(Station A)}} + \underbrace{\frac{T_o}{N_B} + \frac{T_r}{N_{AB}} + T_1 + PS}_{\text{(Station B)}}$$

$$= \frac{T_o}{N_A} + \frac{T_o}{N_B} + 2\left[\frac{T_r}{N_{AB}} + T_1 + PS\right]$$

A. 3 Illustrative Parameter Values

It was agreed by the Panel members and economic consultants that a typical standard (85-ft, 50°K) earth station, equipped for about 100 circuits, represents an investment of about \$5, 000, 000. Assuming a 10-year life and an 8 percent return after taxes, the level annual cost was taken as \$1, 000, 000. In addition, operating and maintenance costs were assumed to raise this to a total of \$1, 800, 000 per year. One recognizes, however, that this annual cost cannot be entirely independent of the number of circuits for which the station is equipped. Thus, the above annual cost contains T_o plus some typical $N T_1$. The value T_1 = \$3, 000 per year has been chosen for illustrative purposes, with recognition of its uncertainty and its probable dependence on the modulation and multiplexing method and whether preassigned or demand-assigned circuits are considered. Assuming 100 circuits leads to T_o = \$1, 800, 000 - 100 x \$3, 000 = \$1, 500, 000 per year for present standard stations.

The value T_r = \$10, 000 per year has been used as the route cost coefficient, recognizing that this value is very uncertain and probably high. For a lower value, however, the effect would be less evident and often negligible, as will be seen.

Additionally, it has been assumed that S and the T_o (for standard stations) will decrease with time, as follows:

	T_o (\$ x 10^3)	S (\$ x 10^3)
today	1500	20
"soon"	500	5
"sometime"	150	0

The values of T_1 and T_r have been assumed constant with time, and P remains unity because only standard stations are being considered, thus far. The "soon" value of T_o represents the result of expected economies from the use of slightly steerable antennas, uncooled (or Peltier cooled) preamplifiers, other similar improvements, plus "learning," longer amortization, etc. The "sometime" value represents a tenfold reduction, which is as much as now seems hopeful for a large-antenna station, even if unattended and using an earth-supported reflector, etc. The "sometime" $S = 0$ would be an unrealistic lower limit, except that we still have $T_1 + S = \$3,000$/year, and this can be split to one's preference.

The corresponding parameters for small stations, ones with smaller antenna apertures and higher noise figures, will be treated in Appendix C. In respect to such stations, it should be recognized that this time-decrease in S may be accompanied by system changes and new penalty factors that may not be so devastatingly high.

Figure 9. A. 1 provides a graphic interpretation of the cost per circuit year when two stations serve a single route of N circuits, using present parameter values. Thus, for 60 circuits between stations of this capacity, each circuit would cost \$96, 000 per year.

If multiple access is considered and one assumes that these two stations have other routes, to which they add this route of N_{AB} circuits, we use the "per route" curve, for which N_{AB} is the independent variable, while N remains constant: $N = 60$ in this illustration. Thus, for $N_{AB} = 1$, this single circuit would need to carry both stations' additional cost for this additional route, $2T_r = \$20,000$, and the above \$96, 000 circuit cost would increase to \$116, 000 as shown in Figure 9. A. 2. If this were a 5-circuit route, however, each circuit's share would be $2/5 \times \$10,000 = \$4,000$, thus bringing the annual circuit cost to \$100, 000, as shown. For heavier routes the effect of T_r becomes negligible. *

The extension to routes between stations of unequal size follows from noting that

$$\frac{T_o}{N_A} + \frac{T_o}{N_B} = \frac{2\,T_o}{N}$$

where

$$N = \frac{2N_A\,N_B}{N_A + N_B}$$

---

* One may note that this has been an approximate method for dealing with the cost of an additional route, in that it introduces an apparent discrepancy at $N = N_{AB}$, amounting to $2T_r/N$ at the point where the two curves intersect. However, when $N_{AB} = N = 60$, this would be the only route and not an added route. Additionally, no consideration has been given to whether the two stations have many light routes or only one additional heavy route. The introduction of a more refined treatment may well be deferred until values of T_r are better known.

Thus, if A has 20 circuits and B has 200, we calculate $2T_o/N$ for determining the intersection with the per-route curve as if both stations had 36.4 stations, but remembering not to use this per-route curve beyond $N_{AB} = N_A = 20$ circuits.

A. 3. 1 Terrestrial Circuit Costs

Figure 9. 3. 2 showed families of comparative annual circuit cost curves for 18 U. S. types of terrestrial facilities, carrying from 10 to 100,000 circuits, and having a straight trend-line, to which all the curves cling within about ±50 percent. A careful examination will show that the "circuit's" ordinate is not truly logarithmic, being compressed at its upper end, presumably to straighten the trend line over this four-decade range. This scale-distortion is relatively slight so that for N = 5000 circuits or less, its slope is in close agreement with that of $N^{0.7}$. Considering that the abscissa is converted to dollars if its comparative costs are divided by five, one obtains a cost trend expression,

$380N^{-0.7}$ \$ per circuit mile year. *

Considering, next, that terrestrial routes are indirect, with an average length about 1.3 times the airline distance between their ends, we arrive at a trend cost for U. S. surface circuits of

$$500\ D/N_{AB}^{0.7} ,$$

D being the airline length in miles between points A and B.

One recognizes that this trend coefficient may be higher or lower in other countries, depending on the local labor and equipment costs, the terrain difficulty, etc. Also, whenever an actual terrestrial system of known costs is being considered, its costs surely should be used instead of the trend costs. With these reservations, this trend cost relation will be found useful in studying break-even distance trends and other comparisons with satellite circuit cost relations.

A. 4 Break-Even Relations, Graphical Solution

Equating the costs of terrestrial and satellite circuits on the above basis, one obtains:

$$\frac{500D}{N_{AB}^{0.7}} = \frac{T_o}{N_A} + \frac{T_o}{N_B} + 2\left[\frac{T_r}{N_{AB}} + T_1 + PS\right]$$

---

* A similar relation which has been used by the RAND Corp. and by COMSAT is $300N^{-2/3}$ \$ per circuit mile year.

This, of course, is easily solved for the break-even distance, D, corresponding to N_{AB} circuits, or for the number of circuits at some given distance. Nonetheless, a graphical solution can be more illuminating and instructive as readily seen.

Referring to Section 3. 4, Figure 9. 3. 3 showed the per station and per route curves of Figure 9. A. 2 used as an overlay to the family of terrestrial cost-trend curves, plotted from the above relation. That figure showed the break-even to be about 3500 miles (on this trend-line basis) for a single 60-circuit route, dropping to 1000 miles for a 10-circuit route and to about 250 miles for a single-circuit route.

Next, Figure 9. A. 3 shows a more complete story, for a 10 to 1000 range of circuits per station, and using the "soon" anticipated S = $5, 000/year space-segment rate. Looking first at the "circuits per station" curve, one sees that this lower space-segment rate would permit two 60-circuit stations to terminate a single '60-circuit) route that would break even with the trend cost of terrestrial systems of this capacity at about 2400 miles (as compared with 3500 miles when S = $20, 000/year, Figure 9. 3. 3. Equally important, or more so, the cost per circuit year would be reduced from $96, 000 to $66, 000. Following the "circuits per station" curves further for these two figures, one sees something that frequently is overlooked--a deterioration of the break-even relation for too-heavy single routes. At the present S = $20, 000, a single route between 200-circuit stations would break even at 5, 000 miles, as would such a route between 1000-circuit stations when S = $5, 000. In the latter case, however, the cost of only $19, 000 per circuit year would become interesting. For example, a 100-circuit route between such stations would break even at 1000 miles and, even with the heavy assumed value of T_r, 10-circuit routes could be as short as 200 miles, according to Figure 9. A. 3.

In subsequent figures, only the circuits per station curves will be shown, since these are worst-case curves, satellite communications being least competitive when used for single routes between station-pairs. The use of multiple access leads one to the left of these curves, to shorter break-even distances for lighter routes.

Next, Figure 9. A. 4 shows that the no-circuit coefficient, T_o has its most important effect when there are few circuits per station, as one would expect. Thus, with 4-circuit stations, the 10 to 1 reduction in T_o would result in more than an 8 to 1 reduction in the cost per circuit, whereas for 400-circuit stations the corresponding reduction would be only about 1. 4 to 1, or 29 percent. Moreover, 40-circuit stations at today's high T_o would have the same cost per circuit as would 4-circuit stations at the "sometime" value of T_o = $150, 000.

In Figure 9. A. 5, the no-circuit coefficient has been held constant at T_o = $500, 000, its assumed "soon" value, while the value of T_1 + PS is lowered in steps. Note that the highest value applies to a standard (P = 1) station at today's S = $20, 000, with the assumed T_1 = $3, 000. Of course, the same curve would apply with other assumptions, such as S = $5, 000, but P = 4 (a somewhat smaller antenna), so long as T_1 + PS and T_o remain unchanged. The straight line, $T_1 + PS = 0$, provides an absolute lower limit, requiring that the satellite service be free and the multiplexing and other T_1 costs be negligible. The obvious conclusion is that, for any given T_o, the reduction of $T_1 + PS$ will become increasingly important and beneficial as the station traffic capacity, N, is increased. As $N \longrightarrow \infty$, the cost per circuit year will approach $2(T_1 + PS)$. If, however, $T_1 + PS$ could be kept negligible, costs per circuit year could be made arbitrarily low, irrespective of T_o. With a higher T_o, one only would need correspondingly more circuits per station to achieve any given circuit cost.

Finally, Figure 9.A.6 shows the time-trend which may be anticipated, if $T_1 + PS$ and T_o are both lowered, as shown. For these values, there would be similar cost-reduction ratios, almost irrespective of station size, with a reduction in the single-route break-even minimum to less than 400 miles, a reduction ratio of nearly 10 to 1. In the latter case, this minimum is at about 20 circuits, though very broad. The corresponding cost, about \$25,000 per circuit year, might create demands for many more than 20 circuits per station!

A. 5 Traffic versus Circuit Length

Thus far, no adequate statistics have been found relating traffic volume to circuit length. It is common knowledge from personal use of the telephone that local calls are by far the most frequent. As a guess, there may be 100 local (10-mile) calls to each 100-mile (state) call, and 100 of these to each 1000-mile (national) call, with these outweighing 10,000-mile intercontinental calls by at least another 100 to 1. The determination of some more accurate distribution probably should be undertaken by the World Plan Committee of the I. T. U. The impact of this argument, however, is that:

1. Reduction of break-even distances will be accompanied by corresponding increases in numbers of earth stations; otherwise there would be too few stations that were not at much greater distances from a given station. A few more will be at lesser distances, as is true today in Western Europe, and they would not normally communicate with each other via satellite if terrestrial circuits were available.
2. These shorter routes will carry (or soon attract) heavier traffic. This, together with the increasing number of stations with which any one station will be able to communicate, will increase the average number of circuits per station, and greatly increase the circuits to be carried by the satellite(s).
3. With more circuits per station, means of reducing PS and T_1 will assume greater importance (see Figure 9.A.5), while reduction of T_o will become less important (see Figure 9.A.4).
4. With shorter routes attracting heavier traffic per route, there will be an opposing or balancing force toward increasing the break-even distance (see Figure 9.A.3), because of the downward cost trend of the heavier surface circuits. This relationship actually may be a favorable one for the

developing nations, as will be shown. Assume that a nation installs earth stations A and B at cities D miles apart, these cities not having previously been linked by terrestrial circuits (other than by HF radio—sometimes). We assume these to be multiple-access stations, each having many other routes, totalling many more circuits than N_{AB}. Based on prior lack of good reliable communication, the forecast or initial N_{AB} probably would be low, and D probably would be well beyond the break-even for this N_{AB}, N_A and N_B. Opening of this satellite circuit might be followed by a large and rapid increase in N_{AB}, to a value well in excess of the break-even traffic for this distance. Neglecting further reductions in the space-segment rate, etc., it would become advantageous to install a suitable terrestrial system between the two cities, based on the demonstrated assurance of adequate traffic. In this and other ways there should develop a healthy mixture of satellite and surface routes.

A. 6 Some Aspects of Domestic or Regional Systems

This appendix has ignored the specific characteristics of the satellite(s) and the geographic distribution of the users, etc., except as these influence the penalty and space-segment costs, PS, and as the maximum distance of interest may be constrained by the system boundary, be this determined by national boundaries or by the satellite's earthward beam.

Proposals for domestic systems usually are predicated upon narrowing the satellite's antenna beam (or beams) to cover only the desired earth-areas of the nation or region to be served by the system. For example, by narrowing the satellite's antenna beam from an earth-subtending 18 degrees to a Brazil-covering 5 degrees, its EIRP would be increased by 11 dB, for the same transmitter. A 1-degree beam would buy additional 14 dB with which to cover only 4 percent as large an area. To an extent (as treated in Appendix D), the modulation can be softened and the increased EIRP can increase the satellite's traffic capacity per earthward beam. In this way, and in others, the traffic capacity of the satellite can be increased and its cost per channel can be lowered. Calculations of satellite costs for such systems frequently predict segment rates (S) which are well below $1000 per unit year, even with adequate amortization of R&D, etc. Such rates also depend on "filling" the satellite adequately from the heavier traffic of the many shorter routes.

It frequently is proposed, also, that much of the EIRP-increase from these narrower earthward beams be used to "cheapen" the earth stations, via smaller antennas and less-sensitive receivers. Some of the problems or constraints associated with this will be discussed in Appendix C.

A. 7 Large Satellites and "Economy of Scale"

By now, the "economy of scale" aspects of earth station costs should be clear, that costs per circuit may be reduced toward some $2(T_1 + S)$ limit by letting the circuits per station, N, be large enough to use a standard (P=1;

station and to make T_0/N arbitrarily small. Additionally, the value of T_1 may depend upon the proportion of demand-assigned to preassigned multiple-access circuits. Heavy-traffic stations would use a larger proportion of the latter, and might thus reduce their T_1 coefficients somewhat. The remaining factor, S, depends heavily upon the satellites.

An obvious way to decrease the per circuit share of the satellite cost is to increase its number of circuits, assuming of course that they will be adequately used. Thus far, from Early Bird through INTELSAT-III, this has required little more than raising the satellite's antenna gain (while retaining earth-coverage) and using more of the available 500-MHz bandwidth, while keeping the FM modulation index relatively high. Thus far, this increase in channel capacity has been achieved without the increased cost of using the Atlas or other larger boosters, so this has provided an impressive example of economy of scale, as applied to the satellite. It is to be hoped that this will lead to a correspondingly impressive reduction in S, the space-segment rate, soon after INTELSAT-III enters service.

The extent to which satellites can achieve further economy of scale does not yet seem sufficiently clear. Many steps can be taken to achieve further increases of channel capacity but the cost-effectiveness of such "improvements," and their eventual orbit-use costs, seem in need of further study. For example, Appendix D, Section D. 3. 7, shows that a fourfold increase in channels could be achieved by decreasing the modulation index from D=7 to D=1, but this would require more than a hundredfold increase in the EIRP. If the satellite's antenna gain cannot be increased another 20 dB, because of the narrower beam no longer covering the user nations, one faces the expense of this large increase in "hot" power.

It would be less costly to increase the satellite channel capacity if the 500-MHz band could be broadened. This seems unlikely, except by opening additional broader bands at frequencies above 11 GHz and it may be somewhat more expensive to use these more difficult frequencies.

The use of multiple earthward beams, separated to reuse the same frequencies, holds promise of great increase in satellite channel capacities but, again, the magnitude of any economy of scale remains uncertain.

Altogether, the cost-effectiveness of the larger satellites of the future should present an important field of study. Today, all that seems certain about extending the economy of scale of satellites indefinitely is that this will become progressively more difficult to accomplish than to talk about.

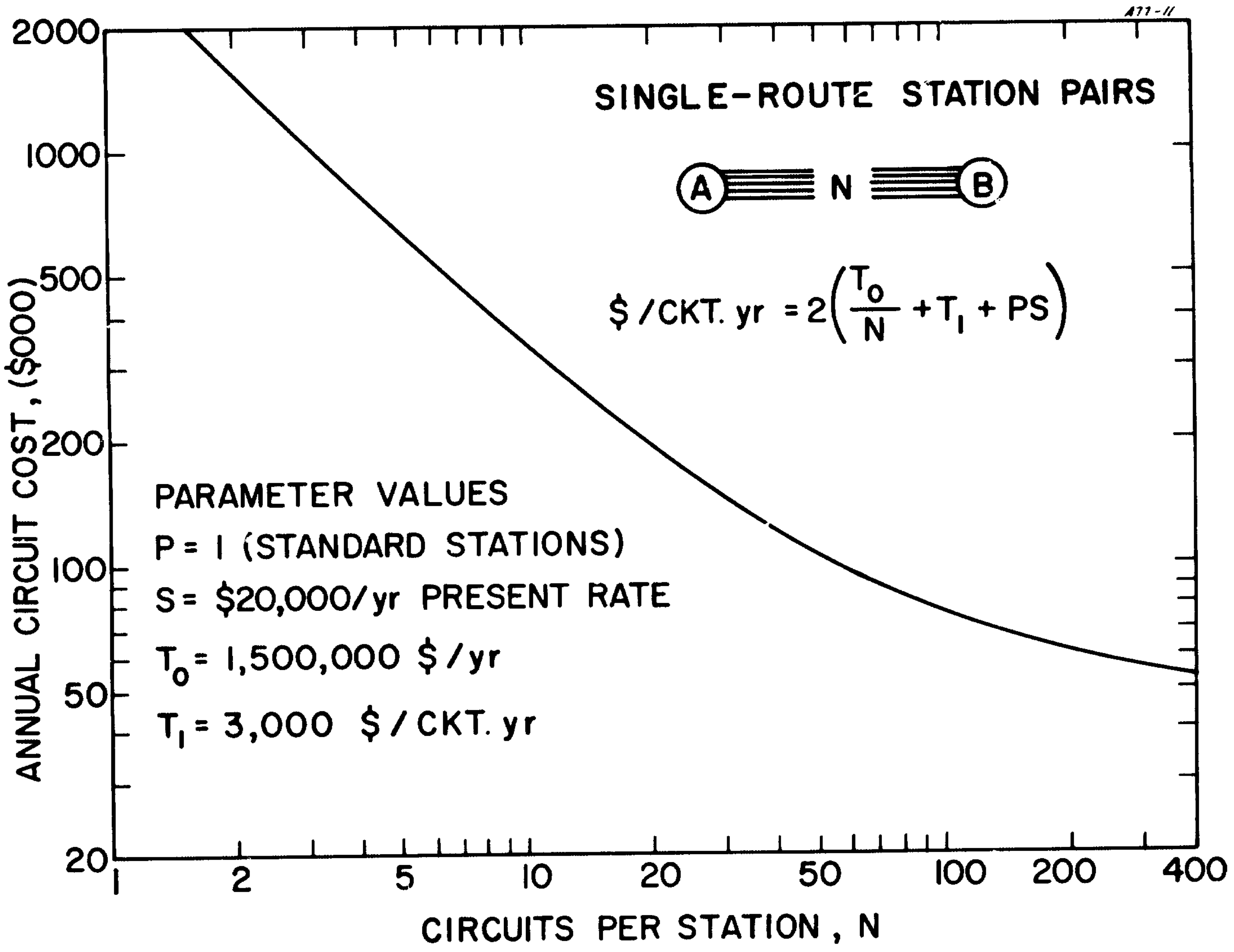

FIGURE 9. A. 1 Annual circuit costs for single-route station pairs.

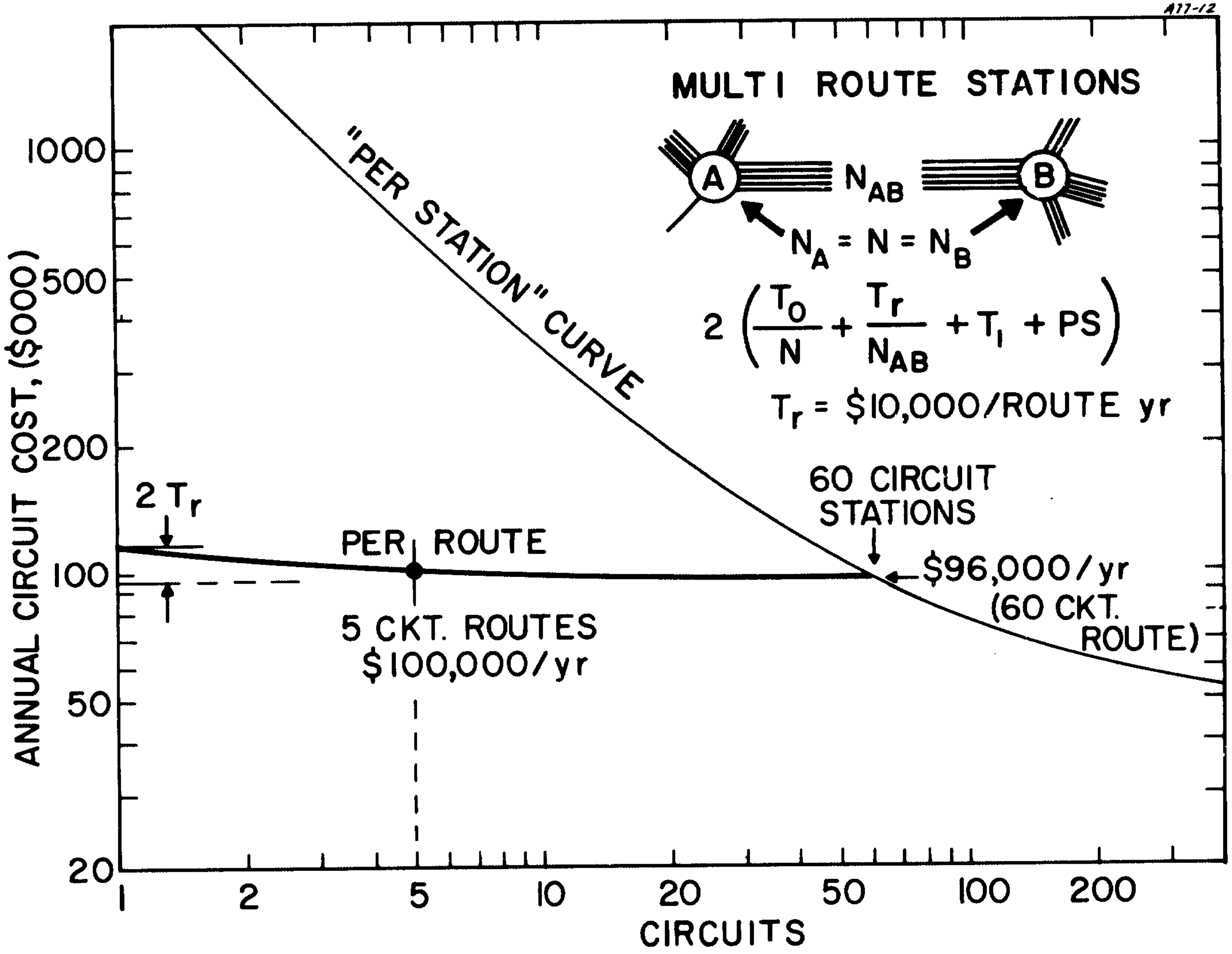

FIGURE 9.A.2. Annual circuit costs for routes between 60-circuit stations.

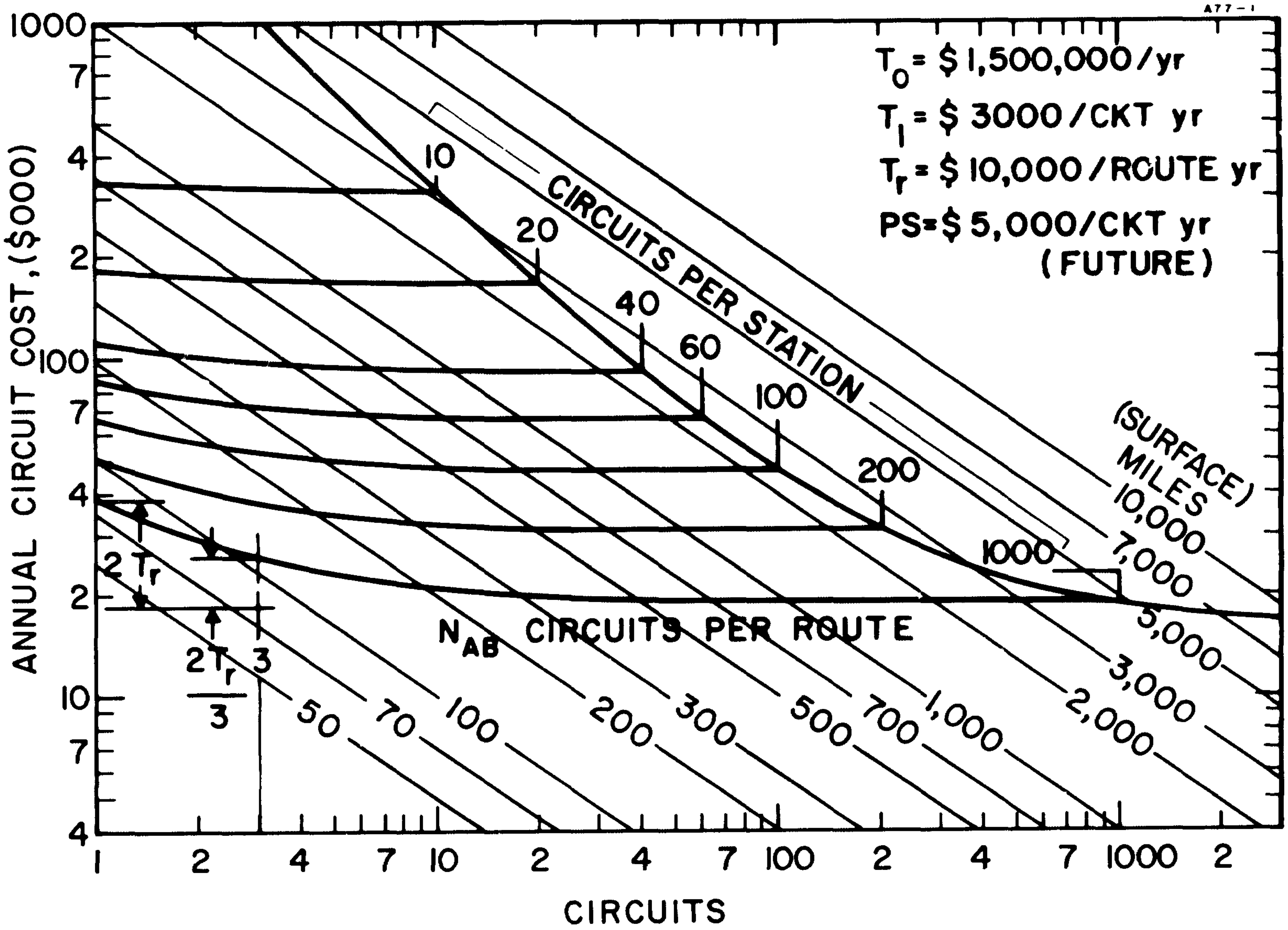

FIGURE 9.A.3 Break-even relations with multiple access, S = $5000.

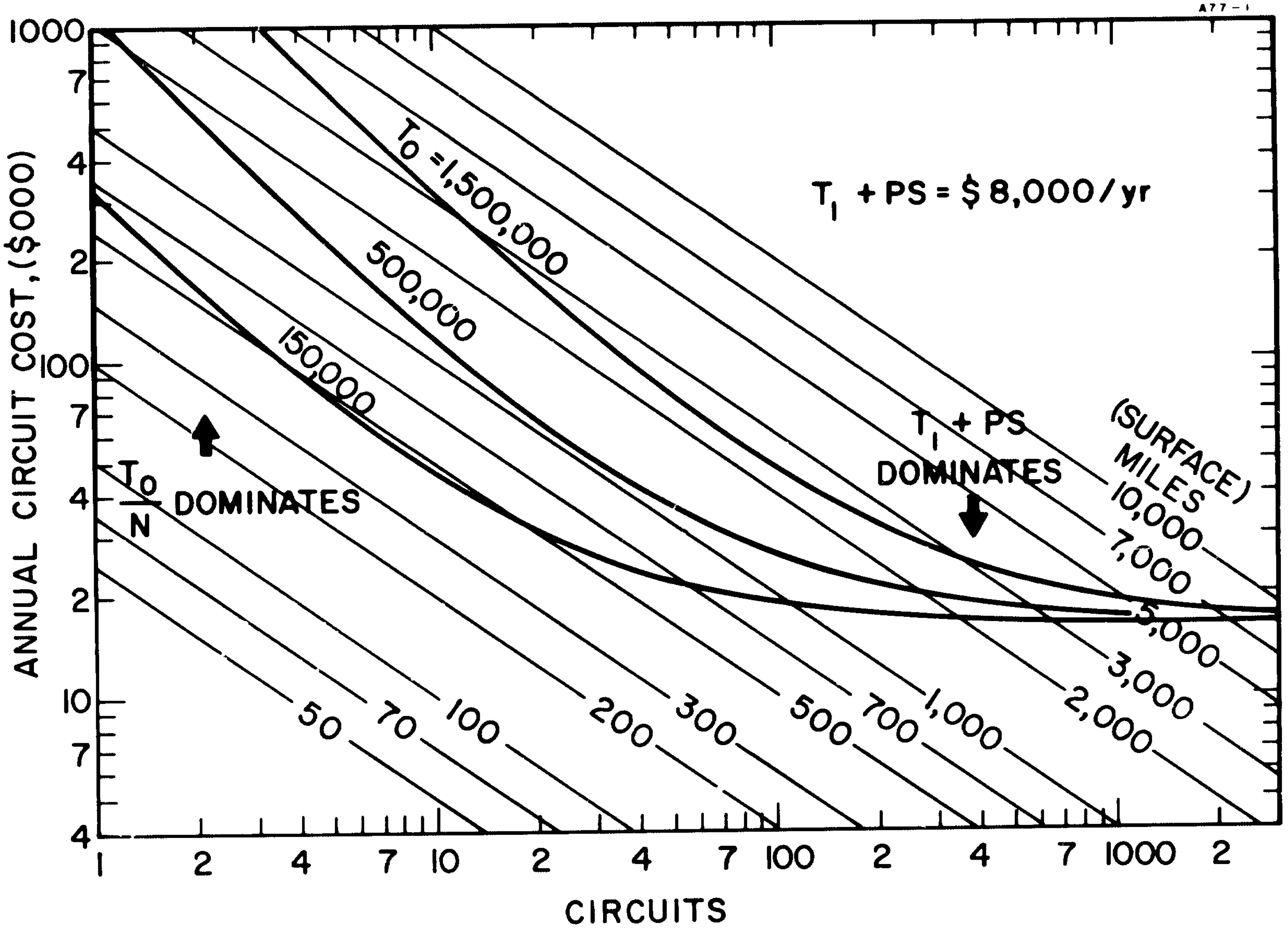

FIGURE 9.A.4 Effect of T_o (no-circuit cost).

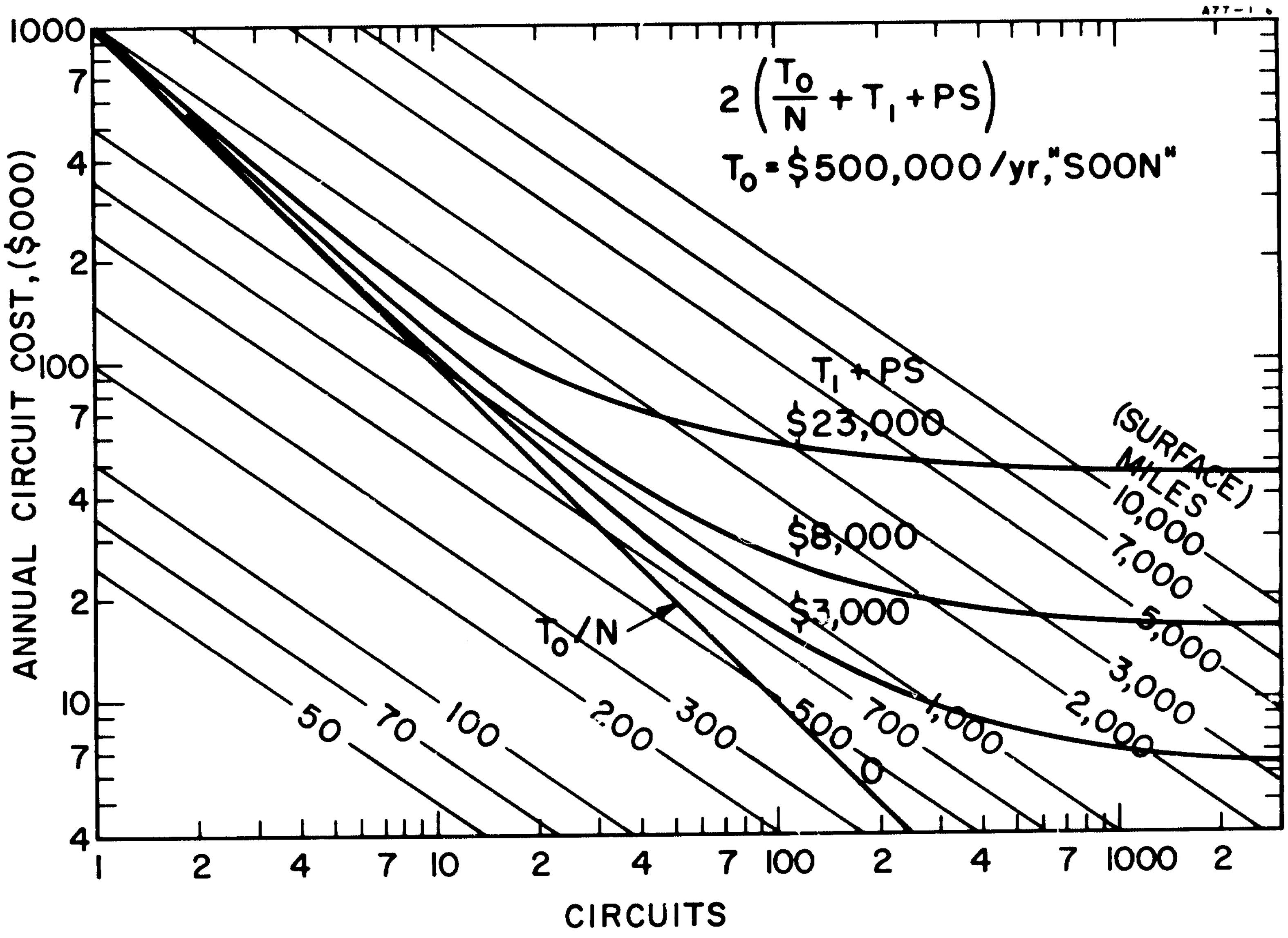

FIGURE 9. A. 5 Effect of increased number of circuits.

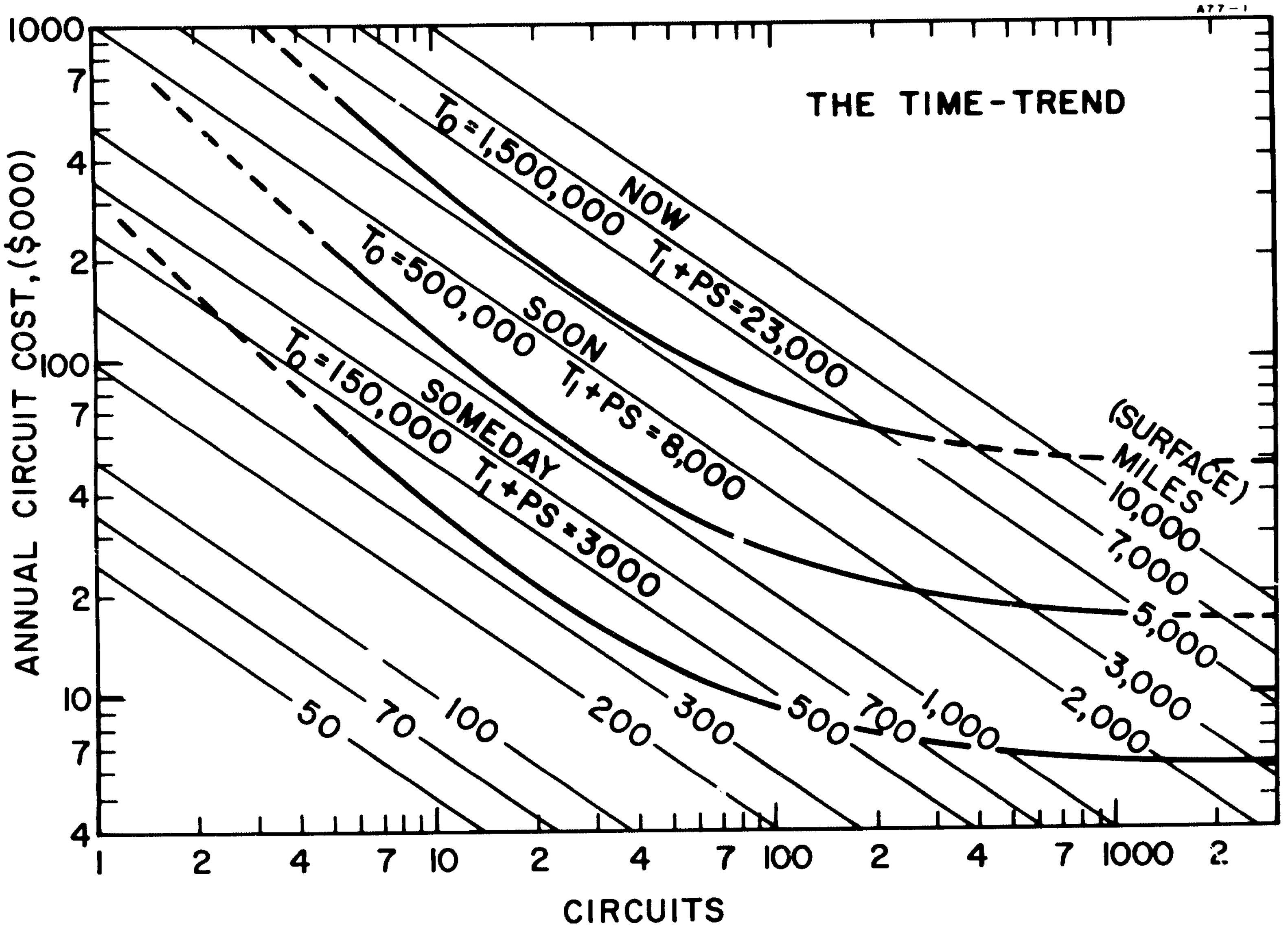

FIGURE 9. A. 6 Anticipated time-trend if T_1 + PS and T_o are both lowered.

APPENDIX B

MULTIPLE-ACCESS SATELLITE-COMMUNICATIONS PROGRAMS

Samuel G. Lutz

B. 1 Introduction

The communications section of NASA SP-142, *A Survey of Space Applications*, should be commended for having recognized and enunciated the desirability and possibility of large-scale, multiple-access communication between an ever-increasing number of relatively inexpensive earth stations, particularly those having the light and diffuse traffic patterns that may characterize stations in developing areas. This, of course, is in support of the policy enunciated by the late President Kennedy, and by the Communications Satellite Act of 1962, in "... providing services to economically less developed countries and areas as well as to those more highly developed.... "

B. 2 Forms of Multiple Access

Multiple access in point-to-point satellite communication refers to the ability of three or more stations (probably many more) to communicate with each other simultaneously, via the same satellite. If N such stations share the satellite, each has N-1 possible one-way direct routes to the other stations, giving the system a total of $(N-1)N/2$ possible two-way routes. for example, 25 stations would have 300 such routes. One recognizes that a terrestrial system would not use nearly this many direct routes between any 25 cities, but neither would such a system have a central node, such as the satellite offers to its earth stations.

Multiple-access satellite systems can provide circuits ("go" and "return" channel-pairs) of two kinds, either preassigned or demand-assigned. *Preassigned circuits* connect two particular stations, permanently or at prearranged hours. For such circuits, both channels are preassigned at both ends. *Demand-assigned circuits* are those that can be used between two stations upon demand, and for the duration of a call, after which the circuit may be assigned to some other route to satisfy another demand.

B. 2. 1 *Forms of Demand-Assigned Multiple-Access Systems*

Demand-assigned multiple-access systems are of two classes: *fully variable* if the channels can be assigned variably (to any station) at *both* ends, and *semivariable* if the channels are variably assignable at only one end and are preassigned at their other end. Thus, there are four possible forms of semivariable multiple access, corresponding to the four ways in which the go and return channels can be preassigned at one end. Of these, the variably received form* has its channels preassigned at their transmitting ends, thus making it compatible with INTELSAT's present "multidestination carrier" form of multiple access, as will be discussed later.

B. 2. 2 Traffic Efficiency Aspects and Example

First, consider that a single-circuit route will have more than 1 percent probability of being found busy (i. e., the CCITT 1 percent loss-probability would be exceeded) if it were in use more than 1 percent of the time during the busy hour (i. e., if offered more than 0. 01 erlang of traffic). A two-circuit route could be offered 15 times as much (0. 153 erlangs) traffic with this same 1 percent loss probability while with 12 circuits this rises to 5. 88 erlangs, or nearly 50 percent continuous use of each circuit while preserving a 1 percent probability that all these circuits will not be found busy.

With the demand-assigned (variable) forms of multiple access, circuits may be used by (or to) different earth terminals in succession. It will be seen that this leads to the pooling of circuits with respect to traffic capacity at a given loss probability.

As a specific example, it has been forecast that by 1975 South Africa will use one 35-circuit route (to the U. K.), in addition to 13 "thin" routes, 10 with single circuits and three with two circuits. The one heavy route could be offered 24. 64 erlangs, or 0. 704 erlang per circuit, at 1 percent loss probability. The light routes, however, could be offered only

$$\frac{10 \times 0.01 + 3 \times 0.153}{16} = \frac{0.559}{16} = 0.035 \text{ erlang per circuit.}$$

If South Africa were able to use demand-assigned circuits and if only this 0. 559 erlang of traffic could be anticipated, just four such circuits could be offered 0. 701 erlang, at 0. 5 percent loss probability. With the form of demand assignment being assumed, the 1 percent overall loss probability would be apportioned 0. 5 percent each to the two stations. It is possible that South Africa would want all 16 circuits, but with the ability to use them on a demand basis for temporary routes to these 13 stations and to others. Used this way at 0. 5 percent loss probability, these 16 circuits could be offered 8. 10 erlangs, or 0. 506 erlang per circuit.

Perhaps a more important consideration is that these 16 preassigned circuits were planned for routes to only 13 chosen stations, with no direct routes being provided to about 30 other stations. With demand-assigned multiple access, South Africa could obtain 16 direct circuits in any combination to any of these stations when needed. Such unprecedented capability for di-

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* This also has been termed the "variable destination" form, because of its possible use with "multidestination carriers." Unfortunately, "destination also has long been used as the "called" end of a circuit, the calling end being the "origin." Thus, "variable destination" also implies preassignment of the channel-pair to the calling station, with their destination ends being variably assignable to the receiver and transmitter of the called station. This line of reasoning shows that "multidestination carriers" could more logically have been called "multiply received carriers," but the former term has already achieved acceptance.

rect intercontinental communication surely would stimulate traffic growth far in excess of this present forecast.

B. 2. 3 Economic Aspects

Section 3 and the analysis in Appendix A showed that multiple access, even in its preassigned form, permits lowering the cost per circuit for any route, heavy or light, by letting the station achieve an economically large total number of circuits for many routes. Circuits are not always a good economic measure, however, except for leased circuits. Traffic is more closely related to revenue and it has been shown above that single-circuit routes do not bring a station enough traffic, unless users are kept waiting too often. The demand-assigned forms of multiple access permit stations to pool their traffic, even from their light and too-seldom used routes, rather than merely pooling circuits, thus achieving efficient circuit use.

The negative aspect, economically, is that demand-assignment will require some additional equipment, such as variable channel selectors, and this will tend to raise the T_1 component of station costs by some uncertain amount, relative to the T_1 for preassigned circuits. More design and operating experience will be needed to evaluate this. This ratio of T_1 costs may determine the minimum number of preassigned circuits per route, demand assignment being used for the lighter routes.

B. 2. 4 System Traffic Efficiency Estimates

A recent study* provided a comparison of the traffic efficiencies to be expected in an Atlantic system model with 25 earth stations (one per ITU zone) and a traffic matrix similar to an INTELSAT forecast for 1975. It was assumed that preassigned multiple access would be used for 60 "heavy" routes of 12 or more circuits and it was found that these would have an overall efficiency of 0.733 erlangs per circuit, at 1 percent loss probability. In comparison, the 12-circuit routes would have minimum efficiency, 0.485 erlangs per circuit. The remaining 80 routes, with 1 to 11 preassigned circuits, would be carrying only 0.326 erlangs per circuit, overall. In addition, there would be an additional 129 "too-light" routes between these stations, ones with too little traffic for even a single preassigned circuit.

With demand assignment, and an allowance of about 30 percent more traffic from these too-light routes, the 80+129 routes would lead to an average earth-station efficiency of 0.58 erlangs per circuit, which is considerably higher than that for a 12-circuit preassigned route. This efficiency is limited by the traffic-pooling at each station for its light routes and therefore it does not depend on whether the demand assignment is semivariable or fully variable.

Fully variable demand assignment promotes efficient use of the satellite, which then can pool all such circuits. Thus, for the above example, the satellite would need only 186 fully variable circuits to carry 0.822 erlangs

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* Lutz, S. G., A Traffic Study of Multiple Access Satellite Communication Based on an Atlantic System Model, Telecommunications, Part I, pp. 27-32, July 1968; Part II, pp. 25-31, August 1968.

per circuit, as compared with 406 preassigned circuits at 0.293 erlangs each, for the routes with 1 to 11 preassigned circuits.

Studies such as this may tend to be misleading in their prediction of fewer satellite circuits with the use of demand assignment. In interests of conservatism, very little allowance has been included for the growth-stimulation of demand-assigned service. There would quickly be more circuits carrying this light-route traffic than if such circuits were preassigned.

B.3 Modulation and Multiplexing Aspects

The modulation and multiplexing aspects of multiple access have been studied extensively and from various viewpoints. For example, some of these studies have started by assuming "hard-limiting" satellite repeaters. Other studies have assumed a mix of large and small earth stations, in the sense of the latter using lower-gain antennas and some signal compensation, without first establishing system conditions (numbers of stations, circuits per station, space-segment rates, etc.), that show an economic necessity for such a station-mix. Few studies have been directed toward the demand-assigned circuits in a compatible manner.

In the direction of such a study, it has been found helpful to consider how or whether channels can be variably assigned, in relation to various modulation and multiplexing methods. For example, considering the use of single-sideband, FDM, both to and from the satellite and overlooking the problems of such a system in favor of its conceptual simplicity, one sees that the channels "belong to the system." One station could select its receiving end. Thus, channel selection could be fully variable. Though this is possible, it is not necessary, because channels could be preassigned at either or both ends, if so desired. SSB-FDM, is capable of fully variable multiple access, whereas this would not be true with FM-FDM, for example. Equally important, SSB-FDM may be regarded as having a carrier-per-system, even though its common carrier frequency be suppressed. It would indeed be difficult ("impossible" in a practical sense) to have a carrier-per-system FM-FDM system, with all signals arriving in phase at the satellite. Therefore, FM-FDM is used on a carrier-per-station basis (i.e., the "multidestination" or multiply received carrier technique), and FM also may be used on a carrier-per-channel basis, as in the STAR system*. The latter basis permits fully variable selction of channels, though not without certain limitations or problems.

Turning our attention to digital modulations, such as PCM-TDM, it would be possible to achieve multiple access on a carrier-per-system, carrier-per-station, or carrier-per-channel basis. In the first case, the use of nanosecond pulses could be difficult, but not impossible, as with FM. The carrier-per-station use of PCM-TDM has attractions, but it limits demand-assignment to the variably received form, as with FM-FDM. The carrier-per-channel form provides full variability, as with the STAR system.

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* STAR System, NEC Research & Development, No. 8, pp. 1-66, October 1966. Also published in Telecommunications, Vol. 1, No. 2, pp. T22-T25, October 1967.

Finally, the "matched filter" method of selecting certain spread-spectrum signals offers an example of variably transmitted demand assignment systems. Here, channels are preassigned to receiving stations by their selection filters and the transmitting station varies its modulating waveform to conform with that to which the desired channel filter will respond.

B. 4 Calling and Routing Methods

In considering this matter, it should be recognized that centralized control of channel assignments is not essential with all forms of demand assignment, so that the familiar objections to nations entrusting their communication channels to some master-control station can be avoided. At the opposite extreme, channel or circuit assignment probably cannot be on a simple "ring-down" basis in any large-scale system, if only for economic reasons. It would cost too much to separate and equip all incoming channels at all stations. Between these extremes, there are ample opportunities for routing or assignment systems via order-circuits between the earth stations.

Centralized control of channel assignments first was proposed about 1961, in connection with studies of a fully variable demand-assignment system.* It was proposed that a central computer be used to keep track of the satellite channel use and availability and to assign available channels in response to demands. It was recognized that multiple channel seizures and related troubles would be encountered if stations were permitted to seize channels which "sounded idle," partly because of the propagation time being more than a quarter-second. More recently, the STAR system also made similar use of its "routing center." An alternative to this centralized control of channels would be to let each station keep track of channel usage via computer and then provide an automatic system for establishing priorities in the event of multiple-channel seizures.

An attractive but often overlooked aspect of the semivariable systems is that the station to which one end of a channel is preassigned can know the availability of that channel. Thus, "order-wire" communication between stations can be used to let the stations control their channel assignments.

B. 5 The Urgency Problem

Possibly the most serious problem has been the seeming lack of urgency in regard to demand-assigned multiple access. As evidence of this, the CCITT (at the New York meetings of Study Groups XI and XIII, spring of 1966) decided in its terms of reference for study of the World Routing Plan that only the preassigned form of multiple-access satellite communications need be considered within the time-frame (5 years) of its study. These terms of reference were not modified at the January 1967 Geneva meeting of the working party on this plan, nor were they modified subsequently at the Tokyo CCITT meetings. Further comments doubtless will

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* Hunter, L. C., and J. A. Stewart, A Multiple Access Global Satellite Communication System, National Space and Telemetry Conference, Albuquerque, New Mexico, September 1961.

occur to those who examine the participation in these CCITT meetings and note the lack of representation from those nations to which demand-assigned circuits would be most useful.

B. 6 Need for a Demonstration Experiment

It is recognized that NASA has sponsored studies of multiple access and has conducted experiments, such as the single-sideband multiple-access experiments with ATS-I and its successors. Also, it is understood that NASA has cooperated recently (summer, 1968) with Japan in three station tests of a PCM-TDM, variably received (carrier-per-station) demand-assigned multiple-access system, but adequate information about this system and its tests has not yet been made available.

Although these tests are commendable, there still is a great need for a program that would demonstrate openly the provision and use of demand-assigned satellite circuits between participating stations in several of the less-developed nations. Although few such stations exist today, contracts are being awarded at such a rate that enough suitable stations should be available by the time this demonstration program could be implemented, perhaps in 1969.

APPENDIX C

SMALL EARTH STATIONS

Samuel G. Lutz

C. 1 Introduction to the Small Station Problem

NASA SP-142 in its discussion of point-to-point satellite communications tends to associate "small terminals" with multiple access, to associate "small" with both a station's traffic and its cost, and also with the aperture of its antenna. In interests of clarity, it seemed best to present a separate discussion of multiple access in Appendix B, thus devoting this section to small-station problems, even those of orbital and frequency considerations for those applications that might need very small antennas such as man-pack applications, for example. Most emphasis here will be placed on the economic and traffic aspects, however.

Nearly everyone recognizes a continuing need for large-scale parametric tradeoff studies of multistation satellite-communication systems, toward reducing overall use costs (and thus attracting more customers) by using larger and better satellites of greater cost in order to achieve a significantly greater overall reduction in the use cost of earth stations of which there will be a large and growing number. Though such studies certainly should be encouraged and refined, they are inherently complex and are controversial in regard to the assumptions used and the interpretation of the results. Efforts to simplify or shortcut such studies frequently try to treat the space segment and the earth stations separately, as if they were independent or nearly so. For example, it sometimes is assumed that the present INTELSAT standard (G/T = 40. 7 dB) earth stations are too expensive for those nations who may need only 12 to 24 satellite circuits at present, and that satellite service could be made more attractive to these light users by letting them use smaller stations. Such stations could be much less expensive, as a consequence of smaller antennas and simpler cryogenics (if any).

When interrelation of these small stations with the space segment is considered, recognizing the lower figures of merit (G/T) of these stations, it seems usual to propose the use of a correspondingly stronger satellite signal, obtained perhaps by merely increasing the satellite's antenna gain. However, there still would be a station-mix problem, in that the standard stations would expect to take advantage of their higher G/T and the satellite's higher EIRP to obtain more channels at less cost. Using FDM-FM, these stations would want to reduce their modulation index (frequency deviation) toward unity as a probable lower limit.

Another common suggestion is that the lower G/T stations be subsidized in their less efficient use of the satellite, perhaps by being given a sufficiently larger per-channel share of the satellite's power and bandwidth, at little if any increase over the standard rate, S. This approach tends not to recognize the great disparity between standard and small stations in respect to space-segment utilization, as expressed by the penalty factor, P.

C. 2 Illustrative Station Parameters

In interests of clarifying the economics of the small stations and their use, it was decided to apply methods of Appendix A to stations of three sizes, whose characteristics follow:

	STATION SIZE		
	LARGE (Standard)	MEDIUM	SMALL
Antenna Aperture, feet,	85	42. 5	30
Gain (at 4 GHz, 55% Eff.) dB.	58. 0	52. 0	49. 0
System Noise (degrees K)	50	100	200
Margin, dB (rain, etc.)	6	4	4
Penalty Factor, P	1. 0	6. 5	27

The above noise temperatures might correspond to the use of liquid helium by the standard stations and progressively less expensive cooling of the parametric amplifiers by the smaller stations. Note that the degradation margin is 2 dB higher for the standard station because, at 50°K, the noise temperature of rain clouds will be more detrimental. The penalty factors conform with INTELSAT practice and reflect the loss of satellite channels relative to use by standard stations. Thus, for each channel between these 30-foot stations, INTELSAT could have provided 27 channels between standard stations.

Next, panel members agreed on representative total annual costs for stations of these three sizes, as shown in the following tables. These estimates assumed the use of conventional tracking antennas and allowed for maintenance and operating costs as well as for amortization, as was explained in Section A. 3. Similarly, these annual costs were inclusive of the T_1 costs associated with some typical but unspecified number of circuits, N_o. Consequently, the no-circuit cost component, T_o, was estimated for each station, as shown:

	STATION SIZE		
	STANDARD	MEDIUM	SMALL
		(Thousands of dollars)	
Total Annual Cost, $T_o + N_o T_1$	1, 800	600	300
$N_o \times T_1$	100 x 3	33 x 3	10 x 3
T_o	1, 500	500	270

Finally, it was decided to study cost relations both on the basis of the present, S = \$20, 000/year and the anticipated future S = \$5, 000/year space-segment rates.

C. 3 Circuit Cost and Break-Even Relations

As was explained in Appendix A, if two stations are of the same size and number of circuits, N, the worst break-even relations (vs the terrestrial cost-trend curves) occur when there is a single N-circuit route between these stations; the corresponding cost relation is:

$$2\frac{T_o}{N} + T_1 + PS \quad \$ \text{ per circuit year.}$$

Figure 9. C. 1 shows the curves thus calculated for the three station sizes at the present S = $20, 000/year rate. It is immediately apparent that, on this basis, 30-foot stations would be expensive bargains! For one or two circuits, the cost would be less than with the large standard stations, but few applications would justify circuit costs in excess of $1, 400, 000 per year. Moreover, for more than five circuits the break-even distance would exceed the maximum span of a one-hop satellite circuit. Even if the stations were donated and operated free, the space-segment costs for the circuit would be 2PS = 2 x 27 x 20, 000 = $1, 080, 000 per year.

The 42-foot stations, at this value of S, would be better than the 30-foot stations irrespective of the number of circuits. Also, they would be better than the 85-foot stations, provided that no more than 9 circuits would be needed.

The case for the small stations becomes a little better at the anticipated future rate, S = $5, 000 per year, as shown in Figure 9. C. 2. Here, the 30-foot stations would yield lower circuit costs than standard stations, but only so long as the need did not exceed 9 circuits. Even the 42-foot stations would be better than the smallest ones if more than two circuits were needed. The 42-foot stations remain preferable to standard stations, if not more than 40 circuits are needed. Compared with the trend costs of terrestrial communication the single-route minimum break-even distance appears somewhat better for the 42-foot stations than for standard stations, though the number of circuits is low and their cost is relatively high.

C. 4 Ways of Reducing Earth-Station and Overall Costs

Taking a long-term view, one recognizes that the space-segment rate, S, and penalty factor, P, should change to reflect the benefits from future use of bigger and better satellites by a growing number of earth stations. It seems likely that the future trend will be toward the use of higher EIRP satellites with larger numbers of earth stations having correspondingly reduced cost. Fully steerable 85-foot antennas look expensive, perhaps too expensive, so they become a too-obvious target for economy in such a cost tradeoff, especially so when possible costs of orbit-waste are not considered. There are many other possible earth-station economies, such as less-costly cryogenics, lower transmitter power, fixed-reflector antennas (of large aperture), unattended operation, etc. These less-obvious earth-station economies should be considered thoroughly, before taking the orbit-wasting "economy" of a too-small antenna.

On the other hand, forces may come into play that will let the penalty factors be reduced to less devastating values. As an extreme example (see Appendix D, Section 3), if the satellite EIRP were raised until today's standard stations were to operate at or near unity deviation ratio, a station having a 10- dB lower figure of merit, G/T, might obtain half as many channels from the same fraction of the satellite's power. As a possibly better example, it may be decided that, for reasons of good orbit utilization, lowering of the deviation ratio should be limited to some value such as 4. 0. Then, as the satellite EIRP is increased beyond the value which standard stations would require, the somewhat lower G/T stations might be enabled to operate at this same deviation ratio. Standard stations might take advantage of their extra EIRP in other ways. Additionally, this might lead to redefinition of standard stations, perhaps as having 60-foot antennas and 200° K noise temperatures. Further studies of this nature seem desirable.

C. 5 How Small is "Small"?

At least two other aspects of the small-station problem should be considered. One is that standard (G/T = 40. 7 dB) stations are now selling at around $5, 000, 000, which is less than the cost of many microwave routes. Thus, even these present costs are not prohibitive, though they can and should be reduced.

The second aspect of the problem is that present forecasts show little need for light-traffic stations. For example, Table 9. C. 1 shows that among those developing nations believed likely to have earth stations by 1970, only two have forecasts for less than 18 circuits, whereas 11 would use 18 to 35 circuits. On the other hand, Table 9. C. 2 shows 11 other nations whose forecasts (for 19 or fewer circuits) have been excluded because it seems unlikely that they will have earth stations by 1970. These INTELSAT forecasts were made on the assumption that these stations would have only preassigned-circuit routes to about one-quarter of the other stations. With more stations per satellite and using demand-assignment to provide routes between all stations, there will be an influence toward more traffic per station. Moreover, it seems unlikely that a need for fewer circuits per station would be created by adding intranational routes (between several stations in Brazil, for example) because such routes will tend to add heavy traffic.

Another consideration is that the traffic efficiency would deteriorate for smaller stations, even with demand-assigned circuits. At P = 0. 5 percent, 18 circuits would carry 9. 58 erlangs, or 0. 53 per circuit. (See Section 3. 4.) With only 9 circuits, this would drop to 3. 33, or 0. 37 erlangs per circuit. For such reasons, it seems unlikely that there will be any compelling need, commercially at least, for stations with much smaller numbers of circuits than the present INTELSAT forecasts indicate.

C. 6 Very Small Antennas—Frequency and Orbit Utilization

There have been frequent references to an objective of communicating with physically small ground stations, even man-pack, mobile, or small data-collection stations. Thus far, however, there seems to have been insufficient consideration of the frequency needs and orbit-utilization aspects of such stations which would require antennas of relatively small size, hence small aperture and broad beamwidth.

Aperture, not gain, is the measure of an antenna's energy-collecting capacity. For a given power-flux density, we would be able to collect essentially as much energy at any frequency from an antenna of given aperture. A two-foot parabola, however, could be used at 570 MHz with a 3-dB beamwidth of 60 degrees, whereas it would have a one-degree beamwidth at 34 GHz and probably could not be used from a bouncing automobile. Thus, from a convenience (and cost) standpoint, broad antenna beams are desirable, making the use of relatively low frequencies equally desirable.

An opposing factor to the above is the desirability or eventual necessity of orbit conservation. For example, the 60°-3dB antenna would have an interference beamwidth that would be essentially hemispheric. It would be difficult, except perhaps with very "hard" modulation requiring low interference-suppression ratios, to reuse a low-frequency band from several orbit stations because of the large separation angles required.

Higher frequencies and higher satellite powers do not solve the problem of small earth stations that require broadly directive antennas. Rather, they only serve to complicate the problem. For example, the gain of a 60° antenna is 9 dB at any frequency. We might receive at 4 GHz with such an antenna if the satellite ERP were raised by 50 dB or so, but what would this do to nearby earth stations receiving with 59-dB antennas from normal power satellites at adjacent orbit stations? Similarly, what about the inverse problem of transmitting to the satellite at 6 GHz with a broad antenna beam?

A positive conclusion from this discussion is that the many possible small-station applications of satellite communication require careful consideration of their ability to share orbit-space and to share frequency bands with other similar small-station systems or even with the large-antenna (highly directive) point-to-point satellite systems.

Another apparent conclusion is that, in terms of these small and broad-beam-antenna type applications, there is a much greater need for allocating broad frequency bands below 4 GHz than for allocating millimeter-wave bands.

TABLE 9. C. 1

INTELSAT 1970 TRAFFIC FORECASTS FOR DEVELOPING NATIONS THAT PROBABLY WILL THEN HAVE EARTH STATIONS

Less than 18 Circuits: (2)

Kenya - 13
Bahrein - 14

18 to 35 Circuits (11)

Kuwait - 18
Korea - 18
Vietnam - 19
Morocco - 20
Singapore - 22
Ivory Coast - 23
Israel - 26
Peru - 29
Malaysia - 31
Panama - 31
Taiwan - 33

36 to 59 Circuits (10)

Colombia - 37
Chile - 37
East Pakistan - 41
Saudi Arabia - 42
Mexico - 44
West Pakistan - 45
Ceylon - 47
Thailand - 47
Lebanon - 51
Nigeria - 52

60 or more Circuits (7)

Turkey - 61
Philippines - 80
Venezuela - 69
Brazil - 101
Argentina - 103
Hongkong - 118
India - 119

TABLE 9. C. 2

INTELSAT 1970 FORECASTS FOR DEVELOPING NATIONS NOT EXPECTED TO HAVE EARTH STATIONS AT THIS DATE

Nation	Circuits	Reason for exclusion
Jordan	5	No station yet planned
Syria	3	No station yet planned
Ethiopia	9	No station yet planned
Senegal	19	No station yet planned
Iraq	1	No station yet planned
Okinawa	13	Primarily U. S. military base
Cuba	4	No station yet planned
Martinique	11	No station yet planned
Ecuador	2	No station yet planned
Uruguay	8	Could use Argentine station
Paraguay	4	Could use Argentine station

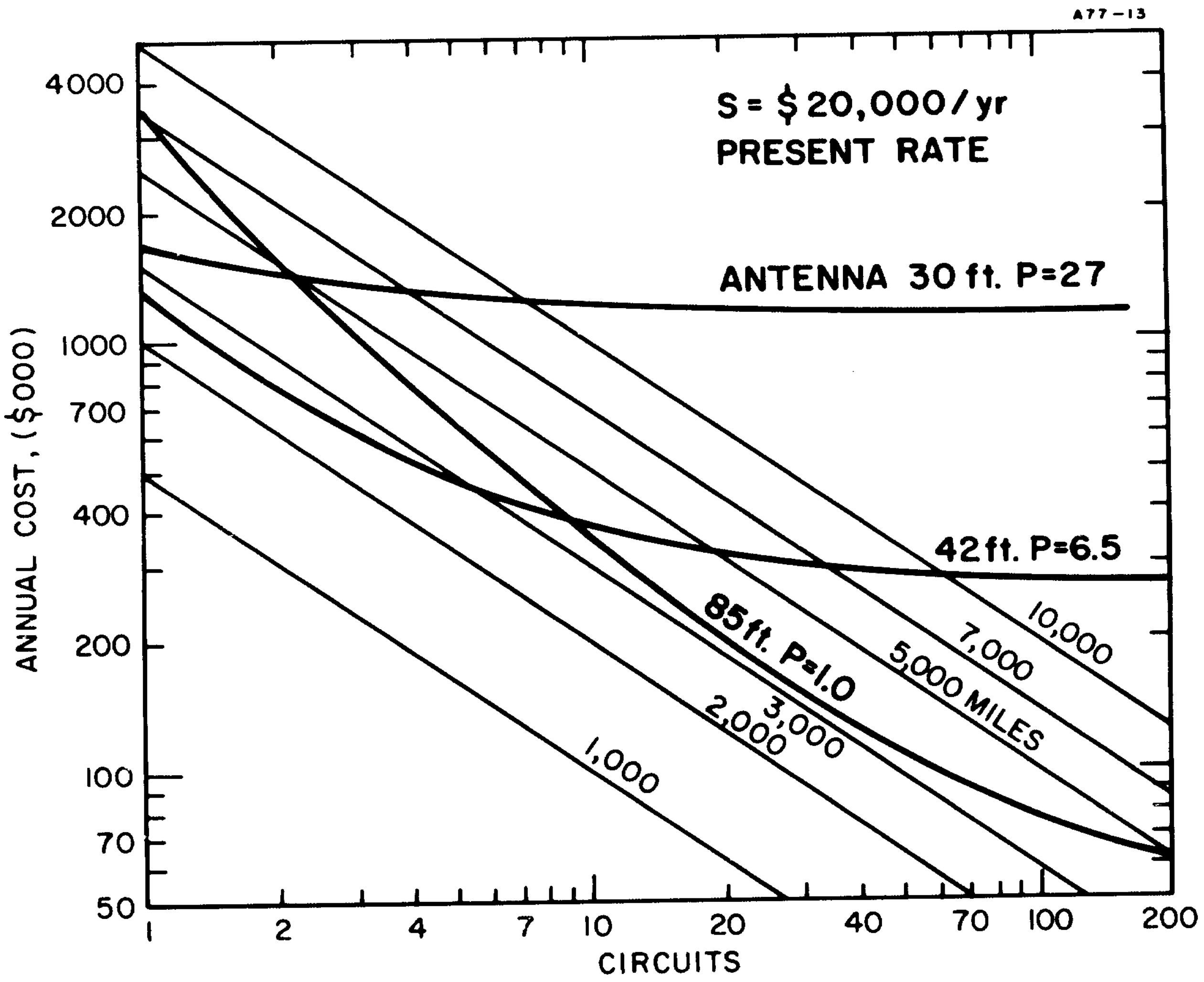

FIGURE 9. C. 1 Small-station circuit costs at present space-segment rate.

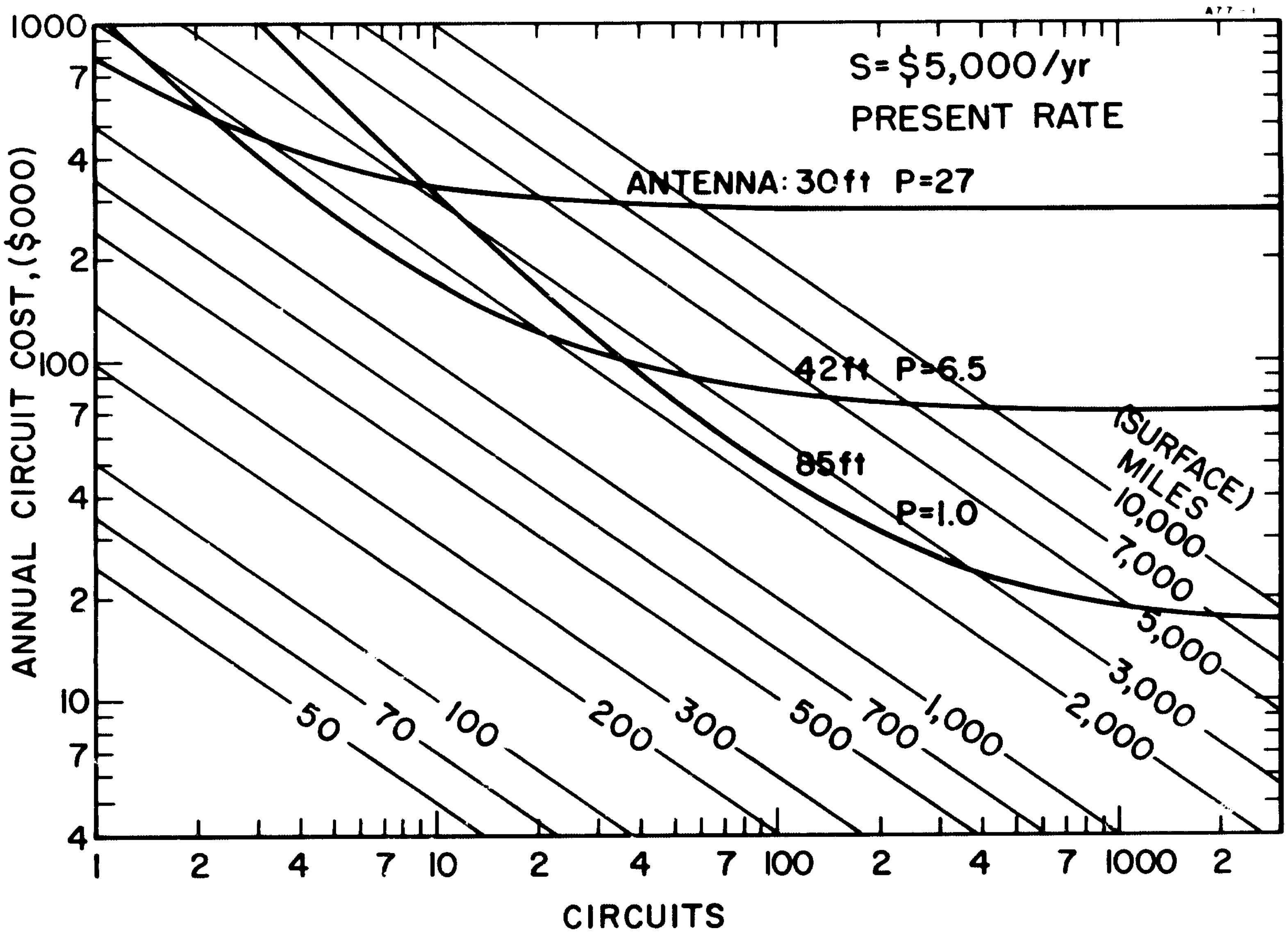

FIGURE 9.C.2 Small-station circuit costs, at S = $5000.

APPENDIX D

MULTIDIMENSIONAL SPECTRUM UTILIZATION

James D. Rinehart

D. 1. 0 Introduction

As the application of communication satellites expands and more systems come into being, the utilization of the allotted frequency spectrum and of the useful geostationary orbit positions becomes a problem. It often is said that the frequency spectrum is a natural resource that must be conserved. However, the same frequencies can be reused from different orbit stations, if sufficiently separated, so the geostationary orbit constitutes another spectrum that should be conserved. An important difference is that this orbit-spectrum is not open-ended. Additionally, a satellite can have multiple earthward beams with which it can reuse the same frequencies from its orbit station, aided perhaps by use of orthogonal polarization. Thus, there actually is a multidimensional spectrum whose conservation should be considered. It will be seen from this appendix that the communication capacity of this spectrum is tremendous, if efficiently used, far greater than foreseeable needs.

On one hand, it does not appear necessary to insist on the most highly efficient use of the spectrum, since this would delay and even prohibit good and useful applications of satellite communication. On the other hand, it seems necessary to recognize and limit those applications which would waste this spectrum excessively. Judgment in these matters will require knowledge of these spectrum dimensions, and of their use-interrelations or tradeoffs. A major purpose of this appendix is to provide some of this information. Its other major purpose is to show the importance of generating further information and of making it available in a thorough though simple and readily useful form.

The Atlantic INTELSAT at 24.5°W (see Figure 9. 3. 1) offers an example of orbit-spectrum value, and of associated problems. A satellite in this position can be used by the earth stations of four continents, thus maximizing the number of users and their interconnectability to other users. A satellite farther east could not be used from Mexico, whereas others could not use a satellite if farther west. Once this becomes an accepted satellite position it becomes desirable for all these stations to continue to pass their traffic through the satellite at this position, even though there is a strong possibility of overloading it. The addition of a second satellite near the first, to carry additional traffic, probably would require considerable facility additions at every station desiring to use the second satellite. Instead, a relay link might connect the two satellites, but its complications might raise the cost of the satellites. Similar considerations would apply to the use of two or more earthward beams from the same satellite. The simplest and usually the most tempting means of increasing the satellite's traffic capacity would be just to increase its channel density by "softening" its modulation, decreasing the frequency deviation and raising the EIRP, for example. Unfortunately, doing this would require that other satellites be kept at a somewhat greater separation, thus making available fewer channels per orbit degree at this highly desirable part of the orbit.

Domestic and regional systems pose a more severe problem in utilizing the multidimensional spectrum because the requirements for service in these systems may exceed the capacity of a single satellite very early, and because the systems of more than one region may place demands on the same orbital space. As an example, Figure 9. D. 1 shows the portions of the synchronous arc that could be used by several possible regional systems (assuming 5° usable elevation angle at land-mass limits). When regional systems are contemplated for these areas, considerable care must be exercised to ensure that this multidimensional spectrum is used efficiently. The systems proposed should offer growth into the foreseeable future and should protect the potential growth of other users of the spectrum.

In the light of the above discussion, means for increasing the use of the multidimensional spectrum can be categorized as follows:

1. The provision and use of additional frequency bands of greater width, ones above 11 GHz, for example.

2. The use of many satellites around the geostationary orbit and (when and if necessary) the use of more satellites in other orbits, ones compatible with the geostationary orbit.

3. The use of narrow-beam antennas, having low sidelobes, to permit use of small orbit separations.

4. Precision orbital station-keeping; more satellites if less of the orbit must be reserved for drift.

5. Frequency reuse. by means of multiple earthward beams, adequately separated, using orthogonal polarization for additional isolation to the extent applicable. Note that multiple beams become more attractive at the higher frequencies.

6. The use of modulation having near-optimum "hardness" to interference, recognizing that this involves a bandwidth/interference trade.

7. The use of higher EIRP by all cofrequency satellites, with redistribution of the thermal noise vs interference budgets, letting the stronger signal override less thermal noise and more interference.

8. Grouping of satellites according to near-equal EIRP's. Satellites using low EIRP must be separated farther from high-power satellites, thus wasting orbit if they are intermixed indiscriminately.

This appendix does not attempt to dispose of the above matters but does provide some exploratory and illustrative analyses which indicate the type of investigations that are needed and the kind of results to be expected. Section D. 2. 0 derives a generalized upper limit on orbital-arc information-rate capacity, based on Shannon's Law. Section D. 3. 0 examines effects of changing the modulation hardness, the deviation ratio in the case of FDM-FM telephony, and the PSK levels in the case of PCM-PSK telephony.

Additionally, this section examines the earth-coverage area vs the interference area and beam separation required for the use of multiple earthward beams reusing the same frequencies. Section D. 4. 0 shows the use of redundant coding, and particularly that of the Forward Error Correction (FEC) type, for the further hardening of digital modulation.

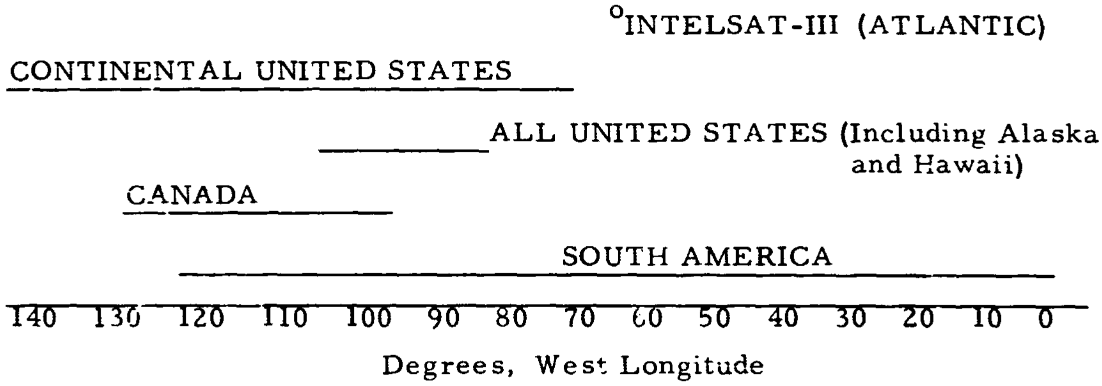

FIGURE 9. D. 1 Synchronous-orbit positions that are usable for various regional systems (5-degree minimum elevation angle).

D. 2.0 THEORETICAL LIMIT OF COMMUNICATION CAPACITY OF AN ARC OF GEOSTATIONARY ORBIT *

William E. Bradley

D. 2. 1 Three Dimensions of Frequency

Consideration of frequency utilization by communication-satellite systems must include not only frequency but also wave-propagation direction. Both frequency and direction of a plane wave can be described by the propagation vector of the wave $\overline{K}$. All field components vary with position as

the real part of $[\exp(j\omega t - j\,\overline{K} \cdot \overline{r})]$

where the vector $\overline{r}$ specifies the position in space at the point of observation and $\omega = 2\pi f$. The magnitude of K is $\frac{2\pi f}{C} = \frac{2\pi}{\lambda}$ where f is the frequency, C is the velocity of light, and λ is the wavelength. An antenna has a directivity function $\psi(\overline{K})$ that is equal to the (complex) ratio of the amplitude of the signal at the antenna terminals to the amplitude of a plane wave being received with a propagation vector $\overline{K}$.

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*Bradley, W. E., Communications Strategy of Geostationary Orbit, Astronautics & Aeronautics, Vol, 6, No. 4, pp. 35-41, April 1968.

A frequency band B specifies only a spherical shell in K space lying between

$$\left| K_1 \right| = \frac{2 \pi f_1}{C}$$

and

$$\left| K_2 \right| = \frac{2 \pi f_2}{C}$$

A directional antenna further delimits the volume in K space corresponding to signals that may be received. The power gain of the antenna for a plane wave is $\psi^* \psi = \left| \psi \right|^2$. The relative power gain F (θ, ϕ) is the ratio of $\left| \psi \right|^2$ at the direction specified by the two angles θ and ϕ to the value of $\left| \psi \right|^2$ at the beam center. The two angles θ and ϕ may represent east-west and north-south departures of the wave vectors from the beam axis respectively.

By means of a multiplicity of antenna beams, either from separate complete antennas or from a single multiple-beam antenna, it is possible to receive several independent wide-band signals at a given space location in exactly the same frequency band. Thus, both satellites and earth stations can reuse the assigned frequency spectrum many times to the extent that they can distinguish desired signal sources from interfering signals by antenna directivity. Since the directivity functions of the several beams at a given terminal are likely to overlap slightly, each received signal from a particular source received by a particular beam will be contaminated with interference from other sources in other directions, and the permissible number of frequency-band utilizations is limited by the interference to signal ratio.

D. 2. 2 Communication Capacity of a Single Satellite

The maximum rate at which information can be received in a bandwidth B from a single direction at such a terminal is

$$\dot{I}_i = B \log_2 (1 + S/N)$$

where $\dot{I}$ is the rate of information transmission in bits per second, S is the power of the desired signal and N is the competing noise and/or interference power.

Instead of communicating with the entire face of the earth exposed to it by means of an earth-coverage antenna, a satellite alternatively may have an antenna system in it that limits its coverage to two or more discrete regions. Such a satellite may use the same portion of the frequency spectrum to communicate with both regions provided only that the antenna system directivity of the satellite together with the type of RF modulation employed assure that no objectionable cross-talk between the two regions will result.

If a single satellite communicates with M such separate regions, each of which is provided with a regional coverage antenna beam and a separate repeater in the satellite, then the bandwidth B can effectively be used M times over. If no interconnections in the satellite exist between the regional repeaters, then the satellite cannot provide interregional, but only intraregional communication. Obviously some channels could be permanently cross-connected in the satellite so that a fraction of the channel capacity could be available for interregional communication, but this would correspondingly reduce the effective amount of frequency band reuse.

The bandwidth B can be fully utilized M times by M regional-coverage antenna beams only if the satellite contains means within it to switch base band information, groups of channels, or individual channels from region to region under control of an addressing or routing system.

It follows that the upper limit of communication capacity of a single satellite is

$$I_M = MB \log_2(1 + S/N)$$

if all its M beams are independently fully utilized in the same frequency band B.

D. 2. 3 Maximum Capacity of an Earth Station

Frequency-spectrum sharing among other than geostationary satellites is complicated by the time variation of satellite directions and consequent intermittent use of satellites. Geostationary satellites offer the opportunity to reuse the assigned spectrum at each earth station as many times as angularly distinct satellites are available.

The number of earth-station spectrum reutilizations possible using n equally spaced satellites in geostationary orbit all contained within an arc of longitude extension, θ , is

$$n = \frac{\theta}{\Delta\theta}$$

where $\Delta\theta$ is the intersatellite orbital spacing.

The amount of communication capacity provided to a particular earth station by such a set of geostationary satellites cannot exceed*

$$\dot{I} = \frac{\theta}{\Delta\theta} \quad B \log_2 (1 + S/N)$$

According to CCIR data, the power gain of existing large microwave antennas can be conservatively assumed to decay with angle away from the

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*This assumes that each satellite is placed in the center of its angular domain of width $\Delta\theta$.

beam axis as $\Delta\theta^{-2.5}$. This can conveniently be represented by the approximation to $F(\phi, \theta)$ for $\phi = 0$ given by

$$F(\theta) = \frac{1}{1 + \left(\frac{\Delta\theta}{\theta_0}\right)^{2.5}}$$

where θ_0 is the angle of departure from the beam axis at which the gain is reduced by 3 dB from its value on the axis.

If all the satellites have equal effective radiated power, and if noise other than intersatellite interference is negligible, then

$$\frac{N}{S} = \sum_{K} \frac{1}{1 + \left(\frac{K\Delta\theta}{\theta_0}\right)^{2.5}}$$

where K is an integer and where the sum includes all satellites except the desired one.

This sum can be approximated by

$$\frac{N}{S} = 2b \left(\frac{\theta_0}{\Delta\theta}\right)^{2.5}$$

where $b = 1 + \frac{1}{2^{2.5}} + \frac{1}{3^{2.5}} + \frac{1}{4^{2.5}} + \ldots$ is approximately 1.343.

Then the total aggregate capacity provided by the set of satellites to any one ground station cannot exceed

$$\dot{i}_\theta = \frac{\theta B}{\Delta\theta} \log_2 \left[1 + \frac{1}{2b} \left(\frac{\Delta\theta}{\theta_0}\right)^{2.5}\right].$$

At small values of $\Delta\theta$ the capacity varies as $\Delta\theta^{1.5}$, while at large values the capacity decreases with $\Delta\theta$. It follows that there is a maximum possible capacity determined by an optimum value of $\Delta\theta$. See Figure 9. D. 3.

This optimum value of $\Delta\theta$ corresponds to a root of the equation

$$\log_2 (1 + x) = \frac{2.5\,x}{1 + x} \log_2 e$$

where

$$x = \frac{1}{2b} \left(\frac{\Delta\theta}{\theta_0}\right)^{2.5}.$$

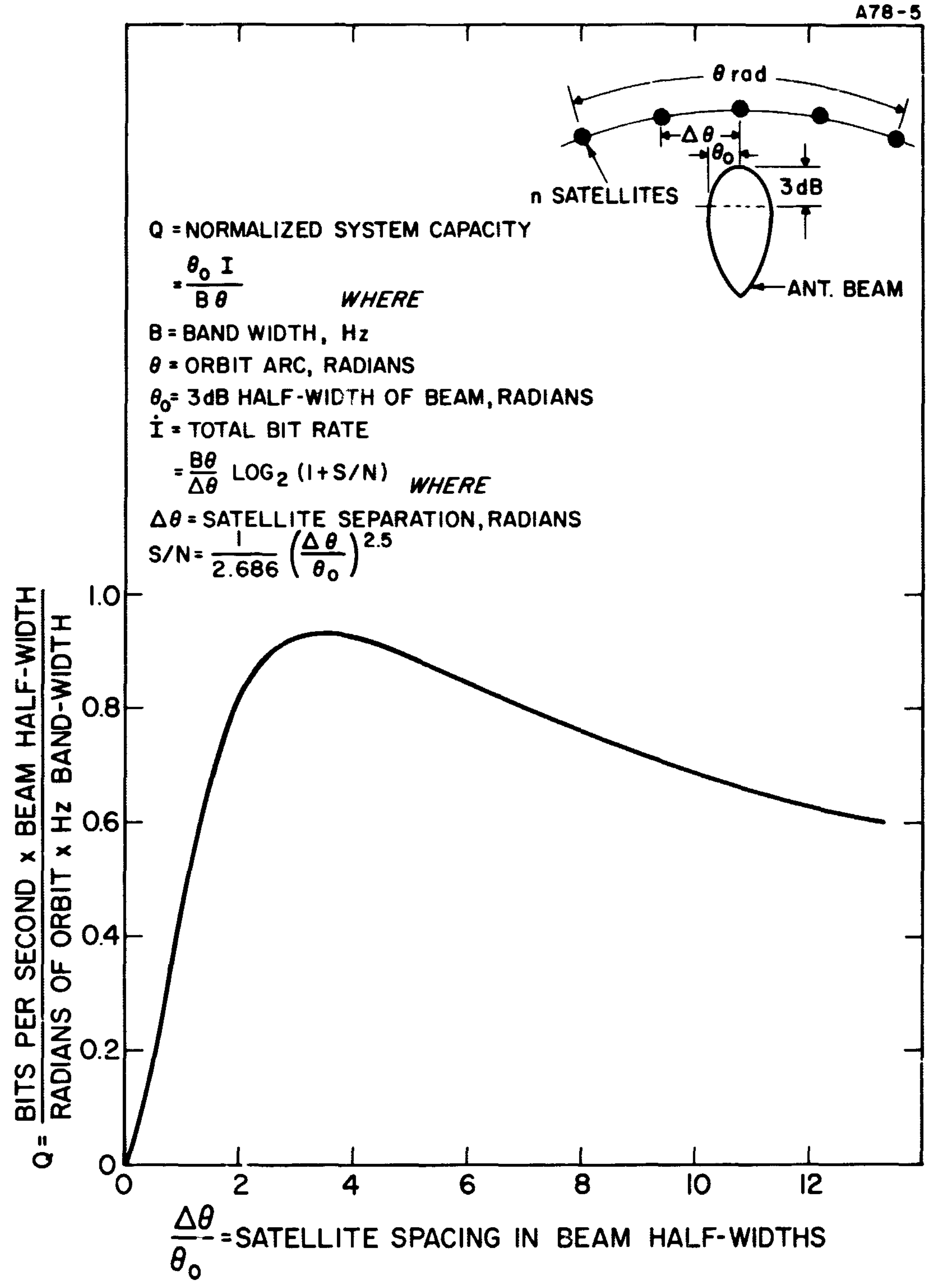

FIGURE 9. D. 2 Earth station information rate versus satellite angular spacing in geostationary orbit, assuming Shannon limit on each path.

The value of this root is about $x = 8.2$, and since the value of b is approximately 1.343, the optimum value of $\Delta\theta$ is

$$\Delta\theta = 3.6\,\theta_o \quad .$$

This corresponds to a power ratio of interference from one adjacent satellite to desired signal of about 1/23 or -13.6 dB.

To achieve high-quality communication with a power signal-to-noise ratio of 8.2, as corresponds to the "optimum" choice of $\Delta\theta$, would require an intricate system of modulation and coding. For a practical system, a larger value of $\Delta\theta$ would be economically more attractive. Thus, if a practically attractive signal-to-noise ratio ρ is selected, then

$$\rho = \frac{1}{2b}\left(\frac{\Delta\theta}{\theta_o}\right)^{2.5}$$

and

$$\Delta\theta = (2.6\,\rho)^{1/2.5}\,\theta_o \quad .$$

Thus if $\rho = 100$, $\Delta\theta = 9.24\,\theta_o$ instead of the minimal $3.44\,\theta_o$.

The maximum earth-station capacity, using the optimum value of $\Delta\theta$ is

$$\dot{I}_{\theta\ \max} = 0.86\,\frac{B\theta}{\theta_o} \quad .$$

Using the more practical signal-to-noise ratio $\rho = 100$ (instead of the minimal $\rho = 3.44$) gives:

$$\dot{I}_\theta = 0.719\,\frac{B\theta}{\theta_o} \quad .$$

D.2.4 Anomalous One-Satellite Advantage

An apparent anomaly exists in that a single satellite appears to be able, in accordance with Shannon's law, to transmit an infinite amount of information while a multigeostationary-satellite system has a finite limit to its capacity with given antenna sizes. Thus $\dot{I}_1 = MB \log_2 (1 + S/N)$ for a single satellite approaches infinity as S/N is increased, although only logarithmically, while $\dot{I}_\theta = 0.86\ MB\,\frac{\theta}{\theta_o}$ is finite with optimized satellite spacing. The explanation is that no practical means is known to trade bandwidth for signal-to-noise ratio sufficiently to fully realize the theoretical possibilities of Shannon's law, while the use of a second satellite (or any other source of noise) reduces the signal-to-noise ratio and leads to the optimization process described above.

D. 2. 5 Upper Limit to Capacity With Ideal Antennas

The foregoing analysis is based on the CCIR semiempirical data on sidelobe amplitude and hence the possibility exists that larger system capacity could result if the details of sidelobe structure were taken into account. An upper bound to a multigeostationary-satellite capacity per Hz per degree of orbit on fundamental grounds can be derived by assuming that the earth-station antennas are rectangular and are uniformly illuminated by their feed radiators. Only the east-west dimension of such an antenna controls the intersatellite angular spacing. The directivity function of a uniformly illuminated rectangular antenna is approximately

$$F(\theta, \phi) = \frac{\lambda^2}{\pi^2 D_\theta \; D_\phi \theta \phi} \sin\left(\frac{\pi D_\theta \Theta}{\lambda}\right) \sin\left(\frac{\pi D_\phi \phi}{\lambda}\right)$$

where

D_θ is the east-west dimension and $D\phi$ the north-south dimension of the rectangular antenna aperture.

The nulls or zeros of the directivity function $F(\theta, \phi)$ are spaced at angular intervals $\Delta\theta = \frac{\lambda}{D\theta}$. It follows that the maximum capacity of a segment of geostationary orbit would be

$$\dot{I}_\theta = M \frac{\Theta D_\theta}{\lambda} B \log_2 (1 + S/N)$$

where S/N is now independent of $\Delta\theta$ because each satellite is located in a null of the directivity function of every earth-station beam not intended to communicate with it.

To approach such a limit practically, account must be taken of several details:

1. Even with perfect station-keeping, equally spaced geostationary satellites will not appear to be angularly equally spaced from more than one earth station, so that the positions of the nulls of the antenna-directivity function would have to be slightly altered from the equal angular intervals specified above to accommodate more than one small region.
2. Thermal noise sets a limit to S/N that can be controlled by choice of satellite ERP. In practice, some intersatellite interference would also result from failure to place antenna nulls on other satellites with perfect accuracy.
3. The rectangular illumination pattern desired above would not be necessary in practice. In Appendix E, "Antennas," it is pointed out that multiple-beam, fixed-reflector antennas present the attractive possibility of controlling the placement of nulls in the directivity pattern by adjustable external cross-couplings between the multiple-beam output terminals. Analysis of this possibility shows that the antenna-illumination pattern, provided that it has an east-west dimension larger than that for the ideal rectangular antenna, is noncritical. It is necessary, however, to choose carefully the time delays as well as the attenuations of the cross-coupling connections in order to avoid change of null-angles with frequency.

D. 2. 6 Conclusions

1. The maximum total communication capacity of a geostationary orbit segment Θ, operating within a frequency bandwidth B, with each identical satellite in the segment using the band M times by means of multiple antenna beams, with identical intersatellite angular spacings and assuming ideal earth-station antennas having an east-west dimension D is

$$\dot{I}_{max} = \frac{MD\Theta B}{\lambda} \log_2 (1 + S/N) .$$

2. The maximum capacity of a single satellite is

$$\dot{I}_s = MB \log_2 (1 + S/N) .$$

This equation applies when any earth-station antennas providing adequate signal-to-noise ratio are used.

3. The maximum capacity that can be provided to a single earth station by the arc Θ is

$$\dot{I}_E = \frac{D\Theta B}{\lambda} \log_2 (1 + S/N)$$

for the conditions stated in Conclusion 1.

4. If sidelobe level of the earth-station antennas is assumed to decay as $(\Delta \theta)^{-2.5}$, then an optimum intersatellite angular spacing exists that depends on the beamwidth of the earth-station antennas. If the 3 dB beamwidth is $2\theta_o$, then with optimum satellite spacing, the three preceding limits of capacity become

$$\dot{I}_{max} = 0.932 \frac{M\Theta B}{\theta_o}$$

$$\dot{I}_s = MB \log_2 (1 + S/N)$$

$$\dot{I}_E = 0.932 \frac{\Theta B}{\theta_o}$$

Discussion:

An estimate of the upper limit of communication capacity, for joint use of a community of earth terminals, provided by a string of equally spaced identical satellites in a geostationary orbit arc of θ radians and in a band BHz is given by the expression $\dot{I}_E$ above if all satellites have earth-coverage single-beam antennas, or alternatively have identical coverage of a single region containing all earth terminals of the system.

This estimate is the least upper bound to capacity in the sense that the approximations used in the analysis to calculate aggregate interference have tended to overestimate that interference, while Shannon's law was used to determine an upper bound to the capacity of each path, subject to the aggregate interference and the bandwidth limitation.

The capacity estimated in this way is large but not unlimited. For example, suppose that the bandwidth is 500 MHz and the beamwidth, $2\,\theta_o$, of each earth terminal beam is 0.006 radians, such as might be obtained from an antenna of effective diameter of 40 feet at a frequency of 4000 MHz.

Then in an orbit arc of 10 degrees the upper limit of capacity would be at least

$$\dot{I}_E = 0.932\,\frac{B\theta}{\theta_o} = 2.91 \times 10^{10} \text{ bits per second.}$$

At 50 kilobits per second for a high-quality voice band, this upper limit amounts to 582,000 one-way voice bands in the 10-degree orbit arc. To do this, 17 satellites spaced 0.59 degrees apart would be necessary. A signal-to-noise power ratio of 8.2 would characterize each path of the system, necessitating sophisticated coding and modulation methods to maintain the required quality.

Using the more practical signal-to-noise ratio of 100, satellite spacing becomes 1.6 degrees and the number of satellites 6. With this nonoptimum intersatellite spacing, the capacity is reduced because of the smaller number of satellites but this loss is partially offset by the improved rate of information transmission per path achievable with the improved signal to noise ratio, in accordance with the factor $\log_2(1 + S/N)$ of Shannon's law. The system capacity is then reduced to 426,000 voice bands.

With simple, available modulation systems it is easy to achieve an information rate of 2B bits per second in a bandwidth B if the power signal-to-noise ratio is 100. Using this ultraconservative figure for information rate on each path and with the satellites spaced 1.6 degrees apart, as is appropriate to achieve the stated S/N, then the number of voice bands furnished by the ten-degree arc containing six satellites would be 128,000. This last readily attainable figure is included to give some idea of the order of magnitude of improvement that can be obtained by closer approach to ideal modulation techniques.

The analysis in this section illustrates the importance of modulation hardening for economy of spectrum-orbit resource conservation. If modulation techniques carried over from older communication practice, in which every effort was directed to packing voice bands into the smallest possible frequency space, are used for satellite communication links, then even small amounts of RF interference greatly degrade output signal quality.* As a result the intersatellite spacing $\Delta\theta$ must be maintained at a relatively large value and geostationary orbit space is wasted.

---

*This follows directly from Shannon's law; as B is decreased, S/N must increase disproportionately for a given information rate.

To use both resources, frequency space and orbit space, most efficiently, the modulation must be such that the ratio of bits per second transmitted to bandwidth utilized should not exceed about two. The actual value of the ratio that optimizes resource use is different for each type of modulation, both for base band and carrier. The optimization procedure for any particular system is as follows: (a) find the relation between the band-spreading parameter of the selected modulation system and the signal-to-noise ratio required for adequate quality; (b) from the expression $S/N = \frac{1}{2.68}\left(\frac{\Delta\theta}{\theta_o}\right)^{2.5}$ find the value of $\Delta\theta$ as a function of the band-spreading parameter that with the antenna beamwidth selected, will produce this signal-to-noise ratio; (c) calculate system capacity in the assigned orbit arc and bandwidth with $\Delta\theta$, and hence the number of satellites, parametrically determined from b as a function of the band-spreading parameter. It is anticipated that a well-defined optimum will be found for the band-spreading parameter that will maximize system capacity within the frequency and orbit space constraints. Too much band spreading wastes frequency space while too little wastes orbit space.

Section D. 3. 0 of this appendix contains examples showing how system capacity within a given band and orbit arc varies with deviation ratio for an FDM-FM modulation format, and with multiplicity of levels for PCM-PSK modulation.

Antenna size in the east-west dimension has an important effect on spectrum/orbit utilization efficiency. The analysis shows that the system communication capacity available to a community of earth stations sharing the same frequency band and having identical antennas varies directly with east-west antenna aperture, provided that multiple identical satellites equally spaced in orbit are packed as closely as the aggregate signal-to-noise ratio requirement will permit. The smaller the east-west antenna aperture, the farther apart must be the satellites, so that small antennas tend to waste orbit space.

The analysis also implies that reducing either satellite ERP or earth terminal antenna gain to the point that receiver noise is appreciable is wasteful for the system since the S/N is thereby decreased with no compensating benefits. An efficient system should have its capacity limited only by self-interference.

D. 3. 0 SOME PERTINENT PARAMETER INTERRELATIONSHIPS

Hayden W. Evans

D. 3. 1 Introduction

This section develops the interrelationships between system parameters affecting the number of telephone channels that can be derived from (a) the frequency bands allocated to commercial satellite service and (b) the stationary orbit. Since the major use of this analysis will be to point out (in other sections) that there is a real need for wider frequency allocations, it is addressed primarily to the large user and does not take into account the problems of apportioning capacity among very small users. Some of the relationships used and developed are approximations, good enough to demonstrate an argument, but not accurate enough for final system design. Most of the "small print" that would delineate these restrictions has been omitted so as not to interfere with the main arguments.

We consider two types of modulation: FDM-FM (frequency division multiplex transmitted by frequency modulation) and PCM-PSK (pulse code modulation transmitted by phase-shift keying).

For FDM-FM, we will bound the probable range of frequency deviation, which relates the capacity of the system to the occupied bandwidth. We will calculate the suppression required between two such signals in terms of the interference, and we will calculate the angular separation required between satellites to attain this suppression. Knowing the capacity per satellite and the separation between satellites, we can calculate the capacity of the presently allocated frequency bands.

For PCM-PSK, we will go through the same sequence, but in less detail, and we will compare PCM-PSK capacity to FDM-FM capacity.

Finally, we will point out that multiple beams from satellites can multiply frequency usage and hence multiply the capacity of the stationary orbit. We will recommend a program leading to an understanding of the advantages of multiple beams.

A common nomenclature is used in the following presentation and is given in Section D. 3. 12.

D. 3. 2 Frequency-Deviation Ratio for FDM-FM Telephone Systems

A formula will be derived for the peak frequency-deviation ratio that results in meeting the noise and breaking margin requirements simultaneously.

D. 3. 2. 1 Noise Requirement

$$B = 2f_d + 2f_b = 2f_b\,(D+1)$$

$$f_b = \frac{B}{2(D+1)} = 4,200\ n$$

$$n = \frac{B}{8,400(D+1)} \qquad (1)$$

The FM equation, for $n > 240$, can be written:

$$C = \frac{N_3}{N_c P} \cdot \frac{W_{peak}}{D^2} \qquad (2)$$

where $N_3 = KTB = 1.38 \times 10^{-23}\,T\ 3,100$ (3)

and $W_{peak} = 3.16 \times 10^{-5} \times 15.85n$ (4)

assuming average talker power = -15 dBm0 = 3.16×10^{-5} watts

multiplex peak factor = 12 dB = 15.85

Inserting (1), (3) and (4) into (2):

$$C = \frac{1.38 \times 10^{-23} \times 3100 \times 3.16 \times 10^{-5} \times 15.85}{8400} \quad \frac{BT}{N_c P} \quad \frac{1}{D^2(D+1)}$$

$$= \frac{2.55 \times 10^{-27}\ BT}{N_c P} \quad \frac{1}{D^2(D+1)} \tag{5}$$

D. 3. 2. 2 Breaking Margin

At threshold: $$\left.\frac{C}{N_B}\right|_{\text{threshold}} = \sqrt[3]{250D} \tag{6}$$

At normal working point: $$\frac{C}{N_B} = \frac{C}{KT'B} \tag{7}$$

where T' takes into account all the sources of noise that contribute to breaking, such as down-link thermal noise and up-link thermal noise.

$$T' = T\ \frac{N_c + N_u}{N_c}$$

$$\frac{C}{N_B} = \frac{C}{KTB} \quad \frac{N_c}{N_c + N_u} \tag{8}$$

$$\text{Margin} = M = \frac{\dfrac{C}{N_B}}{\left.\dfrac{C}{N_B}\right|_{\text{threshold}}} = \frac{C}{KTB} \quad \frac{N_c}{N_c + N_u} \quad \frac{1}{\sqrt[3]{250D}} \tag{9}$$

The use of threshold-extension receivers is not assumed. Threshold-extension receivers trade bandwidth for breaking margin and would demand higher deviation ratios and yield fewer channels than standard receivers.

D. 3. 2. 3 Simultaneous Noise Requirements and Breaking Margin

Inserting Eq. (5) into Eq. (9):

$$M = \frac{2.55 \times 10^{-27}\ BT}{N_c P} \quad \frac{1}{D^2(D+1)} \quad \frac{1}{1.38 \times 10^{-23}\ BT}$$

$$\times \frac{N_c}{N_c + N_u} \quad \frac{1}{\sqrt[3]{250D}}$$

$$= \frac{2.935 \times 10^{-5}}{(N_c+N_u)\ P} \qquad \frac{1}{(D+1)D^{7/3}} \tag{10}$$

Rearranging:

$$(D+1)\ D^{7/3} = \frac{2.935 \times 10^{-5}}{(N_c+N_u)\ PM} \tag{11}$$

Note that D is independent of bandwidth, number of voice channels, and carrier power.

D. 3. 2. 4 Typical Values

Noise in international circuits must not exceed 10,000 pWpO according to CCIR recommendations, but 500 pWpO of this is allocated to interference from radio-relay transmitters to the satellite and 500 pWpO is allocated to interference from radio-relay transmitters to the earth-station receiver. Although the CCIR does not specify it, we should also allocate perhaps 500 pWpO to interference to the satellite from other earth stations and 500 pWpO to interference to the earth station from other satellites. This leaves:

$$N_c + N_u = 8,000 \text{ pWpO} = 1.42 \times 10^{-8} \text{ watts unweighted}$$

P and M are not completely independent, particularly if M is small. If M is 3 dB = 2.0, which is reasonable for economical earth stations, P cannot be taken greater than 3 dB = 2.0.

Putting these values into Eq. (11):

$$(D+1)D^{7/3} = \frac{2.935 \times 10^{-5}}{1.42 \times 10^{-8} \times 2 \times 2} = 520$$

$$D = 6.2$$

D. 3. 3 Interference Between Two Wide-Deviation FDM-FM Signals

An expression is developed to relate the ratio of wanted to unwanted carrier power to the interference in a telephone channel, for the case of a wide-deviation FDM-FM signal interfering with a similar signal similarly modulated.

$$f_d = Df_b = \frac{B}{2}(D+1) \tag{1}$$

If the peak power of the multiplex signal is 12 dB greater than the average power, then

$$f_s = 0.251\ f_d = \frac{0.251B}{2}\ \frac{D}{D+1} = 0.1255\ B\ \frac{D}{D+1} \tag{2}$$

Assuming that the spectrum is Gaussian (which it approaches when D exceeds 2), and integrating the power from -2,000 to +2,000 cps relative to the carrier, we find, if $f_s >> 2,000$ cps:

$$\frac{C}{C_4} = \frac{\sqrt{2\pi}\ f_s}{4,000} \tag{3}$$

Inserting (2) in (3):

$$\begin{aligned} \frac{C}{C_4} &= \frac{\sqrt{2\pi}\ 0.1255\ B}{4,000} \quad \frac{D}{D+1} \\ &= 7.85 \times 10^{-5}\ B\ \frac{D}{D+1} \end{aligned} \tag{4}$$

Following the argument made in CCIR documentation that the interfered-with earth receiver reacts to noise-like interference just as it reacts to thermal noise,* we can write:

$$\begin{aligned} \frac{I_4}{N_4} &= \frac{I_c}{N_c} \\ I_4 &= N_4 \frac{I_c}{N_c} \end{aligned} \tag{5}$$

Now

$$\begin{aligned} N_4 &= KTB = 1.38 \times 10^{-23} \times 4,000\ T \\ &= 5.52 \times 10^{-20}\ T \end{aligned} \tag{6}$$

Inserting (6) in (5):

$$I_4 = 5.52 \times 10^{-20}\ T\ \frac{I_c}{N_c} \tag{7}$$

Since the interfering and interfered-with signals are similar:

$$\frac{I}{I_4} = \frac{C}{C_4}$$

and inserting (4) and (7):

---

*This is recognized to be an approximation, since the interfering signal is coherent. The exact solution involves a convolution of the two spectra and is complicated.

$$I = I_4 \frac{C}{C_4} = 5.52 \times 10^{-20}\ T \frac{I_c}{N_c}\ 7.85 \times 10^{-5}\ B \frac{D}{D+1}$$

$$= 4.34 \times 10^{-24}\ BT \frac{I_c}{N_c} \quad \frac{D}{D+1} \tag{8}$$

Formula (5) of Section 4.2.1 gives an expression for C as follows:

$$C = \frac{2.55 \times 10^{-27}\ BT}{N_c\ P} \quad \frac{1}{D^2\ (D+1)} \tag{9}$$

Dividing (9) by (8):

$$S = \frac{C}{I} = \frac{2.55 \times 10^{-27}\ BT}{N_c\ P} \quad \frac{1}{D^2\ (D+1)} \tag{10}$$

$$\times \quad \frac{1}{4.34 \times 10^{-24}\ BT} \quad \frac{N_c}{I_c} \quad \frac{D+1}{D} = \frac{5.89 \times 10^{-4}}{P I_c D^3}$$

D.3.4 Suppression versus Angle, in Beamwidth

An expression is developed to relate suppression at specified angles off the major lobe to the beamwidth of a circular antenna.

D.3.4.1 Antenna Gain versus Beamwidth

$$\text{Conical Gain} = \frac{\text{Area of sphere}}{\text{Area of spherical segment}} = \frac{4\pi\ r^2}{2\pi\ rh} = \frac{2r}{h}$$

$$r-h = r \cos \frac{\theta}{2}$$

$$h = r - r \cos \frac{\theta}{2} = r\left(1 - \cos \frac{\theta}{2}\right)$$

$$\text{Conical Gain} = \frac{2r}{r\left(1 - \cos \frac{\theta}{2}\right)} = \frac{2}{1 - \cos \frac{\theta}{2}} = \frac{4}{\sin^2 \frac{\theta}{2}}$$

$$\text{Actual Gain} = \eta \ \text{Conical Gain} = \frac{4\eta}{\sin^2 \frac{\theta}{2}} = \alpha$$

If θ is small, $\sin \frac{\theta}{2} = \frac{\theta_r}{2}$ and $\sin^2 \frac{\theta}{2} = \frac{\theta_r^2}{4}$

$$\theta_r = 0.01745\ \theta_d$$

$$\text{and} \quad \alpha = 52,500 \frac{\eta}{\theta_d^{\,2}} \tag{1}$$

$$\text{If} \quad \eta = 0.6, \quad \alpha = \frac{31,500}{\theta_d^{\,2}} \tag{2}$$

Compared to actual (nonconical) antenna beams, results from (2) are about 0.5 dB higher than if θ_d were the half-power (3 dB) beamwidth. Stated differently, for an actual antenna of gain α at its beam center, θ_d would give the beamwidth at slightly below the half-power points, the difference being negligible here.

D. 3. 4. 2 Suppression

The gain of an antenna with circular aperture can be written:

$$\alpha = 1.02 \times 10^{-17} \, \eta \, d^2 \, f^2 \tag{3}$$

In decibels:

$$\alpha_{dB} = -170 + 10 \log \eta + 20 \log d + 20 \log f \tag{4}$$

The gain $\Delta\theta$ degrees off the major lobe can be written*, according to CCIR documentation:

$$\alpha_{\Delta\theta} = 32 - 25 \log \Delta\theta \quad \text{decibels} \tag{5}$$

Suppression is the difference between gain on beam and gain off beam. Subtracting (5) from (4):

$$S_{dB} = -202 + 10 \log \eta + 20 \log d + 20 \log f + 25 \log \Delta\theta$$

If $\eta = 0.6$, as assumed in (2)

$$S_{dB} = -204 + 20 \log d + 20 \log f + 25 \log \Delta\theta$$

$$25 \log \Delta\theta = 10 \log \left[2.5 \times 10^{20} \frac{S}{d^2 f^2} \right]$$

---

*See CCIR Report 391, Radiation Diagrams of Antennae at Communication-Satellite Earth Stations, for Use in Interference Studies, Vol. IV, pp. 420-425, Documents of the XIth Plenary Assembly, Oslo, 1966. This CCIR reference should be used with caution, recognizing that it was intended as a guide to the average values of the sidelobes of large-aperture antennas. Some sidelobes will exceed this reference value. Examination of Figures 2 and 3 of the CCIR report also will show that the near sidelobes of well-designed actual antennas may be as much as 10 dB better than this reference. This suggests that careful attention to the suppression of the near-sidelobes would permit reducing the satellite separations below the values predicted by (8).

$$\log \Delta\theta = 0.4 \log \left[2.5 \times 10^{20} \frac{S}{d^2 \; f^2} \right]$$

$$\Delta\theta = \left[\frac{2.5 \times 10^{20} S}{d^2 \; f^2} \right]^{0.4} \tag{6}$$

Now setting (2) equal to (3):

$$\frac{31500}{\theta_d^{\,2}} = 1.02 \times 10^{-17} \; \eta \; d^2 \; f^2$$

$$d^2 \; f^2 = \frac{5.12 \times 10^{21}}{\theta_d^{\,2}} \tag{7}$$

Inserting (7) into (6):

$$\Delta\theta = \left[\frac{2.5 \times 10^{20} S}{\dfrac{5.12 \times 10^{21}}{\theta_d^{\,2}}} \right]^{0.4} = \left[0.0489 \;\; S \, \theta_d^{\,2} \right]^{0.4} \tag{8}$$

D. 3. 5 Sum of Set of Interfering Satellites

Assume that an earth station is receiving a signal from the center satellite in the figure below, and that this signal is interfered with by satellites A ... D and A'... D', spaced $\Delta\theta$ degrees along the stationary orbit. (The angle between the satellites as seen from the earth station is almost identical to the angle seen from the center of the earth.) What is the interference from all the interfering satellites as compared to the interference from satellite A ?

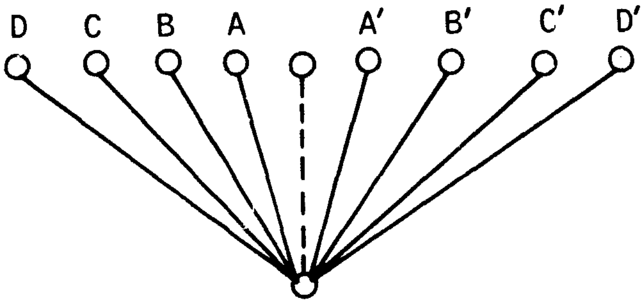

FIGURE 9. D. 3 Set of interfering satellites.

From equation (8) of Section D. 3. 4. 2,

$$S = K(\Delta\theta)^{2.5}$$

$$\frac{\sum \text{Interference}}{\text{Interference from A}} = \frac{2\left[\frac{1}{(\Delta\theta)^{2.5}} + \frac{1}{(2\Delta\theta)^{2.5}} + \frac{1}{(3\Delta\theta)^{2.5}} + \ldots\right]}{\frac{1}{(\Delta\theta)^{2.5}}}$$

$$= 2\left[1 + \frac{1}{2^{2.5}} + \frac{1}{3^{2.5}} + \frac{1}{4^{2.5}} + \ldots\right] = 2.686$$

The total interference is 2.686 times the interference from the adjacent satellite.

D. 3. 6 Suppression versus Angle, in System Parameters

From equation (10) of Section D.3.3, the suppression required between a wanted wide-deviation FDM-FM signal and a similar unwanted signal is as follows:

$$S = \frac{5.89 \times 10^{-4}}{PI_c D^3} \tag{1}$$

From equation (6) of Section D. 3. 4. 2, the suppression obtained $\Delta\theta$ degrees off the main beam is as follows:

$$S = \frac{d^2 f^2}{2.5 \times 10^{20}} (\Delta\theta)^{2.5} \tag{2}$$

Setting (1) equal to (2):

$$(\Delta\theta)^{2.5} = \frac{2.5 \times 10^{20}}{d^2 f^2} \qquad \frac{5.89 \times 10^{-4}}{PI_c D^3} = \frac{1.47 \times 10^{17}}{PI_c D^3 d^2 f^2} \tag{3}$$

$$\Delta\theta = \left[\frac{1.47 \times 10^{17}}{PI_c D^3 d^2 f^2}\right]^{0.4} \tag{4}$$

As an example of the practical application of this equation, assume that the total interference from adjacent satellites should not exceed 500 pWpO, that the frequency-deviation ratio is 3, corresponding to that inferred for INTELSAT-IV, and that the earth-station antenna diameter is 85 feet.

From Section D. 3. 5, the interference from the adjacent satellite should be about 200 pWpO if the total is to be 500 pWpO.

$I_c = 200 \text{ pWpO} = 3.54 \times 10^{-10}$ watts

$D = 3, \qquad D^3 = 27$

$d = 85$ feet, $\qquad d^2 = 7{,}200$

$f = 4 \times 10^9$ Hz $\qquad f^2 = 16 \times 10^{-8}$

$p = 4.8$ dB $= 3.0$

$$\Delta\theta = \left[\frac{1.47 \times 10^{17}}{3 \times 3.54 \times 10^{-10} \times 27 \times 7{,}200 \times 16 \times 10^{18}} \right]^{0.4}$$

$$= (44.6)^{0.4} = 4.57 \text{ degrees}$$

D. 3. 7 Maximum Capacity of 500-MHz Band with FDM-FM

Assume that the 500-MHz band is divided into N sub-bands B MHz wide and that 20 percent of the bandwidth must be reserved for filter crossover. Then:

$$NB = 0.8 \times 500 \times 10^6 = 4 \times 10^8$$

Assume further that each sub-band transmits n frequency division multiplexed voice channels by frequency modulation with peak frequency deviation D, such that the Carson's rule bandwidth just equals the width of the sub-band. When channel, group, and super-group filters are taken into account, each voice channel requires 4, 200 Hz of basebandwidth.

Total basebandwidth $= 4{,}200\, n$

Carson's rule bandwidth $= 8{,}400\, n\, (D + 1) = B$, and

$NB = 8{,}400\, n\, N\, (D + 1) = 4 \times 10^8$

The total one-way voice-channel capacity of the 500-MHz band is n N, and:

$$n\,N = \frac{4 \times 10^8}{8{,}400\,(D + 1)} = \frac{47{,}600}{D + 1}$$

What range in D can we expect in practical systems? At one extreme, there is no reason to expect that D will be less than unity because the spectrum does not continue to contract as D is reduced below unity. D = 1 thus represents a bandwidth-limited system. At the other extreme, it is shown in Section D. 3. 2 that the CCIR noise and breaking margin requirements appropriate to 4 GHz are met simultaneously where D is about 6. 2. This represents a power-limited system. Practical designs lie between D = 1 and D = 6. 2, and the range in voice-channel capacity is thus:

$$nN\Big|_{\substack{\text{frequency}\\\text{limited}}} = \frac{47,600}{1+1} = 23,800 \text{ one-way voice channels}$$

$$nN\Big|_{\substack{\text{power}\\\text{limited}}} = \frac{47,600}{6.2+1} = 6,600 \text{ one-way voice channels}$$

As an example of the present state of the art, INTELSAT-IV, working with standard earth stations, is expected to transmit about 12,000 one-way voice channels. On the basis of the arguments above this would correspond to D = 3.

It is of interest to observe that although the capacity of a single beam varies strongly with D, the total capacity of the stationary orbit, at least as measured by the ability of an earth station to separate adjacent satellites, is not strongly dependent on D, because when the number of channels per satellite is large, the spacing between satellites is also large, and vice versa. This is illustrated in Table 9. D. 1. Separation angle is computed according to equation (4) of Section D. 3. 6, and the channels per 500 MHz are computed as above. Relative satellite power is normalized on D = 6. 2. Below 6. 2, relative power varies according to equation (5) of Section D. 3. 2. 1, and above 6. 2 according to equation (6) of Section D. 3. 2. 2. The calculation of suppression is accurate only to about D = 30.

Although it would appear from this table that high deviation ratios are desirable, they may result in an unfavorable economic balance in the complete system because more earth-antenna beams are required to work with the lower-capacity satellites.

Also, it is suspected that a more accurate solution as mentioned in the footnote in Section D. 3. 3 would require greater separations at higher values of D so that the channels per degree of orbit might fall off at high deviations.

TABLE 9. D. 1

EFFECT OF D (PEAK FREQUENCY DEVIATION RATIO)

D	Separation* (Degrees)	Channels/ 500 MHz	Channels/ 500 MHz/ Degree	Relative Satellite Power
1	17. 05	23, 800	1, 390	137
2	7. 45	15, 900	2, 110	22. 9
3	4. 56	11, 900	2, 580	7. 67
4	3. 24	9, 500	2, 930	3. 43
5	2. 48	7, 900	3, 180	1. 83
6. 2	1. 91	6, 600	3, 450	1. 0
8. 0	1. 40	5, 290	3, 750	1. 08
10	1. 08	4, 330	4, 000	1. 18
20	0. 47	2, 270	4, 800	1. 48
30	0. 288	1, 540	5, 500	1. 70

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*For 85-foot earth-station antennas.

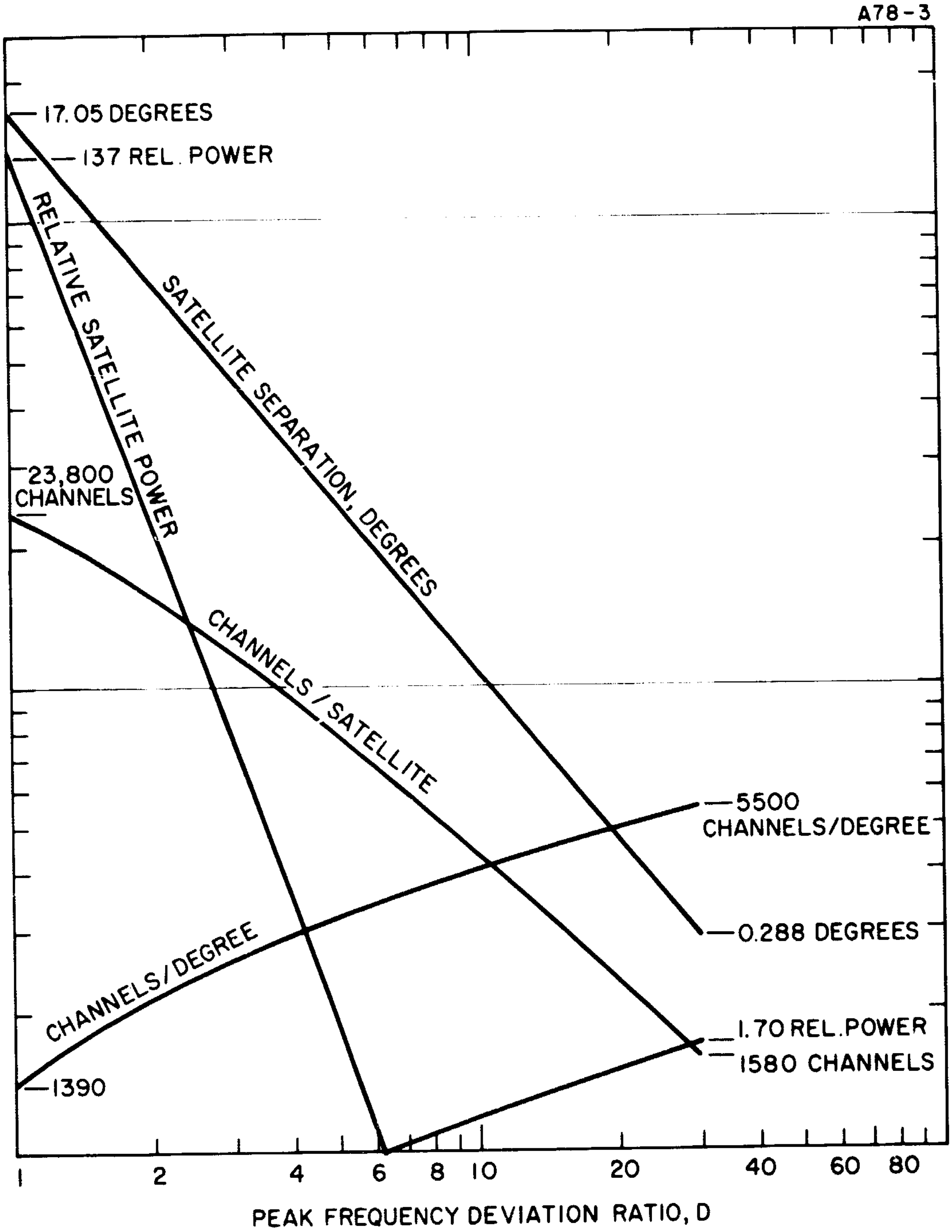

FIGURE 9. D. 4 Effect of deviation ratio, FDM-FM telephony.

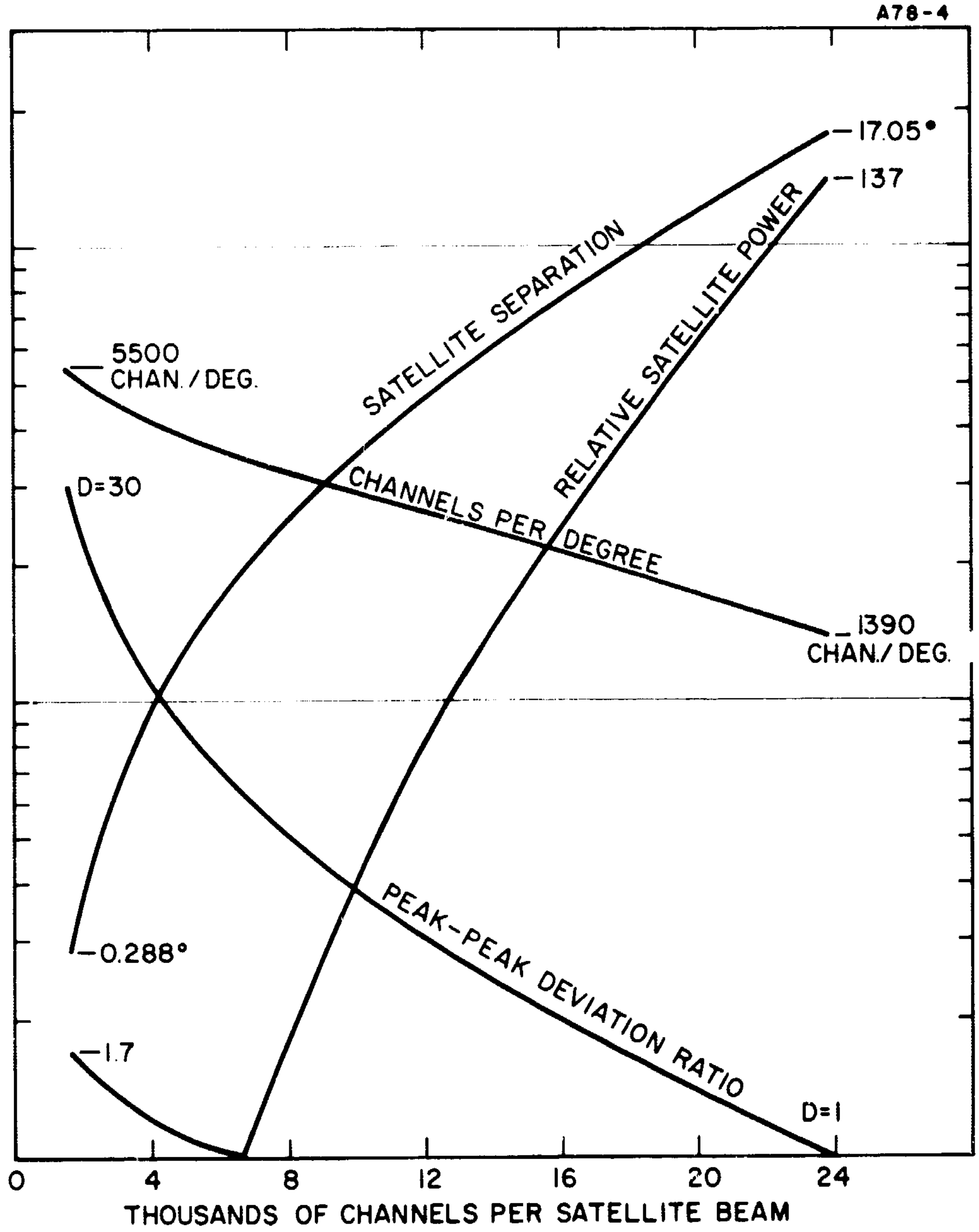

FIGURE 9.D.5 Orbit utilization, FDM-FM telephony.

Figure 9.D.4 shows the above data plotted as a function of the peak deviation ratio, to log-log scales. Additionally, Figure 9.D.5 shows a semi-log plot of the data against channels per satellite. Although a single-beam satellite has been implied, the results apply on a per beam basis to multi-beam satellites. These figures show that low deviation ratios achieve high channel capacities per satellite at the expense of greatly increased power, excessive separation of satellites and poor orbit utilization in terms of channels per orbit degree. At the other extreme, high deviation ratios appear to require many close-spaced satellites with few channels each to achieve only about a fourfold improvement in orbit utilization.

D.3.8 Maximum Capacity of 500-MHz Band with PCM-PSK

If a PCM signal is not filtered, it will occupy far more bandwidth than is necessary for accurate transmission.

If the system incorporates one-third cosine roll-off baseband filtering, then the first null in the baseband spectrum will occur at frequency $2/3f_b$, where f_b is the baud rate, and it is safe to assume that spectral content above that frequency can be removed without noticeable degradation. The radio frequency bandwidth of the two-sided spectrum is about $4/3f_b$, assuming low-index PSK modulation. It is necessary to increase the bandwidth 25 percent to allow for filtering crossover and higher order sidebands, so that the total width of the rf channel is $5/3f_b$.

The total baud rate that can be accommodated in a 500-MHz band is thus:

$$f_b = 3/5 \times 500 \times 10^6 = 300 \text{ megabauds.}$$

It is possible to increase the capacity of the band by using multilevel PSK, at the expense of providing a higher S/N ratio. Remembering that

$$\text{Levels} = 2^{\frac{\text{Bit Rate}}{\text{Baud Rate}}}$$

then

PSK Levels	Voice Channels in 500 MHz
2	4,560
4	9,120
8	13,680
16	18,240

The CCITT has not yet set standards for PCM transmission, and it is not possible to infer standards from those which have been set for FDM transmission because with PCM, imperfect transmission causes occasional clicks that cannot be compared with the thermal-type noise of FDM systems. It seems reasonable to design PCM systems for an error rate of 10^{-6}, and then to tolerate interference that will degrade the error rate one order of magnitude. A "worst-case" analysis leads to the following table, in which the total interference is divided among 10 possible interferences.

PSK Levels	Total Interference Ratio (dB)	Interference Ratio per Exposure (dB)
2	19	29
4	25	35
8	30	40
16	36	46

In the following table, the separation angle is computed according to equation (4) of Section D. 3. 6 and the capacity is taken from the first table in this section.

It is seen that 2-level PCM-PSK uses frequency space too lavishly, whereas 16-level PCM-PSK is too "soft" from the standpoint of interference. Although 4-level and 8-level are nearly equal, 4-level will require less transmitter power.

Levels	Separation* (degrees)	Channels/500MHz	Channels/500MHz/degree
2	1.25	4,560	3,650
4	2.16	9,120	4,200
8	3.44	13,680	4,000
16	5.95	18,240	3,060

Figure 9. D. 6 has been plotted from the above data.

D. 3. 9 A Spot Comparison of FDM-FM and PCM-PSK

The last table in the preceding section showed that four levels of PCM-PSK make better use of the orbit than more or fewer levels, and provide 9, 120 one-way voice channels in a 500-MHz band. The last table in Section D. 3. 7 showed that an FDM-FM system with D = 4 provides 9, 500 one-way channels. The PCM-PSK system yields 4, 200 channels per degree of orbit, whereas the FDM-FM system yields 2, 930 channels per degree of orbit.

What about the power required in the satellite? Is this increased orbit capacity at the expense of satellite power?

For FDM-FM, from equation (5) of Section D. 3. 2. 1.

$$\frac{C}{T} = \frac{2.55 \times 10^{-27} \times 400 \times 10^{6}}{1.42 \times 10^{-8} \times 3} \quad \frac{1}{D^2(D+1)} = 2.39 \times 10^{-11} \quad \frac{1}{D^2(D+1)}$$

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*For 85-foot earth-station antennas.

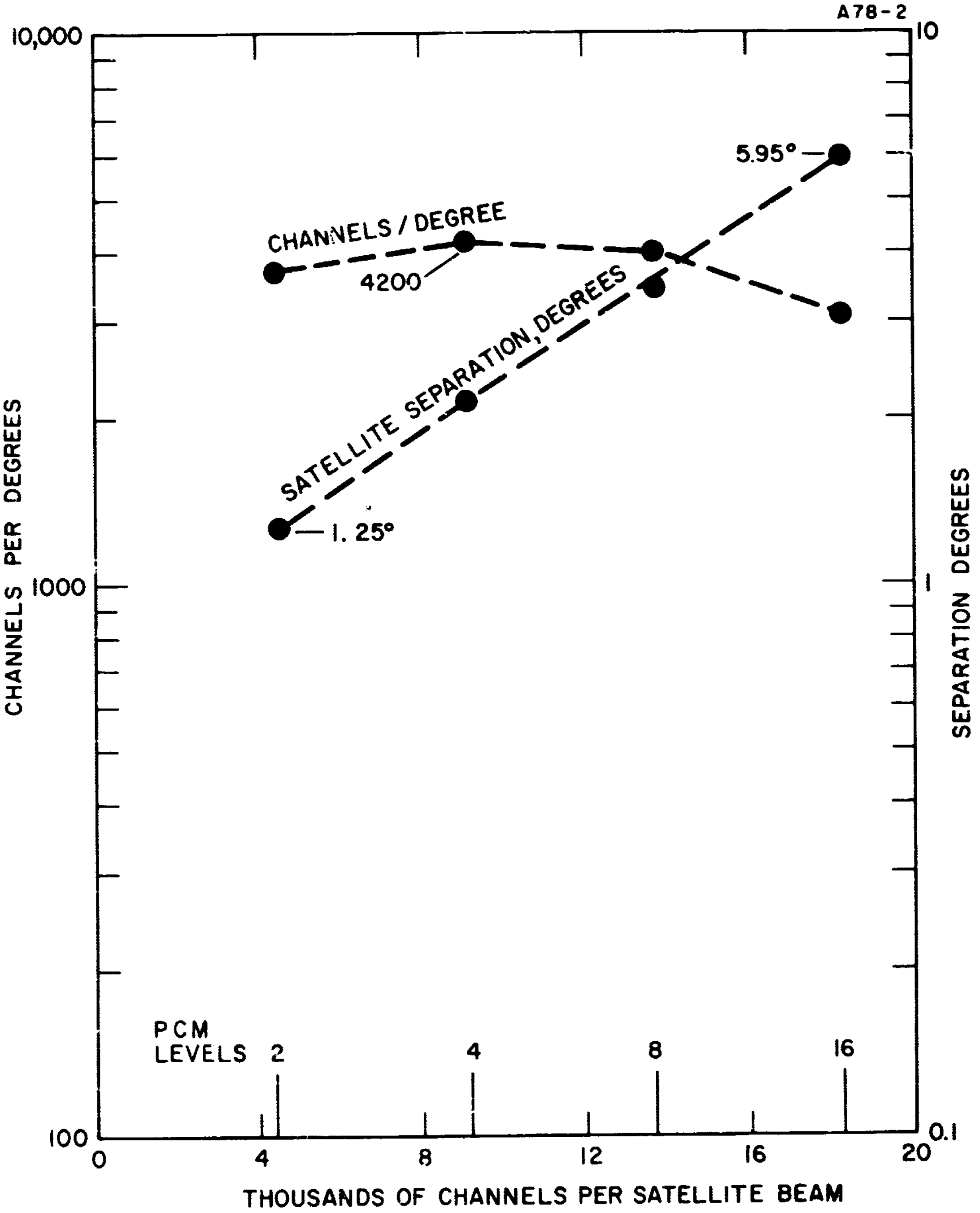

FIGURE 9. D. 6 Performance of multilevel PCM.

and for D = 4,

$$\frac{C}{T} = 3 \times 10^{-13} \qquad \text{(FDM-FM)}$$

For 4-level PCM-PSK, and an error rate of 10^{-6}, and making a 1-dB allowance for up-link and a 2-dB allowance for transmission degradations:

$$\frac{C}{N_{400\text{MHz}}} = \frac{2.5}{m^2}$$

For a Gaussian spectrum, which is desirable for interference coordination, the frequency-deviation ratio m should not exceed the inverse of the number of levels. For 4-level PCM-PSK:

$$\frac{C}{T} = 2.5 \times 16 \times 1.38 \times 10^{-23} \times 400 \times 10^{6} = 2.2 \times 10^{-13} \quad \text{(PCM-PSK)}$$

The two systems put essentially the same demands on the satellite and earth stations.

We conclude that PCM-PSK warrants further exploration for communication-satellite applications. We suggest experimental verification of what appears to be a considerable advantage in interference suppression. In this regard, we note parenthetically that PCM-PSK systems never have idle carriers as do FDM-FM systems, so the knotty problem of carrier dispersal during periods of light load is avoided.

D. 3. 10 Multiple-Beam Antennas: Coverage Area versus Interference Area

It is difficult to set out the interrelationships between multiple beams in a way that can be comprehended, because so many design choices are possible. An example will be constructed for frequency-modulated television. This is a less difficult case, and hence more favorable than frequency-modulated telephony, but it is more difficult and hence less favorable than PCM-PSK telephony and television.

It has not been found possible to compute interference between two FM television signals, so it is necessary to base the case on experimental observations. At least three such measurements have been reported, with results in close agreement. A 35-dB ratio of wanted to unwanted carrier power has been found to result in "barely perceptible" interference. These measurements were made with unity frequency deviation ratio, and by informed but unskilled observers. Satellite systems will use higher frequency deviation ratios, resulting in smaller ratios of wanted to unwanted carriers, but part of this advantage may be lost to more critical observation of the interference. Some studies have estimated a 30-dB requirement. This will be used here. It should be pointed out parenthetically that there is an urgent need for exactly pertinent tests, carefully observed.

With multiple-beam antennas, the number of interference exposures is multiplied along with the number of beams so that the objective applied to each particular interference must be less than with single-beam satellites. When both up and down directions are taken into account, with adjacent satellites, adjacent earth stations and adjacent beams, the requirement per exposure is likely to be about 40dB. (Some requirements may be higher, some a little less, because the overall objective will be allocated somewhat in accordance with the difficulty of meeting the separate requirements.)

In Section D. 3. 4. 2, the angle off the main beam, $\Delta\theta$, necessary to obtain suppression S is related to the beamwidth θ_d as follows:

$$\Delta\theta = \left[0.0489\ S\ \theta_d^{\,2}\right]^{0.4}$$

If S is 40 dB = 10^4, as discussed above, then

$$\Delta\theta = \left[0.0489 \times 10^4\ \theta_d^{\,2}\right]^{0.4} = \left[489\ \theta_d^{\,2}\right]^{0.4} = 11.9\ \theta_d^{\,0.8}$$

This formula was used with an approximation for the earth area illuminated by a conical beam to define the area within which excess interference will occur. The approximation is not very accurate at the angles involved, but it is accurate enough to make the point we will bring out. For comparison, the coverage area is also given. The coverage and interference areas assume the satellite is straight south of its coverage area and that the beam is aimed at 40° latitude. The areas are approximately elliptical, w miles wide (east to west) and h miles high (north to south).*

Beamwidth θ_d (degrees)	Satellite Separation $\Delta\theta$ (degrees)	Interference Area		Coverage Area	
		w (miles)	h (miles)	w (miles)	h (miles)
0.1	1.89	770	1,110	41	59
0.2	3.27	1,325	1,910	81	117
0.4	5.7	2,320	3,340	162	234
0.6	7.9	3,210	4,610	242	350
0.8	9.95	4,050	5,820	325	469
1.0	11.9	4,840	7,100	406	585
1.2	13.75	5,600	8,080	486	700
1.4	15.65	6,380	9,200	568	819

Figure 9. D. 7 has been plotted from the above data. Subject to the assumptions used, one sees that the area ratio is large, even for the broadest beams considered, and that it increases as the beams are narrowed. This tends to discourage area-coverage applications of multiple beams, in favor of directing very narrow and well separated beams toward known earth-station locations, leaving the intervening areas uncovered.

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*The widths and heights of these interference and coverage ellipses were calculated by an approximate method. For better accuracy and convenience, see RAND Memo RM-5228-NASA-Sept. 1967, The RAND Sync-Sat Calculator, by N. C. Ostrander.

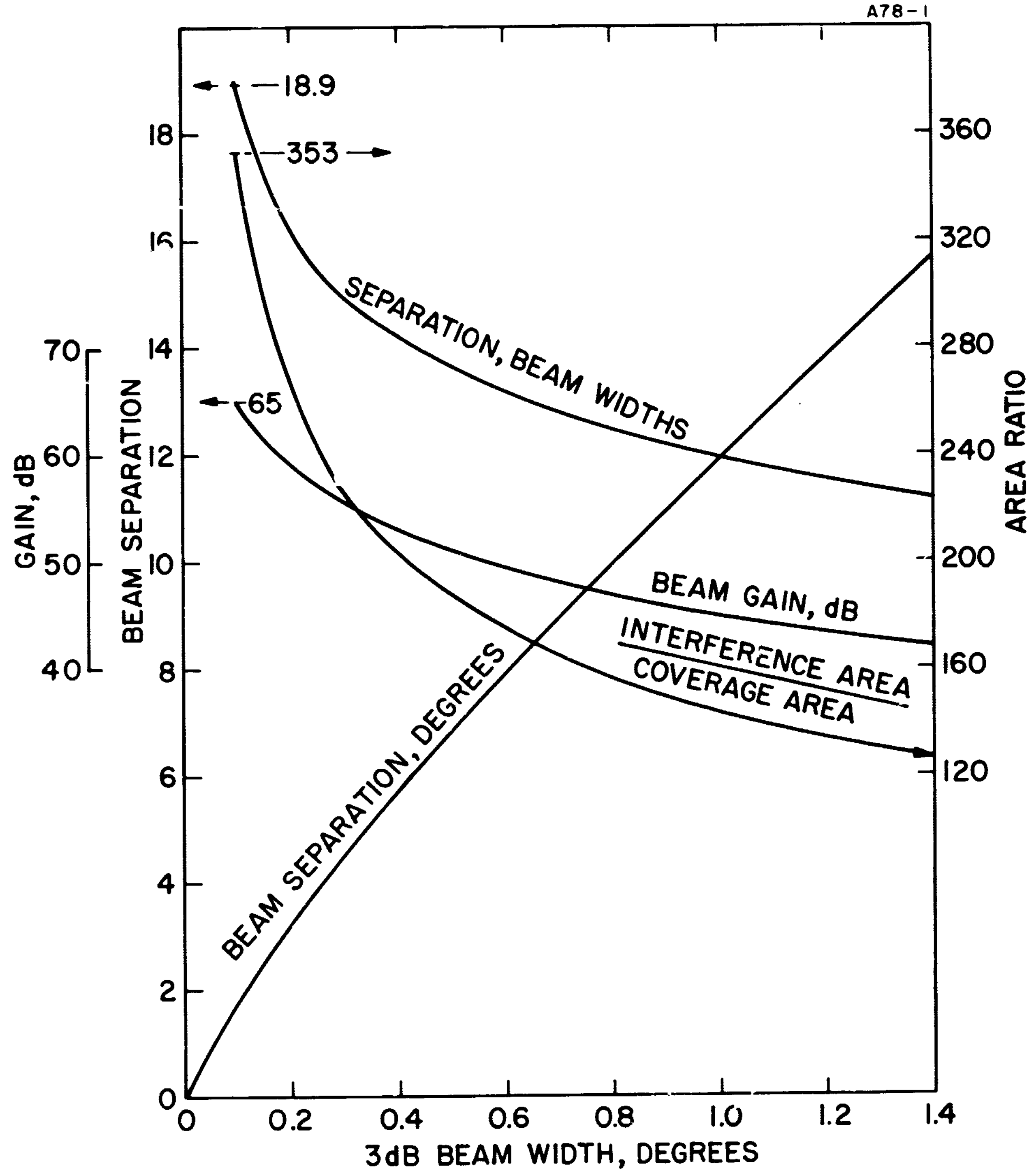

FIGURE 9. D. 7 Relations for multibeam satellites.

D. 3. 11 Time Zone Systems

Proposed applications for multiple-beam satellites are of two distinct types: (a) interconnection of specific cities, where the broad objective is to make the beams as narrow as possible and then reuse the same frequencies to as many cities as possible, and (b) services to several areas, such as time zones in the United States, reusing the same frequencies for at least two time zones. The table is encouraging to the first application, but not to the second unless some tricks are used. Fortunately, there are a few tricks available.

As an example of point-to-point service, if the beamwidth of the satellite antenna is 0.2 degrees, other beams can be aimed at cities 662 miles east and 662 miles west of the first beam, and also to cities 955 miles north and 955 miles south. In an area as large as the 48 contiguous United States, some ten such beams could be put down, if their spacing happens to coincide with cities to which service is needed. Practically, fewer beams than 10 would probably be preferable and this would give more possibility for maneuvering the beams to cities with large requirements for service.

As an example of the problem of area coverage, assume it is desired to cover four zones in the 48 contiguous United States, reusing frequencies in zones 1 and 3 and in zones 2 and 4. Each zone must be about 1,000 miles east-to-west by 1,800 miles north-to-south. The center-to-center distance between zones 1 and 3 or 2 and 4 is about 1,500 miles. The table shows that to meet the interference requirements, the coverage area cannot exceed about 100 by 150 miles. Conversely, if the coverage requirement is met, another beam cannot be used anywhere on the earth's surface.

What can be done?

1. The first possibility is to accept impaired service. This is unattractive because the customers are known to demand a very high grade service, and contrary to the telephone case, it is not possible to trade crosstalk for thermal noise.

2. The interference allowed to the various sources of interference could be reapportioned so as to favor adjacent beam interference at the expense of wider spacing between satellites, etc.

3. A reevaluation of the required ratio of wanted to unwanted carriers might result in an easier requirement.

4. The carrier frequencies of interfering beams could be staggered. Twenty MHz separation between carriers will reduce interference 20 to 30 dB, depending on the out-of-band selectivity and the AM-to-FM conversion characteristics of the receiver subject to interference. A separation of 40 MHz between interfering carriers would probably result in negligible interference. (These numbers have been calculated and need further experimental verification). This mode of isolation is usually counted on to permit simultaneous transmission to adjacent zones, such as 1 and 2, 2 and 3, etc., and cannot be used for adjacent zones, such as 1 and 2, and second adjacent zones, such as 1 and 3.

5. Cross-polarization discrimination, either from two linearly but perpendicularly polarized signals or from opposite circular polarized signals can provide as much as 30 dB suppression if the satellite antenna is very carefully designed.* Departures from reflector symmetry about the main beam

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*Appendix E calls attention to the fact that practical factors may limit the suppression to as little as 10 dB.

axis, illumination asymmetry, the likely use of small horn feeds, the incorporation of multiple feeds, reduction in focal length to fit constraints imposed by the launch vehicle, and the use of offset feeds all serve to worsen the polarization discrimination, and their effects need further investigation.

6. It is possible to devise combinations of frequency-staggering and cross-polarization, such as the following, which apply at least one benefit to each of the interference paths (V and H denote simply opposite polarization, and do not imply an endorsement of linear polarization.)

Satellite		Area 1	Area 2	Area 3	Area 4
S_1	Frequency set	A	B	A	B
	Polarization	V	V	H	H
S_2	Frequency set	B	A	B	A
	Polarization	H	H	V	V
S_3	Frequency set	A	B	A	B
	Polarization	V	V	H	H

Note that, in each area, adjacent satellites use staggered frequencies and polarization discrimination. Second adjacent satellites use neither and must get all their protection from antenna directivity.

7. It is possible to conceive of a neutralization matrix, using energy from one feed to cancel the interference on another.

8. There is a real possibility of improved antenna sidelobe performance by careful design.

In regard to point-to-point service, the smallest beam angle that can be used is determined by:

a. the degree to which the beams can be stabilized so that they do indeed hit their intended destinations,

b. the size of antenna that is practicable in view of the dimensional restrictions of possible launch vehicles, or the state of the art in antennas unfurled or assembled in space from pieces which do conform to the dimensional restrictions, and finally,

c. the spacing between earth stations of diversity pairs when system design considerations dictate that diversity is necessary.

Investigation is needed into stabilization arrangements capable of at least ± 0.1 degree beam accuracy and a lifetime of 10 years without excessive fuel or weight requirements.

As to antennas, it will be seen from the following table that if ± 0.1 degree accuracy can be obtained it will be feasible to use 10-foot apertures at 16 and 30 GHz, thus making full use of the launch vehicle dimensions. Furthermore, it makes unfurlable antennas attractive for point-to-point service at 4 and 6 GHz.

	d = 10 ft		d = 40 ft	
f (GHz)	Gain (dB)	Beam (degrees)	Gain (dB)	Beam (degrees)
4	40	1.8	52	0.45
6	43.5	1.2	55.5	0.3
16	52	0.45	64	0.11
30	57.5	0.24	69.5	0.06

(If the antennas are equipped with multiple-beam feeds, somewhat less than the full aperture will be available to each beam. To cover the 48 contiguous states of the United States for instance, the gain must be about 1 dB less and the beam will be about 12 percent wider.)

D. 3. 12 Nomenclature

B	occupied bandwidth, Hz
C	wanted carrier power, watts
C_4	power in that 4-kHz bandwidth about the wanted carrier containing most power, watts
d	diameter of aperture of antenna, feet
D	peak frequency deviation ratio = f_d/f_b
f	frequency, Hz
f_b	top baseband frequency, Hz
f_d	peak frequency deviation, Hz
f_s	rms frequency deviation, Hz
h	altitude of spherical segment
I	power of interfering carrier, watts
I_4	power in that 4-kHz bandwidth about the unwanted carrier containing most power, watts
I_c	interference power in a voice channel, watts
K	Boltzmann's constant
m	PCM-PSK frequency deviation ratio
n	number of voice channels
N_B	noise in occupied bandwidth B at receiver input, watts
N	number of sub-bands
N_3	noise in 3100 Hz at input to earth receiver, watts
N_4	noise in 4 kHz at input to earth receiver, watts
N_c	down-link thermal noise in a voice channel, watts
N_u	up-link fluctuation noise in a voice channel, watts

P	preemphasis advantage
r	radius of sphere
S	suppression
T	noise temperature of earth station, degrees Kelvin
W	baseband signal power, watts
w	width of coverage area (east-west), miles
α	antenna gain, numerical
α_{dB}	antenna gain, decibels
$\alpha_{\Delta\theta}$	antenna gain $\Delta\theta$ degrees off main lobe
η	antenna efficiency
ϑ_d	beamwidth, degrees
θ_r	beamwidth, radians
$\Delta\theta$	degrees off main beam

D. 4. 0 CODING AND SIGNAL RUGGEDNESS

Dan C. Ross

Efficient utilization of spectrum and orbital space is facilitated by employing "rugged" signals to reduce the effect of interference from adjacent bands and beams. As signal ruggedness is increased, a point of diminishing returns is reached at which the added resistance to interference is offset by the need for additional bandwidth as shown in the derivations in Section D. 2. 0 based on the Shannon limit and in Section D. 3. 0 based on FDM-FM and PCM-PSK.

Other well-known approaches to the design of rugged signals* include various spread-spectrum techniques such as pseudo-noise or code-division multiplexing and polynomial codes for forward error correction (FEC). Automatic request query (ARQ) schemes currently used for terrestrial data transmission would lead to inefficient use of synchronous satellite communications because of the long propagation delay, unless some other techniques were employed to reduce the number of times that the ARQ system is required to operate. FEC coding is quite feasible for use in satellite communications, not only for data transmission but also for telephone and other applications.

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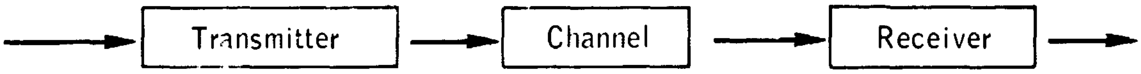
*See Digital Communications, Solomon Golomb, ed., Prentice Hall.

The purpose of this section is to indicate the applicability of FEC techniques to improve the efficiency of utilizing satellite-communication channels and to suggest the need to include coding along with modulation parameters in studies of optimum utilization of spectrum, orbit, and equipment costs. The utility of FEC will be illustrated by a simple example based on the binary transmission systems shown in Figure 9. D. 8. System A will be used as a point of departure to consider improvements in error rate by two different procedures:

1. Maintain constant signaling rate and increase transmitted power to yield System B.
2. Use FEC coding and increase signaling rate through the channel to maintain overall throughout; the result is System C.



System A without FEC

System C with FEC

FIGURE 9. D. 8 Systems to be compared.

The parameters of the three systems will be indicated by subscripts A, B, and C on the following symbols:

p	probability of error in one bit
b	transmitted block length of FEC code
n	maximum number of correctable errors
d	number of data bits per block
P_2	probability of error in one block
S^2	(k) (signal-to-noise power ratio) where k is a constant determined by the waveform of the signals transmitted over the channel and the reference band used for defining noise power

Consider a code with $b = 24$, $n = 3$, and $d = 12$. Such a code requires that the signaling rate through the channel of System C be greater than that in A by a factor of

$$\frac{b}{d} = 24/12 = 2 \tag{1}$$

The ratio of signal energy to noise energy involved in each binary decision is assumed to be inversely proportional to the signaling rate over the channel.

$$\frac{{S_C}^2}{{S_A}^2} = \frac{d}{b} = 1/2 \tag{2}$$

Assuming normally distributed noise, the probability of an error in one bit is given by

$$p = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{-S} dx \; e^{-x^2/2} = F(-S) \tag{3}$$

where F is the normal distribution function.

The probability of an error in a block of d data bits at the output of each of the three systems is given by:

$$P_A = 1 - (1 - p_A)^d \approx dp_A \tag{4}$$

$$P_B = 1 - (1 - p_B)^d \approx dp_B \tag{5}$$

$$P_C = 1 - \sum_{i=0}^{n} P_i = 1 - \sum_{i=0}^{n} \binom{b}{i} p_C^{\,i} (1 - p_C)^{b-i} \tag{6}$$

where P_i is the probability of exactly i errors in a block of length b.

For n = 3, i.e., triple-error correction, we have

$$P_C = \frac{b!}{4!(b-4)!} p_C^{\,4} - \frac{4b!}{5!(b-5)!} p_C^{\,5} + \frac{10b!}{6!(b-6)!} p_C^{\,6} - \cdots$$

$$P_C \approx \frac{b!}{4!(b-4)!} p_C^{\,4} \left[1 - \frac{4(b-5)}{5} p_C + \frac{(b-5)(b-6)}{3} p_C^{\,2}\right]$$

For the assumed code, we have

$$P_C \approx 10{,}626 \, p_C^{\,4} (1 - 15.2 \, p_C + 114 \, p_C^{\,2}) .$$

Suppose that the S/N ratio in System A is such that $S_A^{\,2} = 8$; then $S_C^{\,2} = 4$ from Eq. (1) and

$$p_A = F(-2.828) = 0.0024$$

$$p_C = F(-2.000) \approx 0.0228$$

i.e., about an order-of-magnitude increase in the probability o[illegible]t error. The corresponding probabilities of block error are

$P_A \simeq (12)(0.0024) = 0.0288$

$P_C \simeq (5.5)\ 10^{-4}\ (1 - 0.345 + 0.059) = 3.9 \times 10^{-4}$

i.e., a reduction by a factor of about 70.

Let System B have the same block error rate as C.

$P_B = 3.9 \times 10^{-4} \simeq 12\ p_B$

$p_B \simeq 3.2 \times 10^{-5} = F(-S_B)$

$S_B \simeq 4$

$(S_B{}^2)/(S_A{}^2) \simeq \frac{16}{8} = 2$

Thus, the use of FEC coding in this example yields about the same overall improvement as doubling the S/N ratio. The particular code in this example was chosen rather arbitrarily. Better choices can undoubtedly be made.

The problem of varying the choice of signal parameters to find optimum combinations for spectrum and orbital-space utilization is somewhat more involved with FEC codes than with classical modulation schemes. The code parameters are restricted to positive integers and not all combinations of b, d, and n correspond to feasible codes, while FM parameters, as an example from classical modulation, form a continuum. However, much is known about FEC codes and they may be readily examined by straightforward computer techniques.

FEC codes exhibit threshold effects just as in FM. The example given above was selected to illustrate the behavior of triple-error correction near its threshold where it tends to be "brittle," as does any "hard" modulation technique.

In addition to error-correction capability, most FEC codes also have a considerable error-detection power that can be conveniently employed in ARQ loops around a duplex circuit employing FEC in each direction. If sufficient FEC were provided for high-quality telephony, some data-transmission applications might require such outer ARQ loops to obtain overall transmission accuracy of the order of one error in 10^9 bits or better.

In general, it appears that FEC and similar forms of redundant coding are means of giving further "hardness" to digital transmissions in exchange for a reduced information bit rate where the basic bit rate (and bandwidth) is fixed. One obvious application lies in lowering the error rate to the values desired in digital data systems.

A salient consideration is that this coding can be introduced at the terminals, by the users, producing much the same effect as if the earth stations had changed to a harder form of modulation such as dropping from 4-level to 2-level PCM. Although the latter course might seem simpler and more direct, most users (of telephony for example) might prefer the higher bit rate despite its higher error rate.

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*See Error Rates in Data Transmission, Siegfried Reiger, Proc. I.R.E., May 1958, pp. 919-920.

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APPENDIX E

POINT-TO-POINT COMMUNICATION ANTENNAS

William E. Bradley
Spencer W. Spaulding

E. 1 Introduction

It has been pointed out in Section 2 of Appendix D that economical utilization of the frequency/orbit space depends heavily on the use of directional antennas. The requirements of the emerging satellite-communication art are exacting and novel in some respects, and in this section it is pointed out that attractive opportunities exist to improve performance and economy of both earth-station and satellite antennas while concurrently making efficient use of the spectrum.

E. 2 Steerability of Earth Antenna Beams

Concerning the earth-station antennas, Appendix C has shown the economic advantage of using high-gain earth antennas with today's international satellites and those of the near future, and for typical numbers of circuits per station. This high gain brings correspondingly narrow beamwidths, less than 0.14° at half-power points for an 85-foot parabolic reflector at 6 GHz. Such a narrow beamwidth, with correspondingly narrow sidelobes, has been a major factor in sharing frequencies with terrestrial services. Also, of increasing future importance, these narrow beams will permit stationary satellites correspondingly smaller orbit-separations and thus enable them to obtain correspondingly more orbital use—more channels per orbit degree.

Thus far, the commercial (INTELSAT) earth stations all have used full-tracking antennas. The usual large parabolic antennas produce only one beam and require rotation of a massive structure to change beam direction. Such a design evolved naturally from the large radar antennas of the past decade, from radio astronomy, and from the early use of low-orbit satellites with their requirement for tracking with whole-sky coverage.

Years before geostationary satellites became a reality it was pointed out* that such satellites should permit the use of fixed-reflector antennas,

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*S. G. Lutz, A Survey of Satellite Communication, Telecommunication Journal, ITU, Vol. 29 No. 4, pp. 107-112, April 1962 (Geneva).

S. G. Lutz, Twelve Advantages of Stationary Satellite Systems for Point-to-Point Communication, IRE Transactions PGSET Vol. 8, pp. 57-65, March 1962.

and that such antennas could employ relatively inexpensive earth-supported concrete structures, resembling tilted swimming-pools. A basic and understandable objection to the use of fixed parabolic reflectors has been the very limited control of the direction of the beam axis which can be achieved satisfactorily by moving the antenna feed. With parabolas having conventional ratios of focal length to aperture ($F/D \approx 0.4$) the beam shape and gain deteriorate excessively if the beam displacement is much more than one beamwidth. Thus far, no effort has been made to hold geostationary satellites on station to these tolerances throughout their life, though this should become possible in the future. Even if perfect stationkeeping were assured, however, there would remain apprehension (or claims thereof) of prolonged service interruptions, between failure of a satellite and the stationing of its replacement, even if this replacement were an orbited spare.

Without question, prompt hand-over would be desirable, following a satellite failure. Equally desirable but more impossible is the prompt repair of a damaged submarine cable! The practical question seems to be, "Over how great an arc need such a hand-over be made; one degree or one hundred?" Proponents of our fully steerable monsters point out that they can be steered to a replacement satellite within minutes, even if it is a hundred degrees away—but how useful would such a distant replacement be to all stations of the system considered? Satellite orbit stations may be critical in longitude, losing certain of the earth stations if moved even a degree east or west. Accepting more prolonged interruptions for a few such stations, one concludes that the hand-over arc could be two or three degrees but should not be much more than ten.

For such limited steerability along the orbit and near it, it becomes attractive to use simpler limited-motion pedestals for conventional parabolic reflectors. It should become even less expensive, however, to employ an earth-supported spherical reflector with a movable phase-correcting feed, as discussed later.

E. 3 Multibeam Earth Antennas

With a spherical reflector, it also would be possible to use multiple feeds to create multiple beams toward a corresponding number of satellites, accomplishing this at little additional antenna cost. Of course, the cost of the transmitting and receiving equipment for these additional beams cannot be neglected.

Such multibeam earth stations are of interest relative to heavy-traffic (domestic) systems, requiring a cluster of satellites. In such a system, each earth station might transmit to one satellite but receive from all. Alternatively, if intersatellite relaying were used, an earth station need receive only from the same satellite(s) to which it transmits. The choice between these two methods for using satellite clusters is not yet clear, but this use of satellite clusters does not appear imminent.

E. 4 Future Satellite Antennas and Problems

The role of satellite antenna gain and considerations relative to the use of multiple earthward beams have been discussed in Section 3. 3. 3, while the separation required between earthward beams for spectrum reuse was treated in Appendix D, Sec. 3.10. Briefly, the most challenging foreseeable need for multiple earthward beams is for heavy traffic "nodes-only" systems, where the individual beams can be sufficiently narrow relative to the beam separation to permit reusing the same frequencies without harmful interference. Area coverage by use of overlapping multiple beams seems to lead to little if any power advantage or spectrum reuse.

The maximum separation between earthward beams would be the angle subtended by the earth, about 17 degrees, whereas the minimum beam separation in a domestic system could be less than a degree. In the latter case, beamwidths less than a tenth degree would be required, but even today's standard earth stations have broader beams! This and other considerations suggest that the frequencies above 11 GHz would be of prime interest for such applications. In an even broader sense, the generation and control of a family of such earthward beams toward traffic nodes appears to be a new and challenging problem in antenna technology.

E. 5 Fixed Spherical Reflector, Movable-Feed and Multiple-Feed Antennas for Earth Terminals of a Satellite-Communication System

In this section, it is pointed out that cheap, large, multiple-beam antennas with each beam independently adjustable in angle are almost certainly feasible by adapting a type of antenna so far utilized only for special purposes such as radio astronomy. Especially attractive is the fact that such antennas need no active elements, unlike phased arrays that have sometimes been proposed. It is proposed that large fixed spherical reflectors be utilized instead of the more usual parabolic reflectors. Such reflectors may be cheaply constructed by excavation and reinforced-concrete lining, using plasterer's techniques to achieve a spherical concave surface to a tolerance of a few millimeters or less. A conductive surface attached to the concrete surface completes the reflector.

A spherical reflector will provide performance equal to that of a parabolic reflector if the portion of the sphere actually illuminated does not differ from a parabola by a dimension, parallel to the spherical radius of more than 1/16 of a wavelength. To meet this condition, the diameter of the illuminated area on the spherical surface, D, must not exceed a magnitude given by

$$D^4 \leq 8 \lambda R^3$$

where λ is the wavelength and R is the radius of curvature of the spherical reflector.

It is convenient to introduce the parameter θ equal to λ/D which is approximately the width of the main lobe of the beam measured in radians. In terms of θ,

$$D \leq 2R\,\theta^{1/3}$$

For example, if the beam angle is 1/125 radian or 0.46 degree, then if the radius of the spherical reflector is 100 feet, D is 40 feet, and the feed antenna should be located at a distance of 50 feet from the center of the reflector. In practice, the reflector should be extended beyond the calculated value of D to provide noise shielding and to permit beam-angle adjustment by changing the placement of the feed.

Use of a spherical reflector imposes the necessity for using a directional antenna for a feed to avoid any substantial illumination of the area of the reflector outside the desired diameter D. Alternatively, the feed may be designed to correct the spherical aberration for such wider zones of the reflector. The feed antenna should be placed at the midpoint of the spherical radius which is the continuation of the desired beam axis. To change the direction of the beam, the feed can be moved to other locations defined by the similar midpoints of sphere radii extending in those directions.

A 1,000-foot spherical reflector having a single movable feed that can move the beam ± 20° in any direction has been operated successfully for several years in Arecibo, Puerto Rico, for radio-astronomy purposes. The feed for this antenna is an end-fire array designed to deliver a broad conical pattern of radiation of nearly constant intensity within the cone and with a low sidelobe level outside it.

Spherical-reflector-movable-feed antennas six feet or more in radius have been used in some rapid-scan radar and radiometer apparatus and performed perfectly satisfactorily.

There is no doubt on theoretical grounds that such a reflector could serve many feeds simultaneously, each governing a single beam and movable to the extent necessary to permit adjustments. Such a design would be eminently suitable for earth terminals of a geostationary satellite-communication system. Such an antenna has several important advantages:

1. The fixed, earth-mounted spherical reflector can be inexpensively shaped to an accuracy of ± 1 millimeter and can be expected to retain its shape for a long time.
2. A spherical contour is easily fabricated with great precision.
3. The mechanism to change beam angle is required only to move the relatively small feed, weighing only a few pounds, and moving in translation along a circular arc. A relatively cheap, low-cost mechanism should be possible.
4. The directional-feed antenna required to limit the area of illumination also helps to discriminate against interference from terrestrial sources and can help to maintain low antenna noise temperature when required.
5. A single fixed spherical reflector can provide many beams. The cost to add a beam is only the cost to add one more feed. Each feed can be adjustable to occupy any position not already occupied by another feed.
6. There is an important possibility that interference received by a feed from a strong source not in its beam can be neutralized by placing a second identical feed so as to most strongly receive the interference and adding its output, properly attenuated and equally delayed, out of phase with the interference. Reduction of mutual interference between a set of geostationary satellites by cross connections between the several feeds corresponding to each satellite would be possible if satellite stationkeeping is accurate enough. (Such neutralization between large, independently located antennas of conventional design is impractical because of difficulties with RF phase stability over the widely differing and varying paths required.)

7. Beam-directivity pattern and sidelobe structure should be unaffected to the first order by change of beam direction. A spherical reflector has no preferred axis, and only when the illuminated area overruns the edge of the reflector will the directivity pattern of a beam be affected by beam angle.

E. 6 Phased-Array Antennas

Fixed-reflector antennas have advantages of simplicity and weight in many applications where a single beam, or at most a very few beams, are required in a fixed or relatively slow-changing geometry. Phased-array antennas have been developed primarily for radar systems in which multiple tracking beams are required and where the ability to switch a beam rapidly from one direction to another is at a premium. To date phased-array antennas have not found much application to communications systems primarily because the physical needs of the systems have favored solution by fixed-reflector techniques. Communications satellites of the future will have new demands placed on them and phased-array techniques may become attractive as solutions to these requirements.

The earth-orbiting data-relay system generates these requirements because:

Several tracking beams are required, readily switched from one direction to another.

Large apertures are required and phased arrays ease the mechanical tolerances required.

Location of users is not necessarily known to any central control point. Retrodirective phased arrays automatically respond with full gain in direction of a pilot tone transmitted by the user.

System requires high reliability and phased arrays have inherent redundancy.

Commercial point-to-point communications generate requirements because:

Many high-gain beams would reduce earth-terminal requirements for users but beams must be reprogrammed to allow for new entries to the system.

Multiple beams facilitate reuse of the spectrum.

Time division multiplexing can be coupled with rapid beam switching to provide a unique, high-capacity, flexible interconnect system for multiple access.

The phased-array antenna can be made in a plane. Retrodirective arrays can be made very tolerant of first-order deflections or errors in the plane. This facilitates deployment of the antenna compared to large-aperture parabolic or spherical reflectors.

The retrodirective phased array is made up of many small transponders, each feeding its own antenna element. The phase of the signal being processed is derived within each transponder from a pilot tone received from the user. Thus, beam forming and switching are automatic and instantaneous, requiring no information other than the pilot tone and a common phase reference distributed to each element of the array. The addition of all the individual transponder elements is done automatically in the interference pattern of the far field. Since several dozen or even several hundred elements are used in a single array, failure of some of the elements has no significant effect on the overall performance. This leads to high reliability for spacecraft antennas.

Each element of an array is low-powered, which permits the use of solid-state devices of potentially lightweight design. In particular, integrated RF circuits for each transponder are a possibility.

For these reasons the retrodirective array has considerable promise for satisfying the future requirements of both orbital relay systems and commercial communications.

The needs of other systems such as direct television broadcasting can also be served by such arrays. While such applications are not considered here, the application to broadcast satellites should be further coordinated. Generation of large amounts of RF power in a phased array alleviates a difficult cooling problem and also enhances the reliability. This suggests that phased-array developments may have direct interest to other missions.

Further development efforts of the retrodirective phased array should include both system and component level of detail. System consideration should include reuse of the spectrum, sidelobe control, application to time-division multiplexing and packaging and deployment. Component studies should be directed toward lightweight, multichannel transponder designs using RF integrated circuits. Frequencies in the UHF, S-Band and C-Band should be included in such component developments.

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APPENDIX F

INTERFERENCE BETWEEN SPACE AND TERRESTRIAL COMMUNICATIONS SYSTEMS

F. J. Altman

F. 1 The Interference Problem

The problem of interference arises between stations in the space service and those in the terrestrial service where they share the same frequency bands. For example, communication-satellite and terrestrial radio-relay systems have common allocations in the 3, 700-4, 200 and 5, 925-6, 425 MHz bands. To control potentially harmful interference, limits have been placed on station power and spacings, which result in turn in limitations on space-service capabilities with regard to maximum number of channels, minimum antenna size, and closeness of earth stations to users. As there are many areas of uncertainty in the derivation of these limits that may be unduly penalizing one system or the other, it is important to perform studies and experiments to minimize these areas. Questions of interference within the space service will not be considered in this appendix.

F. 2 Background Information

The restrictions on the sharing services were set at the Extraordinary Administrative Radio Conference (Geneva, 1963), based on the recommendations of the CCIR, which continues to study such matters. It is, therefore, appropriate to use the CCIR basis in general and the particulars wherever appropriate.

The categories of interference of interest are shown in Figure 9. F. 1, where it may be noted that the up-link and down-link cases concerned with the satellite involve line-of-sight transmission and antenna gain uncertainties. On the other hand, the purely terrestrial cases involve major uncertainties in high-level tropospheric and rain-scatter propagation.

Many of the factors concerned in determining the limitations on the services are subject to fairly precise analysis or bench experimentation, such as modulation technique, carrier dispersal, and (receiver) interference reduction factor. The less easily definable factors are considered in further detail below as appropriate matters for NASA's study program.

F. 3 Terrestrial Interference Problems

Possibly the most difficult interference problem is estimating the tropospheric transmission loss likely to be exceeded 99. 99 percent of the worst month between two stations on the earth's surface. The propagation phenomena involved are anomalous, and, because of the small percentage of

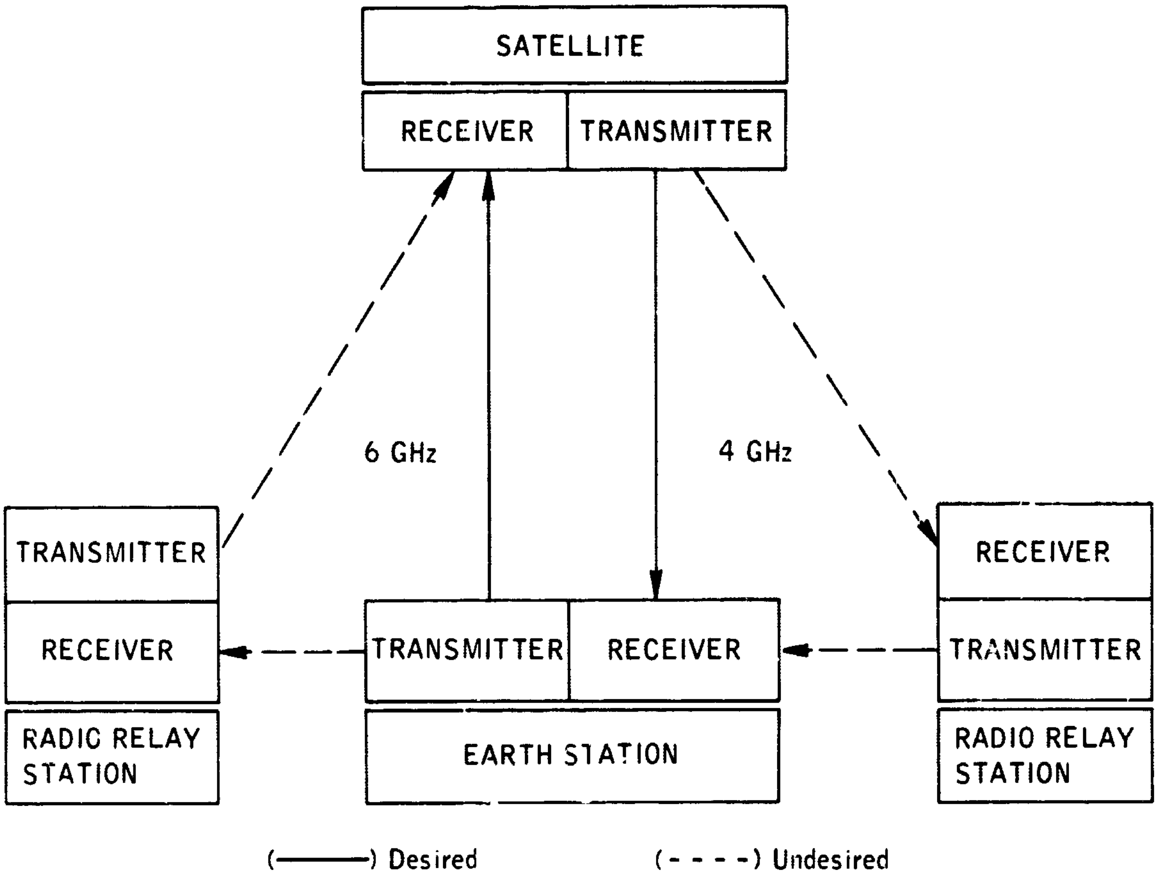

FIGURE 9.F.1 Desired and undesired paths.

time which is of interest, adequate useful data can be collected only over long periods of time. It is, therefore, of utmost importance to attempt to isolate contributory mechanisms and to determine meteorological correlations facilitating predictions based on the large data base of climatological observations, extensive both in time and space. This general area is the subject of the CCIR Question discussed in Doc. IV/317, Oslo, 1966. Two major classes of propagation are involved.

On-path or great-circle tropospheric transmission loss has been the subject of study by CCIR Study Group V and others for a long time, but the difficulties in the anomalous high-signal case may be seen from the fact that the applicable CCIR Report 244 provides three alternate methods of estimation for even the relatively regular low-signal case. A typical important problem may be seen in the small allowances for site-shielding factors even though the shielding high terrain will normally break up the ducting which gives rise to large coordination distances, especially over water.

Off-path or off-great-circle propagation due to precipitation, aircraft, or other scattering is still less understood, although recent experiments by the FCC (POPSI) and others have indicated that it may be a serious problem.

F. 4 Up-Link and Down-Link Interference Problems

The unknown factors at the heart of the up-link and down-link problems are the upward-directed gains of earth-station and radio-relay antennas and the aggregates thereof as viewed from various orbital locations. To determine these factors as well as any other important illumination from the earth factors, full-scale experiments with a satellite in space will be required, although careful measurements are desirable on the periscope or fly-swatter types of antennas for which upward patterns are not available, but which are large contributors to upward flux.

It will be important to know this upward flux to permit appropriate reduction of earth-station transmitter power until up-links and down-links contribute equally to the noise budget. This was not possible when the down link was severely power-limited, but this limitation is being lifted by advances in launching capability, satellite stabilization, satellite antenna gain, and both primary and secondary power generation. It will also be necessary to consider interference noise contributions from actual or potential adjacent satellites for some applications requiring multiple satellites each with multiple beams.

This problem is of special interest in connection with regional satellite systems in which restricted or small-angle, high-gain satellite antenna beams will not be radiating directly into as many terrestrial station antennas as assumed in deriving flux-density criteria. It may be possible from the recommended experiments to increase the number of channels per MHz or to reduce the antenna sizes or both, with large potential benefits for both communications and broadcast systems.

F. 5 NASA Interference Program Evaluation

The NASA program in this area has been addressed to the most critical problem, terrestrial interference. The existence of precipitation scatter at a harmful level has been demonstrated by the Institute for Telecommunication Sciences Administration (ITSA) and by the Stanford Research Institute (SRI), and its occurrence has been estimated by both ITSA and Communications & Systems, Inc. As the Precipitation and Off-Path Scatter Investigation (POPSI) experiments of the FCC indicated clear-air side-scatter beyond that expected, NASA is proposing to conduct an additional experimental program for the Director, Telecommunications Management (DTM) (provided funding is possible) to verify or explain and dismiss the preliminary indications. These programs have incurred a very low expenditure to produce vitally needed information. It has already been shown that it is undesirable to permit earth-station and radio-relay antenna-beam intersections, but that stations with nonintersecting beams may be located within 10 miles of each other, at least so far as precipitation scatter is concerned. If this mechanism is found to be controlling for an extension of the POPSI tests, then it may be possible to locate TV distribution earth stations on top of TV Control Centers instead of at remote locations requiring connecting links at as much as one million dollars each.

F. 6 NASA Interference Program Recommendations

Especially in view of increasing pressures to abandon the shared bands before high ones are thoroughly investigated, it seems essential to verify the basis for the current restrictions and to increase the overall interference program in several areas. The first is the provision in ATS-F and G, or if possible sooner, of a high-gain antenna capable of accurate noise measurements through the 5925-6425 MHz band in order to verify up-link constraints.

Terrestrial interference problems are not susceptible to equally straightforward solutions, but at least an equivalent effort seems in order to provide a basis for answers required even in the higher bands regarding rainfall distribution, ducting, and the like. To this end, the experiments being planned for the DTM, which might be termed TOPSI for Tropospheric Off-Path Scatter Investigation, should be considered as more than an evaluation of POPSI. The following specific items are recommended:

F. 6. 1 POPSI Evaluation

First priority must be given to deciding whether off-path clear-air scatter can produce harmful interference. This requires new data with the POPSI beam-angle configurations, but with sites not high above the average surrounding terrain, with antennas having very low sidelobes, and with carefully controlled calibration routines. If POPSI results are confirmed, large-scale experiments, probably including Wallops Island, will be required to characterize quantitatively the new mechanism under various meteorological conditions in several climates.

F. 6. 2 Precipitation Scatter

If off-path clear-air scatter is found not to be controlling, then chief emphasis should be placed on off-path scatter by precipitation because of its ability to nullify site-shielding and create harmful interference at long range via the large hail frequently found at 50, 000 feet in thunderstorms. Confirmation of the methods of calculating this interference should be part of the TOPSI experiments, but the preferred method of creating the required data base regarding a rare phenomenon (0. 01 percent level) is to use the large number of weather radars throughout the country with appropriate modifications to provide three-dimensional reflectivity data extensive in time and space. This technique has been demonstrated by the Stormy Weather Group of McGill University, and others. The same basic instrumentation, with additional analytic capability, will provide information regarding spatial correlation of reflectivity, useful for determining the diversity spacing essential to using higher-frequency bands above 11 GHz. Studies should be initiated to determine the accuracy to be expected in estimating attenuation from reflectivity considering effects of frequency, type and size of precipitation, and averaging in time and space.

F. 6. 3 Aircraft Scatter

The problem of aircraft scatter interference should be evaluated by considering typical traffic patterns and bistatic radar cross sections. These should be determined experimentally if sufficient data are not available.

The TOPSI experiment should be used to confirm such analytical studies of the severity and occurrence of aircraft scatter. Commercial or military flights should be used if possible but special flights may be required if the TOPSI paths cannot be suitably located with respect to normal traffic.

F. 6. 4 On-Path Trans-Horizon Interference

In view of the uncertainties of predicting on-path interference using CCIR Doc. V/244, it would be very desirable to increase the applicable data base by instrumenting military troposcatter links. Many of these are subject to ducting that will make the normal receiver nonlinear but which, therefore, can be recorded directly from the input waveguide by a video receiver. Such a receiver, recording only time that signal is above a preset level, would be very cheap and yet useful.

F. 6. 5 Additional Experiments

There are several other desirable studies that are not necessarily related to the TOPSI program:

1. Definitive experiments are needed regarding the subjective effects of common-carrier interference with television relaying via the high deviation index frequency modulation appropriate for satellite transmission, and with different amounts of and schemes for carrier dispersal.
2. A study is desirable regarding the obscuration of a terrestrial station beam by intervening rough terrain. If it cannot be shown analytically to be simply calculable, field measurements by airplane may be required.

APPENDIX G

FREQUENCY ALLOCATIONS ABOVE 11 GHz

Hayden W. Evans

The history of radio communications has been a continuous push to higher and higher frequencies to make room for burgeoning needs. The upward push in radio frequencies has met the downward push in optical frequencies as communication engineers look for "windows" in the atmosphere where absorption is not excessive. An example is shown in Figure 9. G. 1,* which covers the range from 10 GHz to the upper frequencies of visible light. We look with interest at the lowest frequency window, from 10 to 50 GHz.

This lowest frequency window is shown in more detail in Figure 9. G. 2.** It contains a water vapor absorption line at 22.5 GHz and is terminated by the oxygen absorption line complex at 60 GHz. The attenuation of a signal from a satellite by the water vapor line depends on the elevation angle of the earth station antenna and the water vapor content of the air, which is not constant. These factors suggest that for most favorable operation very low elevation angles should be avoided. This suggests in turn that these frequencies may be more useful for regional systems than for international systems which are frequently pushed to maximum possible range. This is a fortunate conclusion, because, a priori, regional demands will always be larger than international demand.

This appendix is addressed to three questions that will be discussed in the three sections to follow.

1. Are frequencies above 11 GHz useful for commercial satellite systems and what needs to be known to ensure that they are efficiently used?
2. If these frequencies are useful, then what bandwidths at what frequencies are needed and is their allocation justified, taking into account other possible users of these frequencies?
3. What conditions should be attached to these allocations such as are attached to the present allocations at 4 and 6 GHz?

These three questions relate to "usefulness," "need," and "conditions," and these are the headings of the following sections. It would seem that a justification of need should precede a study of usefulness, but we have chosen to invert the order so as to establish that these frequencies are useful enough to warrant their application.

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*Taken from Windows in Space (from 10^{10}Hz up), by R. Kompfner, presented at American Astronautical Society symposium, Dallas, 1967.

**Taken from Communication Through the Atmosphere at Millimeter Wavelengths, D.C. Hogg, published in Science in Jan., 1968.

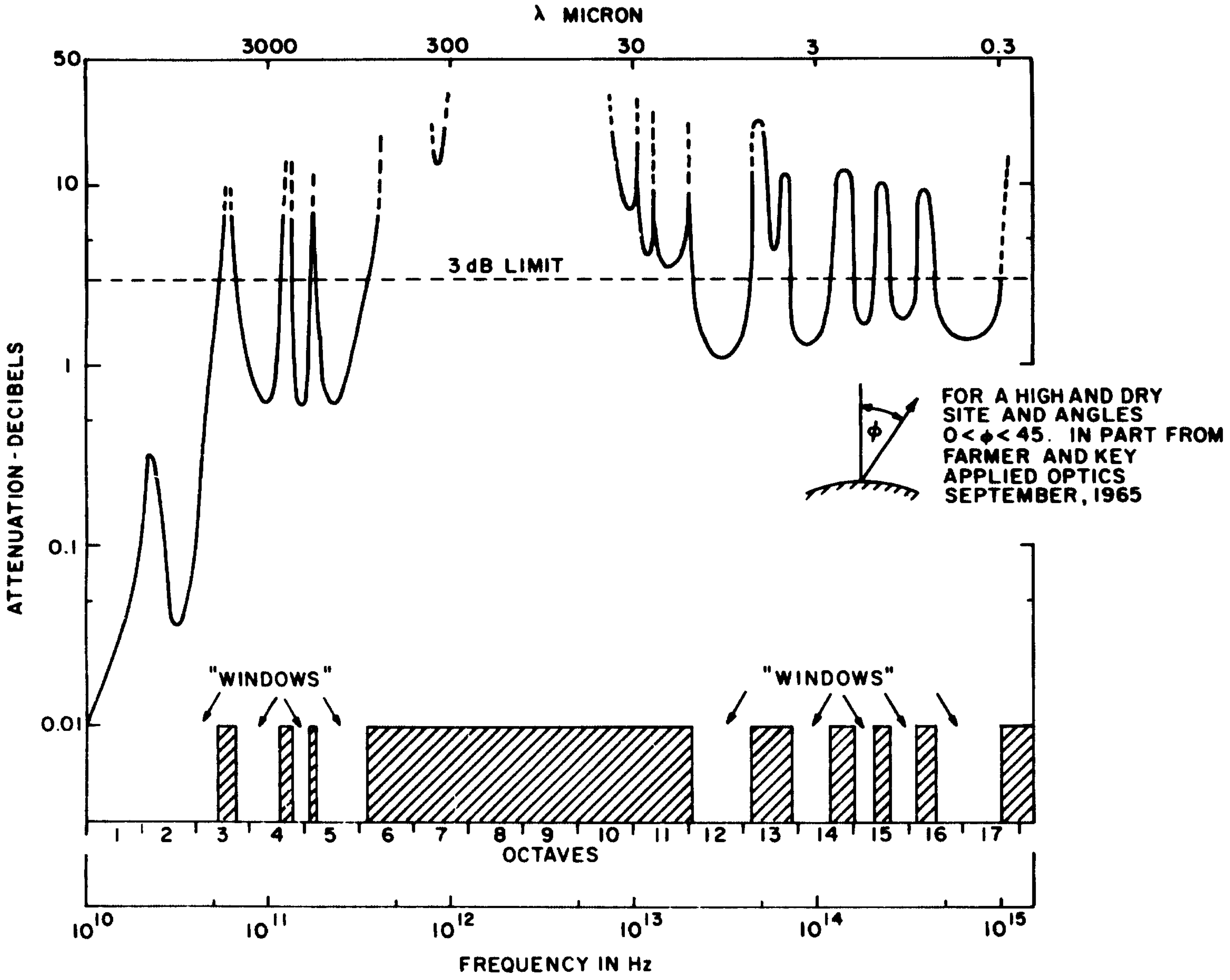

FIGURE 9. G. 1 "Windows" in atmosphere.

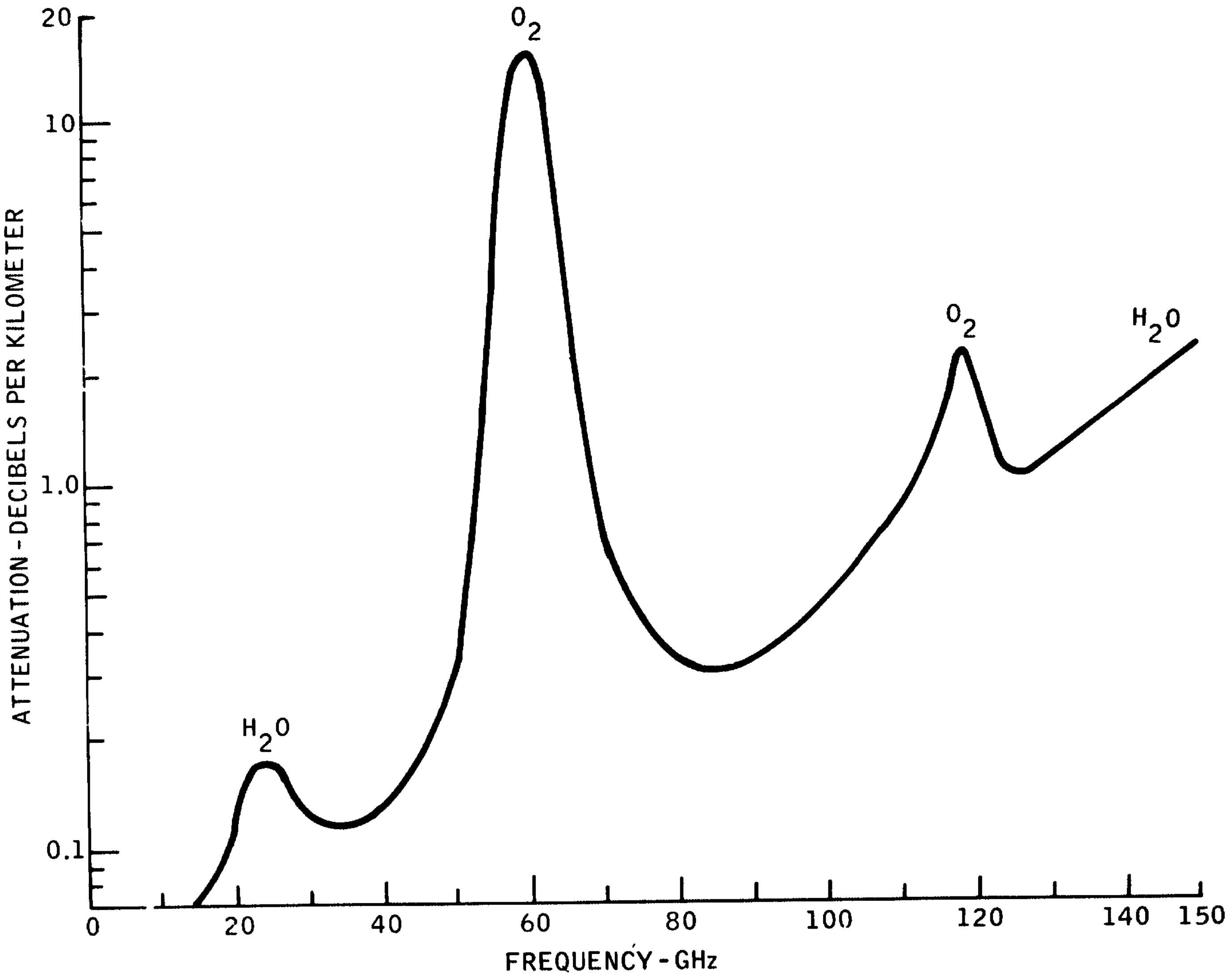

FIGURE 9.G.2 Effects of water vapor and oxygen.

G. 1 Usefulness of Frequencies Above 11 GHz for Commercial Satellites

Figure 9. G. 2, which shows the effects of water vapor and oxygen, does not tell the whole story of usefulness of frequencies above 11-GHz for satellites. Radio transmission above 11-GHz is known to be seriously affected by rain and rain-bearing clouds that increase both path attenuation and receiver noise temperature. These effects are less serious to satellite systems, however, and particularly to regional systems, whose beams escape the rain region in only a few miles. In contrast, terrestrial radio relay beams lie in the rain region from one end of the system to the other. For this reason, we believe it is unlikely that these frequencies will be used extensively for long-haul, heavy-route terrestrial radio relay systems, so that problems of sharing will be much less serious than at 4 and 6 GHz. Similarly, we believe that these frequencies can be used by communication satellite systems, provided the propagation statistics are available by which the systems can be engineered.

Numerous progagation tests have been made in this frequency range over the past 20 years*, principally to correlate attenuation on terrestrial paths with rainfall observed at ground level. The physics of the increases in attenuation and noise are understood, not perfectly, but well enough. To apply these near-earth data to paths to satellites, it is necessary to know the statistics of rainfall aloft, and here data are scant.

There are two ways to acquire a body of statistics on rain effects on satellite paths, the direct and the indirect. The direct method involves measuring increases in attenuation and noise from some signal source outside the atmosphere, either a man-made satellite or some natural sky source. The sun is the only reasonable candidate for the latter. The indirect method involves characterizing the micrometeorology of clouds containing rain by specially equipped weather radars for instance, and inferring the total effect on a satellite beam transiting the cloud by theory or by extrapolation based on terrestrial data.

Experts do not agree as to which method is best. Proponents of the indirect method argue that 65 weather radars now exist and could be modified to produce data in the form required. Machine analysis methods can be made available. They argue that this method will produce a mass of geographically diverse data faster than the direct method can be instrumented.

Proponents of the direct method question the accuracy of the indirect method, particularly regarding its significance to the 11- to 60-GHz range. They question the accuracy of the radar in accurately defining the density of rain and they question the accuracy of extrapolating data taken in the centimeter range, where weather radars must operate in order to penetrate the storm, to the millimeter range. They argue that a proof test would be necessary in any event, so why not accumulate the required mass of data by a method closest to its application?

We recognize that geographically diverse data can be obtained quicker by the indirect method than by the direct. We also recognize that these data

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*Many of these tests are summarized in Rainfall Attenuation of Centimeter Waves: Comparison of Theory and Experiment, R. G. Medhurst, IEEE Transactions on Antennas and Propagation, July, 1965.

have other important applications, that justify their prosecution, such as the effect of rain scatter at 4 and 6 GHz on sharing between satellite and radio relay systems. At the same time, we suggest that the indirect tests are an inadequate substitute for direct tests.

Other propagation problems have to do with (a) the bandwidth that these frequencies will support and (b) the statistics of rain-scatter propagation as it affects frequency sharing. Again, there is disagreement among the experts. Some argue that if bandwidth were a problem, large antennas at these frequencies would evidence degraded gain or increased path coupling loss, and interferometer radio astronomy antennas would be bothered by beam distortion and line broadening. These effects, they say, have not appeared. On the other hand, scintillation is an admitted propagation characteristic, and it can be argued that if a path scintillates, its bandwidth is less than infinite. We see no other course than to support tests designed to resolve the question.

Conclusions and Recommendations

We see the following problems:

1. There is need to know the distribution of increases in attenuation and noise due to rain and rain-bearing clouds:
   a. versus frequency above 11 GHz, and
   b. for the different climatological regions of the North American continent.
2. Assuming that earth stations will be arranged in diversity pairs, there is need to know:
   a. the proper spacing between stations of a diversity pair, and
   b. the proper margin for each station, for various degrees of overall system reliability.
3. There is need to know the bandwidth that radio propagation will support at these frequencies.
4. There is need to know whether scatter propagation from rain is as serious at these frequencies as it is at 4 and 6 GHz.

We recommend the following:

1. In regard to the propagation part of the millimeter wave experiment of NASA's ATS-E satellite, we strongly approve the program and urge that it be accelerated if possible and that the hours budgeted to this experiment be increased if possible. We urge that the number of participating observatories be increased if possible, by support if necessary, to cover as large a climatological range as possible. (We do not attach high priority to adding observatories outside the Americas, where it is not apparent that frequencies above 11 GHz are urgently needed). We urge that the participating observatories be supported to the maximum possible hours of operation.
2. In regard to the phase coherence part of NASA's ATS-E experiment, we recognize that there is difference of expert opinion on whether this effect is serious and we approve the scale of its inclusion in the program.

3. In regard to sun-tracker experiments, we recognize that they are complementary to the ATS-E program, and have some advantage in that they are not keyed to a launch schedule or completely dependent on launch success, and that the test frequency is not geared to the instrumentation in the satellite. This experiment accumulates a slightly different mass of data than the ATS-E experiment, in that the sun runs the gamut of elevation angles every day, and we see that this will add a new dimension to the ATS-E data. We would hope that this experiment could be duplicated in various parts of the country.

4. In regard to required spacing between diversity earth stations, we note that the only instrumentation now planned that bears on this problem is a grid of terrestrial rain gauges that will yield instantaneous earth surface rainfall contours. We recognize the value of this, but at the same time, we would hope that diversity pairs of ATS-E earth stations or sun trackers might be instrumented.

5. In regard to rain-scatter interference, we know that some theoretical studies predict that the scatter-propagated power will be attenuated faster than it is produced, but we wonder whether this will happen under all rain profile conditions. We suggest that the earth stations being instrumented for ATS-E and sun tracking might be arranged to receive a distant transmitter during hours when ATS-E or the sun is not available. Even though we do not anticipate that frequency sharing will be widespread, we note that the history of terrestrial communications is characterized by continual progress to higher frequencies.

6. In regard to weather radar measurements, we recognize their value to predicting rain-scatter propagation at 4 and 6 GHz. We also recognize that their results can be extrapolated to predict performance at frequencies above 11 GHz, although there is serious question as to the accuracy of this. Nevertheless, weather radar measurements offer the opportunity of accumulating a geographically diverse mass of data faster than any other method. We, therefore, support them.

G. 2 Need for Frequencies above GHz for Commercial Satellites

Estimates of U. S. domestic telephone traffic (public message plus private line) that is a candidate for satellite service are given in the AT&T filing in FCC Docket 16495 for 1975 and 1980. These may be extrapolated, albeit speculatively, to 1990 and 2000 by using a compounded growth rate of 16 percent per year. The AT&T estimates do not include point-to-point TV, a necessary ancillary to network TV, or such new services as Picturephone video telephone. When these two services are taken into account, the actual demand may be double that listed in the following table:

Year	Equivalent 2-way Voice Circuits
1975	40,000
1980	83,000
1990*	366,000
2000*	1,620,000

*Extrapolation at 16 percent per year.

No particular allowance has been made for data transmission beyond an extrapolation of the demand that now exists, at the same rate of growth as for telephony. Many experts predict that, in the future, machines talking to machines and machines talking with people may need bandwidths comparable to people talking to people. This need has been slow to standardize, however, probably because of the rapid progress in computer techniques. The service is certain to grow, both rapidly and widely, and will further contribute to making the figures above turn out to be underestimates.

These total U. S. requirements are high enough to raise another very significant question as to whether a viable domestic satellite service can be provided with satellites utilizing only 500 MHz of spectrum bandwidth.

In this section, we will seek an answer to this question by postulating a hypothetical system using the best features brought out in Appendix D. First, we will postulate a joint telephone and television distribution system at 4 and 6 GHz and determine when its capacity is exhausted. Then we will estimate how much frequency space is needed above 11 GHz to last until the year 2000.

At 4 and 6 GHz, we will consider a system for both telephony and television and we will choose frequency modulation to make the satellite compatible to the two services. We will assume operation at a peak frequency deviation of 3, comparable to INTELSAT-IV and about midway between power-limited and frequency-limited designs.

From Section D. 3. 3, the ratio of wanted to unwanted carrier power for telephony can be computed to be 45dB for each exposure, including the adjacent satellite interference at earth stations. From Section D. 3. 11 the ratio of wanted to total unwanted carrier power for television can be computed to be 30 dB, and assuming power addition of all the interference paths, the ratio of wanted to unwanted adjacent satellite power at earth stations should be 40 dB.

Such systems are not likely to use earth antennas larger than 85 feet in diameter for telephony and 30 feet in diameter for receiving television distribution services. Using equation (4) of Section D. 3. 6, with other parameters assumed for this hypothetical system, it was calculated that telephone satellites should be separated 5. 3 degrees, and television satellites 7. 9 degrees, to achieve the above suppression of unwanted carrier power. *

If a satellite can transmit 12, 000 one-way telephone channels per beam, then the total capacity per satellite is 12, 000n one-way channels, where n is the number of beams. In relating the capacity of the satellite to the telephone traffic demand, however, it is necessary to recognize that all channels available cannot be put in service. The ratio of channels used to channels available is called fill, and the net fill of the satellite system will probably be about 60 percent, assuming that 20 percent of the broad-band channels will be reserved for protection use and the fill of the regular broad-band channels will be 75 percent. Thus, the available capacity of the satellite is 7200n one-way channels.

Similarly, if a satellite can transmit 12 television signals per beam, then the total capacity per satellite is 12n television signals.

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*Note that these satellite separations apply only to the hypothetical system being considered for illustrative purposes and they should not be considered as necessarily the best separations for achieving optimum utilization of the orbit.

If telephone satellites must be spaced 5.3 degrees, the number of degrees of orbit necessary to handle C_{TP} telephone channels is

$$\theta_{TP} = 5.3 \frac{C_{TP}}{7200n} = 0.000737 \frac{C_{TP}}{n} \qquad (1)$$

Similarly, if television satellites must be spaced 7.9 degrees, the number of degrees of orbit necessary to handle C_{TV} television channels is

$$\theta_{TV} = 7.9 \frac{C_{TV}}{12n} = 0.66 \frac{C_{TV}}{n} \qquad (2)$$

The total number of degrees of orbit for telephony and television is

$$\theta = 0.000737 \frac{C_{TV}}{N} + 0.66 \frac{C_{TV}}{n} \qquad (3)$$

Estimates of telephone traffic for the period 1975-2000 have been given above. Estimates of the number of television channels needed for the same period can be deduced from AT&T's filing of December 1966 in response to FCC Docket No. 16495* as follows:

Year	Regular	Occasional	Point-to-Point	Total
1975	32	23	27	82
1980	36	26	30	92
1985	40	29	34	103
1990	45	33	38	116
1995	50	37	43	130
2000	56	42	48	146

It can be deduced from the discussion in Section D.3.11 that n = 1 is of course possible, n = 2 is probably possible, and n = 4 is hopefully possible at 4 and 6 GHz, assuming the use of satellite antenna apertures that seem reasonable within the near future (i.e., 30- to 40-foot maximum).

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*The numbers are said to take into account (a) four commercial networks with different programs in each of three or four time zones, (b) enough duplicate channels to allow for regional programs or regional commercials for each network, (c) enough extra channels to provide for occasional broadcast and nonbroadcast services, (d) at least one national public television network and possibly some regional networks and (e) some fixed noncommercial government networks. We are unable to say how accurate these projections are.

From the telephone requirements shown in Table 9. 3. 4 and the television demand figures above, using formula (3):

Year	Degrees of Orbit for U.S. Traffic Using 4 and 6 GHz Only			
	n = 1	n = 2	n = 4	
1975	83.5	41	20.5	
1980	122	61	30.5	
1985	195	97.5	48.7	Possible
1990	344.5	172.3	86.2	Impossible
1995	646	323	161.5	
2000	1286	643	321.5	

How much orbit is available? Taking into account competition with international systems and other domestic or regional systems, we estimate that not more than about 60 degrees could be made available for United States domestic traffic. On this basis, a two-beam system exhausts its capacity in 1980 and a four-beam system exhausts its capacity in 1987.

Suppose we look above 11 GHz. How much bandwidth would be needed to handle 1980 traffic?

Suppose first that television distribution remains in 4 and 6 GHz. Is there enough orbital angle? The television demand table shows 93 regular and occasional channels, and formula (2) tells us these require 65 degrees with one beam per satellite, 32. 5 degrees with two, and 16 degrees with four. This demand can just about be met within the 60 degrees assumed by very simple satellites.

Above 11 GHz, we must provide for 1, 620, 000 telephone channels and 48 point-to-point television channels. Since compatibility is less urgent, we may postulate PCM-PSK modulation for both services, and we can infer from the discussion in Section D. 3. 11 that as many as 10 beams are possible, and 6 beams provide reasonable maneuvering space. Assuming 4-level PCM-PSK for interference resistance, the telephone capacity per beam per megacycle can be deduced from Section D. 3. 8 as follows:

1. With 1/3 cosine roll-off, first null occurs at 2/3 f_b, where b is the baud rate.
2. With low-index PSK, the width of the double-sided spectrum is 4/3 f_b.
3. Increasing rf bandwidth of 2/3 f_b by 50 percent* to allow for filter crossover, the total bandwidth of an rf channel is 2 f_b.
4. With 4-level PCM-PSK, the bit rate is twice the baud rate.

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*We used 25 percent at 4 and 6 GHz, where filtering is easier. We find that AT&T used 100 percent in their proposal of December 1966 for 16 and 30 GHz.

5. If 66,000 bits per second transmit one voice channel, then with 4 levels the baud rate is 33,000, but the bandwidth is twice the baud rate, or 66,000 Hz.

The television point-to-point circuits can be put in the same terms as the telephone circuits by noting that one television channel displaces 1344 voice channels. The total equivalent voice channel demand in 1980 is thus 1,620,000 + (48 x 1344) = 1,685,000 channels. These will require a total bandwidth of 1.11×10^{11} Hz.

With 4-level PCM-PSK, the ratio of wanted-to-unwanted signal must be about 25 dB if interference is permitted to degrade the error rate one order of magnitude. Using the same arguments as before, the ratio of wanted-to-unwanted signal from an adjacent satellite should then be 35 dB. If 30-foot earth station antennas are used, the spacing between satellites at 15 GHz must be 1.723 degrees, using formula (4) of Section D. 3. 6.

At these high frequencies, elevation angle is more important than at 4 and 6 GHz, so instead of 60 degrees, we will assume our satellites must fit into 50 degrees of orbit. Allowing ± 0.1 degree tolerance, the station spacing is 1.923 degrees, and 50 degrees will contain 26 stations. At six beams per satellite, the total number of beams is 156. The bandwidth required per beam is then

$$B = \frac{1.11 \times 10^{11}}{156} = 715 \text{ MHz}$$

We have tacitly assumed uniformly distributed traffic, whereas it is known that as much as one-third of the present traffic is concentrated at the largest node. If by 1980, the Megalopolis effect reduces this to 20 percent, then $0.2 \times 1.11 \times 10^{11} = 2.22 \times 10^{10}$ Hz is required at the largest node, i.e., on one beam of each satellite. Only 26 beams are available at the largest node, so the bandwidth required is, by this method:

$$B = \frac{2.22 \times 10^{10}}{26} = 860 \text{ MHz}$$

Taking into account the approximations made, we conclude that a bare minimum of 1 GHz of bandwidth above 11 GHz if frugally used would probably support the domestic telephone and point-to-point needs of the United States until the year 2000. The needs of the North American region may be as much as 150 percent of the United States needs. Therefore, we recommend that programs involving domestic United States satellite systems look forward to the availability of at least 1.5 GHz for up transmission and 1.5 GHz for down transmission between 11 and 50 GHz. More would be highly desirable.

G. 3 Conditions for Allocations above 11 GHz

Although at this moment we do not foresee that sharing of frequencies will be as prevalent or as serious as at 4 and 6 GHz, it would be prudent to expect that terrestrial uses for these frequencies will indeed materialize and that studies of interference, propagation, and system synthesis should keep this possibility in mind.

APPENDIX H

TRAFFIC MATRIX OPTIMIZATION FOR A HIGH-CAPACITY SATELLITE SYSTEM

Hayden W. Evans

The configuration of the Phase II domestic communication satellite system proposed by AT&T in response to FCC Docket No. 16495 resulted from a process of iterative optimization involving system synthesis, system application, costing, comparison of costs with terrestrial costs, and finally a critique leading to a revised system synthesis, and so on. This loop was traversed six times, with continual but diminishing improvement. Cost was not the only criterion. Equal consideration was given to conservation of the frequency spectrum, conservation of the stationary orbit, and nontriviality. It is no surprise that these criteria were maximized when the system fit the needs most accurately.

To interconnect as many cities as possible, it was postulated that each satellite should have several beams to several cities. To conserve the frequency spectrum, these beams should use the same frequencies. To reduce interference between the beams so they may be aimed at cities close together, the beams must be very narrow, but not so narrow that instability in satellite attitude causes them to miss their targets. Also, PCM-PSK modulation permits closer beam spacing than FDM-FM at equal system capacities. To conserve the stationary orbit, the number of satellites must be small but earth antennas must not be small. If the number of satellites is to be small, the capacity of each must be large, particularly if the system is to be capable of continued growth. Also, if small earth antennas are inadvisable, then earth stations must handle more than a small amount of traffic to justify their existence.

The paragraphs to follow illustrate the process of matching demand to capability. A full-scale optimization requires year-by-year analysis of the entire study period, which was taken as 1969-1980. The illustrations are based only on 1969 demand.

The AT&T toll network connects about 8000 points in the United States. The theoretical number of paths to interconnect 8000 nodes is nearly 3.2×10^7.

To manage the network and to predict its growth, AT&T planning people have reduced the 8000-node matrix to a 135-node matrix, mainly by consolidating nodes such as White Plains, Hempstead, and Newark into a single node at New York, and so on. This matrix is revised every year on the basis of most recent experience. The theoretical number of paths to interconnect 135 nodes is 9045. A check of 3000 possible paths showed that two-thirds were vacant, so the number of occupied paths must be about 3000. Growth rates have been determined for each path, mostly on the basis of recent experience, and vary over a range of about two to one. A year-by-year 135-node matrix exists on computer tape, and a print-out for any single year covers about 200 pages. Print-outs for 10 years make a stack some six inches high. This is a little too much information to be helpful in designing a domestic satellite system.

The matrix can be reduced to comprehensible size by applying two principles:

1. Nodes close together are not likely to be connected by satellite because terrestrial interconnection will be cheaper; the prove-in distance for satellite circuits will be at least several hundred miles.
2. Nodes very close together, say within one hundred miles or so, are not likely to justify separate earth stations.

There are at least three ways to reduce a traffic matrix:

1. Start at the bottom with the smallest path and consolidate it into the nearest nearly coterminous path, and so on.
2. Start at the top with the largest path and consolidate into it all paths that economics permit.
3. Start in the middle by consolidating all paths that do not meet assumed requirements such as size and length into nearly coterminous paths that do meet the requirements.

It turns out that the first course is undesirable because there are so many small paths that many reconfigurations are required. The second course is undesirable because the steps in restructuring are so large. The third course appears to be the most practical, at least for reducing the matrix by hand. At first glance, this method would seem to be at the mercy of the accuracy of the assumptions, but all three methods really are subject to this constraint, and iterative solutions based on revised assumptions are needed.

Figure 9. H. 1 shows the nodes of the 135-node matrix.* This was reduced by successive steps to the 27-node matrix shown in Figure 9. H. 2. When paths longer than 1000 airline miles (corresponding to about 1300 terrestrial route miles) are eliminated, and when nodes no farther than 120 miles from the largest nodes are consolidated into the largest nodes, the estimated telephone channel demand matrix for 1969 is as shown in Table 9. H. 1. The telephone channel demand includes public telephone service and private line, but not Picturephone. The total number of two-way telephone circuits in 1969 in the estimated matrix is 43, 898.

The size of the nodes and the paths are shown by rank in Figure 9. H. 3. The largest path carries nearly 3500 circuits, and 43 paths carry more than 300 circuits. The largest node terminates nearly 15, 000 circuits, nearly one-third of the total, and 23 nodes terminate over 1000 circuits.

One important criterion of the viability of any telephone system is fill, the fraction of the channels that can be used. If 600-channel capacity is

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*The AT&T proposal assumed that one direction of each telephone circuit would be by satellite and the other by terrestrial means to reduce the effects of delay and to take advantage of diversity in failure mechanism. If this assumption were applied to this Appendix, the numbers of channels to be handled by satellite would be just one-half those stated.

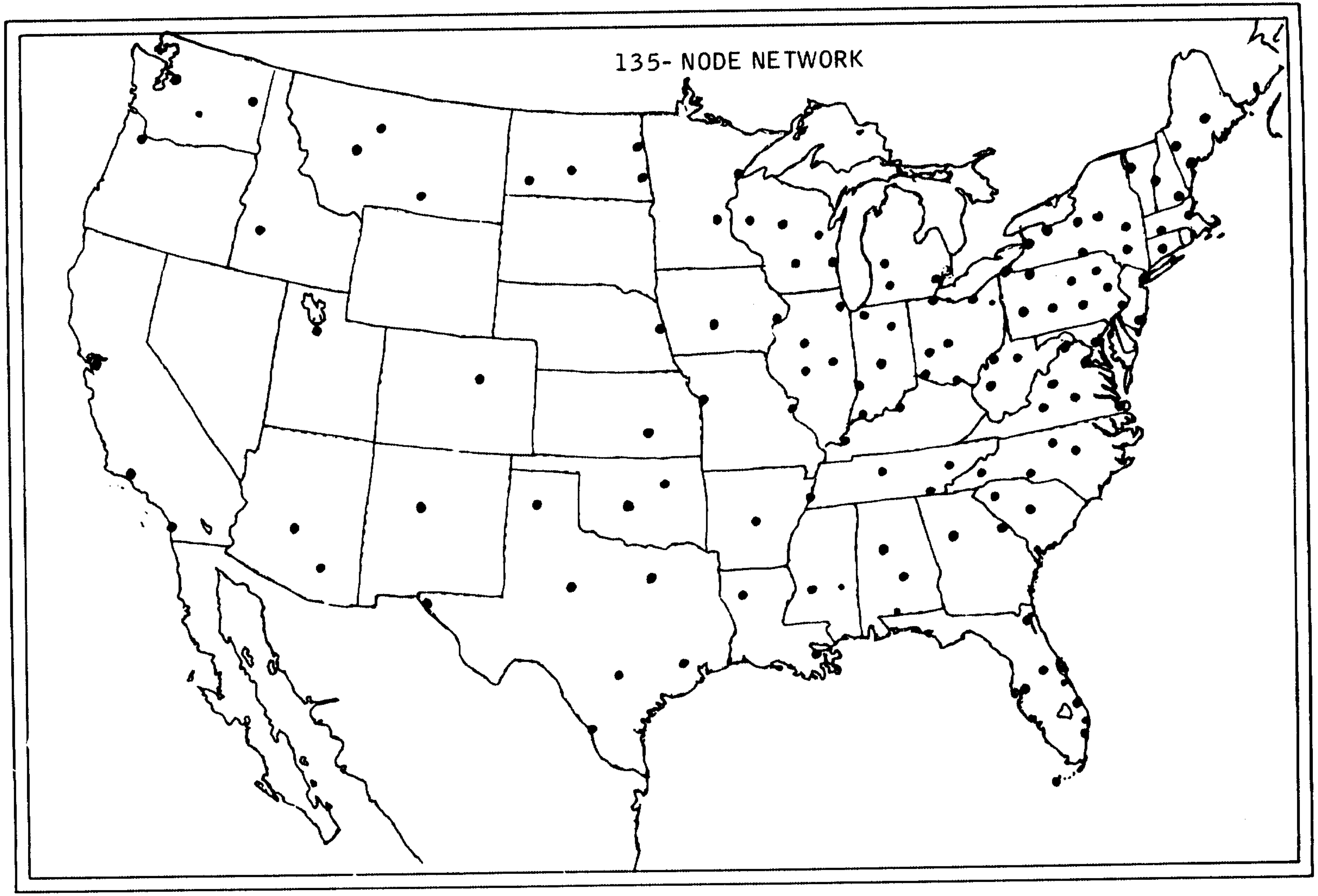

FIGURE 9.H.1 Nodes of 135-node matrix.

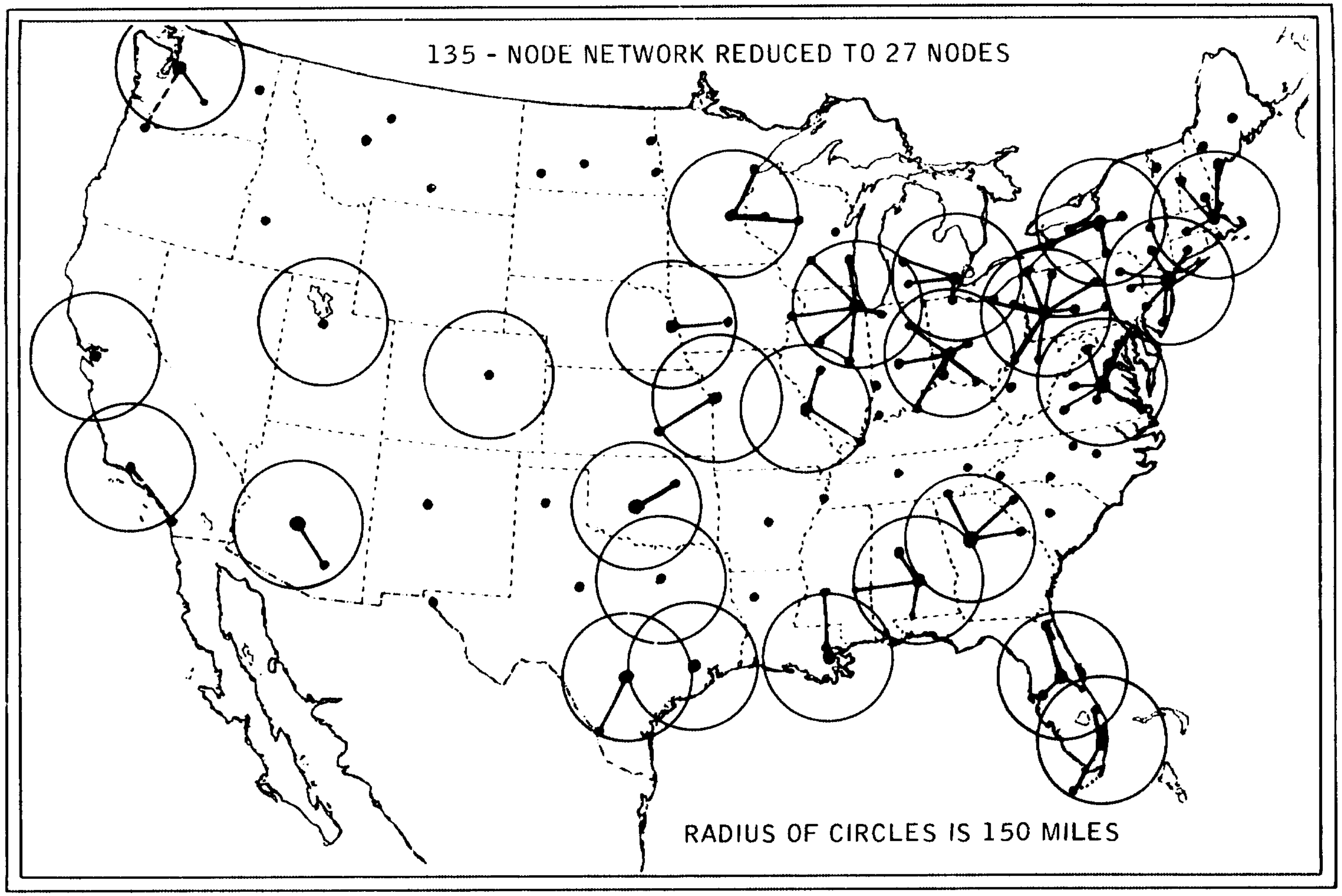

FIGURE 9. H. 2 The 135 nodes reduced to 27-node matrix.

TABLE 9.H.1

1969 TELEPHONE TRAFFIC CONNECTING 27 NODES MORE THAN 1000 MILES APART

		Boston	New York	Syracuse	Fredricksburg	Pittsburgh	Atlanta	Miami	Orlando	Montgomery	New Orleans	St. Louis	Chicago	Detroit	Dayton	Dallas	Denver	Kansas City	Houston	Los Angeles	Minneapolis	Oakland	Oklahoma City	Seattle	San Antonio	Phoenix	Omaha	Salt Lake City						1
1	Boston																																	2
2	New York																																	3
3	Syracuse																																	4
4	Fredricksburg																																	5
5	Pittsburgh																																	6
6	Atlanta																																	7
7	Miami	472	2552	225		276																												8
8	Orlando	462	1058	104																														9
9	Montgomery	69	86																															10
10	New Orleans	22	306																															11
11	St. Louis	76						65																										12
12	Chicago							415	289																									13
13	Detroit							244																										14
14	Dayton							232																										15
15	Dallas	157	1068	112	717	211		49	50																									16
16	Denver	98	693	58	724	183	227	29	116	77	17			165	177																			17
17	Kansas City	52	560	10	2			27	24																									18
18	Houston	42	839	27	195	82		40	146					35																				19
19	Los Angeles	584	3474	314	1515	633	651	113	360	263	107	468	1408	480	573	826		433	240															20
20	Minneapolis	105	564					38	69		10								11	232														21
21	Oakland	351	1998	174	908	521	459	59	112	107	35	463	1122	389	222	460		265	56		121													22
22	Oklahoma City	10	312	62	152	18		19	36											430		132												23
23	Seattle	74	518	27	472	102	151	4	57	24	35	109	388	100	92	182	149	194	11	12	118		43											24
24	San Antonio	21	635	16	109	56		23	39				98	16	33					99	14	62		16										25
25	Phoenix	31	337	50	73	68	62		34			80	282	62	76			76	31		37	262		96										26
26	Omaha	94	375	45	151			42	122						146		173	59					7	160	14	53								27
27	Salt Lake City	12	171		97	43	23		5	6		27	152	28	28				6						18									28
28																													TOTAL					29
29	TOTAL CIRCUITS	2756	15106	1224	5105	2193	1573	4924	3083	634	532	1288	4154	1519	1519	3932	2886	1702	1850	13215	1319	8284	1251	3194	769	1710	1441	619	43898					30
30	TOTAL PATHS	18	17	13	12	11	6	19	17	7	7	7	8	9	9	10	14	11	14	21	11	21	10	24	16	17	13	13	355					31
31																																		32
32	RANK IN CIRCUITS	11	1	23	4	12	17	5	9	25	27	21	6	18	16	7	10	15	13	2	20	3	22	8	24	14	19	26						33
33																																		34
34																																		35
35																																		36
36																																		37
37																																		

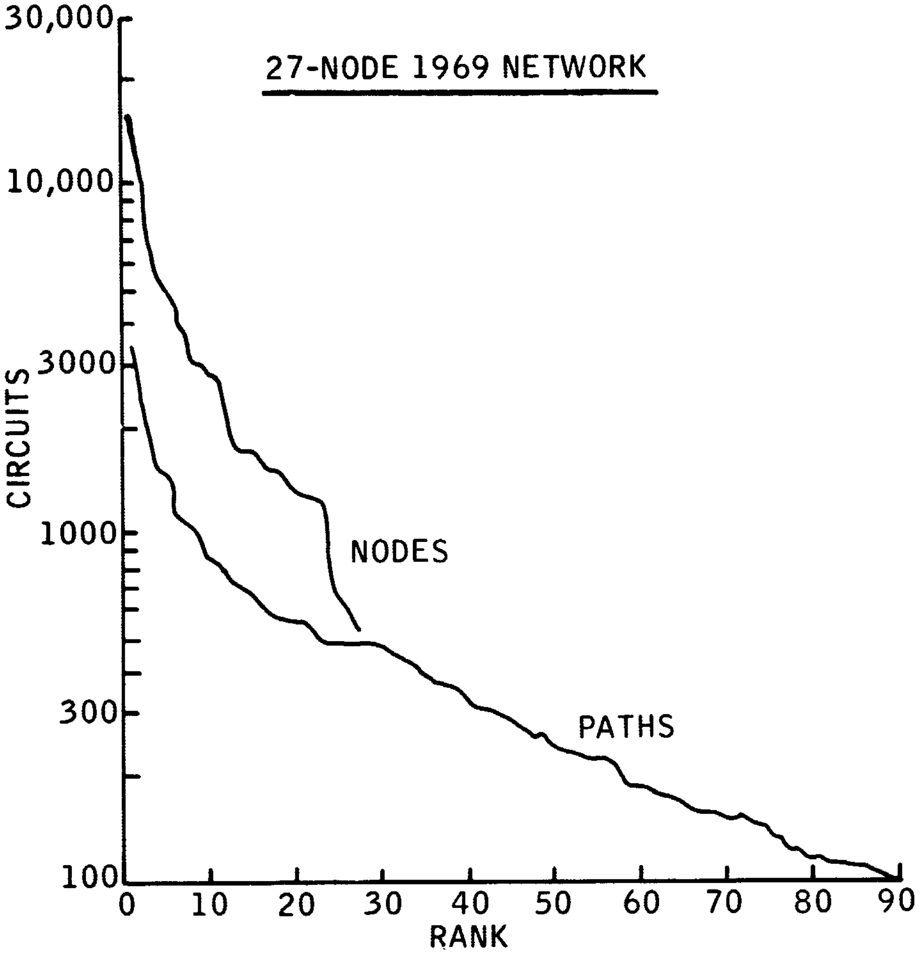

FIGURE 9. H. 3 Nodes and paths shown by rank. The largest node terminates nearly 15,000 circuits. The largest path carries nearly 3500 circuits.

provided on a path needing 300 channels, the fill will be 50 percent.* Seventy-five percent fill is a reasonable objective, and smaller fills will be a symptom of nonoptimum design. Figure 9.H.4 shows the percentage of fill achieved by various sizes of groups on various numbers of paths. Obviously the smaller the group, the better the fit to path size, and the higher the fill. When fewer paths are considered, the smaller paths are eliminated, and a larger group size can be used. For the 40 largest paths, 600 channel groups will produce 75 percent fill in 1969. The transponder capacity of the satellite proposed by AT&T is for several good reasons 1344 channels, and Figure 9.H.4 suggests that 75 percent fill would not be achieved until some five years** after 1969, or 1974. AT&T proposed to introduce this satellite in 1972.

Using the same arguments, it might be concluded that paths needing less than 300 circuits in 1969 are very unlikely to produce acceptable fills of a 1344-channel transponder in 1974. Table 9.H.2 is a 1969 demand matrix with all paths needing less than 300 circuits eliminated. The 27 nodes have shrunk to 23, interconnected by 47 paths, carrying about 32,000 circuits.

Note that Syracuse, New Orleans, Oklahoma City, Phoenix, and Omaha terminate only about 300 circuits each, which is scarcely enough to support an earth station. Syracuse and Dayton can reasonably be combined with New York and Detroit, respectively. This leaves 17 nodes, 38 paths, and 31,[illegible] circuits.

Now enters another restriction imposed by the design of the AT&T satellite. Even though very sharp antenna beams are used, plus PCM-PSK modulation which is quite resistant to interference, service cannot be provided from a particular satellite to nodes very close together. Figure 9.H.5 shows the proscribed areas around several large cities. To be sure, Boston and Fredericksburg could be served by another satellite, but the load terminating in New York is so large that New York must work with every satellite. For this reason, combine Boston, Fredericksburg and Pittsburgh into New York, and St. Louis into Kansas City.

The final 1969 network is shown in Table 9.H.3.

Although we now have a telephone demand matrix, we are still closer to the beginning of the problem than the end. The matrix, for instance, gives equal weight to New York-Miami (1092 airline miles) traffic and New York-San Francisco traffic (2570 airline miles). If, as an example, the prove-in distance for satellite circuits were 1000 miles, a New York-San Francisco circuit should carry 17 times as much weight as a New York-Miami circuit. This suggests another kind of matrix, based on the product of the number of circuits times the mileage excess over the prove-in distance.

Unfortunately the prove-in distance for a particular pair of earth stations depends on the number of circuits each station terminates, and as we have just said, the advantage of terminating a circuit depends on the prove-in distance. This suggests an iterative solution by assuming a prove-in distance and then revising it in accordance with the dimensions of the reduced matrix.

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*There is another kind of fill that must not be forgotten—the fraction of the transponders that can be used.

**Although different paths do have different growth rates, the assumed average growth rate doubles the number of circuits every five years.

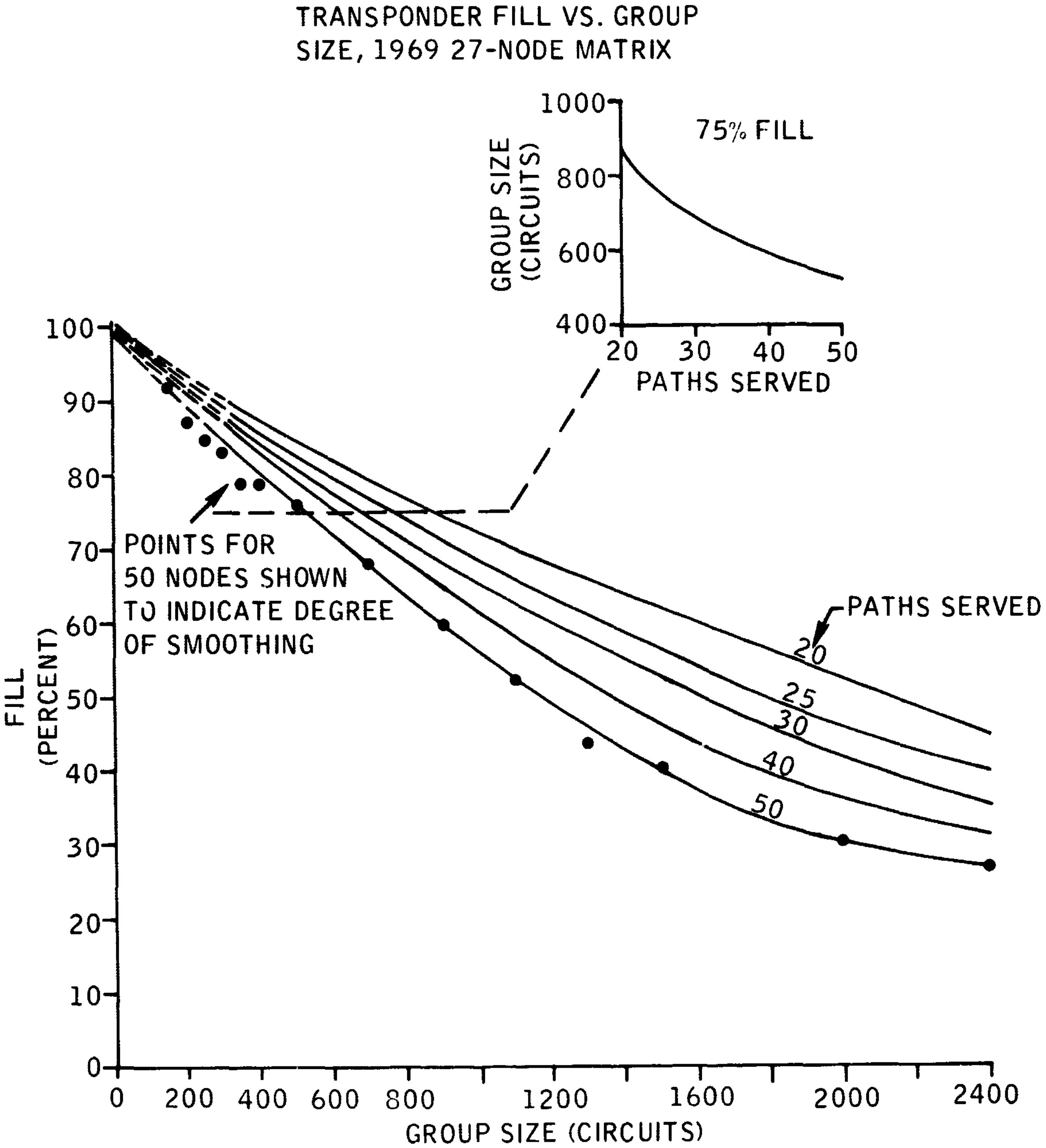

FIGURE 9. H. 4 Percentage of fill achieved by various sizes of groups on various numbers of paths.

TABLE 9. H. 2

1969 TRAFFIC, MORE THAN 1000 MILES, MORE THAN 300 CIRCUITS PER PATH

		Boston	New York	Syracuse	Fredricksburg	Pittsburgh	Atlanta	Miami	Orlando	Montgomery	New Orleans	St. Louis	Chicago	Detroit	Dayton	Dallas	Denver	Kansas City	Houston	Los Angeles	Minneapolis	Oakland	Oklahoma City	Seattle	San Antonio	Phoenix	Omaha	Salt Lake City					
1	Boston																																
2	New York																																
3	Syracuse																																
4	Fredricksburg																																
5	Pittsburgh																																
6	Atlanta																																
7	Miami	A72	2552																														
8	Orlando	A62	1058																														
9	Montgomery																																
10	New Orleans		306																														
11	St. Louis																																
12	Chicago							415																									
13	Detroit																																
14	Dayton																																
15	Dallas		1068		717																												
16	Denver		693		724																												
17	Kansas City		560																														
18	Houston		839																														
19	Los Angeles	584	3474	314	1515	633	651		360			468	1408	480	573	826		433															
20	Minneapolis		564																														
21	Oakland	351	1998		908	521	459					463	1122	389		466																	
22	Oklahoma City		312																	430													
23	Seattle		578		472								388																				
24	San Antonio																																
25	Phoenix		337																														
26	Omaha		375																														
27	Salt Lake City																																
28																																	
29	TOTAL CIRCUITS	1869	14704	314	4336	1184	1110	3449	1880	–	306	931	4269	869	573	3077	1417	993	839	12149	564	6677	312	1438	–	337	375			31969			
30	TOTAL PATHS	4	14	1	5	2	2	3	3	–	1	2	4	2	1	4	2	2	1	14	1	9	1	3		1	1			83			
31																																	
32	RANK IN CIRCUITS	9	1	22	4	12	13	6	8		24	15	5	16	18	7	11	14	17	2	19	3	23	10		21	20						
33																													17	NODES			
34	CONCLUSION		✓								NO			✓									NO			NO	NO		76	PATHS			
35																													31822	CIRCUITS			
36																																	
37																																	

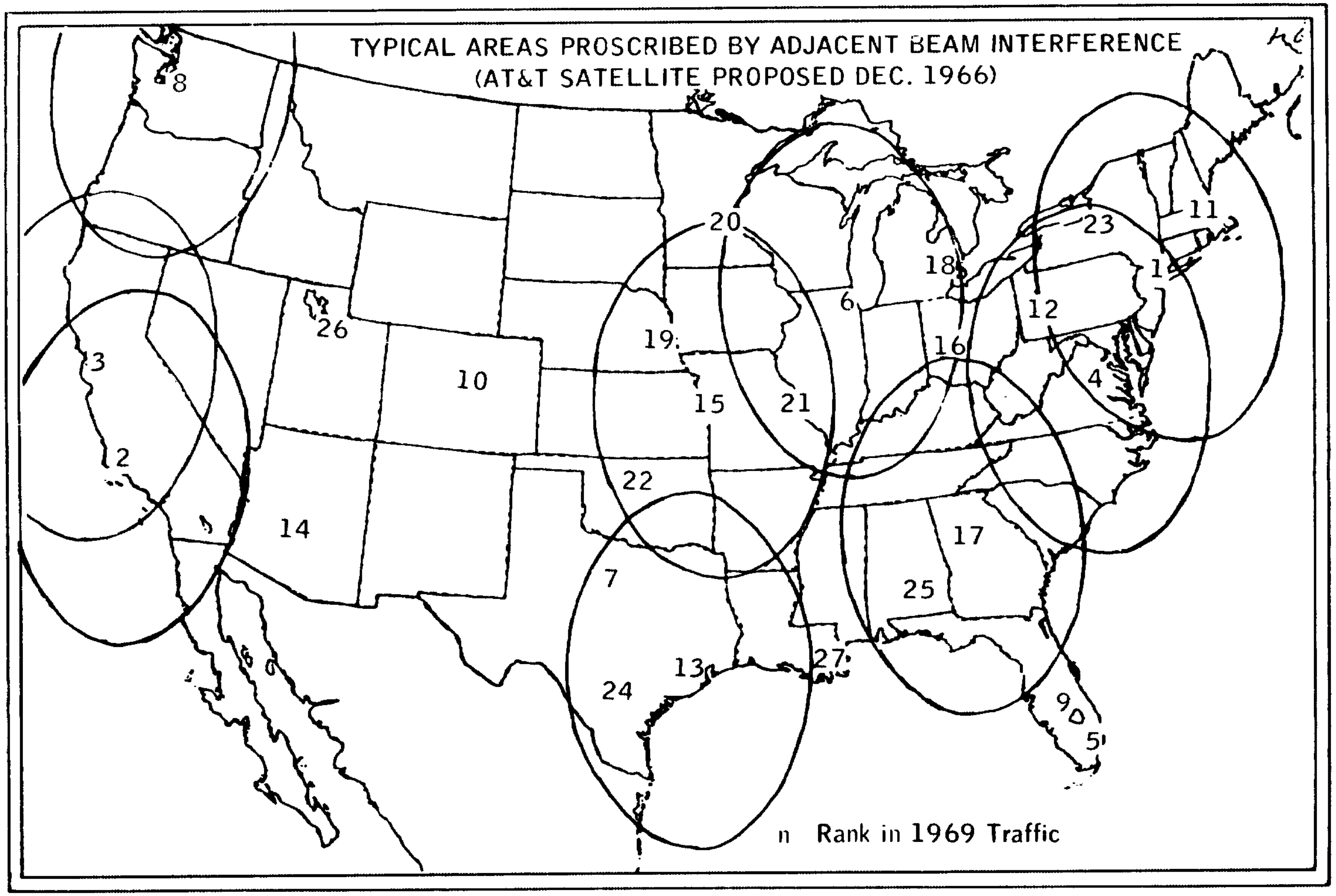

FIGURE 9. H. 5 Proscribed areas around several large cities. Service cannot be provided from a particular satellite to nodes that are very close together.

TABLE 9. H. 3

1969 TELEPHONE TRAFFIC MATRIX

		Miami	Orlando	Chicago	Dallas	Denver	Kansas City	Houston	Los Angeles	Minnea-polis	Oakland	Seattle	TOTAL CIRCUITS	
1	New York	3024	1520		1785	1417	560	839	5890	564	3778	1050	20427	
2	Atlanta								651		459		1110	
3	Miami			415									3439	
4	Orlando								360				1880	
5	Chicago								1408		1122	388	3333	
6	Detroit								1053		389		1442	
7	Dallas								826		466		3077	
8	Denver												1417	
9	Kansas City								901		463		1924	
10	Houston												839	
11	Los Angeles												11089	
12	Minneapolis												564	
13	Oakland												6677	
14	Seattle												1438	
15													29328	
16														

17	NODES RANKED		PATHS RANKED		PATHS RANKED	
18	New York	20427	New York–Los Angeles	5890	Kansas City–Oakland	463
19	Los Angeles	11089	New York–Oakland	3778	Atlanta–Oakland	459
20	Oakland	6677	New York–Miami	3024	Chicago–Miami	415
21	Miami	3439	New York–Dallas	1785	Detroit–Oakland	389
22	Chicago	3333	New York–Orlando	1520	Chicago–Seattle	388
23	Dallas	3077	New York–Denver	1417	Orlando–Los Angeles	360
24	Kansas City	1924	Chicago–Los Angeles	1408		
25	Orlando	1220	Chicago–Oakland	1122		
26	Detroit	1442	Detroit–Los Angeles	1053		
27	Seattle	1438	New York–Seattle	1050		
28	Denver	1417	Kansas City–Los Angeles	901		
29	Atlanta	1110	New York–Houston	839		
30	Houston	839	Dallas–Los Angeles	826		
31	Minneapolis	564	Atlanta–Los Angeles	651		
32			New York–Minneapolis	564		
33			New York–Kansas City	560		
34			Dallas–Oakland	466		
35						
36						
37						

We have been working in one dimension, 1969 traffic. The complete system solution involves the time dimension. The optimum system is not necessarily the sum of the optimum systems for each year, but the set of annual systems which progress in an optimum fashion. Each reconfiguration in number of satellites and number of earth stations must be examined to see if it is scheduled properly and it fits with the progression of the whole system.

If the system is to handle other services, such as point-to-point television service, a necessary adjunct to television distribution, it must be recognized that the telephone matrix will be affected, principally because the other service will assume part of the earth-station cost and thus reduce the prove-in distance. Speaking very generally, point-to-point television circuits interconnect the same large cities that have major telephone traffic, but there are notable exceptions, and in addition capability must exist to many smaller cities, no matter how infrequently used.

Another point to be considered is the policy regarding spare transponders that are to be held in reserve for failures but can be used for occasional services. If they are to be provided at all, their number may be surprisingly large, unless a switching matrix is provided in the satellite, as it is in the AT&T proposal.

Conclusion

The problem of the optimum demand matrix for a domestic satellite system is not very difficult but it is extremely complex, particularly when such factors as restrictions and boundaries imposed by a particular satellite system design are taken into account. We have shown a quantitative example of the generation of a realistic demand matrix, but we have pointed out quantitatively how other factors must be taken into account. We know from applying these methods that the savings of a satellite system versus terrestrial systems are very sensitive to the match between capability and need.

APPENDIX I

SPACE-TO-SPACE LINK PARAMETERS

Spencer W. Spaulding

I. 1 Earth Orbiting Data Relay

The material in this section is based on a report on a NASA contract* and correlates with data included in Section D. E. 6, which deals with retrodirective phased arrays.

The situation analyzed considers the transfer of 1.5 MHz of video data from a low-altitude earth-orbiting satellite to a synchronous satellite for subsequent relay to an earth station.

The system would use three synchronous satellites although total coverage is possible with only two. The choice of three was based on system considerations of eclipse operation, satellite failure modes, and orbital redundancy. The general trade-off conclusions of the NASA contract report are shown in Figure 9. I. 1. The positions of the satellites are shown for the case of covering the gaps in the Deep Space Net for the near-earth portion of deep space flights. The terminal in Australia could be eliminated by a space-to-space link as discussed in Section 9. I. 2.

The link parameters are chosen to provide:

1. FDM/FM base bandwidth 1.5 MHz; peak deviation 3.5 MHz, (RF bandwidth 10 MHz)
2. PCM/PSK; data rate 1 Megabit/second, error rate 10^{-6} (RF bandwidth 2 MHz)
3. Emergency Voice

Other parameters are illustrated in Figure 9. I. 2. The target gain of 0 dB is used in the emergency voice mode.

The total service requirements are summarized in Table 9. I. 1. The link computations are summarized in Tables 9. I. 2 through 9. I. 5 for three frequency plans for the most difficult nominal load of 1.5 MHz video baseband. Table 9. I. 6 includes the analysis for the emergency voice mode.

Figure 9. I. 3 illustrates the number of elements required in a phased array and is the basis for choosing S-Band in preference to X-Band. There is a minimum weight per element for the transponder and the total weight of the satellite is therefore quite sensitive to the number of elements.

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*Orbiting Data Relay Networks, final report on NASA Contract NASW-1447, prepared by Astro-Electronics Division, Radio Corporation of America.

Efficiency of power generation is better at S-Band than at X-Band for the projected technology. This affects the required power supply weight and reinforces the S-Band choice. The net result of the study is summarized in Figure 9.I.1 in the nomograph.

In Figure 9.I.1, the term "no eclipse operation" means that the weight of the satellite does not include batteries. Eclipse operation of the system is still possible, however, because of the three satellites and the fact that at least two are always uneclipsed and can provide service to most target satellites.

The weight of 4.5 pounds per element is based on present day technology not assuming the availability of reduced weight integrated rf circuits. The nomograph shows that service is possible using the Atlas-Centaur launch vehicle but the Titan III-C would relax the requirements on the transmitting satellite or allow more traffic to be sent with the same target performance.

In order to increase the data rate significantly or to handle more target satellites simultaneously, the weight per transponder must be reduced. The development of lightweight rf integrated circuit components is a promising technique for enhancing the satellite capability. This leads to the conclusion that research and development of such integrated circuits should be aggressively advanced.

I.2 Synchronous-to-Synchronous Links

First consider what ERP is needed to work into a one-foot antenna at one mile. The received power, P_R, is equal to $P_R = (ERP)\frac{A}{R^2}$ where A is the receiving antenna effective area and R is the distance in the same units. For a circular antenna of diameter 1.4 feet but 0.5 efficiency and a distance of one mile, one has:

$$P_R = 3.5 \times 10^{-8}\ (ERP) = -75\ dB + ERP\ (dB)$$

The required signal is MKTB, where M is the margin above the basic thermal noise, (KT) and B is the bandwidth. For a bandwidth of 100 MHz, a temperature of 3000, and a signal-to-noise ration of 13 dB, one has:

$$P_R = MKTB = -101\ dB = -75\ dB + ERP$$

$$ERP = -26\ dBW$$

For N miles, the requirement would be

$$ERP = -26\ dBW + (N^2)\ dB$$

Consider first the use of such a link for extending the connectivity of users in a commercial satellite-communications application. Since the two satellites are separated by at least a few earth terminal antenna beamwidths, plus control tolerance, they will be on the order of several hundred miles apart. Let N = 1000, then ERP = 34 dBW.

The 1.4-foot antenna assumed gives about a one degree beam at frequencies around 60 GHz. These frequencies are of interest in space-to-space links because of their attenuation by the atmosphere and thus protection against interference or interception. The choice is included in terms of 60 GHz but the effect is not important to the conclusion since only the antenna size is finally affected. Thus, with this frequency, antenna stabilization and tracking are required for pointing. The antenna gain would be about 44dB and the required power would be 0.1 watt for an ERP of 34 dBW. The conclusion to be reached is that the space-to-space link could be configured using 1.4-foot antennas and a fraction of a watt power and would support about 100 MHz of interconnecting bandwidth.

The use of such a link for the application discussed above would involve a distance of $(3)^{1/2}$ times 26,000 miles. This would require an increase in the link parameter of 2000 for the same bandwidth. Such a large bandwidth would not be required for a single target (10 MHz) but the relay satellite being supported would be tracking several targets. Thus, the 100-MHz total bandwidth might be representative and is used here for this example.

This factor of 2000 could be made up by increasing the power from 0.1 watt to 10 watts and by increasing the antenna size from 1.4 feet to about 6 feet. This would result in a beamwidth of about 0.2 degrees. This would require an accurate tracking mount for the antenna but would not require better total spacecraft attitude control than 0.1 degree as planned for the ATS-F and G program. An example of such an antenna mount is the LEM rendezvous radar system for Apollo.

I.3 Lunar Communications

The use of a satellite relay for communications from the lunar environment to the earth is of doubtful value except for the special requirement of behind-the-moon situations. Lunar operations to date support this conclusion. The use of a communications satellite in some sort of orbit about the moon appears to be the only feasible way of achieving the connectivity required for behind-the-moon links.

One possible orbit is a quasi-stable orbit about the libration point behind the moon. This orbit would require a continuous expenditure of propulsion. Electrical propulsion of high specific impulse would be required for a long life. The orbit about the libration point would keep the relay satellite in view of one or more of the deep space net earth terminals.

An alternate approach would place three satellites in orbit in a single plane about the moon. There would be satellite-to-satellite links among the three so that the one behind the moon would have connectivity to the earth terminals. This would constitute a data relay network about the moon and appears to be the more tractable solution to the problem. An orbital altitude of more then 1000 miles above the moon would suffice to insure the satellite-to-satellite link availability at all time. The same type of 60-GHz systems discussed in the preceding section would easily provide the links and give video bandwidths. The satellite-to-earth links would be at a convenient frequency, perhaps S-Band. Satellites to lunar surface or lunar spacecraft could be S-Band or VHF links.

Further study of the relative merits of these two types of lunar orbital relay systems is required to choose between them. The priority should relate to the timetable of behind-the-moon operations.

I. 4 Deep Space Communications

The relative merits of competitive means of transmitting data from deep space probes has been considered.* The conclusion is reached that the conventional S-Band is preferable to lasers. As long as the transmission needs can be supported at frequencies that readily penetrate the earth's atmosphere, the use of an intermediate satellite relay is generally not needed or cost effective. This is because of the large earth teminals possible (200-foot antennas and 50°K system temperature). Such terminals reduce the weight of the communications system on the deep space probe and are less expensive than orbiting relays because only three are needed for such missions.

In a discussion of a problem with the use of very fine beam lasers it was concluded that the aiming problem is significant.* The analogy of a machine gunner leading his fast-moving target illustrates why this is a problem. A spacecraft moving near Mars is so far from earth that a beam of light aimed at a target at this range would find the target gone when it arrived.

Thus, a laser beam must be aimed ahead of the target in order to make contact. If the laser beam is broad enough to include the target in its beam without such a lead, its main advantage, a concentrated beam using laser optics, is lost. Then the power requirements rise sharply because of the gain loss and the future of lasers is questionable. The spacecraft may make unpredictable manuevers near a planet with atmosphere and by using its onboard propulsion.

Setting aside the question of aiming such beams, the fact remains that microwaves penetrate the atmosphere and the service can be provided by conventional S-Band techniques.

The point was made earlier that three earth terminals in the deep space net represent a more cost-effective solution to the deep-space link problem than would a system of earth-orbital relays. Part of their cost effectiveness relates to the use of these same earth terminals for other missions. One must consider therefore the possibility that an earth-orbiting relay system may have other missions. If indeed one has an earth-orbiting relay system for other reasons, the marginal cost of adding deep-space links may become low enough to make them attractive. If this were so, there still appears to be little merit in lasers because of the fundamental problem of aberration or lead angle and the uncertainties in predicting lead-angle lead to beam-angle requirements that can be achieved at millimeter wavelengths with less power and weight. To accomplish this, the 200-foot earth terminal at a noise temperature of 50°K must be replaced by a relay satellite. If one assumes a 10-foot antenna on the relay satellite and a receiver of 3000°K system temperature, the loss in terminal effectiveness is a factor of 24,000. This must be made up by raising the ERP of the deep space probe by the same factor. Keeping the same 10-foot antenna on the deep space probe as one would have for S-band, but realizing the increase in gain by using about 100-GHz frequency,

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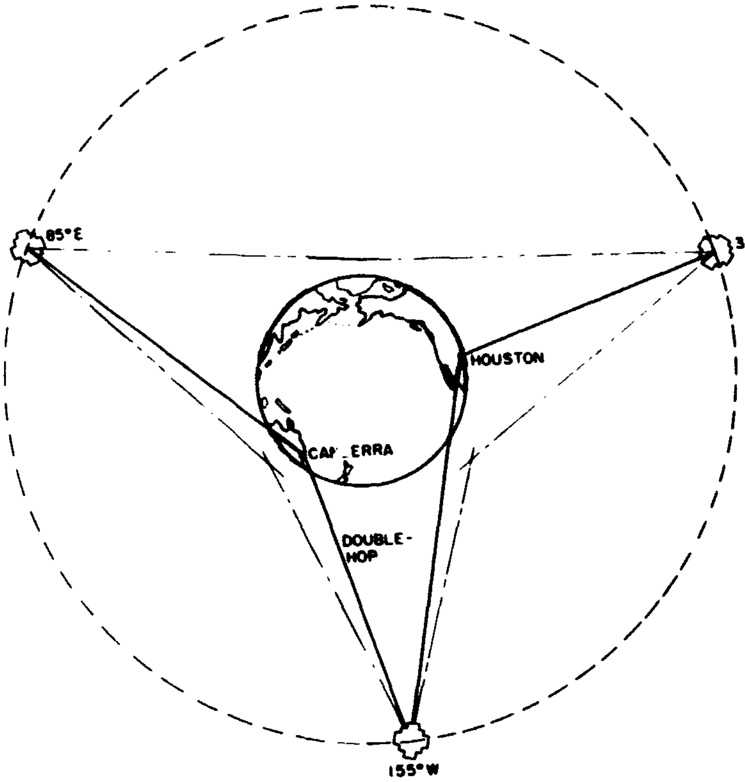
*Gubin, S., R. Marsten, and D. Silverman, Lasers versus Microwaves for Deep-Space Communications, Journal of Spacecraft and Rockets of AIAA, June 1966.

one gains a factor of 2500. The rest, a factor of about 10 times, must be made up by using more power in the deep space probe transmission. While not of immediate obvious advantage, this does align with the general development of space-to-space links using millimeter waves and does represent another service that can be provided by an earth-orbiting relay system. The requirements of such deep-space links should therefore be included in further studies of these two topics.



Three-Spacecraft Synchronous Altitude Orbiting Data Relay Network System, Coverage Pattern

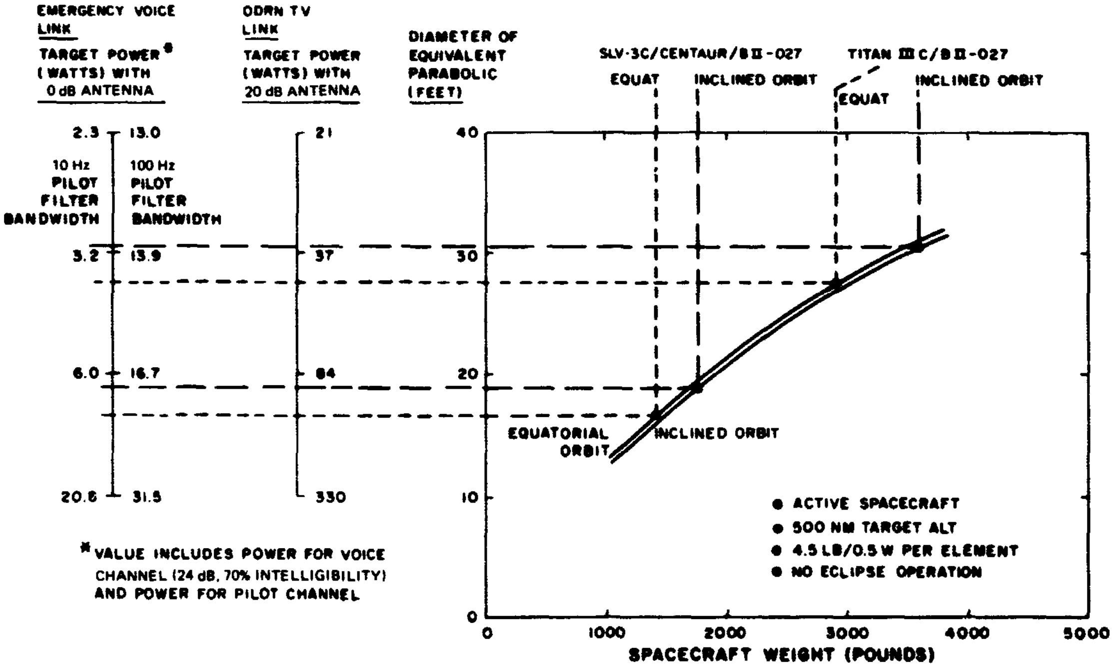


FIGURE 9.I.1 Orbiting data relay system performance nomograph.

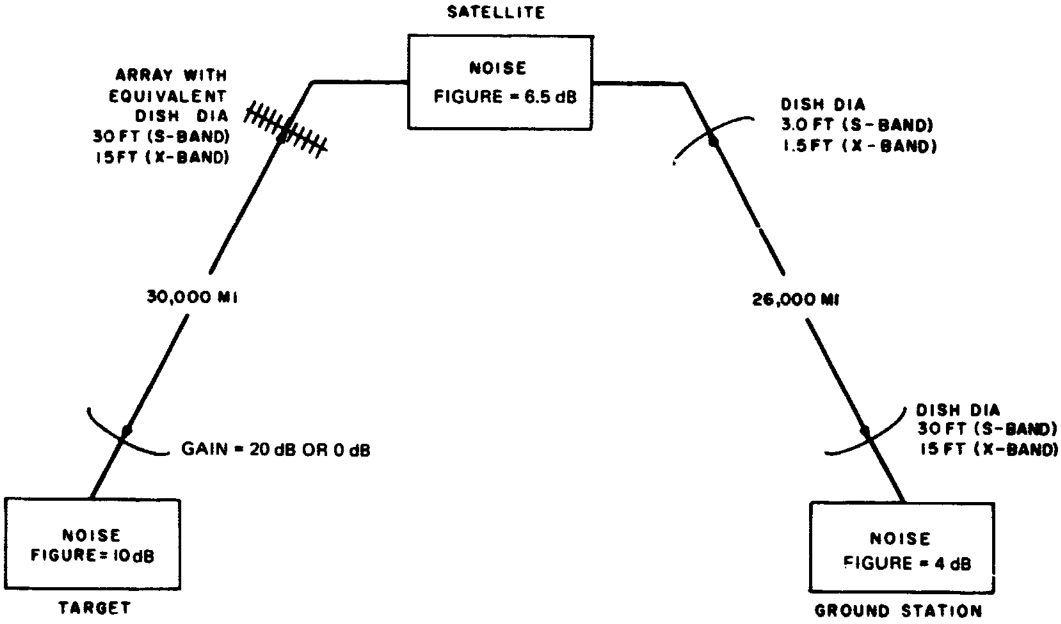


FIGURE 9.I.2 Basic system parameters.

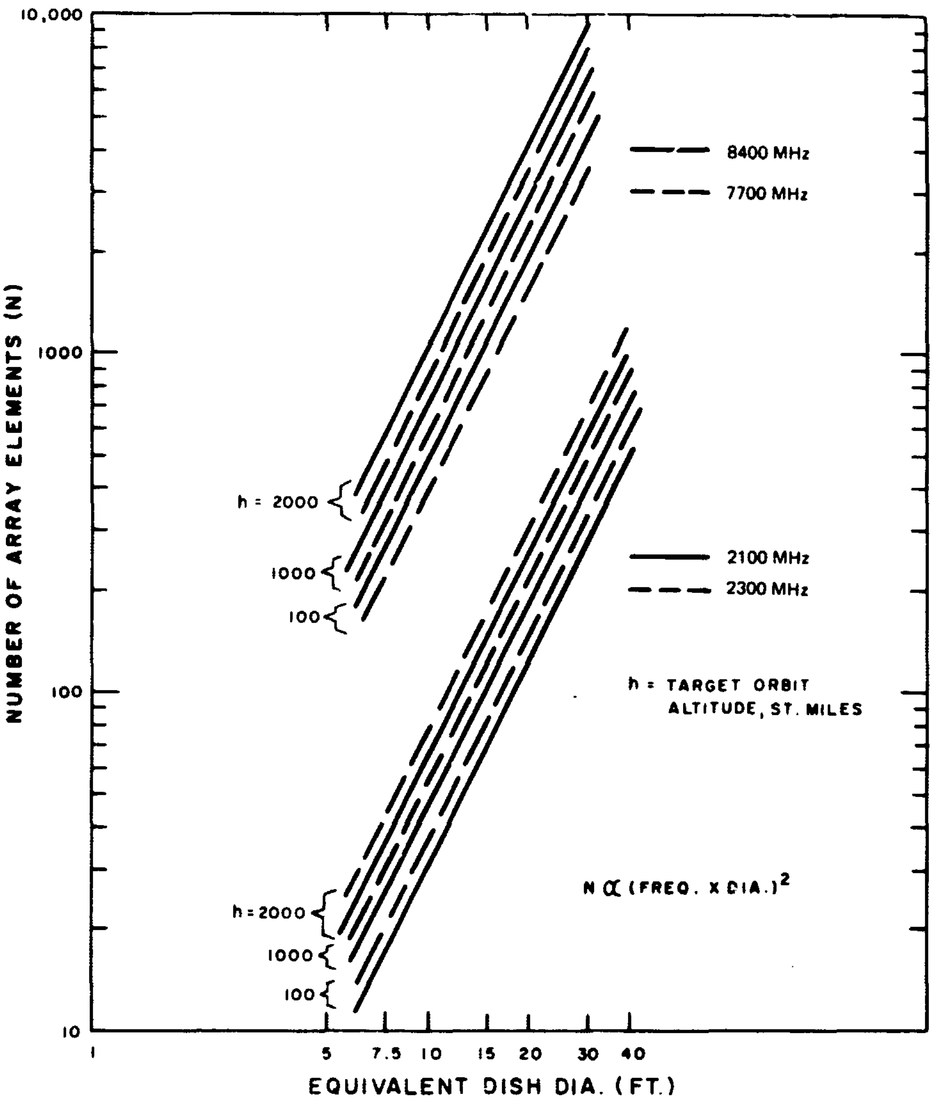


FIGURE 9.I.3 Number of array elements vs equivalent dish diameter for various frequencies and target altitudes.

TABLE 9.I.1
SERVICE QUALITY REQUIREMENTS

Target to Spacecraft to Ground

Parameter	b (MHz)	D (MHz)	B (MHz)	CNR (dB)	SNR (dB)	C/N_0 (dB-Hz)
ODRN Analog (FM)	1.5	3.5	10	9.6	36*	79.6
USB TV	0.5	1.16	3.3	9.6	36	74.8
ODRN Digital (PCM) Data Rate R = 1 Mb/s	....	....	2	10**	....	73.0
	(kHz)	(kHz)	(kHz)			
Voice (PLD)	3.0	5.7	17.4	7	22*	49.4
USB 90% Intell.	3.0	3.05	12.1	7	15	47.8
Range Code	PLL with $2B_{LO}$ = 0.8 Hz			22	....	21
Doppler	PLL with $2B_{LO}$ = 12 Hz			0	....	10.8
Target Pilot	Lowest demand in 10 Hz			6	....	16

Ground to Spacecraft to Target

Parameter	b (kHz)	D (kHz)	B (kHz)	CNR (dB)	SNR (dB)	C/N_0 (dB-Hz)
ODRN Analog (FM)	150	350	1000	9.6	36*	69.6
ODRN Digital (PCM) Data Rate R = 100 kb/s	....	....	200	10**	....	63.0
Voice (PLD)	3.0	5.7	17.4	7	22*	49.4
USB 70% Intell.	3.0	1.75	9.5	7	9	46.8
Range Code	As before			....	....	21.0
Doppler	As before			....	....	10.8
Satellite Beacon	Lowest demand in 1 Hz			10	....	10

* Peak-to-peak Signal/RMS Noise for TV, RMS Speech/RMS Noise for Voice

** Needs $C/(N_0R)$ = 11 dB for Bit Error Rate of 10^{-6}; add 2 dB for degradation; subtract 3 dB because B = 2 R.

Symbols: b = Base bandwidth, D = Deviation, B = RF bandwidth, N_0 = Noise Density (Power in 1 Hz)

ODNR = Orbiting Data Relay Network. USB TV = Unified S-band TV; 10 frames/sec, 300 lines/frame.

PLD = Phase Lock detector. PLL = Phase lock loop.

Note: C/N measured in RF bandwidth, B; S/N measured in baseband b.

TABLE 9.I.2

GROUND-TO-SPACECRAFT LINK CALCULATIONS

C/N_0 desired = 69.6 dB-Hz

Margin needed = 12.4 dB at S band, 12.9 dB at X-band

N_0 = Noise density = -168.6 dBm/Hz (6.5 dB noise figure)

C = Carrier power required = -86.6 dBm at S band, -86.1 dBm at X-band

	Plan A	Plan B		Plan C
f = frequency, MHz	8400	2100	1800	Same as for Plan B
G_4 = Gound antenna gain, dB (30' dish at S band, 15' at X)	49.4	43.4	42.0	
G_2 = Spacecraft antenna gain, dB (3' dish at S band, 1.5' at X)	29.4	23.4	22.0	
L_p = Path loss (26,000 s.m.), dB	203.8	191.8	190.4	
P_4 = Ground power needed, dBm	38.9	38.4	39.8	Like B
watts	7.8	6.9	9.5	

TABLE 9.I.3

SPACECRAFT-TO-TARGET LINK CALCULATIONS

C/N_0 desired = 69.6 dB-Hz

Margin needed = 5.3 dB at S band, 5.5 dB at X band

N_0 = Noise density = -164.4 dBm/Hz (10 dB noise figure)

C = Carrier power required = -89.5 dBm at S band, -89.3 dBm at X-band

	Plan A		Plan B	Plan C
f = Frequency, MHz	2100	1800	7700	2300
G_2 = Spacecraft antenna, gain, dB (equiv. to 30' dish at S band, 15' at XL	43.4	42.0	48.7	44.2
G_1 = Target Antenna gain, dB	20.0	20.0	20.0	20.0
L_p = Path loss (30,000 s.m.), dB	193.0	191.6	204.3	193.8
P_2 = Spacecraft power needed, dBm	40.1	40.1	46.3	40.1
watts	10.3	10.3	42.6	10.3

TABLE 9.I.4

TARGET-TO-SPACECRAFT LINK CALCULATIONS

C/N_0 desired = 79.6 dB-Hz

Margin needed = 5.3 dB at S-band, 5.5 dB at X-band

N_0 = Noise density = -168.6 dBm/Hz (6.5 dB noise figure)

C = Carrier power required = -83.7 dBm at S-band, -83.5 dBm at X-band

	Plan A	Plan B	Plan C
f = Frequency, MHz	2300	8400	Same as for Plan B
G_1= Target antenna gain, dB	20.0	20.0	
G_2= Spacecraft antenna gain, dB (equiv. to 30' dish at S-band, 15' at X)	44.2	49.4	
L_p= Path loss (30,000 miles), dB	193.8	205.0	
P_1= Target power needed, dBm	45.9	52.1	
watts	39	162	

TABLE 9.I.5

SPACECRAFT-TO-GROUND LINK CALCULATIONS

C/N_0 desired = 79.6 dB-Hz

Margin needed = 11.3 dB at S band, 11.8 dB at X-band

N_0 = Noise density = -172.2 dBm/Hz (4 dB noise figure)

C = Carrier power required = -81.3 dBm at S-band, -80.8 dBm at X-band

	Plan A	Plan B	Plan C
f = Frequency, MHz	7700	2300	2255
G_3= Spacecraft antenna gain, dB (3' dish at S-band, 1.5' at X)	28.7	24.2	24.0
G_4= Ground antenna gain, dB (30' dish at S-band, 15' at X)	48.7	44.2	44.0
L_p=Path loss (26,000 miles), db	203.1	192.6	192.4
P_3= Spacecraft power needed, dbm	44.9	42.9	43.1
watts	30.9	19.5	20.4

TABLE 9.I.6

EMERGENCY VOICE-LINK FACTORS

Parameter	Target to Spacecraft	Spacecraft to Target	Remarks
C/N_o desired, dB-Hz	49.4	49.4	For 22 dB SNR is baseband
Margin needed, dB	18.4	18.4	High multipath fading
N_o = Noise density, dBm-Hz	-168.6	-164.4	6.5 dB and 10 dB N.F.
C = Carrier power required, dBm	-100.8	-96.6	
f = Frequency, MHz	2300	2100	
G_t = Target antenna gain, dB	0	0	
G_s = Spacecraft antenna gain, dB	44.2	43.4	Array (30 ft. equiv. dish)
L_p = Path loss, dB	193.8	193.0	
P = Transmitter power required dBm	48.8 48.8	53.0 53.0	
watts	75.9	200*	
P = Transmitter power required for (C/N_o = 46.8 dB-Hz) watts	41.7	110*	For 9 dB S/N in baseband (79% intelligibility, 24 dB clipped speech)

* For spacecraft-to-target link the alternate frequency of 1800 MHz requires the same power as 2100 MHz (reduced path loss compensates for reduced array gain).

** Calculations are shown for one voice channel on the target-to-spacecraft link, using only Frequency Plan A. The saving in fading margin and thermal noise resulting from the use of proper filtering has been ignored here.