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MULTIPLE ACCESS SATELLITE COMMUNICATION

Final Report
Contract NASw-495

20 August 1962 through 20 August 1963

GPO PRICE $ ______

CSFTI ~~OTS~~ PRICE(S) $ ______

Hard copy (HC) 3.00

Microfiche (MF) .75

HUGHES RESEARCH LABORATORIES
Malibu, California

a division of hughes aircraft company

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Final Report
Contract NASw-495

S. G. Lutz

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I. INTRODUCTION

This report summarizes the work performed under NASA Contract NASw-495 from August 1962 to September 1963. The general objective of the program has been to study problems relating to future multiple access satellite communication systems.

In addition to the monthly progress reports, seven formal reports and two informal reports have been issued. Three additional studies were nearing completion at the time the contract ended. This final report contains brief discussions of the issued reports and more complete status reports on the three unfinished studies.

In general, the work performed can be classified within two categories: frequency sharing aspects and system aspects. Reports No. 1 and 2 discuss frequency sharing aspects, dealing specifically with ground antenna beam intersection with circular equatorial orbits and received satellite interference power from ground microwave systems. Reports No. 3, 4, 5, 6R, and 7 deal with system aspects and cover a range of topics: satellite coverage area overlap, 15 to 20 Gc frequency region considerations, calling techniques for multiple access, modulation systems considerations, and satellite ground antenna elevation angle distribution. The two informal reports covered an initial study of compandor considerations and a short report on recent European multiple access work.

II. REVIEWS OF PREVIOUS REPORTS

A. Frequency Sharing Aspects of Multiple Access

It is now generally recognized that common-carrier satellite communication will need 1 Gc or more of the microwave spectrum and that the allocation of such a large fraction of this already occupied spectrum would be nearly impossible, except by shared use of surface microwave communication bands. It is also recognized that interference-free sharing is possible today because no interference to or from experimental communication satellites has been observed. CCIR studies of frequency sharing have led to tentatively recommended power limitations on satellite and surface microwave transmitters and antennas. Unfortunately, these studies did not adequately consider the multiple access type of satellite communication systems, for which stationary satellites seem to have compelling advantages. In addition, the present CCIR recommendations do not make adequate provision for the preservation of sharing in the face of continuing growth of both methods of communication, nor do they permit sufficient increase in satellite transmitter power and antenna gain. If multiple access satellite systems are to be fully exploited, the CCIR recommendations must be improved at its next plenary session. However, any proposal toward better recommendations on sharing must be supported by thorough studies such as those undertaken in this program.

There have been different views of the role of satellite orbits in relation to frequency sharing. Interference to or from a nonstationary satellite would be most severe only as it passed through the beam of a surface microwave antenna. One group considers stationary satellites as "bad," because any microwave station having interference would always have interference. Others consider this "good," because most microwave stations <u>never</u> would have a stationary satellite in their antenna beam. Not more than one or two such stations would have a beamed-interference condition with any one stationary satellite — a condition which could be remedied by moving these stations slightly. Moreover, new stations should be located to avoid directing their antennas toward the stationary orbit. Thus, beamed interference with stationary satellites can be avoided, whereas with random polar orbit satellite systems such interference cannot be avoided.

Under this program, the frequency sharing studies have been directed toward (<u>Report No. 1) determining the antenna azimuth arcs of surface microwave stations which would permit beamed interference with satellites in any given circular equatorial orbit</u> and (Report No. 2 plus uncompleted work) refining the method of calculating the probable interference power at a satellite receiver from all microwave stations within its view and establishing the relative interference from the main lobes and various sidelobe groups of surface microwave antennas.

In early studies it had been assumed that microwave relay paths were horizontal and it had been recognized that, from any point on earth, any given circular equatorial orbit would intersect the horizon in (at most) two directions, equally displaced from due east and due west and dependent only on earth latitude and orbit height. An associated noncontractual study of microwave systems[1] showed that inclined microwave relay paths were rare but not negligible; two in California have inclinations near 5^{o}. Consequently, Report No. 1 included the surface microwave antenna beam elevation ψ in determining the orbit-intersecting azimuth angles. This report further recognized that, for interference study, the antenna beam could be approximated by a cone with "interference beamwidth," the width at which the gain of the actual antenna is reduced by a desired amount, such as 20 dB. A graphical method was presented for determining the azimuth arc beyond which no part of the interference cone, of specified width and elevation, from a specified latitude, would intersect a specified circular equatorial orbit. This method provides the microwave system designer with a tool for selecting routes to avoid beamed interference with circular equatorial satellites at any one orbit height. If used for the stationary orbit's height (22,300 miles), this method provides protection for all future stationary satellites placed anywhere around the orbit.

Report No. 2 relates to methods for calculating the interference to a satellite receiver from the many microwave transmitters to which it is exposed. It improves upon a prior method of analysis, which employed a microwave antenna beam shape correction factor of either $\pi/4$ or unity 1.0, by showing that the correction factor is a function of beamwidth 2β and orbit height and varies from $\pi/4$ at $\beta = 0$ to unity at $\beta = \pi/2$. This correction factor is obtained from an integral which has been evaluated by numerical approximation for certain orbit heights and is expressed as a curve family.

Calculations with such a correction factor have been used previously in predicting the power effectively radiated toward the satellite, but this method neglects the differences in path loss between the satellite and various earth locations. Consequently, a relation for the power reaching the satellite was derived in terms of a modification of the above integral. Values of this integral have been calculated for orbit heights of 6.61 earth radii (synchronous orbit) and 0.1 earth radius. Illustrative interference calculations using an antenna pattern approximation are included.

For the antenna pattern approximation used, these calculations showed (Tables IV and V of Report No. 2) that about 65% of the interfering power at the satellite would come from the beams of microwave antennas rather than from sidelobes. For some antenna pattern approximations this percentage was considerably higher. Based on the microwave station densities assumed, it was shown that this beamed interference probably would come from only one or two stations.

This report failed to consider the angular variation of gain of the satellite's antenna. Similarly, it did not examine the variety of antennas used in microwave relay systems, toward selecting and approximating an average antenna, and it did not elaborate on the uncertainty of estimates of microwave station and power densities or on the tremendous geographic variation of microwave densities. It was planned to cover these and other remaining aspects in a subsequent report. Problems of higher priority prevented completing this study. Its status at the time of interruption is summarized in a subsequent section of this final report.

B. System Aspects of Multiple Access

Report No. 3 dealt with an orbital aspect of multiple access systems, the overlap of coverage areas of two satellites as a function of their height and separation. An important requirement of most multiple access systems is that communication between any one station and all others in the system be interrupted (during hand-over to a new satellite) as seldom as possible. Random-orbit systems contemplate use of many satellites for this reason, even for paired-station operation, but always have some residual probability of interruption. Phased orbit systems (of which the stationary satellite is a special case) make continuous communication possible.

Considering a basic one-hop multiple access system, in which all earth stations in the system communicate among themselves through use of the same satellite at any instant (i.e., neglecting fractional hand-over, intersatellite relaying, and similar techniques of presently questionable practicality), continuity of communication requires simultaneous hand-over by all stations. Hence, both the setting and rising satellites must be visible to all stations at time of hand-over; all stations must be within the overlapping portion of the coverage areas of the two satellites. The exception is a stationary satellite system, whose coverage area is stationary, thus eliminating hand-overs and possible interruptions.

Report No. 3 analyzes the area of overlapping coverage as a function of (circular) orbit height, satellite separation, and earth antenna minimum beam elevation. Even with a medium altitude (10,000 miles) circular equatorial system of 12 equally separated satellites, the overlap area of continuous multiple access for 10^{o} minimum beam elevation is only 70.4% of that provided by a stationary satellite. This drops to 8.2% for twelve 1000 mile satellites and to 2.9% for three 10,000 mile satellites.

It is interesting to note that the "area of mutual visibility" is an older and more familiar concept than "coverage area" and was originated primarily for use with circular, inclined nonsynchronous orbit satellites. The area of mutual visibility is that area of the orbit-sphere (or of its earth projection) within which a satellite is visible to two (or more) stations having known locations. For simultaneous hand-over, two (or more)satellites must be within this area of mutual visibility, an area whose boundaries depend upon the station locations. Circular equatorial satellites only trace an equatorial line through such an area, while stationary satellites only occupy a point. The "coverage area" concept transfers the viewpoint from the stations to the satellite, this area being the earth-area visible from the satellite, and is extremely useful with stationary satellites whose coverage area is fixed. Additionally, its extension to the convenient means of determining the maximum area which can be occupied by earth stations of a one-hop simultaneous hand-over multiple access system is set forth in this report.

Report No. 4 is concerned with one aspect of the future of satellite communication, namely, the possible use of frequencies in the 15 to 20 Gc range. There are many reasons for interest in the eventual use of these or higher frequencies. Use of the lower frequency bands will eventually approach saturation, as has been true with all other forms of radio communication. The use of higher frequencies improves (eases) frequency sharing. Earth antenna directivity and gain improve with frequency, and certain new applications might become possible. It has been suggested, for example, that because a 20 ft reflector at 18 Gc could have the same gain as a 60 ft reflector at 6 Gc, these smaller reflectors could be used on buildings for "private" use of satellite communication by large international companies and similar customers.

Actually, as the report shows, even the free-space path loss increases with frequency at the same rate as fixed aperture antenna gain should increase, but may not. Surface irregularities of antenna reflectors create a "gain barrier" which, for today's steerable metal reflectors, occurs at about 60 dB, corresponding to an rms surface tolerance of somewhat less than a ten thousandth of the aperture. Surface tolerances need be reduced by three to obtain the theoretical 9.5 dB more gain from a 60 ft reflector at 18 Gc. This may be possible if rigid fixed reflectors are used with stationary satellites, but obtaining 68 dB gain from a fully steerable reflector at 18 Gc would be an expensive mechanical achievement. Thus, increasing the frequency does not, of itself, lead to smaller and less expensive antennas; it is often quite the contrary.

Absorption by atmospheric moisture becomes increasingly serious as the frequency is increased, probably becoming prohibitive in the vicinity of 25 Gc in the case of long (low angle) paths through heavy storms. Under clear-sky conditions, however, atmospheric absorption is not apt to exceed 3 dB, at frequencies up to 20 Gc.

Report No. 4 examines available information on cloud and rain absorption and concludes that, in many locations, storms may increase the atmospheric absorption by 25 to 35 dB, or even more, during the worst hour of a year, especially if the earth antenna's beam elevation is low. One cannot yet predict the time statistics of this absorption with any assurance, for many obvious reasons, even though measurements over homogeneous paths agree adequately with theory. To date there have not been sufficient measurements over extended periods, from a sufficient geographic sample of locations and under conditions applicable to earth stations. This absorption is a form of "fading," quite different from multipath (phase opposition) fading in respect to its mechanism and statistics. The familiar diversity techniques (frequency, space, and short-time diversity) would be of no avail. Geographic diversity would be helpful in regions having primarily local storms, but it would be expensive. Locating stations at high altitudes would put them above some of the atmospheric moisture, and the use of well-elevated beams will help by shortening the path through the atmosphere. Thereafter, however, the continuity and quality (S/N) of communication will depend on the amount of "fading margin" which one can afford to incorporate in the system, much as has been true with microwave relay and other radio systems. A major difference is the greater difficulty and expense of providing an adequate fading margin in a satellite system.

It was concluded that these higher frequencies may best be used for those satellite communication services in which quality degradations and occasional interruptions could be tolerated.

Report No. 5 was "An Introduction to Multiple Access Satellite Communication." It was written rather hastily in the hope that it would aid in preparations for the NASA Multiple Access Colloquium, originally planned for late February but finally held August 1-2, 1963. Additionally, the report was written as an introductory survey for the benefit of attendees who might not otherwise correlate and properly evaluate the more specialized papers which would be presented. Actually, this report was not distributed until after the Colloquium but some of its material was presented in the first paper on the program.

Since it is introductory in nature, the report attempts to unify known information about multiple access systems and, consequently, it does not attempt to add much to the knowledge about such systems. The breadth of its subject precluded any treatment in depth.

The report proposed a definition of multiple access satellite systems, which excluded two-station operation and "surface" multiple access. It distinguished between the assigned channel and random forms of multiple access, discussing the advantages and limitations of each and concluding that both should be used complementarily. Relative to the orbital aspect of multiple access, the simultaneous hand-over constraint was established as a constraint on the one-hop system area but not one which prohibits the use of nonstationary satellites. The advantage of the latter appears to be largely economic: ability to use inexpensive fixed antennas at earth stations, ability to cover 95% of the world's population with the first two satellites, etc. The stationary satellite's delay-echo problem should not preclude one-hop systems but may preclude two-hop circuits. However, such circuits are less needed than if lower orbit satellites were used, 17,000 km circuits being possible. The remaining 3000 km to the maximum possible distance on earth (i.e., between antipodes) generally could best be spanned by use of surface communication.

Possible multiplexing and modulation methods were discussed, with emphasis on economic random multiple access operation, with small stations in the system and simple satellite repeaters. Digital modulation, for example, may be essential for a military system but may be unattractive for common-carrier systems.

The discussion of random access use of multiple repeaters and multiple satellites is believed to be new and to have future importance. In general, it is better to use one repeater for random access, increasing its channel capacity as much as possible before adding repeaters or satellites.

Discussion of the economic limitation of calling over the communication channels of a full-random system served to introduce "party-line" methods of interstation auxiliary communication and the delay self-jamming problems of such methods, introducing the probable need for a "Channeling and Supervisory Center," formerly termed "Master Control," and discussion of its operation.

Since the economic aspects of multiple access will become more important than most strictly technical aspects, some of the simpler economic aspects were brought out; for example, the unique aspect of one-hop cost being independent of earth-distance, unlike all prior surface communication. Discussion of "fixed" and "per channel" cost components of earth stations showed that the economic minimum number of channels per station depends on the ratio of these two cost components. The use of steerable antennas to track nonstationary satellites leads to high fixed costs, requiring hundreds of channels per station, thus limiting the number of stations and excluding small ones. Stationary satellites permit the use of inexpensive fixed antennas, thus greatly reducing the fixed cost component and the economic minimum number of channels to within the needs and means of small stations and increasing the number of stations per one-hop system.

The report concluded with brief discussions of fixed antennas, frequency sharing aspects of multiple access, probable need for system simulation studies, and similar matters.

Report No. 6R considered the relative merits of multiplexing and modulation methods for random access satellite communication. It was considered that frequency division is preferable to time division multiplexing, at least for nonmilitary applications, although this view apparently is not unanimous. FDM, however, has become nearly universal in microwave relay and carrier telephone systems, whereas TDM would tend to become difficult and growth-limited in this long-delay multiple access application. Further study of the applicability of TDM, not yet completed, will be discussed in a subsequent section. Common-spectrum techniques were shown to combine the multiplexing and modulation functions and they are potentially interesting, especially for military applications. To date, however, they have not been sufficiently perfected and accepted for common-carrier service and it has not yet been established that the equipment cost would be competitive with that of FDM modems and filters. Consequently, further study was centered on FDM systems using FM, PCM, and SSB modulation.

The choice between these and other modulation methods depends both upon their relative use of power and bandwidth for the required signal quality (noise level) and upon their applicability to a random access satellite system, but chiefly upon the latter. Outstanding power-bandwidth advantages would be needed to outweigh a need for excessive signal processing in the satellite, higher satellite transmitter power, or excessive complication of the smaller earth stations. Nonetheless, this study concentrated on comparing the bandwidth power, and noise relations with these three modulations and examining their possible use in an illustrative reference satellite system.

Since a multiple access system should have both small and large stations, with from 12 to 600 channels, multichannel speech statistics and "loading factors" assume importance with all modulation methods. The Holbrook and Dixon peak to average multichannel speech power ratios (for peaks exceeded 1% and 0.1% of the time) were added to the CCIR channel loading factors (average power in dBm0 versus number of channels) to obtain peak composite channel loading curves. For 300 or more channels speech becomes noiselike, and both peak and average powers become proportional to the number of channels. For less than 300 channels, however, the composite speech peak power decreases more slowly, being almost constant in the case of peaks exceeded less than 0.1% of the time. The implication of this is that, unless these speech peaks are controlled somehow, small stations will be at a disadvantage. They will need nearly as great peak transmitter power (for SSB), peak frequency deviation, or quantization range (for PCM) as a 150 channel station.

Curves were prepared showing the relative transmitter peak power required versus number of channels, with SSB, FM, and PCM, both for 1% and 0.1% time overloading. The SSB curves were highest, as expected, but the unity-deviation ($\beta = 1$) FM curves were only 2 dB lower, though the bandwidth would be at least doubled. Larger FM deviation ratios led to power reductions as great as 20 dB, in the case of β = 10 FM with feedback, but with correspondingly increased bandwidth. The PCM curves assumed the digits per sample to be changed with the number of channels and that quantization noise would be dominant when $C/N \geq 12$ dB for the received signal. On this basis, the required transmitter power was similar to that for β = 5 FM for 200 or more channels. Unlike the other modulations, power continued decreasing with fewer channels, for which more digits per sample (hence more bandwidth) were used.

At the present state of the art, the power-for-bandwidth trade offered by FM or PCM is most advantageous for the satellite-to-earth link. However, since it would be difficult to convert from SSB or FM to PCM in the satellite, PCM would be required for both the up and down links, but its use in this manner would constrain random access operation in the FDM case. FM (or PM) is easier to generate in a simple satellite repeater, so is preferred for the down link. Moreover, unlike PCM, its trade of bandwidth for power can be reversed, when necessary. When more channels are needed, within the same rf bandwidth, and when more satellite power can be used, the frequency deviation can be reduced. SSB is preferred for the up link largely because of its multiple access advantage; it multiplexes the station transmissions at the satellite, so that the composite signal can be phase-modulated on a single carrier. SSB fails to trade bandwidth for power but its bandwidth, being a minimum, never would need be reduced. The use of SSB presents power, linearity, and other familiar problems, but it keeps these problems on the earth.

Report No. 7 very briefly examined the distribution of earth antenna beam elevation angles and the average elevation angle in one-hop stationary systems with many earth stations. Interest in this problem was stimulated by noncontractual study of designs for concrete antenna reflectors. The study first derived the average elevation angle, assuming a uniform distribution of stations over a no-ocean earth, of 33.92° when the minimum angle was 5°.

Recognizing that the satellite's location relative to continental areas and probable station locations could influence the average, station beam elevations for three illustrative systems were examined. Satellite stations at 50°W (Atlantic Basin), 67.5°E (Indian Ocean) and 180° (Pacific) were used, each with 20 to 31 stations. From these it was concluded that the average elevation angle is about 30°, with a geographic variation (with different satellite locations) of about $\pm 5^{\circ}$. These conclusions apply only with many stations per satellite.

C. Informal Reports

The use of compandors (speech compressors and expanders) can partly compensate for the inability to trade bandwidth for S/N improvement, or peak power reduction, in SSB systems and their use seems essential. Consequently, a preliminary study of compandors was undertaken but it was stopped short of completion. However, an informal report was issued which serves as an introduction to the problem. Calculations were given relating S/N improvement with companding ratio. Also, a possible approach toward development of instantaneous compandors was discussed.

Another informal report was issued summarizing the European multiple access work prior to January 1963. Information contained in this report was obtained by Dr. Lutz prior to attending the 1963 CCIR Plenary Session in Geneva. The report dealt primarily with British work because only they had devoted much effort toward systems of this type.

The system favored by the British employed FM up and down, with extensive signal processing being required in the satellite to re-multiplex its many received FM signals for single-carrier retransmission. Moreover, the system necessitated a differentiation between "small" and "large" stations, making it difficult for a small station to grow to a large one. The system lacked random access capability, had no Channeling and Supervisory Center and no apparent provision for interstation auxiliary (service) communication.

III. CALCULATION OF INTERFERENCE TO COMMUNICATION SATELLITES FROM MICROWAVE RELAY SYSTEMS BY USE OF IMPROVED COAXIAL CONICAL BEAM APPROXIMATIONS TO ANTENNA PATTERNS

A. Explanatory Comment

This report would complete and tie together the frequency sharing work of Reports No. 1 and 2, in establishing the feasibility and possible extent of interference reduction possible with circular equatorial orbit satellites by slightly restricting the antenna beam directions of surface microwave stations. Early studies, especially those for the U.S. Committee for CCIR Study Group IV, showed this basic method on a simplified basis and showed that the beamed interference to a stationary satellite from not more than one or two surface microwave transmitters would account for considerably more of the interfering power than that from the sidelobes of the thousands of other microwave transmitters in view of the satellite. Hence, it should be relatively easy to identify these few major sources of interference and to relocate them to correct the beamed interference. Thereafter, CCIR should recommend that new microwave systems be planned and routed to avoid antenna beam directions which would intersect the stationary orbit. Such planning would permit continued expansion of surface microwave communication, by ten or more times, without harmful interference to satellites. Conversely, and perhaps more important, this control of microwave antenna directions would protect microwave receivers from satellite interference, thus making possible an increase of about 20 dB in satellite effective radiated power. The present CCIR power flux density recommendation has the effect of limiting stationary satellites with earth-subtending antenna beams to a transmitter power of about 28 W, or only an order of magnitude greater than present satellite powers. Hence, this limitation will soon constrain the growth of satellite communication by preventing the use of more efficient modulation methods to increase their channel spectral density.

It seems essential that the CCIR recommendation be liberalized at the next (1966) plenary session because it will become increasingly difficult, probably prohibitively so, to liberalize it thereafter. Hence, studies such as this, and many others, are needed to convince CCIR representatives that the present recommendation can and must be modified if frequency-sharing is to continue and maximum use is to be obtained from both satellite and surface microwave communication.

B. Introduction

This study is concerned primarily with the geometric aspects of analyzing the undesired power reaching a satellite receiver, in terms of the earth-distribution of microwave transmitter power, approximations to typical microwave antenna patterns, type of satellite and orbit, etc.

The previous discussions of Reports No. 1 and 2 showed the background for this study and how the prior work had stopped short of correcting for the nose-shape of the satellite's antenna pattern or attempting to improve the cone approximation to microwave antenna patterns.

The present study is attempting to arrive at an antenna pattern approximation which will typify an average microwave relay antenna and then to use this pattern, with all the mentioned corrections, to determine the relative importance of beam and sidelobe interference components at the satellite's receiver. Additionally, the magnitude of this interference will be calculated for a range of possible present to far future microwave transmitter power densities, assuming a uniform global distribution of microwave stations. To date, our knowledge of the world distribution of microwave transmitter power, or even of the average power density, is inadequate — little better than a guess. An associated noncontractual study has shown that the world has some "hot-spots" of microwave power density, such as in certain Western European nations, Japan, and parts of the U.S., whereas many large but underdeveloped areas (such as Western Australia) have negligible power densities. Hence, it appears that the accuracy of satellite interference predictions can be improved by the use of microwave power density maps, from which the effective power density of each interference belt could be estimated more accurately, as will be explained.

C. CCIR Recommendations Relating to Frequency Sharing

CCIR has recommended allowable noise conditions on hypothetical reference circuits, both for microwave relay and communication satellite systems as summarized in Table I. It is interesting to note that the satellite reference is a one-hop circuit which can span as much as 17,000 km (assuming a stationary satellite) compared with only 2500 km for the microwave relay reference circuit; their noise allowances, however, take little account of this difference in length. The tolerable interference recommendations are also summarized in Table I; the interference powers are in addition to the allowable noise powers and are roughly 10% of the power or of the time.

TABLE I

Summary of CCIR Noise and Interference Recommendations (Recommendation numbers in 1959 "Green Books" or document numbers, 1963 Plenary Session)

	System	
	Microwave Relay	Satellite Communication
CCIR Hypothetical Reference Circuit	2500 km	one-hop
Source Reference — CCIR	Rec. 286 (1059)	Doc. 2087
Noise power at point of zero relative level in any telephone channel:		
Source	Rec. 287	Doc. 2273
(a) psophometrically weighted, mean in any hour	7500 pW	10,000 pW
(b) psophometrically weighted, one-minute mean, 20% of any month	7500 pW	10,000 pW
(c) psophometrically weighted, one-minute mean, 0.1% of any month	47,500 pW	—
(c') psophometrically weighted, one-minute mean, 0.2% of any month	—	80,000 pW
(d) unweighted (5 msec integrating time), 0.01% of any month	1,000,000 pW	—
Additional noise, intersystem interference:	satellite to surface	surface to satellite
Source	Doc. 2222, 2214	Doc. 2284
(a) psophometrically weighted, mean in any hour	1000 pW	1000 pW
(b) psophometrically weighted, one-minute mean, 20% of any month	1000 pW	1000 pW
(c) psophometrically weighted, one-minute mean, 0.01% of any month	50,000 pW	—
(c') psophometrically weighted, one-minute mean, 0.02% of any month	—	80,000 pW

Additionally, Doc. 2247 recommended that surface microwave relay transmitters not exceed +13 dBW (20W) fed to the antenna or +55 dBW equivalent radiated power. Document 2291 recommended that satellite transmitters and antennas be such that, at the earth's surface, the power flux density of a wide-deviation FM signal not exceed $-130\ dBW/m^2$ nor the spectral density $-149\ dBW/m^2/4$ kc, and that with other signal modulation (such as SSB) the spectral density not exceed $-152\ dBW/m^2/4$ kc. The interference power recommendations of Docs. 2214 and 2284 are the primary ones, whereas the recommendations of Docs. 2247 and 2291 are "derived" ones, whose observance should satisfy the primary recommendations, at least for the immediate future.

The values of these "derived" recommendations actually were not derived (in any adequate manner) from the primary ones. Rather, these values seemed sufficiently reasonable for unanimous approval, whereas some delegations opposed values which would have been more favorable to satellite systems. Clearly, if both satellite and surface microwave communication were to grow without control, there would be some microwave power density which would cause harmful interference to satellite receivers. Similarly, too many satellite transmitters, collectively, could cause harmful interference to surface receivers. We certainly should know the approximate levels of use at which harmful interference may occur, according to present recommendations, and how best to modify these recommendations for the preservation of frequency-sharing in order to make fullest use of both satellite and surface microwave communication.

D. Assumptions Concerning Microwave Relay Systems

Except as noted subsequently, it will be assumed that

1. The earth is covered uniformly with microwave transmitters which (collectively) radiate white noise of p W/Mc bandwidth/$10^6\ km^2$ of the earth's surface.

2. All microwave paths are horizontal and uniformly distributed in azimuth.

3. All microwave antennas will be assumed to have a 3-m aperture with "good" sidelobe patterns which can be approximated by a coaxial family of conical beams, as will be discussed later.

4. The main beams of these antennas are directed at the horizon so that the upper half of the pattern is radiated into space. The lower half of the pattern is perfectly reflected by the earth except for the lower half of the main beam being perfectly absorbed.

5. Atmospheric absorption and refraction are negligible.

6. Coupling, polarization, and miscellaneous losses total 5 dB.

7. The use of overhead passive reflectors is neglected, except as it is discussed separately.

The first of these assumptions is a convenient oversimplification, as previously explained. Assumptions 2 and 3 have been justified by independent noncontractual studies of typical microwave systems. Assuming the lower half of the beam to be absorbed and lower-half sidelobes to be perfectly reflected seems more reasonable than the prior assumption of reflection of the entire lower half of the pattern.

E. Approximations to Microwave Antenna Patterns

The use of coaxial cone or "keyhole-shape" approximations to microwave antenna patterns is well established, although prior use has been of envelope keyholes to approximate the worst interference case. Use of envelope approximations becomes unrealistically pessimistic when considering the total interference from many such antennas. In the latter case, the total power radiated through an enclosing sphere by the approximated pattern should be the same as that radiated by the actual pattern and the same as that from an isotropic antenna. An antenna cannot generate and should not absorb power. Consequently, all antenna approximations were adjusted to "unity total gain."

Actual antenna patterns are not figures of revolution about the beam axis but only the horizontal and vertical (or E and H plane) patterns generally are measured, and sometimes only one of these. The two orthogonal patterns may be quite different. A visually good keyhole approximation to one of these patterns may have greater than unity total gain, whereas the companion approximation would have less than unity total gain. Consequently, when orthogonal patterns were available they were superimposed and the keyhole approximation was made in relation to both.

The main lobe sector of a keyhole approximation generally is the major contributor to the total gain, and the unity gain adjustment could be made to this sector with the least apparent change. However, the measurement accuracy of the main lobe generally is the best, in addition to its interference contribution being the greatest. Consequently, the main-lobe sector was determined as accurately as feasible and only sidelobe sectors were changed in making the unity-gain adjustment. By comparing the nose shapes of many patterns it was determined that the width of equivalent conical beams (same maximum gain) varied negligibly from the 4 dB width of the actual beams.

The patterns of a considerable variety of microwave antennas have been studied, as listed in Table II. Chiefly, these have been those used in extensive common-carrier microwave systems, rather than the smaller and less expensive ones used in "private" systems serving pipelines, electric power systems, etc., and not operating in the 4 and 6 Gc common carrier bands. It has been concluded that a typical "average" antenna in common-carrier service is a 3-m parabola, with no far-sidelobes having positive gain. The Telefunken 3-m parabola has tentatively been chosen as typifying this average. About half the antennas in use appear to be better (e. g., horn-reflectors, shell and shielded parabolas), while half seem somewhat poorer (e. g., simple 6 ft and 8 ft parabolas). Figure 1 shows the superimposed patterns of this antenna and its keyhole approximation.

TABLE II

Antennas Studied

Company and Designation	Type	Frequency, Gc
Telefunken, Ps 1.75	Parabola	2.2
Telefunken, Ps 3-4/1	Parabola	4.0
Telefunken, HP 3.7/3 - 4/2	Horn	4.0
Telefunken, Pe 3/3 - 4/1	Shell	4.0
Telefunken, no designation	Parabola	4.5
Bell, no designation	Horn	2.39
Bell, no designation	Horn	3.74
Nippon T & T, 1U5	Shielded Parabola	4.0
RCA, MM600	Cassigranian	6.17
Andrews, RCA - WU No. 1	Parabola	6.225

F. Effect of the Satellite's Antenna Pattern

It is assumed that the satellite will employ earth-directed beams and will have a 3-dB width equal to the angle subtended by the earth. Hence, this antenna will have its maximum gain only toward the subsatellite point and will have 3-dB lower gain toward the beamed interference belt around the satellite's earth horizon. More generally stated, this antenna gain will be a function of the earth angle from the subsatellite point, or of the earth angle from the horizon.

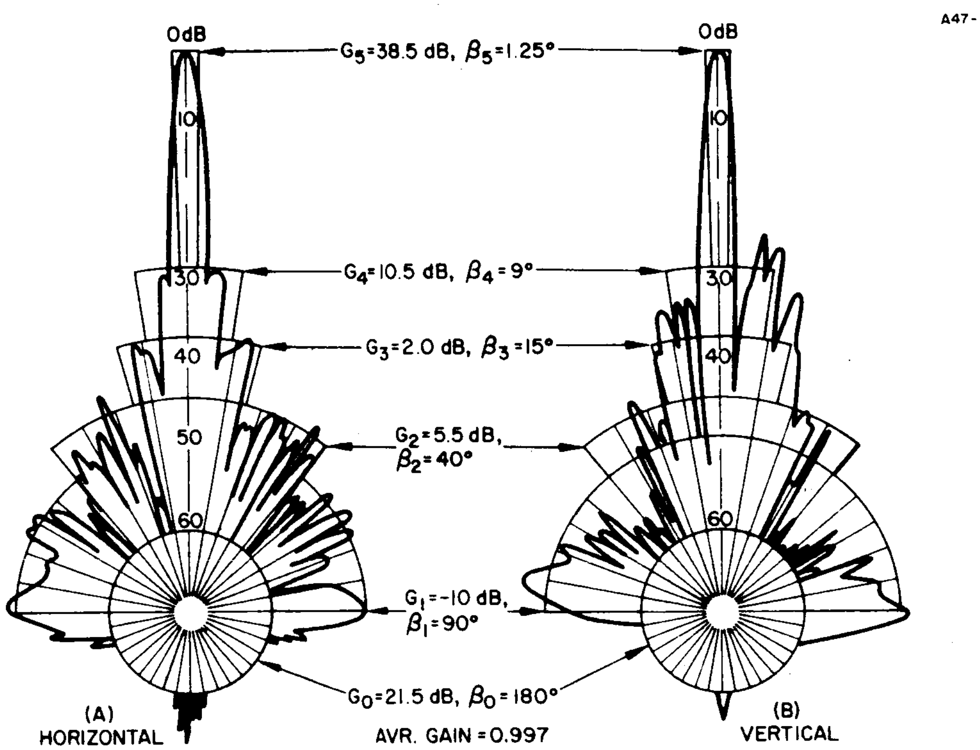

Fig. 1. Segment approximation to a typical 3-m parabolic antenna pattern at 4 Gc.

An empirical equation has been selected to fit the nose of a satellite antenna pattern of typical shape, expressing the reduction from full (axial) gain as a function of the earth-center angle from the subsatellite point. This gain reduction is being combined with the path loss variation and the earth antenna beam shape correction to obtain a new function of the interference belt width $F(\beta)$, whose use will be similar to that of eq. (21) of Report No. 2 but will include the satellite antenna gain correction. Shortly after it had been decided to include this correction, other more urgent work caused this study to be interrupted. Consequently, the new $F(\beta)$ has not yet been tabulated and used.

G. Effect of Geographic Variation of Microwave Power Density

In prior work, a uniform distribution of microwave power density has been assumed, even though it has been recognized that a stationary satellite in one location could be exposed to a much different effective density than from another location. For example, a satellite at 100° W would have its beamed interference belt passing almost entirely over oceans and arctic land, with practically no microwave transmitters in this belt; hence there is a negligibly low probability that there will be any beamed (full gain) interference. There would be other locations for which this belt passed through "hot spots" of high power density, such as Western Europe, the Eastern United States, or Japan. Similarly, the relatively broad sidelobe interference belts may have considerably different effective power densities, depending on land areas which they include. Consequently, it should be possible to improve satellite interference predictions significantly whenever we know enough about the global distribution of microwave power densities to prepare density maps. With such maps, one could estimate the effective density within each belt, allowing for oceans, underdeveloped areas, etc. Figure 2 shows illustrative interference belts superimposed on a (hypothetical) microwave power density map. The density shading of this map is not based on power density statistics or forecasts because these are not yet available.

Efforts are being made under a noncontractual program to obtain microwave power density data from a representative number of nations. These data should provide a better basis for estimating the average power density. Prior density estimates have been based on United States microwave systems alone. To date, data have been obtained from Japan, Australia, England, Germany, Sweden, Spain, Portugal, Canada, and Argentina, but data reduction and preparation of a report has been interrupted by the pressure of other work. It is hoped that this study of the geographic distribution of microwave power density will eventually be taken over by a suitable international organization and that useful density distribution maps will be issued.

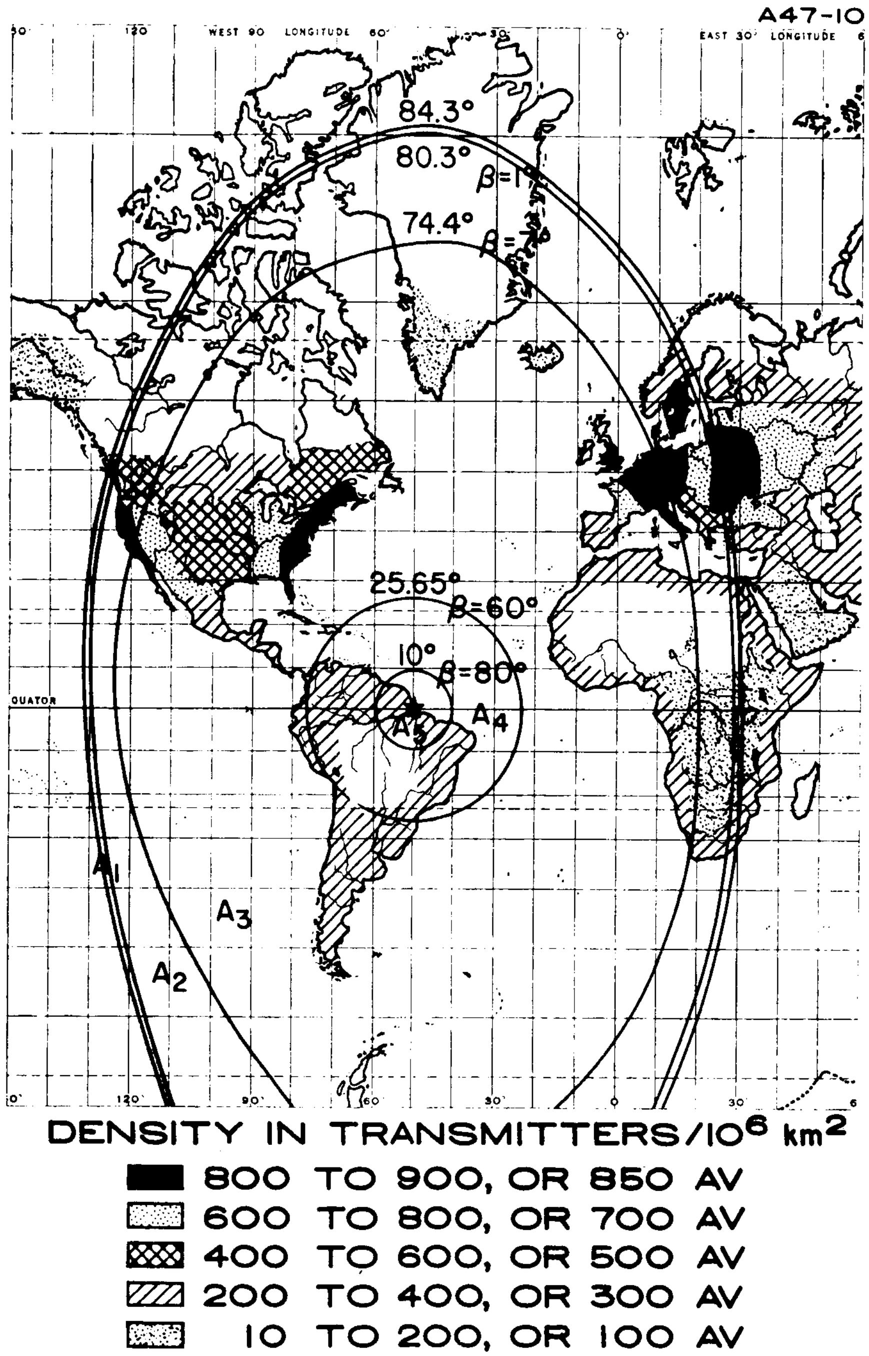

Fig. 2. Hypothetical microwave power density map for Atlantic satellite.

H. Concluding Phases

The objective in completing this study will be to forecast the probable future of frequency sharing, primarily in relation to interference to and from stationary satellites, using the accurate method developed in this study. It is expected that use of realistic present values of satellite characteristics and microwave power densities will further confirm that there should be no harmful interference at the present time. However, some yet unknown increase in microwave power density will bring the interfering power at the satellite up to a harmful level. Assuming, then, that the directions of microwave antennas are controlled to suppress gain toward the satellite by, for instance, 20 dB below maximum, there will be some greater just-interfering level of microwave power density. The dates at which these conditions may occur will depend upon even less certain forecasts of the rate of increase of microwave power density. Hopefully, this density increase will tend to flatten off with the growth of satellite communication and with shortening of the break-even distance for surface versus satellite communication.

IV. TIME-DIVISION MULTIPLE ACCESS SYSTEMS

A. Explanatory Comment

At the June briefing to NASA representatives on this study program, the discussion of multiplexing for multiple access emphasized frequency-division and tended to dispose of time-division possibilities as being "obviously" too difficult and noncompetitive. NASA representatives expressed the opinion that we had tried to "bury" time-division without an an adequate death-certificate, and that there were many who consider time-division systems to be still very much alive. Consequently, we were requested to make a more thorough study of the possible capabilities and limitations of time-division systems.

The Multiple Access Colloquium in August contained several papers which have helped to clarify the nature and status of work on time-division systems at other laboratories. Additionally, discussion with representatives of RAND have been helpful in orienting this study.

Portions of this study deal with propagation aspects, such as the predictability of delay differences and the probable shape distortion of very short pulses. This portion of the work is credited largely to Larry Miller, a student employed during the summer.

This study had not been completed at the time the contract ended, but the following status report seems reasonably comprehensive and conclusive. Most aspects seem sufficiently clear that little additional study is recommended.

B. Introduction

In a cursory consideration of possibilities for time-division multiplexing of PCM or Delta modulation for multiple access satellite communication, one recognizes that pulse widths may be of the order of 50 nsec, while the propagation delay between earth and a stationary satellite will be between 0.12 and 0.14 msec, or more than 10^9 times as great. In many prior applications of frequency division, such as for multiplex telegraphy, propagation delay has been less than the pulse period. This, and similar reasoning, has led to some premature predictions that a satellite system's synchronization and timing problems would be prohibitive. One could apply similar reasoning to a SSB-FDM system, using 4 kc voice channels at 6 Gc and obtain a comparable ratio. Clearly, quite a broad study of the pros and cons of TDM and FDM systems is needed to predict which system should be best. Even the term "best" needs to be defined in terms of system requirements, as will be attempted in this summary report.

C. Analog versus Digital Information and Modulation

Information to be transmitted may be of "analog" form (voice, television, voltage sensor, etc.) or "digital" (teletype, computer data, etc.). Analog information may be quantized and converted to digital modulation such as PCM or Delta, if sampled at least twice its highest essential frequency. For example, voice has essential components up to 3 kc, so it must be sampled at least 6000 (generally 8000) times per second. If each sample is quantized into $2^7 = 128$ levels, each such level can be specified as a seven-digit binary number. PCM transmission entails using a pulse position per binary digit (hence 7 x 8000 = 56,000 pulse positions/sec), requiring about 56 kc of bandwidth on a reciprocal pulsewidth basis, more than 18 times the 3 kc voice bandwidth. Actually, normal seven-digit PCM has too much quantization noise to comply with CCIR recommendations, and instantaneous compandors (or nonuniform quantization) are required for common-carrier service. With uniform quantization, about 11 digits per sample is needed to achieve CCIR quality, but correspondingly greater bandwidth is required.

The importance of this greater bandwidth required for digital transmission of analog information depends considerably on the application, as will be discussed later. The present reason for distinguishing between analog and digital modulation is that FDM is "natural" for the former, whereas TDM generally has been used with digitally modulated information. To the best of our knowledge, proposals to use TDM in multiple access satellite systems contemplate that telephony be digitalized, although many TDM proponents try to change the subject of digitalization when television is mentioned! In contrast, an FDM system can carry digital signalling on frequency channels of adequate width, or possibly two channel groups (24 "telephone" channels) for an eleven-digit PCM voice signal.

D. Information Carried by Common Carrier and Military Satellite Systems

Security against intelligible interception rates high among military system requirements for obvious reasons and is considered impossible to achieve <u>except</u> with digital cryptographic techniques. Analog "speech scramblers" confer privacy against casual eavesdropping but are incapable of military-grade security. Similarly, PCM and certain other pulse modulation methods confer a degree of privacy, but not security, since the latter results from secure encryption and cannot be provided by only a normally unintelligible modulation method. This and related arguments make an all-digital TDM satellite system attractive as a military system.

Parenthetically, one notes that most military telephony has been (and still is) insecure analog telephony because of the many "costs" of PCM circuits; in addition to their dollar costs, broad-band circuits generally have not been available. For those few conversations of sufficient importance, cryptographic voice security has been achieved over normal voice-bandwidth circuits by voice bandwidth compression techniques such as a vocoder with digitalization, followed by encryption. Such systems are not only complex and expensive but many users find the speech unnatural and difficult to understand. Satellite communication seems to offer the possibility of uncompressed PCM voice circuits at militarily reasonable costs. Consequently, military satellite systems with all-digital signalling have been studied and proposed by many companies. A considerable number of the papers at the recent NASA Colloquium seem to have arisen from such studies, although their authors did not state that this was indeed the case.

One speaker aroused considerable interest and discussion by the observation that satellite communication would have "unprecidented exposure" in that anyone (owning a suitable earth station) could listen in on hundreds, and soon thousands, of international conversations, but that such would not be the case with a PCM-TDM multiple access system. Actually, the "exposure" of HF radio channels has existed for over 30 years, with exposure of more channels to anyone interested enough to buy a relatively inexpensive "all-wave" receiver. "Privacy" from this casual-type of interception has been provided readily on common-carrier circuits by the use of simple speech-scrambling equipment. Satellite systems should provide <u>less</u> exposure of this type because expensive earth-station equipment and a very conspicuous antenna are needed in order to listen to any one satellite channel. Moreover, dozens or perhaps hundreds of operators would be needed to monitor adequately all channels of a random-access satellite system, even when using recorders. The use of PCM-TDM, without cryptography, would offer no protection against such an organized intercept effort. In a common-carrier system only a small fraction of the traffic would be sufficiently sensitive to justify the cost and troubles of its encryption. Moreover, its being encrypted would tag it as probably being worth recording and studying.

Considering a common-carrier FDM system which provides its users with special channel widths in multiples of telephone channel widths, the few users who need cryptographic security can obtain it by taking (and paying for) a block of channels which otherwise could have carried more telphone calls between parties unconcerned about exposure. The TDM system using PCM (or other digital modulation) requires all telephone users to pay for the digital modulation and lets the security user pay only the additional increment for his cryptographic service. Of course, the strength of this argument depends on the relative cost per telephone channel of the two systems and would be greatly weakened if the basic telephone channel in the PCM-TDM system were nearly as cheap as those in a comparable FDM system. Clearly, however, the "exposure" threat alone does not justify a PCM-TDM common-carrier system but probably does justify all-digital military satellite systems.

Henceforth common-carrier service will be assumed, with only such military communication service as the common-carrier might normally provide.

E. Timing and Synchronization

In discussing multiple access it is useful to distinguish between timing and synchronization. Timing refers to the location and control of the transmission time-slots of the various stations and of the guard-slots separating them. Synchronization refers to the ability to separate and correctly interpret the digit groups for each channel, during each station's transmission.

Heretofore, with TDM transmissions from a single source, it has been possible to carry synchronization through the entire sampling-time cycle. Synchronization need be established and corrected only at the beginning of the cycle. With multiple access transmissions from several earth stations, having different and changing propagation delays, the guard-slot widths (i.e., "timing") separating these transmissions may vary so much as to disrupt synchronization. Consequently, synchronization may be re-established at the beginning of each station's transmission.

1. Random versus Assigned Access with TDM

A TDM system in which each station has only one time-slot in the cycle but uses the time channels of its slot for tranmissions to one or more other stations is the analog of an FDM system having groups of adjacent transmitting frequency channels assigned to each station. Unfortunately, all stations do not generally use all of their channels at the same time; their traffic peaks are not simultaneous. Consequently, for better use of the system's capacity, it is desirable to reassign idle channels to stations which temporarily need more channels. With TDM, the station slot widths might be changed periodically for this purpose, but this requires "sliding" many channels which are in use, with obvious complications, as also is true with FDM systems. The fullest utilization of FDM channels can be achieved with "full random" multiple access, with which a station may be assigned any transmitting channel, call by call. The TDM analog would have time slots for each channel, any of which would be used by any station, as needed. Each station might transmit in several scattered time slots. Clearly, doing so would further complicate the timing and synchronization problems, possibly to a prohibitive extent. Insofar as known, such full-random TDM systems have not been seriously proposed for common-carrier satellite communication, whereas full-random FDM systems have received intensive attention. Consequently, subsequent discussion will assume assigned channel multiple access, each station having its individual time slot in the cycle.

2. Timing in TDM Systems of Increasing Complexity

The degree of propagation delay uncertainty has been studied and presents one possible constraint on TDM system timing. It will be shown that the importance of any long time delay uncertainties can be diminished arbitrarily by adding various system refinements. We will start with a "too simple" system in which relatively large time guard slots are used to separate the transmission periods of successive stations. Such a system would have fixed station transmission periods separated by fixed guard slots, the latter being long enough to allow for all probable delay differences, including the relatively large difference related to the station location. Considering station location alone, the one-way delay would vary from 120 msec at the subsatellite point to 137 msec at the 5° coverage limit, for which differences one might choose a 200 msec guard-slot, per station, if using a simple long-cycle, printed message only, type of system. However, for digital voice sampled at 8 kc, and without storage for bursts of many such samples, the complete transmission cycle for <u>all</u> stations should have this 8 kc sampling rate, thus ruling out 200 msec guard slots! One has two paths toward remedying this difficulty: narrow these guard slots drastically by better use of delay information and/or lengthen the multiplexing cycle to many times the sampling period. The latter course required storing, transmitting, and subsequently spreading correspondingly many sample digit groups per channel for each transmission, thus introducing obvious complications and costs. Consequently, the remaining course will be examined.

One first might refine the propagation delay difference information to account for the dependence of path length or the station locations and for the predictable deviations of the satellite's position. Doing so would shrink the guard slots to a width sufficient to accommodate the delay variations of propagation through the earth's atmosphere and ionosphere, plus those caused by unpredicted variations of the satellite position. The near-earth delay variations are predictable to a degree which is dependent on knowledge of meteorological conditions, electron density in the ionosphere, etc. A subsequent section will examine the probable maximum magnitude and the predictability of these near-earth delay variations. Also, the effect of satellite position variations will be discussed. It will be seen, however, that even these smaller delay differences would necessitate objectionably large guard slots.

Perhaps at this point one considers an adaptive system, one in which the system timing would adjust itself to follow these relatively slow delay changes, after all stations have been timed in and are operating.

For example, when a station sensed shrinkage of the guard slot preceding its transmission it would delay the start of transmission sufficiently to restore the guard slot to normal width. Ideally, such a system should need guard slots just larger than the maximum delay-change which might occur during the time required to observe the effect of its previous delay correction, namely the propagation time to and from the satellite, 280 msec or less. Delay changes over so brief an interval should be negligible. As a further refinement toward the total elimination of guard slots, the signal coding could be made tolerant of errors occurring at the beginning or end of the transmission period.

From this discussion one concludes that long-term unpredictability of delay has an importance which can be decreased arbitrarily by refining (complicating) the TDM system with adaptive timing. Only with nonadaptive timing would the guard slots need to allow for long-term unpredicted delay changes. Nevertheless, it is desirable to examine the magnitude of delay changes to be expected, if for no other reason than to design an adaptive timing system capable of accommodating these changes. Additionally, there may be delay-difference problems in starting a TDM system.

3. The "Last Station" Timing Problem

We next consider the start-up of such a system, assuming that before each station can transmit it can predict its delay difference only from normal delay within some comparatively large increment S, which is large compared with the minimum transmission periods and hence much larger than the guard slots. The possible range of unpredicted delay differences under various assumptions is discussed in a subsequent section. It will be assumed that the stations start and time in sequentially, as indicated in Fig. 3. First in (a), station #1 starts at some relatively large time $T > \delta$ after the cycle start reference, then advances its transmission up to the start reference as shown in (b). Thereupon, station # 2 starts, using a correspondingly large delay from the end of station #1's period, then advances its timing to close the guard gap. This continues until station #N-1 has timed-in and a gap remains which is just long enough for the last station's period. However, this last station has no $T > \delta$ left with which to time in. Its initial timing should be nearly perfect, or else it will overlap and temporarily jam part of the periods of its neighboring stations.

Actually, this last-station timing problem has several possible solutions. For example, we can let #N be the largest station, needing the longest period in the cycle, and assume that its period is greater than twice its initial delay uncertainty δ. It can start by transmitting pulses when predicted to arrive at the center of its period, knowing that this trial position may be in error by $\pm\ \delta$ without causing interference. Another obvious possibility would be for # N to time in on a separate channel. Unfortunately, since pulse width determines the channel width,

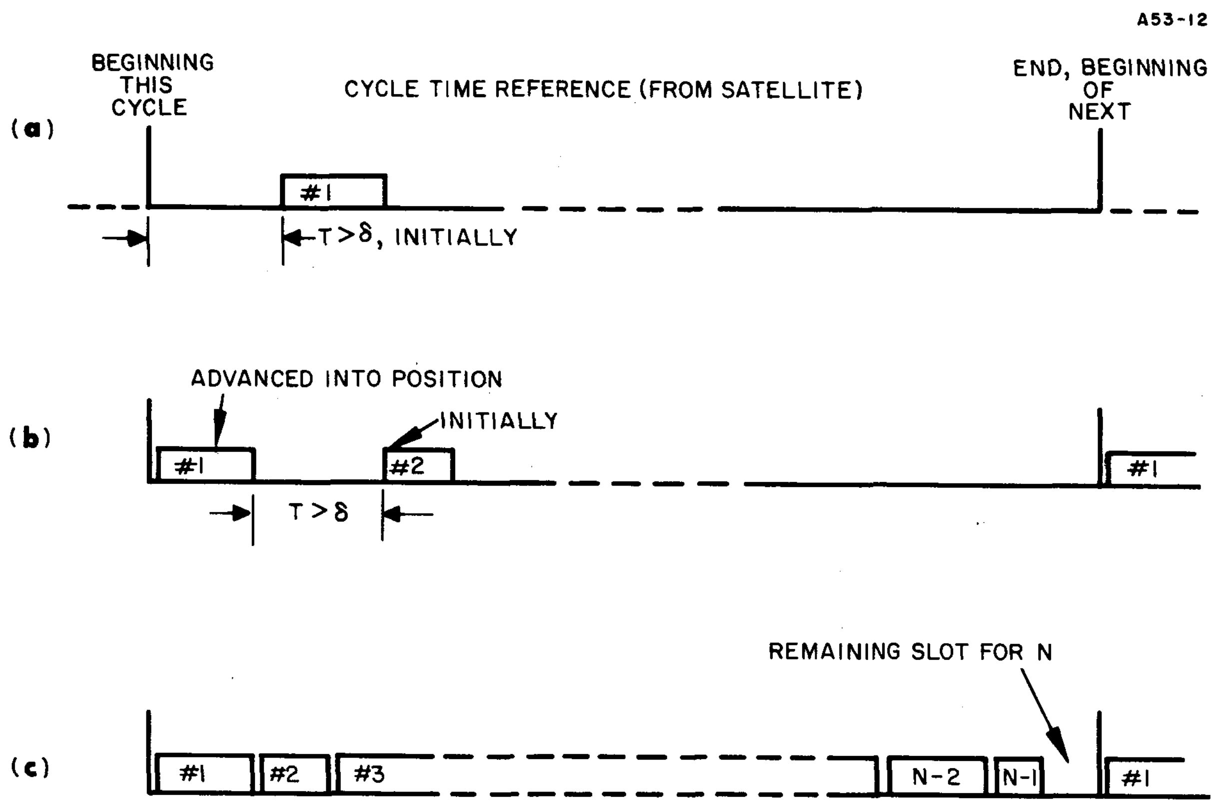

Fig. 3. "Last-station" problem.

this separate channel should be as wide as the regular channel. Also, it is probable that the system would not start carrying traffic until this last station had timed in, or that the interference it might cause in timing in would be tolerably brief.

In summary, it is concluded that TDM systems probably can "buy their way out of" this type of delay-difference timing difficulties for an undetermined increase in system complexity and cost.

F. Atmospheric Time Delay Variations

1. Tropospheric Effects

The increase in propagation time through the troposphere is caused by the tropospheric refractive index being slightly greater than one. This phenomenon has been extensively investigated with regard to radar range errors. Unfortunately, in the radar problem average values of propagation time are of concern rather than peak deviations a certain small percentage of the time. For any TDM satcom system, allowances must be made for the peak timing variations rather than the average. Therefore, published data regarding radar range errors cannot be used directly.

It can be shown that the propagation delay in clear weather is given by

$$\tau_1 = \frac{2.45\ P}{T} + \frac{67 \times 10^3\ e^{0.066T}H}{T^2} \qquad (1)$$

where

$P \equiv$ atmospheric pressure in millibars

$T \equiv$ atmospheric temperature in degrees Kelvin

$H \equiv$ relative humidity.

To the clear weather propagation delay τ_1 must be added the additional delay τ_2 caused by clouds (fog) and rain. Experimental data are available for the attenuation as a function of frequency under various cloud and rain conditions. However, the conversion of attenuation to propagation delay is not readily obtainable. Therefore, this part of the problem is considered from a strictly propagation delay standpoint and is a function of the total water content of the atmosphere. It is assumed that the diameter of water droplets is much smaller than a wavelength; this is certainly true and therefore the electric field gradient across a water droplet is negligible. With this assumption, as well as the additional assumption that the magnetic permeability of water is unity, the index of refraction can be calculated from the susceptibility of the atmosphere as a function of air and water dielectric constants. The resulting calculation yields both τ_1 as well as τ_2.

There is some question at this point regarding the correctness of the approach because of our limited work in regard to atmospheric phenomena. However, from private converstaion with experienced people in this field, the anticipated results would be that rain and clouds would have only a second order effect on the total propagation delay. This conclusion does, in fact, follow from

$$\tau_2 \approx 0.116 \ r \tag{2}$$

where $r \equiv$ potential inches of water in a vertical column. Considering the possible values of r in (2), $\tau_2 << \tau_1$.

Equation (1) shows that the variations of P, T, and H all influence τ_1. However, experimental data are available which lump these variations together as a certain number of N-units. Over a long time interval this variation can be as much as 45 N-units. From (3), which was used to obtain (1) in the first place, the tropspheric time delay

$$\tau_t = \frac{10^3}{c} \int_0^n N_t \, dh \text{ nsec} \tag{3}$$

where

$N_t \equiv (n_t - 1)\, 10^6 = N_o \, e^{-0.13h}$ for the troposphere

$n_t \equiv$ refractive index of the troposphere

$c \equiv$ velocity of light $= 3 \times 10^5$ km/sec

$h \equiv$ vertical height in statute miles,

$$\Delta\tau_{t_o} \approx \frac{10^{-2}}{3 \times 0.13} \; \Delta N = 1.15 \text{ nsec} \tag{4}$$

Equation (4) gives the uncertainty in propagation time through the troposphere in a vertical direction over a very long time interval. The maximum variation will occur at the lowest ground antenna elevation angle since the path length through the troposphere will then be the longest. Because the earth can be considered flat with regard to the small height of the troposphere, the maximum propagation time variation is simply

$$\Delta\tau_{t\,max} \approx \Delta\tau_{t_o} \csc \psi_{min} \qquad (5)$$

where $\psi_{min} \equiv$ minimum elevation angle. Assuming a 5° value for ψ_{min},

$$\Delta\tau_{t\,max} \approx 1.15 \times 11.5 = 13.2 \text{ nsec.} \qquad (6)$$

2. Ionospheric Effects

Propagation time delay through the ionosphere is caused primarily by free electrons. Since the propagation velocity is equal to the velocity of light times the index of refraction, the ionospheric time delay

$$\tau_i = 10^9 \int_{\text{ionosphere}} \left(\frac{1}{cn_i} - \frac{1}{c}\right) dh \approx \frac{10^9}{c} \int_{\text{ionosphere}} (1 - n_i)\, dh \text{ nsec} \qquad (7)$$

where $n_i \equiv$ ionospheric refractive index ≈ 1. The relation between n_i, the electron density N_e, and the critical or plasma frequency f_c is given by

$$(n_i)^2 = 1 - \left(\frac{f_c}{f}\right)^2 = 1 - \frac{N_e}{0.0124(f)^2} \qquad (8)$$

where

$f \equiv$ carrier frequency of the transmission in Gc

$N_e \equiv$ electrons/cm^3.

For our purposes

$$n_i \approx 1 - \frac{1}{2}\left(\frac{f_c}{f}\right)^2 \qquad (9)$$

since $f_c << f$.

The variations in τ_i can now be determined from experimental data of f_c versus time. These data are given in either daily or yearly variations. Unfortunately, however, the variation of f_c as a function of height can be measured only from earth to the maximum value at a particular height, i.e., the electron density increases with height and then decreases, because pressure continues to decrease with height toward hard-vacuum conditions. Relatively few measurements have been made from satellites, and therefore the variation in electron density or f_c beyond the height for the peak value is generally assumed to be exponential. Using this assumption and averaging the approximate integrations from several sets of data, the average value of τ_i for 90° elevation angle was determined as well as the anticipated daily and yearly variations. Approximate graphical integrations yielded a daily peak to peak variation of about 2 nsec and a yearly variation of daily means amounting to about 2.5 nsec peak to peak. Thus, at vertical incidence, the total ionospheric propagation delay variation is about 4.5 nsec.

In the tropospheric case we multiply the $\Delta\tau$ for 90° elevation angle by the csc ψ_{min} to obtain the $\Delta\tau$ max, using the thin-troposphere flat-earth approximation. However, in the ionospheric case the height of the refractive layer is not small; in order to determine the actual path length through the ionosphere at a slant angle ψ_{min}, the curvature of the earth is quite important. A rather involved geometric problem thus results which will not be detailed here. The approximate result is that

$$\Delta\tau_{i_{max}} = \Delta\tau_i(\psi_{min}) \approx \frac{1}{2}\,(\csc\psi_{min})\,\Delta\tau_i(\psi = 90^\circ) \tag{10}$$

$$\underline{\Delta\tau_{i_{max}} \;\frac{1}{2} \times 11.5 \times 11.5 \times 5.5 = 31.7 \text{ nsec}} \quad . \tag{11}$$

From Fig. 4 then, eq. (10) states that because of the earth's curvature, the path length through the ionosphere is approximately one-half what it would be if the earth were flat for the same h_i. Even if the ionosphere could be probed and corrections programmed into the system on a daily basis, for example, there would still remain an uncertainty or variation in τ_i throughout a day of 10 to 15 nsec for the minimum elevation angle.

G. Satellite Position Variation

Even though a synchronous satellite is supposed to be stationary with respect to the earth, it probably will move a small amount both laterally and radially. The Advanced Syncom satellite, for example, is expected to have lateral deviations not exceeding ± 0.1 mrad and radial

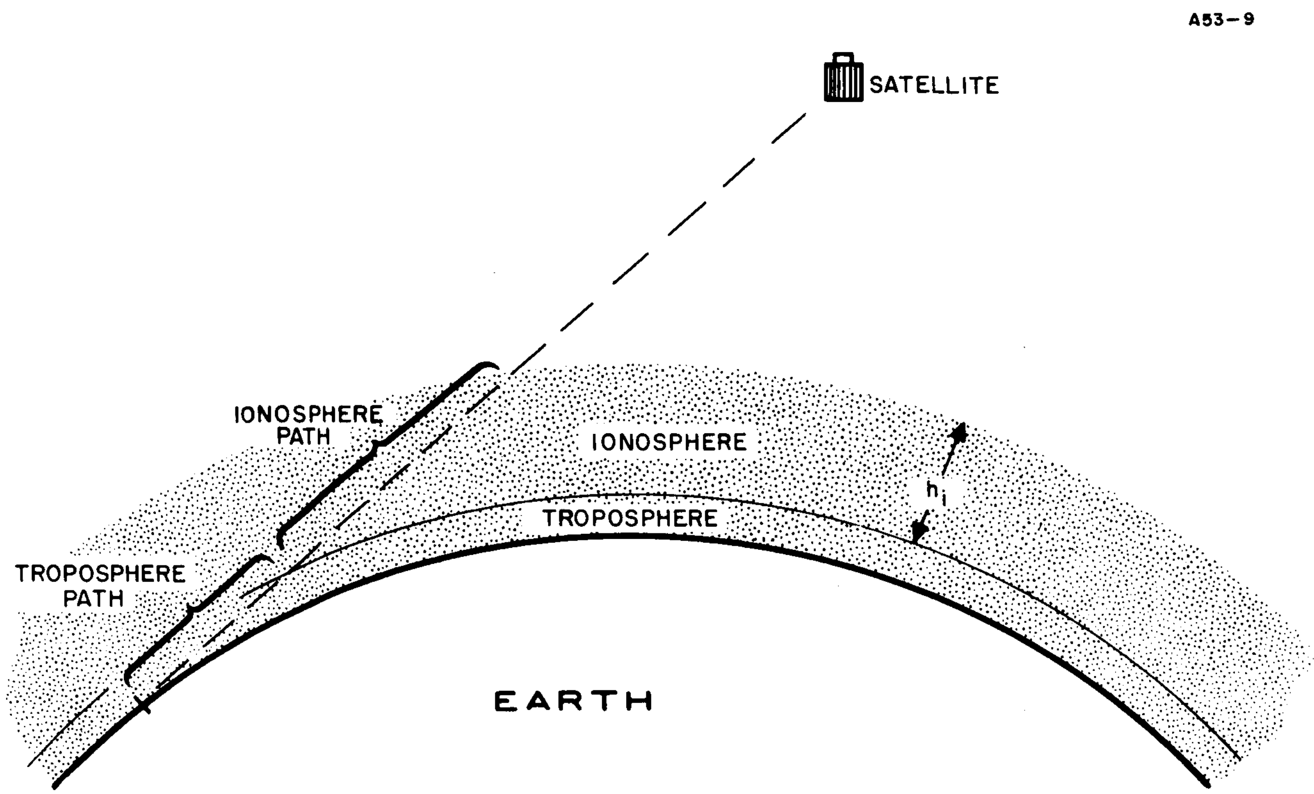

Fig. 4. Troposphere and ionosphere paths showing effect of earth curvature.

deviations not exceeding $\pm$ 5 miles. However, it will be possible to measure these deviations and, hence, to predict their change with time (until a pulse-jet correction is made) with an accuracy of about $\pm$ 50 ft. However, the delay change per foot change of path length is $1/(186,000 \times 5280) = 1.02 \times 10^{-9}$ sec, or approximately 1 nsec/ft. Thus, even a 50 ft change in distance to the satellite changes the delay by more than 50 nsec, or considerably more than the maximum probable combined atmospheric and ionospheric delay differences. A 5 mile radial deviation would change the delay by about 26 μsec, but a time-varying correction for most of this periodically changing delay could be programmed into even a nonadaptive TDM system. The accuracy of such a correction ultimately would be limited by the measurement uncertainty.

The manner in which satellite deviations affect a station's propagation depend to some extent on the station location relative to the subsatellite point. Figures 5 and 6 show that this dependence on station location is quite different for radial and lateral deviations of the satellite. According to Fig. 5, path length to a station at the subsatellite point would be changed by the entire radial deviation d. However, the most distant stations, those at the 5° elevation limit, would experience a path length change $D_2 - D_1$, slightly less than d (less by about 0.045 miles or 240 ft for the case shown). Figure 6 shows that a lateral deviation of the satellite's position may either increase or decrease the path length and delay, depending on whether the direction of the deviation lengthens or shortens the path. For a station at the subsatellite point, lateral deviations can only lengthen the path. The effect of lateral deviations is slight because they are so nearly normal to any propagation path.

H. Pulse Width versus System Capacity

Having considered propagation delay differences and uncertainties, we will return to the system capabilities on limitations of PCM-TDM systems and note that their channel capacity ultimately may be limited by whatever minimum pulse width can be propagated through the ionosphere without excessive distortion of its shape. First, however, we will examine how pulse width may limit the system's channel capacity.

As previously mentioned, seven-digit PCM with an 8 kc sampling rate requires the transmission of 56,000 pps/voice channel, although finer quantization (more digits per sample) may be needed to comply with CCIR noise recommendations. The 56 kilobit rate is at least illustrative and convenient. Assuming that 20% of the cycle is used for guard slots, synchronization, service and supervisory communication, etc., a purely sequential system with N channels would need a pulse period

$$T_p = \frac{1}{1.2 \times 56,000 \text{ N}} \text{ sec} = \frac{14.9}{\text{N}} \ \mu\text{sec} .$$

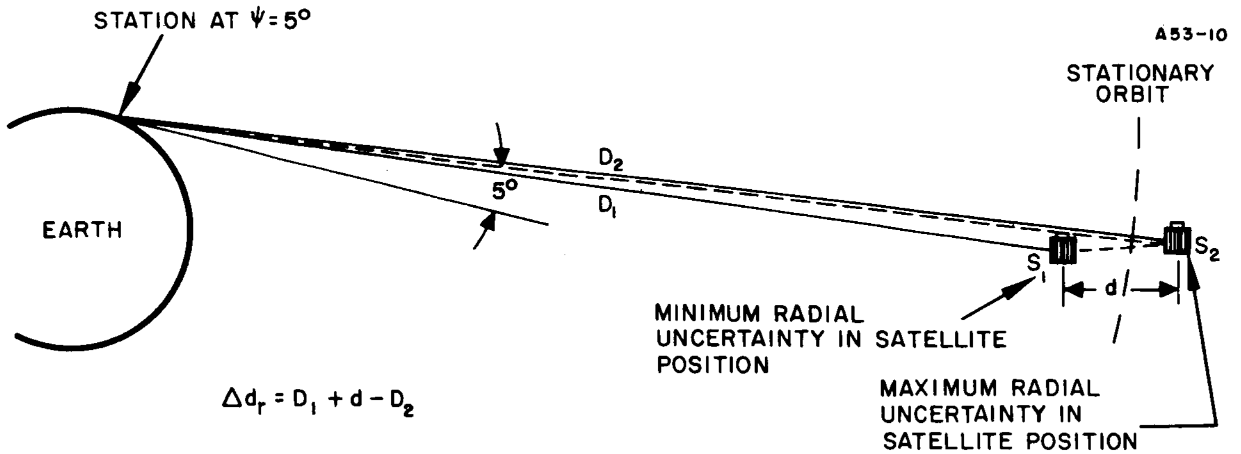

Fig. 5. Radial propagation path variation, Δd_r.

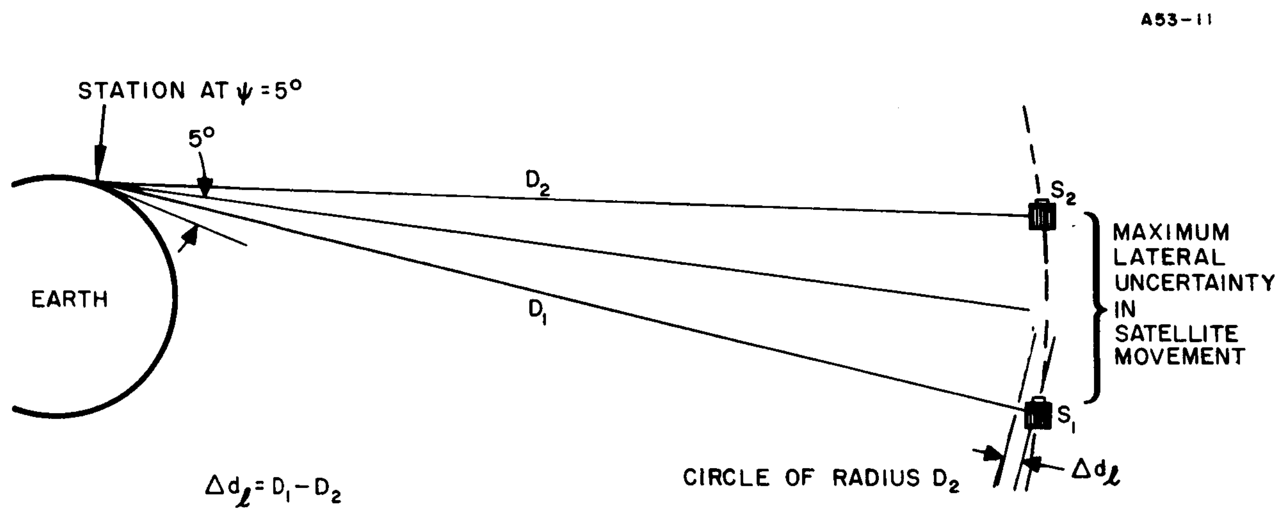

Fig. 6. Lateral propagation path variation, Δd_ℓ.

Thus, such a system using 1 μsec pulses would carry about 15 voice channels. Increasing the capacity to 600 channels, on this basis, would require the use of 25 nsec pulse widths in an rf bandwidth of at least 40 Mc. It will be shown shortly that ionospheric dispersion may limit useful pulse widths to about 25 nsec, recognizing that experimental confirmation is needed.

It would be dangerous to conclude that PCM-TDM systems need be limited by pulse width to about 600 channels because there are tricks, such as those which have been used in HF digital systems. For example, the use of quadrature phase-change modulation would double the channel capacity. Another course, shown in Fig. 7, would be to transmit each sample group of seven digits simultaneously on seven separate channels. For a given minimum pulse width, this technique increases the total bit rate and channel capacity by the number of bits per sample, seven in this example. However, it also increases the total bandwidth by somewhat more than this factor because of the guard bands between the digit channels. The channel and pulse periods become identical, so that 50 nsec pulses would permit the capacity to approach 2100 channels. However, the total bandwidth would become at least 140 Mc, probably 200 Mc. Thus, there could be only two or three such blocks of channels in the 500 Mc satellite communication bands. Additionally, simultaneous systems have synchronization advantages, coupled with multichannel peak power and other economic handicaps. Also, such systems can be viewed as "using FDM to improve TDM!"

Whenever such tricks have been exhausted, channel capacity still will be limited by the minimum useful pulse width, whatever it may be. Consequently, one probable limitation on pulse width has been studied.

I. Limitation of Ionospheric Dispersion on Minimum Useful Pulse Width

Since propagation time through the ionosphere is a function of frequency, each spectral component of a pulse will undergo a slightly different delay. This will cause broadening and other distortion of the shape of short pulses, ultimately causing errors This ionospheric dispersion has not been troublesome to S- or X-band radars using microsecond pulses. This indicates that the minimum pulse width must be less than 1 μsec, and hence is probably in the nanosecond range, the range of interest with these SSB-TDM systems.

In estimating the probable minimum pulse width, the approach has been to operate on the pulse frequency spectrum by the equivalent of an ionospheric transfer characteristic, then reconstitute the distorted pulse shape from its phase-shifted frequency components. Such a study of pulse distortion by ionospheric distortion has been reported by Dyce,[2] based on earlier work by Elliott.[3] The shapes of progressively degraded

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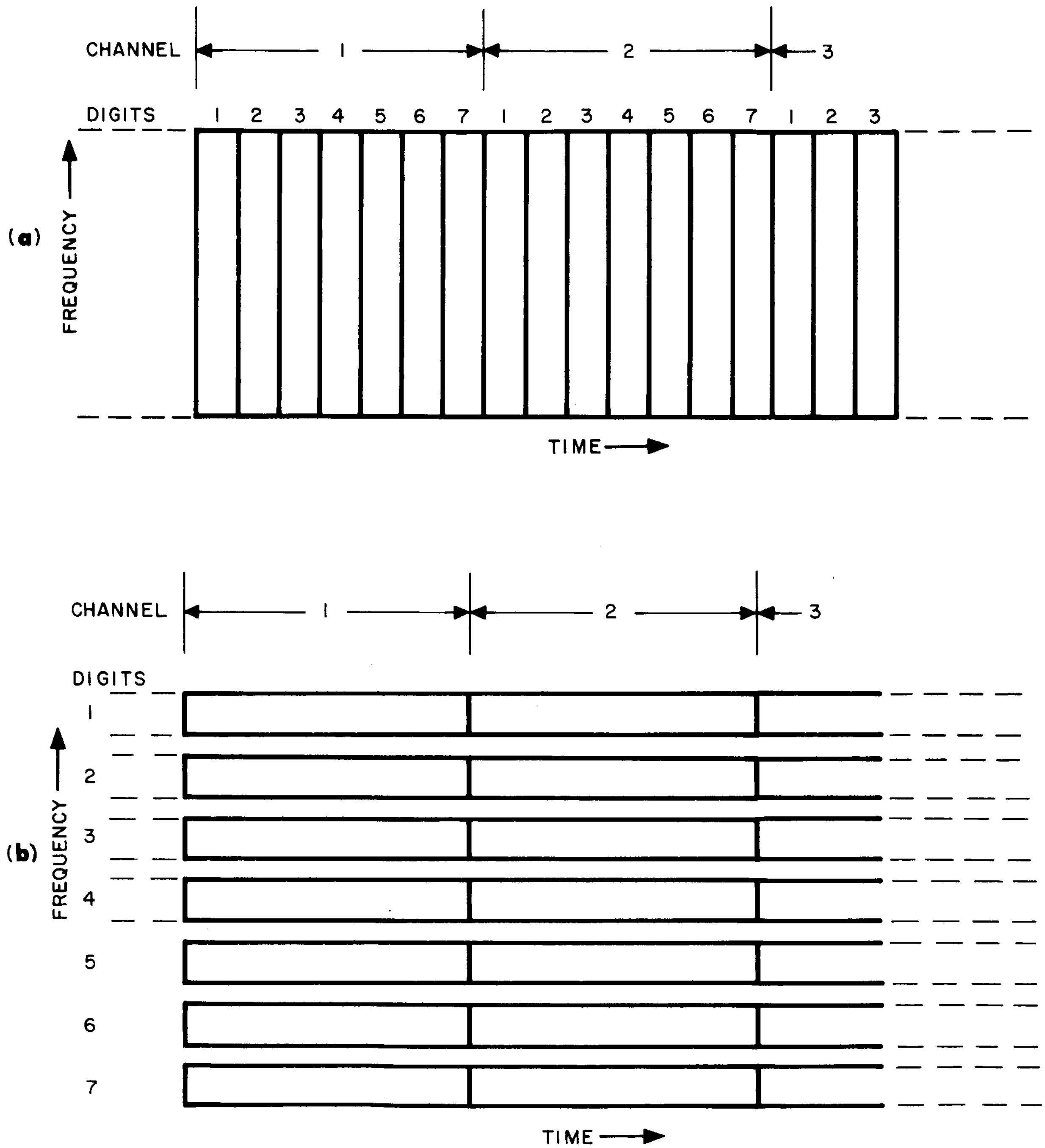

Fig. 7. Sequential versus simultaneous time division. (a) Sequential PCM-TDM. (b) Simultaneous (seven-channel) PCM-TDM uses longer pulses.

waveforms, obtained by Elliott in terms of a parameter "a," are shown in Fig. 8. Although judgment may differ concerning acceptable shape distortion, it appears that a pulse shape about as distorted as that for $a = 0.32$ could be used successfully in a pulse phase-change SSB-TDM system.

From Dyce's eq. (10), the pulse width is

$$T(a) = \frac{1}{a} \times \frac{2}{\sqrt{\pi c}} \times \frac{1}{f^{3/2}} \sqrt{\int_{\text{path}} \frac{f_o^2}{n^3} \, ds} \qquad (12)$$

where

$f \equiv$ carrier frequency of the pulse

$f_o \equiv$ plasma frequency or critical frequency of the medium, at which the refractive index is zero

$n \equiv$ refractive index.

At frequencies above the critical frequency (and hence for microwaves),

$$n = \sqrt{1 - (f_o/f)^2} \simeq 1 - \frac{1}{2}(f_o/f)^2 \approx 1 \quad (\text{for } f >> f_o) \; .$$

Evaluation of the path integral in (12) depends on the electron density profile and the path inclination assumed. For a quiet ionosphere, Dyce assumed values of $\int f_o^2 \, ds$ to lie between 10^{18} for vertical incidence at night and 10^{20} for daytime and a low elevation angle. For the latter case, which is worse, and using $a = 0.1$, he obtained $T = 20$ nsec at 5 Gc. Correcting this to $a = 0.32$ and $f = 4$ Gc, the nominal frequency of the lower satellite communication band, leads to $T = 8.8$ nsec. However, for an $a = 0.1$ pulse shape at 4 Gc, $T = 28$ nsec. Dyce's "low" elevation angle was not specified in degrees but one assumes that it was less than 10^o.

Pulse shape distortion due to ionospheric dispersion has been investigated independently, both for infinite bandwidth and bandwidth limited cases, using a more direct approach than Elliott's and obtaining solutions on the IBM 7090 computer. The pulse waveforms obtained were not fully in agreement with Elliott's, but the amount of shape distortion was similar. The details of this work are too involved for inclusion in this report.

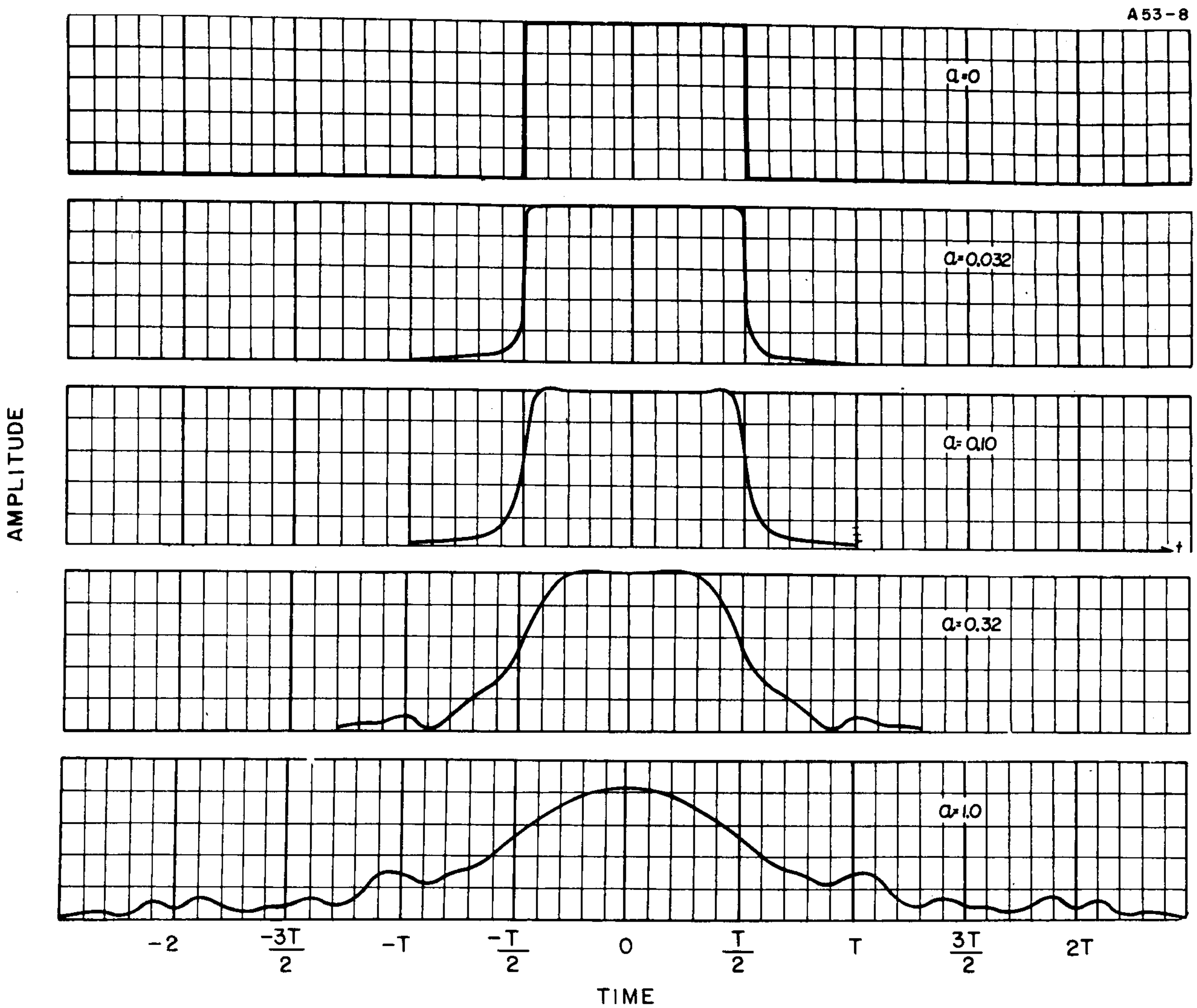

Fig. 8. Degraded waveforms (reprinted from Elliott[3]).

Lacking experimental verification, which seems to be needed, one concludes that the pulse width limitation on PCM-TDM systems will be on the order of 10 to 25 nsec. Stations using high elevation angles at night could use considerably shorter pulses. On the other hand, systems should be designed for better than marginal pulse shapes under the worst probable ionospheric conditions and for 5° elevation angles — hence about 50 nsec pulse widths. It also is interesting to observe that, at the NASA Multiple Access Colloquium, Lindholm of RAND intuitively suggested 30 nsec as a probable minimum useful pulse width. Irrespective of whatever minimum width may finally be agreed upon, such width will limit the channel capacity of PCM-TDM systems, probably to lower capacities than those obtainable from comparable FDM systems.

J. Economics and Common-Carrier Acceptance of TDM Systems

It is not yet possible to make an unequivocal cost comparison between multiple access satellite systems of equal capacity and capability, one using FDM and the other using TDM. To date, no adequately complete TDM system designs and pricing information have been available. The design of FDM systems has progressed farther, but the pricing of such designs still seems controversial. It seems that FDM systems should benefit from the extensive availability and volume production costs of multiplexing filters, modems, etc., which are widely used in microwave and carrier telephone systems. However, it would be hazardous to predict that thin-film technology, etc., may not lead to the development of even less expensive high speed commutators for TDM systems.

Perhaps the best clue as to which type system is apt to survive in common-carrier service can be obtained by observing that early microwave relay systems were of both types, but the FDM systems survived. All of the world's telecommunication administrations have become accustomed to thinking in terms of frequency-division. They will use FDM microwave or carrier systems to feed their new satellite earth stations. Consequently, it seems that a TDM satellite system would need to offer compelling advantages, beyond any foreseeable advantages, to break through the ultraconservatism and frequency-division acceptance of the world's telecommunication decision makers.

K. Growth Problems

It would be a serious mistake to overlook the probability of satellite communication growing far beyond the extent of present 20-year predictions. Unusually careful attention should be given to growth-potential in selecting the common-carrier satellite communications system, looking beyond present problems which may diminish or be overshadowed by more fundamental problems in the future.

Today it is highly attractive, in choosing a modulation system to trade bandwidth for less power, especially for the satellite to earth link. Satellite transmitter power seems terribly expensive while the probable 500 Mc satcom frequency bands seem delusively inexhaustable, compared with our narrower bands at lower frequencies, but the HF spectrum seemed equally inexhaustable in 1925. At such time as the satcom bands start becoming congested, pressure will appear to reverse the trade of bandwidth for power to crowd more capacity into available satellite channels even at the expense of increased transmitter power. This trend has been noticeable in microwave relay systems which, until recently, were considered "large" at 600 one-way voice channels per repeater. These have been followed by systems and CCIR recommendations for 960 channels, 1800 channels, and now 2700 channels. Such narrow FM deviation now is being employed that the "FM improvement" has become a net loss and power efficiency has become poor compared with SSB, although the latter uses minimum bandwidth and has no such signal to noise "improvement." Along with this increase in capacity of microwave systems their transmitter power has risen from a few milliwatts to 10 W and more, while their "conventional" (about 12 dB noise figure) receivers are giving way to parametric amplifiers.

A presently attractive feature of PCM-TDM systems is their excellent trade of bandwidth for noise suppression and power conservation. With PCM, quantization noise normally is dominant and its level is determined by the fineness of quantization, by the number of digits per sample. PCM of CCIR quality is comparable with wide-deviation FM (or PM) in respect to its noise-improvement and its trade of bandwidth for power. Unlike FM or PM however, PCM's bandwidth trade is not readily reversible, but might require the use of multilevel pulses or other not-generally-accepted techniques, which would impose expensive major equipment changes on all earth stations. Practically, it can be said that PCM's trade is irreversible.

Additionally, it is difficult and expensive, if possible, to increase the per-repeater channel capacity of a PCM system. Since the sampling rate or cycle rate is fixed, adding channels requires shortening the pulses, with consequent equipment changes at all earth stations. Consequently, it would be desirable to design a TDM system for minimum pulse widths and, hence, maximum potential channel capacity, even though this number of channels might seem superfluous for current needs. Doing so, however, would increase the initial cost of the system.

In contrast, a system employing SSB from earth to satellite and PM (or FM) from satellite to earth, such as the Advanced Syncom system, has excellent growth capability. A new satellite would be equipped with repeaters having higher channel capacity, say 2400 or 2700 one-way channels instead of the initial 1200 channels. For the earth to satellite ("up") link, the total baseband merely would be extended by the addition of these 1200 to 1500 new SSB channels. Most of these could be used by new stations, while old stations continued using their old channels and added new ones as needed to increase their channel capacity. In essence, the SSB channel spectrum is open-ended and can be added to, whereas TDM operates with a closed cycle of channel time-slots, all of which must be narrowed (or otherwise changed) in order to add channels.

Next, considering the satellite to earth ("down") link, this higher capacity satellite repeater would use lower deviation (with correspondingly greater power) to keep the 2400 to 2700 channels within the previous 25 Mc rf bandwidth. On earth, the same bandwidth would be received but the detector would deliver the increased baseband. The earlier demultiplexing equipment would remain useful and additional equipment would be installed only for these new channels. Obsolescence thus would be avoided or greatly reduced. It is believed that this superior growth-potential of the SSB-PM FDM system should become a decisive advantage over PCM-TDM type systems for common-carrier multiple access satellite communication.

V. ECONOMIC FACTORS OF MULTIPLE ACCESS SATELLITE COMMUNICATION

A. Explanatory Comment

Copies of the draft for this section were distributed to several well-qualified people for criticisms and comments. The replies were not received in time to re-draw curves and make other changes, so the essence of these comments will be abstracted here, to indicate changes which will be made in completing this study.

This study assumes an average call length of 5.5 revenue min, with six such calls per "busy" hour per channel (i.e., 4.5 nonrevenue min between calls), with daily traffic equivalent to that of three busy hours per day and 250 business days per year; hence, not more than 25,000 revenue min/channel year. This value now appears overly conservative by a factor of about two. The average length of trans-atlantic calls is closer to 8 min, with about 2 min between calls over the cable during busy hours. Also, despite time-difference, there is so much non-business-hours traffic that the daily traffic approaches that of 5 busy hours. Hence, the 25,000 revenue min/channel year used in this study was too conservative. British studies of satellite traffic have assumed 45,000 revenue min/channel year and even this value may be too low.

In considering the surface communication cost component, between the user and his earth station, it is shown that the U.S. day rate (station to station, first 3 min) can be approximated as $\$1.07 + 0.0005\ d$ for $d > 200$ miles. To the extent that this rate reflects cost plus a small profit, the constant term relates to the cost of access to the domestic long distance system as compared with the local system. Time of a long distance operator or the use of additional automatic equipment is involved. The corresponding access component of international rates is not yet known but certainly is greater than \$1.07. If satellite communication were to be used domestically this \$1.07 would not be applied at both stations. Rather, the appropriate rate would appear to be $\$1.07 + 0.0005\ (d_1 + d_2)$.

Since the satellite system will be a "common carriers' carrier," its competitiveness will depend on its cost compared with equivalent surface communication costs, without reference to the additional cost for user-to-station surface communication. For AT&T surface systems, the annual cost per channel mile decreases with the number of channels N and is approximately $\$300/N^{2/3}$ per channel mile (duplex, presumably).

Thus, a 2400 mile system of 600 duplex channels would cost about \$10,000 per channel year. Transoceanic submarine cable channels are considerably more costly. Hence, in completing this study, more emphasis will be placed on comparative station-to-station costs.

The per mile component of the user-to-station communication cost is important in determining the optimum area to be served by an earth station, so the analysis presented in Section V-G is valid within the scope of its assumptions (i.e., $\bar{d} >> 200$ miles). It would become unrealistic to assume that metropolitan users of a metropolitan earth station (if such a station could overcome its interference problems) would have only "local" surface communication costs.

B. Introduction

This study is intended to clarify the interrelation of cost factors in Multiple Access Satellite Systems on a user-to-user basis. It is intended to show which cost components would become the dominant components under various conditions and, hence, which cost components need most to be controlled. The study is not restricted to specific cost estimates (of earth stations, etc.) but considers system cost performance over a probable range of values.

The study assumes a single stationary satellite system, generally of the Advanced Syncom type, although systems with satellites of smaller and greater channel capacity also are considered. The methods can be extended to nonstationary or other multisatellite systems, as will be evident.

Attention is focused on the user to user cost components, as follows: (1) cost of surface communication between users and their earth stations, (2) cost of earth station use, and (3) cost of satellite system use. The total of these costs must be less, on an average, than established rates. Hopefully, under favorable conditions, the over-all cost can be enough less than present rates to lead to lower intercontinental rates and, hence, to more rapid increase in traffic. Major attention is focused on the economic aspects of smaller stations serving population centers in "newly emerging" areas where surface communication facilities are still limited. A related problem is that of the optimum service area for earth stations, a problem which seems to have been neglected previously.

C. Surface Communication Rates

Long distance rates are a matter of public record, whereas their relation to actual cost is obscure. Therefore, we have studied rates primarily and postulated that the true cost would be somewhat lower than the rate. CCITT Recommendation E.51 (Ref. 4) covers principles of rate structure for European continental circuits and shows the effects of crossing international borders, etc. It appears too difficult to obtain a useful generalization of European rates solely from this source. Consquently, the day station-to-station rates from Paris to other European cities were plotted against distance, as shown in Fig. 9. The scatter of points in this plot shows the perturbing effects of border crossings and other international aspects of the European rates. Nevertheless, a useful approximation is

$$\$/\text{min} = 0.0011\, d\ (\text{miles})\ .$$

The per minute rate does not drop after the initial 3 min minimum, as does the U.S. rate. The latter rises sharply with distance (Fig. 10) within the first 200 miles, but thereafter becomes approximately

$$\$1.07 + 0.0005\, d\ (\text{miles})\ (\text{for first 3 min, day station-to-station}).$$

For subsequent minutes (or fractions thereof) the rate is a quarter of the above rate, rounded upward to the nearest nickel. Taking 5.5 min as the average duration of overseas calls, the average per minute U.S. rate becomes (neglecting the round-off)

$$\$0.316 + 0.000148\, d\ (\text{miles})\ .$$

Thus the U.S. and European rates cross at 332 miles and $0.365/min. This distance is a sufficiently large average user-to-earth-station distance for Europe, assuming a station per larger nation or group of smaller nations (Benelux, for example) but for the U.S. this average distance would be about 890 miles from a centrally located station and considerably more if there were a single station in Maine.

On intercontinental calls, the 3 min day rate to London is $12.00, either from New York or Los Angeles. From London to anywhere in the U.S. the corresponding rate is only 3 pounds, or approximately $8.50. It would appear that the actual cost would be the same in either direction and this tends to point up the seemingly nebulous relation between rates, cost, and distance.

It seems that the actual cost of user to earth station communication could be somewhat less than between individuals at equal distance, because the station would be a "big user." Also, it would seem inappropriate to charge the constant $0.316/min at both ends. Altogether, the information obtained to date is not adequate to predict the user-station communication cost relation with the desired accuracy. To be conservative, rates have been used, supplemented where appropriate by discussion of the effect of different cost or rate relations.

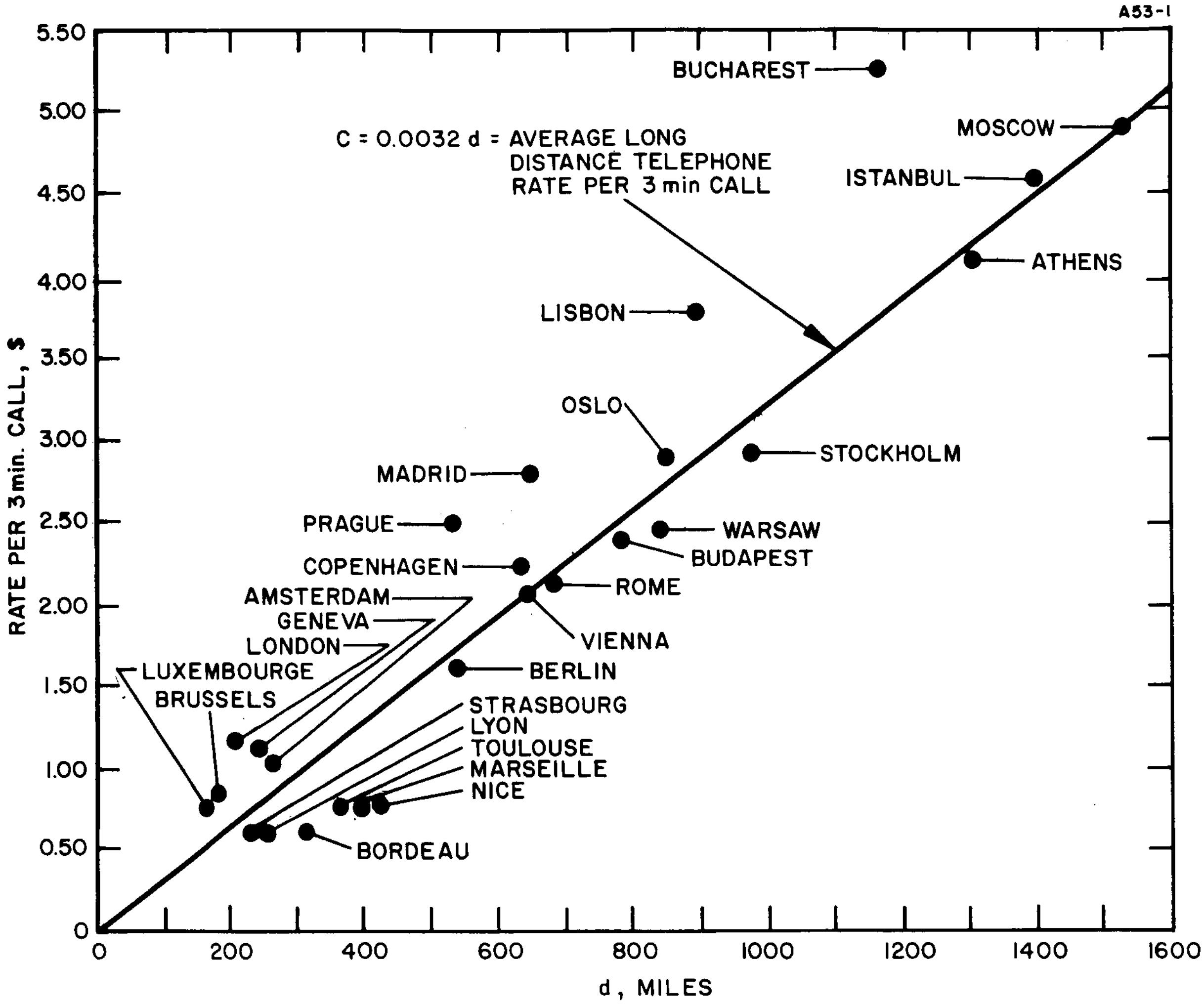

Fig. 9. Telephone rates from Paris.

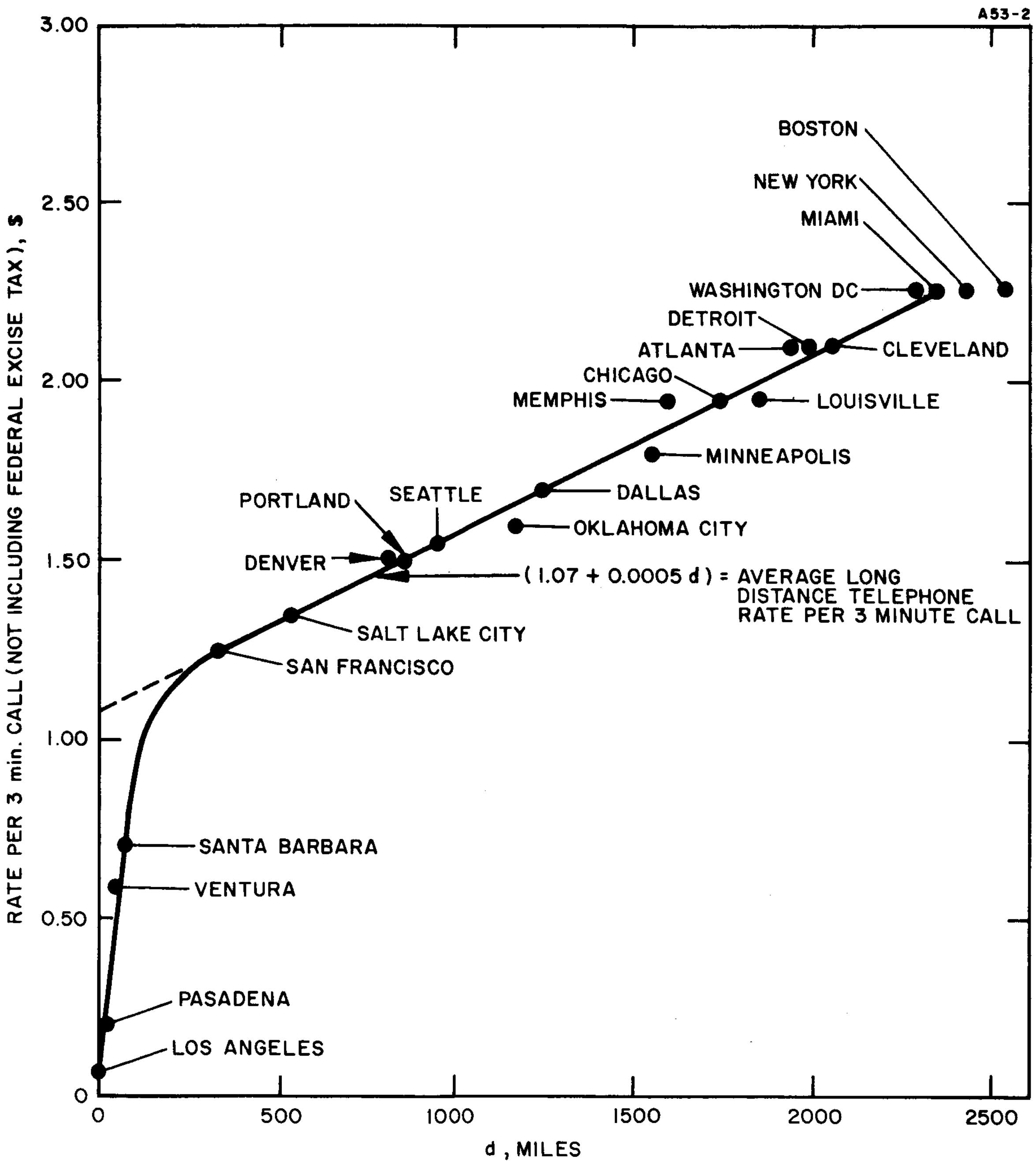

Fig. 10. Continental USA telephone rates from Los Angeles (station-to-station).

D. Earth Station Use Costs

One recognizes that, to a first approximation, some items of earth station capital cost are proportional to the number of channels (compandors and echo suppressors, for example) while others (such as the antenna, land, etc.) could be the same irrespective of the number of channels. The cost of some components, such as the transmitter, have both fixed and per channel components of cost. Practically, even the antenna, buildings, etc., tend to have a per channel cost component because it becomes "appropriate" for a large station to have better facilities than a small station. This trend is evident in prior cost estimates, such as those of Lenkurt[5] for small and large stations, as (partially) tabulated below.

Costs	Station	
	"Small" 12 Duplex Channel Capacity	"Large" 150 Duplex Channel Capacity
Land	\$ 10,000	\$ 50,000
Access road	20,000	250,000
Building	80,000	150,000
Antenna (incl. feed, etc.)	75,000	230,000
TOTAL (less installation)	\$859,000	\$5,635,000

Assuming a straight line total cost versus number of channels relationship between these two points (recognizing that these estimates were not intended to be used this way), one obtains

$$S_o + S_1 X = \$444,000 + 34,600 \ X \qquad (13)$$

Here the channel cost S_1 is considerably greater than that of all the clearly "one per channel" items, such as compandors, echo suppressors, etc., while the equivalent fixed cost S_o is less than that of all the clearly "one per station" items. It must be clearly recognized that this example is only illustrative and that the above coefficient values probably are not accurate. These Lenkurt station cost estimates were used because they seem to be the most detailed estimates which are widely available. However, they are not fully suitable for this use. For example, different antenna apertures (gains) were postulated for large and small stations and the large stations' television capability has not been accounted for in calling it a 150 channel station. Ideally, this type of analysis should be made by designing and pricing out four or more comparable earth stations of different channel capacities. To date, the time and detailed information for such cost estimates has not been available.

Recognizing the purely illustrative use of these cost estimates, we will make similar use of the corresponding annual operating cost estimates, also from the Lenkurt Study, which were \$301,000 for small stations and \$1,520,000 for the large stations. Using these, with X designating the number of channels, the approximate annual operating cost equation becomes

$$T_o + T_1 X = \$195,000 + 8,830\,X \text{ dollars per year.} \quad (14)$$

These values at least help to establish a range of annual cost components T_o and T_1, which will be of use in this study; this range should bracket whatever actual values are determined later and still remain within the foreseeable state-of-the-art. These values are given in Table III.

TABLE III

Annual Cost Estimates

	T_o	T_1	T_o/T_1
Present and pessimistic	\$250,000	\$10,000	25.0
Near future, probable	150,000	7,000	21.4
Future, optimistic	60,000	4,000	15.1
Lenkurt values (above)	195,000	8,830	22.1

It is believed that the Lenkurt station cost estimates were conservative, almost pessimistic. Competition and technological progress will bring substantial reductions in these station cost components. For example, earth stations should evolve toward unattended operation, as have microwave relay stations, thus saving \$22,500 to \$45,000 per year in T_o operating costs.

In examining the cost per channel year we divide (14) by the number of channels

$$\frac{T_o}{X} + T_1 = \$ \text{ per channel per year} \qquad (15)$$

Obviously, T_1 is the minimum possible channel cost, approached by large stations as $X \rightarrow \infty$. T_o/X is the additional per channel share of the annual fixed cost. More bluntly, it is the small stations' "penalty." It remains a reasonable penalty, however, not over 2:1, so long as

$$X \geq T_o/T_1 \quad . \qquad (16)$$

Table III showed that T_o/T_1 may vary from a pessimistic 25 down to perhaps 15 channels, on the basis of the values assumed. Figure 11 shows over-all cost per channel versus number of channels for various combinations of T_o and T_1. Clearly, the ability of small stations to furnish economic service depends upon reducing the fixed cost component T_o and not upon artificially inflating T_1!

It must be recognized that stations <u>may</u> see fit to operate with fewer than T_o/T_1 channels, or with insufficient traffic for their channel capacity, if only because such decisions are not always made on strictly economic grounds. Some nations may want a station even though they do not yet have enough long-haul traffic to justify it. Such nations may consider chiefly the initial investment and whether they can obtain the money. Even according to the Lenkurt estimates, the initial investment for a small station should be modest, compared with that for a relatively large microwave system, or with that for an airport. Having a station, the satellite system will furnish the service and the customers will pay for it, even with relatively high rates, especially if the customers have no other competitive communication service. By analogy, transportation in many parts of the world jumped from oxcarts to aircraft because airports were cheaper than highway or railroad systems, even though the users had to pay more. Additionally, a nation might see fit to subsidize its satellite communication service by "donating" the relatively modest fixed component (S_o) of its station's cost, thus depressing its annual T_o and letting it operate economically with very few channels.

As to the station cost per minute of paid use (i.e., excluding the idle time and time lost in calling and connecting the users, etc.),

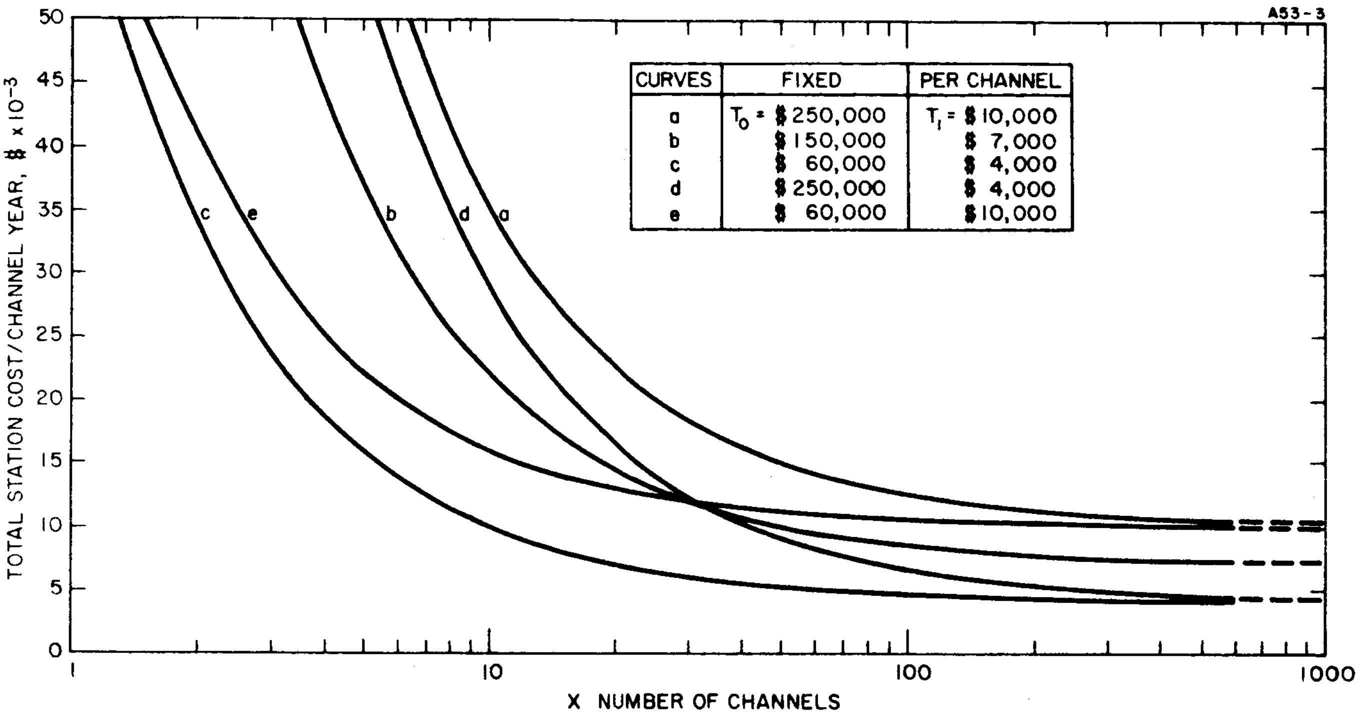

Fig. 11. Station cost component as a function of channels.

$Y \equiv$ revenue minutes per year

$Y_{ch} \equiv$ revenue minutes per year per channel

$Y_k = XY_{ch} \equiv$ station k's revenue minutes per year, for its X channels

$Y_{max/ch} \equiv$ maximum revenue minutes per channel year, without excessive queuing of potential users.

Frequently, Y_{ch} will be used as the independent variable, with $Y_{max/ch}$ as its normal upper limit, as will be discussed soon. Note that it is assumed that station use cost is the same for calls which it initiates or receives; these Y's are total minutes for both directions. Note also that Y_k later will be related to station k's transmitting channel minutes per year in relation to its use of the satellite.

From eqs. (14) and (15),

$$\$/\text{revenue minute} = \frac{T_o + T_1 X}{Y_k} = \frac{1}{Y_{ch}} \left(\frac{T_o}{X} + T_1 \right) \quad (17)$$

As to the maximum use of channels, CCITT Recommendations E. 91 and E. 92 cover the number of circuits necessary to carry a given amount of traffic (in Erlangs) in manual or in semiautomatic operation.[4] These recommendations seem most applicable to European international service, for which the time differences are small. A reasonable approximate approach is to assume that during a busy hour each circuit can carry six 5.5 min calls per hour, with 33 min of revenue earning time and the remaining 27 min being idle, calling, or waiting time. Moreover, the total traffic per day would be equivalent to that of three busy hours, or to 100 revenue min per day for 250 business days per year; hence, $Y_{ch/max}$ = 25,000 min $Y_{max/ch}$ per year is a probable maximum per channel. This total is somewhat uncertain for several reasons. The large time differences between users of a stationary satellite system lead to little or no overlap of business hours and, hence, to brief and exaggerated traffic peaks. There will be considerable nonbusiness and other off-peak traffic, however, which probably can be stimulated by preferential rates. In general, with excess channel capacity, stations would have less than this 25,000 revenue min per channel year. Higher values probably should not be considered except when heavy off-peak usage has been assured. Figure 12 shows station use cost per revenue minute for various annual total costs per channel year, from \$5000 to \$25,000.

An apparent conclusion is that a station should not have more channels than it needs, but this is true only within reason. For example, consider a station for which T_o = \$150,000 and T_1 = \$7,000 and

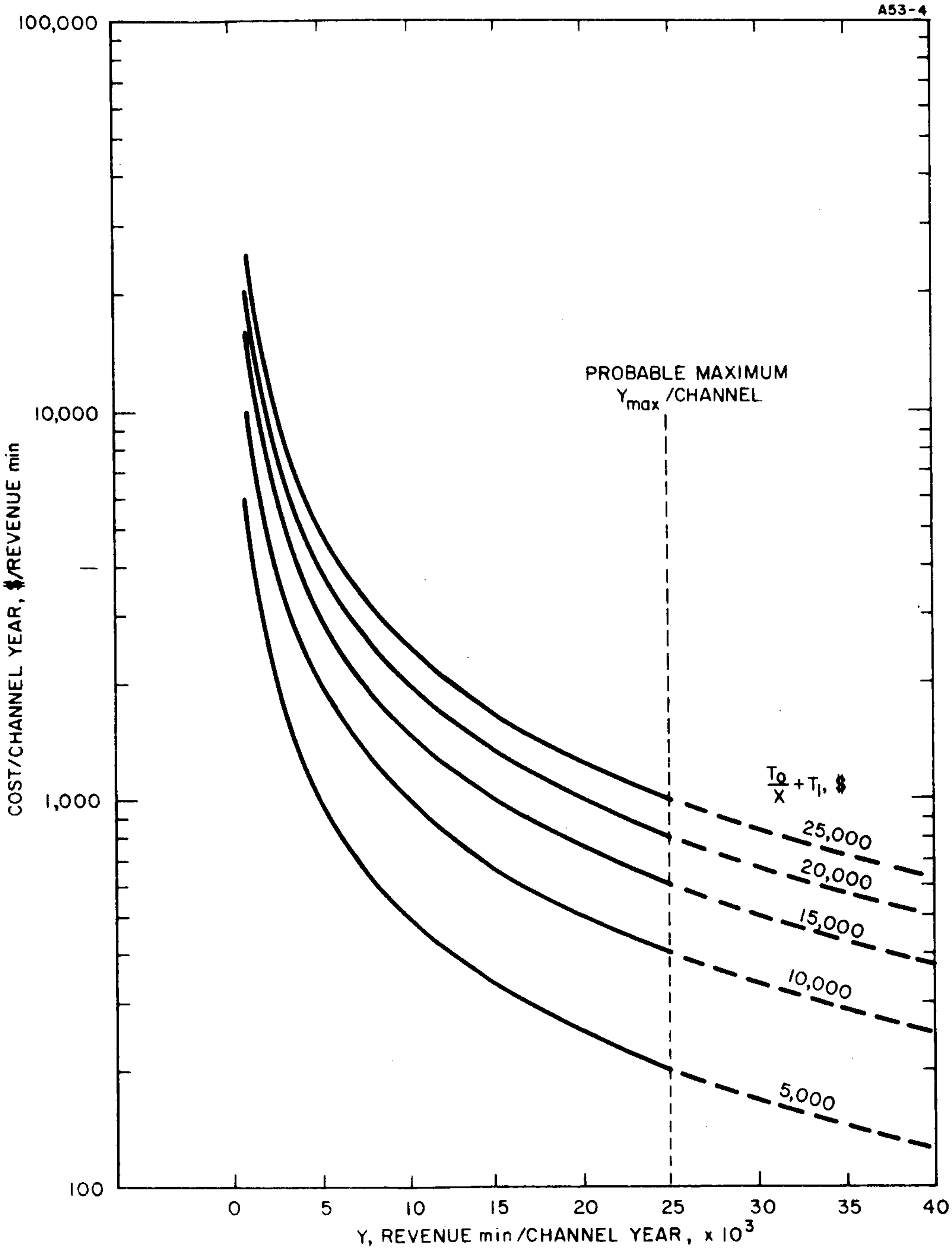

Fig. 12. Station cost component as a function of traffic.

which has Y_k = 1,250,000 min/year, a traffic volume which could be handled by 50 channels at $Y_{ch/max}$ = 25,000 and a cost of \$0.40 per revenue minute. Using a group of 60 channels would decrease channel usage to Y_{ch} = 20,833, or \$0.456 per revenue minute. Thus, providing this 20% additional channel capacity would increase this part of the call costs only 14% and would provide better service and capacity for growth. Next, consider a too small station needing five channels but using six. The cost per revenue minute would increase form \$1.48 to \$1.535 or only 3.7%. The explanation, of course, is that the T_o = \$150,000 accounts for \$1.20 of this station's cost per revenue minute, for Y_k = 125,000. Small stations probably have greater need for additional channels because of less diversity of their use.

E. Satellite System Use Costs

Values to be assigned to this cost component become speculative for reasons which soon should become clear. However, there will be some yearly cost C_a for CSC operation (an amortization), management salaries, engineering support, etc., in addition to the yearly cost of keeping an operating satellite on station. This latter cost will be the cost per launch C_s divided by the probability p of launch success (of the satellite reaching its station), and the satellite's life expectancy, r years. Hence, the total satellite service cost per year can be expressed as

$$C_a + \frac{C_s}{pr} ,$$

and it is assumed that this cost will be allocated to the stations in proportion to their use of the satellite, as will be discussed later.

Experience to date has been only with experimental satellites, whose lives sometimes have been disappointingly short, on the order of six months. Operational communication satellites should soon have a life expectancy of, say, two years, increasing in time to ten or more years. Launch probability, with Thor Deltas and simple orbits has become excellent, but the Atlas-Agena is a newer booster and the stationary orbit is a "difficult" one. An initial launch probability of 0.5 has been used for the Advanced Syncom, and seems a reasonable value. This probability should improve rather soon to 0.7 and eventually perhaps to 0.9, assuming that this satellite and booster continue to be used for many years. Any radical change, such as to a larger satellite and booster, might temporarily lower this probability.

The on-station cost of an operational Advanced Syncom has been estimated as \$22,000,000 based on 50% probability of successful orbit, \$8,000,000 per Atlas-Agena launch, and \$3,000,000 per satellite, with its apogee motor. The first Advanced Syncom in orbit may cost considerably more, because of development costs, and especially if more than two launches are required. Launching costs tend to decrease with time, as evidenced by a more recent NASA estimate of $7,200,000 per Atlas-Agena. Eventually this launch cost may drop to, say, $6,000,000 and the satellite cost to about $1,000,000 after development and reliability improvement costs have been absorbed. If launch probability increases to 0.9 by then, the cost on station would drop to

$$\$ \frac{(6 + 1) \times 10^6}{0.9} = \$7,800,000 \ .$$

As to reliability or life, the Advanced Syncom philosophy has been to provide ample redundancy and to permit "graceful degradation," this being far preferable to the alternative of keeping one or two spare satellites close to each satellite station. The Advanced Syncom will have four repeaters on different rf channels each with 1200 (one-way) voice channel capability, and with corresponding redundancy in its noncommunication equipment. Unless the frame or antenna were to fail, or a tank burst, no individual failure would be catastrophic. So long as any one repeater and one set of auxiliary equipment (command receiver, etc.) remain operating the satellite remains useful.

The satellite use and replacement policy will, of course, be established by the system management, so the following discussion merely shows how life and channel capacity can be interrelated, considering only the four repeaters. Initially, the 600 duplex channel capacity of one repeater would be adequate, except when a second repeater is needed for television. At this time, any two repeaters could fail and there would still be a spare repeater, used occasionally for television. Presumably, steps toward replacement would be started upon failure of the second repeater but it might be a month or more before the new satellite would be in orbit and ready for service. During this time, if a third repeater failed there still would be no interruption of telephone-type traffic. After traffic grows to more than 1200 duplex channels during peaks, three of the four repeaters would be used to make 1800 duplex channels available. When thus used, the failure of any one repeater would not curtail service but would leave no spare repeater, so a new satellite would be orbited as soon as possible. Failure of a second repeater, prior to replacement, would leave 1200 duplex channels operating and might cause some queuing delays during traffic peaks, but such degradation would be minor and temporary. Of course, there would be greater probability of failure of any one of the four repeaters. However, during the period of growth from 600 to 1800 duplex channels, repeater life should improve to such a point that the average period to first failure would at least be as great as that to a second failure had been initially.

Returning to consideration of the entire satellite system, we next need some illustrative values for the C_a annual cost term. The Lenkurt estimate reduces to $6,400,000 per year on a single satellite basis but seems conservative to the point of pessimism. For example, this estimate postulated the use of a separate CSC station with a general purpose digital computer, the station having its own expensive transmitter, antenna, etc. It may be found less expensive to attach the CSC to some major station and to use automatic telephone type equipment for its computing function. Three illustrative values of C_a will be used for this study: \$6,400,000 as an initial and pessimistic value, \$4,500,000 as a more probable later value, and \$2,000,000 as an optimistic "eventual" value.

On the basis of the most pessimistic of these values the annual cost per satellite would be

$$C_a + \frac{C_s}{pr} = \$(6.4 + \frac{8 + 3}{0.5 \times 0.5}) \times 10^6 = \$50.4 \times 10^6 . \tag{18}$$

Note that in this case, the C_a term is nearly negligible. If considered as a 600 duplex channel satellite (only one repeater used), the cost per available channel becomes \$84,700 per year. In comparison, earth station channel costs would be relatively unimportant, as will be discussed later.

Using the more realistic near-future estimates,

$$C_a + \frac{C_s}{pr} = \$(4.5 + \frac{7.2 + 3}{0.7 \times 2}) \times 10^6 = \$11.79 \times 10^6 \tag{19}$$

or only \$9,820 per channel year, if considered as a 1200 duplex channel (2 repeater) satellite. One notes that this represents a better balance between the C_a term, the satellite replacement, and earth station channel costs.

Using the optimistic far-future estimates,

$$C_a + \frac{C_s}{pr} = \$(2.0 + \frac{6 + 1}{0.9 \times 10}) \times 10^6 = \$2.78 \times 10^6, \tag{20}$$

most of which is now the C_a term. The cost per available channel year, based on 1800 duplex channels, drops to \$1,544 or less than the probable minimum cost of earth station channels. Of course, a low cost per available channel can be misleading, except when all are used and paid for. Even then, it means that more channels should be made available, but the cost can be distributed only over the channels used.

To date, only satellites of the Advanced Syncom type and size have been considered, chiefly because its planned characteristics are suitable and best known. Additionally, no comparable designs have been available, especially for comparable satellites of smaller or larger channel capacity and cost. It would be interesting to study the variation of the annual cost per available channel with size (weight) of the satellite but one encounters problems, one of which is similar to that of trying to compare horses with pigs. Satellites of greatly different size would not be comparable in their capability. For example, one can envision a smaller satellite to be orbited with a Thor-Delta or perhaps one with an additional solid-fuel booster. Without the Agena guidance system an equatorial launch might be required. The "dry" weight on station might drop from the Advanced Syncom's 624 lb to perhaps 200 lb. At this weight one would sacrifice redundant reliability and the greater gain of the despun phase-directed antenna, as well as sacrificing channel capacity. More satellite transmitter power (or still fewer channels) or more expensive earth stations might be required to compensate for this loss of about 10 dB of satellite antenna gain.

Proceeding toward a considerably heavier satellite which might be orbited with a Saturn or other comparable booster at some future date, it does not seem reasonable to expect that all of its greater weight would be used for correspondingly more 1200 simplex channel repeaters (600 duplex channels), with 25 Mc transmitting bandwidth. Each might need 1800 or 2700 simplex channel capability, with the same 25 Mc transmitting bandwidth, requiring reduced deviation and correspondingly greater transmitter power. Additionally, it seems certain that beamed antennas would be used for receiving, as well as for transmitting, so the earth station could use less powerful and expensive transmitters or perhaps make the use of compandors less essential. Altogether, about all that can be concluded with safety is that, as the demand for satellite service grows to justify the use of larger satellites and boosters, such satellites should further reduce the cost of satellite communication, perhaps to a substantial extent.

Returning to satellite system costs, there remains the problem of allocating this cost among the earth stations on a per revenue minute basis. Complications arise from the various classes of service (from telegraphy to television) and even from the difference between random and assigned channel types of multiple access service. For simplicity, television will be neglected as being an "as available" service, having no "cost" in terms of displacing other revenue services. If desired, it can be included as equivalent in cost to some uncertain number of voice channels. Other services will be treated as their equivalent in voice channels, recognizing that a voice channel may be used for a single telex channel or for several. This amounts to considering all-telephone operation, but at a rate of use which is proportionately higher than the actual telephone use rate.

Turning to the random versus assigned channel problem, the latter method of operation is potentially less costly (when adequately used) because the CSC channel allocation service is not used. Stations would not normally lease channels (except for "hot-line" services, etc.) unless their anticipated use were heavy enough to lead to some cost saving. On the other hand, random access can make fuller use of its fraction of the satellites' channel capacity, when necessary, because any available channel can be assigned between any two stations, as needed. The total of the earth station random access channel capacity can exceed that of the satellite because all stations would not use all of their random access channels at any one time. The argument becomes important, however, only as demand approaches the satellite's capacity, and then it probably means that satellite capacity should have been increased sooner.

Rather than pursuing further the cost division between these classes of service at this time, it seems best to simplify the problem by assuming that the cost per channel minute of customer use is nearly the same for the different classes and that an average can be used. This further assumes that customer usage of assigned channels can be determined, on a sampling basis, or otherwise, because the CSC normally would not record messages over these channels. In effect, this is equivalent to assuming all-random operation but at somewhat lower cost per channel minute. On this basis, it will be assumed that station k's use of the satellite is Y_k transmitting channel minutes per year, so that the total satellite use by all N stations is

$$2Y_s = \sum_{k=1}^{N} Y_k \quad . \tag{21}$$

Note that Y_s denotes the number of duplex satellite channels, each corresponding to two station transmitting channels. Station k's fraction of the satellite system cost is then

$$f_k = \frac{Y_k}{2Y_s} \quad . \tag{22}$$

Note that f_k cannot exceed 0.5 and could reach this value only if all traffic were from and to this one station, with none between other pairs of stations.

The cost of satellite service per duplex channel minute of customer use is

$$\frac{C_a + C_s/pr}{Y_s} \quad , \tag{23}$$

half of which would be charged to each station as part of its fraction of the satellite system cost. The yearly costs to stations h and k are

$$\left(C_a + \frac{C_s}{pr}\right) f_h = \left(C_a + \frac{C_s}{pr}\right) \frac{Y_h}{2Y_s}$$

and

$$\left(C_a + \frac{C_s}{pr}\right) \frac{Y_k}{2Y_s} \quad . \tag{24}$$

For both stations, the satellite cost per transmitting (simplex, not duplex) channel minute is therefore (from (22), (23), and (24))

$$\left(C_a + \frac{C_s}{pr}\right)\left(\frac{f_h}{Y_h} + \frac{f_k}{Y_k}\right) = \left(C_a + \frac{C_s}{pr}\right)\frac{1}{Y_s} \quad , \tag{25}$$

which is the satellite's duplex channel minute cost.

F. Over-all User-to-User Cost

Combining the cost components, from user to user,

$$C = \underbrace{C_{1h} + C_{1k}}_{\text{surface}} + \underbrace{\frac{T_o + T_1 X_h}{Y_h} + \frac{T_o + T_1 X_k}{Y_k}}_{\text{stations}} + \underbrace{\left(C_a + \frac{C_s}{pr}\right)\left(\frac{f_h}{Y_h} + \frac{f_k}{Y_k}\right)}_{\text{satellite system}} . \tag{26}$$

One recognizes that the station costs may be quite different for stations of greatly different size, the cost per channel minute being higher for the small station. The special case of equal-cost stations is of major interest because the combined station use cost will be least when both stations are large and will be greatest when both are small. As a further simplification we will use the total surface communication cost

$$C_1 = C_{1h} + C_{1k} \tag{27}$$

and, for the present, consider C_1 to be constant. Hence,

$$C = C_1 + \frac{2}{Y_k}\left[T_o + T_1 X_k + f_k\left(C_a + \frac{C_s}{pr}\right)\right] . \quad (28)$$

For illustration, we will first assume $C_1 = \$0.72$/min (both users about 330 miles from their stations), and the near future coefficient values, $T_o = \$150,000$, $T_1 = \$7,000$ $C_a = \$4.5 \times 10^6$, and $C_s/pr = \$7.29 \times 10^6$. Also, for the first case, we assume a two-station system, so $f_k = 0.5$, and both have installed $X_k = 600$ channels, whether yet needed or not. This channel capacity could carry as much as $600 \times 25,000 = 15 \times 10^6$ revenue min/year (if available) or somewhat more if off-peak uses were adequately stimulated. Initially, the use would be much less, so Y_k will be used as the independent variable, and (28) becomes

$$C_{600} = 0.72 + \frac{10^6}{Y_k}\left[8.7_{(\text{stations})} + 11.79_{(\text{satellite})}\right] \text{ \$/revenue minute.}$$

With all 600 channels installed, there is reasonably good balance between station and satellite costs. Figure 13 shows how this cost per revenue minute falls as Y_k increases. Considering the present transatlantic cost (actually the rate) to be \$4.00 per minute, this system would not break even at less than $Y_k = 6.3 \times 10^6$, or about 42% capacity. However, if the stations started with only 300 channels, the annual station cost would drop to \$4,500,000, lowering the break-even Y_k to 5.03×10^6 revenue minutes per year, or about 30% of capacity. Clearly, lowering the satellites system's $\$11.79 \times 10^6$ per year, or lowering the $T_1 = \$7,000$ channel cost, would be necessary to achieve any much lower break-even volume.

Next consider two 30 channel stations on a similar basis, with $f_k = 0.025$ and $Y_k = 30Y_{max/ch} = 0.75 \times 10^6$ revenue min/year:

$$C_{30} = 0.72 + \frac{10^6}{Y_k}\left[0.72_{(\text{station})} + 0.59_{(\text{satellite})}\right] .$$

Here, the greater fraction of the cost is for station use, though it is still not badly out of balance with the satellite use cost. For $C = \$4.00$/revenue min, $Y_k = 0.404 \times 10^6$, or 54% of the station capacity. The stations could not start with just half of their 30 channels without becoming slightly overloaded before they could break even after increasing to 30 channels. Hence, they might start with, say, 20 channels, but this would lower the station cost only to \$580,000/year and the \$4.00 break-even to $Y_k = 0.361 \times 10^6$, or 48% of full capacity.

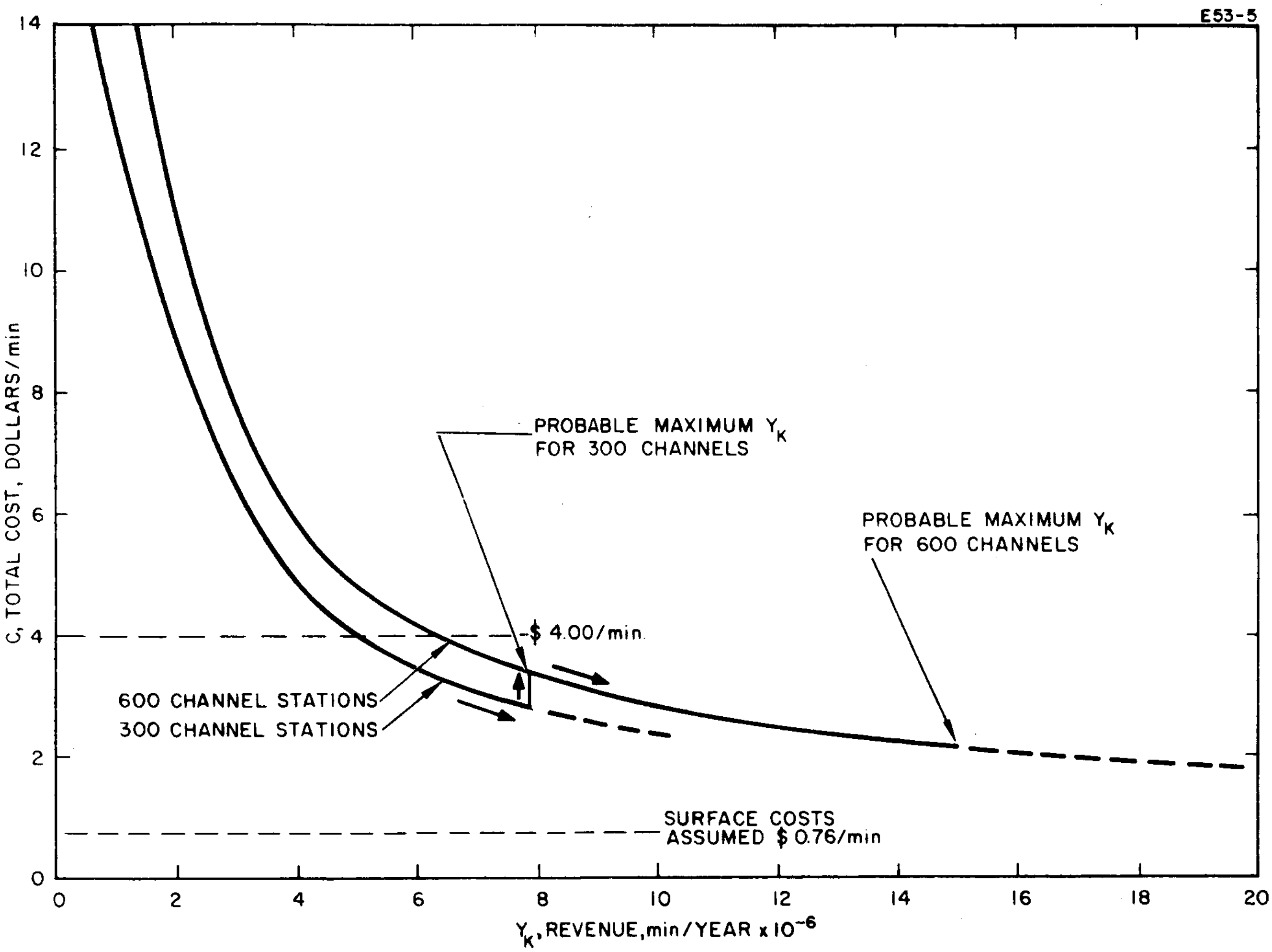

Fig. 13. Total cost as a function of traffic.

Carrying this to absurdity by considering a pair of three-channel stations,

$$C_3 = 0.72 + \frac{10^3}{Y_k}\left[2(150 + 3 \times 7)_{(\text{station})} + 59.0_{(\text{satellite})}\right].$$

Station use costs, primarily in the fixed component, have greatly exceeded the satellite use cost. For $C_3 = \$4.00$, $Y_k = 124 \times 10^3$ min/year, but the three channels would be fully loaded at only 75×10^3 min/year!

If it is assumed that the satellite is used to its 1800 duplex channel (three repeater) capacity by correspondingly more or larger stations, we assume that the f_k's are lowered proportionately, thus helping the 600 channel stations considerably, but not helping the three-channel station significantly.

Changing the assumed surface communication cost only changes the total cost C by the same amount.

Use of the optimistic or far future assumptions leads to a much brighter picture in many respects. Still using \$0.76/min for the surface communication, the cost equation becomes

$$C_x = 0.72 + \frac{10^3}{Y_k}\left[2(60 + 4X) + 2780 \times \frac{2X}{3600}\right].$$

Note that the satellite fractional cost per station f_k has been taken as X/3600, its fraction of the one-way channels of three repeaters, and that two stations are considered. In an all-random access system of many stations a somewhat lower fraction could be used because all stations would not use all their capacity at the same time. For further simplification, we let $Y_k = 25,000$ FX, when F is the fraction of the station's use of full capacity (25,000 revenue minutes per channel year). This leads to

$$C_X = 0.72 + \frac{1}{F}\left[\frac{4.8}{X} + 0.382\right].$$

Figure 14 shows C_X versus F for station pairs of X channels each. With full use of large stations (F = 1 and 4.8/X negligible), the user-to-user cost would approach \$1.14/min, of which only \$0.38 is for use of the satellite system and earth stations! Remembering that the $C_1 = \$0.72$ was based on U.S. and European surface rates for users

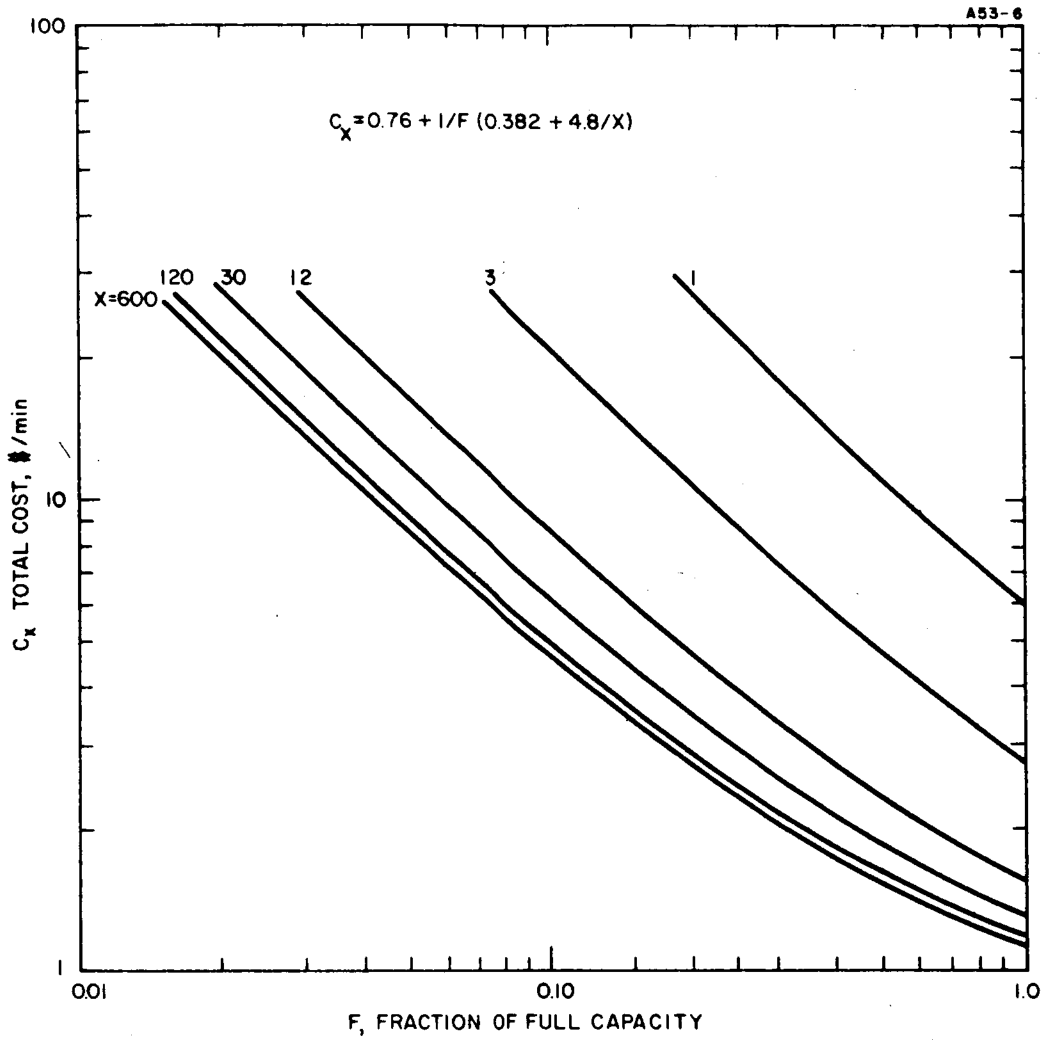

Fig. 14. Total cost as a function of fractional use.

about 330 miles from their stations and that the average user may be considerably farther from his station, one recognizes the possible future importance of surface communication rates in the use of satellite communication. In the above case, about one fourth of the cost is to span up to 10,000 miles between stations and the remaining three fourths to cover the 600 surface miles between users and their stations. This seems comparable to jetting from Chicago to Washington in less than two hours, but over four hours from hotel to hotel!

G. Optimum Service Area of Earth Stations

Recognizing that the surface communication cost component increases with user-to-station distance, and that it could become a major cost component in the future, it is appropriate to study the probably optimum service area of earth stations. Letting stations serve smaller areas reduces the user-to-station average distance and, hence, reduces the surface communication cost component, but requires smaller stations having greater cost per channel. Consequently, under any given set of assumptions, there must be an optimum service area per station, leading to a minimum average user-to-user cost. The practical considerations of geographic boundaries, inequalities of population distribution, industrialization, economic development, etc., preclude attempting a rigorous solution. Instead we assume an unbounded area uniformly populated with potential users of satellite communication. Under this assumption the ideal service area for each earth station will be hexagonal with d_o being the radius of an inscribed circle as depicted in Fig. 15. The area of each hexagon is

$$A = 2\sqrt{3}\ d_o^2 \quad , \tag{29}$$

and the average distance $\bar{d}$ from all points within the hexagon to the station at its center is $0.6825\ d_o$. We assume a traffic density of D revenue minutes per year per square mile for calls from and to this area. The yearly traffic of station k is $Y_k = DA = 3.464\ D\ d_o^2$ revenue min/year. We assume an average surface communication cost (actually the "rate") in the form

$$C_{lk} = C_{ok} + C_{dk}\,\bar{d} \tag{30}$$

and use the U.S. and European values, remembering that the approximation for the U.S. is not accurate at less than about 200 miles.

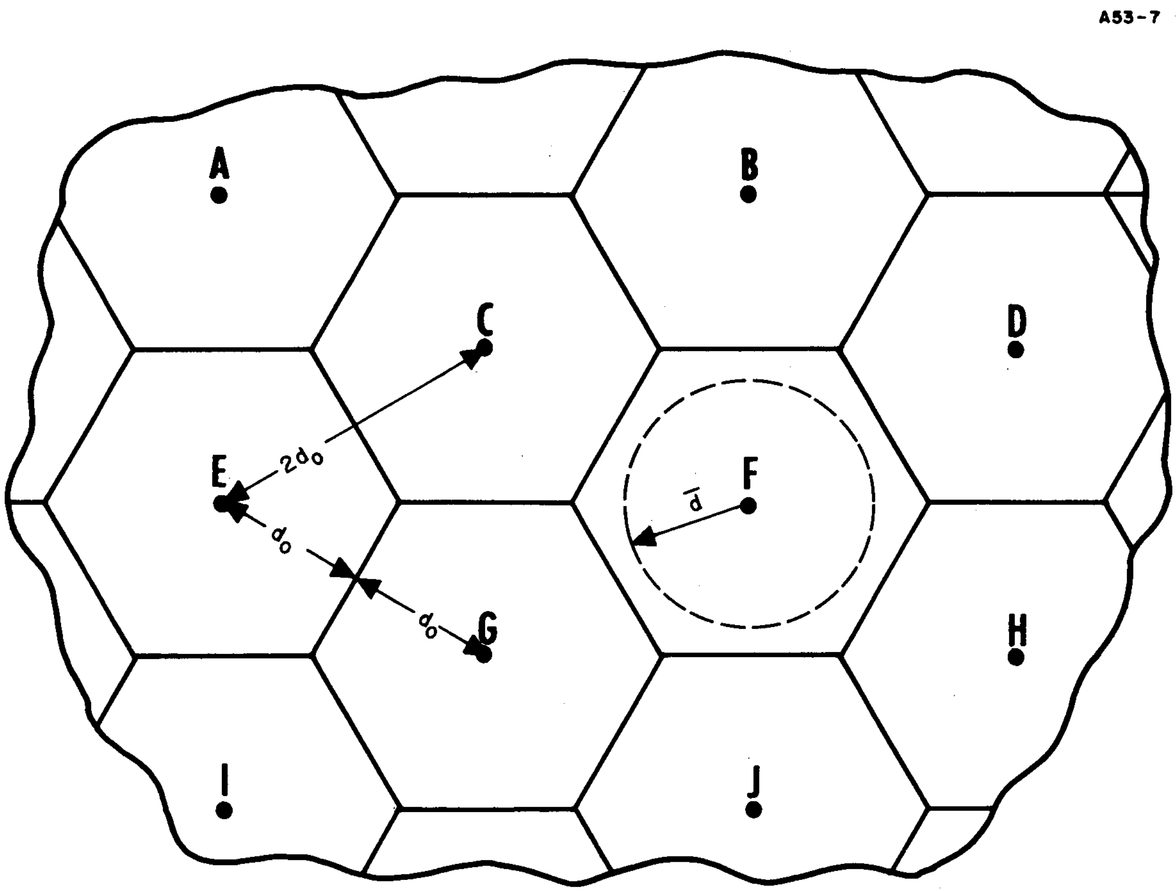

Fig. 15. Ideal hexagonal service areas of earth stations.

The surface plus station cost at one end of a satellite circuit (e.g., the U.S.) is independent of that at the other end (e.g., Europe) and the satellite use cost per revenue minute does not depend on how many stations serve the same users, if its total use remains the same. Hence, only the surface and station cost at one end need be considered in determining the optimum value of d_o at that end. Let this be, from (14) and (30),

$$C_k = C_{ok} + C_{dk}\bar{d} + \frac{T_o + T_1 X}{Y_k} \qquad (31)$$

Clearly, X is related to Y_k because each channel will carry not more than 25,000 revenue minutes per year; with full channel use,

$$X = \frac{Y_k}{25,000} = \frac{3.464\ D\ d_o^2}{25,000}\ , \qquad (32)$$

and, consequently,

$$C_k = C_o + C_d\bar{d} + \frac{T_o}{3.464\ D\ d_o^2} + \frac{T_1}{25,000}\ . \qquad (33)$$

Expressing $\bar{d}$ as $0.6825\ d_o$ and equating the derivative to zero, the optimum d_o for minimum C_k is determined:

$$\frac{dC_k}{d\,d_o} = 0 = 0.6825\ C_d - \frac{T_o}{3.464\ D\ d_o^2} \times \frac{2}{d_o^3} \qquad (34)$$

from which

$$d_o = 0.946\left(\frac{T_o}{DC_d}\right)^{1/3} \qquad (35)$$

or

$$\bar{d} = 0.645\left(\frac{T_o}{DC_d}\right)^{1/3}\ . \qquad (36)$$

To establish an illustrative value of D we use the AT&T estimate[6] of 7,000,000 overseas telephone messages from the U.S. in 1965, increasing to 100,000,000 in 1980, and assume that half is carried by the stationary satellite system in 1965, increasing to 90% by 1980. If the 3×10^6 square mile continental area of the U.S. were of uniform traffic density and average calls were 5.5 min long,

$$D_{65} = \frac{0.5 \times 7 \times 10^6 \times 5.5}{3 \times 10^6} = 6.4 \text{ revenue min/square mile/year}$$

Hence for this 1965 forecast, and using $C_d = 0.148 \times 10^{-3}$ \$/mile/min and $T_o = \$150{,}000$, the hexagonal service areas' inscribed diameter should be $d_o = 510$ miles, for which the average user distance is $\overline{d} = 348$ miles. These distances would be modified somewhat by taking account of the decreasing surface cost per mile at short distances. However, for this d_o, the station's service area would be 905,000 square mile, or about 30% of the area of the continental U.S. Thus, if the U.S. were uniformly populated and could be divided into such hexagonal areas, it should have about three earth stations. Certainly there should be more than one; probably there should be one near each coast and one in the midwest.

Using the 1980 forecast and $T_o = \$60{,}000$ leads to distances less than 200 miles, and to correspondingly more stations, but the surface communication cost approximation is not valid at such short distances. It is apparent, however, that the optimum number of stations for 1980 may be surprisingly large.

The simple approximation (eq. (30)) appears valid for Europe, even at short distances and its slope C_d is much larger than for the U.S. Hence, for the same density D, the optimum separation of stations in Europe would be less than for the U.S. by the ratio

$$\sqrt[3]{148/1100} = 0.514 \ .$$

Actually the density of telephone use in Europe is considerably lower than ours, but it may increase more rapidly.

Altogether, it appears that further study of earth station service areas would be useful. Such study should consider effects of other surface rate structures, geographic constraints, nonuniform density distributions, effects of deviation from optimum areas, etc.

The eventual feasibility of using satellite communication within the United States, say from coast to coast, seems to depend on whether the C_o term in the surface rate equation would be applied from both stations or just from one. If for the first 3 min surface communication is charged as ($ 1. 07 + 0. 0005 d_h) + ($ 1. 07 + 0. 0005 d_k), these two distances could not exceed 220 miles total, with free satellite service, without this surface cost exceeding the $ 2. 25 transcontinental rate! If, however, the surface charge were $ 1. 07 + 0. 0005 (d_h + d_k), as seems more reasonable, the surface charge when $d_h = d_k = 300$ miles would be $ 1. 37, leaving $ 0. 88, or about $ 0. 29/min for the station and satellite system costs. This obviously would not be possible except with a very large and efficient satellite system of the relatively far future.

H. Concluding Comments

The numbers which have been used in this study are not claimed to be accurate, but are only illustrative and presumably reasonable estimates, with which readers may disagree. The methods of analysis are more important and the reader is encouraged to try them, using whatever numbers he considers reasonable. It is believed that the use of any reasonable numbers will lead to similar general conclusions, as follows:

1. Initially, if launch probability and satellite life expectancy are low, the annual cost for satellite use will considerably exceed that for station use and the surface communication cost will be still lower.

2. At present transatlantic rates, the system may operate at a loss, even between large stations, until the traffic builds up to a substantial fraction of the system capacity.

3. For very large earth stations, the annual fixed cost per channel T_o/X should be negligible. Hence, the small stations' economic handicap is T_o/X. The annual cost per channel of a small station will become twice that of a very large station when its number of channels is $X = T_o/T_1$, the ratio of fixed to per channel annual costs. At present, T_o/T_1 appears to be about 20 to 25 channels for a stationary satellite system, but sufficient effort toward reducing station fixed costs may lower T_o/T_1 to about 15 or even 12 channels. For non-stationary systems T_o/T_1 would be much larger because of the more expensive earth antennas. For $X << T_o/T_1$ the annual over-all per-channel cost increases rapidly toward $T_o + T_1 \simeq T_o$ for a single channel station, a cost which generally would be prohibitive.

4. Initially, if satellite system annual costs are high, the small stations' economic handicap may be relatively unimportant. The user-to-user cost may not be much greater between small stations than between large ones.

5. As the cost per launch decreases, and especially as life expectancy and orbiting probability improve with time, the annual cost of the satellite system will decrease. The cost per channel decreases further as the satellite's channel capacity and usage are increased. It should not be long until the total earth station and satellite system annual costs are in balance. Thereafter, further reduction of satellite system annual costs will make the earth station costs relatively more important, thus tending to increase the small stations' economic disadvantage.

6. The use of small earth stations may become relatively large in isolated or underdeveloped parts of the world, despite relatively high user-to-user costs. The relatively low initial investment required for a small earth station is within the means of many nations which have not been able to invest in extensive surface communication systems. Moreover, ownership of an earth station and participation in satellite communication may become an important "space age status symbol."

7. Eventually (based on continued use of Advanced Syncom type satellites) the annual satellite system costs would become much less than the earth station costs. These latter costs, in turn, would become less than the user to station surface communication costs when users are 300 or more miles from their stations.

8. There is an optimum average distance from users to their station which is proportional to the cube root of the station's annual fixed cost T_o and inversely proportional to the cube root of the use density D and the per mile surface communication cost C_d. Since this is a cube root relation the optimum average user distance is not highly sensitive to variation of these parameters. Nevertheless, the relation enables one to predict that it should not be many years until the United States, for example, should have several earth stations to achieve minimum cost service.

9. Intensive effort should be made to encourage off-peak uses of satellite communication, thereby increasing $Y_{max/ch}$ beyond the postulated 25,000 revenue min/year, which corresponds to only three busy hours per business day. Television, for example, is essentially an off-peak service because the most popular viewing hours are several hours after the close of the business day. An overnight facsimile "V-mail" service might be another "valley-filling" possibility.

10. Compared with all prior (surface) communication, satellite communication is unique in two respects: (a) within the one-hop distance (up to about 11,000 miles) satellites use cost is independent of the distance between stations; (b) this constant cost, and the satellite being a system mode for all its stations, make "exchange" type multiple access operation not only possible but so attractive as to be virtually essential. Such operation will revolutionize long-haul communication, increasing its "value" with the number of available stations, much as the value of local telephone service increases with the number of telephones which can be called. Hence, future engineering effort should be directed toward keeping the cost of satellite communication minimized within the advancing state of the art, paying special attention to controlling those cost factors which otherwise would become dominant ones.

11. Further study of the optimum service area of earth stations seems important and potentially rewarding. The results of such study could assist telecommunication administrations in their long-range planning and probably will revise market forecasts for earth stations.

12. A substantial increase in numbers of earth stations, and decreased spacing, may make interference coordination more difficult. The difficulty in obtaining sufficient interference-free station sites may limit the increase in number of stations and may further increase the importance of studying the control of surface interference.

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