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Communications Satellites: Countdown for INTELSAT VI

L. Pollack and H. Weiss

In the two decades since the formation of the Communications Satellite Corporation (COMSAT), the number of active international satellite telephone circuits, worldwide, has grown 400 times and the cost of a telephone call has decreased by 12,000 percent, while the quality of service has improved. The timely exchange of televised news and cultural events via satellite is now commonplace among most countries worldwide. This dramatic progress has been made possible because of the introduction of geosynchronous communications satellites.

Summary. Since the formation of COMSAT 20 years ago, the number of international telephone circuits made through satellites has grown 400 times and the cost of a telephone call has decreased by 12,000 percent. Worldwide communications linking 109 nations are achieved with 14 satellites in earth-synchronous orbit. Advances in microwave technology have expanded the transmission bandwidth per satellite from 50 to more than 3000 megahertz. Improvements in solar cell, battery, stationkeeping, and microwave amplification technology have increased satellite lifetime from 1.5 years to 10. The sixth generation of INTELSAT satellites, now being manufactured, will be introduced into the system in 1986, and each satellite will carry more than 40,000 telephone channels plus two television programs. The next generation of satellites, now under design for expanded capacity, will be needed by the middle 1990's to meet the traffic demand. These satellites are likely to add new frequencies (20 and 30 gigahertz), onboard signal processing and switching, and more bandwidth-efficient modulation, to achieve larger communication capacity at each orbital location.

In 1964 COMSAT joined together with communications entities of 15 nations to form an international body known as INTELSAT, the International Telecommunications Satellite Organization. The organization which now includes 109 members is preparing for the introduction of its sixth generation of satellites. INTELSAT's global system provides communications along 1132 paths with earth stations in 169 countries and territories through more than 670 antennas, to which about 100 are added each year. In addition to seven full-time television channels and 5550 hours of occasional television, more than 31,000 simultaneous telephone circuits carrying voice, Telex, facsimile, and data are now in service.

Basic Technology

A geostationary satellite being an active radio relay repeater at a point 35,786 km above the equator, the early technology requirements were of a kind still of importance today. The four fundamental elements provide the means to (i) place the satellite in orbit; (ii) keep it stationary and stable in attitude; (iii) provide the repeater with a housing, thermally controlled environment, and operating power; and (iv) perform microwave amplification of signals received and transmitted between points on the earth by the satellite relay. While these technologies were available to inaugurate a modest satellite service in 1965, subsequent progress has been made possible by major research and development advances.

Supporting Technologies

Launching satellites. Although the first basic technology area (that associated with the launch vehicle, the launch process, and the transfer and injection of a satellite into geostationary orbit) is essential for the establishment of a network—a satellite and its associated earth stations—in INTELSAT planning it is considered mainly in the dimensioning of the payload. Dimensioning refers to both the physical dimensions of the satellite and its "wet" mass, which is the total mass to be carried by the launch vehicle at lift-off and includes the fuel needed to manipulate the satellite after it has separated from the launch vehicle for the remainder of its mission. Satellite dimensions must be commensurate with the mass-lifting and size limitations of the launch vehicle. In the case of the NASA Space Transportation System (the space shuttle), its lift capability of 29,480 kg and cargo bay measuring 4.5 m in diame-

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ter by 18.3 m are not a restriction for current satellite sizes, but the occupied fraction of the cargo capacity determines the launch cost. In addition to the satellite mass, allowance must be made for raising the satellite from the shuttle's low earth orbit (about 300 miles) to synchronous orbit. This is accomplished with a perigee kick motor, while the injection into the geostationary orbit relies on an apogee kick motor. Other primary boosters available to launch an INTELSAT VI satellite are the Ariane 4 and Titan 34D.

Stationkeeping and attitude control. Satellites are kept in an orbital position as closely as possible above a nominal geographic point on the equator and maintained in a stable attitude with respect to the earth by use of chemical fuel. The mass of the fuel, expelled in precise amounts and carefully controlled directions at high velocity, provides reactive impulses for linear or torquing movements of the satellite. These compensate for velocity decay and attitude changes due to gravitational (lunar, solar, and terrestrial) perturbations and solar electromagnetic radiation pressure. Unchecked, these effects would cause a satellite to drift in longitude and assume orbits that deviate increasingly from the equatorial plane. They also affect the satellite's attitude in space. Taking advantage of the gyroscopic stability of a rotating mass, all but one of the INTELSAT satellite types have been "spinners," with their main mass rotating about an axis normal to the equatorial plane and a lighter section "despun" by a counterrotating motor. The latter section is a stable, stationary (with respect to the earth) platform which supports earth-pointing antennas and microwave repeaters. Nevertheless, the stable spin axis is subject to tilt and precession, both of which must be removed from time to time.

In the INTELSAT V series, there are now seven satellites in orbit and eight under construction. These are body- or three-axis-stabilized satellites with the entire spacecraft body permanently aligned with respect to the earth. A high-speed momentum wheel whose axis of rotation is aligned with the north-south (pitch) axis of the satellite provides a gyroscopic stable reference. Small hydrazine thrusters adjust the velocity and attitude of the satellite by an onboard controller and by ground commands.

Maneuvers to counteract perturbations of a satellite, whether a spinner or three-axis-stabilized, are controlled in response to observed deviations from prescribed position and attitude tolerances. Information on the magnitude of the perturbations is gained from optical and infrared sensors on the satellite and from tracking data of the earth stations receiving satellite radio beacon transmissions. The optical sensors use the sun as a reference, and the infrared detectors determine the earth's limbs to locate the center of the earth. The earth station tracking data provide the information used to calculate the satellite position and its orbit parameters. In addition, the beacon carries the sensor information (telemetry) originating in the satellite.

Ability to change the orbit, the satellite position along the orbit, and the attitude with respect to the earth requires that the satellite carry a significant depletable mass of fuel (185 kg for INTELSAT V) at the time it is placed in geosynchronous orbit. The amount of

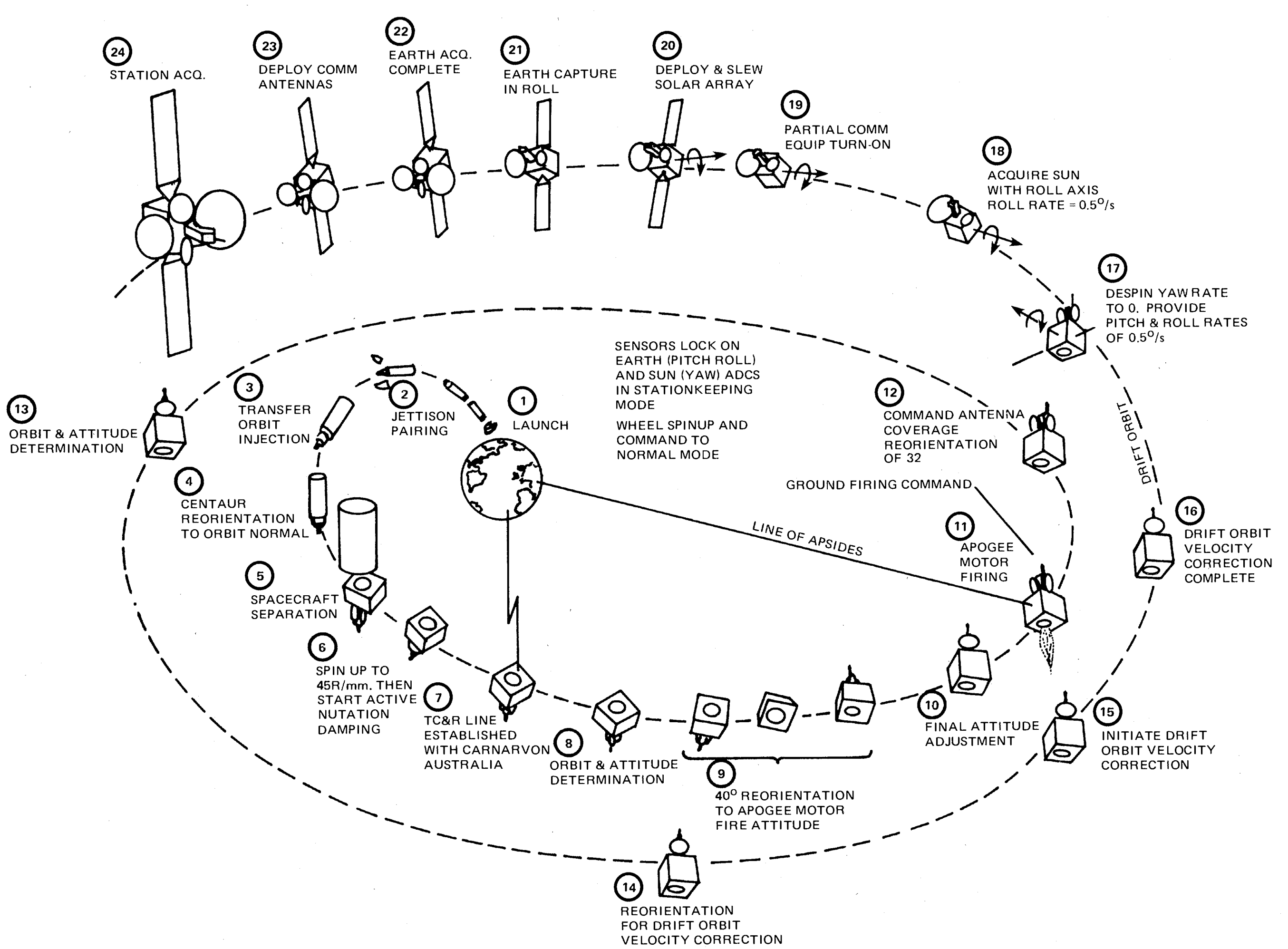

Fig. 1. Sequence of events from lift-off to orbit injection to on-station operational configuration using an Atlas-Centaur launch vehicle.

fuel on board is one of the factors determining the life of a satellite. The largest demand on fuel is for maneuvers to keep the satellite in an equatorial orbit—six to seven times as much as the fuel needed to keep it on station in longitude and attitude-stable. Additional fuel reserves are carried to allow the satellite to be moved, within a reasonably short time, to a different orbit longitude to accommodate a change in assignment. Finally, a small amount of fuel is kept in reserve to move the satellite into an orbit about 100 km higher than synchronous once its useful life comes to an end; at that point it could no longer be controlled at geostationary altitude and would constitute a collision hazard.

The amount of satellite sensor information carried by the microwave beacon increases with satellite complexity. More and more onboard satellite functions need to be continually monitored. The measurements are transmitted to the earth as telemetry, in a time-sequential digital format, to indicate the satellite's health. There are as many as several thousand of these status indications or measurements, and they are used to anticipate or detect and locate functional anomalies that might require corrective action. In the reverse direction, the telecommand function can be exercised by transmitting to the satellite any one of a large number of coded signals. Each command triggers a specific onboard function designed to respond to a prescribed operational requirement or recover from a malfunction.

In addition to these major areas of mission-supportive technology there are "bus" technologies, which are related to spacecraft structure, thermal design, and dynamic behavior (both during launch, when coupled to the launch vehicle's vibration and acceleration environment, and during other motion phases until orbit is attained) and to configuration changes of the spacecraft (unfolding of solar panels and antennas, acquisition of operational attitude, repointing of antennas, and switching the assigned transponders into each antenna beam).

Figure 1 shows the sequence of events from lift-off through orbit injection to the on-station operational configuration, using an expendable launch vehicle.

Early Mission-Associated Technologies

The major planning effort in the INTELSAT system has revolved around the function of communications. The supportive and background technologies discussed in the preceding section are taken into account mainly as constraints on the definition of the communications payload. To some degree fuel mass (which affects satellite life expectancy), primary power, and the mass of the communications payload (which affects capacity) can be traded off against each other within the overall mass constraint imposed by the launch vehicle. The communications payload, originally of very simple overall design, has today reached an impressive degree of sophistication.

INTELSAT I, or Early Bird, was designed to have a transatlantic TV or a multichannel voice transmission capability. There were two system constraints. The earth station concept was developed around a 21-m-diameter horn antenna at Andover, Maine, which, with the least noisy radio-frequency amplifier then available—a liquid-helium-cooled maser—offered a receiving system sensitivity (ratio of antenna gain to noise temperature) of 40.7 dB/K. Today this is the required sensitivity of INTELSAT's standard A receiving antenna systems. The second constraint was the internationally recommended transmission quality, expressed as a weighted signal-to-noise power ratio, of 50 dB.

The communications payload was a simple nondemodulating frequency-translating microwave repeater, or transponder. It consisted of a microwave receiver, a frequency down-converter, a microwave preamplifier-driver, and an output power amplifier with a traveling-wave tube (*1*). It was powered by solar cells, which covered the spinning drum surface of the satellite body, part of which was always exposed to the sun. Additional modest signal amplification was provided by an antenna system which, spinning with the satellite, concentrated microwave energy through a toroidal gain pattern in the orbital plane containing the earth. The satellite received its signals at 6 GHz and retransmitted them at 4 GHz, the two frequency bands allocated to what is now known as the fixed-satellite service by an Extraordinary Administrative Radio Conference (EARC) of the International Telecommunications Union in 1963. The bandwidth of the transponder was about 50 MHz; frequency modulation was used.

Most of today's communications payloads have retained the basic design principle of a simple frequency-changing transponder with an output traveling-wave tube. However, in some cases the traveling-wave tube is being replaced by transistor amplifiers, and there is growing interest in advancing from the "transparent" transponder to a design that would enhance and restructure the signal received by the satellite before it is retransmitted toward the earth (onboard signal processing).

The spinning drum with the solar cell skin for power generation continues to be used, although with the higher power requirements of today's satellites, its diameter has grown and it has acquired an extendable "skirt" which increases its energy-collecting surface along the spin axis dimension. Body-stabilized designs (INTELSAT V) have a pair of large solar array panels.

Technology Requirements

INTELSAT II. Early Bird technology reflected a pioneering effort to demonstrate a practical communications capability. Its successor, INTELSAT II, which was designed and contracted for almost immediately after the launch of INTELSAT I, incorporated improvements: (i) a higher gain toroidal-pattern spacecraft antenna, with a northward "squint," providing higher effective radiated power toward the Northern Hemisphere and thus providing increased bandwidth and more capacity, and (ii) rechargeable batteries to power the communications equipment of the satellite during solar eclipses. Twice a year for several days (near the vernal and autumnal equinox), a geostationary satellite moves through the earth's shadow, which cuts off direct solar power for up to about an hour each day.

INTELSAT III. Demand for additional circuit capacity became the main driving force for the next generation satellite, INTELSAT III. This satellite, like its two predecessors, was a spinner, but it was designed with a major technology advance—a despun antenna system. A horn antenna, generating a conical beam roughly equal in angular width to the apparent hodocentric (*2*) width of the earth, was despun in relation to the spinning satellite body with the beam constantly pointing toward the earth. This concept was chosen over one in which an earth-oriented antenna beam would have been generated by electronic means. The decisive factor was the higher expected net antenna gain of the mechanical over the electronic solution. The antennas of all current commercial communications spinner satellites are mechanically despun.

INTELSAT III's antenna system, coupled with 500 MHz of transponder bandwidth (the total bandwidth then allocated), offered an enormous increase in satellite capacity: from INTELSAT I's 240 voice channels to about 1200

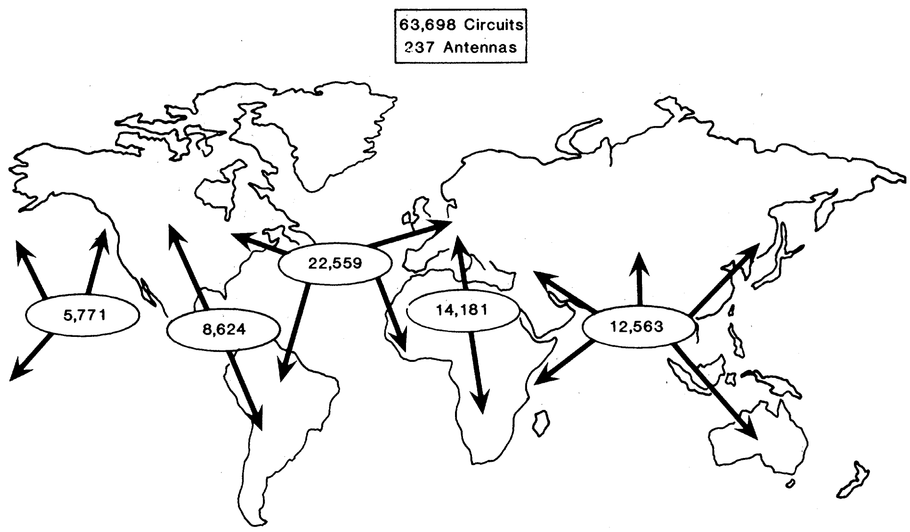

Fig. 2. Projected global traffic and antennas in the INTELSAT system—1987.

voice channels. This large capacity increase produced a dramatic drop in circuit cost, to the point that INTELSAT could compete economically with transoceanic undersea cables. Satellites have a network capacity which cables, with relatively few "landing points," lack. Any earth station in view of the satellite can access the satellite and establish a circuit with the satellite and with any other earth station. However, using this capability exacts a price in the form of reduced satellite loading efficiency to accommodate many small to medium-size traffic requirements not served by cables. The loading efficiency reduction is absorbed by means of a uniform "unit of utilization" charging rate for all users. Such rate averaging has now become of major concern in competing economically with cables, which tend to serve the more efficient high-density traffic routes.

Another consequence of the large capacity increase and corresponding traffic increase was that, first in the Atlantic and then in the Indian Ocean region, additional satellites had to be provided. The addition of satellites and growth in the number of earth station antennas to operate with them created several networks within the same ocean region. Originally, it was envisioned that the second, or major path, satellite would gradually be loaded with major traffic streams transferred from and relieving the first, or primary path, satellite. The primary path satellite would provide access for new users and capacity for part of the traffic growth, while the major path satellite would be accessed by "two-antenna countries" with large mutual traffic requirements and would also provide growth capacity. Up to a point this growth by transfer has worked, especially as several single-antenna countries found that their connectivity requirements could be satisfied by use of only the major path satellite within a community of access. A few residual low-capacity paths were established through "via-routing," using a neighboring country's facilities to gain access to another satellite.

A practice has developed by which pairs of countries, operating through two or more common satellites, split their mutual traffic into equal-capacity "diversity" streams. This leaves a substantial part of the high-capacity traffic to the primary path satellite, thus diminishing the transfer relief for that satellite and resulting in an earlier need for more earth station antennas and major path satellites.

INTELSAT IV and IV-A. INTELSAT IV, with additional satellite power and the available 500-MHz bandwidth divided into 12 increments of 40 MHz, each with a separate power amplifier, had triple the capacity of INTELSAT III. Although some of the transponders on INTELSAT IV could be switched into transmitting "spot" beams with limited coverage, that capability was never used in operation. All the available bandwidth was used in the global beam so that any country's transmission could be received by any other country.

With INTELSAT IV-A, a new technology—frequency reuse—was introduced. This was done by taking advantage of the geographic separation of country groups with major traffic requirements. INTELSAT IV-A had two satellite beams which used the same frequencies to transmit and receive but were isolated against interference from each other by the sharply declining antenna gain of each beam in the direction of coverage of the other. Moreover, the beams were shaped, providing reasonably uniform maximum gain over areas on the ground that conformed to the outlines of the two major land masses of the Americas for one beam, and of Europe and Africa for the other beam, as seen from an orbit location over the Atlantic Ocean. The same beam shapes proved reasonably appropriate for the other two ocean regions, although in the Indian Ocean region a few countries had to use INTELSAT IV-A's global beam because they were located between the areas covered by the two hemispheric beams.

The introduction of frequency reuse significantly increased capacity but engendered additional complexity of the system architecture. A transponder accessed through one beam had to retransmit to the earth through either the same beam or the other beam in order to maintain the frequency reuse capability. Thus, there coexisted four connection possibilities for each transponder which could be established by ground command—east-to-west, west-to-east, east-to-east, and west-to-west—and in addition, some transponders continued in global coverage beams. While frequency reuse through hemispheric beams nearly doubled the bandwidth available, two new system constraints had to be considered. One was the degree of interference between transmissions using the same frequencies in different beams, which affected the transmission power budget and placed moderate constraints on the choice of carrier frequencies so that the capacity did not quite double. The other was the need to split transmissions. The main transmission offering was analog voice telephony, with the voice channels frequency-division multiplexed onto a common frequency-modulated carrier (FDM/FM). Many carriers contain voice channels destined for different receiving stations, each of which extracts the channels addressed to it. In the INTELSAT IV-A satellite the voice channels that were addressed to earth stations in different satellite transmission beams required two different carriers. This increased the number of transmitted carriers and caused some loss in the satellite utilization efficiency, which tends to decrease as the number of transmitted carriers increases.

Two other factors were more important. One was the limitation in filling all transponders, since carrier-loading capability was truncated by the satellite bandwidth committed to either one or the other beam. The other was the limitation in filling some transponders because the traffic that had to be carried on east-to-east and west-to-west transponder connections was not equal. Thus, the "configured" capacity of the satellite, which is realized in the operating system, was less than its "assignable" or theoretically possible capability. An operating utilization of about 75 percent has been achieved.

INTELSAT V and V-A. Demand growth and the geographic distribution of the traffic flow became the major design criteria for multibeam frequency-reuse satellites. It was necessary to provide beam capacity to various geographic areas in approximate proportion to the traffic expected to originate and terminate in them. At present the highest density traffic flows between the northeast and northwest quadrants of a satellite's field of view (Fig. 2). INTELSAT V was designed to provide additional capacity for these high-traffic regions.

This was done in two ways. First, in addition to the two spatially isolated east and west hemispheric beams available on INTELSAT IV-A, the northeast and northwest quadrants were augmented by two "overlay" beams, referred to as zone beams, which were orthogonally polarized with respect to the hemispheric beams. Transponders could, by ground command, be switched between any of the four beams. Added to this fourfold frequency use at 6 and 4 GHz were two beams in frequency bands at 14 and 11 GHz, which had been allocated to the fixed-satellite service at a World Administrative Radio Conference in 1971. These two beams were fairly narrow, and the resulting higher gain permitted somewhat smaller earth station antennas to be used and helped to offset the occasional rain attenuation which, although of little consequence at 6 and 4 GHz, must be allowed for at 14 and 11 GHz. These beams also reuse frequencies and can be repointed by ground command. In the Atlantic Ocean region they are pointed toward North America and Europe. Moreover, the beam-switching capability on the satellite was designed to interconnect the four 6- and 4-GHz beams not only with each other but also with the 14- and 11-GHz beams in what has become known as "cross-strapping."

In light of the capacity provided by the 14- and 11-GHz spot beams toward the highest density traffic regions, the 6/4-GHz overlay beams were made sufficiently broad to include countries other than Canada and the United States in the west and Europe in the east. This allows traffic loading to be flexibly balanced among the three east and the three west beams.

In designing the beam coverages, attention had to be given to the traffic distribution in the Indian and Pacific ocean regions, since INTELSAT V had to serve all three ocean regions. It was necessary to provide for an in-orbit reshaping capability of the hemispheric and zone beams to account for the differences in traffic distribution. This was accomplished at 6 and 4 GHz by adopting fairly large receiving and transmitting antenna reflectors (1.6 and 2.4 m), illuminated by an array of individual feed elements (90 to receive and 88 to transmit). The relatively narrow elemental beams generated by the individual feed elements are combined, through a beam-forming network controlling the feed excitation, to produce the hemispheric and zone beams as required for service coverage.

With the introduction of the INTELSAT V series, a number of major technology advances were realized: (i) fourfold frequency reuse at 6 and 4 GHz through spatial and dual polarization isolation; (ii) beam shaping, reconfigurable in orbit through ground command; (iii) use of the 14- and 11-GHz frequency bands; (iv) twofold frequency reuse of 14 and 11 GHz through a combination of spatial and polarization isolation; (v) cross-strapping between 14/11 and 6/4 GHz; (vi) use of body stabilization with onboard control; and (vii) continuously sun-oriented solar arrays.

INTELSAT V-A, a version of INTELSAT V with slightly higher capacity, will be launched in 1984. It has increased 6/4-GHz zone beam bandwidth and an additional global beam bandwidth on the orthogonal polarization not used in INTELSAT V.

INTELSAT VI. The most advanced spacecraft in INTELSAT's satellite fleet is INTELSAT VI, which is being manufactured and is scheduled for launch in 1986 (Fig. 3). Unlike INTELSAT V, it is a spinner design, but it is not capable of being launched on the Atlas-Centaur vehicle. Instead, it requires the launch capability of either the space shuttle or Ariane 4.

Its distinguishing technological features, apart from the fact that it is more than twice as heavy as INTELSAT V and uses about 1.6 times as much power, are: (i) sixfold frequency reuse at 6/4 GHz; (ii) twofold frequency reuse in 80 MHz of "new" 6/4-GHz bandwidth; (iii) addition of twofold frequency reuse in previously unused 14/11-GHz bandwidth; (iv) addition of a 10 by 6 dynamic switching matrix in two of the sixfold-reuse 6/4-GHz transponder-beam combinations, for satellite-switched time division multiple access (TDMA, discussed below); and (v) an integral liquid-propellant motor for attaining synchronous orbit and stationkeeping.

Most of the mass increase is for the

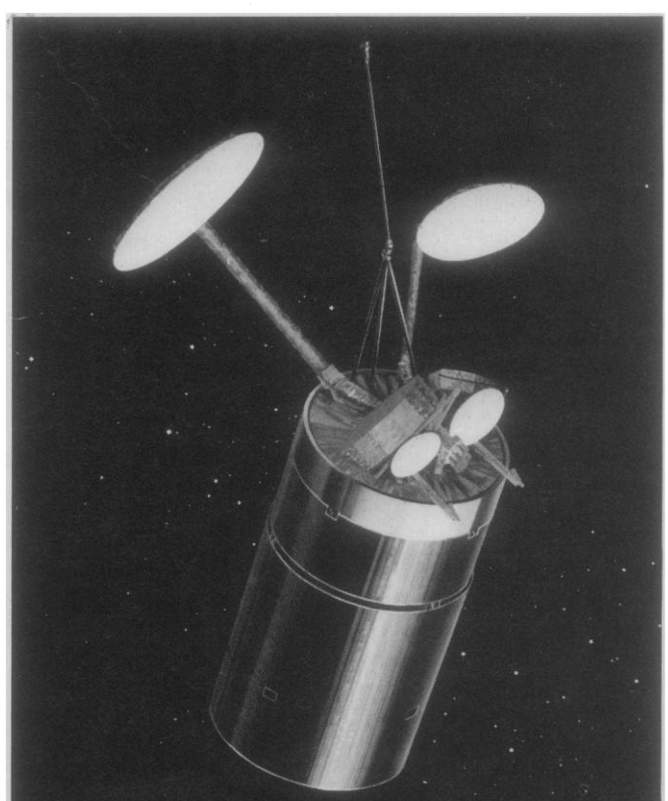

Fig. 3. Artist's rendering of INTELSAT VI.

sixfold frequency reuse capability, which requires a larger increase in the number of antenna feed elements (143 receive and 147 transmit), in the reflector size (2 m receive and 3.2 m transmit), and in the complexity of the beam-forming network (which adds two southern zone beams at 6/4 GHz in addition to the northern zone beams of INTELSAT V and V-A.

The bandwidth of INTELSAT VI exceeds that of INTELSAT V-A by about 40 percent. However, INTELSAT VI appears to represent the limit of what can be achieved in frequency reuse at 6/4 GHz with current satellite antenna designs and sizes; new technology will be needed for further progress. The constraints are intranetwork interference and the geographic distribution of INTELSAT traffic.

Other System Requirements

Spacecraft planning and design in the INTELSAT system have had to meet a variety of other requirements. One is a requirement for spacecraft universality—that is, operational compatibility of the spacecraft with the traffic requirements in the three ocean regions. This has proved economically preferable to designing satellites specific to the different ocean regions. It permits larger production runs of a common design, and it allows spacecraft coming to the end of their useful mission life to be transferred to a less demanding role or a different region. A related requirement is that each spacecraft be capable of assuming the role of a predecessor spacecraft without major difficulties. Thus, it has been customary simply to transfer existing traffic from the old to the new spacecraft, either by redirecting earth station antennas or by nearly collocating the satellites and switching old transponders off and new transponders on. Finally, to recover from system outages due to a satellite failure, it is necessary to maintain spare satellites, of which only one in each ocean region is required if it is of the most recent design and capable of replacing any like or earlier satellite.

There are now three operational satellites in the Atlantic Ocean region (one primary and two major path satellites) and additional satellites will soon be introduced in the other two ocean regions. Additional service packages will be provided on some satellites. On INTELSAT V, a maritime package has been included to provide spacecraft capability to INTELSAT's sister organization, INMARSAT, for communications to ships at sea. A business services package, for digital transmission in a newly assigned frequency band (around 12 GHz), will be carried on later INTELSAT V-A spacecraft. These new services will increase requirements related to spacecraft deployment and spares.

Another requirement is for the provision of national domestic service to a number of countries under transponder lease arrangements. At present, 25 countries lease the equivalent of 55 transponders. Although this service promises to grow and would benefit from technical optimization of spacecraft characteristics, so far it has been accommodated with the spare protection capacity of INTELSAT satellites. With growing demand, however, it may prove desirable to include a specially designed satellite for this service.

Table 1 gives an overview of the major technical characteristics of INTELSAT satellites.

Nonspacecraft Technologies

Not all the technology advances in the INTELSAT system have been spacecraft-related. Others have been related to earth stations, transmission, and systems.

Earth station technology. The earth station technologies introduced in the INTELSAT system were mainly re-

Table 1. Technological progress in INTELSAT satellites.

Characteristic	I	III	IV	IV-A	V	V-A	VI
Year of first launch	1965	1968	1971	1975	1980	(1984)	(1986)
Dimensions							
Diameter (m)	0.72	1.41	2.38	2.38	2.01 × 1.98	2.01 × 1.98	3.64
Height (m)	0.60	1.01	5.28	6.93	6.4	6.4	11.82
Solar panel height (m)		1.14	2.82	2.82	15.6	15.6	6.12
In-orbit mass (kg) B.O.L.*	38	152	700	793	1,016	1,071	2,231
Launch vehicle	Thor-Delta	Thor-Delta	Atlas-Centaur	Atlas-Centaur	Atlas-Centaur or Ariane I	Atlas-Centaur or Ariane III	Ariane 4 or STS
Total power load (W) B.O.L.	46	134	462	600	1,111	1,251	1,958
Operating frequency (GHz)	6/4†	6/4	6/4	6/4	6/4 14/11 1.6/1.5‡	6/4 14/11	6/4 (extended 14/11 1.6/1.5‡
Effective bandwidth (MHz)	50	450	432	720	2,137 (four 6/4 GHz)	2,137 (four 6/4 GHz)	3,086 (six 6/4 GHz)
Number of times frequency reused				2	(two 14/11 GHz)	(two 14/11 GHz)	(two 14/11 GHz)
Number of receivers	2	2	2	3	8	8	10
Number of output amplifiers	2	2	12 (6 W)	16 (5 W) 4 (6 W)	11 (8.5 W), 4 GHz 10 (4.5 W), 4 GHz 6 (10 W), 11 GHz 1 (60 W), 1.6 GHz	11 (8.5 W), 4 GHz 10 (4.5 W), 4 GHz 6 (10 W), 11 GHz	10 (16 W) 6 (13.5 W) 12 (10 W) 2 (5.5 W) 4 (3.2 W) 6 (1.8 W) 4 GHz 10 (8.5 W), 11 GHz
Capacity (telephone circuits)	240 or 1 TV	1,200 or 4 TV	4,000 plus 2 TV	6,000 plus 2 TV	12,000 plus 2 TV	14,000 plus 2 TV	40,000 plus 2 TV
Design lifetime (years)	1.5	5	7	7	7	7	10

*Beginning of life. †Receive/transmit. ‡Maritime package.

sponses to space segment requirements for dual-polarization capability at 6/4 GHz, and capability at 14/11 GHz. In a recent development, these two technologies have been combined; the new U.S. earth station at Roaring Creek has an antenna system that provides dual polarization at 6/4 GHz and at 14/11 GHz.

Another development, made by COMSAT, is a multibeam earth station antenna (torus antenna), which can operate with several satellites simultaneously, using a single reflector structure. Substantial improvements have been achieved in the radiating efficiency of earth station antennas and in the suppression of unwanted side-lobes, which are a major source of interference between geostationary satellite networks.

Transmission technology. In this area the major advance was the development of time division multiple access coupled with digital speech interpolation (DSI). TDMA allows a mix of low- and high-capacity digital signals to be routed dynamically to any desired satellite beam, eliminating the multicarrier penalties and carrier-splitting requirements associated with frequency division multiple access (FDMA). DSI is a capacity multiplication technique in which pauses in human speech during one telephone conversation are used to transmit speech elements from other conversations. An earlier transmission mode known as SPADE (*s*ingle channel per carrier, *p*ulse code modulation, multiple *a*ccess, *d*emand assignment *e*quipment) applied speech statistics collectively to a transponder entirely loaded with speech-activated single-voice channel transmissions through global coverage beams, providing a fully interconnective multiple access capability for small traffic links.

While FDMA, for years the standard access mode in the INTELSAT system, is capable of providing a transmission density of about 15 voice channels per megahertz of bandwidth, SPADE and TDMA/DSI can provide more than 40 equivalent voice channels per megahertz. TDMA/DSI operation will begin in 1984 and is expected to become the predominant transmission mode. Equivalent voice channel capacity will be further increased through the introduction of bandwidth compression techniques (source coding), which will strip speech and video signals of redundant content and allow operation with a lower demand on bandwidth (lower bit rate) and no undue sacrifice in transmission quality. The present coding rate for speech, 64 kilobits per second, is expected to be reduced by a factor of 2 and later in this decade by a factor of 4.

Systems technology. These advances have been mainly in the area of computer software development for the analysis and synthesis of systems planning alternatives. The increasing interference between networks engendered by multiple frequency reuse required extensive measurements and modeling to develop analysis programs. Similarly, the growing complexity of INTELSAT system transmission planning led to a need for automation. Satellite designs require consideration of actual traffic and loading scenarios; computer programs have become indispensable for system design and planning and for determining actual frequency assignments and optimizing satellite deployment sequences.

Current plans to increase system capability emphasize more efficient access and multiplication techniques rather than added satellite capacity. However, traffic growth is expected to require expanded satellite capacity in the 1990's. If a trend toward smaller and more customized spacecraft is followed, this would fundamentally alter the architecture of the INTELSAT system.

Conclusions

The technology base from which INTELSAT embarked to develop a global communications system was substantial, and each new generation of satellites has incorporated new technological advances. The continued demand for growth and diversification of services is reflected in a broad range of ongoing studies, which include areas of investigation such as 30/20-GHz technology, intersatellite link technology, onboard signal processing, advanced modulation and multiple access techniques, higher frequency-reuse techniques, interference suppression and cancellation, dynamic satellite beam coverage generation, and advanced coding techniques for information compression and extension of performance.

References and Notes

1. B. I. Edelson and L. Pollack, *Science* **195**, 1125 (1977).
2. Hodocentric means "as seen from a point on the orbit."

RESEARCH ARTICLE

Chromosome 4 *Jt* Gene Controls Murine T Cell Surface I-J Expression

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In vertebrates the immune system protects the animal from disease-causing organisms, such as viruses and bacteria, by producing an immune response to eliminate foreign intruders. Certain lymphocytes regulate both the magnitude and type of immune response. Helper T lymphocytes enhance and suppressor T lymphocytes diminish immunity in a highly selective manner. These regulatory lymphocytes are crucial to survival.

The I-J structure on a membrane glycoprotein distinguishes suppressor T lymphocytes from all other cells (*1*). This same structure comprises part of secreted glycoproteins with suppressive activity (*1*). Antibodies have been produced that react with the I-J structure; these bind to the suppressor T cell surface and to the secreted glycoproteins (*1*).

A gene cluster termed the major histocompatibility complex has been preserved throughout vertebrate evolution. In the mouse, it is known as the H-2 complex, and the products of these genes function by permitting the animal to discriminate between self and nonself (*2*). Genetic mapping experiments placed

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