HUGHES
RESEARCH LABORATORIES

RESEARCH REPORT NO. 303

ROUTING AND ECONOMIC PRINCIPLES OF MULTIPLE ACCESS SATELLITE COMMUNICATION

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APRIL 1964

HUGHES RESEARCH LABORATORIES
Malibu, California

a division of hughes aircraft company

Research Report No. 303

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Samuel G. Lutz
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*Parts of this study stem from work performed for NASA under Contract NASw-495.

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ABSTRACT

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Multistation random access satellite communication techniques and the present status of communication satellites are discussed as background. The subsequent portions of the report examine the routing aspects of a random access system, the economic aspects of earth stations, and the economic break-even relations between satellite and surface communication. The economic constraints on random access stationary satellite communication differ from those on surface systems in ways which may mean that such a communication method will best meet the needs of areas having low surface communication densities. This form of satellite communication also should lead to simpler and more direct routing between distant subscribers than has been the practice with multichannel surface communication techniques.

Author

PART I

PRINCIPLES OF MULTIPLE ACCESS SATELLITE COMMUNICATION

A. Introduction

The purpose of this paper is to aid in clarifying over-all aspects of multiple access satellite communication and thereby promote understanding of how it may best be used in conjunction with surface systems to meet global needs.

It will be seen that with high or even medium altitude satellites a multiple access system permits direct and flexible interconnection of large or small capacity earth stations, much as if the satellite were a switching center. Consequently, the availability of such systems may modify presently planned practices of routing intercontinental circuits over trunks between traffic switching centers of national, regional, and continental levels. The extent to which satellite communication will modify such routing practices will depend, of course, on the type of satellite system and on its economic aspects relative to surface communication. Concerning the economic aspects, costs may remain uncertain until systems are operating. However, a few important economic principles are clear and can be used with whatever cost estimates the reader prefers. The numerical examples in the subsequent parts of this paper are intended only to be illustrative of the methods, using cost data which are at least within the bounds of reason.

Part I of this paper explains the over-all principles of multiple access satellite systems. It can be seen that such systems are compatible with surface communication practices such as the use of automatic switching and signaling systems. Such systems have been studied and partially designed, and several systems do not appear to have problems which are necessarily beyond the state of the art. In Part II concepts of the important boundaries of an earth station and their relation to traffic routing are developed. The outer boundaries are those containing all earth stations which can be reached (a) as members of a single one-hop system, or (b) by participation in more than one such system. These outer boundaries can be located geometrically. The next smaller boundary is that of transition or break-even between surface and satellite communication, the latter being preferable beyond this transitional boundary. A station's innermost boundary is that containing its subscribers. This section also discusses global routing via one-hop and multihop satellite circuits and the use of surface tails.

The final two parts deal with the economic principles of satellite and surface communication in relation to determining a station's two inner boundaries. From a purely economic viewpoint, subscribers should be within an area such that the average per circuit cost for earth station use plus that for subscriber to earth station communication is a minimum. Practically, this area will be modified by such considerations as geography and national policy; these will help formulate a decision whether to use a regional station in another nation, whether there should be a national station, or whether a large and highly developed nation should have several stations.

The transition boundary depends economically on the volume-distance break-even between surface and satellite communication; this is developed in Part IV. Practically, this transitional boundary may also be modified by considerations of geography, policy, etc., or by the impracticability of surface communication other than by high frequency radio.

B. Multiple Access Concept

One simple proposed use of artificial earth satellites has been that of providing two-way communication between only a pair of earth stations. Such a satellite link would be equivalent to a high capacity cable between these terminals and would be used in much the same way as a cable link in establishing intercontinental circuits. Obviously, such a pair of stations should have enough traffic to utilize the channel capacity of the satellite's repeater, perhaps 600 channels. Such a satellite might be within view of many earth stations simultaneously, but might only be used by two stations (at any one time).

Multiple access refers to the use of the same satellite by three or more sations at one time to permit each station to communicate simultaneously with any or all of the others. Topologically, the satellite is a nodal or interconnection point for the circuits of all stations which use the satellite simultaneously.* Up to this time, there have been no such nodal points for intercontinental communication, such as across the Atlantic Basin, largely because the cost of surface communication increases with distance. One can conconceive of

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*A nonstationary satellite might be used by different pairs or groups of stations at different times (not simultaneously) while over different parts of the earth. In establishing the concept of multiple access it is simplest to consider a stationary satellite (one having a synchronous circular equatorial orbit), because it always can be used by the same group of stations. Of course, nonstationary satellites can also provide multiple access, as discussed in Part II.

a multiple access system using its satellite much as if it were a switching center or a "telephone exchange in orbit." However, communication satellites should be kept simple to be reliable, so any circuit switching should be done by the earth stations. The study of methods for making and controlling these interconnections between the earth stations, while using simple satellite repeaters, has formed an important part of the study of multiple access systems and is discussed later.

C. Distinction Between Assigned Channel and Random Multiple Access

As an introductory analogy, we consider a manual telephone switchboard (the satellite) serving a number of PBX switchboard stations (earth stations) of institutions or large business firms. The central switchboard's operator can connect any circuit from any station to a circuit from any other station, more or less at random. The same circuit may be connected to one station and later to any other. Before the central operator leaves at night she may plug in certain night-line connections between stations. These become permanently assigned interconnections until switchboard service is resumed in the morning. Users of this system would have random access to all other telephones during the day, but have access only via the assigned circuits at night. Of course, there could be a combination of both types of service, with certain important (leased) circuits being left connected at certain hours or throughout the day.

In a random multiple access satellite system, each station has a presumably adequate number of circuits (sending and receiving channels) to the satellite, but their frequencies (or time slots) may be changeable. A station may use any one of its circuits to communicate with some other station for as long as necessary, then use the same or a different circuit to communicate with a different station. In an assigned channel system, each station would always (or during prearranged periods) have each circuit connected to a specific other station. One sees that the assigned channel form of multiple access can be simplest, and hence least expensive, when fully used. However, it lacks flexibility and tends to limit the system to a few relatively large stations having a predictable traffic distribution. To illustrate these limitations, perhaps to the point of absurdity, consider a system of 50 stations. Each would need at least 49 circuits for any communication with each of the other stations. With only one circuit between stations their total would be $1/2\ (49 \times 50) = 1225$, requiring 2450 one-way channels through the satellite. The circuits to many of the other 49 stations might be used infrequently, possibly once a week on an average, whereas at times a dozen circuits to a particular station might be needed. Most of these 50 stations would need no more than 24 circuits at any one time, provided that each circuit could be used, at random or whenever desired, with any of the other stations. The satellite repeater would carry the collective traffic from all these stations,, thus making good use of its large circuit capacity.

Multiple access systems of the future may provide both random and assigned channel service, possibly through separate repeaters in the satellite. The assigned channel service might be used for the heavy "base" traffic between certain pairs of larger stations, while the random access service would be more useful to the smaller stations and for the temporary traffic peaks between the larger stations.

Except as mentioned, further discussion will be directed toward the more general case of random access systems. Assigned channel systems may be disposed of as a special case, as being equivalent to a "frozen" random access system whose interstation circuit connections remain unchanged.

D. Multiplexing and Modulation for Multiple Access

The following discussion will show that multiple access can be achieved by many methods, using relatively simple satellite repeaters. Moreover, these are similarities in principle which can be translated from discussions of one method to another. For example, the time slots of a time division multiplexed (TDM) system are closely analogous to the frequency channels of a frequency division multiplexed (FDM) system.

The principal requirements for a random access satellite system are simple. They include the following:

1. The satellite repeater(s) must be highly reliable and relatively light. Hence it should be <u>simple</u>, at least for the present. It should require relatively low power and have no critical requirements on input noise, linearity, selectivity, etc. Signal "processing," such as switching or rearrangement of channels, and difficult modulation changes, such as analog/digital, should be avoided.

2. Each earth station must transmit its channels to the satellite's receiver with all such transmissions combining suitably for retransmission from the satellite. Each earth station receives the satellite's signal containing all the channels, but it selects (separates) and uses only those channels directed or addressed to it.

3. A random access system must have means (on earth) to "call" the stations and must have channels allocated between stations when needed. It must also be able to release these channels when they are no longer needed, and sufficient supervisory control must be provided to maintain the system's effectiveness.

4. The system must be compatible with present and probable future surface communication practices; for example, in relation to transmission standards, adaptability to direct distance dialing, etc.

5. The system must provide adequately for earth stations requiring widely differing numbers of channels. In doing this, it should not impose distinctions between large (heavy traffic) and small (light traffic) stations, nor impose cost barriers to small stations becoming large.

6. The system must be economic. The best system will be the one which meets the requirements with the least cost per circuit.

The fifth requirement above merits discussion in relation to the economic requirement (item 6) because it can bear heavily on the selection of multiplexing and modulation methods. Specifically, it will be seen that both requirements strongly favor the use of a stationary satellite. With such a satellite, even the smallest stations can use less expensive fixed reflector antennas of large aperture and high gain. Additionally, the use of a stationary satellite minimizes Doppler and delay difference problems, thus reducing the influence of these problems upon the selection of modulation and multiplexing methods.

With present experimental earth stations which must use any satellite, the cost of the fully steerable antenna and its associated tracking and control equipment accounts for about half of the station cost. Even for single antenna installations for intermittent experimental use, antenna systems with 20 to 30 m apertures have cost several million dollars. Hence, most proposed satellite communication systems have assumed that light traffic stations would use

10-m antennas in order to reduce their cost. The lower gain of these smaller antennas imposes a corresponding burden on the satellite, and as a result it is able to serve fewer small station channels per repeater at a correspondingly greater cost per channel. In addition, this special service to small-antenna stations creates a distinction, complicates communication between small and large stations, and raises a cost barrier to station growth.

Large fixed-reflector antennas should cost less than a tenth as much as a corresponding fully-steerable installation, as is shown later in this report. With such an antenna, the small station can be good, though inexpensive, but fixed-reflector antennas require that the satellite be adequately stationary. The use of such a satellite eliminates hand-over complications and costs (as discussed later), minimizes Doppler frequency shifts, facilitates the use of time division multiplexing, and otherwise influences the comparison of modulation and multiplexing methods. On the other hand, the stationary satellite's relatively great propagation delay requires the use of good echo suppressors. Several improved echo suppressors have been developed recently and are being tested by various laboratories.

Accepting the premise that an adequately stationary satellite is essential to fullest development of random access systems because it allows smaller stations to use high-gain, low-cost fixed antennas, permits one to weigh the relative merits of various possible multiplexing and modulation methods without overemphasizing the problems which are related to the satellite's motion relative to the earth. Specifically, it is not necessary to discard the use of SSB-FDM or PCM-TDM (pulse code modulation-time division multiplexing) techniques on the grounds of the difficulty introduced by the satellite's motion.

Although there are many possible combinations of multiplexing and modulation methods, most can be discarded for failure to meet all of the above requirements. For example, a system would require too complex a satellite to receive multichannel FM transmissions from all earth stations at different frequencies, separate these channels, and retransmit them with the use of PCM-TDM techniques. On the other hand, certain modulation techniques such as FM and PCM, have been incorporated in proposed systems because of their ability to maintain a given signal-to-noise ratio with less signal power in exchange for greater than minimum signal bandwidth. These techniques appear attractive today because the spectrum now available for satellite communication has not yet become congested, and because today's satellite transmitters radiate 5 W or less. Time may change these views and practices, as it has done with prior radio techniques.

Modulation methods for use in satellite communication have been compared, primarily on a relative power basis, and have often emphasized use of the same modulation to and from the satellite, without adequately weighing all the multiple access requirements. Such comparisons[I-1] favor FM and PCM and suggest that SSB modulation would require prohibitive powers and require amplifiers with unattainable linearity. As far as is known, no serious proposal has yet been made to use FDM-SSB from satellite to earth within the foreseeable future. Single sideband modulation is most attractive for use from earth to satellite, so that the channels from all stations arrive at the satellite properly multiplexed in frequency, as if coming from a single station. The composite signal is converted by simple circuits in the satellite repeater to a wide-deviation, phase-modulated signal at the proper frequency for retransmission. Thus, relatively low power is required for the satellite to earth link. At the earth stations, the transmitter power is less critical and can be controlled considerably by use of compandors, high efficiency amplifiers, and other techniques. Earth stations all receive and detect the satellite's phase-modulated signal, but select only those channels desired.

Several all-FM systems have been proposed. These require the earth stations to transmit separate carrier frequencies, since perfect synchronization of their carriers would seem impossible. In one system, all these signals are amplified and retransmitted by the satellite at their same relative frequencies. Each earth station receives, separates, and detects all these frequencies (except possibly that from its own transmitter), and then selects the desired channels from each signal. With this system the satellite can be relatively simple, but the earth receivers become more complex. On the other hand, the high-power earth transmitters need not be as linear as required with SSB. The channel capacity of the satellite repeater is greatest when it carries a single FDM-FM signal and decreases when carrying several signals, because their resultant amplitude is highly variable, whereas the amplitude of a single FM or PM signal is essentially constant. Despite this capacity reduction, the basic simplicity and present acceptance of this multi-FM approach makes it attractive for an initial low-capacity multiple access system.

A similar comment applies to amplifying several PCM or other digital signals at several different frequencies. Except with amplitude (on-off) coding, a TDM-PCM signal has constant amplitude and can use the maximum power capability of the repeater. The sum of several such signals at different frequencies has a highly variable amplitude and hence lower average power, with the result that fewer channels can be used.

Since either of these two methods limits the satellite repeater to fewer channels from a multiple access system of small stations than from a pair of large stations, the small stations might have a correspondingly higher cost per channel for their use of the satellite.

Another all-FM system[I-2] proposes that each station's signal be detected at the satellite and that its channels be recombined at base band for FM retransmission on a single carrier. This proposal would limit flexibility and require undesirable complexity in the satellite.

Proposals to use TDM usually involve the use of digital modulation such as PCM or Delta modulation. Very narrow pulses are required to obtain many channels and it is seldom that more than 240 channels per repeater are proposed. The difficulties of synchronization, Doppler correction, etc., are obvious but not insurmountable. However, greater difficulties generally lead to greater costs. One notes that digital TDM carrier and microwave relay systems have faced difficult competition, despite their multirepeater advantages for long surface circuits. Perhaps a worse objection is the growth constraint imposed by time division's closed cycle of commutation. All voice channels must be sampled, and these samples digitized, e.g., 8000 times/sec. Time division multiplexing of N such channels provides a time slot of not more than 1/8N msec in which to transmit the digits for each channel sample. Increasing the number of channels in a sampling cycle shortens all their time slots and requires the use of correspondingly shorter pulses for <u>all</u> channels. With FDM, however, the base-band spectrum is open ended. New channels can be added above the existing ones.

An alternative is FDM-PCM, in which each digital voice channel is separated in frequency from all others, much the same as with FDM-SSB. The bandwidth of each PCM channel would be in excess of 50 kc, and guard bands would also be needed.

A major objection to PCM is that its trade of bandwidth for signal-to-noise improvement (power reduction) is essentially irreversible, unlike frequency modulation. With FM, channel capacity can be increased within a given rf bandwidth by decreasing the frequency deviation and then increasing the power to maintain the required signal-to-noise ratio. With PCM, quantization noise depends on the number of digits (pulse positions) per sample and cannot be decreased by increasing the power.

Another class of system proposals employ the newer common spectrum modulation and multiplexing techniques, in which each channel's signal is coded so as to spread its bandwidth to that of the entire satellite channel, and to impart distinguishable characteristics relative to the other signals whose band it shares. Thus, all signal channels are superimposed, both in time and frequency, and must be separated at the earth receiver by correlation techniques or matched filters, each uniquely responsive to the distinguishing characteristics of the desired channel's signal. These techniques are foreign to present common carrier practices. Considerable time and experience may be required for such systems to achieve acceptance, and to determine their operational advantages and limitations relative to systems which use the more familiar FDM or TDM techniques.

In summary, one sees that there are many methods for achieving multiple access and it is only a question of arriving at the "best" method. A point worth noting is that the attributes or criteria of this best method may change with time, if only because of the obvious starting and growth problems of random access systems. The best method at first may be one which requires least development and can accommodate the first few stations, even though such an initial system falls a bit short of satisfying all the ultimate objectives. Such an initial system should, however, be able to change and grow to the ultimately best high-capacity random access system with a minimum of obsolescence. Experience with such an initial system should demonstrate the usefulness of random access and create the demand which is needed to justify better, higher capacity, lower cost systems.

Insofar as most of this study is concerned, it is relatively immaterial which multiplexing and modulation methods eventually are preferred. However, if only for reasons of conceptual simplicity, it will be assumed in subsequent sections that FDM-SSB is used from all earth stations to the satellite at which the frequency multiplex of all these signals is phase modulated for retransmission to earth. This assumption need not be restrictive because, in most aspects of calling, channel allocation, etc., there will be well-known analogies between FDM and TDM, such as between frequency slots and time slots.

E. Calling, Channeling, and Supervisory Aspects of Random Multiple Access

Consider a small earth station having equipment for only 12 circuits (12 transmitting and 12 receiving channels) and participating with other stations of all sizes in random multiple access use of a 600 circuit (1200 one-way channel) satellite repeater. Such a station probably could not afford to use conventional multiplexing by channel groups, super groups and master groups, at least not unless it were restricted to some specific channel group for transmitting and a different group for receiving. However, with these channels permanently assigned, the station would not have random multiple access. The station needs the use of any 12 of the 1200 channels for transmitting, or any other 12 for receiving, otherwise, it never could communicate with all of the other stations. The station preferably should not have permanently assigned channels for either receiving or transmitting because when idle they could not be used by other stations.

An incrementally tuned heterodyne frequency translator permits the selection of any receiving channel or the generation of any transmitting channel. Such translators are relatively expensive, but 12 of them certainly would be much less expensive than conventional modem multiplexing equipment for all 1200 channels.

If each station's receiving channels were permanently assigned, only these channels would need to be selected and demodulated. Each station then could afford to use automatic call detection equipment on its idle receiving channels. However, if the receiving channels were not thus assigned among the stations but were used at random, a small station would need to demultiplex all 1200 channels and use 1200 automatic call detectors on them, even though it never used more than 12 channels at a time.

This call detection problem has led system designers to consider "out of band" signaling systems. The simplest of these is a party line signaling and service circuit to all stations. To see how this might be used (and why it would be troublesome!), assume that station H has a party wishing a circuit to station K. The operator at H determines that channel 293 is idle at the moment so she informs K's operator to select channel 293 for receiving. Operator K informs H that he will use another idle channel, 376, for the return circuit. Both would then release these channels when their parties finished. The relatively long propagation delay via a stationary satellite (about 270 msec up and back) introduces a potentially serious problem. In determining an idle circuit, or even the availability of the interstation circuit, these circuits still would sound idle even though someone else had started using them during the previous 1/4 sec. Interference from near simultaneous use of this interstation circuit would be intolerably frequent, even though the interstation communication were automatic and used brief digital transmissions.

This delay self-jamming and related problems have led system designers to incorporate some form of Channeling and Supervisory Center (CASC) to allocate channels upon request, record their use for accounting purposes, monitor the channel frequencies and transmission levels, etc. Each station would have its individual channel to the CASC, from which there would be a broadcast channel back to all stations. With coded digital signaling, the station channels could be either TDM time slots, or narrow (teleprinter) frequency channels so their total bandwidth would be small. The CASC broadcast replies would be at a suitably high bit rate, occupying the equivalent of a voice channel. Such systems already have been worked out in sufficient detail to assure that they can be compatible with worldwide automatic signaling and switching systems.

F. Small and Large Stations, Satellite Use, and Multiple Access

Certain aspects of the possible distinction between small and large stations, on an antenna size and cost basis, were discussed briefly in relation to requirements which influence the choice of modulation and multiplexing methods for a random access system. The remaining division of opinion, or even misunderstanding, about small stations and their role in the future of satellite communication needs to be recognized and eliminated before it leads to unfortunate decisions which could retard the growth and utility of this new form of communication.

The crux of this difficulty seems to lie in the prevalent belief that the smaller stations must necessarily be poorer stations, whereas only the large stations can afford to be good enough to make efficient use of a satellite repeater. Proponents of this view reason that if all earth stations were charged for use of the satellite at the same rate per satellite circuit, there would be no incentive for a station to improve and make more efficient use of the satellite as the station grows to the point where it can afford a bigger and better antenna and other more expensive equipment. This argument suggests that the satellite operator is selling repeater power and bandwidth rather than repeater channels. On this basis, if two stations contract for the use of some fraction of a satellite repeater, they should be able to use their fraction for one channel, with inexpensive poor stations, or for a hundred channels if they are able to afford good stations. This laissez faire, or "buy a fraction for use as you please" philosophy of satellite use-cost allocation would seem logical in a strictly paired station (two-terminal) system. However, a multiple access system cannot operate on this laissez faire basis; a considerable degree of coordination and conformance to standards is required if each station is to be able to communicate with all other individual stations in the system.

Ideally, all stations should be able to transmit equal signals to the satellite, use the satellite with equal efficiency, and receive any channels from the satellite with satisfactory quality. If one thinks only in terms of fully steerable antennas, this ideal has seemed to require that all stations use antennas and other equipment as inexpensive as the smallest stations could afford. If this meant that all stations used relatively small (lower gain) antennas and relatively noisy receivers, all stations would make relatively inefficient use of the satellite repeater. It is argued, however, that the large station which can afford larger antennas and better receivers could and should make better use of the satellite and therefore should pay less per satellite channel used.

Recognition of these problems has led to proposals for dual standard systems. In such systems the large stations would conform to high standards and use the satellite efficiently in communicating among themselves, while small stations would be granted lower standards and make less efficient use of the satellite in order to lower their equipment costs. To avoid segregation, large stations would add equipment with which to communicate with the small stations according to the small station standards.[I-2]

These dual standard systems require distinguishing between the two classes of stations. Should a medium size station consider itself small, or should it make the considerably greater investment necessary to call itself a large station? And what about the small station which needs to grow, but can't make the additional large station investment? A triple standard system would seem only to make these problems worse. It is clear that at least the random access portion of the system should be a single standard system based on the choices which permit small stations to be both good and inexpensive. If such choices can be made so that all stations in the random access system use the satellite with equal efficiency, then each station should obtain satellite service at the same cost per channel minute.

G. Why Steerable Antenna Systems Are Expensive

A good earth station presumably requires a large, high-gain antenna, and these have not been an inexpensive item. The cost of the fully steerable antenna system has accounted for roughly half the cost of the experimental stations which have already been installed or are in the planning stage, even though such stations need only one antenna. Large antenna installations with apertures of 20 m or more have cost $2, 000, 000 and often considerably more. Small 10-m antenna installations have cost around $500, 000.

The cost of parabolic reflectors for steerable antennas increases rapidly with an increase in its aperture at a given operating frequency. The reflector must be light, and yet strong and stiff enough to maintain its parabolic contour within close tolerances despite such conditions as wind loads, changes in the relative direction of the gravitational vector, and changing thermal stresses. The state of the art rms surface tolerance for such reflectors is not much better than one ten-thousandth of the aperture diameter, or 2 mm for a 20 m reflector. Attempting to improve this tolerance increases the cost rapidly. A reflector's gain increases with frequency and aperture only as long as these tolerance departures from parabolic contour remain negligible compared with the wavelength. This state of the art surface tolerance has imposed a "gain barrier" on steerable antennas at about 60 dB, irrespective of frequency and aperture. Thus, at 6 Gc/sec, an 80-m reflector would provide no more gain than a 20-m reflector and probably less.

The reflector accounts for only a part of the cost of a steerable antenna installation. This relatively heavy reflector must be supported by an expensive pedestal or circular track and carriage that is capable of rotating and elevating the antenna accurately. This steering requires a servo system of considerable power and accuracy. A control system and operator's console are required and possibly a computer to convert ephemeris data to azimuth and elevation functions of time. Since computed tracking data may not be sufficient, satellite signal tracking facilities are also provided, at additional cost.

To make matters worse, operational earth stations should provide uninterrupted service, and this will require more than one such antenna installation. If using nonsynchronous satellites, it is necessary to acquire and start tracking and using a new (rising) satellite before the one previously used disappears (sets). This periodic hand-over to a new satellite probably requires a second transmitter and receiver, in addition to a second antenna system; this is explained in Part II. In addition, since these steerable antenna systems are complex and require considerable maintenance, there should be a third such system for use as a spare.

H. Potential Economy of Fixed Reflector Antennas

With a truly stationary satellite, the need for multiple antennas and satellite tracking capability vanishes. Only a single fixed reflector is needed and it can be of inexpensive rigid construction. Specifically, it can be a metallized concrete structure, set in the side of a hill or otherwise earth supported. Detailed design studies of such reflectors have shown that for a 26-m (85-ft) equivalent aperture, the cost should be less than \$100, 000, or 300, 000 gold francs.* Figure I-1 shows a sand-table model of such an antenna. Being a relatively rigid structure, it would be possible to achieve and maintain the desired 2 mm surface tolerance more easily than with the present all-metal and somewhat flexible steerable antennas.

Certain other earth station costs seem to be related to the cost of its antenna system. For example, it seems appropriate with an expensive steerable antenna system to use a large and expensive site, with correspondingly expensive buildings, access roads, etc. The use of an inexpensive fixed antenna tends to focus attention toward reduction of these other costs.

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*One dollar = 3. 061 gold francs, as used by CCITT.

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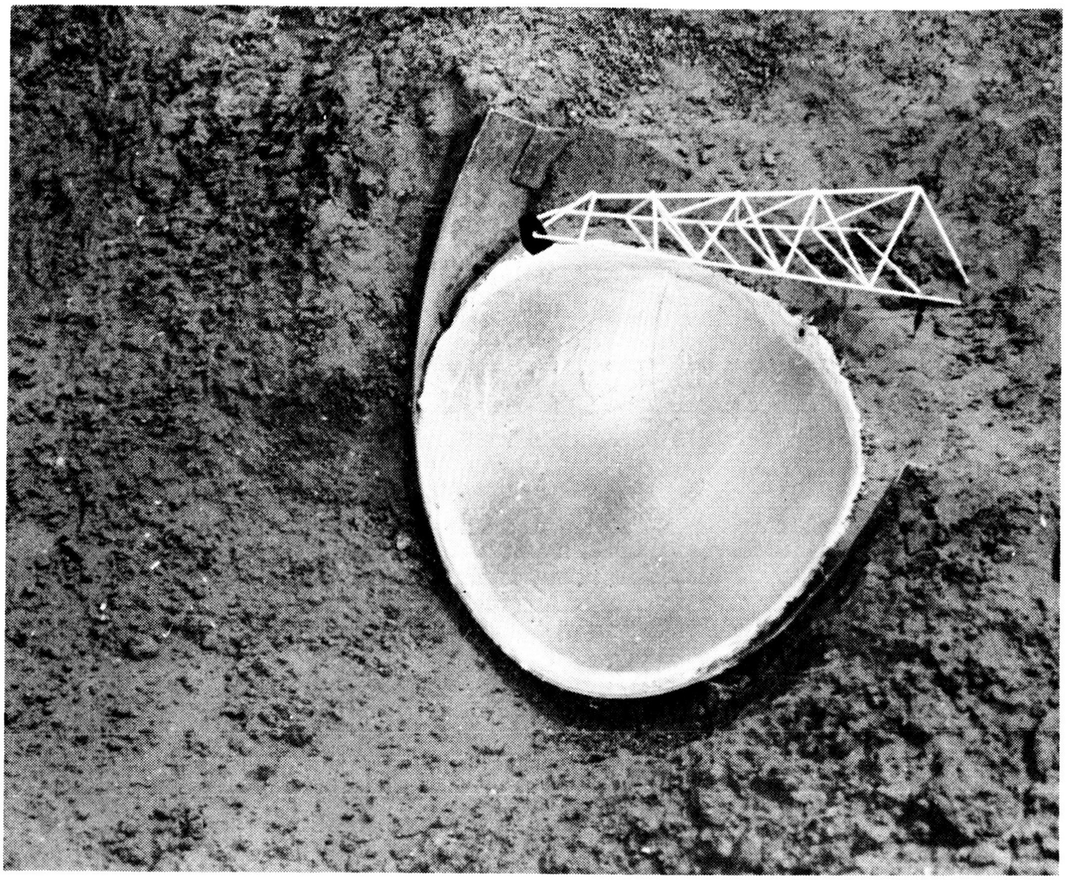

Fig. I-1. Model of earth-supported reinforced concrete fixed-reflector antenna, providing high gain at relatively low cost.

Why has there seemed to be so little interest in low-cost antennas of this type? Such interest has been delayed, quite understandably, by skepticism as to the station-keeping ability of stationary satellites, an ability which has not yet been demonstrated. At 6.0 Gc/sec, an 85-ft antenna should have a 3 dB beamwidth of 0.13° and a 1 dB beamwidth of 0.077°. Thus, if there is to be no adjustment of the antenna beam direction, the satellite should be held within, for example, 0.03° of the orbit station at which the antennas are directed. However, the beam center of such an antenna can be moved relative to the reflector axis by shifting the antenna feed. For conventional ratios of focal length to reflector aperture, the beam can be shifted somewhat more than 0.1° in any direction without significant loss of gain. Additionally, this feed point steerability of the beam can be increased considerably (at slight increase in cost) by increasing the focal length and thus using a more nearly spherical reflector surface.

Hughes Aircraft engineers who are developing SYNCOM and similar satellites have expressed confidence that satellites now being designed can be held indefinitely within 1/10 mrad (0.0057°) of its assigned station; this is less than a fifth as much drift as would be permissible with a fixed antenna beam. The prediction of such accurate station keeping is based on the use of precision optical tracking, using astronomical telescopes.* The demonstration of such accurate station keeping, whenever it can be accomplished, should dispel the skepticism and opposition toward low-cost fixed antennas. Clearly, the development of satellite communication should be directed toward precision station keeping to bring low-cost, high-gain fixed antennas into use. This would permit small stations to be good stations and would lead to random access communication between the many stations which can share the use of each stationary satellite. Any other course of development which perpetuates the use of steerable antennas would seem to limit the number and minimum size of earth stations, and thus limit the utility of satellite communication.

I. Importance of Receiving System Noise Temperature

Another apparent obstacle to small low-cost stations becoming efficient stations lies in the present belief that a station is not good unless it has an ultralow noise receiving system. In clear weather, when the sky temperature is negligible, a station using a maser cooled with liquid helium and an expensive low noise antenna (such as a horn-reflector) may achieve a receiving system noise temperature of about

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*Observatories were able to locate and track SYNCOM-I and thus determine its orbit accurately. SYNCOM-I had become electrically dead only seconds before burnout of its apogee motor. Telescope tracking is easier when the satellite's approximate position is known.

30°K. Under similar conditions, a station with a simpler antenna and a nitrogen cooled parametric amplifier may have a noise temperature near 80°K, or 4.3 dB more noise. Operational stations will not always have clear skies; they should operate in conformance with CCIR recommendations during the worst hours. When heavy storm clouds cause 3 dB absorption, the corresponding sky temperature becomes approximately 140°K, raising the receiving system temperatures of these two stations to 170° and 220° K, respectively, a difference of only 1.1 dB. The ultralow noise receiving system's improvement is greatest when it is least needed. Thus, it might be better to use the additional cost of a maser toward further increasing the antenna gain. The CCIR recommends[I-3] that the noise in any voice channel at a point of zero relative level should not exceed 10,000 pW psophometrically weighted mean in any hour, that is, during the "worst" hour in a year. These worst hours are those when heavy rain clouds cause the average sky temperature to be highest. During these critical hours, when maser receivers lose most of their advantage, stations with good nitrogen cooled parametric amplifiers and high-gain antennas seem good enough. Consequently, in this respect as well, small earth stations can be good without becoming excessively expensive. Such stations can make as efficient use of their satellite repeater as can the large stations, and all stations could thus be charged for satellite use at the same rate per voice circuit for the same type of satellite service.

J. The SYNCOM Program

Many of the foregoing aspects of multiple access satellite systems have been developed in connection with the synchronous communication satellite programs at the Hughes Aircraft Company. The programs of this company are mentioned chiefly because of the writer's familiarity with them, although it is recognized that excellent work is in progress at many other laboratories.

Studies of satellite communication started at Hughes late in 1957. At first, inclined, highly elliptical orbits with northern apogees were studied. Stationary satellites were considered an ultimate objective which might not become practicable within 10 or 20 years. Fortunately, only two years later, Dr. Harold Rosen recognized that a stationary satellite could be simple and light it is used spin stabilization. He designed a satellite weighing only 15 kg (32 lb) when in orbit and, with Mr. D. D. Williams, computed that the SCOUT solid-fuel booster with added staging could put this satellite into a stationary orbit if launched from near the equator.[I-4]

An operating prototype (Fig. I-2) was built at company expense and its television relaying and other capabilities were demonstrated in the laboratory (Fig. I-3). The electronic portion weighed only 3 kg (6.5 lb) including the self-erecting 8 dB collinear slot array antenna and a 0.5 lb, 2.5 W Hughes-developed traveling-wave tube. In retrospect, it would have been possible, but risky, to have orbited this satellite from the equator with a solid fuel rocket meeting the SCOUT's design objectives.

In August 1961, the National Aeronautics and Space Administration (NASA) decided to sponsor the development of stationary satellites in a series of steps by sponsoring the SYNCOM program.* The first objective was to demonstrate the achievement of a near-circular synchronous (24 hour) orbit, inclined to the plane of the equator, and to perform station-keeping and simple communication experiments. The SYNCOM satellites resembled that shown in Fig. I-2 but were slightly larger, weighing about 80 lb in orbit. In interests of reliability, all components except the frame and antenna were made redundant; one set of pulsed jet controls was operated by compressed nitrogen and a second set used hydrogen peroxide. The only communication requirement was for one two-way voice circuit, although the actual repeater bandwidth was capable of low definition (2 Mc) television.

SYNCOM-I was launched from Cape Kennedy (then Canaveral) on 14 February 1963, with a THOR-DELTA booster; it came within 1 sec of success, but a catastrophic failure occurred just prior to burnout of the apogee kick rocket. All available evidence suggests that the vibration and acceleration produced by this final rocket caused a nitrogen tank to burst. After making extensive precautionary modification, SYNCOM-II was launched successfully on 26 July 1963. It was subsequently drifted to and stopped at its desired equatorial crossing point and thereafter it was used for communication for about 15 hours each day. Within a month, its total communication time had exceeded the total for all prior communication satellites.

As of the date of writing (April 1964) no electronic malfunction has occurred. Its redundant electronics should permit SYNCOM-II to continue operating with full capability after one or perhaps several electronic failures. Prior to moving SYNCOM-II over the Pacific area its pulse-jet gas supply appeared adequate to maintain synchronism of its equatorial crossings for possibly another 10 years. At present, it appears that cumulative radiation damage to its solar cells (P on N) may prevent continuous operation after next fall or winter. The more radiation resistant (N on P) cells were not available when these

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*NASA Goddard Space Flight Center Contract NAS 5-1560.

M 3125

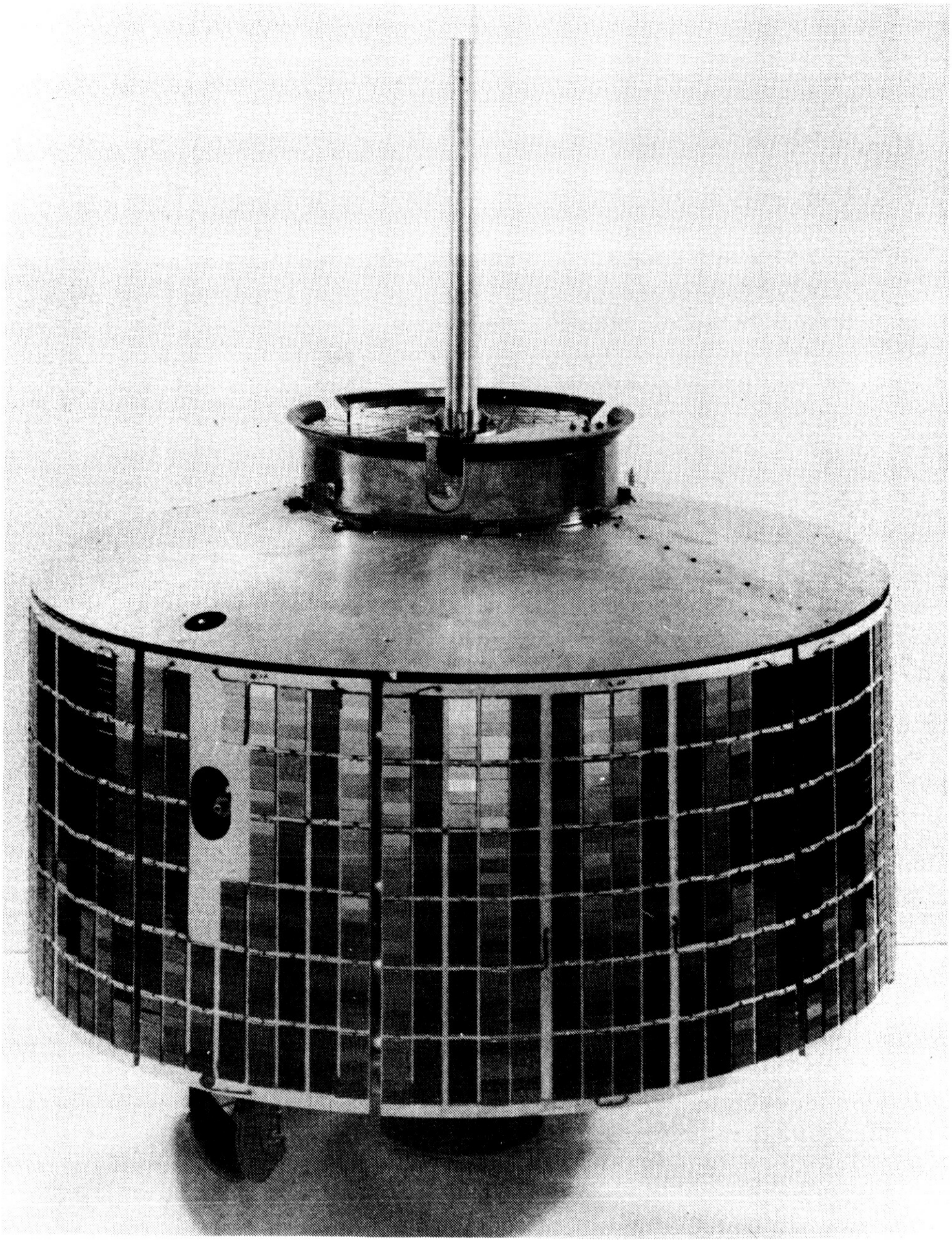

Fig. I-2. Original (1959) Hughes COMSAT, operating prototype.

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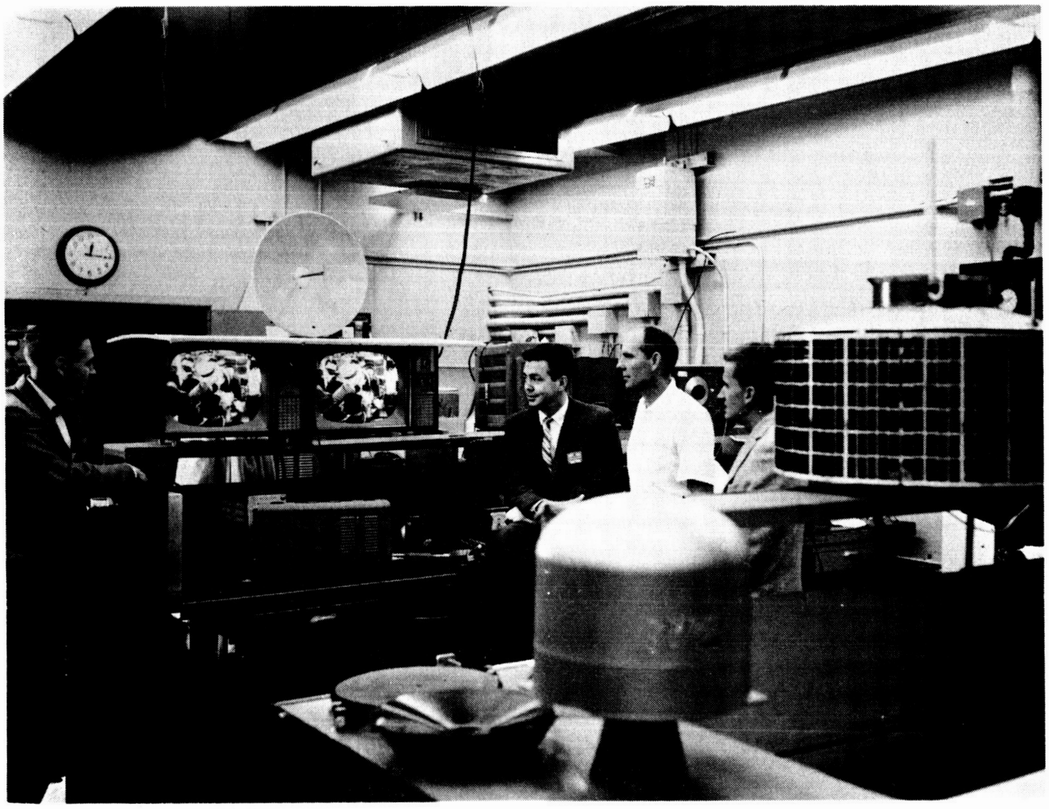

Fig. I-3. Laboratory demonstration of television relaying through the original COMSAT.

satellites were built but they are being installed in SYNCOM-III. Altogether, SYNCOM-II is showing that the first operational stationary satellites can have a life expectancy of at least two years and its designers believe that 10-year life and 90% launch success probability will become attainable. One observes that present technological progress is so rapid, and the use of satellite communication may become so explosive, that the first operational stationary satellites may become obsolete long before they fail.

NASA has announced that SYNCOM-III is to be launched during the second quarter of 1964, using an improved version of the THOR-DELTA booster and a midcourse correction maneuver to achieve a near-equatorial orbit plane. SYNCOM-III is expected to be nearly stationary and to be continuously usable for communication between Japan and the U.S. if it is stationed over the Pacific.

1. ADVANCED SYNCOM and Other Programs

Recognizing that extensive study and development should precede building more advanced stationary satellites, NASA inaugurated the ADVANCED SYNCOM program[*] in 1962. The design objectives were to achieve a highly stationary satellite, having multiple access and other communication capabilities approaching those desirable in an operational communication satellite. This was supplemented by a small contract[**] for studies related to multiple access satellite communication. In addition, in 1963, the company sponsored a design study of earth stations and of their integration into an intercontinental communication system. This latter study placed emphasis on small earth stations of low cost and flexible growth capability. It was completed in the fall of 1963.

The ADVANCED SYNCOM was designed to be orbited by an ATLAS-AGENA booster permitting it to be much larger, with a weight in orbit of about 600 lb. Its full-scale mockup, Fig. I-4, shows retention of the previous cylindrical shape. The use of

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[*] NASA Goddard Space Flight Center Contract NAS 5-2797. This contract was completed early in 1964 and the follow-on program has been reoriented as a multimission program to study such techniques as gravity gradient attitude control. Subsequent discussion and references should be understood as applying to the initial program, whose objective was a high-capacity, multirepeater, highly stationary communication satellite which might serve as a prototype for an operational communication satellite. The follow-on program is not referred to as ADVANCED SYNCOM but as ATS (Advanced Technological Satellites).

[**] NASA Headquarters Contract NASw-495.

M 3152

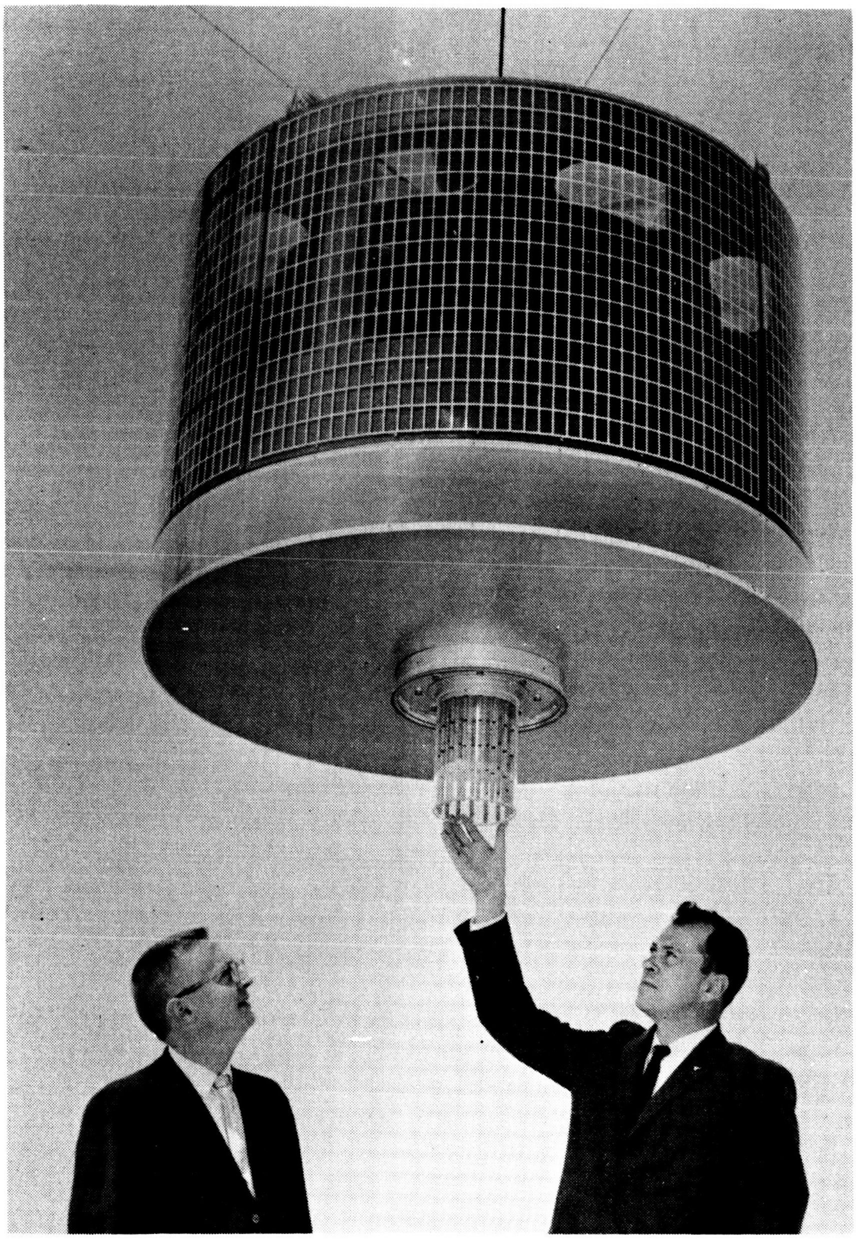

Fig. I-4. Full-scale mockup of ADVANCED SYNCOM satellite, 1963 high capacity communication version.

redundant major components was carried farther than in the smaller SYNCOMS to the extent of having all components for four satellites mounted in the common frame, and this left a negligible possibility of catastrophic failure after achieving its orbit. All probable failures would only cause "graceful degradation," with ample opportunity to orbit a replacement satellite and maintain uninterrupted service.

The four communication repeaters have separate rf channels with separate traveling-wave tubes; each repeater provides a choice of two operating modes. One mode can receive 1200 SSB voice channels for retransmission with wide phase modulation and is the preferred mode for multiple access use by many earth stations. The second mode provides "straight-through" frequency translation and is preferred for television relaying but can be used with other proposed multiple access systems previously discussed.

One assumption as to use of the ADVANCED SYNCOM is that there would not be more than 600 (duplex) telephone circuits at first, requiring use of only one of the repeaters. A second repeater might be used occasionally for relaying television. At this early period the repeater life expectancy would be uncertain and presumably it could be low. Hence, a conservative policy would be to start procedures toward orbiting a replacement satellite following the first failure of a SSB/PM repeater, recognizing that this replacement might require several months. Even if two more repeaters failed during these months, the fourth would continue to carry all the multiple access traffic. Television service, being FM/FM, would not necessarily be interrupted even by failure of all four SSB/PM repeaters, because all repeaters can be used in either operating mode.

At a later date the multiple access traffic might increase to the equivalent of 1200 to 1800 telephone circuits during peak hours, and require the use of three of the SSB/PM repeaters. Upon failure of any one of these, steps would be started toward replacing the satellite, presumably in less time than at first. The time expectancy of a second repeater failure should by then be well in excess of this delay in satellite replacement. Even if a second repeater did fail, the remaining two would carry 1200 circuits. This might cause some traffic delays during busy hours until replacement was completed. Certainly, it does <u>not</u> appear essential to keep spare satellites of this type in orbit for prompt replacement.

Another significant feature of the ADVANCED SYNCOM is its de-spun directive transmitting antenna. Other stationary satellite designs, such as for the ADVENT program, have involved three-axis attitude control of the satellite to permit use of conventional directional antennas. The beamwidth of such antennas would be the angle (17.5°)

subtended by the earth, the corresponding gain being 19.3 dB. SYNCOM-II employs a collinear slot array antenna whose radiation pattern is a solid of revolution about the spin axis, providing only about 8 dB gain. The ADVANCED SYNCOM antenna has a circular array of 16 collinear slot elements which are phased by an electronic goniometer to form a beam whose gain is about 17 dB. The goniometer spins this beam at a rate which cancels the satellite's spin and keeps it directed earthward. Laboratory tests of this antenna have been successful.

Looking even farther toward the future, the Hughes Research Laboratories has developed low-thrust cesium ion engines.* Such engines hold promise for attitude control and station keeping with future generations of stationary satellites.

Returning to today's matters, the Communication Satellite Corp. has decided that satellite communication service can be started soonest between stations in Europe and North America, by the use of a near stationary satellite termed EARLY BIRD. This satellite is to be built by Hughes Aircraft Company and orbited by NASA in 1965. It will be generally similar to SYNCOM-III and is to provide 240 telephone circuits between a pair of earth stations.

2. Conclusions

Experience from this series of programs strengthens the belief of the writer and his associates that there is no simpler and better way to start uninterrupted commercial satellite communication than by use of a spin-stabilized stationary (or near-stationary) satellite. The use of any nonsynchronous orbit would require many satellites to provide essentially uninterrupted service and would require expensive earth stations with multiple tracking antennas, thus tending to exclude small stations. Stationary satellites can best serve as an exchange in orbit, permitting random access interconnection of small earth stations with more other stations than would be possible or economic with other satellite orbit systems. Such use of stationary satellites can provide direct interconnection of distant earth stations, when and as needed, and permit jumping over most of the switching centers of intercontinental surface communication systems. Thus, this form of satellite communication may introduce new and simpler concepts of routing intercontinental communications; this is discussed in Part II.

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*NASA Lewis Research Center Contract NAS 5-2510.

PART II

TRAFFIC ROUTING PRINCIPLES FOR MULTIPLE ACCESS SATELLITE COMMUNICATION SYSTEMS

A. Restriction to One-Hop Circuits

It has been proposed, especially in connection with satellite communication systems using medium-altitude orbits, that very long circuits be relayed through two or more satellites, as shown in Fig. II-1. The dotted line between satellites is intended to indicate that in the distant future it may become feasible to relay directly between satellites; however, this possibility appears too remote to be considered here. Earth relaying is simpler today because in effect such an earth relay station is similar to a pair of terminal earth stations (requiring less multiplexing equipment, etc.). Hence, as has been recognized by CCIR,[II-1] the one-hop circuit is the basic element of any multihop circuit and merits first attention. It is shown in a later section that multihop use of stationary satellites appears unnecessary and undesirable.

Certain concepts are first developed in terms of stationary satellites before being extended to other satellite orbit systems. This is done primarily in the interests of clarity. Stationary systems are conceptually simple, since they have no hand-over constraints and other such complications which are best introduced after the general concept has been established.

B. Boundaries of an Earth Station

From the above and from Fig. II-2, one sees that an earth station at E is bounded first and innermost by the perimeter of the area (double-shaded in Fig. II-2) which contains the station's surface traffic feeder system to the local exchanges and thence to the subscribers whose satellite calls normally would pass through this station. The qualification "normally" has been made because, occasionally, more distant subscribers may use this station instead of their nearby station. For example, in Fig. II-2, a subscriber who normally would use station F for communication with the stations of satellite No. 1, might use a surface circuit to Station E in order to communicate with station G via satellite No. 2. This use of surface "tails" to satellite circuits will be discussed subsequently.

This innermost boundary generally will be the station's national boundary, or the boundary of a group of nations which share use of the station. However, this inner boundary need not follow national boundaries; it could be partly internal if the nation had more than one station.

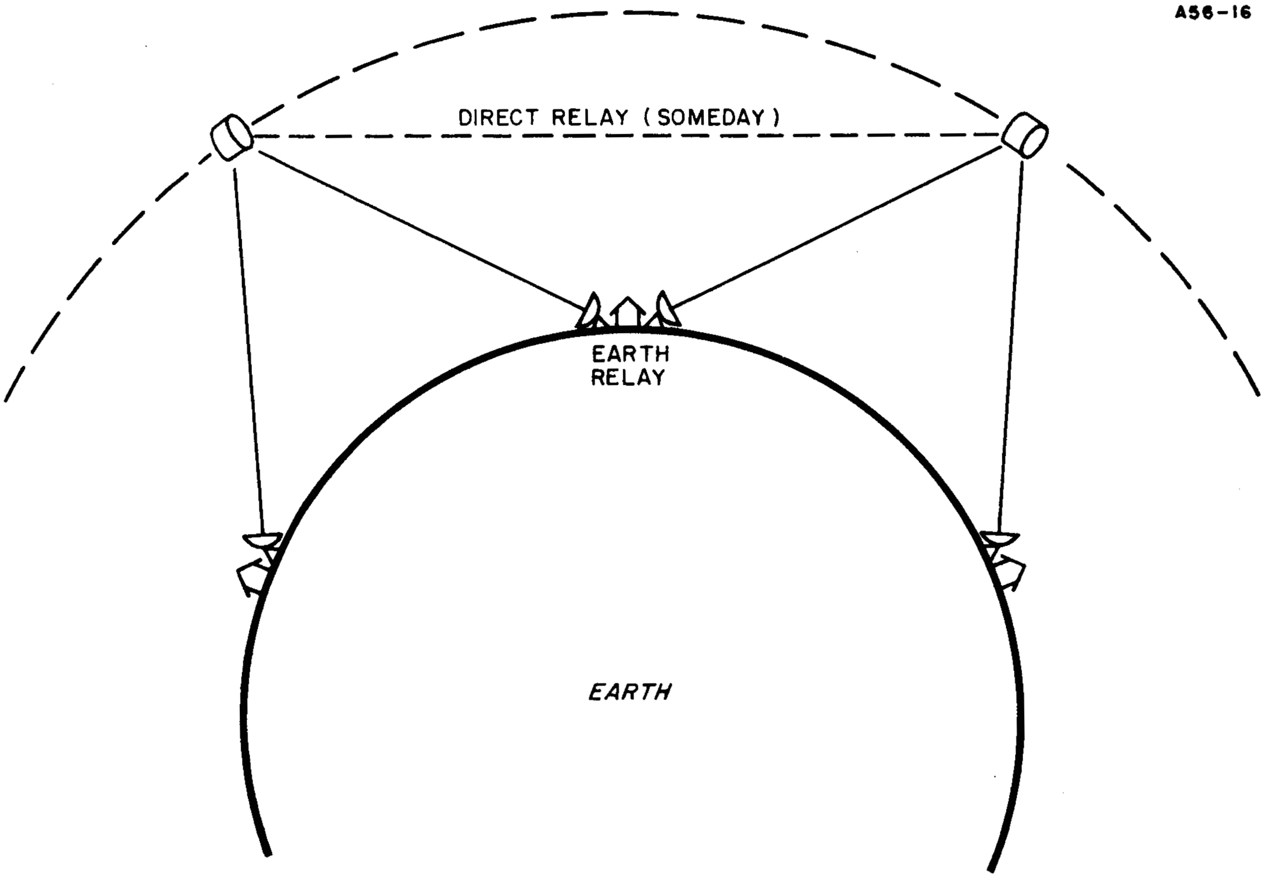

Fig. II-1. Two-satellite circuits, via earth or space relay.

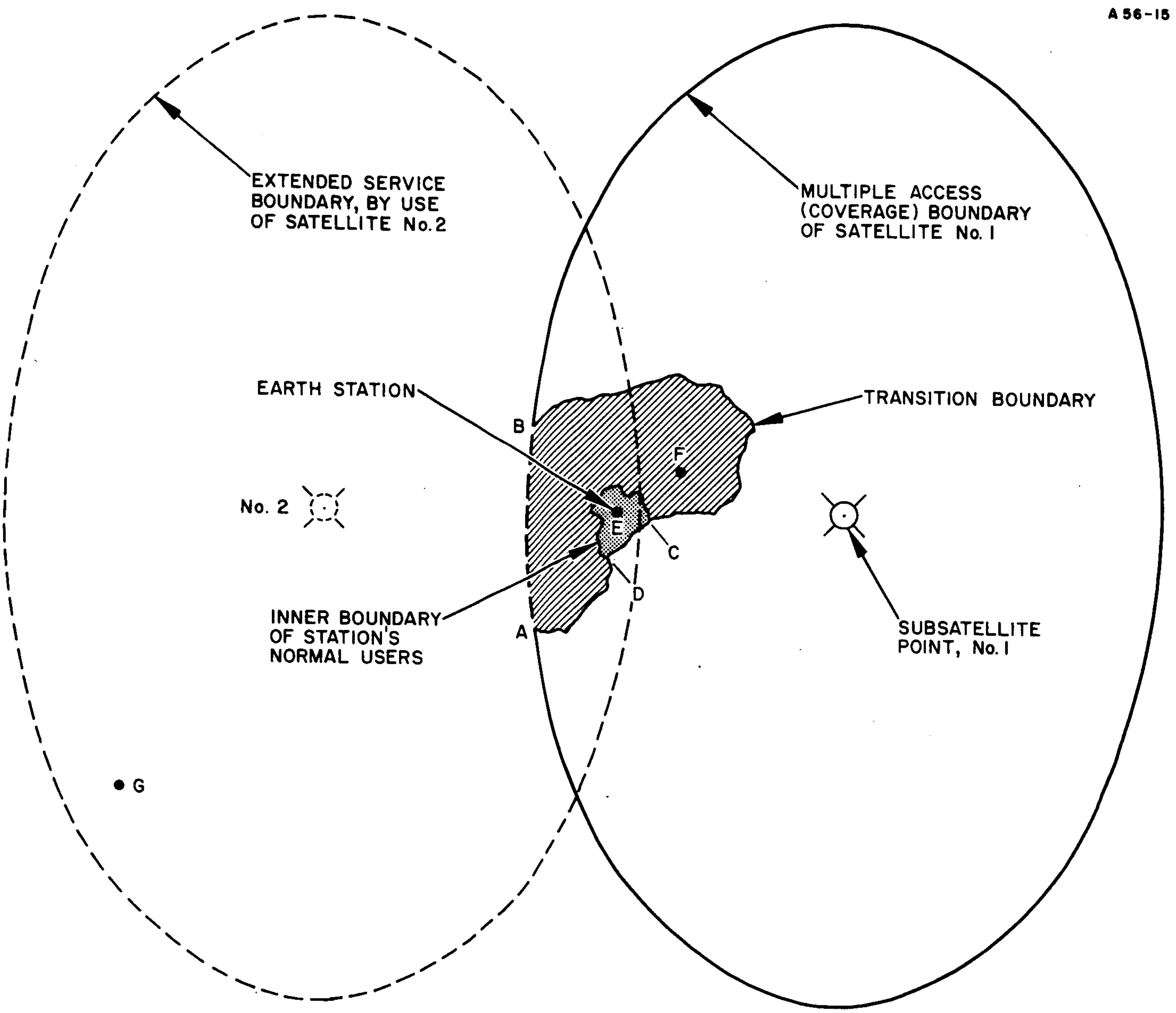

Fig. II-2. Boundaries of an earth station.

The next larger boundary will be termed the "transitional boundary," inside of which surface circuits normally would be used in preference to satellite circuits, the preference being for economic and possibly other reasons. In Fig. II-2, this boundary surrounds the single-shaded area. This boundary has been shown dashed between points A and B, along the coverage boundary of satellite No. 1 because, considering only satellite No. 1 and assuming that No. 2 were not yet in orbit, it would be impossible to use satellite communication beyond this dashed portion of the transitional boundary. Between C and D the transitional boundary is shown as following the innermost boundary to illustrate that surface communication across this portion may be unavailable for topographic, economic, or other reasons.

The next larger boundary will be termed the "single-satellite system boundary." This is the boundary within which all earth stations can have continuous multiple access communication, each with any or all other stations which all share the use of the same satellite. If nonsynchronous satellites are used all stations would hand over their circuits simultaneously from the same setting satellite to the same rising satellite, so they always would share the use of a particular satellite. The effect of hand-over upon this single-satellite system boundary is discussed later. With a stationary satellite, this boundary is the satellite's useful coverage boundary, or the boundary within which it always will have a useful elevation angle (e.g., 5° or more) above the horizon.

Note that subscribers and their local exchanges may be located somewhat beyond this boundary, as long as they use earth stations located on or within this boundary.

A station which participates in two or more one-hop multiple access systems, using two or more satellites at a time, has a somewhat larger boundary to its one-hop communication with other stations. In Fig. II-2, station E could extend its one-hop circuits to all stations within the dashed curve by also using satellite No. 2. The combined and extended boundary thus obtainable will be termed the multisatellite one-hop boundary, or the outermost boundary.

Local exchanges and subscribers beyond this outermost one-hop boundary could be reached via a surface tail from a station within this boundary, or possibly via a multi-hop satellite circuit.

C. Constraints and Costs Imposed by Simultaneous Hand-Over

Everyone who has watched live telecasts which have been relayed via a nonsynchronous satellite remembers that programs were timed to the mutual visibility of the satellite and that they often ended rather abruptly. Presumably, an operational system would use enough such satellites that a second one would rise and become mutually visible before use of the first satellite were lost. If so, stations would hand over their circuits to this new satellite and thereby avoid interruption of their communication, as was first mentioned in Part I.

Present experimental earth stations use only one large tracking antenna and it requires many seconds or even minutes to slue such an antenna to a different direction and then acquire and start tracking and using a new satellite. To avoid such interruptions it generally is proposed* that stations use a second large tracking antenna to acquire and start tracking each new satellite, after which the hand-over can be instantaneous and uninterrupted. However, providing each station with a second tracking antenna may not be sufficient; there should also be a third to be used as a spare. In addition, there should be at least two large transmitters and low-noise receivers, so that communication can actually be established over the rising satellite while the setting satellite is still in use. Propagation delays (path lengths) and Doppler frequency shifts via the two satellites generally will differ and will require correction prior to the instant of hand-over, so as not to introduce errors in digital transmissions or similarly disrupt certain other services. Although there is no question as to the feasibility of interruption-free hand-overs by a pair of stations, these would <u>not</u> be the single-antenna experimental stations that we have today. Each operational station would have to be equivalent to two or more experimental stations and would be correspondingly more costly.

With multiple access systems, hand-over introduces additional problems and constraints, such as the constraint on the single-satellite system boundary which has been mentioned in the preceding section. First, however, one may ask why all stations within this system boundary should execute hand-over simultaneously. Why shouldn't stations A and B hand over to a second satellite, while A and C continue to use the first satellite until the second also is visible to C? A simple but inadequate answer is that this would violate the postulate of there being a <u>single</u> satellite (at a time) multiple access system, because A would be tracking and using two satellites. More important, stations B and C could not be in the same system unless there could always be circuits between them. If B lost visibility of the first satellite and

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*It has been suggested that any two single antenna stations, which are reasonably close together and have adequate surface communication facilities, could cooperate in performing the hand-overs, in order to avoid the multiple antenna requirement. This would be possible experimentally. However, neither station would be independent in the sense of having only its own circuits. Also, if used operationally, <u>both</u> stations should have spare antenna systems, bringing the total to four. In effect, one would have a needlessly expensive single station which needlessly occupied two sites.

handed over to a second before C could also see the second satellite, the circuits between A and C would be interrupted. In general, the simultaneous hand-over requirement bars so-called fractional hand-over techniques and there are other reasons to believe that, with many stations in the system, such techniques would become too unwieldy to be used.

To determine the single-satellite system boundary for nonsynchronous satellites by means of the mutual visibility concept[II-2] would require that at the instant of hand-over, there must be two satellites within that portion of the orbit plane which is mutually visible to all stations, hence visible from all points on this system boundary. Determination of the system's boundary becomes simpler if the earth is viewed from the satellite, rather than if the orbit plane is viewed from the earth.

From a satellite at altitude H above the earth whose radius is R, (Fig. II-3 shows that) the earth is visible out to a horizon at θ^o from the subsatellite point. For an earth station to use the satellite satisfactorily it must have a minimum elevation of θ_o, or about 5^o. Hence, a satellite's useful coverage area is the area of the earth lying within approximately* $\theta - \theta_o$ degrees of its subsatellite point. In the case of a stationary satellite this area is fixed and amounts (for $\theta_o = 5^o$) to 38.18% of the earth's area. All earth stations within this area could use this stationary satellite continuously. Consequently, the boundary of a multiple access system which uses a stationary satellite is the boundary of its (fixed) useful coverage area. For $\theta_o = 5^o$, this boundary lies at $\theta' = 76.33^o$ from the subsatellite point.

With a nonstationary satellite the useful coverage area moves around the earth beneath the satellite. Hence, the earth area from which any two satellites are both visible at elevations of θ_o or more is the area for which their useful coverage areas overlap. It is only within this overlap area that all stations can hand over simultaneously; thus the boundary of the multiple access system is that of this overlap area, within which simultaneous hand-over is possible. Practically, this boundary is slightly smaller because a minute or so may be needed to complete the hand-over.

For a circular equatorial orbit system of equiphased (equally separated) satellites, successive coverage overlap areas will be of identical shape and size and the earth stations of a one-hop multiple access system would hand over periodically. Hence, at hand-over, the identical boundary of these identical coverage overlap areas would constitute the boundary of the multiple access system.

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*The accurate expression is given in Fig. II-3.

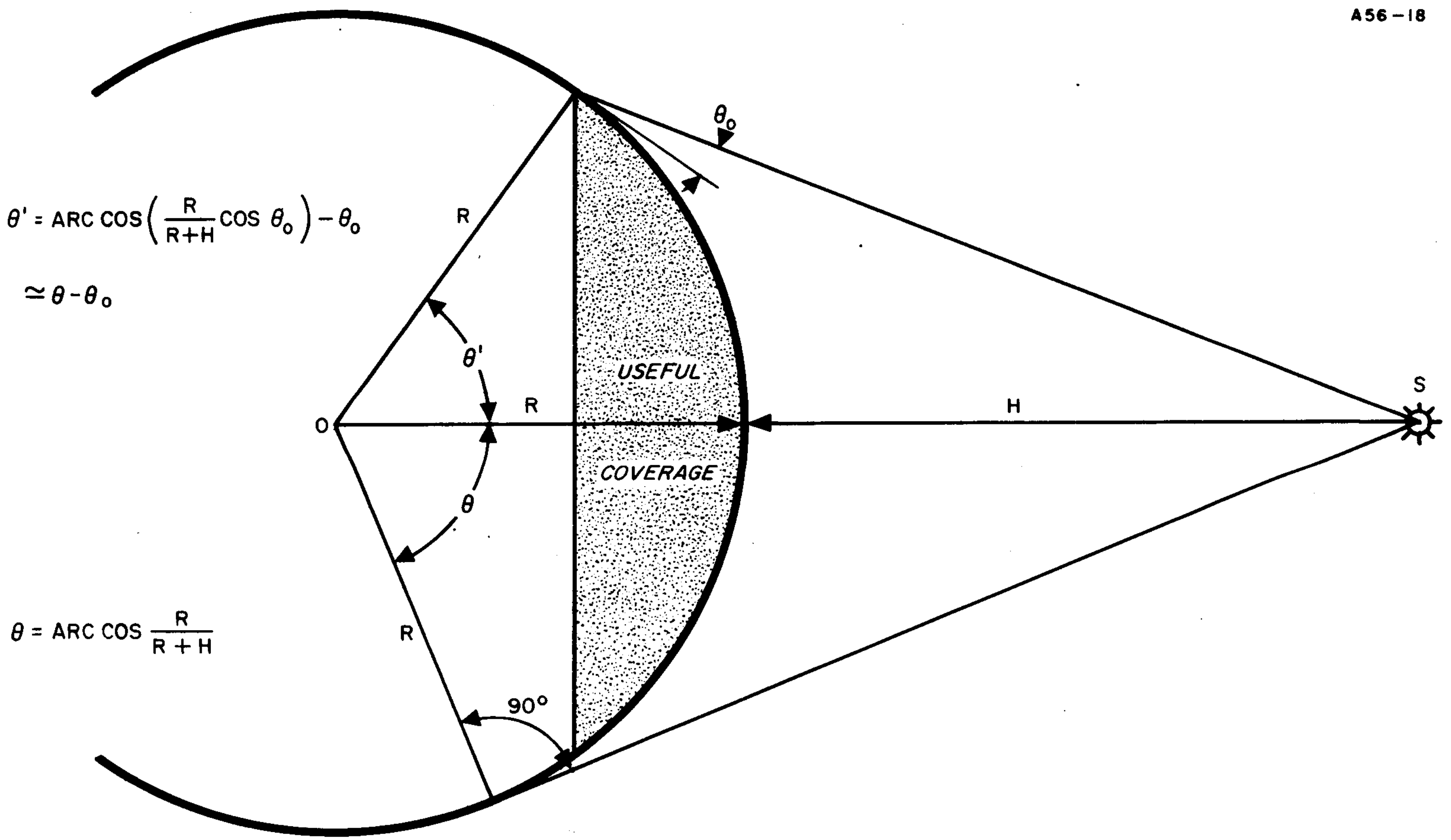

Fig. II-3. Useful coverage angle θ' at which a satellite has a minimum useful elevation θ_0 above the earth horizon.

Table II-1 (Ref. II-3) compares coverage overlap areas for several orbit heights and numbers of satellites with the coverage area of a stationary satellite, for $\theta_o = 0^\circ$ and 10°. This table shows that 10 or more satellites are needed to permit the overlap area to approach the coverage area. In addition, Fig. II-4 (from referenced report) shows a Mercator map comparison of multiple access areas (a) for a stationary satellite and (b) for satellites 30° apart around a 14,000 km circular equatorial orbit. Although the latter could provide coverage of the Atlantic basin, the stationary satellite at 20° W would cover all of Africa and much more of Europe, Greenland, and North America, and even some of Antarctica.

It might seem that N equiphased equatorial satellites could provide service to N multiple access areas. This might be possible if the hand-overs could be instantaneous. However, there should not be more than N - 1 such areas to assure that one area completes its hand-over and releases the satellite before the next area starts its hand-over.

It will be seen that even one-hop circuits via phased-orbit or other nonstationary satellites may cost more than those via a stationary satellite because many satellites must be kept in orbit and used by much more expensive earth stations. To the extent that this is true, the break-even distance relative to surface communication would be increased. Combining this increase in a station's transition boundary with the decrease in its outer boundary would leave a correspondingly smaller area, relative to that for stationary satellites, within which satellite communication would be used.

The extension of this treatment to other orbit systems becomes difficult, particularly so in the case of the so-called random orbit system. For such a system there is only some probability of having two satellites available for hand-over. This probability depends on the number of satellites and on the separation and location of the pair of earth stations. For a multiple access system of many stations, the system boundary would be that within which the probability of uninterrupted hand-over is acceptably high. Thus, there would be an annular family of such boundaries, with this probability improving toward its center.

Random orbit systems of types which have been proposed might provide multiple access service between one or more stations in Eastern North America and several stations in Western Europe, for example. A station in Western Europe which wished also to use random orbit satellites for communication elsewhere would use a different satellite to reach stations in Africa, a third satellite to reach the Middle East or India, and possibly a fourth to reach Iceland, Finland, and Northern Russia. Additional tracking antennas and other equipment would be required for each such additional satellite. Although some limited multiple access operation is possible with random orbit satellites, it has been most frequently proposed that such satellites be used primarily by pairs of large stations, and for this their use seems feasible.

Fig. II-4. Comparison of one-hop multiple access areas for a stationary satellite and for 12 equiphased (30^o separated) 14,000 km equatorial satellites.

TABLE II-1

Coverage Overlap as Percent of Stationary Orbit Coverage

Orbit's Height H, st. miles	n^* / θ_o, deg	3	4	5	6	7	8	10	12	24	36	∞
22,236	0	33.6	59.0	72.0	79.5	84.2	87.3	91.2	93.5	97.7	98.7	100.0
	10	23.5	35.8	60.7	70.4	76.6	80.9	86.4	89.5	96.0	97.6	100.0
10,000	0	16.7	40.3	53.3	61.1	66.1	69.5	73.8	76.3	81.3	82.5	84.4
	10	2.9	26.1	41.3	50.8	57.1	61.5	67.1	70.4	77.3	79.1	81.9
6,000	0	5.5	26.0	38.6	46.3	51.4	54.8	59.3	62.0	67.4	68.8	71.0
	10	0	12.1	26.5	35.5	41.6	45.9	47.9	54.8	61.8	63.7	66.7
3,000	0	0	8.3	18.8	25.8	30.7	34.2	38.5	41.2	46.9	48.4	50.8
	10	0	2.6	8.3	15.5	20.8	24.7	29.8	33.0	39.9	41.7	44.6
1,000	0	0	0	0	3.5	6.7	9.3	12.9	15.2	20.2	21.6	23.7
	10	0	0	0	0	0.8	2.7	6.0	8.2	13.6	15.0	17.4

*Number of satellites equally separated around their common orbit.

D. The Extended One-Hop Boundary and Use of Tails

In connection with Fig. II-2 it was pointed out that a station could extend its area of one-hop communication if it has use of more than one stationary satellite. Thus, tropical stations would be able to cover the greatest areas. For example, Fig. II-5 shows that if there were stationary satellites at 3° W and 154° W, a station near Quito, Ecuador, could have easterly coverage to India, and westerly coverage of Japan and much of Australia. However, these two satellites would not provide northerly coverage of sections of the United States and Canada. Use of a third stationary satellite at 80° W would extend the northerly coverage to Devon Island, far above the Arctic Circle. One recognizes, of course, that there might never be enough communication between Quito and this area of additional coverage to justify the cost of this 80° W satellite. However, satellites at stations in the 60° W to 110° W range would be useful for their coverage of North and South America at some time in the future. The dotted line along the 77° parallel denotes the northern coverage limit which could be approached when many stationary satellites become available, assuming that such satellites are useful if they are 5° or more above the horizon.

Figure II-6 illustrates the possible use of surface tails at both ends of a one-hop stationary satellite circuit, assuming satellites at (or near) 74° W and 105° E. Vienna could reach Honolulu, for example, via a surface circuit to a station near Brest, France, from there via the 74° W satellite to Tahiti or to San Francisco, and thence via cable to Honolulu. An alternate route would be eastward to a station in Turkey, thence via satellite to a Fiji station and from there via surface communication to Honolulu. One concludes that when there are a sufficient number of stationary satellites even the longest near-antipodal paths can be spanned by the use of surface tails at one or both ends of a one-hop satellite circuit. The traffic on circuits requiring such tails should constitute a very small fraction of the total satellite traffic and there would be no real need for two-hop circuits via stationary satellites. Existing cables and other surface communication facilities will remain useful for these tails.

Many writers have repeated Arthur Clarke's suggestion[II-4] that global coverage be achieved by three stationary satellites, each separated by 120°. Practically, it is probable that stationary satellites will be orbited when and wherever they can pay for themselves. The first such satellite probably will be located so as to best serve the Atlantic Basin and Middle East, possibly at 10° to 20° W longitude. The next might be over the Pacific, near 165° E, since this location would provide coverage from San Francisco westward to Burma. However, a second Atlantic satellite might be needed first. In time, there should be many more than three such satellites and they are not likely to be separated by equal distances.

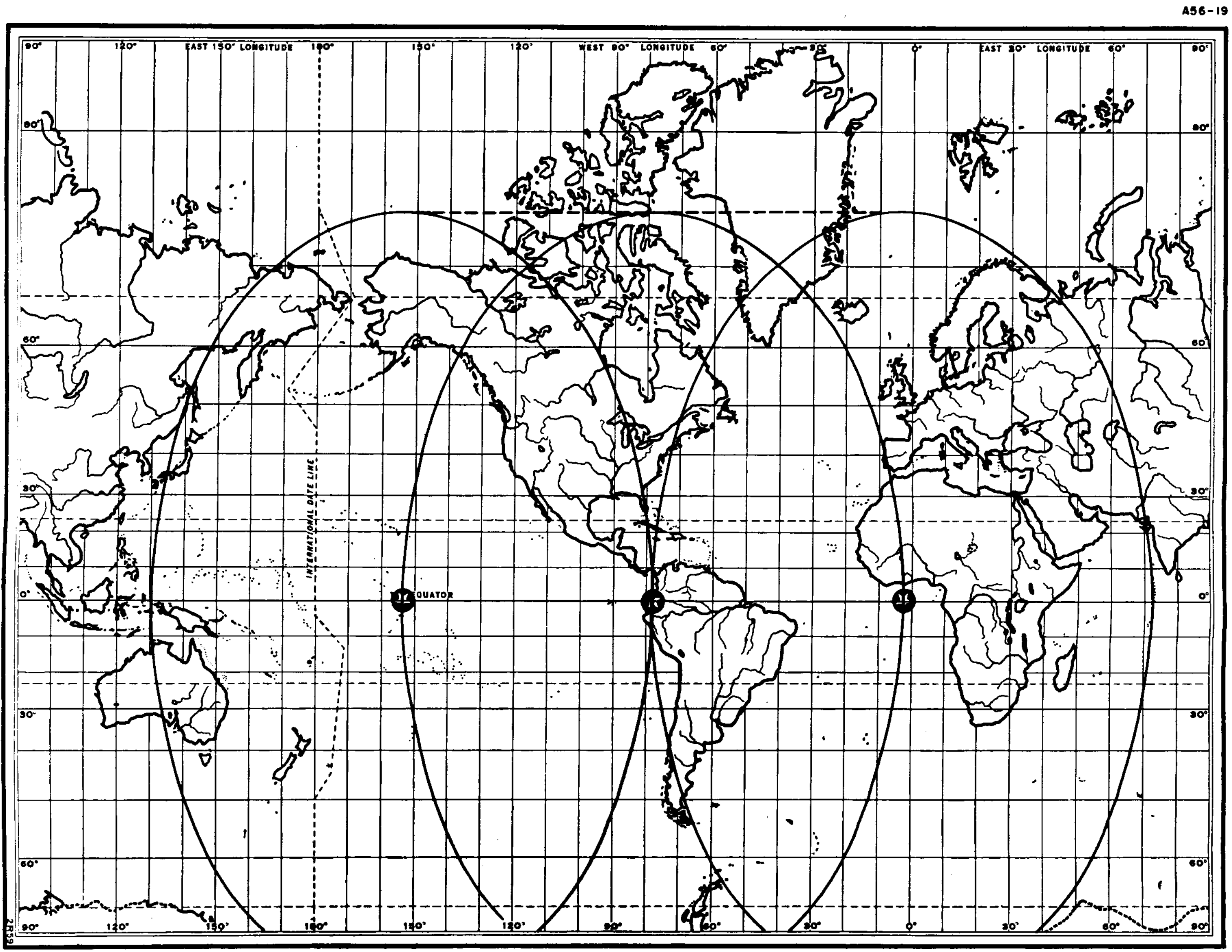

Fig. II-5. The extended coverage boundary of a station at Quito, Equador, using several stationary satellites for one-hop circuits.

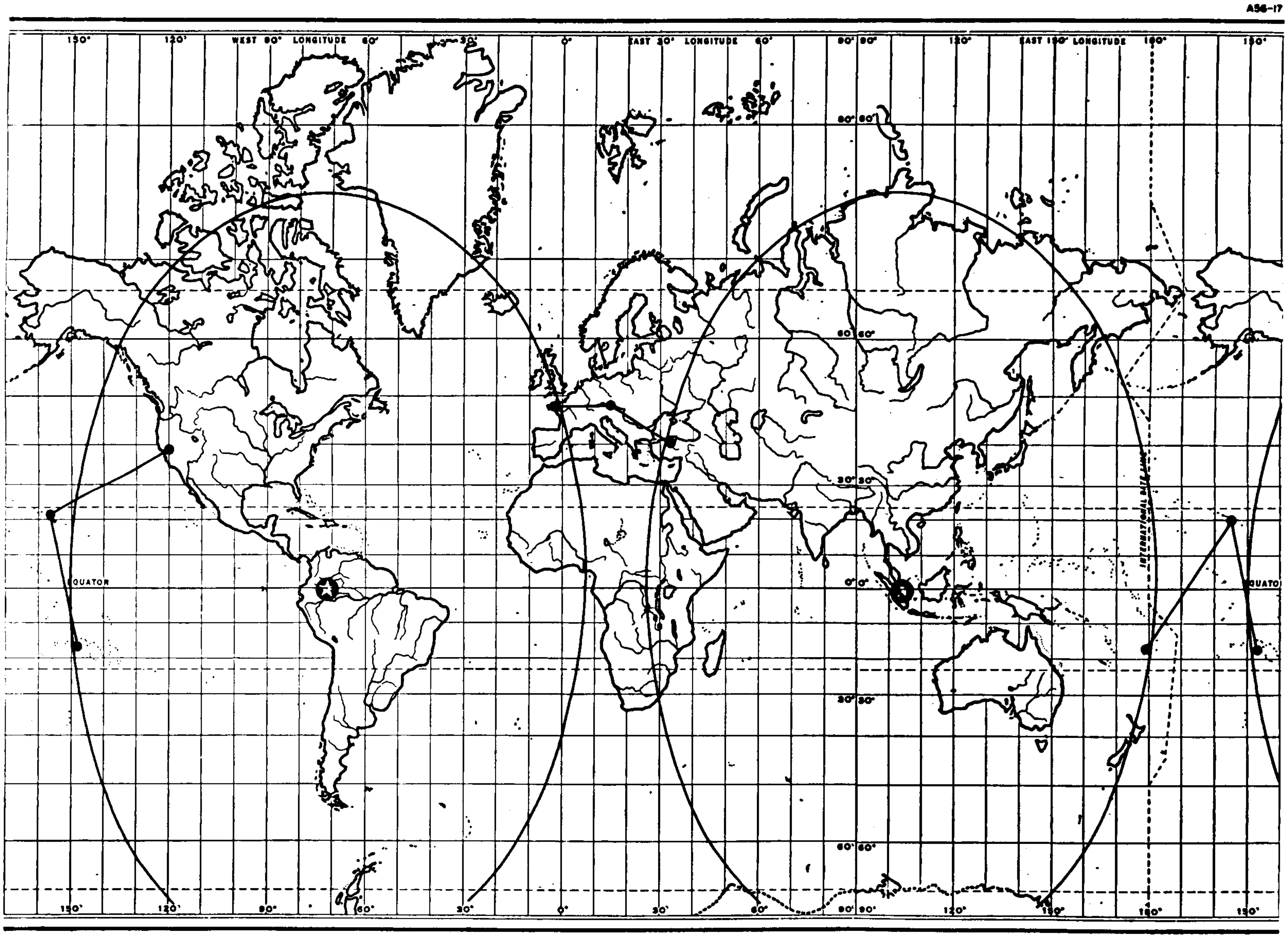

Fig. II-6. Illustrative use of surface tails and two stationary satellites.

With a system of phased equatorial satellites a station also might be part of two or more one-hop multiple access systems, using one for easterly and another for westerly traffic. Other than the need for additional tracking antenna installations, the chief difference is that these multiple access areas would be smaller, as was shown in Fig. II-4. From London to New Zealand, for example, a one-hop satellite circuit would require tails of excessive length. It would be preferable to use two or more satellite hops with earth relay stations. One notes, however, that the propagation delay of a three-hop circuit probably would exceed that of one-hop via a stationary satellite. Additionally, the cost of an N-hop satellite circuit probably will be about N times the cost of a one-hop circuit, because each earth relay station would be nearly as expensive as two terminal earth stations.

E. Routing Decisions with Stationary Satellite Communication

One sees that the routing decisions may be different with the availability of stationary satellite communication than has been contemplated to date in CCITT planning for global surface communication. These plans contemplate the use of a three-level hierarchy of traffic switching centers (CT's), in order that the lowest level (CT3's) would serve individual countries or other relatively small areas. The next level (CT_2's) would be regional, each serving several CT_3's within its region. The highest level of switching centers (CT_1's) would each have intercontinental trunks to the other CT_1's, in addition to trunks to its own CT_2's. Thus a call from a subscriber in one continent to one in another would normally be routed up, across, and back down through this hierarchy of switching centers somewhat as follows:

Subscribers → local exchange → $CT_3 \rightarrow CT_2 \rightarrow CT_1 \rightarrow CT_1 \rightarrow CT_2 \rightarrow CT_3 \rightarrow$

→ local exchange → subscribers.

Considering a one-hop multiple access satellite system of a type which can have many relatively small earth stations, there presumably would be such a station associated with each CT3. This satellite system then would provide <u>direct</u> circuits between CT_3's, jumping over the CT_2's and CT_1's, as was pointed out by Wallenstein.[II-5] For example, a stationary satellite can serve the Atlantic Basin as an intercontinental exchange, or "CT_0," through which Peru's CT_3 could obtain circuits to Iran's CT_3. Such a system would not be concerned with or restricted to today's international and intercontinental communication routes; <u>all</u> routes between the system's CT_3's (earth stations) could be just "up and back down," much like the "in and back out" routes between subscribers via a local switchboard. Actually, more than this would be involved, as can be seen by examining the series of decisions which may be made in order to prepare route lists for use by the operators, for subsequent use in connecting any two subscribers via their respective CT_3's. This series of decisions will be discussed as if they were made on a call-by-call basis at the CT_3's.

We first assume either that the subscribers have different CT_3's, or that no international or inter-CT_3 route is required. Hence, the calling subscriber's CT_3 would determine the answers to the following:

1. Where is the called party's CT_3?

2. Is it located within the transitional boundary?

If "yes," the call would be routed via surface systems, possibly through one or two CT_2's. Hence, we assume a "no" answer, indicating that satellite communication should be used, and we next determine:

3. Does the called CT_3 have an earth station within the calling station's outermost, one-hop boundary?

If "yes,"

3(a). Which satellite's multiple access systems include both stations and which one of these should be used?

Admittedly, it may be many years until stations have a choice between two or more stationary satellites and many factors might affect that choice. Such factors do not merit discussion at this date. Since one satellite serves both stations, the call would be placed through its CASC, the called CT_3 would ring the called party, and thus complete the route.

If "no" is the answer to question 3, it is indicated that the called CT_3 must be reached via a surface tail from one or both ends of a one-hop satellite circuit. In this case we ask:

3(b). Which satellite has a pair of stations, one (or both) of which is most readily accessible via a surface tail to either (or both) CT_3?

Having determined this, the satellite and surface circuits would be set up to the called party. For example, a London to Wellington call might present two possibilities: (1) London to Ankara via a surface tail and from there via a satellite over Singapore to Wellington's station, or (2) London to Adelaide (or elsewhere in Australia) via a more westerly satellite and thence via land circuits and cable to Wellington.

F. Routing Decisions with Nonstationary Satellite Communication

With nonstationary satellite systems the routing decisions may be both similar and different from those previously discussed. For example, if random orbit satellites were used only by pairs of large stations without multiple access, these stations might as well be connected by a cable insofar as routing is concerned. Consequently, this use of satellites might be least disruptive to prior and present routing practices. The station boundary concepts would not be directly applicable unless there were multiple access.

With a phased equatorial orbit system there probably would be relatively few stations in each one-hop multiple access area, with each having a larger inner boundary for its much larger number of users. There would be fewer national stations. Most would be regional stations serving several nations because, as is shown in Part III, the greater cost of such items as the tracking antenna installations would necessarily be distributed among more circuits per stations.

The probable use of two-hop circuits would introduce a new routing decision since the relay station would have its own transition boundary. Use of a surface tail to points within this boundary would be preferable to use of the second satellite. It will be seen that the per circuit cost for a two-hop circuit is nearly double that for a one-hop circuit because use of the relay station would be nearly as expensive as use of two terminal earth stations.

G. Growth of Global Satellite Communication

Finally, it is interesting to compare how the global use of satellite communication might develop, depending on the satellite orbits used. A nonsynchronous, inclined orbit satellite has "global availability" in that it would be visible at times from any point on the earth, even from the Poles. However, there is a difference of many satellites, many earth stations, many millions of dollars, and many years between Telstar or Relay and the existence of a truly global system. The visibility of satellites from the extreme polar regions would not open these regions to worldwide communication if there were no economic (or other) justification for earth stations in these regions. Also, there must be enough such satellites for reasonably continuous service before there would be sufficient incentive to build the number of stations necessary to encircle the globe.

The first stationary satellite probably will be stationed to cover the Atlantic Basin, perhaps at about 20° W (as shown in Fig. II-4). Assuming multiple access capability, the availability of just this one satellite would stimulate the installation of earth stations throughout its coverage area. Thus, satellite service would start as a regional service to the region containing most of the world's telephones. Additional satellites then would be orbited as soon as needed and stationed wherever they were most needed. There would not be just three stationary satellites, as is often assumed, but as many as are economically justified at any point in time. Thus, the system would grow from a regional one to a progressively better worldwide system.

PART III

THE EARTH STATION AND ITS AREA OF USE

A. Introduction

In the preceding sections we have discussed multiple access satellite communication and the boundaries within which an earth station can have one-hop satellite communication with any and all other stations by participating in one or more multiple access systems. It was shown in Part II that the "outer boundaries" to a station's direct service with other stations are determined by the coverage areas of the satellites being used, so these boundaries are well-defined geometric functions of the satellite orbit system.

In this and the final part of this report, we consider the remaining two inner boundaries around an earth station. We consider first the innermost boundary which encompasses the subscribers who normally would originate or receive satellite calls through this earth station. The qualification "normally" excludes the small fraction of extremely long circuits for which there may be a surface tail from the subscriber's exchange to some more distant earth station, as was discussed in Part II. Thus, this innermost boundary may be termed the surface traffic feeder boundary surrounding the station's area of normal use.

The remaining boundary is the transitional boundary within which the traffic between subscribers' local exchanges might best be routed entirely via surface communication facilities, without the use of a satellite link. Unlike the outer boundaries, these two inner boundaries are governed by economic, geographic, and policy considerations. The economic considerations are especially important in that they may constrain the others. For example, a nation would find it desirable to have its own station, if this were not much more expensive than obtaining satellite service from a large regional station in another nation. Consequently, the remaining two parts of this report emphasize economic principles of multiple access communication and their effect on a station's two inner boundaries. It again should be pointed out that actual costs remain uncertain and that cost estimates will be used only to illustrate the economic relations.

B. Use of Equivalent Telephone Circuits

Subsequent sections will refer to satellite and earth station traffic and traffic capacity in terms of telephone circuits, as if the system did not also carry all other forms of communication, from telegraphy to television. This concentration on telephony is in the interest of conceptual simplicity and because (except possibly for television) the telephone channel probably will be the primary unit for dividing the satellite repeater's base band into channels. Several adjacent telephone channels would be combined in order to carry digital voice or other similarly wide-band signals. Additionally, there are slow digital signals, such as telex, which require bandwidths less than that of a voice channel. As many as 24 telex signals can share a voice channel but a single such signal would also probably be allocated a voice channel.

A group of 12 channels carrying PCM voice or other wideband service may not cost 12 times as much as a voice channel because there probably would be a lower rate for a channel group service. Certainly, television rates over a microwave relay system are less than for the 900 voice channels which would otherwise have been available but probably not all used. For the purposes of this study services other than ordinary (analog) telephony will be disposed of by considering them to be equivalent to some unspecified number of telephone channels which do not necessarily have the same total bandwidth.

C. Cost Components of a Satellite Circuit

Figure III-1 shows that the subscriber to subscriber cost of using a one-hop satellite circuit is the sum of (1) the satellite use cost to both stations, (2) the costs of using both stations, and (3) the surface communication costs between both users and their stations. It is assumed that the satellite is used simultaneously by any number of stations in a multiple access system and that each station shares the cost of using the satellite (or succession of nonstationary satellites) in proportion to its own use. All stations are assumed to make equally efficient use of the satellite's channel capacity, as with the ADVANCED SYNCOM System.[*] Thus, small stations would not be charged more per channel than the larger stations. Note that this assumption would not be valid if, for example, the smaller stations were permitted to use more bandwidth per channel (such as with greater FM deviation ratios) with fewer channels per satellite repeater, in order to use smaller and less expensive antennas.

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[*] This system contemplates both random and assigned channel forms of multiple access, as explained in Part I. Random access entails additional CASC costs for its calling and channel assignment service but this mode permits fuller use of the satellite repeater channels. For simplicity, any difference in the cost per channel for these two modes of service will be neglected.

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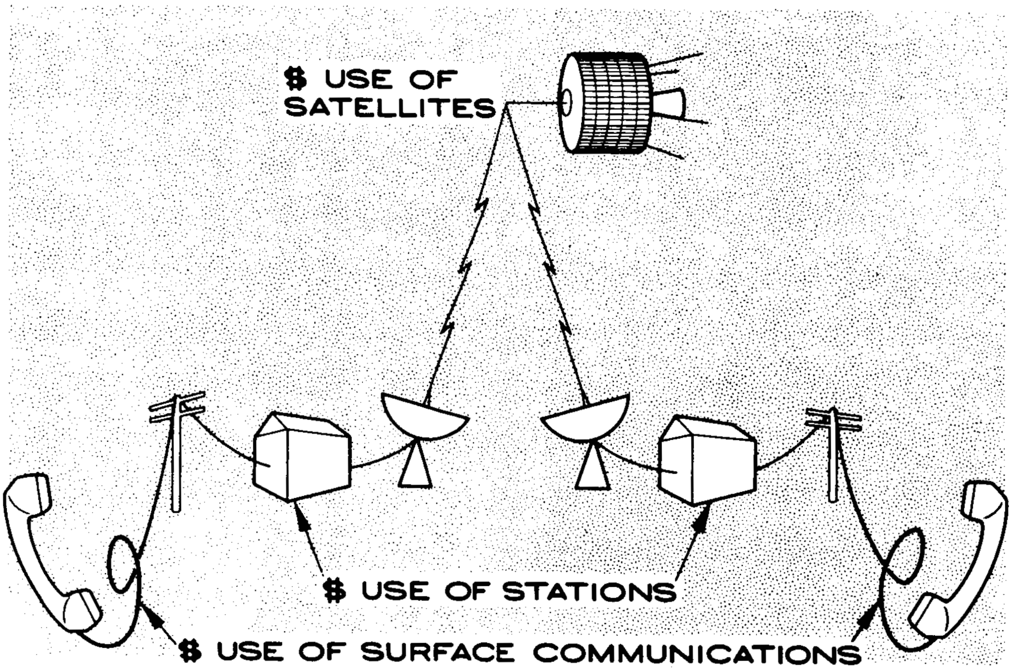

Fig. III-1. Subscriber to subscriber cost components via a satellite circuit.

The sum of the subscriber to station and the station use costs at one end of a satellite circuit such as that shown in Fig. III-1 certainly is independent of the corresponding cost components at the opposite end of the circuit. Moreover, since the cost of satellite use per paid circuit minute has been shown to be essentially independent of the earth station's circuit capacity, only these first two cost components are significant in determining the best size and service areas of earth stations. The economic objective would be to minimize the sum of the subscriber to station and station use cost components. Although it is probably obvious, it is shown below that the station use cost per circuit decreases with the number of the station's circuits to the satellite. Thus, this cost component would be reduced by letting the station serve more subscribers within a larger area. However, increasing this area increases the average subscriber to station distance and cost component. The major objective of this part will be to establish the requirements for optimum station size and service area and the modifying influences of practical considerations. One recognizes that achieving minimum cost may be relatively unimportant, particularly if these two cost components may be a small part of the total circuit cost. Rather, one generally would want to know whether a certain nation, some part of that nation, or some group of nations would supply enough traffic to an earth station to prevent these cost components from becoming excessive.

D. Earth Stations and Their Use Cost

It must be recognized that existing stations for satellite communication are experimental facilities and that their costs are not necessarily a useful guide to the cost of stations for an operational satellite communication system. All these experimental stations must have large and expensive antennas which can track today's nonstationary satellites, and one such antenna is sufficient for this experimental use. With any medium altitude satellite system, two or more such antennas per station and per satellite are needed, thus making operational stations correspondingly more expensive. Only one antenna per stationary satellite is needed and, whenever such satellites become sufficiently stationary, large but inexpensive fixed reflector antennas can be used.

In addition to the factors discussed above, experimental stations have used ultralow noise receivers, such as those with helium-cooled masers, and have employed other expensive features which are desirable during experimental programs. An operational system should provide good quality service even during storms, when the sky noise temperature exceeds 100°K. With this sky noise the maser's advantage over a nitrogen-cooled parametric amplifier becomes marginal and the latter is less expensive as was indicated in Part I.

Even experimental earth stations have varied in cost by several orders of magnitude, depending on the stations's purpose. At the lower extreme, Fig III-2 shows the very low cost facility which the Hughes Aircraft Company installed to receive from SYNCOM-II. The 10-ft (~ 3 m) antenna is directed by hand and an uncooled parametric amplifier is used. This antenna is on the top of a 12-story building on the edge of the Los Angeles International Airport and, in tracking SYNCOM-II, it is used at low elevation angles and azimuths toward the heart of the city. Noise and electrical interference, however, have not been serious problems. The station is used only for reception of single voice channel signals at a test tone to noise ratio of about 20 dB. Since the antenna and other components were already available, the only costs were those of building the roof platform and renting a crane to lift the antenna from the street! This is obviously <u>not</u> an example of a station for operational service.

At the opposite extreme, stations like that at Andover, Maine, are ideal experimental facilities, but have features which would be unnecessarily expensive for operational use under conditions of economic competition.

The cost of operational earth stations will not be known accurately until a specific satellite system is selected, and stations for this system have been designed and built. However, a number of cost estimates for operational stations have been made for various purposes and with various degrees of thoroughness, generally using quite different assumptions.

In studying earth station cost estimates, one recognizes a functional relationship to station size to the number of satellite circuits X which the station is equipped to use. In general, the investment cost C_s can be expressed as a power series in X,

$$C_s = S_o + S_1 X + \dots$$

Ordinarily, the first two terms alone provide a usefully accurate approximation. On this basis, S_1 will be termed the channel-proportional coefficient of investment cost, and S_o the channel-independent component. It might seem that S_1 could be obtained by adding the costs of the channel modem, echo suppressor, and other one-per-channel components, and that S_o would contain the land, building, antenna, low-noise amplifier, etc. However, one cannot actually classify all components as contributing only to S_o or to S_1. The transmitter cost, for example, would contribute both to S_o and to $S_1 X$, because minimum power would be used for the smaller stations but would be increased for the medium and large capacity stations. Even the cost of the building contributes to S_1, as well as to S_o, because more channels would

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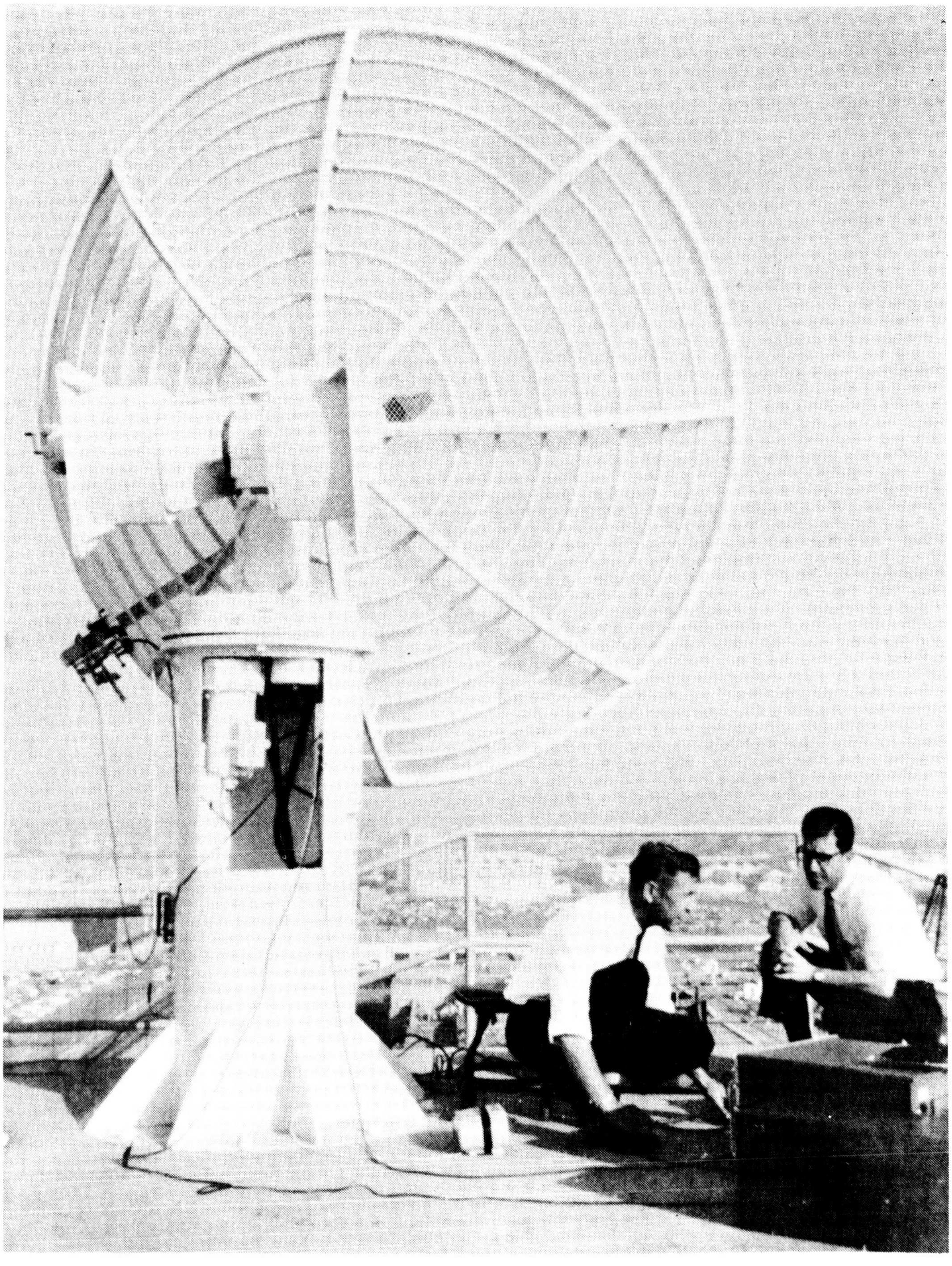

Fig. III-2. Lowest cost earth station, used by Hughes Aircraft Company for single voice channel reception from SYNCOM-II.

require more floor space. Even more important, it would seem appropriate to use a better constructed building for an expensive large station and to economize on the building for a small station. Consequently, S_o and S_1 can best be found by plotting station cost versus number of circuits for comparable stations of several sizes, and then finding the intercept (S_o) and slope (S_1) of a straight line approximation to these plotted points.

It will be more convenient to deal with the annual costs of earth stations, obtained by amortizing their investment cost and adding an appropriate amount for maintenance, operating, and any other annual costs. A straight line approximation can be obtained,as before, which has an intercept or "no circuit" annual cost T_o and a slope or "per circuit" component T_1; this permits annual cost C_A of the station's X circuits to be expressed approximately as

$$C_A = T_o + T_1 X \quad .$$

For any one of these circuits,

$$C_X = T_o/X + T_1 \quad .$$

The interpretation of this relation is that each circuit must bear its share $(1/X)$ of the "no circuit" or base annual costs T_o. If there were a very large number of circuits to share a reasonably small T_o, then C_X would be negligibly greater than T_1. However, if very few circuits must share a large T_o, C_X would become many times greater than T_1, and the small station would have an excessive economic handicap.

As an approximate guide to the minimum economic number of circuits for an earth station, C_X will be only twice as great as for an infinitely large station if the number of circuits is

$$X = T_o/T_1 \quad .$$

Clearly, the economic feasibility of small earth stations depends on cutting their "no-circuit" cost component T_o down to the absolute minimum. The alternative course, that of unnecessarily increasing the circuit-proportional component T_o, would only increase C_X and lead to a noncompetitive system.

At this point it is interesting to observe that if a small nation can somehow subsidize all or most of its earth station's T_o it can offer service at as low C_X as the largest stations, even if its station has only one circuit! Such subsidies may prove to be a worthwhile means of stimulating the growth of small earth stations toward a more economic number of circuits.

It is seen later that the relative importance of subscriber-station surface communication costs tends to modify the optimum number of circuits. Sometimes the savings of surface communication costs to a small local station may offset the savings in C_X through the use of a large but distant regional earth station. Additionally, if the satellite use cost were high compared with C_X, as might be the case initially, the small station's higher C_X might be a relatively unimportant fraction of the over-all subscriber-to-subscriber cost.

E. Illustrative Earth Station Costs

Many earth station cost estimates have been published for various purposes and are applicable to various systems and assumptions. Few such estimates have seemed sufficiently detailed and applicable to a random multiple access system using a stationary satellite. One possible exception is a study made by the Lenkurt Electric Company[III-1] which has had wide distribution. This study contained detailed cost estimates for 12-circuit and 150-circuit stations which, unfortunately, were not strictly comparable in their capability. These Lenkurt estimates seem somewhat conservative in that, for example, they assume use of expensive horn-reflector type fixed antennas. Values of T_o and T_1 have been derived from the Lenkurt estimates and are included in Table III-1 for purposes of comparison.

In parallel with the SYNCOM programs, Hughes has sponsored studies of designs and probable costs of earth stations which might best be used in a flexible multiple access system with a satellite similar to the ADVANCED SYNCOM.* Space does not permit describing more than some significant aspects of the contemplated system and its earth stations.

Experience with SYNCOM-II has established confidence that an ADVANCED SYNCOM could be held on station within a negligible fraction of the beamwidth of an antenna of 85-ft (~ 26 m) aperture. Studies by independent consultants have estimated that the cost of an earth-supported concrete antenna of this aperture, with ± 1.6 mm surface tolerance, should not exceed $100,000, even if built in the United States.

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*NASA Contract NAS 5-2797

This cost would be less in regions where labor costs are lower. One notes that a comparable tracking antenna would cost several times this much. If a smaller fixed antenna were used, the cost saving would be offset by increased transmitter costs or by reduction of the satellite's channel capacity. Hence, these high-gain antennas are best for even the smallest stations.

TABLE III-1

Illustrative Earth Station Annual Cost Components

Assumption	T_o, Circuit-Independent		T_1, Circuit-Proportional		T_o/T_1, Circuits
	$	GF	$	GF	
Present, pessimistic	250,000	766,000	10,000	30,610	25.0
Near future, probable	150,000	459,000	7,000	21,400	21.4
Future, optimistic	60,000	183,600	5,000	15,305	12.0
Lenkurt study	195,000	597,000	8,830	27,000	22.1
Nonsynchronous	1,000,000	3,061,000	7,000	21,400	143.0

Station designs have been made on a building block basis, so that there need be no basic distinction between small and large stations. A small station can add equipment to increase its circuit capacity, use assigned channel service, handle television, or add other capabilities — all without replacing its antenna or most of its other initial equipment. Based on these earth station design studies, it has been possible to establish a range of values within which it is believed the T_o and T_1 annual cost coefficients should fall. The annual costs were obtained on the basis of a 10-year life, with the investment cost amortized at 15%, and with annual maintenance and operating costs added.

Table III-1 lists three pairs of coefficient values. The "present pessimistic" estimates include a reasonable safety factor for completion of development and for other costs which the first stations might encounter if built today. The "near-future probable" coefficients are those which it is believed may be achieved by the time a system of this type is in operation and after some of its stations have been installed. The "future optimistic" values represent future objectives and contemplate unattended or semiattended stations with other advances and economies, which can be anticipated.

The cost coefficients may change considerably if only because it is not yet certain that a satellite with the ADVANCED SYNCOM characteristics will ever be placed in service. The Communication Satellite Corporation's "Early Bird" (1965) SYNCOM will be more similar to SYNCOM-III. It will have an approximately stationary orbit, a straight-through repeater for the separate FM/FM form of multiple access with relatively low channel capacity, and its antenna pattern will favor the northern latitudes. Consequently, it probably will be used for traffic across the North Atlantic between only a few stations, and these stations will need antennas whose beams can be steered about 5° in any direction, more steerability than can be obtained readily with a fixed reflector.

Table III-1 also contains values of T_o and T_1 derived from the Lenkurt study, as previously mentioned. Additionally, the last entry applies to stations of the type needed with nonsynchronous satellites. The value of T_o was estimated after examination of the cost component of several experimental stations with large antennas. Typically, such stations have cost \$5, 000, 000 or more and their annual maintenance and operating cost is about \$500, 000. These costs are predominantly of the no-circuit type. In addition, it has been assumed that the circuit-proportional cost of such a station would be T_1 = \$7, 000, the same as for a fixed antenna station under the near-future assumptions. These values raise T_o/T_1 to 143 circuits, thus showing that such stations would need to handle correspondingly heavier traffic from a larger area.

Figure III-3 should further clarify the importance of the no circuit cost component T_o, in relation to the number of circuits X. This curve compares the over-all station annual cost per circuit C_X as a function of X for the "near future, probable" coefficients of the stationary satellite earth stations with those for stations using nonsynchronous satellites. One sees that the station for nonsynchronous satellites requires nearly seven times as many circuits over which to spread its high T_o in order to achieve any given annual cost per circuit, compared with stations using a stationary satellite. This means that with satellite repeaters of equal channel capacity, a one-hop multiple access system using nonsynchronous satellites would, at best, consist of a relatively few large earth stations. With a stationary satellite there can be smaller stations serving smaller or less densely populated areas, with a correspondingly greater number of stations distributed over the larger multiple access (coverage) area and providing more direct and flexible service.

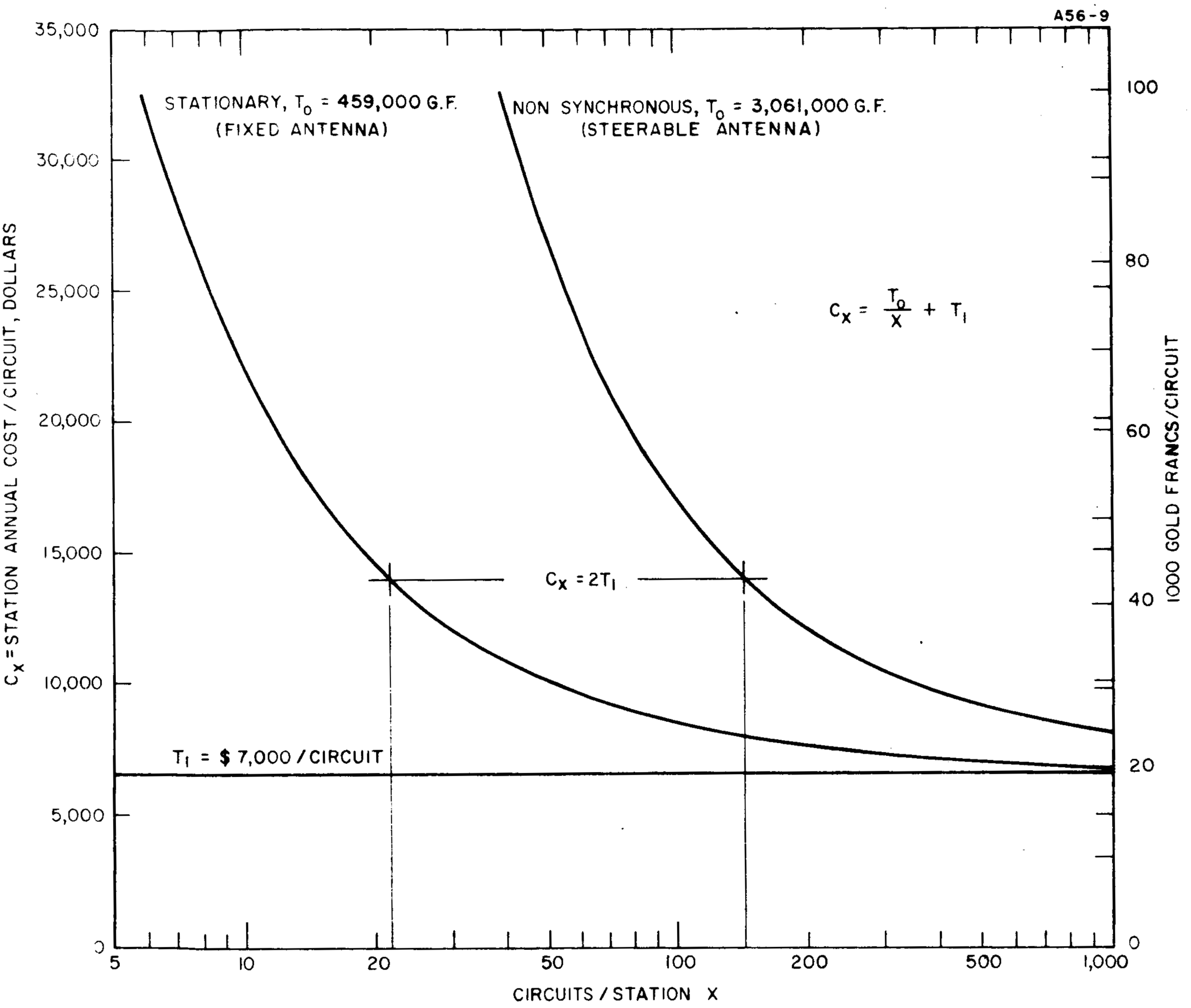

Fig. III-3. Comparison of earth station use costs per circuit year, fixed versus steerable antennas.

F. Surface Communication Costs

The use cost of surface communication facilities between a subscriber and his earth station is best known to the telecommunications administration or the operating company concerned. Lacking detailed knowledge of the existing or planned routes, the availability and cost of circuits over these routes, and the probable cost of new facilities to link an earth station into the existing communication system, it is best to use some average cost per circuit and per unit of airline or crow-flight distance. But how does one arrive at cost, even if it is to be used only for illustrative purposes?

In attempting to answer this question it was noted that the CCITT has recommended[III-2] that certain typical cost elements be taken into account as a basis of tariff charges, and that these should include costs per 3-min call and per 100 km of crow-flight distance under old, transitional, and modern conditions. The recommended values are intended to cover costs of depreciation, interest on capital involved, and maintenance of the circuit concerned. These recommended values, converted to dollars and to gold francs per kilometer-minute, are shown in Table III-2.

TABLE III-2

Long Distance Rate Approximations and
CCITT Recommended Distance Costs
(Cost per minute = $C_a + C_d d$, for $d > d_{min}$)

	C_a		$C_d (\times 10^{-3})$		Approx. minimum distance, km
	GF	$	GF	$	
United States[a]	1.122	0.366	0.292	0.0954	1000
France	0.255	0.0833	0.856	0.280	250
Europe, from Paris	0.306	0.100	1.92	0.628	250
CCITT Recommendation:					
Old conditions			2.0	0.654	
Transitional conditions			1.33	0.435	
Modern conditions			0.883	0.288	

[a] Based on rate for first 3 min, day, station-to-station. Overtime rate is about 75% of the initial rate.

In addition, it seemed instructive to examine actual long-distance rates for the United States, France, and for Europe, the latter in terms of the rates from Paris to cities in other nations. It was reasoned that rates are so established that the total revenue will cover costs plus a fair profit.

Day station-to-station rates for the U.S. were obtained from American Telephone and Telegraph Long Lines Schedule No. 1 of April 4, 1963, which lists the rate for the initial 3 min and for each additional minute according to mileage brackets extending to 3000 miles. The additional minute rate is a quarter of that for the first 3 min, neglecting the round-off. The rate for the first 3 min was plotted and approximated by a straight line,

$$C_{s3} = 1.10 + 0.46\, d \times 10^{-3} \text{ dollars/first 3 min}$$

where d is in miles. This approximation is close at distances beyond 600 miles (1000 km). At shorter distances the rates drop gradually to the local message-unit rates which apply at less than 25 miles. For very long calls the effective rate per minute would approach a quarter of this first 3 min rate, or somewhat more for calls of average length. To be conservative, this saving on longer calls was ignored and the above equation was converted to gold francs per minute, with d in kilometers, as shown in Table III-2. This table also shows the corresponding rate approximation coefficients C_a and C_d which were obtained similarly for France and from Paris to cities elsewhere in Europe. In the latter case the plotted points were scattered considerably and the straight line approximation was correspondingly uncertain.

To some extent, one can interpret the constant term C_a in these straight line rate approximations as reflecting the cost of access to a long distance telephone system rather than to the local telephone system. This cost might, for example, cover the time of the long-distance operator or the use of the corresponding automatic long-distance signaling and switching equipment. One probably should not attempt to draw conclusions from the range of values of C_a in Table III-2 other than that there also may be some uncertain access costs for calls via a random access satellite system or other intercontinental system. However, since this access cost is a constant (per minute), it would not influence the optimum circuit capacity or service area of earth stations and when the distance involved is great, it probably would not affect the choice between satellite and surface circuits.

The distance slope C_d coefficients in Table III-2 are of greater interest. For France, C_d is close to the CCITT value for modern conditions while the International European C_d is closer to the CCITT value for old conditions. In the latter case, however, C_d is influenced by the costs of transit exchanges and other costs not directly related to distance and should not be interpreted as indicating that the CCITT's old conditions still apply. The very low C_d for the United States is accompanied by a correspondingly high C_a and these values also should be interpreted with caution. Transcontinental distances approach 5000 km and the traffic volume over distances in excess of 1000 km is so great that it can be carried at relatively low cost. If the U.S. rate curve had been approximated only to 1000 km, a considerably lower C_a and higher C_d would have been inferred.

Table III-2 shows that the CCITT value for modern conditions, 0.883×10^{-3} GF/km-min, should be sufficiently typical for illustrative use in this study. The reader can use higher or lower values if these seem more appropriate in special cases of interest. In particular, higher values probably should be used for those areas of the world in which surface communication is still relatively light.

G. Significant Cities Approximation

In attempting to determine the cost of surface communication between an earth station and the subscribers using it, one recognizes the impracticality of locating and determining distances to all such subscribers. Fortunately, within any nation or region, most traffic for a satellite system would be to or from the relatively few cities which are centers of industry and international business; thus these can be considered the only "significant" cities. If these cities (probably not more than 12) make up, for example, 80% of a station's traffic, we can, for our purposes, prorate the remaining 20% among the same cities.

H. Station Location for Minimum Surface Communication Cost

Two classes of problems relative to the location and use of earth stations are considered, and the examples use the significant cities approximation. One class of problem involves the question of whether it would cost less to use a relatively large regional earth station in some nearby nation or to use a smaller national station at a determined location. A related problem, which cannot be solved here, assumes that the use of a national station might cost a known amount more initially, and asks whether this additional cost is politically or otherwise justifiable, and how long it may be until the national station grows to an economic size. This class of problems assumes that the locations of the national and regional stations have been determined.

The second class of problems relates to determining the optimum station location relative to the nation or region which it is to serve. There are interference coordination considerations, cost of land and access roads, etc., in addition to the desirability of minimizing the cost of surface communication to the significant cities. The latter requirement generally should be considered first. Sometimes, as will be seen, some major city will be the point of minimum surface communication cost; in this case the station site should be just far enough away from this city to be satisfactory with respect to interference, land costs, and other requirements. If the minimum cost point is elsewhere, there generally will be a surrounding region within which the cost would not be significantly higher than its minimum and within which the other site requirements can be satisfied. In some cases, knowledge of existing communication routes may eliminate or simplify the problem of finding the minimum cost point. Here, however, the problem will be considered on a weighted crow-flight distance basis, much as if there were no usable existing circuits.

For illustrative purposes, Fig. III-4 shows a hypothetical nation having 12 significant cities, among which the total satellite traffic has been apportioned in percent of the nation's total. One desires to find the station location having the least kilometer-minutes relative to the significant cities. This problem has a formal solution by means of vector calculus, as given in Appendix III-A. Unfortunately, this solution, although it appears simple, can be tedious to evaluate, so much so that it becomes quicker to build and use a special purpose analog computer. Such a computer, shown in Fig. III-5, requires only a map, some thread and adjustable weights. For this photograph, the map was inked on a stiff card, which then was supported between two desks and photographed from a high camera angle. A hole is drilled at each significant city and the thread through that hole is tied to a weight which is in proportion to the city's traffic weighting factor. All the threads are then knotted above the map and the knot is released. Its equilibrium position* on the map denotes the station location for minimum surface communication cost.

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*Friction limits accuracy but can be reduced by using monofilament nylon thread, by lining the holes with well-rounded eyelets, and by jarring the board to break the static friction. The knot should be released several times from different directions, marking each trial result. These marks will define an area containing the true equilibrium position.

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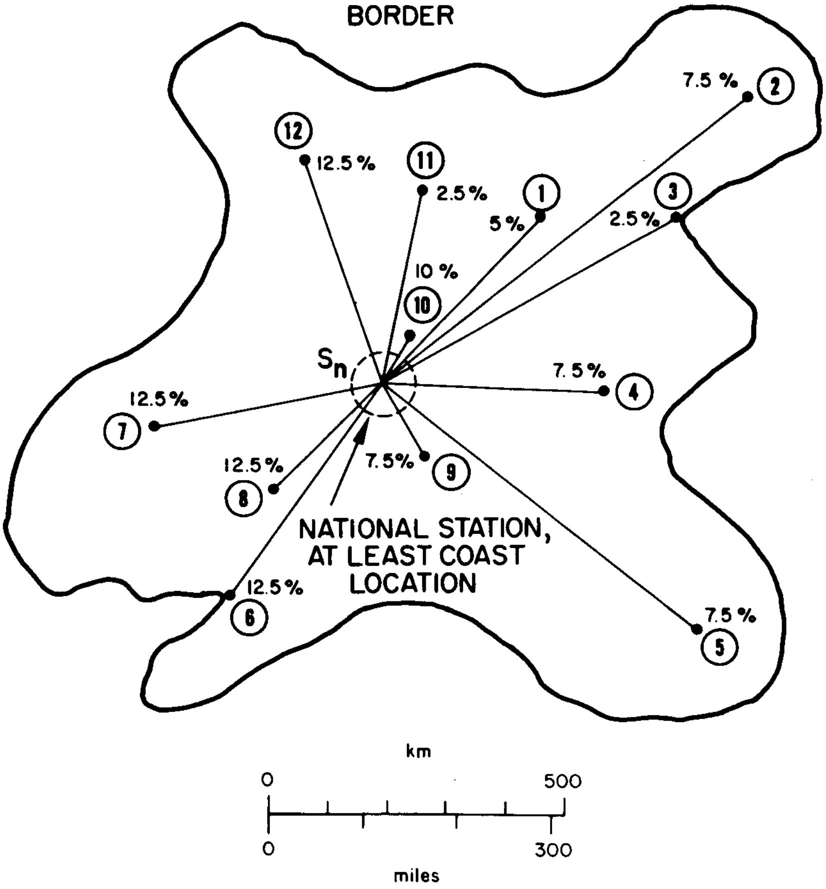

Fig. III-4. Significant cities and earth station location for a hypothetical nation.

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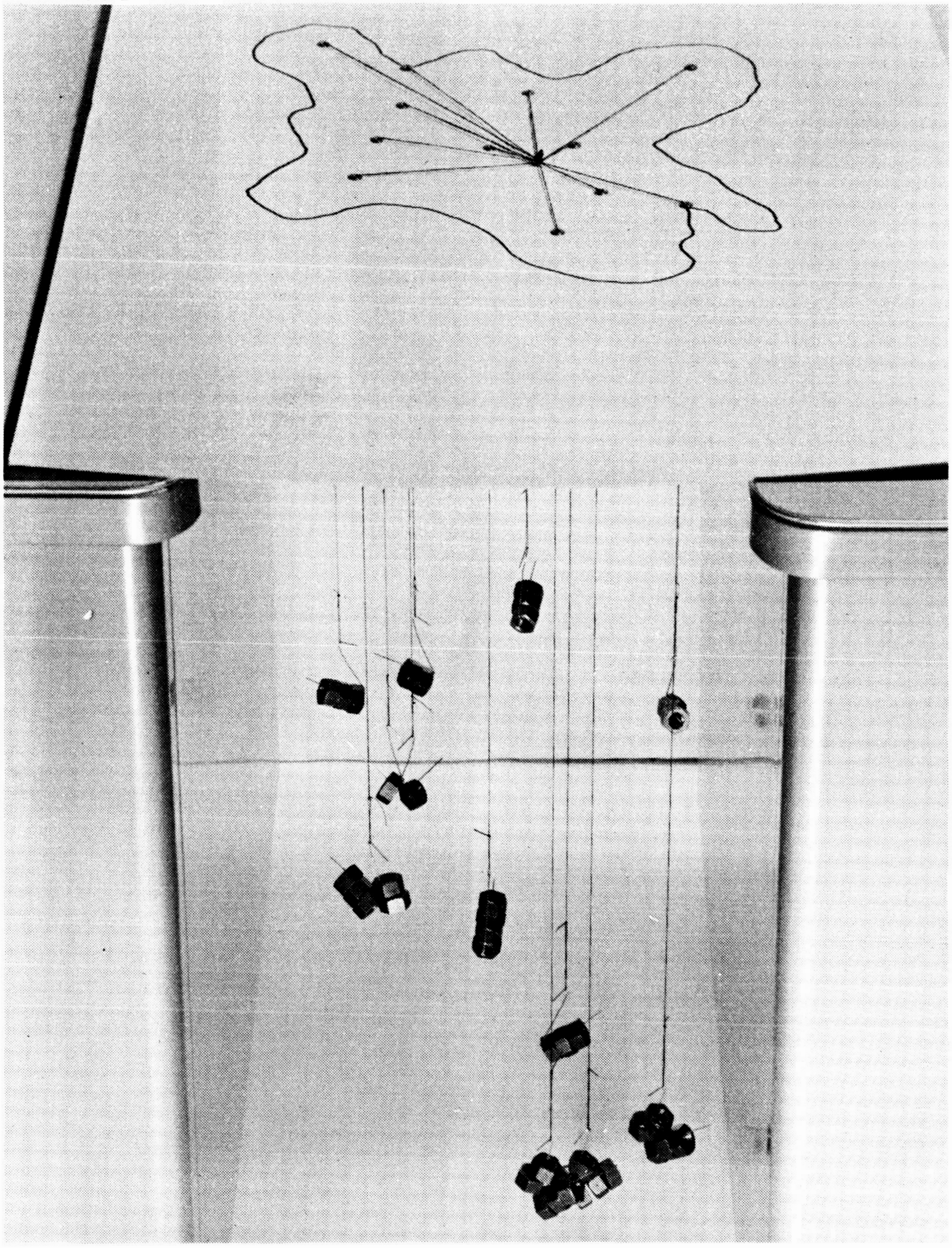

Fig. III-5. Simple analog computer for determining minimum cost station location.

Figure III-4 shows the relative traffic for each city, in percent of the total, as used for the example photographed. This figure also shows the (dashed) area of uncertainty obtained from several trials and the assumed optimum station location at its center.

I. Relative Cost of Using National or Regional Stations

Having determined a station location, one can measure the distance to each significant city and compute the surface communication cost for each, knowing its traffic and assuming a cost per kilometer-minute. This is illustrated for the station location of Fig. III-4 with the scale shown, assuming the total traffic to be 1,000,000 paid min/year* and using the modern conditions cost of 0.883×10^{-3} GF/km-min. Table III-3 shows the computation of the total kilometer minutes per year as 388.75×10^6, for which the cost would be 343,000 GF ($112,000), excluding terminal exchange and other access (C_a) costs.

We then assume that there is a regional earth station in some nearby nation, as shown in Fig. III-6, to which routes are available through border gateways M and N. Note that M is also one of the significant cities (No. 3). Table III-4 shows the computation of total kilometer minutes for this case.

In this example, the surface communication costs to the regional station would be about three times greater than to the optimally located national station. However, there is still the question of station use costs: Can the large regional station be used at a sufficiently lower cost, compared with a relatively small national station, to offset this greater surface communication cost? It can be seen that this may depend on the no circuit T_o component of the station annual cost, and hence on whether stationary or nonsynchronous satellites are used.

It is first necessary to obtain an estimate of the number of satellite circuits X required. The CCITT PLAN Committee has used 150 paid min/day/international circuit. This would correspond

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*This 10^6 paid min/year would require 20 satellite circuits, each carrying 50,000 min/year. The area of this hypothetical nation is 1.1×10^6 km^2. The area of the United States is approximately 7.7×10^6 km^2, or seven times larger. Thus, this hypothetical nation is larger than typical European nations but is comparable to that of many nations in Africa and South America. For such nations the value of C_d may be higher than for the CCITT modern conditions.

TABLE III-3

Yearly Kilometer-Minutes for a National Station (Fig. III-4)

Significant City	Yearly Traffic in 10^4 min	Distance to Station, km	km-min
1	5.0	390	19.50×10^6
2	7.5	800	60.00×10^6
3	2.5	580	14.50×10^6
4	7.5	370	27.75×10^6
5	7.5	680	51.00×10^6
6	12.5	450	56.25×10^6
7	12.5	390	48.75×10^6
8	12.5	260	32.50×10^6
9	7.5	140	10.50×10^6
10	10.0	95	9.50×10^6
11	2.5	340	8.50×10^6
12	12.5	400	50.00×10^6
Total	100	Total	388.75×10^6

TABLE III-4

Yearly Kilometer-Minutes Using a Regional Station (Fig. III-6)

Significant City	Yearly traffic in 10^4 min	Distance, km	km-min
1	5.0	230	11.50×10^6
2	7.5	240	18.00×10^6
3	2.5	0	0×10^6
10	10.0	500	50.0×10^6
11	2.5	430	10.75×10^6
12	12.5	640	8.00×10^6
(To Gateway M)	40.0		
4	7.5	180	13.50×10^6
5	7.5	270	20.25×10^6
6	12.5	730	91.25×10^6
7	12.5	870	108.75×10^6
8	12.5	670	83.75×10^6
9	7.5	420	31.50×10^6
(To Gateway N)	60.0		
M to Station 40.0		790	316.0×10^6
N to Station 60.0		800	480.0×10^6
			$1,315 \times 10^6$
$1.315 \times 10^9 \times 0.883 \times 10^{-3} = 1.161 \times 10^6$ GF/year = \$379,000/year.			

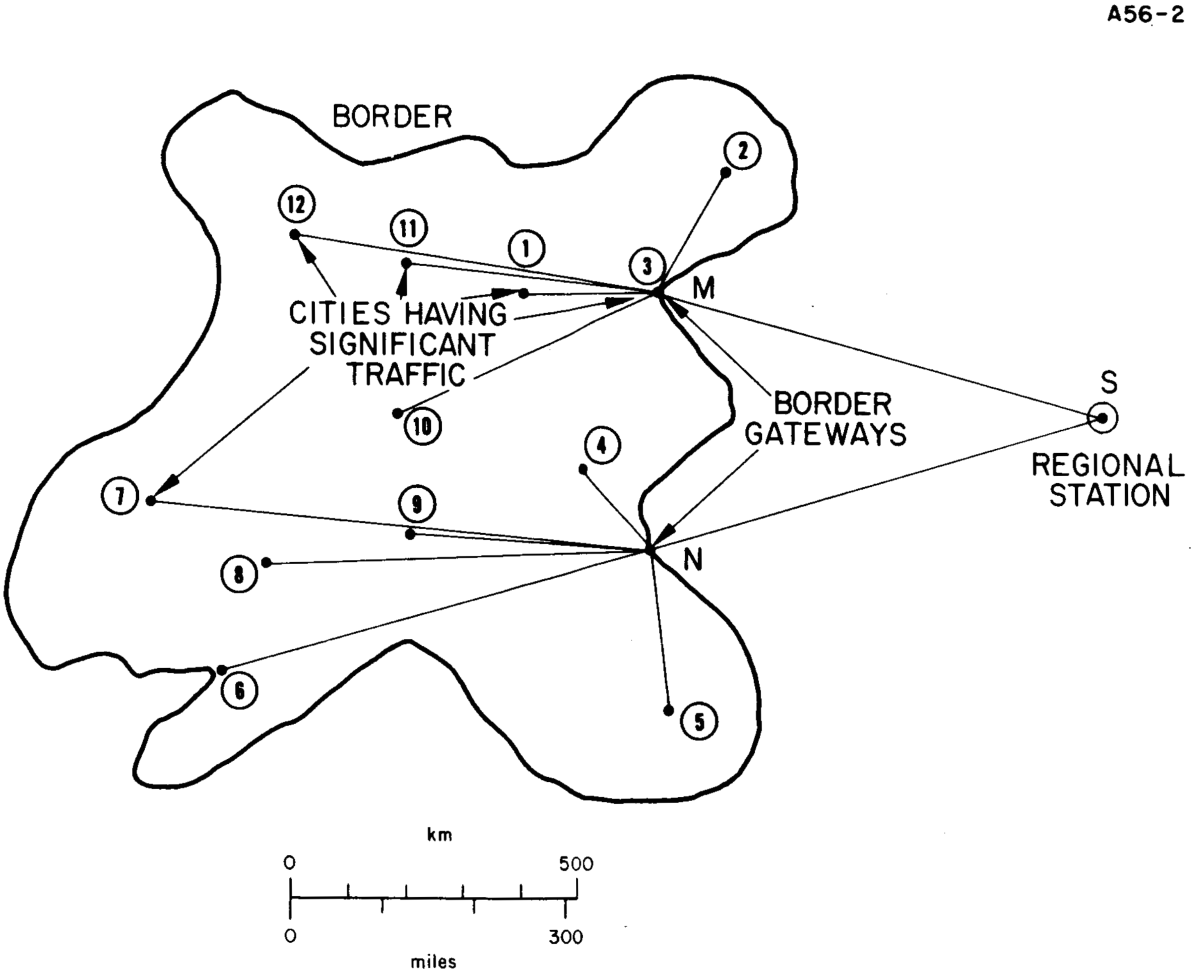

Fig. III-6. Use of a large but remote regional station by a hypothetical nation.

to 45,000 min/year of 300 business days. For convenience, and to allow for nonbusiness traffic and for the high circuit utilization possible with a random access system, we round this off to 50,000 min/circuit year. This hypothetical nation's 1,000,000 min/year would thus require a 20-circuit national station or the use of 20 of the regional station's circuits, and it will be assumed that the station has 120 circuits.

We first assume that these stations use a stationary satellite and have the "near future, probable" annual cost coefficients of Table III-1, converted to gold francs, as $T_o = 459{,}000$ and $T_1 = 21{,}400$. For the 20-channel station with its relatively low surface communication costs,

$$343{,}000 + (495{,}000 + 20 \times 21{,}400) = 1.266 \times 10^6 \text{ GF/year} =$$

$$\$\,414{,}000/\text{year.}$$

For use of the regional station,

$$1{,}161{,}000 + 20\left(\frac{495{,}000}{120} + 21{,}400\right) = 1.671 \times 10^6 \text{ GF/year} =$$

$$\$546{,}000/\text{year.}$$

Next, assume that this hypothetical nation's annual satellite traffic were only 500,000 min/year, requiring only 10 satellite circuits and noting that $T_o/T_1 = 21.4$ circuits. Use of this smaller national station would cost 880,500 GF ($287,000)/year, compared with 736,000 GF ($240,000)/year for using the regional station. The saving of only 144,500 GF ($37,400) might not outweigh other advantages of having a national station. For the example considered, the break-even would occur between 10 and 11 circuits.

Finally, assume that these stations had to use nonsynchronous satellites and that the corresponding coefficients from Table III-1 applied. In gold francs, $T_o = 3{,}061 \times 10^6$ and $T_1 = 21.4 \times 10^3$. For the 20-circuit national station,

$$343{,}000 + (3{,}061{,}000 + 20 \times 21{,}400) = 3.83 \times 10^6 \text{ GF/year.}$$

Note that the T_o term alone is nine times greater than the surface communication cost. Clearly, it would be worthwhile to pay only a share of this cost of a regional station, even though paying more for surface communication. Using the regional station the cost would be only

$$1,161,000 + \frac{20}{120} \times 3,061,000 + 20 \times 21,400 = 2.1 \times 10^6 \text{ GF/year.}$$

This is nearly twice as much as for the national station using a stationary satellite. In this case the break-even would occur when the hypothetical nation's traffic requires 46 satellite circuits.

A more general comparison of the per circuit year costs of using national or regional earth stations can be presented by families of curves, such as Figs. III-7 and III-8 which apply to the "realistic-stationary" and nonsynchronous satellite cases, respectively. For both figures, each curve corresponds to a mean subscriber-to-station distance, D_N to the national station, or D_R to the regional station. The D_N curves are plotted against X_N, the national station's number of circuits, whereas the D_R curves are plotted to a different scale for the regional station's larger number of circuits X_R.

In the case of stationary satellite earth stations, one notes that a 25-circuit national station serving a single large city ($D_N = 0$) would cost 40,000 GF ($13,000)/circuit year, and that this cost would be the same for the use of a 500 circuit regional station at a 400 km distance. Similarly, a five-circuit station at $D_N = 0$ would break even with use of a 100-circuit station at 2000 km, but each circuit would cost 115,000 GF ($37,600) /year. If $D_N = 1000$ km and $X_N = 10$, the break-even would be with a 200 circuit station at $D_R = 2000$ km. In general, this curve family shows that stations having 10 to 25 circuits within 1000 km of their mean subscribers can be competitive with the use of large but relatively distant regional stations.

In the case of earth stations for nonsynchronous satellites, Fig. III-8 shows that each of 32 circuits would cost 115,000 GF ($37,600)/year, even with $D_N = 0$, and the same cost per circuit year would apply to the use of a 600 circuit station at 2000 km or a 130 circuit station at 1600 km. In general, stations with $D_N \leq 1000$ km would need 40 to 120 circuits to be competitive with the use of larger but relatively distant stations. Nations needing fewer than 40 satellite circuits would be forced by economics to obtain service from a large regional station and, even so, the per circuit year cost might be excessive unless there were a 120-circuit station at $D_R \leq 1200$ km, or a 400-circuit station at $D_R \leq 1600$ km.

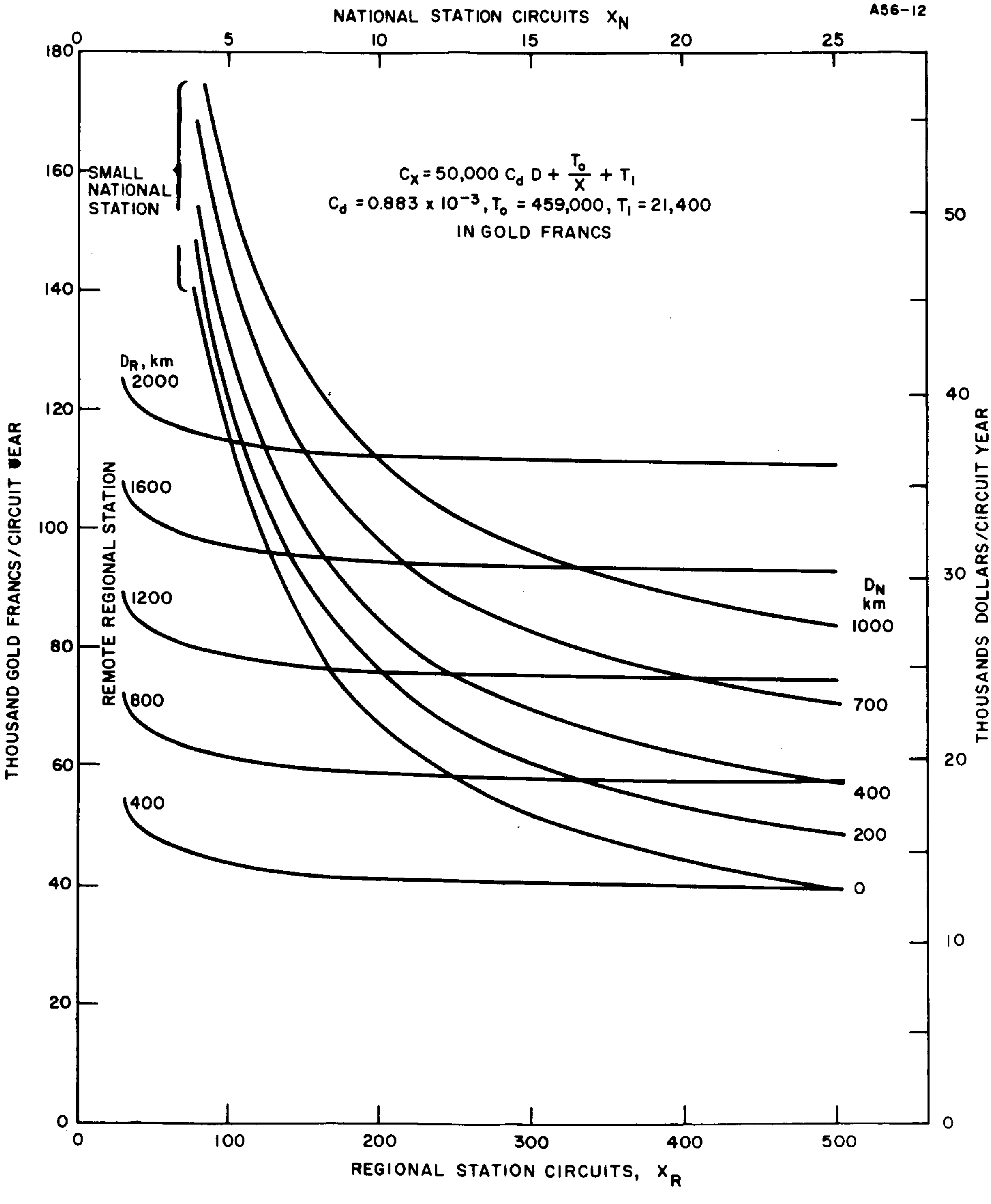

Fig. III-7. Per circuit year cost comparison between small national and large regional stations, using fixed antennas with stationary satellite.

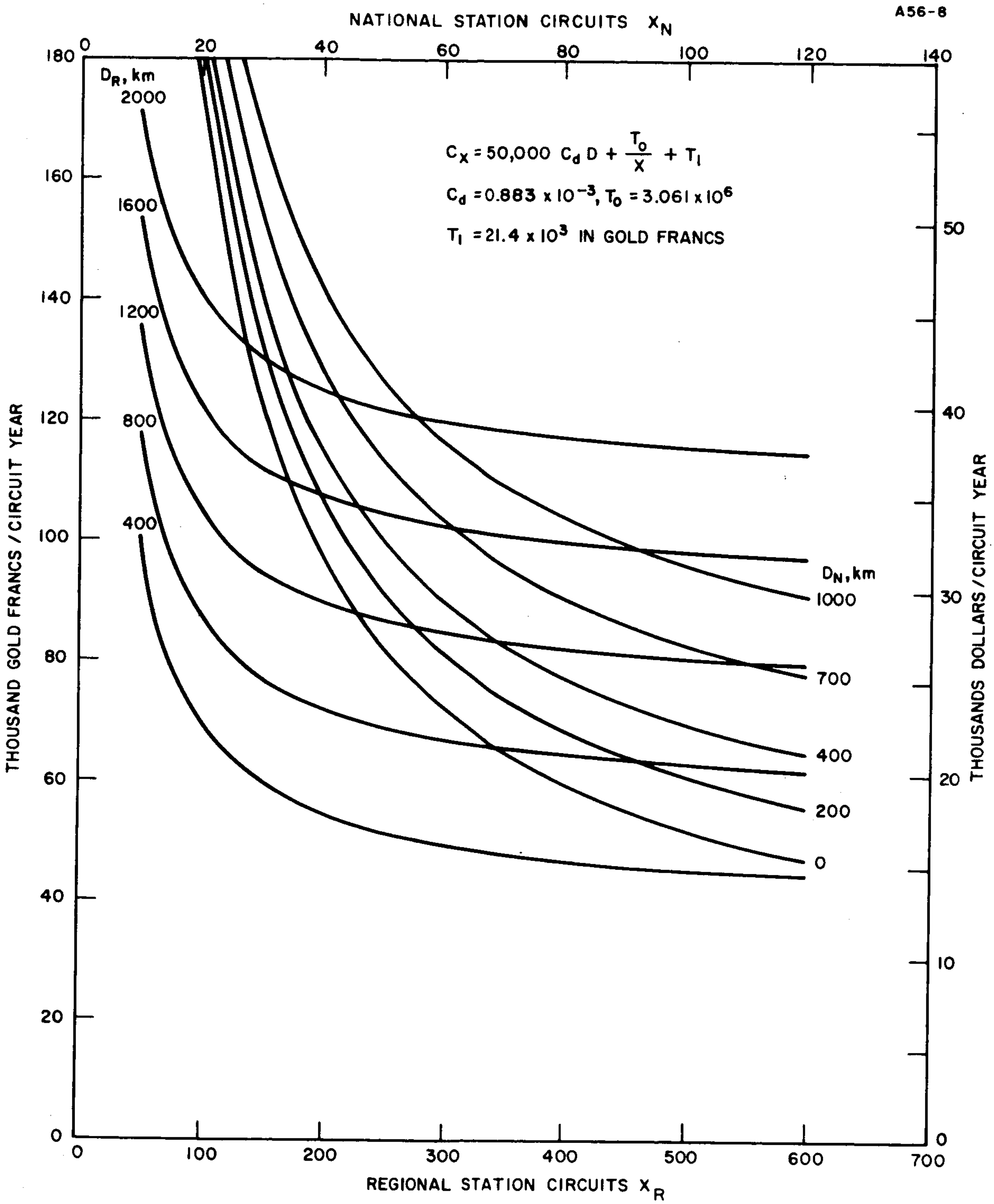

Fig. III-8. Per circuit year cost comparison, national and regional stations, using steerable antennas with nonsynchronous satellites.

J. Possible Effect of Satellite Use Cost

The foregoing study of the comparative use cost of national and regional earth stations has considered only the sum of the station use cost and the subscriber to station communication cost. The subscriber to subscriber cost of a satellite circuit includes the satellite use cost. Consequently, if the use cost of a circuit through a stationary satellite were excessive compared with that for some nonsynchronous orbit system, such a system might be preferable in spite of its higher earth station costs. It seems probable that the use cost would be lowest for the stationary satellite. It is shown in Part IV that the stationary satellite's use cost, under probable near future assumptions, would not be a dominant fraction of the subscriber to subscriber cost. In fact, according to far future assumptions, the stationary satellite use cost may become a small fraction of the subscriber to subscriber cost.

K. Optimum Separation of Earth Stations, Assuming Uniform Geographic Distribution of Traffic

It is at least interesting to examine the optimum area per earth station, and the consequent distance between stations. This is done under the simplifying assumption that subscribers use satellite communication over an unbounded area at a uniform use density of Y paid min/km^2/year. Such uniform use is an admittedly unrealistic assumption whose only justifications are its mathematical convenience and its provision of a rough guide to the number of stations per continent or other large area.

The assumed uniform density area can best be divided into hexagons, each with a station at its center, as shown in Fig. III-9. The inscribed radius of each hexagon is d_o, so the minimum distance between earth stations is $2d_o$, as shown. The earth station's yearly traffic Y is proportional to the area of its hexagon,

$$Y = 2/3d_o^2y$$

$$= 3.464\ d_o^2y \text{ total paid min/year.}$$

Letting C_d represent the surface communication cost per kilometer minute and K represent the paid minutes per satellite circuit year, the combined surface communication and station use cost per minute, at average distance $\bar{d}$ becomes

A53-7

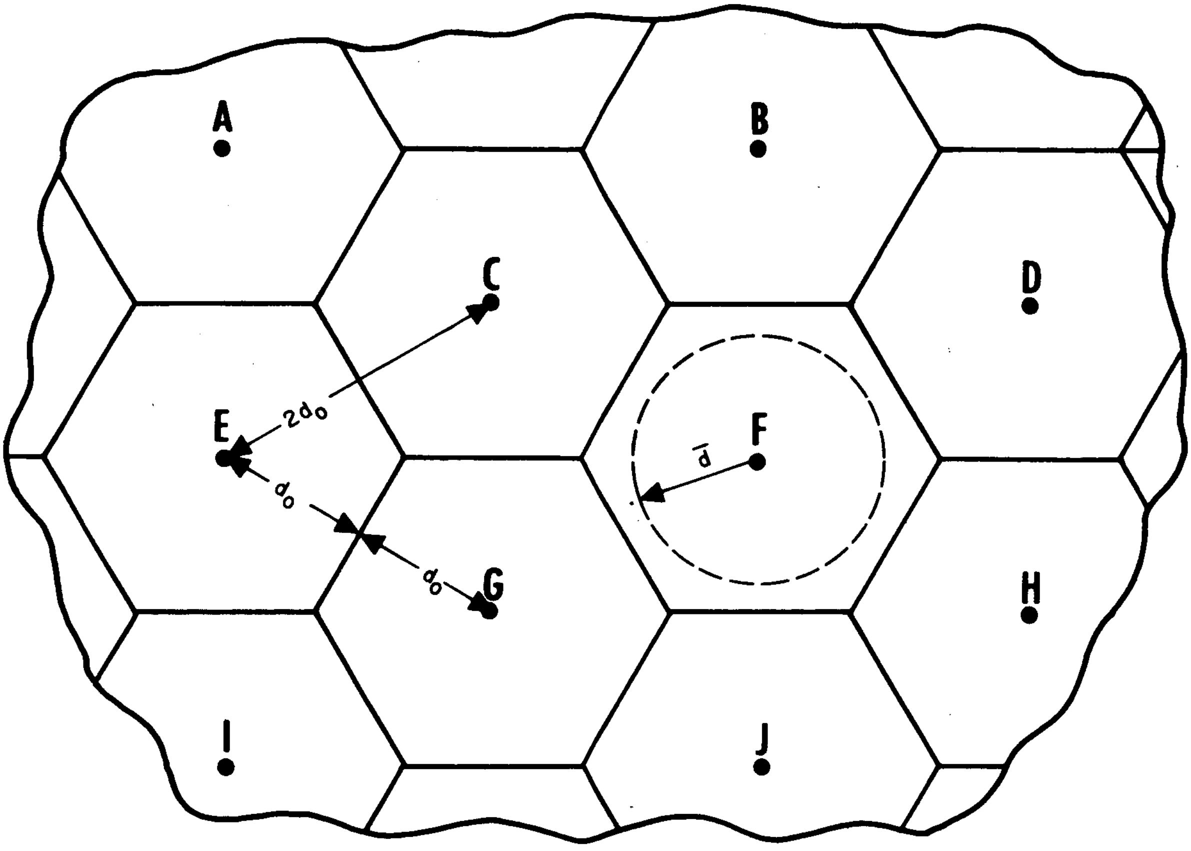

Fig. III-9. Region with uniform traffic density divided into equal hexagonal areas, each with a central earth station.

$$C = C_d + \frac{T_o}{Y} + \frac{T_1}{K} = 0.6285\, C_d\, d_o + \frac{T_o}{3.464 d_o^2 y} + \frac{T_1}{K} .$$

Minimizing,

$$\frac{dC}{dd_o} = 0 = 0.6825\, C_d - \frac{2}{d_o^3} \times \frac{T_o}{3.464y}$$

from which

$$d_o = 0.946 \left(\frac{T_o}{C_d y} \right)^{1/3} .$$

Interesting aspects of this result are that it is independent of T_1, the per circuit component of the station's annual cost, and that d_o bears only a cube root relation to $T_o/C_d y$. An eight to one change in T_o, C_d, or y produces only a two to one change in the optimum d_o of the station's hexagonal surface area. By way of illustration, assume

C_d = 0.883 x 10^{-3} GF/km-min (CCITT, modern conditions)

y = 1.0 paid min/year/km^2*

T_o = \$150,000 = 459,000 GF .

For these values, d_o = 776 km, corresponding to 1552 km between nearest stations. Each station would serve an area of 2.083 x 10^6 km^2 and the annual cost would be 2.33 x 10^6 GF, or 55,200 GF(\$18,000)/ circuit year. In comparison, the hypothetical nation's 20 circuit station would cost 63,300 GF(\$20,650)/circuit year. Thus in this case the agreement is reasonably good, despite the assumption of a uniform density of use.

L. Summary

The preceding examples and their cost factors were given for illustrative purposes, although it is believed that the earth station cost factors are as good as others available. The reader is encouraged

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*Traffic density for the hypothetical nation, with 10^6 paid min/year from its 1.1 x 10^6 km^2 area, would be 0.91 min/km^2/year.

to carry out similar studies for actual nations and their anticipated satellite traffic loads, using whatever cost factors are considered most applicable. It is believed that all such studies will support the following general conclusions.

1. The T_o or no circuit base component of earth station annual cost is the most important in determining the minimum economic numbers of circuits per station. If T_o is too high relative to T_1 it must be distributed over too many circuits and only large stations could achieve a reasonable cost per circuit. Hence, reduction of T_o becomes the key to small earth stations.

2. Earth stations using nonsynchronous satellites require multiple installations of expensive steerable antennas and tracking equipment and these costs add heavily to T_o. Attempting to reduce T_o by using smaller steerable antennas, with less gain, requires satellites of correspondingly higher power or fewer channels per repeater, thus increasing the satellite use cost and nullifying the saving in station costs.

3. Earth stations using a near-stationary satellite, such as the Early Bird,* need only a single, slightly steerable antenna. In the future, when satellites become sufficiently stationary, fixed reflector antennas will be used. Such antennas will provide high gain at low cost, thus reducing T_o and making small stations economically attractive.

4. The cost of surface communication to a remote regional earth station often will be considerably greater than to an optimally located national station. Even though the use cost of a national station will be higher than the corresponding cost for the use of a large regional station, the saving in surface communication cost may make it less expensive to have a national station. However, such a saving would most probably be achieved only with a stationary satellite. Otherwise, unless the nation's traffic volume were great, the high cost of tracking antennas, etc., would cause the cost of a national station to more than nullify the surface communication cost saving.

5. The use of stationary satellites can make it economically advantageous for many nations to use their own earth stations, and for certain large nations with heavy traffic to use several stations. Some small nations will find a station to be advantageous for other reasons, even though the use of a regional station would be somewhat less expensive.

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*The Communication Satellite Corporation's 1965 satellite which was discussed in Part I.

6. Since more stations would share use of a stationary satellite, the utility of multiple access operation would increase correspondingly. Each station could communicate directly with each and every other station.

7. With stationary satellites, the relatively long propagation delay causes today's echo suppressors to impede conversation slightly. The degree of such degradation is being investigated intensively and has not yet been established to everyone's satisfaction. Conclusions should not be made without considering the importance of any such degradation relative to the ability of stationary satellites to bring direct multiple access intercontinental communication to more nations at lower cost.

8. An earth station's inner boundary, containing its normal users, will not normally be determined on economic grounds, in the sense of being continuously expanded or shrunk to obtain the least cost per circuit. This boundary is likely to follow national boundaries, except when a nation has more than one station. Hence, this inner boundary will be determined by whether the station can best serve a nation, some part of a nation, or a region consisting of several nations.

9. The advisability of using several stations within a large nation to lower the combined surface communication and station use cost may be questioned by the telecommunications administrations or operating companies concerned. Doing so is desirable to the extent that lowering the subscriber to subscriber cost of satellite communication is desirable.

APPENDIX III-A

Mathematical Determination of Earth Station Location Having the Minimum Total Crow-Flight Circuit Distance to Significant Cities

To formulate the problem, we let $\dot{V}$ be the vector (distance and direction, from the origin of the coordinate system) to the earth station, whose location is variable, and let $\dot{V}_n$ be similar vectors to each of n significant cities. Thus, the distance from the station to each city is $\dot{V} - \dot{V}_n$. The satellite traffic of each such city is weighted as W_n, this being either its number of circuits to the station, or its annual traffic in paid minutes. Letting ϕ denote the total weighted distance to all cities,

$$\phi = \sum_{1}^{n} W_n \dot{V} - \dot{V}_n \; .$$

The gradient is

$$\Delta\phi = \sum_{1}^{n} W_n \frac{\dot{V} - \dot{V}_n}{|\dot{V} - \dot{V}_n|} \; .$$

At the point of minimum ϕ, its gradient will be zero (if the minimum occurs between cities), or the direction of the gradient will be indeterminate (if the minimum is at a heavy-traffic city).

PART IV

THE TRANSITIONAL BOUNDARY – BREAK-EVEN BETWEEN SURFACE AND SATELLITE COMMUNICATION

A. Introduction

Previous sections have introduced random multiple access satellite communication systems, with which many earth stations can intercommunicate as flexibly and directly as if the satellite were an exchange in orbit. It has been shown that the uses and economic aspects of such a system can be clarified by recognizing that each of its earth stations is surrounded by three or sometimes four boundaries. The outer (one-hop coverage) boundaries were shown in Part II to be geometric functions of the satellite orbit system. In Part III we discussed the innermost boundary, containing the station's subscribers, and showed the importance of considering both subscriber to station communication and station use costs. This concluding section is concerned with determination of the transitional boundary beyond which satellite circuits would be preferable to surface circuits.

The locations of these two inner boundaries involve economic and geopolitical considerations, as was evident in the preceding section. In the case of the transitional boundary the economic consideration is the break-even distance between surface and satellite circuits, since the cost of one-hop satellite circuits is essentially independent of distance. Establishing this break-even distance depends on determining the probable cost of satellite communication and of applicable surface communication. It should be recognized again that the cost of surface communication is best known to the administrations or operating companies concerned, while the cost of satellite communication cannot be established accurately until an operational system has been defined, and perhaps not until it is operating. It is possible and useful, however, to identify the cost factors of a satellite system and their dependence on such factors as launch probability and life expectancy. Cost estimates will be used strictly for illustrative purposes.

B. Type of Satellite System to be Considered

From a business viewpoint, it appears logical to start random multiple access satellite service with a system which will cover the Atlantic Basin; this would constitute the first step toward a globe-encircling system. A single stationary satellite at or near 20° W would be available to about 90% of the world's telephones. At any reasonably early date, this should be a spin-stabilized satellite, having de-spun directive antennas and certain other features of the ADVANCED SYNCOM design, as discussed in Part I.[*]

It should be noted that the use of the ADVANCED SYNCOM will be assumed, because it costs, life expectancy, and other factors are best known to the writer.

It is shown subsequently that the cost of surface communication, per circuit and per unit distance, decreases with increasing circuit capacity. The per circuit cost for a 12-channel system is considerably higher than for a 600-channel system of the same length. Similarly, it seems probable that the per circuit satellite use cost will decrease as the channel capacity of satellites is increased, but the relation between satellite capacity and per circuit use cost is not yet clear. This relation is clouded by the fact that system parameters, other than channel capacity, are changed as larger satellites are designed. For example, SYNCOM-II and III sacrifice some 8 dB of antenna gain, compared with ADVANCED SYNCOM's de-spun antenna. Moreover, designs are related to the payload capabilities of specific available boosters such as the THOR-DELTA, ATLAS-AGENA, ATLAS-CENTAUR, and the future SATURN series. Until SATURN-size satellites are designed, incorporating features and techniques which may not yet be practicable, it will not be known what channel capacity would be provided or whether other improvements may take priority over additional channels in the use of the permissible weight. However, increasing the capacity does not decrease the satellite use cost until the additionally available channels are used; in fact, quite the opposite is true.

C. Satellite System Use Cost Components

Considering that the cost of attempting to launch a replacement satellite is C_r, that the probability of placing it on station and in operation is P, and that its life expectancy is r years, the annual cost of satellite replacement is C_r/Pr, neglecting such complications as interest on this replacement fund.

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[*] The Communication Satellite Corporation's EARLY BIRD (1965) satellite will be more similar to SYNCOM-III, in that it will have a near-stationary (slightly inclined) orbit, no de-spun antenna, and no SSB-PM random access capability. It is to be used, with assigned channel access via multiple FM signals, between one or two North American stations and a few European stations. This may be followed by a satellite smaller than the ADVANCED SYNCOM but having random access capability. The cost of such a satellite is currently being studied.

In addition, there will be an annual cost component C_o for such expenses as amortization of the initial satellite, providing the channeling and supervisory (CSC) service, management costs, sustaining engineering, and development of future satellites. These costs are independent of P and r. Moreover, when additional satellites are placed in service, the management, development, and engineering costs would be divided among them. However, we consider C_o to be the cost per satellite in operation. Consequently, the total annual cost per satellite in operation becomes

$$C_s = C_o + \frac{C_r}{Pr} \quad .$$

It is assumed that this cost will be allocated among the earth stations in proportion to their use of the satellite. If station K uses N_k channel min/year and the combined use by all m stations is expressed as a summation, station K's fraction F_k of the total satellite use cost would be

$$F_k = \frac{C_s N_k}{\sum_{1}^{m} N} \quad .$$

Each call uses two satellite channels, one from each station. In practice, the station originating a call may be billed for the use of both channels, but this is immaterial to this discussion.

D. Allocation of Satellite Use Cost Among Its Earth Stations

It is assumed that this annual satellite use cost C_s should be allocated equitably among its using earth stations. The meaning of this equitable allocation depends on whether one considers that the satellite sells circuits or whether it sells repeater bandwidth and that portion of its transmitted power.

This divergence of views on equitable allocation was discussed in Part I, where it was shown that the laissez-faire view might be justified for paired-station operation but that it was incompatible with the high degree of coordination and conformance to standards required in any large multiple access system. In addition, it was shown that it should not remain necessary or desirable to distinguish between small and large stations by considering small stations to be poor stations which would need to use the satellite less efficiently than the large stations, and which should therefore pay more per channel because of their less efficient use. Given an adequate stationary satellite, all stations should use fixed high-gain antennas of relatively low cost. Additionally, the system should be designed to permit satisfactory service during hours of high sky noise temperatures. At such times a relatively inexpensive nitrogen-cooled parametric amplifier is only slightly less efficient than a helium-cooled maser. The only difference in satellite use by large and small stations might be that the former would be more likely to use assigned channels, in addition to their use of random access.

Assuming that a multiple access system is designed on the basis of all stations being good stations, with all conforming to the same standards and making equally efficient use of the satellite, it becomes equitable to charge all stations an equal rate per circuit (or perhaps per circuit minute) for their use of the satellite's random access service.

Random access systems have another interesting aspect which may affect the satellite use cost, viz., the use diversity of the satellite's random access channels. Any earth station can use any idle repeater circuit (transmitting and receiving channels). Consequently, the earth stations can have equipment and peak capacity to use more channels than the satellite's random access channel capacity, because their traffic peaks would not all coincide. The ratio of satellite channels to total (equipped) station channels has not yet been determined. Neither has it been determined how much it may cost to provide the channel allocation and supervisory service for this random access method of operation. However, the cost of this service will tend to cancel the channel use diversity advantage, so that the effective cost per channel year would be about the same as if these random access channels had been permanently assigned. Consequently, for simplicity, it will be assumed that the satellite's use cost is allocated equally per channel among the repeater channels used, without distinguishing between random and assigned channel uses.

E. Satellite Use Cost Estimates

The 1963 cost of launching a satellite with an ATLAS-AGENA booster was estimated to be $8,000,000. For 1964 launches, NASA lowered this estimate to $7,200,000. With further production economies and experience, it seems reasonable to predict that this cost may drop to $6,750,000 by the time the first commercial satellite of this type would be orbited (say by 1967 or 1968) and that it would reach $6,000,000 by about 1975. Of course, ATLAS-AGENAS probably will be obsolete before 1975 because of some unpredictably better and cheaper means of launching an equal payload, but economic studies should not be based on the unpredictable.

The cost of the first operational ADVANCED SYNCOM payload was estimated at $3,000,000, on the assumption that NASA would complete development and test of its experimental version. After experience with the first few, this cost might drop to $2,500,000, and eventually to $2,000,000.

The initial probability of achieving a successful orbit has been estimated as $P = 0.5$. This seems conservative, because the ATLAS-AGENA is rapidly becoming a highly reliable vehicle. The SYNCOMS being orbited with THOR-DELTAS are generating experience and dispelling the fears associated with the difficult maneuvers required to achieve a stationary orbit. After gaining experience from orbiting the first ADVANCED SYNCOMS this probability should reach 0.7 and eventually 0.9 or better.

Life expectancy r is the most important parameter for the reduction of satellite use cost, as will be seen, and its importance was emphasized by the premature failure of COURIER, early troubles with RELAY-1, and with both TELSTARS. However, SYNCOM-II has, at the time of writing, survived nine months without even a partial failure. Consequently, a six month life now seems a pessimistic estimate for early ADVANCED SYNCOMS and its designers are confident that two years is realistic. It is also believed that life in excess of 10 years ultimately will be achieved after sufficient experience and effort.

The effective channel capacity of an ADVANCED SYNCOM would depend both upon its growth in use and upon the replacement policy established by the system management. It seems reasonable to assume that at first, a single repeater (1200 channels) would be used, except when television is being relayed. Soon, two repeaters would be carrying traffic other than television, and eventually three repeaters would be used to increase the capacity to 3600 channels (1800 duplex voice circuits). One recognizes, of course, that repeater usage is related to life expectancy.

The C_o component seems the most uncertain because the management, development, and engineering costs will depend on decisions made by the Communication Satellite Corporation or other operators of satellite communication systems. From the Lenkurt study, $^{IV-1}$ one arrives at $C_o = \$6,400,000$ per year, much of which was for amortization of $22,000,000 for the first satellite assumed to have been orbited on the second attempt. If heavy initial development or other expenses are incurred this figure could rise as high as $9,000,000 per year. On the other hand, C_o could drop to about $4,000,000 after the management and similar costs are distributed among several operating satellites.

Table IV-1 summarizes these satellite use estimates under three assumptions which are similar to those used in Part III for the earth

TABLE IV-1

Annual Satellite Use Estimates, based on the ADVANCED SYNCOM

$(C_s = C_o + C_r/Pr)$

Class of Estimate Applicable Time	Pessimistic, Present	Realistic, Near Future	Optimistic, Far Future
Booster Cost, $	7.2×10^6	6.75×10^6	6×10^6
Payload Cost, $	3×10^6	2.5×10^6	2×10^6
C_r, $ each launch	10.2×10^6	9.25×10^6	8×10^6
Orbit Probability, P	0.5	0.7	0.9
Life Expectancy r, years	0.5	2.0	10.0
C_r/Pr, $ per year, av	40.8×10^6	6.6×10^6	0.889×10^6
Constant Annual Cost C_o, $	9.0×10^6	6.4×10^6	4.0×10^6
Total Annual Cost C_s, $	49.8×10^6	13.0×10^6	4.89×10^6
Satellite Channels Available	1200	2400	3600
Annual Cost Per Available Channel, $	41,500	5,520	1,360
Annual Cost Per Station to Station Circuit, C_{sc}, $	83,000	11,040	2,720
Annual Cost Per Station to Station Circuit, GF	254,000	33,800	8,330

station estimates. The "pessimistic" estimates are the highest and are based on today's state of the art. The "probable" estimates seem better for the period (1967-1968) when such a satellite might enter service. The "optimistic" estimates are for such a time as several satellites are being heavily used, and the 10 year life expectancy has been achieved. This time may be around 1975.

Remembering that these estimates are only illustrative, Table IV-1 leads to some significant conclusions. If the orbiting probability and life expectancy are low, as in the pessimistic estimate, the cost of several launches per year becomes the determining cost, even though a high C_o is assumed. At such a stage a vigorous life-improvement program would be rewarding even though it further increased C_o. On the other hand, after the optimistic conditions have been attained and a less expensive payload is launched on an average of once every nine years with a less expensive booster, the annual cost for replacement would be less than 20% of the total. At that time it would become more rewarding to find ways to further reduce the management and other C_o costs.

The annual cost per available channel showed even greater decrease in Table IV-1 only because it was assumed that only one of the four repeaters would be available initially, whereas eventually three could be used. It must be remembered that these costs per channel assume that all channels are used. If only some of the channels were to be used, each would carry its fraction of the total annual cost C_s, irrespective of whether one or three repeaters were available. The major difference is that, with three spare repeaters, the satellite probably could last longer.

Finally, the 30 to 1 spread shown in costs per available channel, and the probability that larger satellites may lower the per channel costs even more, suggests that the break-even distance relative to surface communication may decrease similarly. A 17,000 km satellite circuit for only $2,720 per year certainly would appear to be a revolutionary bargain! However, the availability of satellite channels has no value until a pair of earth stations use these channels for a circuit between them. Hence the earth station use costs must be added to the satellite use cost in determining the actual cost of their circuit. Additionally, from the subscriber's viewpoint, there would be the cost of subscriber to station communication at both ends, plus the possible cost of access to the international or intercontinental system such as the cost associated with dialing more digits. It is recognized, of course, that rates will be established and that these rates will determine the amount which a subscriber actually pays for making a call. It is assumed that this rate will be related to the average cost from subscriber to subscriber.

F. How the Pie and its Slices May Change

At this point it is interesting to examine pie-diagrams of subscriber to subscriber costs, to see how the relative importance of these cost components may change with progress from the pessimistic to optimistic conditions under the following additional assumptions.

1. Seventy-five percent of the satellite's available channels are used 50,000 min/year each.

2. At each end of the circuit the average station to subscriber distance is that for the hypothetical nation (Part III), or 390 km, and the surface cost is 0.883 x 10^{-3} GF/km-min, hence 0.688 GF/min, or $0.225/min for the surface circuits from both stations.

3. The access cost component is $0.175/min. This is strictly an estimate dictated by convenience, since it brings the combined surface communication and access cost to $0.40/min.

4. Both earth stations use 20 satellite channels. Note that this assumption is an oversimplification because the traffic from the hypothetical nation probably would change drastically with the conditions assumed. For example, the low costs might stimulate traffic growth so greatly that the hypothetical nation could use four stations, each closer to its subscribers, and thus cut in half its surface communication cost per circuit.

On the basis of these assumptions, Fig. IV-1 shows the total costs for the three conditions by the relative areas of three pies, with the slices showing the cost distribution for each condition. For the pessimistic condition, the cost for 3 min would be 32.15 GF, or $10.50. Recognizing that the present U.S. rate for calls to Europe and many other overseas locations is $12.00 for 3 min, satellite communication might be only marginally attractive under these conditions. Moreover, until the satellite use built up toward the assumed 450 duplex circuits (75% capacity of the one repeater) the system might have to operate at a loss. Also, since such a large fraction of the cost is for satellite use, it would be relatively less important whether the surface communication and earth station use costs were properly related to each other.

Turning to the optimistic far-future assumptions, the calculated cost for 3 min is only $2.38, which is comparable to the U.S. transcontinental day rate of $2.25. Good circuits at rates even close to this cost, from England to Australia, France to Tahiti, or even from Iceland to Antarctica, could be a revolutionary stimulus to global communication. Perhaps more important, satellite communication would be useful within South America, Africa, probably within Australia, and certainly between East and West Pakistan.

The 9.1% satellite use cost for the optimistic or far-future conditions suggests that at such a time, better satellites should take more of the system burden from the earth stations, so that smaller and less expensive stations could serve even smaller areas. An increase in satellite use cost might thus permit a greater decrease in the station use and surface communication costs and thus minimize the over-all

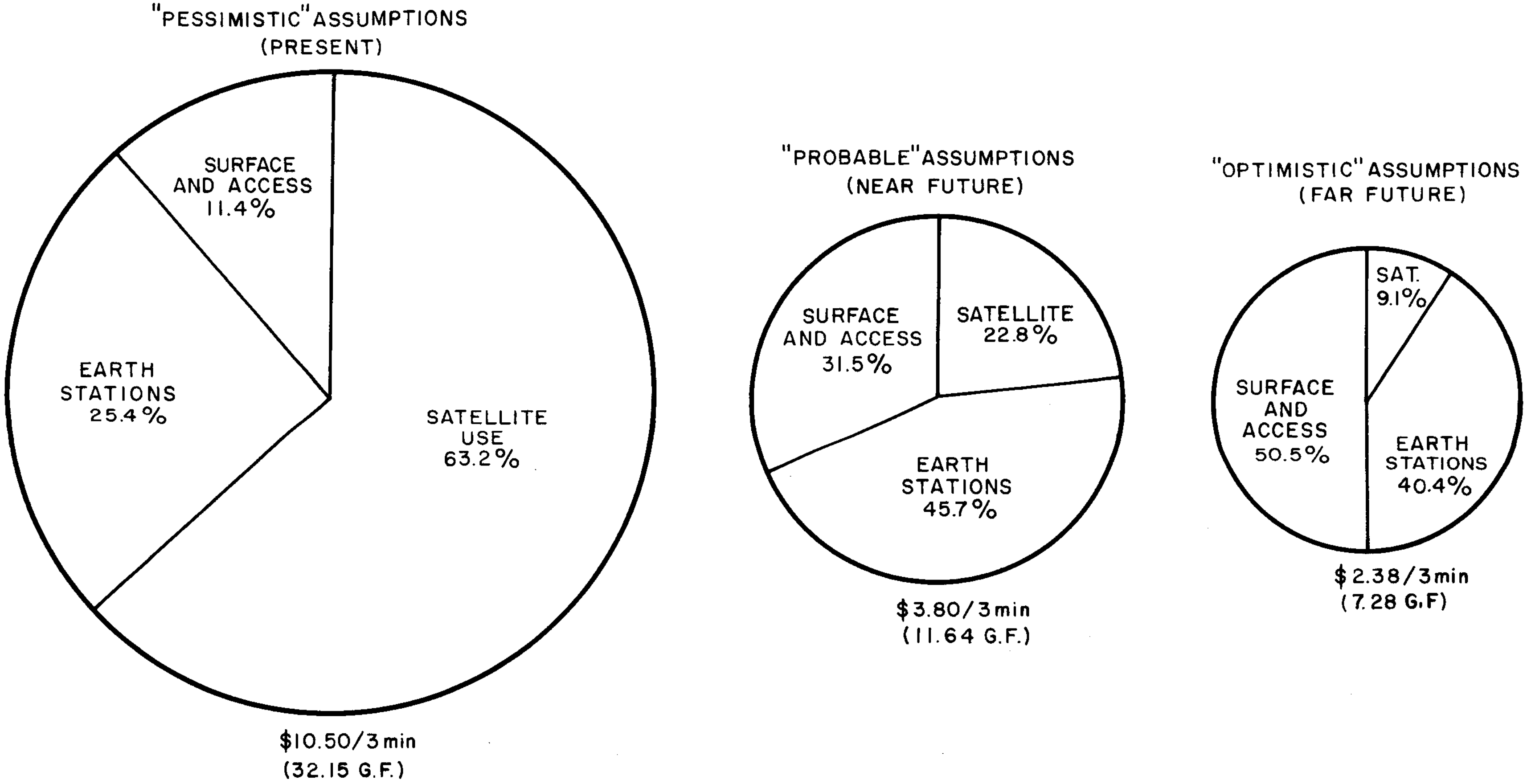

Fig. IV-1. The foreseeable trend in satellite communication cost components.

circuit costs, thus bringing satellite communication to still more users, bringing it closer to its prior users and making it competitive with surface circuits at shorter distances.

G. The Break-Even with Surface Communication

It has been observed previously that the least expensive form of communication generally will be used, assuming that it is satisfactory. To date, HF radio circuits often have been the only economic means of communication for light traffic and long distances, but such circuits may not be available every day or at all hours. Interference, multipath distortion, and fading often impede the flow of conversation. Compared with wire, microwave relay, or satellite circuits, HF radio circuits are not satisfactory. They would generally not be used if good circuits were available at reasonably higher cost. Hence, we need not consider break-even relations between satellite and HF radio circuits.

Considering the better forms of surface communication, whether already in existence or not, the applicable cost as a function of distance and direction will be best known to the telecommunications administration or operating company concerned. Lacking specific information, some generalizations and illustrative cost relations will help to clarify the factors to be considered in determining the break-even point relative to satellite communication.

For simplicity, it can be assumed that a nation's satellite earth station and its CT_3 switching center (the point of access to the international and intercontinental surface communication system) are both centrally located. Consequently, the airline distance between CT_3's and between corresponding earth stations will be essentially the same. In cases where the distance between subscribers, or between their CT_3's is significantly less than between their earth stations, the chances are that these distances also are considerably less than the break-even distances.

It is necessary to recognize a distinction between existing surface communication facilities and new facilities. Existing facilities continue to be used as long as they are satisfactory and do not require excessive maintenance. For example, the first successful transatlantic submarine cable was used for 100 years – long after better cables were laid. It is difficult to compete with an old but satisfactory facility, especially if it has paid back all or most of its investment cost. The new facility generally carries the additional traffic, without taking traffic away from the old one. The cost of using any existing facilities generally is known, but such facilities may be lacking, fully loaded, or otherwise inadequate; our attention can better be directed toward the probable cost of new surface communication facilities. Even with new facilities, there are complications in determining the break-even distance, and one of these is the probable inequality of the traffic volumes to be considered.

As is shown in Part IV-H, the cost per unit distance decreases with increasing traffic volume over a surface system. Thin-route systems, with less than 30 circuits, may cost up to 100 times more per circuit kilometer than microwave relay or coaxial carrier systems which carry thousands of circuits. For this reason, the practice is to route surface communication systems in such a way as to collect and carry heavy traffic. To the extent possible, surface communication systems are planned along routes which will connect heavy-traffic regions and pass through large cities and other heavy-traffic regions, dropping and picking up additional traffic, much like a railroad route. This aspect of surface routing is illustrated conceptually in Fig. IV-2. Intercontinental surface communication routing practices also take cognizance of the importance of concentrating traffic, as shown in Fig. IV-3. Hence, in trying to compare the cost of satellite communication between any two points A and B with the cost via surface communication, one must recognize that the surface system may have the advantage of carrying more traffic than just that between A and B; however, the length of this surface route also will be greater than the airline distance between A and B.

In addition, there are noneconomic considerations, such as the probability of greater switching and queuing delays in obtaining surface circuits over long distances and the possibility of surface service being interrupted through some intervening nation. Only the administrations concerned can evaluate the additional worth of the direct up and down circuits obtainable via a satellite system. Also, from a practical standpoint, most areas of the world do not yet have enough telephones and enough potential intracontinental traffic to support high-capacity surface systems. There may be only one or two main routes, which may be indirect or even inaccessible to the two points being considered. In addition, some of these main routes are still only in the planning stage.

In comparing satellite circuits with surface circuits in order to obtain a break-even distance on a basis of equal cost, the satellite circuit cost should include the use cost of both earth stations, plus the use cost of the satellite. The corresponding surface circuit cost may be taken as that between the two national switching centers (CT_3's), assuming that these and the earth stations are centrally located relative to the nation (or other area) which they serve. Under this assumption, the average cost of surface communication between subscribers and their earth stations would be about the same as between subscribers and their CT_3's; these subscriber circuit costs thus need not be included.

Another interesting point to be remembered is that the satellite circuit cost, under the assumptions being used, does <u>not</u> depend on the number of circuits used <u>between</u> a pair of stations. It will depend only on the satellite circuit <u>capacities</u> of the two earth stations. In addition,

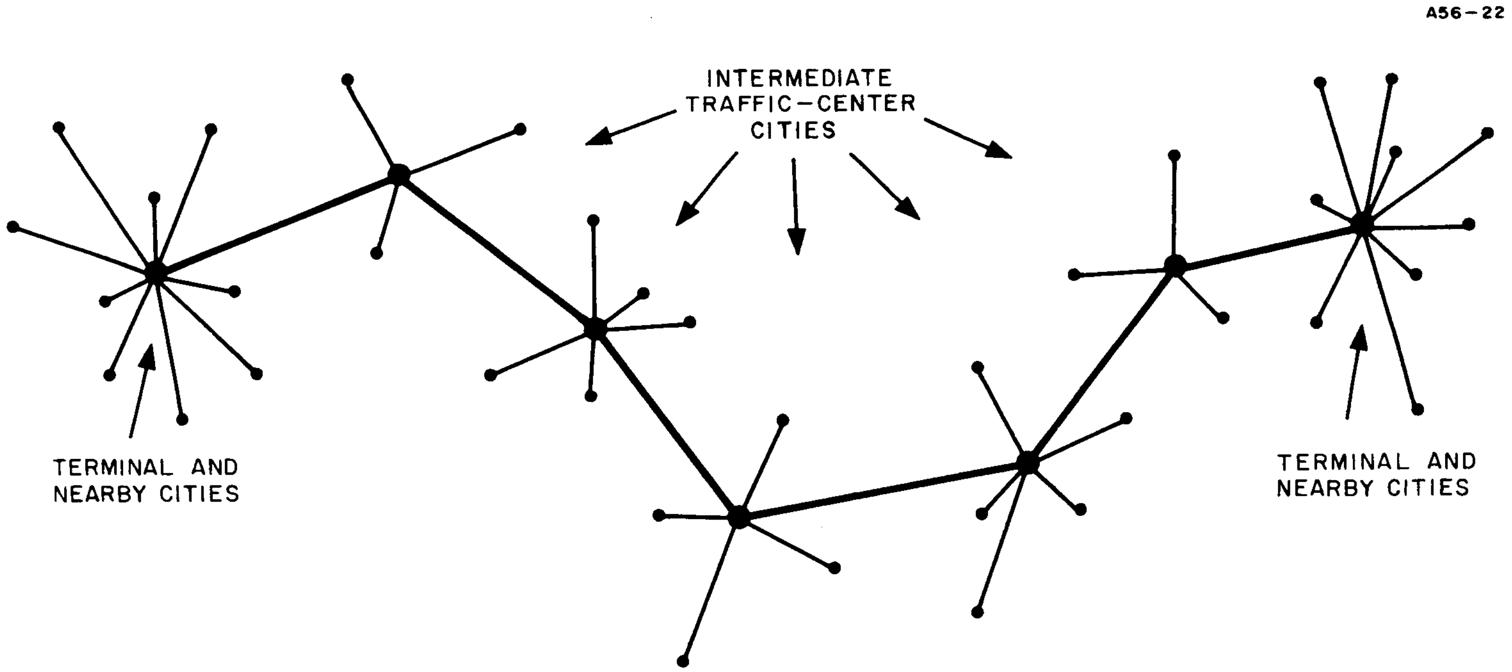

Fig. IV-2. Surface communication system routing via intermediate traffic centers to maintain heavy traffic.

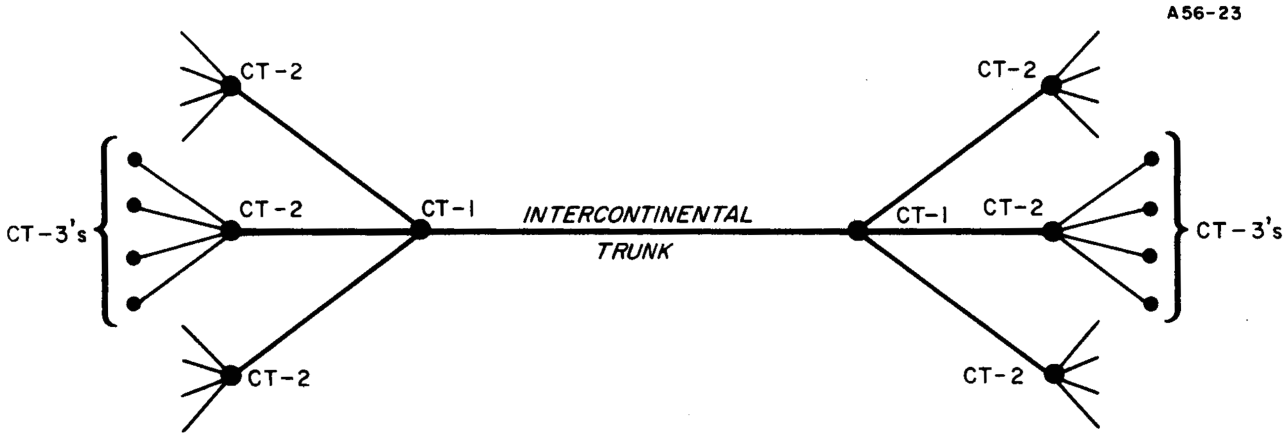

Fig. IV-3. The CCITT plan for collecting and distributing intercontinental trunk traffic.

the satellite use cost per circuit has been assumed to be the same for all stations. As shown in Part III, earth station use cost decreases toward a minimum of T_1, its per circuit cost component, with an increase in its number of satellite circuits. The small station has a higher use cost per circuit because its no-circuit cost component T_0 must be shared among fewer circuits. Hence, for a satellite circuit between a small station and a large one, the latter will contribute a relatively low use cost and the small station will contribute a larger use cost. The total circuit cost would be less if both stations were equally large and would be greater if both were equally small. Therefore, one can concentrate on the case of equal capacity stations, letting their circuit capacity vary from small to large.

It should also be recognized that the cost of surface communication between two CT_3's may not be determined solely by their traffic with each other and by their airline separation from each other, unless they are to be joined by a submarine cable. In general, the surface system which would be used would be one which also carried traffic to and from intermediate and more distant points and which followed some longer route which would link certain large cities. One generally should not consider just the traffic between two points as being carried either by satellites or by a surface system alone.

H. Surface Communication Circuit Costs

Figure IV-4 shows, for illustrative purposes only, the comparative annual cost per circuit mile versus number of telephone circuits for AT & T (U.S.) systems, as of 1957.[IV-2] The equation of the straight trend line is

$$\begin{aligned} C &= 380\ X^{-0.706} && \text{\$/circuit mile} \\ &= 722\ X^{-0.706} && \text{GF/Ckt km} \quad . \end{aligned}$$

Subsequent information[IV-3] indicates that the cost of certain typical systems has increased approximately in proportion to the general inflation of costs which has occurred since 1957. The additional cost of terminal equipment required for the system considered (i. e., for the carrier multiplexing and demultiplexing equipment, but neglecting the subscriber's loop and such of its central office equipment as would be required with any long distance system) is negligible for voice-frequency systems, and only about $380 per circuit year for both terminals of high-capacity carrier or microwave relay systems. Thus, if such systems are more than 380 miles long, these terminal costs increase the cost per circuit mile by not more than $1.

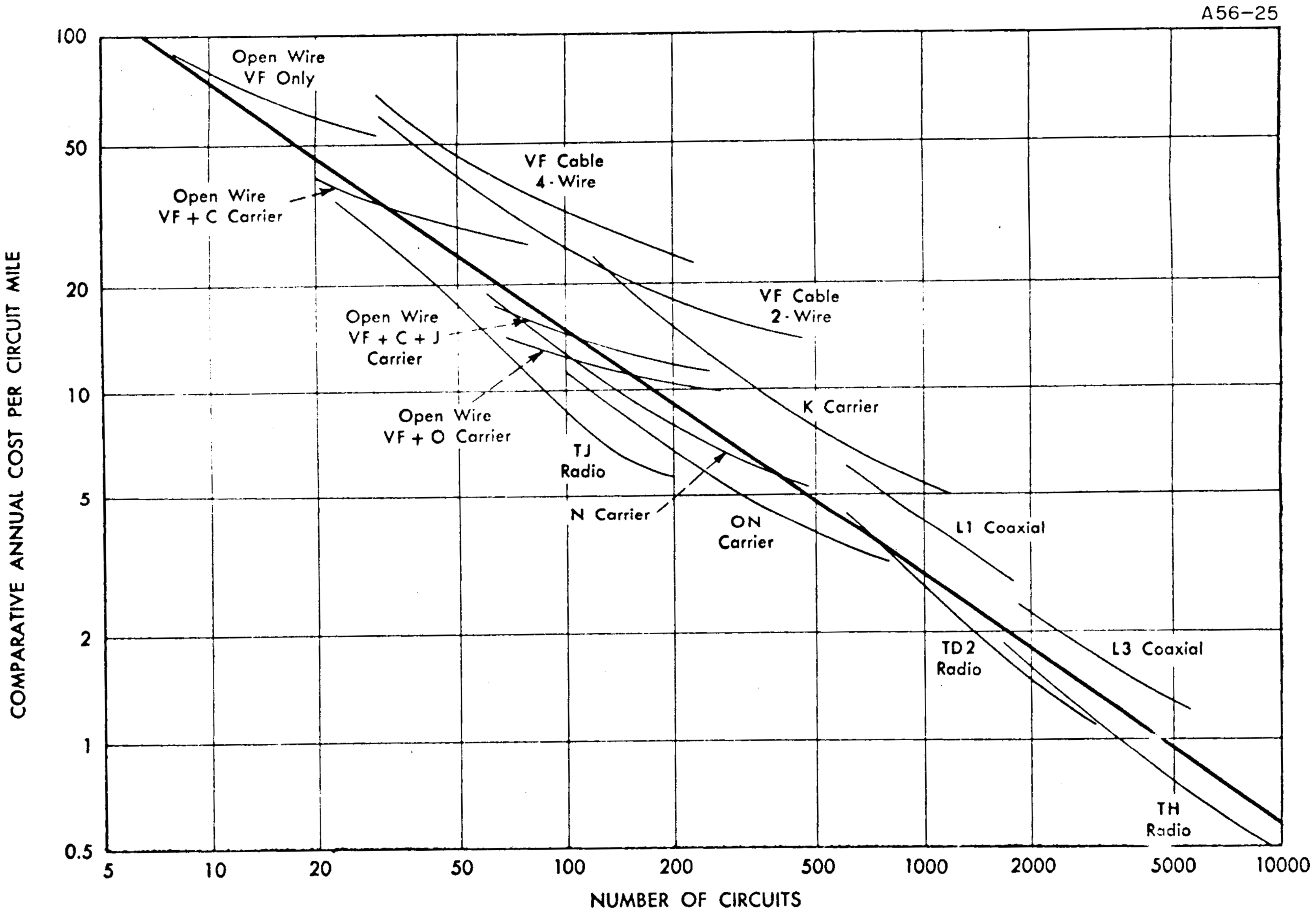

Fig. IV-4. Circuit cost versus number of telephone circuits for various U.S. systems. From AT&T Exhibit No. 2253, F.C.C. Docket No. 11866, 1957.

Note that Fig. IV-4 does not include tropospheric scatter systems or submarine cables. The former are attractive for thin routes and for crossing difficult terrain in relatively long hops. The variability of tropospheric propagation has a marked effect on the cost per circuit mile. If the application permits the circuits to be noisy and to fade badly at bad hours of bad days, the cost per circuit mile can be lower than for other systems of comparable capacity. If, however, a chain of troposcatter link must form a part of a long international system and must meet the CCIR noise recommendations for such systems during any hour of the year, the links require more transmitter power, antenna gain, diversity, etc., and the cost per circuit mile tends to become higher than for other systems of equal circuit capacity.

Submarine telephone cables are achieving relatively high circuit capacities and their cost per circuit mile is taking a downward trend similar to the trend line of Fig. IV-4. The TAT-3 cable, recently placed in operation, provides 128 channels (without using TASI) and is estimated to cost about $20 per circuit mile per year, assuming that all circuits are used. A 720 circuit transistorized cable also has been proposed and its annual cost might be about $6 per circuit mile when fully used. It should be noted that if these two points were plotted on Fig. IV-2 they would be in keeping with the cost of land cable systems for the same number of circuits and would be only about 60% above the trend line.

Recognizing that this trend line probably has risen since 1957, it can be seen that submarine cable circuit costs, for systems of equal capacity, are very little different from those of land circuits. Thus, contrary to a popular belief, satellite communication is not inherently more competitive across oceans than across land. The primary difference is that land systems generally have higher circuit capacities than have been needed with submarine cables.

I. Some Break-Even Examples

We first consider a pair of earth stations A and B, each of which has the same satellite circuit capacity of X circuits. Each may use as many of these X circuits to other stations as may be needed. The number of circuits used between stations A and B is immaterial and can be any number not exceeding X. As explained in Part III, the annual use cost per circuit for either station can be expressed as

$$C = \frac{T_c}{X} + T_1 \quad .$$

Adding this use cost for both stations to the cost for use of a satellite circuit C_{sc}/K, where K is the fraction of the satellite's circuits which are used,

$$C_{AB} = 2\left(\frac{T_o}{X} + T_1\right) + C_{sc}/K \quad .$$

For example, using the near-future values assumed for T_o and T_1 (Table III-1), and for the satellite circuit use cost C_{sc} (from Table IV-1) and assuming that only half of the satellite's 1200 available circuits are in use, the annual cost of circuit between stations A and B would be

$$\begin{aligned} C_{AB} &= 2\left(\frac{150,000}{X} + 7000\right) + \frac{11,040}{0.5} \\ &= \frac{300,000}{X} + 36,080 \quad \text{in dollars.} \end{aligned}$$

Figures IV-5, IV-6, and IV-7 illustrate break-even trends between satellite and surface communication. In each, the family of diagonal lines are surface system cost trend lines for the distances shown, obtained from the trend line of Fig. IV-4. The superimposed curves show satellite circuit costs between earth stations of circuit capacity shown by the abscissa, with other conditions as shown. Thus, on determining the cost of any particular satellite circuit from the ordinate scale, this cost applies for any distance between stations, from 0 to 17,000 km. The same cost would apply to the trend curve for a surface system of known length but unknown number of circuits, or to one of a known number of circuits but of a length to be determined. Thus, a satellite circuit of known annual cost would "break even" with a relatively long surface system of high circuit capacity, or with a relatively short thin-route surface system, as can be seen.

Figure IV-5 shows satellite circuit costs for four conditions as labeled; each assumes that the satellite and earth station circuit capacities are fully used. Considering the lower three curves and circuit cost of \$30,000 (92,000 GF) per year, it can be seen that stations with large steerable antennas would need about 400 circuits each. For the corresponding case with fixed antennas (the stationary-probable curve) only about 60 circuits per station would be required. For the optimistic or far-future conditions, this same circuit cost would be obtained with only four circuits per station, but the circuit cost could be cut in half by using 50 circuit stations. For surface system trends, this \$30,000 a

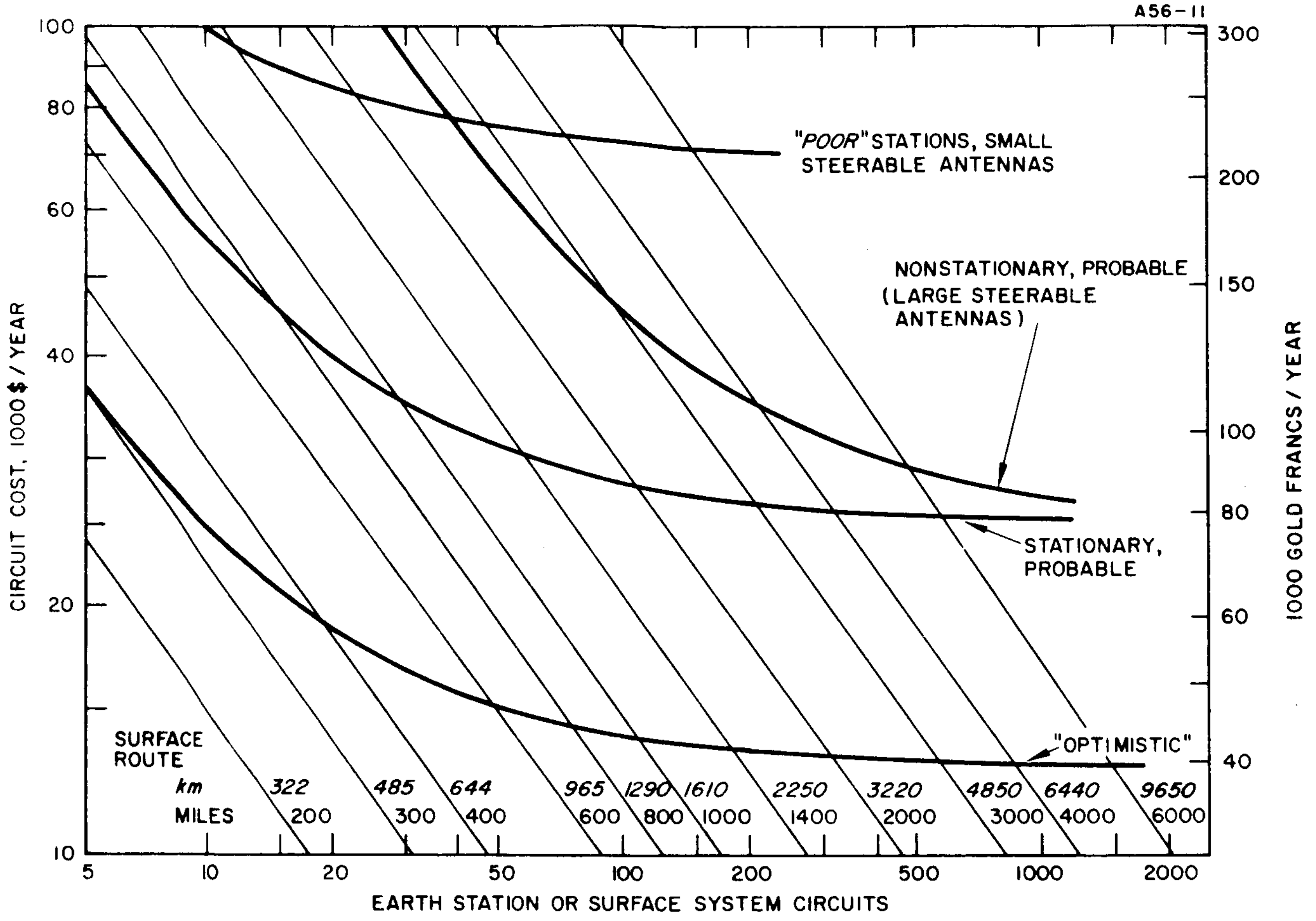

Fig. IV-5. Comparison of surface and satellite circuit costs, for assumptions shown, with full use of satellite and earth station circuits.

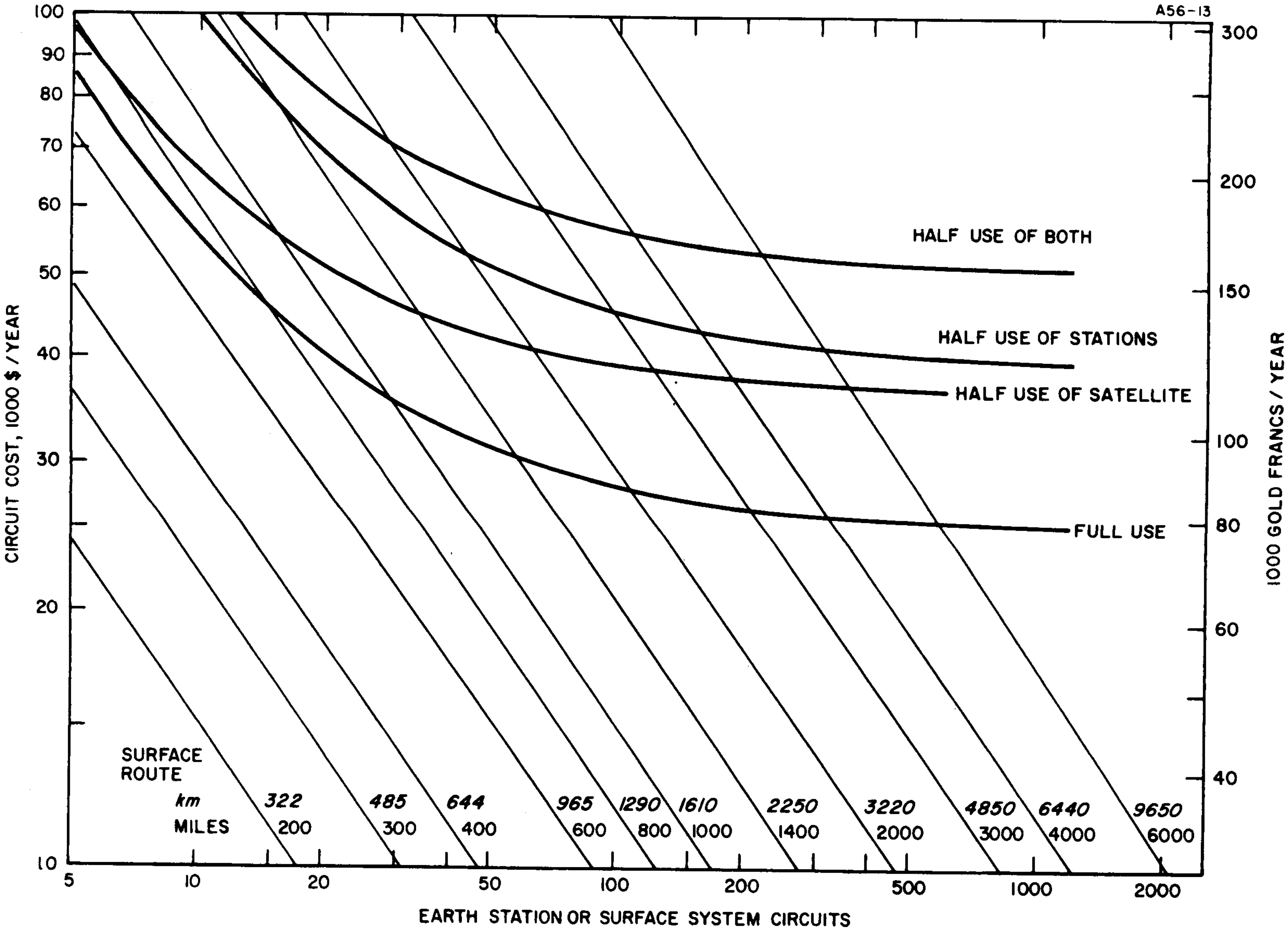

Fig. IV-6. Change in satellite circuit costs with fractional use of circuits—probable assumptions.

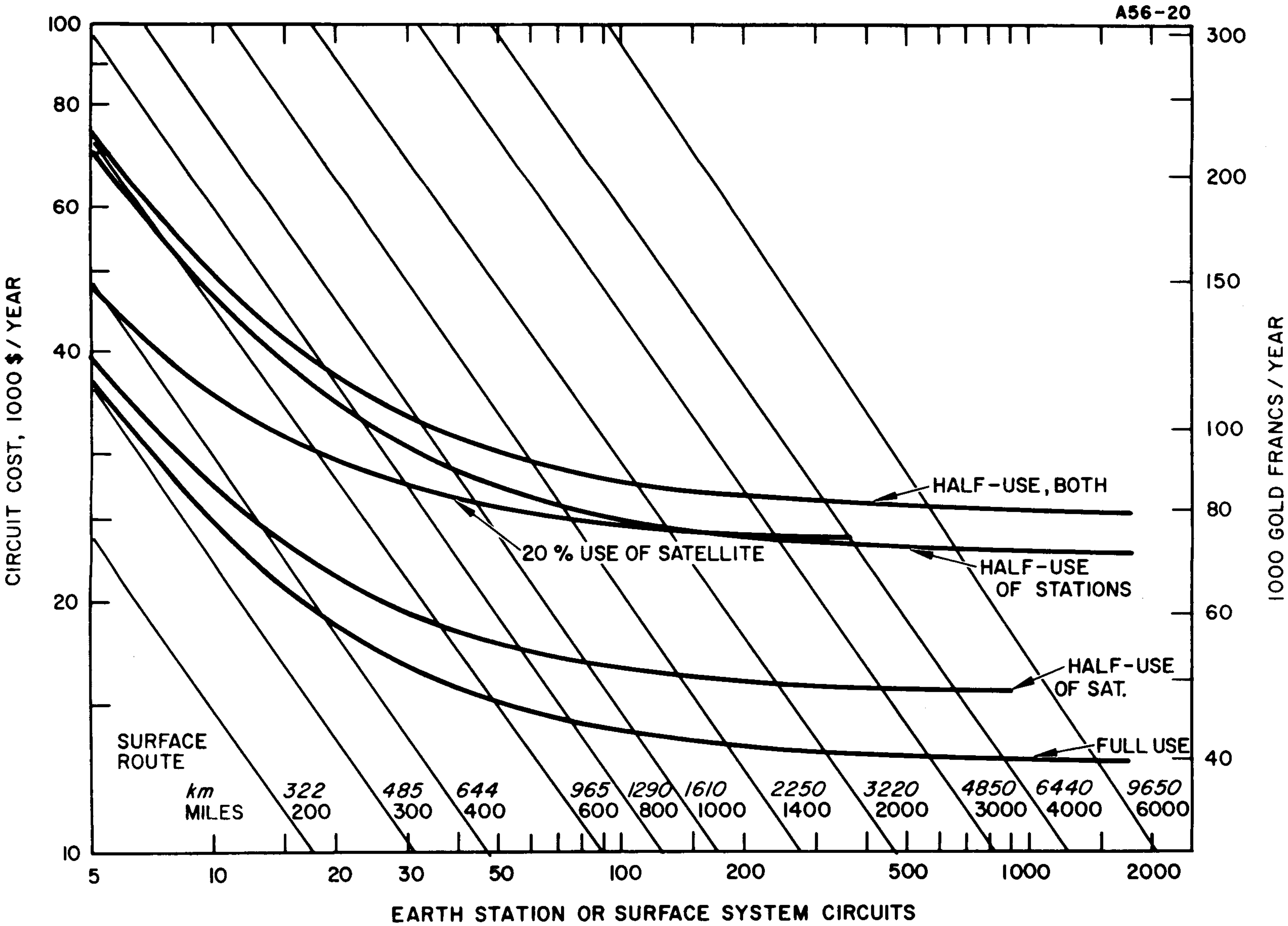

Fig. IV-7. Change in satellite circuit costs with fractional use of circuits – optimistic assumptions.

year per circuit would apply to a 10 circuit system only 400 miles (640 km) long, to a 60 circuit system 1400 miles (2250 km) long or to a 600 circuit system nearly 7000 miles (11, 000 km) long.

The top curve, labeled "poor" (smaller antenna stations) was calculated on the assumption that small stations be permitted to use smaller steerable antennas, with the satellite compensating for this reduction of earth antenna gain by carrying fewer channels per repeater. Specifically, it was assumed that the satellite capacity would be reduced from 600 to 120 circuits per repeater, thus raising the "probable" satellite use cost from $11, 040 to $55, 200 (33, 800 to 169, 000 GF) per circuit year. It was also assumed that the cost components for these stations with small steerable antennas would be T_o = $150, 000 and T_1 = $7, 000 per circuit, the same as the probable components for stations with large fixed antennas. This assumption seems overly favorable, in that two 30-ft steerable antennas with all their associated drive and tracking equipment certainly would cost considerably more than the one fixed antenna. However, use of the same values of T_o and T_1 facilitates comparison. This curve intersects the curve for stations with large steerable antennas at about $78, 000 per circuit year when both have about 39 circuits per station. Thus the "poor" stations would be advantageous only with fewer than 39 circuits, for which the cost would exceed $78, 000 per circuit year. This crossover cost would correspond to the circuit year cost of a 10 circuit surface system slightly more than 1000 miles (1600 km) long, or to that for a 150 circuit surface system nearly 6000 miles (9600 km) long. Clearly, under the conditions assumed, stations with small steerable antennas would be "poor" competitors to surface systems!

It should be recognized, however, that the surface circuit costs indicated by the diagonal trend lines are questionable for several reasons, some of which were discussed in connection with Fig. IV-4. They seem particularly questionable for few circuits over long distances. In particular, type N or ON carrier cable systems would not be satisfactory over routes longer than a few hundred miles. Similarly, open wire or cable voice frequency circuits would require the use of repeaters, and the cost of these does not seem to have been included in the curves of Fig. IV-4. Finally, the length of the surface route would exceed the distance between earth stations by a factor of roughly 1.5; a 2000 mile satellite hop corresponds to about 3000 miles via less direct surface circuits.

Subject to these reservations concerning the validity of the family of diagonal trend lines, another significant observation from Fig. IV-5 is that as the number of circuits per earth station decreases, the satellite circuit cost curves attain a slope equal to that of the surface system trend lines. For fewer than a given number of circuits a trend line for a given surface system length coincides (or nearly coincides) with each satellite circuit cost curve. This coincidence relation is termed the "equal capacity break-even." For the stationary-probable curve, it is seen that the break-even occurs for eight or fewer circuits and a surface route distance of about 700 miles (1120 km). For the optimistic curve, this break-even is at about 300 miles (480 km) for five or fewer circuits. However, if both stations must use steerable antenna systems, the nonstationary-probable curve shows that this equal capacity break-even occurs at about 1800 miles (2900 km) and with less than about 60 circuits. Although this equal capacity break-even appears useful for system comparisons, the costs per circuit year become excessive in this region. It would be preferable to use more circuits per station to lower the circuit costs.

Figure IV-5 is optimistic in that it assumes full use of all satellite repeater channels and all earth station circuits to the satellite. Full use would not be the normal situation or even an entirely desirable one. If the satellite channels were fully used, system growth would be halted until more or larger satellites were provided. Earth stations may have less need for reserve circuit capacity because it should be possible for them to add circuits, a few at a time, as they are needed. In any case, one should examine the effects of making fractional use of satellite and earth station circuit capacities.

Figures IV-6 and IV-7 show the extent to which partial use of satellite and earth station circuit capacity may increase satellite circuit costs and impair the break-even with surface communication. Figure IV-6 applies to the probable or near-future cost assumptions. It is obvious that use of only half the available circuits of the satellite and of both earth stations results in doubling the break-even distance relative to surface systems of given circuit capacity. If only half of the satellite's 1200 available circuits are used by all stations collectively, the 600 used must also carry the additional cost of the 600 idle circuits, thus increasing the annual cost per circuit used by $11,040 to $22,080 (33,800 to 67,600 GF). One notes that for very small stations having a high use cost per circuit, this increase is relatively slight. For large stations, however, it increases the cost as much as 43%. The remaining curve, for half use of stations with the satellite used to its capacity, shows that the small stations can least afford to be equipped for more circuits than they need.

Figure IV-7 applies to the optimistic far-future cost assumptions and tells a similar story, except for one interesting difference. The pie diagrams of Fig. IV-1, together with Table IV-1, show that the satellite use cost per available circuit should become relatively low. Consequently, it would become more important for stations not to over-install equipment for circuits not yet needed. The satellite could operate at half capacity, however, with relatively little increase in total cost per circuit; this would be especially true between small stations. In fact, the use of only 20% of the satellite's circuits would increase the cost about the same as if the two stations each had 150 circuits when they needed only 75.

The penalties on partial use of surface communication systems should also be considered. Their total use cost also must be distributed over the circuits used, not over their available circuits. Considering only the available circuits and assuming that all or some fixed fraction are used, the available circuit capacity of any given type of surface system can be varied considerably and the cost per circuit will decrease as the capacity is increased. This variation in circuit cost with circuit capacity was shown by the individual curves for specific systems in Fig. IV-4. The trend line in this figure tends to allow (approximately) for this capacity variation.

Whenever possible, instead of the trend lines, it is better to use the cost versus distance and number of circuits curve family for the type of surface system which would be in competition with a station's satellite circuits. This surface system would be used to points inside of the station's transitional boundary. The example illustrated in Fig. IV-8 assumes that this surface system is a thin-route system, such as voice-frequency open wire lines, and that its cost per mile is twice that given by the open wire curve of Fig. IV-4. The cost has been doubled, partly because these values from Fig. IV-4 seem lower than those experienced in practice, partly to allow for using repeaters on these long circuits, and partly to allow for the route distance being longer than the airline distance.

The curves for satellite circuits in Fig. IV-8 assume full use of satellite and earth station circuit capacities under the probable near-future cost assumptions. The upper satellite circuit curve applies when both earth stations are of equal size. One notes that this curve lies very close to that for the surface system covering 350 airline miles (560 km).

The lower satellite circuit curve in Fig. IV-8 applies when one earth station is a large 150 circuit station and the second is a small station having the number of circuits shown by the abscissa. The large station has an annual use cost of \$8,000 per circuit, only \$1000 greater than the minimum $T_1 = \$7,000$ of an infinitely large capacity station. Consequently, a satellite circuit between these stations costs only

$$\left[\left(\frac{150}{X} + 7\right) + 11.04 + \left(\frac{150}{150} + 7\right)\right] \times 10^3 \text{ dollars}$$

$$= \left(\frac{150}{X} + 26.04\right) \times 10^3 \text{ dollars.}$$

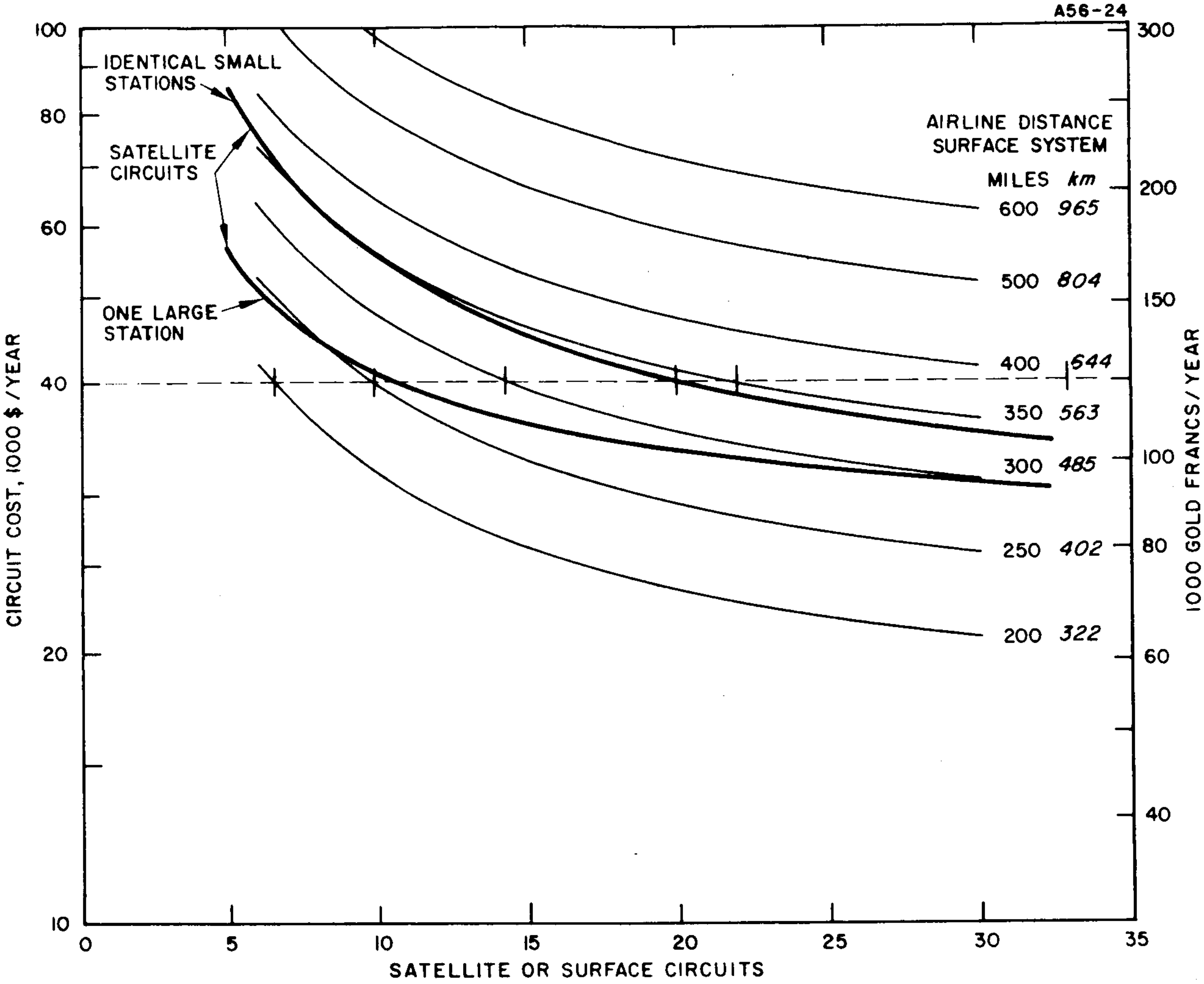

Fig. IV-8. Comparison of probable satellite circuit costs with those of a thin-route surface system, showing break-even conditions.

Clearly, from this curve, it costs less for the very small station to talk to a large one than to an equally small station.

From the upper curve of Fig. IV-8, one notes that a circuit between a pair of stations, each having a 20-circuit capacity, costs $40,000 per year. The destination of other circuits from these two stations is, of course, immaterial. The dashed $40,000 line intersects the surface system cost curves at various numbers of surface circuits, for example, 10 circuits for 250 miles. Each such intersection provides a point for a break-even curve; this curve is shown in Fig. IV-9. The companion curve, for circuits to a 150 circuit station at a cost of $33,500 per year, was plotted similarly.

J. Conclusions

The cost of a surface communication circuit is proportional to distance but decreases rapidly with the number of circuits required as was shown in Fig. IV-4. These characteristics have influenced today's circuit routing practices, favoring the use of heavy trunks. Multiple access satellite communication promises to be revolutionary because the cost of a one-hop satellite circuit is independent of the distance and of the number of circuits needed between any pair of earth stations. A station's use cost per circuit depends only on its number of satellite circuits and not on the circuit destinations. Thus, there will be a break-even (equal cost) relation between satellite and surface communication which, for any given satellite circuit cost, will be determined by the length and traffic volume of the surface communication system. Figures IV-5 to IV-9 showed that with a random access satellite system of the type assumed, i.e., one with a highly stationary high capacity satellite being used by many inexpensive (fixed-antenna) earth stations, the break-even distance relative to thin-route surface systems can become less than 1000 km. In relation to high capacity surface systems, however, the break-even may occur at much greater distances, exceeding the greatest distances within Western Europe or the United States. Thus, assuming that the satellite is efficiently loaded by the combined traffic of the many earth stations of a multiple access system, satellite communication should be of great use within those continents or large nations which do not have extensive high capacity surface systems.

The utility of multiple access satellite communication increases with the number of stations in the system, because each station then has a choice among more stations, one of which is closer to the subscriber to be called. Thus, relatively small light traffic stations are needed. These must have nearly as low use cost per circuit as the largest stations and must use the satellite efficiently in order to enjoy the same satellite use cost per circuit as the large stations. Reduction of the economic minimum circuit capacity depends on reduction of the station's

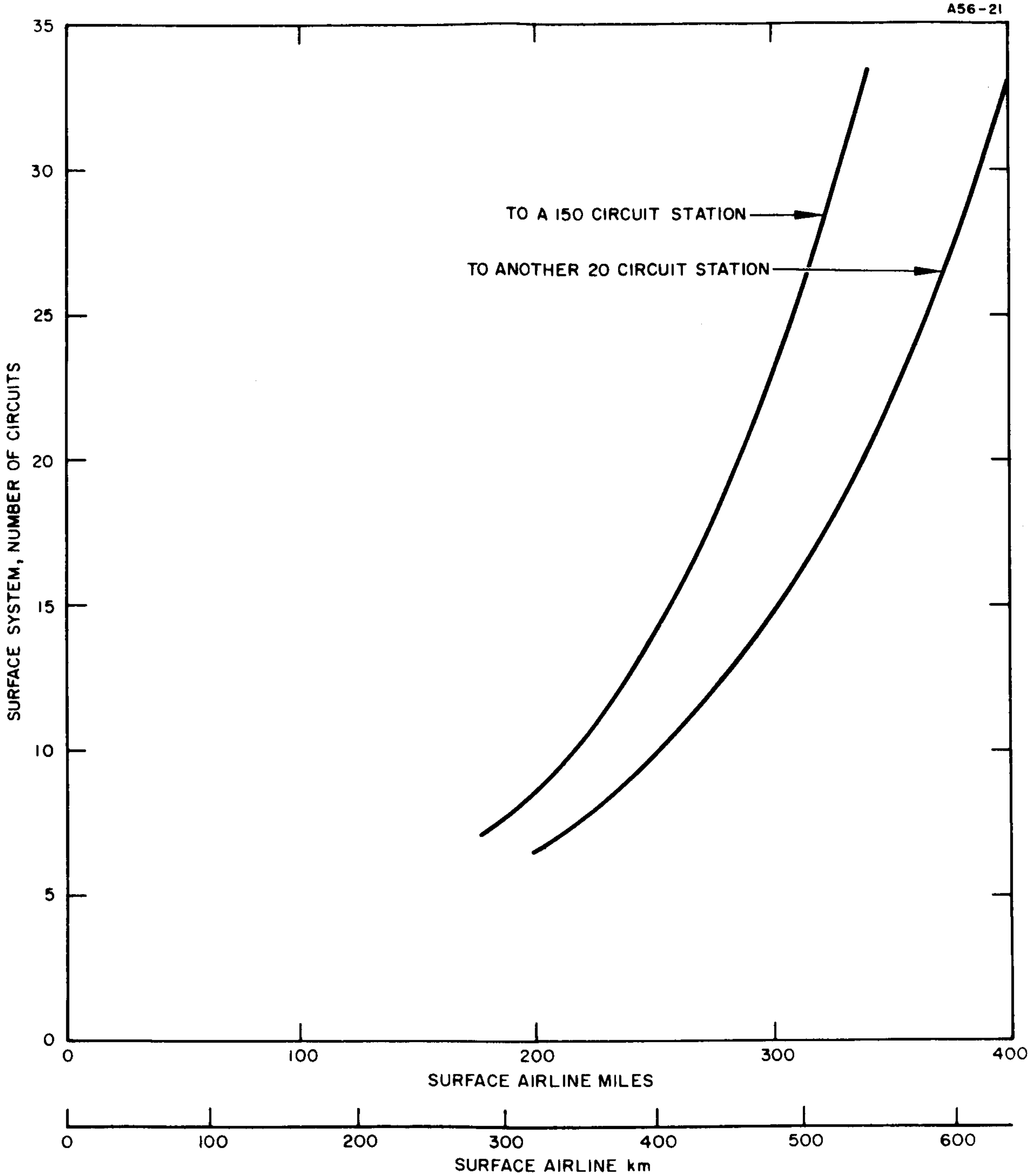

Fig. IV-9. Break-even distances relative to a thin-route surface system.

"no circuit" cost component T_0, whereas efficient use of the satellite prohibits reducing the antenna size (gain) as a means of reducing T_0. Consequently, large aperture fixed antennas must be used, as will be possible with an accurately stationary satellite. Demonstration of precision station keeping is needed to dispel present skepticism toward the installation of fixed antennas. Such a demonstration may be provided by NASA's Advanced Technology Satellite Program.

In addition, the realization of this multistation, multiple access satellite communication system, with greatest direct use to the greatest number of nations, will require further development and comparative test of laboratory simulations of several possible systems. However, the realization of such a system at an early date may depend even more upon the degree of interest and activity displayed by the telecommunication administrations of those nations which must still depend on HF radio circuits for long-haul communication. Studies applicable to national conditions should first be made, using methods such as have been developed in this paper. These studies will help to clarify the potential advantages and possible limitations of multiple access satellite communication relative to national needs. It is believed that these studies will show that multiple access satellite communication is urgently needed, that it can revolutionize international and intercontinental communication, and permit most nations to take a giant step toward strengthening their bonds with the rest of the world. More specifically, such studies may lead to revision of a nation's forecasts of long-haul communication requirements, recognizing that the CCITT PLAN Committee forecasts were constrained to continued use of surface communication techniques and practices. These nations then must make known their desire to use satellite communication, and their ability to pay for its use.

Random access satellite communication should be of greatest importance to areas of the world which still must use HF radio or expensive thin-route surface systems. In such areas stations will have small transitional boundaries and use satellite circuits to span shorter distances than would be the case in Western Europe or the United States. It thus seems probable to the writer that the collective traffic of many such stations would soon exceed the heavy North Atlantic traffic in its importance to operators of satellites. Today, however, revenue from this North Atlantic traffic seems certain and quickly available, whereas there is not yet any definite demand for this random access service, nor even any aggressive interest in it by those whom it should benefit the most. If such apparent apathy continues, those who must decide on the satellites and invest in orbiting them are likely to be guided by present traffic forecasts and concentrate on providing North Atlantic trunk service between pairs of large earth stations.

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