A Model of a Domestic Satellite Communication System

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A preliminary study of a domestic satellite system is reported. Since the objective was to determine what might ultimately be possible, no attempt is made to relate system capacity to estimated needs; rather an effort has been made to conceive a system to carry the greatest possible amount of traffic. By making full use of modern rocket technology including the Saturn V class propulsion systems, highly directive multibeam antennas operating in the range from 15 to 40 GHz, interference resistant modulation methods, highly stabilized synchronous repeater platforms, and integrated solid state microwave repeater electronics, a very large communication capacity is obtained. For example, using 50 ground stations and 50 satellites operating in bands at 20 and 30 GHz, each 4 GHz wide, a total of 100 million voice circuits, or equivalent, can be provided.

I. INTRODUCTION

Domestic satellite systems can be expected to handle a large amount of traffic compared with that carried by transoceanic systems; this is true even if for various reasons only a fraction of the total domestic traffic goes via satellite. For this reason among others, the presently allocated frequency bands at 4 and 6 GHz are not well suited to domestic use. Frequencies above 10 GHz are attractive in that they are not as heavily loaded as the lower frequency bands. But they are subject to propagation difficulties which generate new problems in their use.* The amount of atmosphere traversed by a ground-to-satellite path can be relatively small if the look angle is restricted to elevations which are not too small. However, attenuation will be large under conditions of excessive rainfall and diverse ground terminals will

* Similar arguments apply to terrestrial systems operating above 10 GHz. These are not discussed here, but some of the propagation studies described here were designed with the needs of terrestrial as well as satellite systems in mind.

be needed when common carrier grade continuity of service is required.

The frequency range from 10 to 40 GHz can offer a unique opportunity if broad continuous bands are allocated for satellite service. Modern rocket technology gives us the opportunity of placing large multichannel satellite repeaters in synchronous (24 hour) equatorial or inclined orbits, thus making it possible to exploit broad communication bands and to use orbit space very efficiently. This would make possible best use of orbit space, frequency space, and the investment in facilities since very large amounts of traffic could be carried by each satellite repeater. The availability of such frequency allocations and adequate orbit space is assumed in what follows. *A basic assumption made here is that frequency space and orbit space are precious and limited resources which must be conserved.*

Radio frequencies above 10 GHz have disadvantages in propagation, but their short wavelength makes possible very narrow beams from antennas of a size suitable for use on a contemporary satellite. If we combine this feature with interference resistant modulation techniques, such as PCM and multiple feed antennas, we can construct multichannel, multibeam satellites which can communicate simultaneously with many ground stations using only one frequency assignment. The idea can also be used in reverse to enable a single ground station to communicate simultaneously with several satellites. Thus if we have N channels per frequency assignment, S satellites, G ground stations, and every satellite "sees" every ground station, and vice versa, we have a total communication capacity of $C = G \times S \times N$ channels. With tens of ground stations and tens of satellites working in bands a few GHz wide, this can results in a truly prodigious capacity.

In order to take full advantage of these possibilities, very reliable, efficient, and small radio repeaters for satellites will be required. Solid-state integrated microwave circuits and devices will help insure reliability and small size, and we have reason to hope that eventually efficient use of dc power can also be obtained. This is important since a significant part of the total in-orbit satellite cost results from the solar power supply.

II. SYSTEM CONCEPT

Designers of communications systems normally have as their objective a facility to meet a fairly well defined need and naturally try to choose a system configuration which is most economical in serving that need. Thus, one of the most important parameters influencing system design is the present traffic level and the expected growth rate. In addition to the amount, the geographical distribution of traffic is important. If a large part of the traffic terminates at one node, the usable system capacity will be reached when all of the channels from the satellites to that node are full. If the traffic volume continues to increase but the geographical distribution remains unchanged, growth must be handled by other (terrestrial) means.

While much of the present-day telephone traffic is concentrated in large metropolitan centers, an assumption that this trend will continue into the indefinite future may not be warranted. There are many signs that some of these areas have reached a "critical mass" and are beginning to explode; future growth may be spread much more uniformly over the United States. At any rate, we have assumed uniform traffic density when calculating total system capacity; to the extent that this is untrue, part of the system potential will be unrealizable. This approach has the disadvantage of making the study somewhat more abstract, but our goal is to display the potential of a satellite system designed for domestic communication rather than to design a specific system.

To this end we postulate 50 ground stations distributed more or less uniformly over the continental United States working with 50 satellites in synchronous orbit stationed due south of the United States and spaced 1° apart. Each satellite is precisely stabilized in attitude, carries a 10 meter multibeam antenna operable at 20 and 30 GHz, transmits down with a power output of 2 watts at 20 GHz and receives from the ground at 30 GHz. We further assume that two bands each 4 GHz wide and centered at 20 and 30 GHz are assigned to this service. Given these frequency bands, we can design for eight 630 megabit per second two-way channels using four-phase angle modulation. To serve 50 ground stations each satellite will require (eight RF channels per beam) $\times$ (50 beams) $=$ 400 repeaters. At 10,000 voice circuits per RF channel (630 megabits per second capacity) this results in 4 million (one-way) voice circuits per satellite. In terms of present day telephone traffic, this is a very large cross-section, but for broadband services which require 100 (*Picturephone®* visual telephone) to 1,000 (television) times more bandwidth, it is not so large.

If the ground stations are equipped with 10 $\times$ 17 meter multibeam antennas, 10 watt 30 GHz transmitters and a cooled parametric receiver preamplifier operating at 20 GHz with an equivalent noise temperature of 150°K, one can calculate carrier-to-noise ratios with the result shown in Table I. Several factors are worthy of note. The ground-to-satellite link is assumed to suffer interference −39 dB relative to the desired carrier; the down link interference is assumed −33 dB relative to the carrier. In both cases the most important interfering signals are admitted by the sidelobe response of the multibeam satellite antenna. Interference at the satellite caused by minor lobes of the ground station antennas can be controlled by spacing of the satellites, and in fact, if the satellites are 1° apart as assumed and the 10 × 17 meter 30 GHz ground station antennas have a response

TABLE I — C/N ON HEAVY ROUTES

System Parameters

d = 23,000 miles = 3.7×10^7 m.
f = 30 GHz (up link)
f = 20 GHz (down link)

Width of RF assignments (2)		4000 MHz
Two-way RF channels per beam		8
Pulse rate		315×10^6/s
Bit rate (4 φ angle mod.)		630×10^6/s
RF channels	per satellite	8(G)
	per ground station	8(S)
	in system	8(G)(S)
Picturephone® circuits per RF channel		100.
Voice circuits per RF channel		10,000.

Rocket class: Saturn V

Satellite

Antenna	
Diameter	10 m
Diameter illuminated by each feed	8.3 m
Allowance for illumination taper (−2 dB)	0.63
Effective area	34.0 m^2
Transponder power output	+3 dBw
Receiver noise figure	6 dB
Receiver noise bandwidth	400 MHz

Ground Station

Antenna	
Dimensions	10 × 17 m
Sector illuminated by each feed	10 × 10 m
Allowance for illumination taper	0.80
Other problems (−1.5 dB)	0.70
Effective area	56.0 m^2
Transmitter power output	+10 dBw
Receiver noise temperature, T_e	150°K
Receiver noise bandwidth	350 MHz

Carrier-to-Noise Ratio	Up link at 30 GHz	
Net path loss $P_T/P_R = \lambda^2 d^2/A_T A_R$	78.6	dB
Transmitter / Receiver system loss, including filters	1	dB
Receiver power, $P_R = P_T - 80.6$ dB	−70.6	dBw
Satellite receiver noise	−112	
C/N at satellite	41.4	
C/I for ground stations 264 miles apart	39	dB
C/N + I at satellite	37.0	
	Down link at 20 GHz	
Net path loss $P_T/P_R = \lambda^2 d^2/A_T A_R$	82.1	dB
Transmitter / Receiver system loss, including filters	0.5	dB
Received power, $P_R = P_T - 83.1$ dB	−80.1	
Ground station receiver noise (no rain)	−121.5	dBw
C/N in ground receiver (no rain)	41.4	
C/I for stations 275 miles apart	33	
C/N + I (including up link)	31.1	
C/N + I for 10^{-7} error rate	20.0	dB
Margin (no rain attenuation)	+11.1	
C/N + I for 10^{-5} error rate	17.0	
C/N + I (for 10 dB rain attenuation)	25.7	
Margin during moderate rain	+8.7	

envelope which follows a fourth power law, interference at the nearest neighbor will be so small as to be negligible.

A similar comment applies to interference at a ground receiver admitted by the sidelobe response of the 20 GHz 10 × 17 meter ground station antenna. Under conditions of normal propagation (no rain) the system will be interference limited on both the up and down links. This is unusual in present day radio system design and comes about because we are attempting to get the maximum possible communication capacity. Any further improvement will require better antennas. Notice also that the down link margin for a 10^{-5} error rate is +8.7 dB during a rainstorm which produces 10 dB of attenuation.* For a similar, but independent fade on the up link the margin is 14 dB.

Another important feature of the model satellite system is the fact that a given repeater can be seen from many areas in the United States. This makes possible a flexibility not found in terrestrial links

* Calculation of error rates corresponding to the stated ratios of $C/(N + I)$ indicates much smaller rates than those given in Table I. The stated larger values allow for imperfection in a high bit rate PCM receiver.

where standby or alternate facilities must be provided link by link. In the satellite case we have, at least in principle, the possibility of making good a fault in one part of the network with capacity normally assigned to a distant link and temporarily unused because of time zone or other differences.

On the other hand, if we adopt the now generally accepted rule that only one 24-hour synchronous satellite link is allowed per circuit, this ubiquitousness of satellite system ground terminals is not just a convenience, it is a necessity. If a satellite system is to carry the bulk of the domestic traffic, we require not just circuits from outlying stations into a network node, but circuits which go directly from every place to every other place; thus we require many ground stations for complete coverage. The fact that channels from every ground station pass through each repeater makes available in one place channels serving widely separated parts of the country and provides us with the opportunity to reroute channels on board a satellite in accordance with changing traffic patterns.

To accomplish this, we must provide a suitable switching matrix; this is most conveniently implemented at the intermediate frequency which can be common to all repeaters, and hence channels can be interchanged as desired upon command from the ground. This flexibility also makes it possible to make good a limited amount of failed apparatus on board the satellite.

III. PROPAGATION STUDIES

Since electromagnetic waves with frequencies above 10 GHz are severely attenuated by liquid water, satellite systems using these frequencies must be designed to tolerate a few dB of attenuation which may be experienced for long periods and to switch to a diversity ground station on those rare occasions when a very large attenuation is caused by excessive rain. Also the diversity ground station must be far enough removed so that there is little likelihood that an intense rainstorm will cover both ground stations at the same time.

If the attenuation statistics on the two paths are uncorrelated and enough margin is provided to make both outages small, the system outage time can be reduced to a satisfactory degree. In general, this requires a more detailed and a more quantitative knowledge of rainfall and attenuation caused by rain than presently exists. Accordingly, measurements have been undertaken at Bell Telephone Laboratories to determine for terrestrial paths and for ground-to-satellite paths, the constraints on system design imposed by this natural phenomenon.[1] These programs are discussed elsewhere; only a summary is attempted here.

Measurements of rain made at the earth's surface are not sufficient to determine attenuation along a satellite-to-ground path, but they can indicate the amount of structure characteristic of a typical rainstorm. A sample contour map of instantaneous rain rate as measured by the Crawford Hill rain gauge network is shown on Figure 1.[2] These data form a snapshot of a specific area at a given moment. It

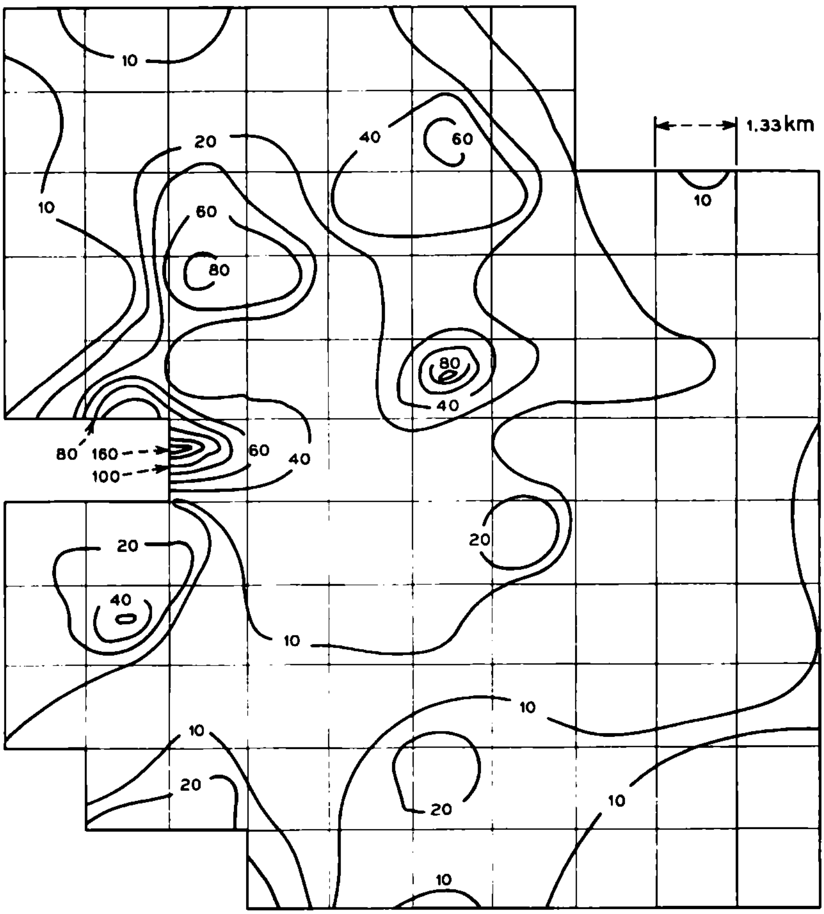

Fig. 1 — Sample scan of Crawford Hill rain gauge network for August 25, 1967 at 20:43 EST, contours in mm per hour.

was selected from many hours of data to illustrate one of the most intense rainstorms observed during a one-year period of measurement. The data illustrate that the most intense rain occurs in very limited cells and that rain which covers large areas (square miles) falls at the rate of one inch per hour or less. These are the considerations behind the proposal to use diversity ground stations separated by several miles.

A more quantitative determination of attenuation statistics is being made with a radiometer which tracks the sun. This installation, which has been described by Wilson,[3] measures the noise received from the sun at 16 and 30 GHz and thus determines the attenuation caused by any intervening precipitation. Figure 2 is a photograph of the Crawford Hill sun tracker. At night the radiometer is pointed to a cold part of the sky and detects precipitation as an increase in effective temperature. Good accuracy is obtained to about 35 dB of attenuation, when tracking the sun, and to about 10 dB when the cold background is used. Thus we are accumulating data which will be helpful in the design of domestic satellite systems, especially those operating above 10 GHz.

Unfortunately, if one is to obtain a statistically meaningful result, operation must include at least a year in order to encompass all of the

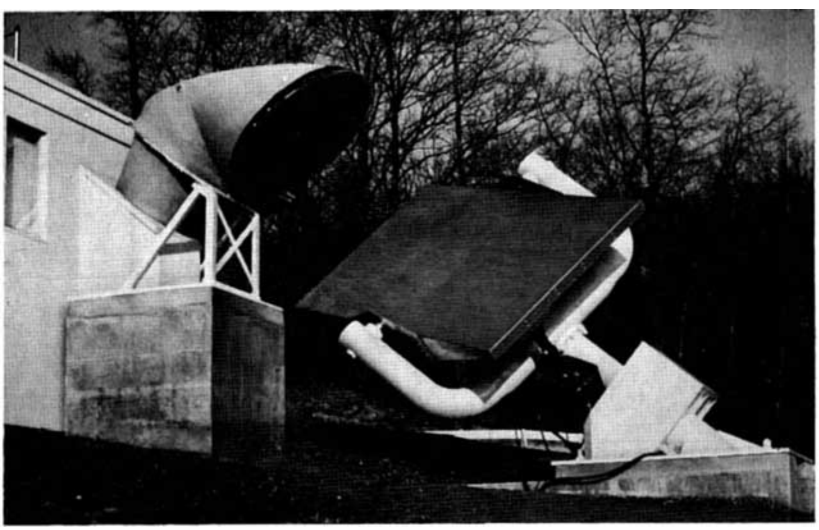

Fig. 2 — Crawford Hill sun tracker.

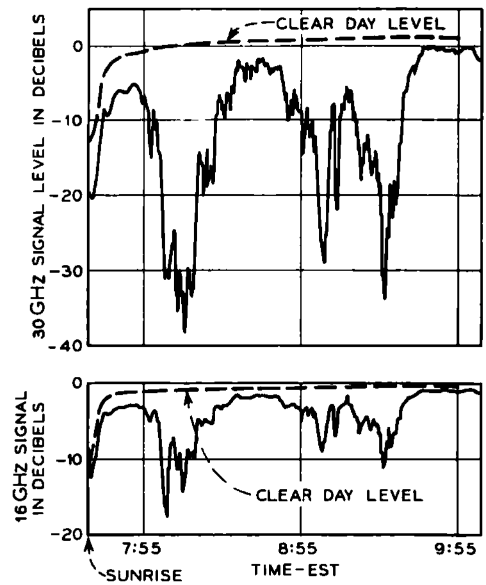

Fig. 3 — Recording by Crawford Hill sun tracker of shower on December 12, 1967.

seasons. And this cannot be hurried. When we have obtained enough data to be worthy of statistical analysis, it will be published; data obtained over a shorter interval must necessarily be regarded as incomplete. With this qualification, we present the following data and observations which, though limited, are relevant:

(*i*) Attenuation exceeding 30 dB at 30 GHz (about 10 dB at 16 GHz) and lasting 6 to 8 minutes has ben observed on several occasions. Figure 3 is a strip chart recording showing such an occurrence along with a plot of the simultaneous attenuations at the two frequencies. Table II summarizes the data obtained for about 10 months through August 9, 1968.

(*ii*) These events are associated with intense rain cells (precipitation exceeding 100 millimeters per hour).

(*iii*) Heavy overcast and even light drizzle produce little attenuation (less than 2 dB at 30 GHz).

(*iv*) Attenuation by fog and snow is no problem at these frequencies.

(*v*) Since a second sun tracker is not yet operating, we have no direct data on diversity advantage. However, data from our rain gauge

TABLE II — DATA FROM CRAWFORD HILL SUN TRACKER

Attenuation (dB) at 30 GHz*	Percent of total observing time 3091 daylight hours
>3	1.93
>6	1.02
>9	0.59
>15	0.32
>21	0.18
>27	0.11
>33	0.08
at 16 GHz†	2520 daylight hours
>1	1.29
>2	0.75
>3	0.49
>5	0.28
>7	0.19
>9	0.14
>11	0.12
>13	0.08

* Data from October 14, 1967 through August 9, 1968.
† Data from December 8, 1967 through August 9, 1968.

network indicate that heavy rains are highly structured and are uncorrelated at distances greater than a few miles.

In addition, a variety of locations representative of all of those areas in which ground stations will be located should be investigated. The present sun tracker is located in New Jersey, which is only one of many possible locations, but which does have the advantage of being climatically intermediate between the extremes represented by parts of the gulf coast area and the western desert regions.

Since the sun moves continuously only a small time is spent looking in a given direction; on the other hand, at least some data on many possible satellite paths are being obtained. At best, these data will leave many questions unanswered, but we will have some quantitative data on which to base our system designs. More locations, and particularly the advantage obtained by using two or more diversity ground stations, must be studied.

A beacon in synchronous orbit would be an ideal source for propagation experiments, but if it is to be worth the cost, a satellite experiment must have some advantage over a sun tracker. A stationary satellite with a highly coherent source of adequate power output would make possible simpler and therefore cheaper ground stations. Because it would be stationary, the satellite would not require precise tracking as does the sun. Tracking the sun is simple but does complicate the installation and costs money. Use of a satellite would make possible more observation points for the same total ground station cost and thus enable us to gather design data more quickly. A highly coherent source, in contrast to the thermal noise emitted by the sun, would ease the measurement of the phase coherence of received signals over very large bandwidths. This is important because the system model requires very broad bandwidths (300 to 400 MHz) and correspondingly short pulses.

Direct evidence that satellite radio channels will support such transmission is scarce and more is needed. Considerable indirect evidence is available, however. A relatively short (12.5 km) terrestrial path has been studied at 12 GHz for over a year with only one instance of moderate multipath activity; a second path 6.5 km long was also observed at 18 GHz for more than a year with no evidence of multipath fading.[4] Very large narrow beam antennas have been used for radio astronomy at 30 GHz with no significant beam broadening observed.[5] Measurement with an array at 30 GHz has shown that the phase front of the incoming wave is not badly distorted.[6]

Scattering from refractive index inhomogeneities in the atmosphere could conceivably introduce time delays which would restrict bandwidth, but this same phenomena would broaden antenna beams and reduce antenna gain. Probably the most sensitive indicators are the wide base interferometers used for radio astronomy; some have obtained resolutions of a fraction of a second of arc. All of the above applies to relatively high elevation angles, say, above 15°. It seems certain that all of the difficulties associated with long terrestrial paths will be experienced as the satellite path approaches grazing incidence. The problems which remains is to make this relationship quantitative; this would be most easily done using a highly coherent source on board a satellite. However, if we are to obtain data useful for system design, the satellite must be continuously available to insure that we do not miss any data, and it must be available over a long enough period of time to insure that statistics derived from the data are reasonably stable, that is, seasonal and other variations are included.

IV. INTERFERENCE CONSIDERATIONS

A radio system designed for maximum efficiency will be interference limited. This is true because doing so makes best use of frequency space, geometry (which in the case of a synchronous satellite system includes orbit space), and the investment in facilities. An interference limited system is the end result of trying to get the maximum possible communication with a given limited resource. We assume that the required technology has reached the state where thermal noise can be reduced to a small value compared with interference at least during normal propagation conditions. Calculations of carrier-to-noise ratios made in this paper (see Table I) verify that such an assumption is warranted.

4.1 *Antenna Patterns*

The statement that a radio system is interference limited is equivalent to saying that the radiation patterns of the antennas used are of crucial importance; hence, we start with these. As in other areas, we look at current practice, estimate what may be possible in the future, and try to land somewhere between.

Patterns for an antenna of current design are compared with greatly simplified relationships in Fig. 4. We see that the microwave

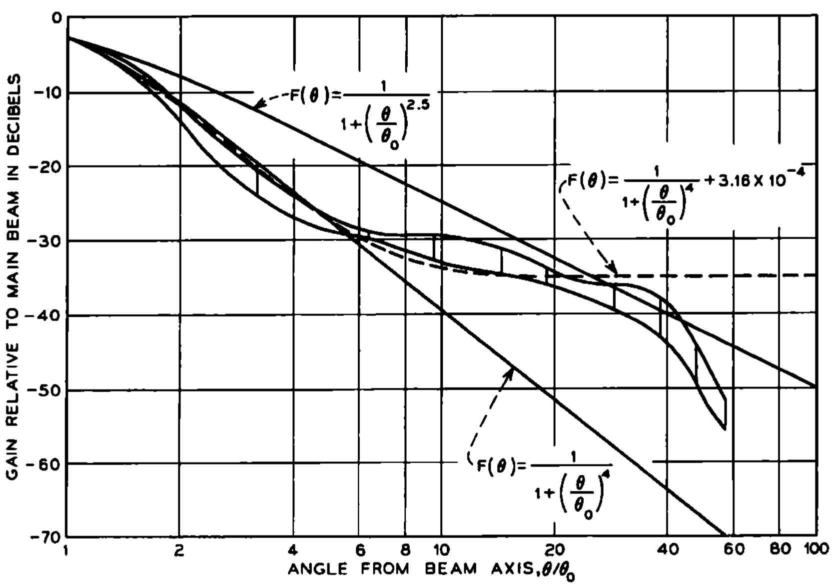

Fig. 4 — Side lobe levels of microwave pole line periscope antenna. Beamwidth = 2.5°, θ_0 = 1.25°. Vertical lines show range of envelope of side lobe levels for both polarizations.

pole line antenna* is almost everywhere better than $F(\theta) = [1 + (\theta/\theta_0)^{2.5}]^{-1}$, where

$$\begin{aligned} \theta &= \text{angle off the peak of main lobe} \\ \theta_0 &= \tfrac{1}{2} \text{ of the 3 dB beamwidth} \\ F(\theta) &= \text{antenna response (power)} \end{aligned}$$

which we understand has sometimes been used in studies by the International Consultative Committee on Radio. In fact, the microwave pole line antenna follows the $(\theta/\theta_0)^4$ curve down to about -25 dB. On Fig. 5 we have plotted theoretical response curves for antenna apertures with specified variations in the amplitude of the illumination together with a uniform phase. We see that the envelope of a $\cos^N [(\pi/2)x]$, where $N = 1$, distribution equals or exceeds the discrimination predicted by the $(\theta/\theta_0)^4$ curve and that for all higher values of N the $(\theta/\theta_0)^4$ curve is greatly exceeded. But, of course, these curves are not for real antennas. However, in Fig. 6 we see the envelope of the pattern of a horn-reflector antenna using a special dual mode feed designed by R. H. Turrin.[7] In this case the pattern discrimination provided by a real antenna considerably exceeds the $(\theta/\theta_0)^4$ curve for all levels of discrimination and both polarizations.†

For our present calculations we use the relationship, $F(\theta) = [1 + (\theta/\theta_0)^4]^{-1}$, with the expectation that a multibeam antenna with a reasonable amount of illumination taper designed to reduce or eliminate aperture blockage by the feeds will be able to do at least this well. We think that the data presented above makes this a reasonable assumption.

4.2 *Interference at Satellite*

Our system model assumes that each ground station communicates with each satellite and vice versa. If we consider the situation at the satellite antenna feed corresponding to a desired ground station, we see that it will receive power from the desired station through its main lobe and from all other ground stations through its side lobes. However, with a fourth power variation in antenna response, the nearest neighbors will contribute most of the interference. Thus if we visualize

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* This is a well-shielded antenna designed for a specific system. It was suggested by A. B. Crawford and measured by R. H. Turrin. (Unpublished work).

† The problem which remains in this case is that no one knows how to build a multibeam horn-reflector antenna.

a rectangular grid of uniformly spaced ground stations, there will be stations stretching out to the north, south, east, and west with spacings 1, 2, 3, . . . times unit distance. The distance from the desired ground station to another ground station having coordinates (n, k) will be $(n^2 + k^2)^{1/2}$; hence, the total interference is

$$F(\theta) = \sum_{n,k}^{\infty} \left[1 + \left(\frac{\theta_{n,k}}{\theta_0}\right)^4\right]^{-1}.$$

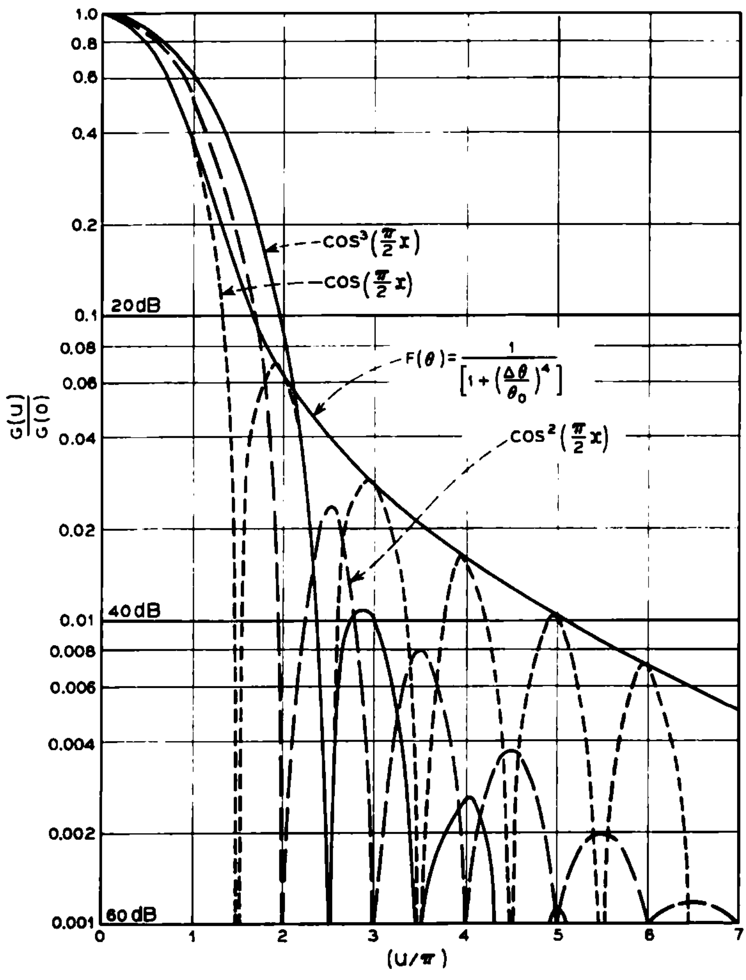

Fig. 5 — Calculated antenna pattern for $\cos^n[(\pi/2)x]$ illumination of square aperture. a is aperture opening. θ is angle with normal to aperture. $u \equiv (\pi/\lambda) a \sin \theta$.

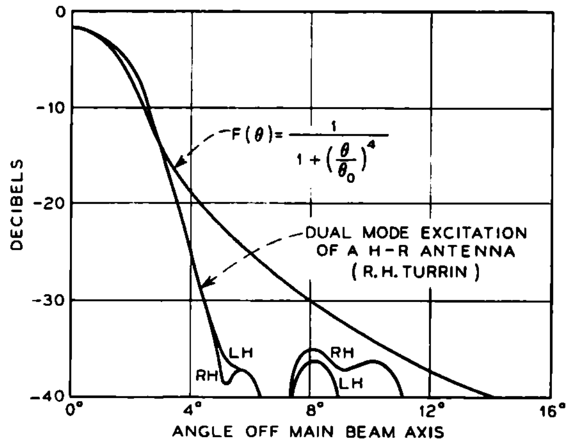

Fig. 6 — Comparison of measured antenna discrimination with assumed value.

When, as in the present case

$$(\theta_{1,1}/\theta_0)^4 \gg 1, \quad \text{and} \quad \theta_{n,k} \doteq \frac{S}{R}(n^2 + k^2)^{\frac{1}{2}}$$

where

S = uniform spacing between ground stations
R = distance to the satellite
$n, k,$ = 1, 2, 3, $\cdots$.

Then

$$F(\theta) = \sum_{n,k}^{\infty} \left[\left(\frac{\theta_{n,k}}{\theta_0}\right)^4\right]^{-1} = \sum_{nk,}^{\infty} \left[\left(\frac{S}{R}\right)^4 \frac{(n^2 + k^2)^2}{\theta_0^4}\right]^{-1}$$

$$F(\theta) = \sum_{n,k}^{\infty} \frac{\theta_0^4}{\left(\frac{S}{R}\right)^4} \frac{1}{(n^2 + k^2)^2} = 5.94\left[\frac{\theta_0}{\left(\frac{S}{R}\right)}\right]^4.$$

Hence, the total interference caused by all of these interfering ground stations will be 5.94 times or about 7.7 dB up on the interference produced by a single nearest neighbor.

As applied to the present case and as assumed for the calculations made in support of Table I where a C/I ratio of 39 dB (net) at the satellite was used, a distance of 264 miles with a 10 meter satellite antenna was obtained. These computations are (see Fig. 7):

$$F(\theta) = \left[\frac{1}{1 + \left(\frac{\Delta\theta}{\theta_0}\right)^4}\right], \text{ or } F(\theta)^{-1} \approx \left(\frac{\Delta\theta}{\theta_0}\right)^4.$$

For C/I = 39 dB (all sources), 39 dB + 7.7 dB = 46.7 dB (one source) thus

$$\left(\frac{\Delta\theta}{\theta_0}\right)^4 = 10^{4.7}, \qquad \frac{\Delta\theta}{\theta_0} = 10^{1.176} = 15.0.$$

For up link $f = 30$ GHz, $\lambda = 1$ cm, and assuming a 10 meter satellite antenna:

$$2\theta_0 = 1.22\,\frac{\lambda}{a} = 1.22\left(\frac{1\text{ cm}}{830\text{ cm}}\right)$$

$$2\theta_0 = 1.47 \times 10^{-3}\text{ rad.}$$

$$\theta_0 = 0.735 \times 10^{-3}\text{ rad.}$$

$$\Delta\theta = 15.0\theta_0 = 11.0 \times 10^{-3}$$

$$S = R(\Delta\theta) = 24 \times 10^3(11.0)10^{-3}$$

$$S = 264\text{ miles.}$$

4.3 *Interference at a Ground Station*

Again we visualize a grid of uniformly spaced ground stations, each of which communicates with every satellite.* Thus a given ground station will be surrounded by beams from the satellite to all of the other ground stations, and the minor lobes associated with these satellite antenna feeds will crosstalk directly into the main beam of the ground station since it is "looking" at the desired satellite. As before, with a fourth power variation in antenna discrimination versus angle, most of the interference will come from the nearest neighbors. The analysis for this case follows the previous one for the interference at a satellite with nearly the same result except that at the longer wavelength (20 GHz) there is slightly less antenna discrimination. As applied to the present example—a 10 meter antenna on a Saturn launched satellite—we obtain the required spacing for the ground stations of 275 miles, as follows (see Fig. 8):

$$F(\theta) = \left[1 + \left(\frac{\Delta\theta}{\theta_0}\right)^4\right]^{-1}, \text{ or } F(\theta)^{-1} \approx \left(\frac{\Delta\theta}{\theta_0}\right)^4.$$

* Obviously this is an idealized model. Even if the ground stations were located in a regular pattern, which is not at all likely, the pattern would appear distorted to the satellite. An accurate calculation must be based on actual locations of ground stations which are at present unknown and north-south spacings will depend on station latitude; the idealized model is adequate for our purpose. No advantage has been taken of polarization. This is deliberate since a quantitative evaluation is not available at this time. We leave any polarization advantage for use in solving unforeseen problems.

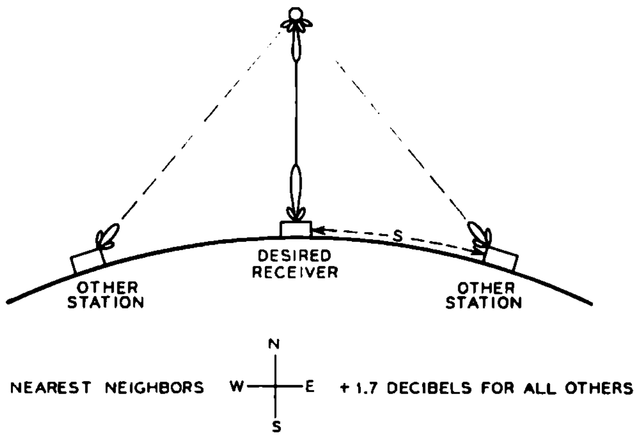

Fig. 7 — Interference at a satellite.

For C/I = 33 dB net, 33 dB + 7.7 dB = 40.7 dB for one source, thus

$$\left(\frac{\Delta\theta}{\theta_0}\right)^4 = 10^{4.07}, \qquad \left(\frac{\Delta\theta}{\theta_0}\right) = 10^{1.02} = 10.4.$$

For the down link $f = 20$ GHz, $\lambda = 1.5$ cm, and assuming a 10 meter satellite antenna:

$$2\theta_0 = 1.22\,\frac{\lambda}{a} = 1.22\left(\frac{1.5\text{ cm}}{830\text{ cm}}\right)$$

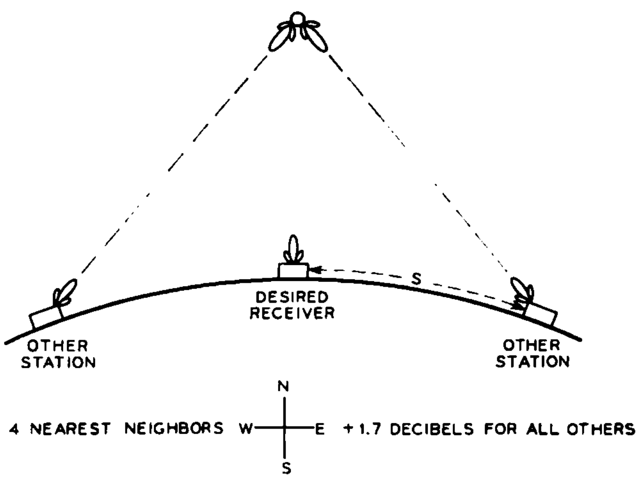

Fig. 8 — Interference at a ground station.

$$\theta_0 = 1.10 \times 10^{-3} \text{ rad.}$$

$$\Delta\theta = 10.4\theta_0 = 11.45 \times 10^{-3} \text{ rad.}$$

$$S = R(\Delta\theta) = 24 \times 10^3(11.45 \times 10^{-3})$$

$$S = 275 \text{ miles.}$$

4.4 *Modulation Techniques*

The use of different look angles to achieve discrimination by antenna pattern is one important means for achieving co-channel operation in a limited geographical area. Another is choice of a modulation technique resistant to interference, particularly co-channel interference. The possibilities here are many, at least in theory. However, when, as in the present case, one is considering channels having bit rates of several hundred megabits per second, complicated encoding schemes—especially those which require appreciable storage—are not worth the cost and complication. In the present case, as is indicated in Table I, we have chosen four-level over binary PCM even though the latter is more resistant to interference.*

While the increased resistance to interference provided by two level modulation is attractive, our studies indicate that the possibility to double the channel capacity in approximately the same bandwidth by using four levels is well worth its cost. It is conceivable that even more levels would be advantageous, but the return diminishes at such a rate that specific situations must be studied to be certain. These studies are being continued.

One of the features of quantized modulation is that the signal can be regenerated at intermediate repeaters in which case any errors made in regeneration accumulate along the system, but thermal noise, interference from crosstalk, and imperfections in repeater characteristics do not. In the present satellite system configuration, the satellite-to-ground or "down-link" is the most difficult from both the standpoint of thermal noise and interference. This comes about because we can use a powerful enough transmitter at the ground station to make thermal noise at the satellite receiver front-end negligible, and we can space the satellites far enough apart (1° in the present example) so that, with highly directive ground station antennas,

* Buried in these statements are assumptions about the manner in which co-channel, adjacent frequency channel, and adjacent time slot interference impair a signal. These problems are being intensively studied and will be reported elsewhere.

interference at adjacent satellites is small. Under these circumstances it is not worthwhile to regenerate on board the satellite.

However, if in the future synchronous orbit space becomes so crowded that we are forced to tolerate the same interference on the up-path as on the down-path, regeneration will be very much worthwhile. If we regenerate, the error rate would increase from, say, 1 in 10^7 to 2 in 10^7 for both links, but if we do not regenerate, the error rate would increase from 1 in 10^7 to 1 in 10^4. However, under actual operating conditions the vagaries of propagation will affect the received signal level and under some conditions can adversely affect the signal-to-interference ratio. Thus an actual system must be designed with some margin for changes in signal level, and even a few dB of margin will make regeneration on board the satellite much less profitable. Regeneration at each intermediate repeater is most useful with very stable media such as coaxial cable or waveguide, where changes in transmission loss are small and systems can be designed to operate continuously at the specified error rate.

V. THE SATELLITE

Satellites of the size and complexity envisaged here have never been built, but there is no particular reason why they cannot be. Once launched, the environment in which the repeater must operate is in many ways more benign than here on earth. In the early days, our ignorance of the space environment clouded our vision and obscured this fact. But experience over the past several years with communication and other satellites has encouraged consideration of larger and more sophisticated spacecraft. Reliability remains a problem, but this is not peculiar to spacecraft since present day terrestrial communication equipment must also be designed to be maintenance free for up to ten years because of cost.

Design of a radio repeater for satellite use has much in common with design of its terrestrial counterpart. This is particularly true where, as in this case, such large high-gain antennas are used on the spacecraft and at the ground station that the loss on a satellite path is not much larger than is encountered on typical terrestrial paths. Using this approach, a satellite repeater can be of rather conventional design, but with special attention to efficiency in the use of dc power and reliability. Integrated microwave circuits and solid-state devices would be used throughout except for the traveling wave tube final RF amplifier.

A repeater of this type is estimated to weigh 3¼ pounds and to require 18 watts of unregulated power from the solar supply for an RF output of 2 watts per channel. To this must be added 2 pounds per ground station (8 RF channels) to allow for diplexers and channel dropping and recombining networks. In addition the *pro rata* share of power supply weight will be at the rate of 2 watts per pound as discussed in Section 5.2 for a total of 9 pounds for 18 watts to power one transponder. Thus 8 transponders to serve one ground station will weigh 8 (3¼ pounds) for electronics + 8 (9 pounds) for power + 2 pounds for filters = 100 pounds.

5.1 *Stabilization*

When very narrow antenna beams are used, as in this design, precise stabilization of the spacecraft is crucial. The first task which must be accomplished is sensing the attitude of the spacecraft with a high degree of accuracy and reliability. In this discussion we assume that crude orientation, that is, within a degree or so about all three axes, is accomplished by present methods. More precise sensing for final attitude adjustment to $\pm 0.01°$ (0.2×10^{-3} radians) can be achieved by radiometric means. For example, at the upper frequency of 30 GHz, antennas spaced a distance a = 10 meters will receive signals differing in phase by π radians when the platform tilt $\varphi = \lambda/2a = 10^{-2}$ meters/20 meters $= 5 \times 10^{-4}$ radians. A comparison circuit should be able to detect a difference of $\pi/100$ radians or a tilt angle of 5×10^{-6} radians. This is about two orders of magnitude smaller than the allowable variation and should be adequate for precise attitude control.*

If we use one-meter antennas on the spacecraft for this purpose, reduce the receiver bandwidth to 400 kHz, and keep the ground transmitter power unchanged at 10 watts, the carrier-to-noise ratio in this sensing channel will be 50 dB. This is more than enough, but the consequences of losing attitude control are severe and plenty of margin is in order. Another basic aspect of attitude control is the amount of fuel (weight) required to stabilize a spacecraft for a long period, say, ten years.

This phase of the problem has been studied from two complementary points of view: (*i*) a study of the basic effects which perturb the satellite orbit[9] and (*ii*) a rudimentary station keeping and attitude control subsystem design. The first study indicates that an impulse

* An ingenious means for keeping most of the complication of the attitude sensing and control system on the ground has been given by C. C. Cutler in Ref. 8.

of 157 feet per second per year would correct for changes in the inclination of the orbit of 0.86° per year caused by lunar and solar gravitation plus the lesser effect of a westward acceleration of 1.68×10^{-3} degrees per day resulting from the nonsphericity of the earth's gravitational field. Attitude control, even to the very precise limits assumed here, appears to be primarily a question of the reliability of components to be used in a system with a design lifetime of many years.

In comparison with the amount of fuel required for station keeping, the weight of fuel required for attitude control is negligible, that is, a few pounds per year per ton of satellite weight. Thus in the design study it was assumed that an impulse of 160 feet per second per year would be required for station keeping. Our conclusion from these studies is that the weight penalty imposed on a satellite having a ten year operational lifetime while significant is not prohibitive.

The very difficult engineering problems which remain to be solved concern reliability in the space environment. We estimate that the hardware plus fuel required to correct an initial velocity error of 100 meters per second, keep the satellite on station and stabilize its attitude for ten years invokes a weight penalty of about 16 percent of the total weight of the spacecraft. Thus $W_{\text{total}} = W_{\text{payload}} + 0.164\, W_{\text{total}}$ or $W_{\text{total}} = 1.20\, W_{\text{payload}}$, and this is the relationship used here to calculate the total spacecraft weight once the weight of the communication equipment, solar power supply, and other necessary components has been determined.

5.2 *Solar Power Plant*

Values of 15 to 20 watts per pound have been reported for sun-oriented solar cell arrays, but 10 watts per pound is closer to present performance. We use two watts per pound. This is reasonable for an unoriented array and very conservative if, in fact, it is decided to point the solar power plant at the sun. Since a single two watt transponder will require nearly 18 watts total solar power, power for each transponder will require a weight of nearly 9 pounds as its *pro rata* share of the solar power plant weight.

5.3 *Structure and Antenna*

An allowance of 20 percent of the total payload weight will be assumed for satellite structure and a like amount for the associated communications antenna together with its feeds. Admittedly this is a guess based on previous experience and would require an innovative design to realize a lightweight antenna operable at 30 to 40 GHz and able to survive the launch environment. However, once the satellite is in orbit and on station, and this is the only condition under which it would be used, the disturbing forces will be very small.

As already mentioned, an attitude and orbit control system capable of keeping a satellite on station and properly oriented for 10 years will require a total in-orbit weight of $W_{\text{total}} = 1.20\ W_{\text{payload}}$. Thus, the payload weight required for eight broadband channels to serve one ground terminal is

$$\begin{aligned} W_{\text{payload}} &= 100 \text{ lbs. for eight two-watt transponders} \\ &+ 0.2\ W_{\text{payload}} \text{ for structure} \\ &+ 0.2\ W_{\text{payload}} \text{ for antenna.} \end{aligned}$$

thus

$$W_{\text{payload}} = 167 \text{ lbs. per ground station}$$

and

$$W_{\text{total}} = 1.20\ (167) = 200 \text{ lbs. per ground station.}$$

VI. EARTH STATIONS

As already pointed out, a terrestrial terminal will consist of two or more diversity locations each equipped with a multibeam antenna suitable for both transmitting and receiving. The number of diversity locations required, and the distance between them will be determined by the specified system reliability and the characteristics of rainstorms in the particular location being considered. Much more extensive (geographically) and complete data on space diversity will need to be obtained before such installations can be designed with confidence, but data available from the Bell Laboratories rain gauge network and other sources[10] make it reasonable to postulate that two sites separated by 10 to 20 miles will be adequate, and this is the assumption used in the following. Actually a study of data of the sort shown in Fig. 1 leads one to hope that a considerably smaller distance would suffice.

Provision of the first spare transmission facility is no great hardship since this is needed in any case to provide for maintenance and for protection against apparatus failure, but the diversity site must be connected by a broadband facility adequate to carry all of the traffic received or transmitted by either ground station. In the model system this will vary from about 80,000 voice channels for a station working with a single satellite up to about four million voice channels for one that works with 50 satellites.

Since the most attractive transmission medium for such large volumes of traffic appears to be a millimeter waveguide of the type described by S. E. Miller,[11] a facility of this sort is assumed as the site interconnecting link. A fully implemented terminal handling four million voice circuits would require eight pipes of two-inch inside diameter, each carrying 60 two-way 630 megabits per second channels. It is expected that for distances up to 15 or 20 miles between diversity ground stations no intermediate repeaters would be required when a low-loss waveguide is used. Concentration of the electronics at two sites which presumably would be attended at least part time should simplify maintenance and increase reliability. This site interconnecting link, with its large volume of traffic to be carried over a short distance and without a need to demultiplex the individual voice circuits at either end, is a good candidate for an optical transmission link when technology has progressed far enough to make such an installation feasible.

The proposed ground station antenna is of the type being studied by A. B. Crawford and T. S. Chu.[12] This is a multibeam antenna 10 meters high by 17 meters long designed for up to 10 feeds for use with a like number of satellites. The common reflector is so designed that working in conjunction with the multiple feeds, good antenna patterns can be maintained over a 10° change in the azimuth angle but with no provision for variation in declination angle. The latter is obtained by tilting the entire assembly to the declination angle appropriate to the particular site.

As already mentioned, these systems will be interference limited, hence good antenna discrimination is more important than gain, and the antenna design takes advantage of this fact. In the long run electronically steerable arrays may prove to be the best and most economical solution to the multibeam antenna problem both on board the satellite and at the ground station. In fact, if crowding of the synchronous orbit eventually makes it imperative to use inclined 24-hour orbits as described by H. E. Rowe and A. A. Penzias, steerable arrays appear to be the only workable solution.[13] At the present time, however, multiple feeds used with a focusing reflector appear to be the most attractive solution.

As indicated on Table I, an over-all effective noise temperature of 150°K is assumed for the ground terminal receiver; this can best be achieved by using a cooled parametric amplifier. Considerably lower effective temperatures are possible. But with an interference limited system operating at 20 GHz where the effective antenna temperature will approach 300°K under conditions of heavy rainfall, little improvement in actual system performance would be obtained. Although Table I specifies a 10 watt 30 GHz transmitter which provides more than 40 dB C/N at the satellite (and this may well be adequate), increased transmitter power is feasible and would not be very expensive if further propagation data makes this appear necessary.

VII. LAUNCH CONSIDERATIONS

The cost of placing a given weight in orbit can be obtained for many different combinations of upper and lower stages. Costs differing by nearly 10 to 1 will be found, depending on the time, scale of production, size of launcher used, and so on. Such a wide variety of combinations of lower and upper stages including future exotic high energy upper stages and injection rockets are technically possible (some are parts of on-going funded and scheduled programs while others exist only on paper), that large variations in load capacity and cost estimates are to be expected.

The time scale being considered is an especially confusing factor; things are always predicted to be much better in the future. In thinking about the present system model, particularly satellite vs ground terminal size and complexity, it has been assumed that launch cost is directly proportional to payload weight. How realistic is this? Rocket capabilities tend to be quantized, and certainly one must pay the entire launch cost if it is made for his benefit. However, if we take a longer range view, a wide variety of combinations of lower and upper stages will become available.

For example, the basic Titan 3-C will place 2,140 pounds in synchronous orbit, but various combinations of lower and upper stages based on Titan have been proposed which would place 650, 2140, 2450, 3450, 5800, 9000, 18,000, and even 23,000 pounds in synchronous orbit. It is true that many of these combinations will require considerable research and development before a reliable launch vehicle results, but at least in concept it is possible to tailor the rocket to the job. In addition, we have the possibility, now amply demonstrated, of combining several small payloads into one for multiple launch. Combinations of these two techniques should eventually make it possible to match the rocket and its payload quite precisely.

VIII. SUMMARY AND CONCLUSIONS

It has been argued that by taking full advantage of modern space and communication technology and assuming that very broad frequency bands in the range between 15 and 40 GHz can be allocated to this service, realization of a domestic satellite system with considerable communication capacity is feasible within the next decade. Some of the parameters of satellites designed for such a system are given in Table III.

Major unresolved technical problems are reliability of the propagation of these very short radio waves through the earth's atmosphere and stabilization of a space platform to $\pm 0.01°$ for up to ten years. Data adequate to provide a solid statistical base for predicting system performance are not available, but a start has been made and more experiments are planned. Several programs are dedicated to improving performance of satellite attitude stabilization systems and achievement of the required value has been predicted. A preliminary study of the basic forces acting on a satellite shows that attitude stabilization even to these very precise limits does not require prohibitive amounts of fuel. However, a considerable advance in technology will be required before an attitude stabilization subsystem of adequate reliability and precision is available. The very broadband radio repeaters which are required to implement this concept are less of a problem since these are already being developed for other purposes and can be adapted for satellite use.

Table III — Summary of Satellite Parameters

	Number of ground stations served			
	8	16	32	50
Weight of satellite (pounds)	1640	3280	6560	11,500
DC power (kw)	1.15	2.30	4.60	7.20
Transponders	64	128	196	400
Gigabits through satellite	40	80	160	252
One-way equivalent voice circuits through satellite (thousands)	640	1,280	1,960	4,000
One-way equivalent TV channels through satellite				

In addition to the problems peculiar to the present proposal, there are, of course, those common to all synchronous satellites: an approximately ½-second absolute round-trip delay and the attendant echo suppression requirement at a cost which is not negligible, slow delay variations resulting from path length changes which may amount to several microseconds, service outages caused by interruption of solar power (or provision of storage batteries), and outages caused by sun transit, which will increase the 20-GHz receiver effective noise temperature from the assumed 150°K to about 15,000°K (20 dB).

Assuming a favorable outcome from the propagation measurements, particularly a demonstration that common carrier standards for reliability can be achieved with diversity ground stations, planning for such a system could begin immediately. Other requirements of a nontechnical nature include resolution of the frequency allocation problem and policy decisions regarding system ownership and operation.

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