Communications Satellites

"Their voice goes out through all the earth"
Psalms 19:4

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I. Introduction

THIS paper reviews the growth of the first decade of operation of INTELSAT, the global consortium of 95 countries. The system has grown from the Early Bird experimental/operational satellite providing a single path across the North Atlantic to one with 500 paths among 150 antennas around the world, carrying the major part (over 8000) of the world's transoceanic telephone circuits. The success of INTELSAT has stimulated the beginnings of domestic, maritime, aeronautical, and broadcast systems. Technical aspects of the present technology, and future directions are discussed, as well as possible future systems.

It is noted that major contributions to a field of endeavor occur when that field is entered by men of vision, men of genius, those who have the talent of counsel and those who can lead. Only rarely, however, does there enter the scene an individual who possesses all these attributes. When that happens, the field of that man's endeavor grows dramatically, and his impact on that period is profound. Such a man was von Karman. It is, of course, unnecessary to elaborate on the impact he made on the aerospace field. Practically every facet of our endeavors bears his imprint in one way or another. He taught many things—the power of proper analysis, the extraction of essentials from a complicated maze of detail, the courage to be daring, imaginative and visionary, and throughout all, the importance of the human element. It included not only the recognition that each individual has his own strengths that, if propertly stimulated and challenged, can lead to meaningful contributions, but that there is a richness and reward in the total span of man's experience and that no individual or field of endeavor can be an island and be meaningful. Some of his vision and the powerful exposition of the results of that vision could be of enormous value to our complicated world of today.

There may be no better way to introduce this subject than to note that over a decade ago, von Karman wrote, "The most immediate payoff of astronautics lies in telecommunications and this I think will make the greatest strides in the coming years." He felt that the synchronous satellite would provide the preferred solution and that a workable system would evolve. He added that "probably a difficulty greater than technology that may stand in the way of world satellite communications is politics...and political disagreement over control of communications is likely to increase." He was correct in his assessment of the synchronous satellite and the rapid growth in communications satellite technology. Its impact has been so profound that rapid development has occurred despite the inertia of political and vested-interest impediments. But now that the honeymoon period is over, future technological growth will surely be heavily influenced and possibly controlled by these other factors even as von Karman had theorized.

The last decade has seen the addition of a new dimension to our global telecommunications capability, the communications satellite. In a single decade we have reached the state where the majority of all long-distance international traffic is carried by satellite. Domestic and regional systems have entered into service and we are on the threshold of using satellites for communications with mobile platforms on a regular commercial basis. Ahead lie new and exciting possibilities which give strong promise of exerting a major impact on the nature of the world of tomorrow. It is therefore

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I am deeply indebted to Mr. Sidney Metzger, Assistant Vice President and Chief Scientist of COMSAT, not only for bringing together the material for this paper, but for his many personal technical contributions, his dedication to the field of satellite communications and for his key role in converting communications satellite concepts into reality.

most appropriate that under this auspices we review the progress to date. We can then, with the advantage of this base, seek to focus our thoughts on the problems raised by these technological developments, but perhaps more fruitfully on the potential of their developments in the world of tomorrow. Although many of you may be familiar with the developments in the communication satellite field in the past decade, it appears useful to present a summary of the technical and organizational history which demonstrates its rather dynamic character and provides a common base for our discussion here of future trends.

Other applications, such as the maritime, aeronautical, and broadcast satellite service, are in about the same stage as international fixed service was ten years ago, but with that experience behind us the technical success of these ventures seems assured, although the political and economic aspects are not as clearly foreseen.

This talk will first address the background of these systems, considering both the organizational arrangements and the technical characteristics. It will then briefly review the present status of satellite communications in the fixed service for international and domestic use and for experiments in broadcasting direct to the home.

The second part of the paper will discuss the more technical aspects of satellite communications and extrapolate these into the future to estimate how this dynamic first decade of satellite communications might evolve.

II. Present Status

A. Organizational Arrangements

1. COMSAT and INTELSAT

In July 1962, after a long series of considerations as to the potential of satellite communications, United States policy in this regard and the organizational means for accomplishing their objectives came to a focus with the passage by the Congress of the Communications Satellite Act.

As a compromise between choosing the existing carriers or the Government, it was decided to form a new private company in which the U.S. common carriers could own no more than half the stock, the remainder to be sold to the public. The actions of this company were to be regulated by the FCC, and it was set up to lease service to U.S. common carriers and to other authorized entities, foreign and domestic. The Communications Satellite Corporation officially came into being in February 1, 1963. Shortly thereafter initial contacts were made with a number of countries around the world regarding United States policy and objectives and for the purpose of discussing arrangements whereby plans could be developed to create a global communications satellite system. There was great interest in this new venture, but it was tempered with a certain amount of incredulity and concern at the very rapid development and implementation program proposed. Through numerous meetings and informal discussions, there emerged over a period of months a confidence that an economically viable communications satellite system at an early date was, indeed, a possibility, and a desire to join as full partners in this unique venture. This was formalized in August 1964 in a pair of agreements—the first signed by all the governments of all the participating nations, and the second signed by designated telecommunications entities of these countries. For the United States, the signatory for the operating agreement was, of course, the Communications Satellite Corporation.

The interim agreement outlined above was superseded on February 12, 1973 by a definitive arrangement—the product of extensive negotiations over a period of more than two years.

2. International Use

From an experimental/operational launch of Early Bird in 1965, the INTELSAT system has grown in one decade to become the major carrier of transoceanic telephone circuits. This system, with satellites operating over the Atlantic, Pacific, and Indian Oceans, includes approximately 80 countries with 130 stations and 160 antennas (see Fig. 1), mainly of 30 m diameter but including some 10 m stations. The system carries more than 8000 two-way telephone circuits over some 500 paths (a path being a link between two stations carrying one or more telephone circuits).

The growth of the system is shown in Fig. 2, with extrapolations for the future. The Atlantic traffic comprises about 66% of the total, while the Pacific and Indian Ocean areas account for are 12% and 22%, respectively. The distribution of traffic per station and the number of paths per station vary widely, ranging from a handful of circuits to 1500 and from a single path to three dozen. About half of the stations generate a total of approximately 10% of the system traffic while the top 10% of the stations generate about half the total traffic.

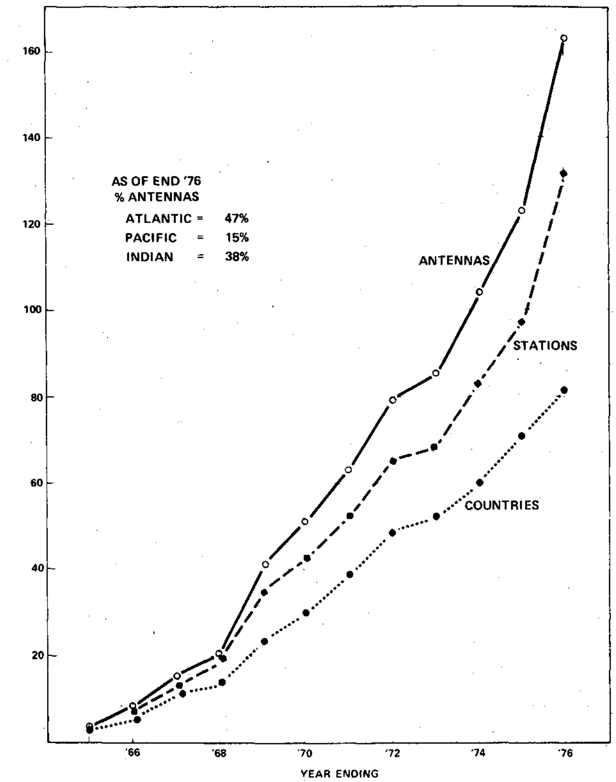

Fig. 1 Growth of countries, stations, and antennas in the INTELSAT system.

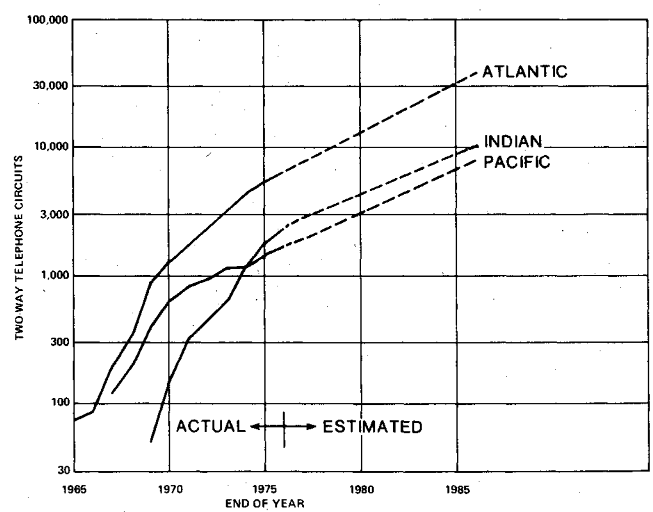

Fig. 2 Growth of telephone traffic in the INTELSAT system.

While the satellites are jointly owned by all members, roughly in proportion to their use, the earth stations are fully owned and managed by the appropriate administrations in each individual country. This makes for a fundamental dichotomy in that the heavy traffic user, whose major cost is for space segment charges at a fixed annual cost per channel regardless of the number of channels, is basically interested in more efficient (and therefore lower cost) utilization of the satellite capacity. To this end he is willing to invest in new earth station equipment to provide for, say, a more efficient modulation technique. On the other hand, the light traffic user has his major cost in the earth station and therefore has little incentive to increase to achieve a reduction in space segment costs.

These stations have achieved an average continuity of service of 99.95% during the last few yars (including both scheduled and unscheduled outages). About 20% of the stations achieved an average outage less than one tenth of this, or 99.995% or better on-the-air performance, corresponding to an annual outage of less than one half hour per year. The performance objective for U.S. cross-country terrestrial microwave relay systems is 99.98%, based on 25 years of experience with such systems. By comparison, the ten-year-old INTELSAT system (about half the stations are less than five years old) can now be considered to have reached the stage of technical maturity.

3. *Domestic Use*

With the success of the international satellite service, a number of countries have investigated and found it economic to provide satellite transmissions for certain domestic communication services using satellite capacity leased from INTELSAT. Such capacity ranges from one quarter of a transponder to two transponders. For reference, the presently used INTELSAT IV and IV-A satellites have 12 and 20 transponders each, respectively. This service is mainly for communications between areas separated by difficult terrain (water, jungle, deserts, or mountains) making terrestrial systems uneconomic. Brazil, for example, is using its system for communications between cities on its eastern and western borders. Malaysia leases a transponder to provide TV and voice communications between their mainland and East Malaysia on the northwest coast of Borneo, 900 miles across the South China Sea. Algeria uses the service for a domestic system of a dozen stations spread over the entire country, Spain for TV transmission to the Canary Islands, and Norway for communications to oil drilling platforms in the North Sea.

B. Other Systems

Some countries have sufficient need for domestic satellite communications to justify their own systems.

The first domestic system was put in operation by the USSR in 1965, and MOLNIYA now includes about four dozen stations located between Eastern Europe and Vladivostok and providing both TV and telephone transmission. Recently the Soviets have launched a synchronous communication satellite (STATSIONAR) and are proposing to launch ten of these around the world.

Canada has a system (ANIK, 1972) with over 50 earth stations in use, mainly for TV transmission around the country and also for "skinny route" transmission with one or two telephone circuits to remote areas in the Far North. The satellites are Hughes-built spinners, about 600 lb each and launched by Delta launch vehicles (2914's).

Indonesia has launched a satellite (July, 1976), "Palapa", using a Hughes satellite identical to the ANIK except for a modified antenna pattern to encompass its thousands of islands stretching over 3000 miles. Forty earth stations (8-m to 10-m antennas) have been built and installed by three American companies (Hughes, ITT, and Ford). The system primarily is intended to provide communications for governmental and administrative purposes and for industry; but it may also be used for TV transmission for education and entertainment.

Since 1974, after a number of years of protracted filings and counter-filings to the FCC, three systems have been launched and are in operation for domestic telephone and TV transmission within theU.S.: Western Union uses a Hughes-built spin-stabilized satellite similar to the ANIK (1974); RCA (1976) uses an RCA Astro Electronics Division design with a momentum wheel stabilization system and dual polarization; and AT&T (1976) at present utilizes two leased satellites (a third is to be launched in 1978) from COMSAT General. These are Atlas-Centaur-launched spinners built by Hughes.

Two studies made about 15 years ago estimated that future satellite communication systems might grow to two or three dozen stations. Today, the INTELSAT, Canadian, Indonesian, Russian, and U.S. Domestic systems total almost 300 nonmilitary earth stations.

Satellite Business Systems, a joint venture of Aetna Insurance Co., COMSAT, and IBM, has proposed a radically different system operating in the 12/14-GHz band rather than the 4/6-GHz band used by the other U.S. domestic systems. It is based on using a 5-m antenna located directly at the customers' plant or office building, as compared to present systems which are aimed at interconnecting central offices, one earth station per major city. The proposal to the FCC (December, 1975) has been embroiled in regulatory filings and counter-filings, and the objective of an operational system in 1979 no longer appears to be feasible.

C. Maritime, Aeronautical, and Broadcasting Satellites

1. *Maritime Satellite System*

a) MARISAT: In 1976, COMSAT General with 86% ownership, and RCA, ITT, and W.U.I. totaling 14% ownership, launched three satellites (spin-stabilized, about 700 lb each, built by Hughes Aircraft Co.), one each over the Atlantic, Pacific, and Indian Oceans, to provide communications to both the U.S. Navy (225-400 MHz band) and to commercial shipping (1540-1660 MHZ). At the present time, several dozen commercial ships are equipped and in operation for telephone, teletype, and data operation.

b) Other Maritime Programs: The European Space Agency is building (with the U.K. contributing the major share of the money) a MARitime-Operational Test Satellite (MAROTS) for launch in early 1978. It will also be launched by a Delta launch vehicle for experimentation and possibly operation of a maritime system.

A new international organization, "INMARSAT", has recently been organized to own and operate a maritime satellite system. Ratification by a certain requisite number of countries is now required for INMARSAT to become a reality. A specific program involving technical, legal, financial, and administrative arrangements must then be developed.

2. *Aeronautical Satellites*

After a confused political picture stretching back into the 1960's, a joint European (47%), U.S.A. (47%), and Canadian (6%) consortium was formed (1974) to develop, construct, launch, and operate an aeronautical satellite system (AEROSAT). The U.S. user will be the Federal Aviation Administration, while COMSAT is the U.S. participant in the development and operation of the system. The European administrations are represented by the European Space Agency and the Canadians by the Department of Communications. By 1975 the technical team began to prepare specifications and a contract is now under negotiation with an international team of contractors headed by General Electric. An attempt will be made to share the spacecraft work in the same proportion as the ownership. The satellite design will include both VHF and UHF equipment† to permit direct

†The VHF system was included at the insistence of the American group and will be paid for by them. The sharing of costs applies only to the UHF system and the launch vehicle.

comparative tests. The satellite is projected to be launched in 1979 by a 3914 Delta vehicle. The program is now again in a "hold" mode pending certain necessary Congressional authorizations.

3. Broadcast Satellite Systems

This term is used to describe systems with earth station antennas of 1- to 3-m diam, as might be used for reception in a home (1 m) or in a school or village (3 m). Such systems are not yet in operational use, but experiments are underway with the NASA ATS-6 and the Canadian CTS broadcast satellites.

The ATS-6 has been in experimental use since June, 1974 over the U.S. and India for one year each and is now back over the U.S. From a technical standpoint it proved the feasibility of unfurling a 30-ft-diameter antenna in space and keeping it properly oriented. The CTS satellite (Hermes) operates at 12 GHz, rather than at 860 and 2600 MHz as in ATS-6. It features two foldout panels, each 6.5 m × 1.3 m, providing over 1 kW of power for a 200-W tube, the highest power yet flown in space. Even so, it was necessary to restrict the antenna beam to 2.5° × 2.5° (a fraction of Canada) to permit a receiving antenna of 2.4 m diameter. In both cases, the systems performed technically as expected, but the economic viability of similar satellites for either education or entertainment is not yet established.

It is of interest to extrapolate these parameters to estimate the requirements for a TV broadcast satellite covering the Continental U.S. and working into a possible future home receiver with a 1-m diameter antenna and significantly lower noise than used for the CTS tests. This results in a satellite solar array power requirement of several kilowatts per channel (2 to 4 kW, depending on receiver performance). Thus, for a four-channel satellite the required power would be 20 to 40 times that of the INTELSAT IV. This could not be achieved with a conventional spinning satellite occupying an entire useful shuttle capability (15-ft diam × 45 ft long). However, a three-axis stabilized satellite would need a foldout array with 1000-2000 ft^2 of surface area which could readily be accommodated. A suitable home receiver, including the 1-m antenna plus a converter for use with a conventional TV receiver, might sell for a couple of hundred dollars in mass production.

Considering that the three major U.S. TV networks spend only about 6% of their gross income for nationwide transmission, there is a question as to the economic justification of direct to-the-home broadcasting within the U.S.

The next decade should see further tests of these and other systems which should help to resolve the question of the future of broadcast satellites considering their economic, social, and political problems.

III. Technical Aspects

A. Initial Considerations

The first technical choice to be made by COMSAT in 1963 was whether our system was to be at medium or synchronous altitude. For a fledgling company embarking on its first venture, the medium-altitude approach of a couple of dozen relatively simple satellites, proven by the Telstar and Relay experiments, appeared to some to be a more prudent choice than the six (three in use plus three spares) more complex satellites needed for the synchronous system. The latter approach also raised the question of the acceptability of the inherent time delay for telephonic communications, a concern of some magnitude since our only customer for telephone usage of the system, AT&T, had serious concerns in this respect. However, the successful launch of one or two medium-altitude satellites, required to prove out a specific design before committing to the two dozen satellites needed for an operational system, would at best be an experiment since their time in view would be far too short for commercial use. On the other hand, the successful launch of one synchronous satellite could not only serve to answer the time-delay question but (if answered positively) could then be used for 24-hour-per-day operation. Based on this reasoning, we started plans for what later became INTELSAT I, "Early Bird," contracted for in the spring of 1964 and launched one year later.

On that contract, and on all of our satellite contracts since, we have written fixed-price contracts with incentives for longer life in orbit. In order that industry may agree to undertake a fixed-price contract, we attempt to write specifications which can be met with a high degree of confidence using known components and technology to the greatest extent possible. But in developing a new satellite the engineers must constantly make choices, and we wanted to temper their desire to meet the specifications at the lowest cost by holding out the promise of incentives for a longer lived satellite. We believe that our excellent record over the years has been attributable, in part, to this general approach.

B. INTELSAT I, II, III

The successful launch of Early Bird (INTELSAT I) on April 6, 1965 proved the feasibility of long-term station-keeping in a synchronous orbit, provided useful data on propagation of earth-satellite paths at 4 and 6 GHz, demonstrated the acceptability of the time delay associated with the use of synchronous satellites for telephone applications, and showed that the satellite system could readily be integrated into the terrestrial network with the use of proper echo suppression devices. Its estimated life of 18 months proved far too pessimistic. The satellite worked successfully for five years, by the end of which period its hydrogen peroxide fuel had largely decomposed into water. Even then its electronics continued for several more years until the solar cell output decreased below a usable value.

The INTELSAT II series (1967-1969) was twice the weight of INTELSAT I, thanks to NASA's uprating of the Delta launch vehicle. This permitted a wider beam covering both hemispheres and with multiple access capability.

INTELSAT III (1969-1975) was our first design to employ a directional beam covering the earth, rather than the doughnut patterns of INTELSAT I and II. It also utilized the full 500-MHz band (as against 50 MHz for INTELSAT I and 125 MHz for INTELSAT II) providing 1500 telephone circuits (against 300 for INTELSAT I and 240 for INTELSAT II). Although this program of eight satellites had three launch vehicle failures (a first stage, third stage, and apogee motor), and experienced some failures due to the mechanical despin mechanism, it permitted us to provide three-ocean coverage so that by January, 1971, when the first INTELSAT IV was launched, we had over 50 earth-station antennas in operation.

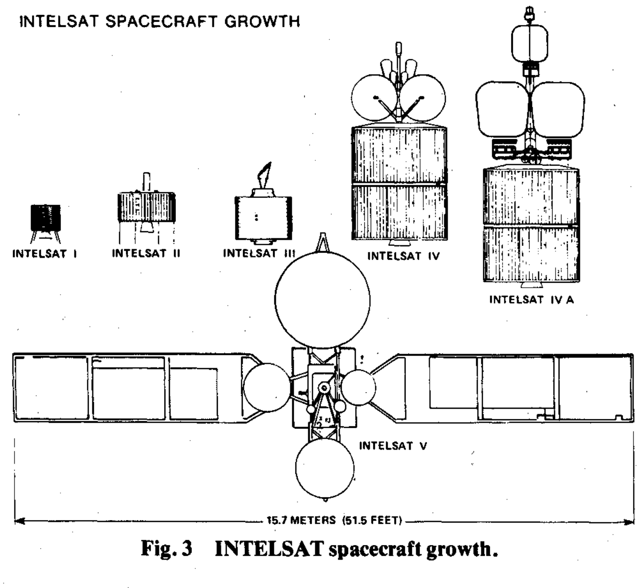

Fig. 3 INTELSAT spacecraft growth.

C. INTELSAT IV, IV-A, and V

The continuing need for more circuits, the lack of any additional bandwidth, and insufficient experience to go to either dual polarization or to multiple beams, were factors which led to the only remaining alternative, viz. more satellite-radiated power. This was obtained by using the larger, heavier, and more expensive Atlas-Centaur launch vehicle, rather than the Deltas used with INTELSAT I through III.

The net effect was to provide from 3000 to 9000 two-way telephone circuits, depending on the number of transponders switched to spot beams or global and the number of carriers sharing each transponder. Typically, about 4000 circuits can be obtained per satellite.

The cost to develop, build, launch, and follow up on eight such satellites totalled about $270 million, roughly half for launch vehicles and half for satellites. This ratio also held for INTELSAT III. The program has been very successful, with seven successful launches out of eight (one failure due to a lanyard in the Atlas not pulling out cleanly).

With the continuing need for more circuits, six INTELSAT IV-A's were purchased, and two are already in use in the Atlantic region. The satellite structure and mechanical features are those of the INTELSAT IV but with an expanded communication package. Its capacity is about 6500 two-way telephone circuits. The increased capacity is obtained by using for the first time in satellite systems the same frequency band twice, once within an antenna beam which illuminates all of South America, Central America, and the eastern part of North America, and again in another beam with a second set of amplifiers using the same frequencies, illuminating Africa, Europe, and the Middle East. The angular separation between the two beams provides sufficient isolation to permit such frequency reuse to double the channel capacity. This principle of frequency reuse is a forerunner for future satellites with even more beams resulting in correspondingly greater reuse and channel capacity.

It is expected that the INTELSAT IV-A satellite will be saturated by 1979, and therefore INTELSAT has embarked on a program for developing and constructing its next generation of communication satellites, INTELSAT V. In order to obtain still more channel capacity (about 12,500 two-way circuits), these satellites incorporate not only the dual-beam concept of the INTELSAT IV-A series, but also will include repeaters in the new frequency bands of 11/14 GHz in addition to those in the present 4/6 GHz bands; they will also incorporate the techniques of dual polarization. In mid 1976, a contract was awarded to an international consortium of companies headed by Ford Aerospace and Communications Corporation to develop and manufacture seven satellites of this series, four to be launched on Atlas-Centaur and three on the space shuttle launch vehicles. The first launch is expected in 1979. The total project is estimated to cost approximately $450 million.

The relative sizes of the members of the INTELSAT satellite family are shown in Fig. 3 and their circuit capacities in Fig. 4. A measure of the relative space segment cost per circuit is obtained by dividing the cost of each program (satellites + launch vehicles) by the number of satellites and by the number of circuits per satellite, with results shown in Fig. 5 for actual costs and also for 1968 dollars. In one decade, the cost per circuit has decreased by a factor of 1.6 in current dollars, or by 3.2 in 1968 dollars.

D. Future Trends

The major spacecraft work is in the areas of attitude control and power supplies, and each of these will be briefly reviewed.

1. Power Supplies

Solar cells have been used as the prime power source for almost every satellite launched since Vanguard I (March, 1958). They have proven to be a stable, reliable source of power, several times less costly than plutonium and without the danger of radioisotope sources. Conversion efficiency remained at about 10% for a decade until 1972 when COMSAT Labs developed the "Violet" cell with an improvement of 20% to 30%, i.e., a conversion efficiency of 12% to 13%. In 1974, the same group further improved the efficiency to 14% to 15% (the "Black" cell).‡

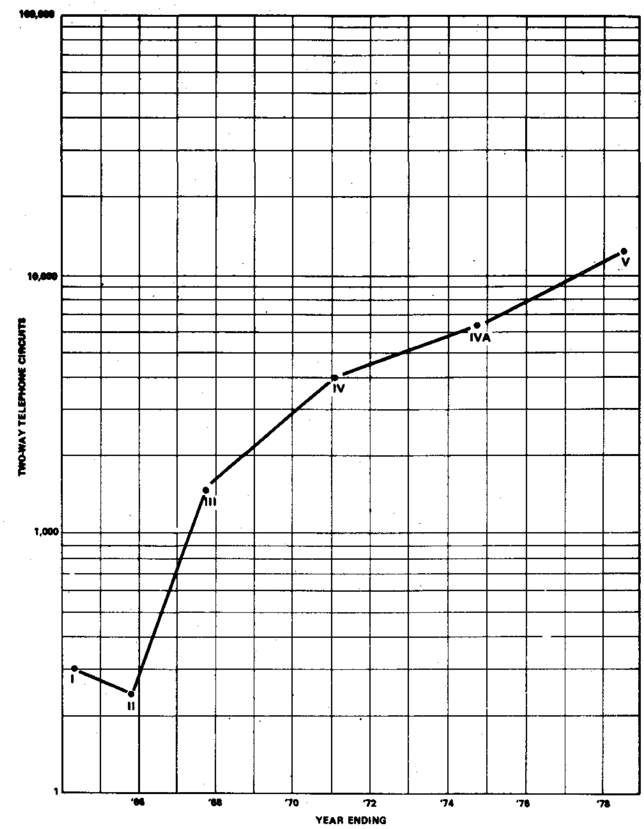

Fig. 4 Capacity of INTELSAT satellites vs date of first launch.

Successful work has also continued aimed at reducing the weight of arrays of solar cells, and the Canadian CTS satellite (1976) has achieved 20 W/kg against earlier designs with twice the weight per watt. It is now possible to design for better than 30 W/kg, while more advanced studies are considering designs of 200 W/kg.

Complementatary to the solar array are the storage batteries to power the satellite during the semiannual eclipse periods. Recent work at COMSAT Labs has led to Ni-H_2 cells with 2 to 3 times greater capacity per kg than the presently used Ni-Cd cells.

2. Attitude Control

With the successful demonstration of spin stabilization in the Tiros (1960) series of satellites at low altitudes, and in the Syncom II (1963) at synchronous altitude, COMSAT chose this approach for its simplicity in INTELSAT I, II, and III.

Both spinning and three-axis stabilization were studied for INTELSAT IV and later for INTELSAT V. For the former, there were no strong differences in price or performance, so we chose the proven spinner design. For INTELSAT V, there was a price difference in favor of a three-axis approach; also, successful orbital experience has been demonstrated with designs of this type. Each has certain advantages and disadvantages, but these are recognized and can be allowed for in a careful design. Significantly, either approach can produce a pointing accuracy of about 0.1° with an RF sensor.

‡For a description of increased conversion efficiency, see *COMSAT Technical Review*, Vol. 6, No. 1, Spring 1976, pp. 57–69.

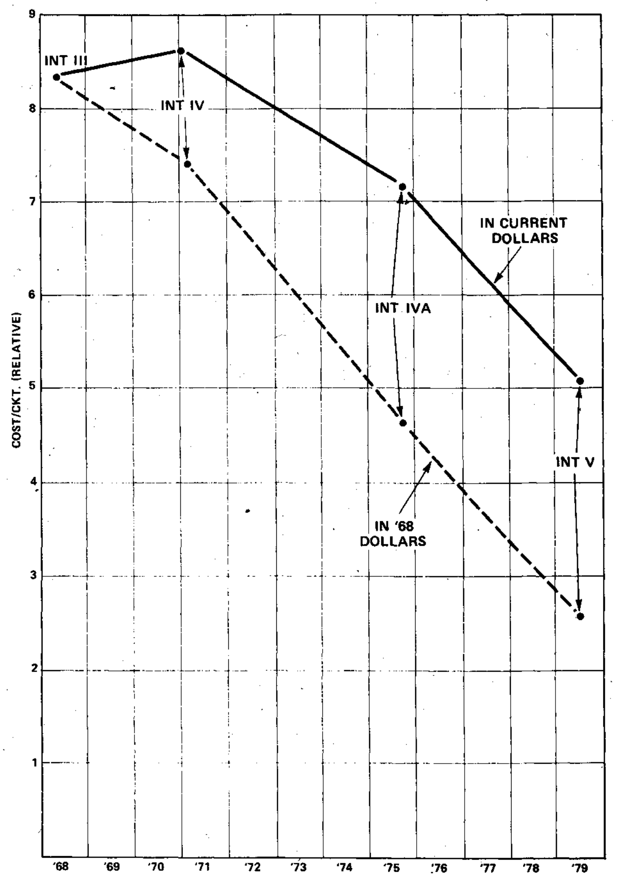

Fig. 5 Relative space segment cost per circuit (invested) for INTELSAT satellites.

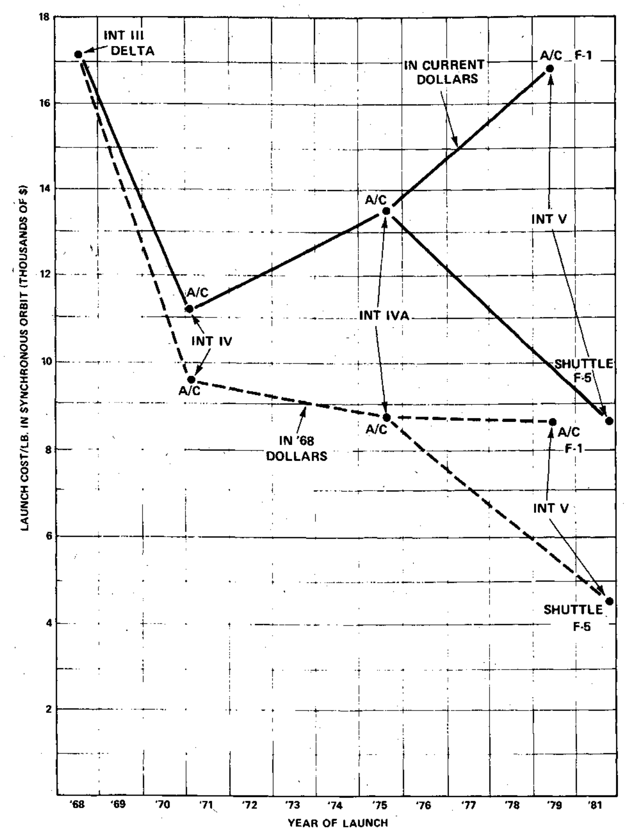

Fig. 6 Launch cost per lb for INTELSAT satellites.

For an order of magnitude improvement, it appears that the three-axis approach may be more suitable. Most design teams favor this approach, but the shuttle, with its 15-ft diameter capacity, may produce the spinner with new opportunities.

3. Launch Vehicles

The Delta vehicle was used for our Early Bird launch because it provided a usable payload at the lowest cost. The remarkable growth in its synchronous capability over the years, from 85 lb in 1965, to 190 lb in 1967, to 325 lb in 1968, to 1000 lb today, is due to the farsighted leadership of NASA and the ingenuity and engineering skill of the McDonnell-Douglas engineers. By using rockets developed for other programs, they have constantly upgraded the Delta capability and maintained an excellent record of successes. There have been 127 Delta launches since 1960 and no failures in the last 27 launches.

INTELSAT pays NASA for launch vehicles plus associated launch costs and tracks the satellite with its own six tracking stations (Maine, Italy, Brazil, Hawaii, Cameroon, and Australia) once the satellite is separated from the launch vehicle. There have been 13 Delta launches for INTELSAT with two failures, due to a first stage and a third stage. Also, there have been two apogee motor failures, but these are not the responsibility of NASA. COMSAT has had three MARISAT satellites successfully launched by Delta vehicles, for a total of 16 with two failures, or an 87.5% launch success record.

For the greater capacity needed for the INTELSAT IV, IV-A, and COMSTAR satellites, we have gone to use of the Atlas-Centaur vehicle. Here we have had a total of 12 launches (eight for INTELSAT IV, two for INTELSAT IV-A, and two for COMSTAR) with one failure in the Atlas stage, a record of 91.7%.

The development of the space shuttle holds open the promise of substantially reduced launch costs. The shuttle should also permit flexibility in designing a satellite for a specific mission without regard to the constraint of a specific launch vehicle, as has been the case till now. Work is needed in learning how to optimize satellite design for shuttle launches in order to minimize launch costs.

Whereas launch costs for the type and quantity of communication satellites have typically averaged about equal to satellite costs for both the Delta and the Atlas-Centaur, for the shuttle it now appears that they may be substantially reduced.§ Some experience is needed to confirm these figures.

Until recently no other country except the USSR has had available as broad a range of launch vehicles. However, the U.S. policy to provide launches to other countries for non-military purposes with rather nominal restrictions has effectively put all countries on an equal footing with respect to launch capability. To date, the U.S. has launched six communication satellites for other than U.S. companies or INTELSAT.

4. Earth Stations

Our original 60-ft-aperture horn antenna at Andover, Maine was designed by Bell Labs for experimental work with Telstar, as an enlarged version of their 8-ft horn antenna used by the thousands in their terrestrial radio relay system. It had a simple well understood geometry, low side lobes, and therefore low noise, and could be scaled up with a high degree of confidence, even in the tight time schedule available. For our purpose, its use of a radome with 6 to 9 dB of loss in rain or wet snow was a serious shortcoming, and its cost was higher than other designs. Since then the trend has been to obtain the desired electrical performance from modified 85-ft-diameter NASA and DOD antennas, to simplify the main-

§Figure 6 shows the launch cost per pound of payload in synchronous orbit for INTELSAT's various satellites in terms of actual dollars at a given time and also in terms of 1968 dollars. For INTELSAT V, the figures are for Atlas-Centaur and also shuttle launches.

tenance and operational aspects and to reduce cost. The latest version uses four reflector plates to act as a periscope for the antenna feed, thus permitting all equipment to be at ground level, a great advantage operationally. All versions other than the horn used about 500 kW of heater elements behind the parabola to melt off the snow and thus eliminate the need for a radome.

Low-noise amplifiers have also changed considerably during this period, with the trend being towards wider band and simpler equipment, but at the price of somewhat higher noise. This is compensated for by increasing the antenna diameter to 97 ft. The cooled amplifiers have proven to be well-behaved, but recent advances in amplifier design have resulted in still simpler uncooled amplifiers with sufficiently low noise to be used in stations with 105-ft antennas and favorable look angles toward the satellite.

The high-power amplifiers used in the earth stations vary widely, from tens of watts to 10 kW output, depending on station traffic, and equipment configuration. Wherever possible (up to 3 kW), the trend is toward air cooling rather than water cooling.

During the last few years, there has been an influx of stations having relatively light traffic per station (one to three dozen telephone circuits each). For these stations it is more economic to use a smaller antenna and pay an increased space segment charge. Accordingly, INTELSAT has approved a Standard "B" station, using an antenna of approximately 11 m diameter, in addition to the Standard "A" station with its 30 m antenna.

Having achieved the desired electrical performance, the emphasis in station design has been in the direction of centralizing the monitoring and control of the equipment to simplify operation and maintainability. Figure 7 shows the continuing decrease in station cost as a result of standardization of design and increased production until 1974, when inflationary factors led to a reversal of the trend. The wide range in station costs reflects differences in cost of land, of traffic requirements, and the degree of austerity used in the station configurations.

5. General

a) Time Delay: The world's several hundred million telephones use two wires to connect each telephone to the local switching office, rather than the four one might expect (one pair for the microphone and one pair for the headphone), in order to halve the amount of copper needed in this most expensive part of a nation's telephone network. However, the long-distance systems use four wires, and a bridge (or hybrid) circuit is used to couple one to the other. Due to imperfact matches, speech energy is reflected back to the talker, its annoyance being proportional to the delay. Typically, echo suppressors are installed on circuits over roughly 1500 miles in length. These act as a switch to open the return path when a signal is sensed on the forward path. Because of the length of satellite circuits, there was concern over the effect of the time delay. Tests were undertaken which showed that the time delay, per se, played a rather minor role in the effect, but that the major contributor was its effect on the action of the echo suppressor, particularly during periods when both parties spoke simultaneously. Improvements were made in suppressor design over those used prior to satellites, and the fact that satellite communication is now the major means of transoceanic telephone communications is a measure of its acceptability.

Spurred by the application of echo suppressors to satellite circuits, a radically new type of echo control system was developed after some 40 years of using the switching method. The new "echo canceller" couples some of the incoming speech signals into the return path with the proper amplitude and phase to cancel out the echo. Field tests have shown significant advantage over the old switching type, but its substantially greater complexity (needed to automatically adjust the cancelling signal to different line conditions) results in significantly greater cost. With the use of integrated circuits and clever circuitry, there are excellent prospects that the costs can be reduced to an acceptable level for implementation in the operational network.

b) Multiplexing and Speech Processing: The multiplexing method used by INTELSAT stations to permit a multiplicity of telephone channels to be combined in a single radio carrier is frequency division, the method used almost universally by terrestrial communication systems. The frequency band comprising each telephone channel is shifted with respect to its neighbor so that the composite signal corresponding to tens, or hundreds, or even a couple of thousand telephone channels may be sent on a single carrier without interference. A shortcoming of the method for satellite use is the reduction in capacity of a satellite transponder when it is shared by a number of earth stations. The total channel capacity is roughly 500 (in the case of INTELSAT IV) or about half of that possible if only one carrier fully utilized the power and bandwidth of that transponder. Since only two out of 120 stations need a capability of 1000 channels, the system operates under conditions where it effectively loses half of its efficiency. The problem of amplifying a number of separate radio carriers through a single amplifier ("multiple access") is one that is unique to satellite communication and has, therefore, been extensively studied by COMSAT in this past decade. Based on both theoretical and experimental work, the process is now well understood, and refined methods of analysis are available.

c) Time Division Multiple Access and Digital Speech Interpolation: In parallel with the methods just discussed, work was undertaken on an alternate method of multiple access, TDMA (time division multiple access), in which each station transmits a burst of pulses representing samples of its telephone channels, so timed that these arrive at the satellite properly synchronized in time to interleave with respect to signals from the other stations. In this way, the satellite amplifier operates on only one signal at a time, thus yielding a doubling of capacity over the present simultaneous multiple carrier method. A nontechnical but very important consideration in the adoption of a new system is that 80% of the INTELSAT members each own less than 1% of the space segment, but each administration owns its earth station

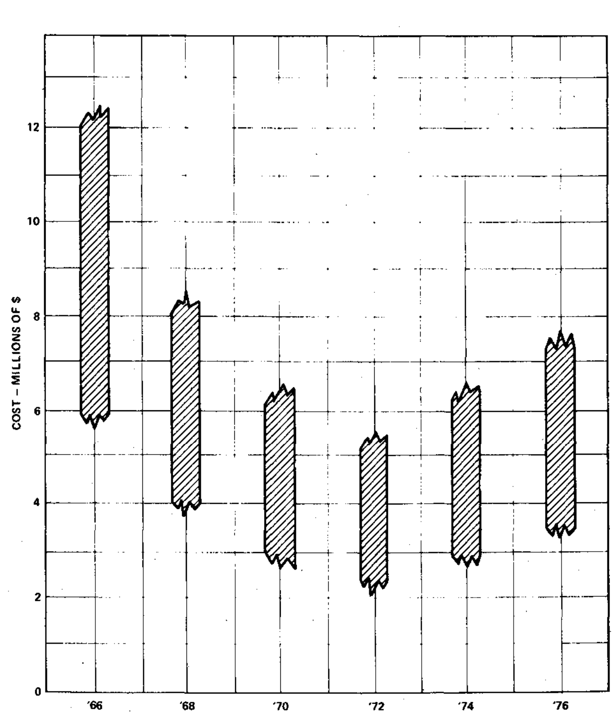

Fig. 7 Range of earth station costs vs time.

100%. Thus, there is a very strong economic pressure on the earth station owners to push off new developments onto the space segment, rather than onto their stations.

Notwithstanding this, there is no doubt but that digital transmission of speech and multiplexing by time division is the wave of the future because of its efficiency, its great flexibility, its ultimate potential for lower costs, and its suitability to the rapidly growing needs of data transmission.

TASI (time assignment speech interpolation) is a system first used about 20 years ago to effectively double the number of telephone circuits available on the first transatlantic telephone cable. The principle of operation is based on the assumption that when one subscriber is talking his correspondent is usually listening, so that, on the average, half the channels of a system are available even when all phones are off hook. With new digital techniques, sophisticated methods can be employed not only to prevent speech chopping (a usual characteristic of TASI circuits) but to increase the number of additional circuits in a system 2 to 3 times or possibly even more. This approach is, of course, inapplicable to data transmission.

d) Adaptive Digital Systems: Digital voice systems now operational in the more industrialized countries use a rate of 64 kilobits/second for transmission of one voice channel. In the last several years work has been underway on adaptive pulse code and delta modulation systems which take advantage of speech characteristics to permit transmission with good quality at 32 kbps or with continuously reduced quality at lower rates down to 9.6 kbps. This reduction involves more sophisticated analog-to-digital coders/decoders, but with integrated circuits the additional circuitry can be added at relatively low cost. Work is continuing on improving speech quality at these lower rates. Here, too, such bit reduction methods are not applicable to data transmission which is becoming a more important part of the total traffic of modern telecommunications systems.

e) Multiple-Beam Satellites: In other sections of this paper several recent improvements have been noted which produce advantages over present components and techniques of 1.25 to 1.5 in efficiency of solar cells; or a reduction of storage battery weight of 2 to 3 times; or increases in voice channel capacity of 2 times for TDMA or 2 to 4 times in digital speech interpolation. All such advances are useful and development along these lines will continue. There is one approach, however, which offers several orders of magnitude greater potential advantage than any of these, viz., the concept of multiple-beam antenna beams. A global antenna beam illuminating the visible earth has a beam width of approximately 20°; but by going to a 2° beam the gain increases 100 times, and similarly a 0.2° beam would have 10,000 times the gain. At 4 GHz, as is now used for satellite-to-earth transmission, the corresponding satellite antenna diameters for these three beam widths are 0.85 ft, 8.5 ft, and 85 ft, respectively. The first is negligibly small, the second can be installed on an Atlas-Centaur launch vehicle without foldout, while the third is about 3 times larger than the 30-ft unfurlable antenna of ATS-6. Antenna engineers are optimistic about achieving antennas of not only several hundred but several thousand feet in diameter, but for such large structures it will be necessary to automatically adjust individual panels of the array in order to achieve the typical surface tolerance of about 1/32 wavelength, which at 4 GHz equals 3/32 in.

Going to the 20/30-GHz band, which was allocated to satellite communications in 1971 but which has not yet been used commercially, the necessary satellite antenna size for the same beam widths as mentioned above would be reduced by 5 times. Thus, for beam widths of 20°, 2°, or 0.2°, the antenna diameters would be .17 ft, 1.7 ft, and 17 ft, respectively, dimensions which are much more amenable to single-antenna design solutions than those required at 4 GHz.

The earth stations would use a time division system to multiplex their voice channels onto a single carrier, and the channels from the various stations could be routed in the satellite to the various beams by suitable electronic switches. These may be electromechanical (coax or waveguide) for a relatively slow operation from time to time, or switching of RF bursts, or actual on-board pulse train demodulation and switching on a pulse baseband basis. Switching can be done prior to, or following, the satellite output amplifiers, and each of these approaches is best suited to certain applications.

The first satellite to use a multiple-beam approach was the INTELSAT IV-A, first launched in 1975, Here two beams were used, one for North and South America and the other for Europe/Africa. The reasons for such narrow beams include the following, singly or in combination: 1) decrease earth station transmitter power; 2) decrease satellite transmitter power; 3) increase channel capacity due to increased satellite radiated power (if transmitter power is constant but antenna gain increases); 4) increase channel capacity due to frequency reuse in each beam (as in INTELSAT IV-A); 5) use increased satellite radiated power to decrease earth station diameter; and 6) new frequency bands.

At the present time, all satellite systems are operating without a single Hertz of frequency space allocated solely to these services. All of these systems are operating on a shared basis in a band already considered heavily used by terrestrial microwave relay systems.¶ It is one of the major achievements in spectrum management that the satellite systems now carry the major share of the world's transmission circuits (over 8000 two-way circuits) on a shared basis.

In 1971, additional bands totalling about 6.5 times the present bandwidth were allocated in the 11/14-GHz and 20/30-GHz regions. These are affected by rain, but this disadvantage is offset in some applications by the greater potential capacity and the smaller satellite antenna size needed for a given beamwidth.

During the next decade, satellites working in these new frequency bands will become operational.

6. *Potential Applications*

Even with today's technology we can, in some cases, provide services which far outstrip our present needs. To illustrate this, examples will be given of a TV broadcast satellite for the Boston-Washington corridor and also a high-capacity satellite for North Atlantic telephone service.

The use of a satellite for a new service, remote data collection, has been approved for a six-month evaluation program, and this will be discussed.

The possibility of transmission between satellites, intersatellite links, is being studies as a means of extending the geographical borders of satellite visibility for a given earth station; or of permitting an earth station with a single antenna to communicate with all stations working with two satellites in a given region.

a) Broadcast Satellite: Broadcast satellites considered thus far have but one or two TV channels because of their relatively wide antenna beams. The great advantage of a narrow antenna beam is brought out in a conceptual design for a Delta (3914)-launched satellite capable of furnishing 12 high-quality color TV channels over the East Coast corridor from Boston to Washington (0.5° × 0.6° beam) covering about 20% of the U.S. population. The signals would be received directly into the home using a 1-m antenna (at 12 GHz). It is estimated that such an antenna and associated electronics might sell for a couple of hundred dollars in large production. The space segment cost per channel would be in the order of $.30 per channel per TV home per year for the 12 million TV homes in this area. By taking advantage of a greatly increased shuttle capability, satellites with a number of such beams could be launched simultanenously to provide similar coverage over other high-population areas of the

¶3700 to 4200 MHz for the satellite-to-earth path and 5925 to 6425 MHz for the earth-to-satellite path.

country. As noted previously, the programming costs will far outweigh the satellite costs and will eventually determine the extent to which we need such additional channels.

b) Transatlantic Fixed Service Satellite: Another example of the increased potential of narrow beam antennas is brought out in its use for transatlantic communications. Specifically, it should be possible** to design a Delta-launched satellite with a 2.5° beam over U.S./Canada, and another over western Europe, with a capacity of over 28,000 two-way voice circuits using conventional frequency division multiplex, or 70,000 to 90,000 two-way circuits using digital speech interpolation methods (but of a type already developed). In place of the 4/6-GHz system described above, a 5 times greater capacity could be obtained with a 20/30-GHz design, but this would require a somewhat larger satellite.

The development, construction, and launch of two Delta satellites (one in use plus one spare) operating at 4/6 GHz, plus two earth stations, would require an investment of $2000 to $4000 per circuit compared to $50,000 per circuit for the latest (1976) 4000-circuit transoceanic cable. Even taking into account the difference in lifetimes still yields an order of magnitude difference in cost per circuit year. This ignores the fact that the satellite system, with its shorter depreciation period, can be uprated several times to reflect advances in technology during the 20- to 25-year lifetime of the cable. Future satellite systems in the 20/30-GHz region, with 5 times the bandwidth available, could further reduce circuit costs by several times.

c) Data Relay System: An interesting application of a system using small antennas is one now being implemented jointly by COMSAT General, the U.S. Geological Survey, and Telesat of Canada for remote data collection. In this experiment, a dozen platforms will each periodically transmit a 0.2-sec burst of digital data every quarter hour. Since all stations will be on the same frequency and since the occupied bandwidth is only 2 kHz, this service can be readily accommodated in a small fraction of the 36-MHz band of a single domestic satellite transponder. It is estimated that 300,000 of such platforms can be accommodated in a single satellite transponder (there are 12 to 24 such transponders per satellite in current designs). The platforms operate in the 6-GHz band using a transmitter with 1 W output from a solid-state source and a 4-ft diameter parabolic reflector. The resulting interference into terrestrial relay systems and adjacent satellites is negligible. Excluding development costs, such platform stations cost a few thousand dollars each, but in large quantity, this price can be substantially reduced.

d) Future Systems: Our telephone system is 100 years old; the first transistor was made less than 30 years ago; the first satellite was launched 20 years ago; commercial satellite communications began a decade ago; electronic switching is also roughly 10 years old; and the mass use of solid-state chips as exemplified by the digital watch and hand calculator is about 5 years old. This rapid growth of relevant technology would appear to show that, as great as the growth of satellite communications has been in its first decade, it is still in its early stages. The availability of miniature solid-state circuits, of low cost and long life, holds open the promise of circuits which would not have been operationally or economically feasible otherwise. Such techniques for low-cost earth station equipment and/or satellite-borne switching, coupled with the satellites' capability of providing coverage over a nation, or over a third of the world, with high-quality wideband signals, makes new applications possible, especially when utilizing the potential of multiple narrow antenna beams.

The three major technical areas involved in a communications system include transmission, switching/processing, and input/output terminals. In transmission, the communication satellites of INTELSAT alone are now providing over 8000 circuits, the major share of the world's transoceanic telephone and data circuits, via 500 paths to over 90 countries. Within the U.S., domestic satellite tariffs are now lower than equivalent terrestrial tariffs. The digital capacity of a modern satellite, e.g., the Comstar, leased by COMSAT General to AT&T for domestic use, is over one billion bits/sec. More significantly, operation in the new frequency band of 11.7 to 12.2 GHz, not shared with terrestrial microwave, permits stations to be installed in the cities right on the subscriber's building, thus eliminating the local loop, heretofore the bottleneck in distribution of wideband communication.

**By covering only high-traffic stations and restricting entry to large-capacity single-carrier-per-transponder operation.

Electronic switching systems are now available in all sizes from small PABX's to high-capacity machines handling thousands or even hundreds of thousands of calls per hour. Related technology permits design of equipment for processing the voice from analog to digital (and the reverse), digital speech interpolation, and echo suppression, in addition to electronic switching.

The public has long used input/output devices in the form of the telephone, TV set, and typewriter and, more recently, the hand calculator and digital watch. However, introduction of a number of new services into the home is still awaiting the development of a complete home terminal including a keyboard display, memory units (plug-in cassette), and a modem for interfacing with the communication network, all at a price acceptable to the public for the services to be rendered, probably in the neighborhood of several hundred dollars each.

Drawing on the technologies from these three areas, novel systems have been proposed for applications in business, home, and in the school. For the business office, the use of electric processing typewriters (already in use) can be connected to the telephone network for real time or delayed transmission of letters. The original is stored in a data bank to be recalled at will, in far less storage space than for paper. The data received at the destination will be reproduced automatically as a letter with as many copies as required and here, too, the received data will be stored and crossfiled. All of an office's communications needs (mail, teletype, data, facsimile, and videophone) will be converted into a digital format and transmitted via satellite to selected other offices or broadcast to all. Great flexibility is possible in that the output bit rate can be varied automatically as required. Teleconferencing may be added to provide means for eliminating physical transportation to conferences. Such teleconferences would include combinations of telephony, data, facsimile, and video transmission. The extent of its use is limited by the ingenuity of our engineers to design reliable, low-cost earth stations.

The concept of a home communications center, for reception and transmission of mail, for reception of the daily newspaper, as a student's classroom terminal, for searching a central data bank, for computation, for a directory of a town's activities,†† for shopping and banking,‡‡ and for entertainment, has been put forth in a number of papers on future communications.

The use of satellites for education has had a first test in the U.S. Rocky Mountain, Appalachia, and Alaskan area and also in India with the ATS-6. More ambitious systems have been proposed, culminating in the one mentioned above, where the student stays at home and "attends' classes via a TV link.

While all of the above systems, which are given as examples of many others in these areas, are technically possible, and some of them with today's technology, it is not clear as to which of these will be utilized by the public or what the

††Experimental CATV systems already provice such services.

‡‡Pilot installations are already testing direct transfer of funds from a purchaser's account to that of the shop, under control of a data circuit between the shop and the bank.

utilization/economic tradeoffs will be. Furthermore, there are difficult social, regulatory, and vested interest aspects involved in such new systems. These will almost surely prove more troublesome than the technical and economic constraints.

Many of these questions cannot be answered realistically without actual field tests, since they involve the public's subjective reaction to novel services and the regulatory agencies' consideration of services crossing old boundaries. The next decade should see field tests of many of these concepts, since the technical potential exists and is not an idle dream.

The conservative will say that our conventional services will be gradually expanded, improved, and augmented, and that satellites are just another adjunct to the arsenal of telecommunication transmission facilities. The optimist will say that satellites will rapidly add a new dimension to telecommunications, create a whole new industry of telecommunications devices, and radically change the way modern society will live and function. The realist will recognize that powerful economic and political forces will constrain development and application but cannot, in the end, deny the genuine benefits of technological developments which have important societal benefits. But the technician has the task of communicating, in terms the layman will understand and appreciate, the benefits to society that particular technological developments may have. It is then society's judgment as to whether they will play an important role or not. The scientist and the engineer have not generally enjoyed the reputation in the past of being good communicators in the broadest sense of the word. It is an essential challenge in the future.