corresponds to that required to escape from the earth's gravitational field and, in addition, requires a number of satellites in a pattern to provide continuous point-to-point communications. A satellite at about 19,000 nautical miles altitude, variously called a 24-Hour, Stationary or Synchronous Satellite, becomes interesting because only one satellite is required for continuous, point-to-point (or point-to-area) communications for nearly a hemisphere of the earth's surface. However, this requires considerably more energy for injection than even an escape mission requires, so that for a given vehicle a lesser payload is possible than for satellites at lower orbits. At the same time the power requirements have gone up in proportion to the square of the additional distance or, more realistically, the bandwidth that can be transmitted has been reduced in proportion to the square of the distance.

These considerations must be balanced against each other and against many others in any selection of a space communications system to meet military needs. The low-flying delayed relay satellites appear to have promise of handling a great amount of the routine communications traffic associated with logistics and personnel operations where moderate time delays are not important and may actually be less than that due to normal HF traffic backlogging. This will relieve the HF circuits for greater reliability in higher priority messages. The higher altitude satellites can be used to provide reliable real time communications where the bandwidth requirements are compatible. As launching vehicle efficiencies improve, in terms of pounds of payload in orbit per dollar, and as reliability and useful life problems are solved, satellites will become increasingly important for military communications.

Communication Satellites*

DONALD L. JACOBY†

Summary—**This paper is intended to provide a review of communication satellites starting with their comparatively brief history and continuing through present developments and future concepts and the probable impact on global communications.**

The advantages and disadvantages are considered for various types of passive and active devices, for various orbits, and from the standpoint of both military and commercial applications. Consideration of all major technical and economic factors leads to the conclusion that a system of 3 or 4 repeater satellites in 24-hour orbits will best meet future world-wide communication requirements. A number of system concepts are described, including time-synchronous and frequency-sharing systems.

Important aspects of communication satellite design are discussed including electronics, antennas, power supply, structure, attitude and position stabilization, command control, and telemetering. Selection of frequency is shown to be not critical over a wide range. Choice of design parameters such as power output, antenna gain, stabilization accuracy, etc., is largely dependent on the desired capacity of the communication system and the available satellite payload. Some typical parameters for a high capacity system are presented.

Reliability is an over-riding consideration in satellite design and it is proposed to achieve desired life by proper choice of components, by use of redundancy, and by minimization of satellite requirements at the expense of the ground equipment.

Based on published information on ARPA-NASA programs and booster capabilities, some estimates are made of the rate of progress which can be expected in communication satellites, leading to their eventual use in military and commercial communications. Wide application is foreseen because of increasing communication requirements which will saturate existing facilities.

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Introduction

THE next ten years will see a revolution in world-wide communications with the advent of the communication satellite. In this age of jet planes, nuclear power, and moon rockets, our communication facilities have simply become outmoded. These facilities have served us well and will continue to do so in the future, but they are not good enough. They will not handle the greatly increased volume of communications. They will not support world-wide television which could contribute to improving international understanding. Present communications are too easily disrupted. A slight increase in sunspot activity can cause all radio communication to Europe to be blacked out. A fishing trawler may accidentally cut the North Atlantic telephone cable. While these events present difficult problems to civilian communications, the implications of even temporarily being cut off from the rest of the world are far more serious from a military standpoint.

During the past two years, communication satellites have attracted considerable interest within both industry and government. There has been a successful launching of a communications satellite (Project SCORE), and development programs have been initiated both within the civilian space agency and the Department of Defense. Rather than discuss any specific programs, an attempt at an underlying philosophy of communication satellites will be presented, starting with the objectives.

Objectives

What should be some of our major objectives in developing a system of communication satellites? First of all, we are looking for *reliable* communications which provide uninterrupted service over long periods. The system should have *high capacity* with capability for handling large volumes of all types of traffic. It should be sufficiently *flexible* to serve the maximum number of potential users. There should be *minimum delay* in transmission. Last but not least, it should be *economical* in terms of the cost of the services rendered. Each of these factors will be discussed in more detail, and the communication satellite will be compared with some of our existing facilities.

Reliability

There are two types of reliability of interest to us. The first of these is propagation reliability. The high-frequency band has always been subject to the vagaries of the ionospheric layers which surround the earth. Thus, only a portion of the HF band is actually useable at any given time over a particular path. In addition, multipath effects seriously limit the amount of information which can be transmitted over a given channel. Added to these limitations are the blackouts which may result from ionospheric disturbances caused by sunspot activity. (As indicated in the *New York Times* last March, similar disturbances can be introduced by high-altitude nuclear explosions.) One is forced to the conclusion that HF radio via the ionosphere is not highly satisfactory as a propagation medium.

By contrast, a communication satellite of the active repeater type employing line-of-sight transmission at microwave frequencies would be extremely reliable from a propagation standpoint. However, the communication satellite introduces a different type of reliability problem, that of reliable unattended operation for long periods while in orbit. Some experts doubt that a reliability sufficient to make a communication satellite economically feasible can be achieved. It is believed that a reliable communication satellite can be developed with a minimum guaranteed life of one year based on the following assumptions: there is major effort to develop components of proven reliability for this application; all components are operated well within their ratings; the satellite design provides adequate protection during the launching and while in the space environment; and, finally, adequate use is made of redundancy to further increase the probability of successful operation. Despite the formidable problems, the satellite does enjoy some advantages. Unlike ground equipment, particularly military, which must withstand extremes of operating temperature, humidity, atmospheric pressure, and mechanical shock, the electronic equipment in the satellite will be provided, once in orbit, with an almost fixed environment devoid of the factors that generally contribute to reducing component life.

High Capacity

Through the years we have been dependent, almost exclusively, on high frequencies in the band 5 to 20 megacycles for our long range global communications. These frequencies are shared among all countries and must support both military and civilian applications. The narrow range of frequencies, and the propagation characteristics discussed previously, seriously limit the total communication capacity.

It is not surprising that there is always great interest in new techniques which promise to open additional areas of the frequency spectrum to long-range communications. Recent examples are ionospheric and tropospheric scatter propagation. The communication satellite will open up the complete range of frequencies to 10,000 megacycles for long range communications, thus providing nearly 1000 times the spectrum available in the HF band.

Flexibility

One of the requirements is to provide sufficient flexibility in our system so that new or changing demands around the world can be satisfied without major overhaul or replacement of facilities. A major disadvantage of the submarine cable, for instance, is its lack of flexibility, being strictly a point-to-point fixed-plant type of facility. On the other hand, a system of communication satellites in 24-hour equatorial orbits, by providing wide bandwidths and essentially global coverage, places a minimum of restraint on the number and location of ground stations served and the volume of communication furnished to each.

Minimum Delay

Another of our objectives is to speed up our communications. All too frequently urgent messages are delayed because our facilities are congested or because propagation conditions are poor. Recently, a television program was seen in the United States only a few hours after it was broadcast in England and this was considered a major achievement. Some of the advantages of communication satellites previously discussed, such as the wide bandwidth, will not only make possible world-wide television broadcasting in real-time, but will reduce delays in all types of communications.

Economics

If one accepts the fact that communication satellites will improve global communications, it is still reasonable to ask how much they will cost. Here we find that communication satellites have some unique characteristics. In the first place, the quantity of satellites required is not sufficient to warrant production tooling, and, therefore, they will always be expensive by comparison with mass-produced equipment. Of far greater significance, however, is the cost of the launching vehicles, which may run 5 to 10 million dollars or more depending on the satellite weight and the orbit. The present state of the art requires perhaps three launchings to insure one successful satellite, but missile experts hope that this ratio can be improved in the future. If the most pessimistic figure is taken, it could cost as much as 90 million dollars for the vehicles alone for a system of 3 satellites in 24-hour orbit. Once in orbit, a communication satellite has no operating and maintenance costs in the usual sense. However we must plan on periodically replacing satellites which have failed. It is easy to see that, on a long term basis, the cost of a communication satellite system is thus intimately tied to the reliability of the satellite, and a few million dollars to improve reliability during development would save many times that amount during each year of operation.

Survey of Types of Communication Satellites

Thorough review of all factors has led to the conclusion that an active repeater type of satellite in a 24-hour equatorial orbit offers the most promise for advancing global communications. However, in view of the reliability problems and the anticipated costs of a communication satellite program, it would be well to briefly review the pros and cons of alternative approaches which are under development or have been proposed.

Passive Reflector

A concept which has attracted considerable interest is that of the passive reflector satellite as described recently.[1] Some of the advantages of such a system are its inherent reliability and the possibility of being shared by a large number of users operating over a wide range of frequencies. However, a typical system operating between two locations 2000 miles apart would require a total of 24 100-foot balloons in randomly spaced orbits at 3000 miles altitude for an outage time of 1 per cent. In addition, to support meaningful communication bandwidths, extremely large transmitter powers, low-noise temperature receiving systems, and large tracking antennas with beamwidths of the order of 0.05° are required. Substantially greater numbers of satellites would be required to provide longer range or wider coverage than the examples cited and, therefore, they do not appear to be an economical solution to providing truly global communications.

The passive reflector satellites would be more attractive if they could be stabilized in attitude, permitting use of more efficient reflecting surfaces, or if the satellite orbits could be synchronized so as to reduce the number of satellites required. However, the satellites then cease to be "passive" and reliability is no longer inherent in the system.

Delayed Repeater Satellite

This concept envisons a satellite in low-altitude (300 to 2000 miles) orbit providing communications between a number of ground stations. Each ground station provides facilities for storing communication traffic destined for other stations and transmitting this traffic to the satellite during the time the satellite is in view. Simultaneously, the ground station will receive from the satellite traffic from other ground stations which have been stored in the satellite. The satellite is equipped with recorders and appropriate control circuits which can be commanded from the ground or perhaps operate on a prearranged program.

A satellite in equatorial orbit can provide communications to stations in the equatorial zone on each satellite orbit. In orbits other than equatorial, a satellite will serve a larger area but will in general serve a particular station less frequently. The higher the altitude of the satellite, the longer is the time in view for each ground station and the larger is the area served.

The delayed repeater satellite appears to be an economical method of providing communications where delays of 2 to 3 hours are tolerable. It is most efficient when operating in the region of the equator. It is not intended to provide global coverage or communication of a high priority nature.

Communication Satellite in 24-Hour Orbit —System Design

This concept is illustrated in Fig. 1. Three satellites at an altitude of 22,300 miles and equally spaced over the equator circle the earth in 24-hour equatorial orbit. Because of the earth's rotation, they appear to remain

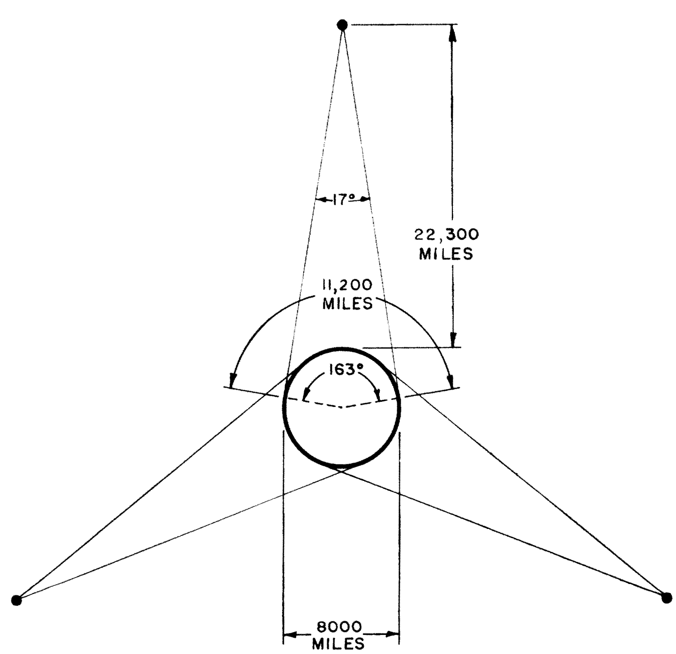

Fig. 1—Concept of three communication satellites in 24-hour equatorial orbit, showing geometrical relationships in the equatorial plane.

[1] J. R. Pierce and R. Kompfner, "Transoceanic communications by means of satellites," Proc. IRE, vol. 47, pp. 372–380; March, 1959.

fixed to an observer on the earth. Such a satellite system will provide complete global coverage with the exception of the extreme polar areas. Each satellite will be equipped to receive, amplify and retransmit signals originating at stations within its area of coverage and intended for other stations in the same area. Switching between areas could be accomplished by direct relay between satellites, but since this might prove difficult to control, a preferred method is to locate ground repeaters in the areas visible to 2 satellites, as shown in Fig. 2.

Within the concept described there are at least three approaches to system design. In the first of these [see Fig. 3(a)] and the most straightforward, two frequency bands are employed, one for transmissions from satellite to ground and the other for transmission from ground to satellite. These frequency bands are subdivided, not necessarily equally, among the ground stations and the inter-area repeaters.

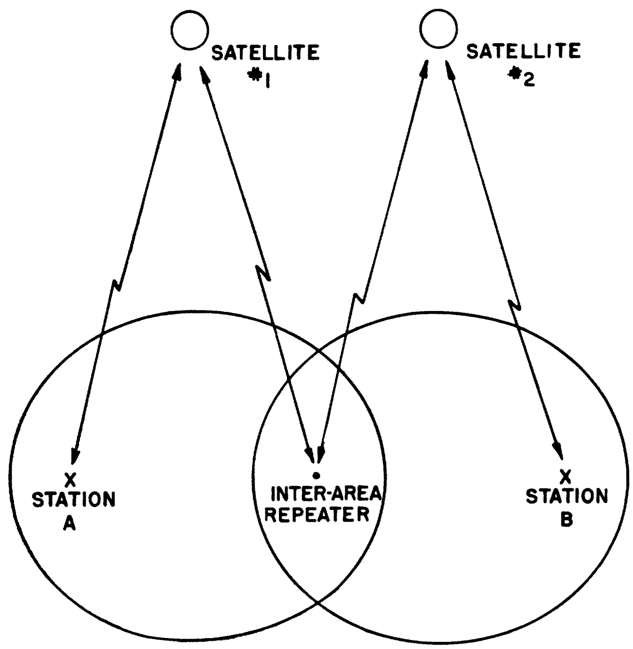

Fig. 2—Method of switching between areas in a 24-hour satellite communication system.

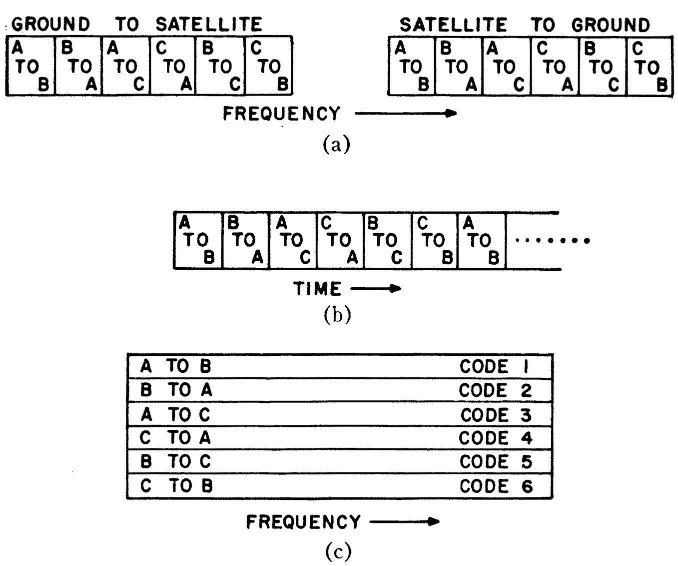

Fig. 3—System design approaches in a 24-hour satellite communication system.

In the second approach [see Fig. 3(b)] all stations would have common frequencies, but would transmit and receive at different times. This system entails greater complexity than the first because of the need for maintaining precise synchronism between stations and the probable variations in delay time in the transmission path due to fluctuations in satellite position.

A third approach would again have all stations sharing common frequencies, but with all stations transmitting and receiving simultaneously. Each signal would be furnished with an identifying code. Separation of signals at receiving stations would be by correlation detection techniques [Fig. 3(c)].

Some discussion of frequencies to be employed for these systems seems appropriate at this point. Frequencies below a few hundred megacycles should be avoided because of ionosphere effects. Frequencies above 10,000 megacycles are subject to attenuation in the atmosphere due to oxygen, water vapor, and rain in varying degrees, the attenuation being most pronounced for grazing paths and less significant for paths normal to the earth's surface. Having established rough upper and lower limits on frequency, the basic formula for transmission in free space will be examined.

$$P_R = P_T + G_T + G_R - 37 - 20 \log f - 20 \log d$$

where

P_T = transmitted power in dbw,
P_R = received power in dbw,
G_T = transmitting antenna gain in db (relation to isotropic),
G_R = receiving antenna gain in db (relation to isotropic),
d = distance in miles,
f = frequency in megacycles.

If we now decide that the satellite antenna should have a fixed beamwidth such that it exactly illuminates the earth, and if we further establish a practical limit on the size of the ground antenna, only one of the antenna gains will be a function of frequency and P_R will then be independent of frequency. Thus, the actual choice of frequency boils down to availability of reliable components, such as tubes having necessary power output, bandwidth, efficiency, and considerations of mutual interference with other users of UHF and SHF frequencies.

Noise is not expected to be a serious problem in the ground-to-satellite path since high-power transmitters may be employed. However, satellite transmitter power may be limited by payload restrictions in which case use of parametric amplifiers or masers may be required to minimize the effective noise temperature of the ground receiver.

Table I lists typical system parameters for a hypothetical communication satellite system handling 12 PCM voice channels between a pair of ground stations.

TABLE I

Frequency	Satellite	Ground
Transmitter Power	2000 megacycles	2000 megacycles
Antenna Gain	18 decibels	49 decibels
Receiver Bandwidth	1 megacycle	1 megacycle
Receiver Noise Figure	10 decibels	3 decibels
Carrier to Noise	37 decibels	24 decibels
Channel S/N		60 decibels

Satellite Design

Some aspects of communication satellite design, which are of particular significance if we are to meet our over-all system objectives, will now be briefly discussed. More detailed information is available in a recent paper.[2]

Weight Limitation

For the next few years we will be severely limited in the payload that can be placed in orbit by available boosters. These capabilities can be expected to increase and within 10 years we should be able to place payloads of several thousand pounds into 24-hour orbit. However, it is generally true that the heavier the payload, the greater will be the cost of the booster to place it in a given orbit. Therefore, it is important to design for minimum weight by use of materials and structures with maximum strength-to-weight ratio, by employing the most efficient power sources, and by minimizing power requirements.

Stabilization

Attitude stabilization of the satellite is essential to positive control of the satellite orbit and is also a major factor in weight reduction. It permits use of a directional antenna with consequent reduction in power requirements. It also permits the incorporation of solar cell platforms that rotate to always face the sun, thus improving power supply efficiency by a factor of 6. Attitude stabilization may be achieved by means of sun and star trackers, horizon sensors, or radio signals from the ground, controlling a system of gas nozzles.

Antennas.

The satellite antenna may be a single fixed parabola. Linear polarization is satisfactory, provided that the ground antenna is circularly polarized. In the case of a 24-hour satellite, a beamwidth of 20° will illuminate the earth with some margin provided for attitude variations. Higher gain antennas may be employed to illuminate specific areas or increase system margin but this either places more severe requirements on attitude stabilization or requires some form of steerable or electronically scanned antenna.

Power Supply

As discussed previously the most efficient power supply in the foreseeable future is a solar cell platform which rotates so as to always face the sun. Present solar cells have an efficiency of 10 per cent and will provide approximately 10 watts per square foot of platform area. Some improvement in efficiency, perhaps to 13 per cent, is foreseen in the future. A battery supply should be added in parallel with the solar cell supply if operation is desired during periods when the satellite is in the earth's shadow. This amounts to less than 1 per cent of the time for a satellite in 24-hour orbit.

Communication Electronics

The major emphasis in the design of the communication electronics must be on reliability. We must select only components of proven reliability; we must operate them well within their ratings; and components must be protected from damage by micrometeorites and radiation. Present microwave tubes are not capable of operating continuously for a year or more for this application and extensive research and development is required in this area. Reliable components will be supplemented by prudent use of redundancy to insure maximum useful life of the satellite. A likely circuit configuration is shown in Fig. 4. This is basically a heterodyne repeater, with traveling-wave tubes a logical choice for the wide-band amplifier stages.

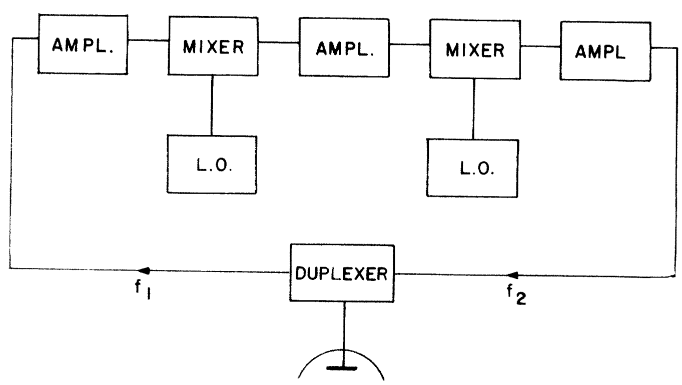

Fig. 4—Basic design of communication satellite repeater.

Command System

The satellite will undoubtedly require some degree of control from the ground through a command link. Such a link could provide control of satellite position as well as commands to activate or deactivate portions of the satellite communications equipment and other functions. Commands would be in coded form to minimize the possibility of interference.

[2] J. E. Bartow, G. N. Krassner, and R. C. Riehs, "Design considerations for space communication," 1959 IRE National Convention Record, pt. 8, pp. 154–166.

Telemetry System

There is also a requirement for a telemetry link from the satellite to the ground to provide information vital to operation of the communication satellite system. The telemetry system will monitor the performance of the communication equipment, the power supply, and the attitude stabilization system and will provide acknowledgment of commands and verification that they have been acted upon. During the research and development phase, the telemetry link serves the additional important function of checking the adequacy of the design, the information derived serving as a basis for design modifications in later satellites.

Orbit Correction

Ideally, a satellite in a 24-hour equatorial circular orbit will remain over a fixed point on the earth. In practice it is anticipated that initial inaccuracies together with effects of the moon's gravity, solar radiation pressure, etc., will bring about perturbations in the orbit requiring periodic correction during the useful life of the satellite. In order that the satellite orbit may be properly controlled from the ground, it is likely that a tracking beacon will be incorporated in the satellite. Tracking will be required at a number of ground locations unless the tracking beacon is of a transponder type, supplying range in addition to angle information. Doppler measurements are useless in tracking a 24-hour satellite because of the small magnitude and unpredictable variations of differential velocity. Information from the ground tracking stations will be fed to a computer which will determine the direction and timing of the corrective thrusts which must be applied to the satellite. It appears feasible to maintain a satellite within 1 or 2 degrees of its desired location by these techniques.

The command, telemetry, and tracking systems may operate close to the communication band and share common antennas. However, they do not require wide bandwidths and could operate at considerably lower frequencies. The decision may depend on whether tracking and position control are performed at the communication ground station or at separate locations.

Structure

As discussed previously, there will be a maximum weight for the satellite. There will also be maximum dimensions for the satellite during the launching period as dictated by the final stage rocket configuration. Hardware which will project from the main body of the satellite, such as the solar cell platform and the antenna, will be in a collapsed position during launching, and extended only after separation from the last stage. The satellite must be designed to withstand the conditions of vibration and shock during launching and to have a maximum degree of dynamic stability in orbit.

Thermal Design

The satellite must provide a satisfactory thermal environment for the electronics and other components. The power dissipated in the form of heat by the electronic equipment must be brought to the outer surface whence it can be radiated. The outer surface must be designed, using special coatings as required, to strike a balance between radiation and absorption such as to maintain internal and external temperature within desired tolerances. In the particular case of the solar cells, it is essential that close thermal control be maintained, since their efficiency drops off rapidly at higher temperatures. Thermal storage devices may be required to prevent wide variations in thermal conditions as the satellite traverses its orbit.

Conclusion

Serious shortcomings exist in our present global communication facilities. Communication satellites promise greater capacity, wider coverage, more flexibility, and fewer delays than present transmission systems. The operating cost of communication satellites is intimately tied to the problem of reliability. With sufficient emphasis on the reliability aspects, satellites will assume the prominent role in communications for which they appear destined.