PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Satellite Communications in the 1980s and after

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Satellite communications in the 1980s and after

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[Plates 1 and 2]

The second decade of satellite communications which we are now entering should show as rapid progress as the first, which saw the creation of a global network of satellites and Earth stations connecting eighty countries on six continents. Domestic systems are providing many types of services to small and large communities, and maritime systems to ships at sea. Future satellite communications systems will have higher capacity and provide varied services to small users. Increased transmission of television, graphics, and computer data will be provided, interconnecting individual users with 'rooftop' and mobile terminals.

Technological advancements in this second decade will involve the use of new frequency bands (30/20 and 14/11 GHz), and frequency reuse through spatial separation and polarization discrimination. Digital transmission techniques will find widespread use.

The third decade will see the application of very large multibeam, multifrequency antenna systems, beam shaping, and satellite onboard switching and processing. The use of the space shuttle with high-energy upper stage propulsion units will allow the deployment of very large, permanent geostationary platforms for providing economical multiple communications service.

1. Introduction

We are indebted to Arthur C. Clarke (1945) for the concept of 'extraterrestrial relays'. Now an internationally known writer of science fiction, Clarke in his early life was a Royal Air Force Signals (Radar) Officer, and later Chairman of the British Interplanetary Society. In 1945 he recognized the unique nature and usefulness of the geostationary arc for telecommunications (figure 1). Although he conservatively predicted that satellite communications might be commercially feasible in this century, the world had to wait only two decades for his concept to be realized.

Today, the practicality of satellite communications is apparent. The unique capabilities of satellites in geostationary orbit to provide cost-effective service is recognized. These capabilities include broad area coverage, highly reliable low-noise transmission paths, and wide bandwidth. Satellites can also provide broadcast capabilities and communications to mobile platforms, and are cost effective for point-to-point fixed service paths over relatively long distances.

The development and expansion of operational satellite communications systems have been rapid, depending on several different areas of technology. The first of these is rocket technology to launch the spacecraft; the second is astronautics, most specifically guidance and control technology to place and maintain the spacecraft in orbit; and the third consists of those many elements of communications technology which complete the system. Contributions to satellite communications came from microwave relay, radar and radio astronomy, and from many developments of this past decade in solid state devices, and computer hardware and software systems.

The technology for satellite communications, then, is truly eclectic, but it took the energy and resources of large government programmes, first in the United States and then in many other countries, to develop and amalgamate these many technologies into a useful system (Pierce 1968). Satellite systems are unique among telecommunications for this dependence on governmental programmes. In this respect they are similar to aeronautical systems rather than to other telecommunications systems.

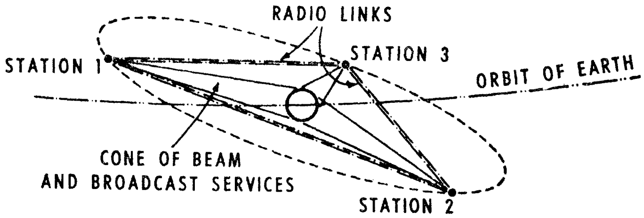

Figure 1. Clarke's extraterrestrial relays.

A rapid sequence of events initiated commercial satellite communications service. In the United States the Communications Satellite Corporation – or Comsat – was formed in 1963 for the express purpose of exploiting the technology for commercial purposes. In 1964 Comsat joined with communications entities of other nations to form an international body known as Intelsat, the International Telecommunications Satellite Organization, to provide satellite communications on a global basis. Finally, to complete the initial sequence, 1965 saw the launch of the world's first commercial satellite, Intelsat I, known as 'Early Bird', and the inauguration of operational telecommunications service along a single path between the U.S. and Europe (Charyk 1977).

2. Intelsat system progress

Today the Intelsat system spans the globe with satellites covering the Atlantic, Pacific, and Indian Ocean regions. Early Bird has been supplanted by eight larger, more powerful Intelsat IV and IV–A satellites operating with 165 Earth stations. The system, shown in figure 2, provides communications along 500 paths terminating in 80 countries. It carries 8000 full-time simultaneous 2-way telephone conversations, telex, data and facsimile traffic, plus television service and leased transponders (International Telecommunications Satellite Organization 1976).

The growth of the Intelsat system during its first decade of operation (figure 3) has been rapid. Growth has stemmed not only from improvement in the existing service relative to previous means such as radio and cable, but also from the offering of entirely new services such as global television and wideband data to areas not previously served by existing means.

The reliability of system operations has increased over the past years to equal or surpass that of other modes. Particular individual links in the system operate at 99.99 % reliability or greater, with a total system reliability of 99.9 % (Edelson, Strauss & Bargellini 1975).

Intelsat launched four generations of satellites from 1965 to 1971, each representing a major step forward in technology and a significant improvement in cost effectiveness. For example, Early Bird (Intelsat I), the first of the series shown in figure 4, weighed 38 kg. With limited

Figure 2. The global system.

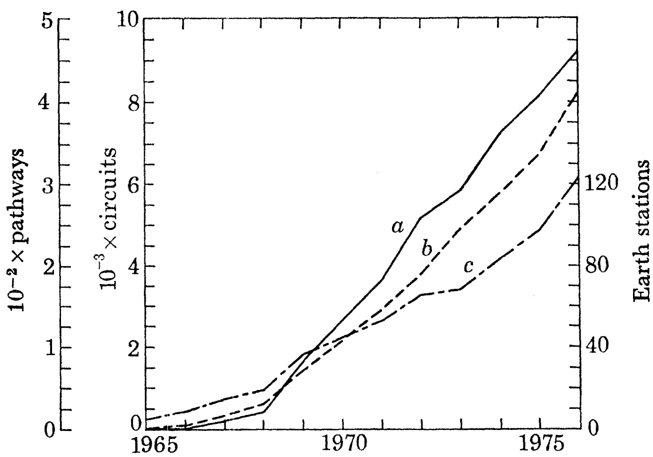

Figure 3. Growth of the Intelsat system: pathways (*a*), traffic (*b*) and Earth stations (*c*).

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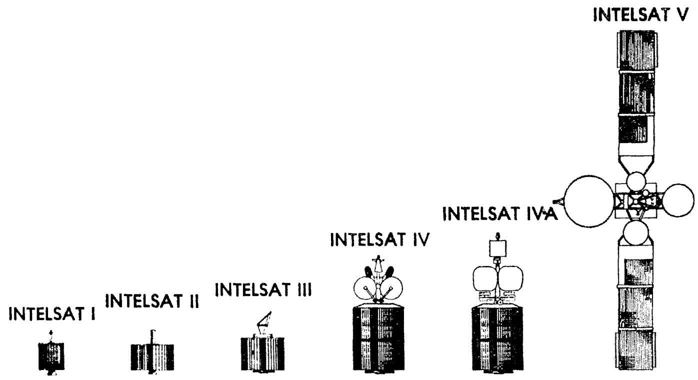
power and bandwidth, its communications capacity could sustain about 240 two-way telephone circuits between Earth stations with 30 m antennae.

Significant improvements were made in the three succeeding generations of satellites so that the Intelsat IV series currently in use represents an order-of-magnitude improvement over Early Bird in most operating parameters, e.g. prime power and bandwidth, and thus operating capacity (Jilg 1972). The most effective technique for increasing capacity through the first four generations of Intelsat satellites came from increased effective radiated power from stabilized Earth-pointing antennae.



	INTELSAT I	INTELSAT II	INTELSAT III	INTELSAT IV	INTELSAT IV-A	INTELSAT V
YEAR OF FIRST LAUNCH	1965	1967	1968	1971	1975	1979
PRIME CONTRACTOR	HUGHES	HUGHES	TRW	HUGHES	HUGHES	FORD AEROSPACE
DIMENSIONS DIAMETER/m	0.72	1.42	1.42	2.38	2.38	2.0
HEIGHT/m	0.60	0.673	1.04	5.28	5.90	15.7
IN-ORBIT MASS/kg	38	67.3	152	700	790	967
LAUNCH VEHICLE	THOR - DELTA			ATLAS - CENTAUR		
PRIMARY POWER/W	40	75	120	400	500	1200
TOTAL BANDWIDTH/MHz	50	130	500	500	800	2300
CAPACITY (TELEPHONE CIRCUITS)	240	240	1200	4000	6000	12000
DESIGN LIFETIME/a	1.5	3	5	7	7	7
(COST/CIRCUIT YEAR)/$	32500	11400	2000	1200	1100	800

FIGURE 4. Technological progress in Intelsat satellites.

First launched in 1975, Intelsat IV–A, an improved version of Intelsat IV, introduced, through spatial separation of antenna coverage areas, the first reuse of a frequency band. The Intelsat IV–A satellite shown in figure 5, plate 1, weighs 790 kg in orbit and its capacity is rated at 6000 telephone circuits for a typical operational arrangement of multiple f.m. carriers in its transponders.

The next generation of satellites, Intelsat V, planned for initial launch in 1979, will be the first body-stabilized spacecraft in the Intelsat series (Rusch & Dwyre 1976). Its capacity will be greatly increased over that of previous generations due in part to the higher primary power available and to a larger extent the increased communications bandwidth used. Intelsat V will employ not only the 6/4 GHz frequency band used in previous Intelsat satellites, but will also inaugurate the use of an additional 500 MHz available in the 14/11 GHz band (Rusch & Dwyre 1976).

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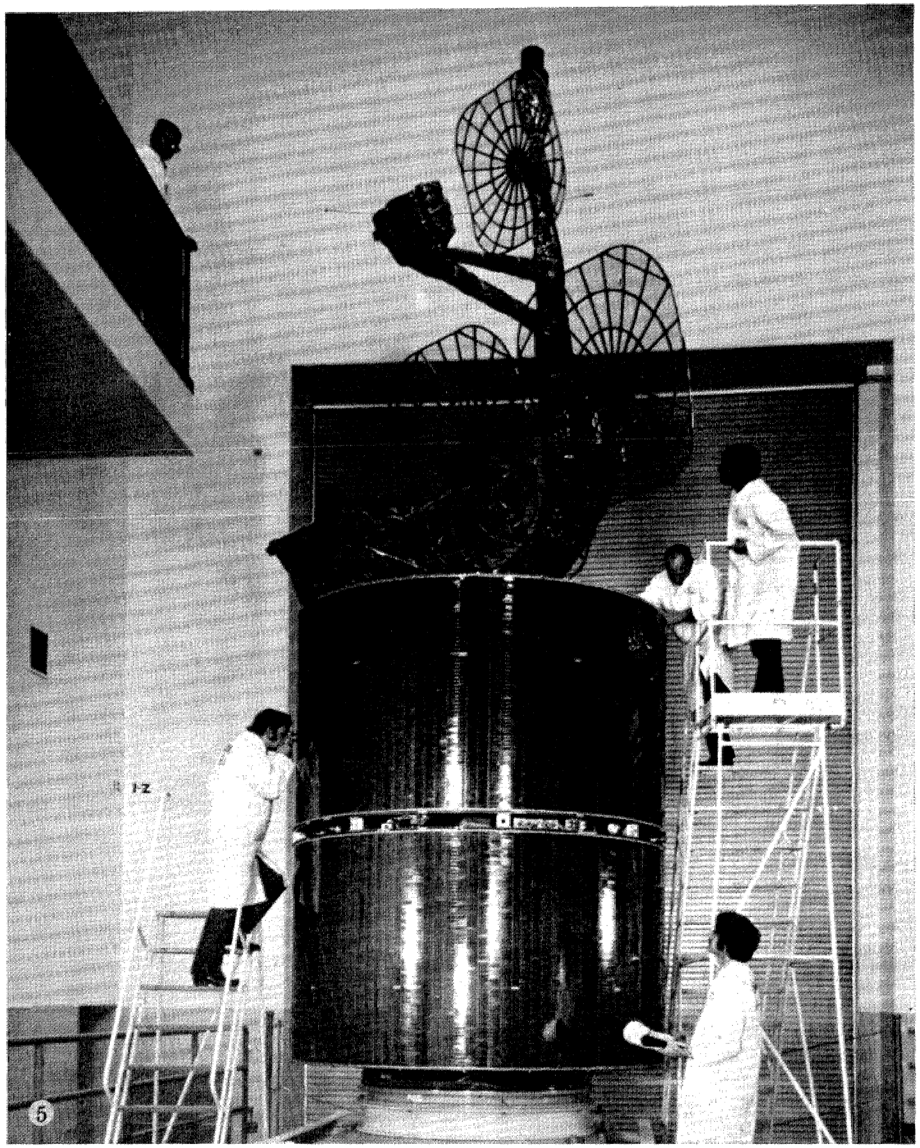


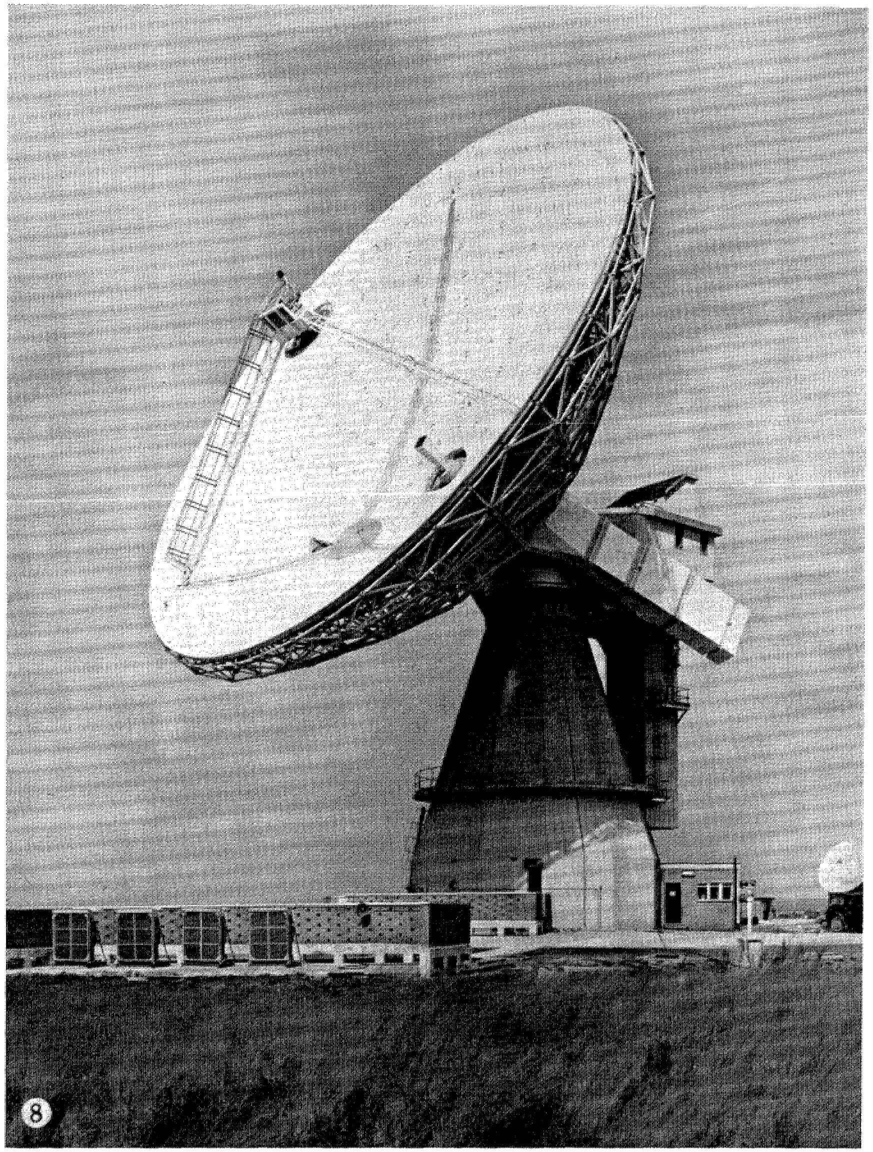
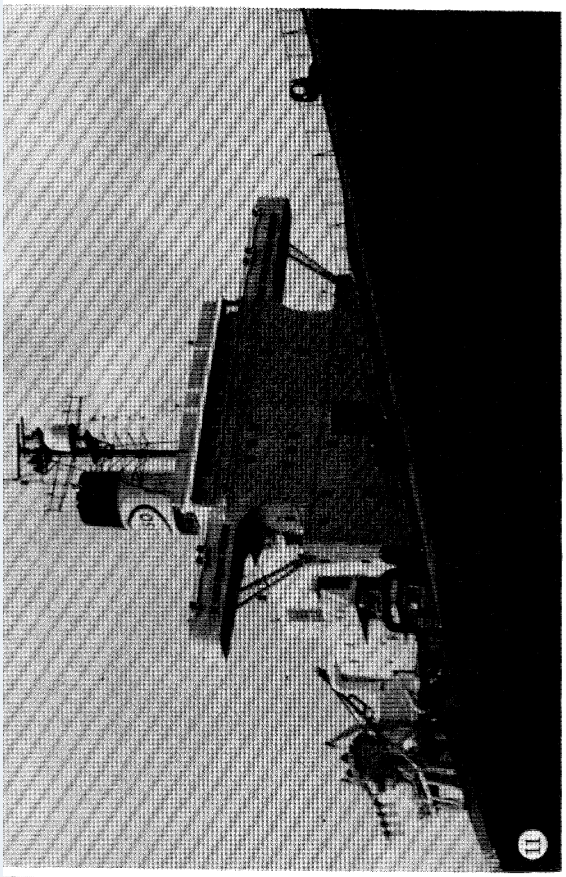
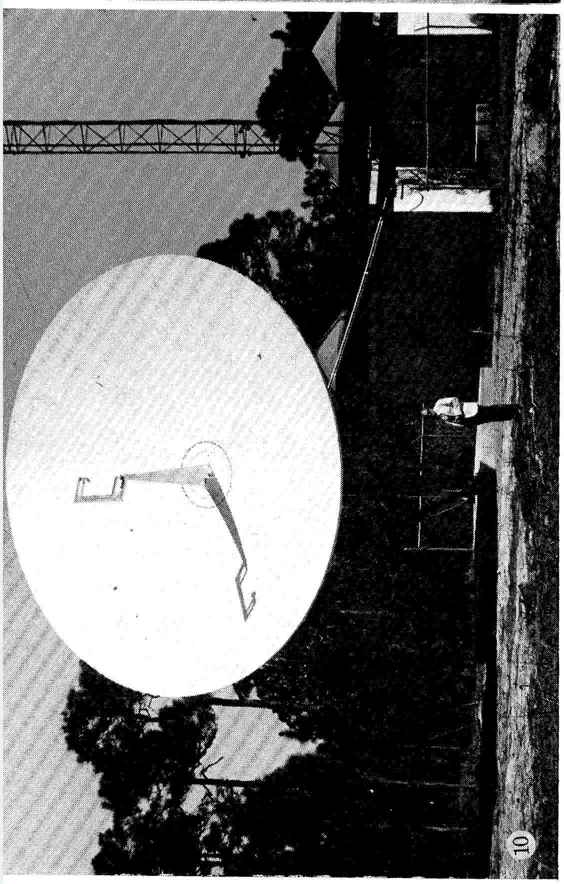


FIGURE 5. The Intelsat IV–A satellite.

FIGURE 8. Standard Earth station, Goonhilly Downs, U.K. (Photograph by courtesy of the Post Office.)





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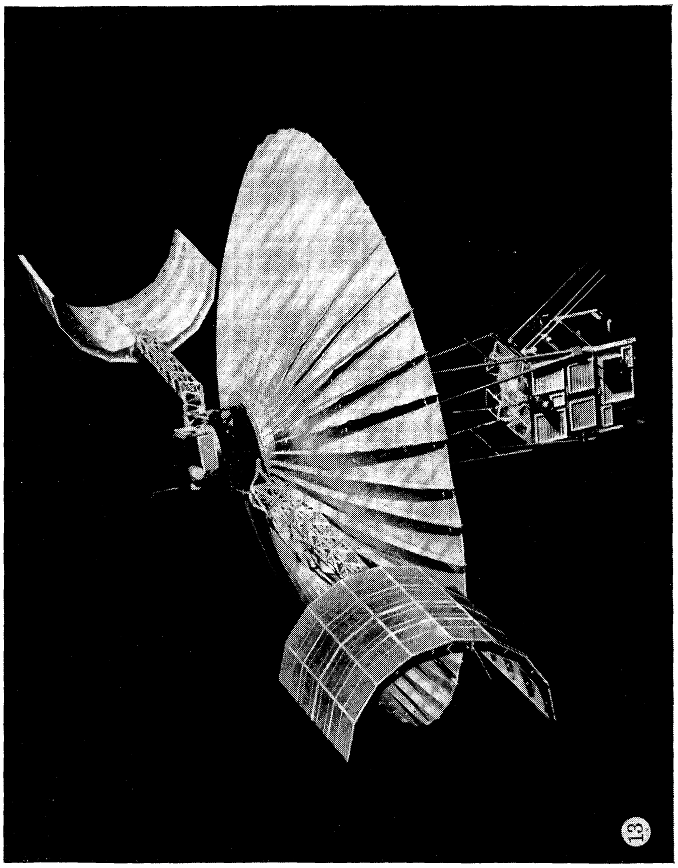

FIGURE 10. Earth station for domestic service.

FIGURE 11. Marisat shipboard terminal.

FIGURE 13. The N.A.S.A. ATS-6 experimental satellite.

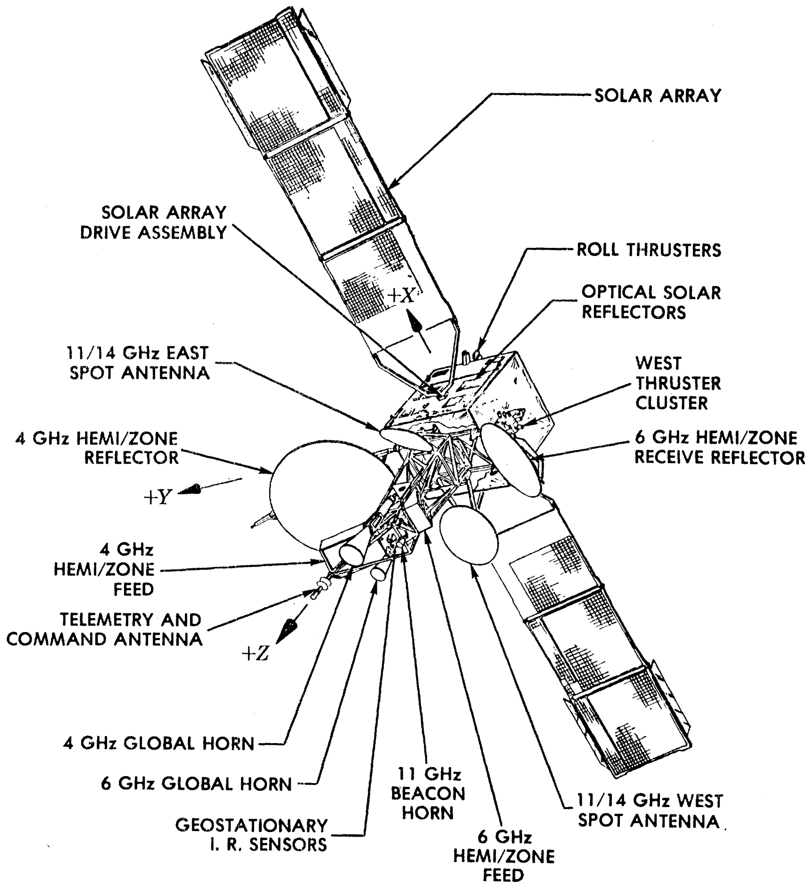

FIGURE 6. The Intelsat V satellite.

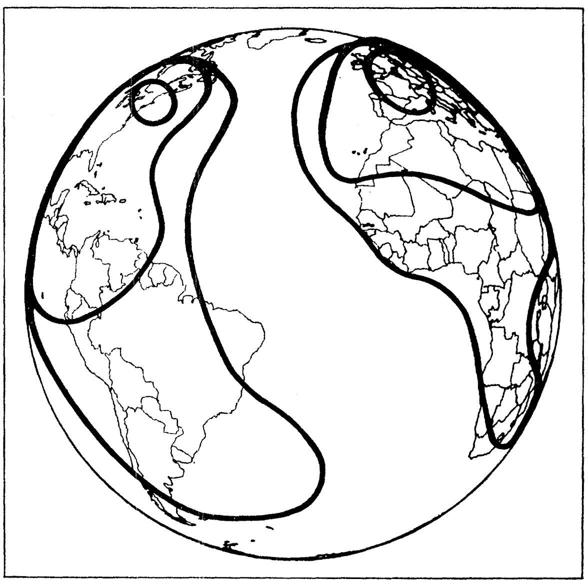

FIGURE 7. Intelsat V antenna beam pattern in the Atlantic region.

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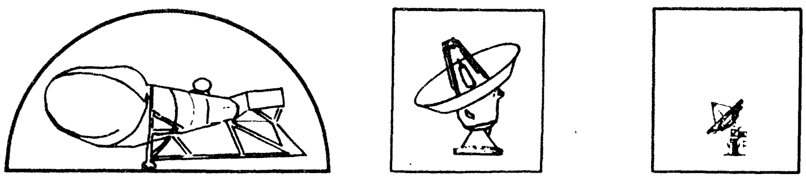
The distinguishing features of the Intelsat V satellite are shown in figure 6. The body of the satellite, stabilized along three axes in space, is used as a platform for mounting the large sun-orientated solar array and the complex of Earth-orientated antennae.

This antenna system provides the beam coverage patterns shown in figure 7 for the Atlantic region. The four larger beams operate in the 6/4 GHz bands and provide fourfold frequency use in 320 MHz of each of these bands, i.e. twofold use by spatial separation of the beams to the east and west, and twofold use by polarization discrimination between the beams in each of these areas which have overlapping coverage. In the west beams polarization discrimination yields a further twofold use in 40 MHz of each of these bands. Global coverage is also provided in 120 MHz of the 6 and 4 GHz bands, in which only single frequency use is employed. Finally, there is twofold use of frequency in the 14/11 GHz bands in the two spatially separated small spot-beam coverage areas, yielding 800 MHz of additional spectrum. The total spectrum utilized in the Intelsat V satellite for communications purposes is approximately 2300 MHz.



	Telstar	Intelsat A	Intelsat B
antenna	horn	Cassegrain	Cassegrain
apetrure/m	26	30	10
h.p.a.	10 kW klystron	8 kW t.w.t.	400 W t.w.t.
l.n.r.	maser	cooled paramp	uncoded paramp
$(G/T)/(\mathrm{dB/K})$	39	40.7	31.7
bandwidth/MHz	30	500	500
mod./m.a.	f.d.m./f.m./f.d.m.a.	f.d.m./f.m./f.d.m.a.	s.c.p.c./p.s.k.

FIGURE 9. Earth station development.

3. EARTH STATIONS

Earth stations in the global system are owned and operated by the individual participating countries. Not all member countries of Intelsat operate their own Earth stations, but several operate two or more stations either for access to the satellite covering two ocean regions, or for diversity. The U.K., for example, has three Earth stations at Goonhilly Downs in Cornwall, one operating with the Atlantic primary satellite, one with the Atlantic major path satellite, and one with the Indian Ocean satellite. A fourth U.K. station is under construction at Madley and is planned for service with the Indian Ocean satellite at 6/4 GHz starting in the second quarter of 1978. Future Earth stations including the one(s) for operation in the Intelsat system at 14/11 GHz will mainly be located at Madley.

The first Earth stations to enter the Intelsat system had been built to operate with the experimental Telstar and Relay satellites. These satellites and the Intelsat I, II, and III series satellites required powerful stations with large antennae and thus incurred high costs. Through its first ten years the standard Intelsat operation used such large antennae, which had apertures of about 30 m coupled with supercooled parametric amplifiers, to yield an antenna gain-to-system-noise-temperature (G/T) ratio of at least 40.7 dB/K. (The U.K. station at Goonhilly, figure 8, plate 1, is a good example.) Improvements in Earth stations over the past decade included the introduction of very wideband system elements such as high-power travelling wave tube amplifiers (up to 12 kW) and low-noise parametric amplifiers (to 55 K without cryogenics). Cassegrain antenna systems were introduced with shaped-surface reflectors to yield higher gain-to-aperture efficiencies. Other changes were made so that today all amplification and signal processing circuits (except the high-power output amplifier) use solid state devices.

As the satellites became more powerful and Earth stations in the system more numerous, it became clear that for many applications smaller Earth stations would be both suitable and cost effective. Therefore, in 1976, Intelsat adopted a second Earth station standard, i.e. smaller, less expensive Earth stations tending to new, lower capacity system applications. The new standard requires an aperture of about 11 m to provide a G/T of 31.7 dB/K with uncooled parametric amplifiers. These stations are expected to see wide use in the Intelsat system in areas with low traffic requirements (e.g. 24 circuits). They will be particularly useful for inaugurating service to new areas and second ocean regions to provide diversity routing.

Improvements in Earth stations in the past decade, although perhaps not as dramatic as those in satellites, have nevertheless been significant. Figure 9 shows some of these changes made in standard A stations over a 12-year period and also the introduction of the standard B station.

4. Domestic systems

Soon after the Intelsat system was established to provide international service, efforts were begun to apply the same technologies to other services. Actually, the first country to establish a purely domestic system was the Soviet Union, whose Orbita system based upon use of the 'Molniya' highly elliptical orbit satellites has provided television distribution for about a decade.

Originally, a frequency band around 800 MHz was employed, but starting in 1971, Molniya-2 satellites operating at 6/4 GHz were launched. In 1975 the first Soviet 'Reduga' communications satellite was placed into a geostationary orbit. Today the Orbita system has about 50 Earth stations in the U.S.S.R. and has been expanded through Intersputnik to incorporate stations in Eastern Europe, Cuba, and one station on the east coast of the U.S.A., which is used as a 'hot line'.

Canada established the world's second domestic system, Telesat, with the launch of its first satellite 'Anik' in 1972. At present three of the first generation satellites are in orbit, providing service to over fifty Earth stations, many in small remote communities. Indonesia established a similar separate domestic system in August 1976.

Other countries, e.g. Algeria, Brazil, Nigeria, and Norway, are leasing transponder capacity from Intelsat for domestic service. Such services are quick to start and operate efficiently since no capital investment is required for the satellites; instead, the country involved can concentrate on building and operating the Earth stations.

The United States now has three separate domestic systems in operation. Western Union was the first of these to inaugurate service via its 'Westar' satellites in 1974. R.C.A. followed with 'Satcom' late in 1975, and by July 1976, the 'Comstar' system became operational, with Comsat General leasing satellite capacity to A.T. & T. and G.T. & E.

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Domestic systems provide communications to regions, cities, and in some cases to individual corporate or governmental users. These services demonstrate the inherent flexibility of satellite communications by using Earth stations configured to meet specific needs (see figure 10, plate 2). Comstar is used with 32 m stations to serve major regions of the U.S. by linking telephone networks much as in the global system. Westar and Satcom employ 10 m stations for inter-city communications and 4.5–10 m stations for television distribution. In Alaska 4.5 m stations are used to meet the special needs of customers in small remote villages.

5. Mobile systems

The ability to operate with mobile terminals is an important advantage of satellite communications over all other modes of long distance wideband communications. Not surprisingly, a number of satellite systems have been proposed to serve mobile platforms, with one now fully operational. The 'Marisat' system, operated by the Comsat General Corporation in conjunction with several other U.S. carriers, provides three-ocean service to ships at sea. Starting in 1976, the Marisat system (Luksch & Martin 1976) provided leased service to the U.S. Navy in the military v.h.f. band (225–400 MHz) and commercial service at L-band (1.5 GHz). Thirty-five commercial ships flying flags of 12 nations were equipped for service at the start of 1977. The shipboard terminals are small and inexpensive. Figure 11, plate 2, shows a mast-mounted L-band antenna on an oil tanker equipped for satellite communications. Marisat provides 2-way ship-shore voice and telex service interconnected to the U.S. national and international public switched telephone networks.

Marots is a maritime satellite to be launched by the European Space Agency in 1978. It will provide L-band service similar to Marisat in the Indian Ocean region (Luksch & Martin 1976). Most countries operating merchant fleets are involved in planning a global maritime satellite system to be known as Inmarsat. Negotiations were completed and the Inmarsat Convention opened for signature in September 1976. The ratification process is expected to continue until 1978. An international maritime system should be operational in the 1980s.

Plans for aeronautical satellite communications systems to provide such service have been considered and proposed for a decade, but difficult international, institutional, and economic problems have impeded progress.

6. Customer services

Whereas the 'customers' for the Intelsat system are the terrestrial networks of the various 'users' countries, domestic and mobile systems may and often do provide service directly to the ultimate user. Not only are the Earth stations tailored to fit the location or platform of the user, but service may be provided directly to the terminal site. For example, a small Earth station may be installed on the customer's premises, the roof of a building such as a newspaper plant for facsimile service, or near a television broadcast tower or c.a.t.v. headend for television relay, or a shipboard terminal may be connected directly to a telex machine or telephone handset.

Over 90% of the traffic in the Intelsat system has been voice band quality, providing point-to-point connections between public switched telephone networks (including telex and telegraph). A small percentage of the Intelsat traffic has been point-to-point or point-to-multipoint television service.

Domestic systems are already providing television broadcast (or distribution) service and high-resolution facsimile service. Computer data transfer, computer networking, and 'electronic mail' are additional services particularly suited to domestic systems that use Earth stations on the customer's premises. The present maritime service is voice and telex, but computer data and facsimile may also be transmitted.

7. Economics

Although there has been an evident political and sociological motivation behind the development of satellite communications systems, the major impetus to start these systems, as well as the incentive to expand them, has been economic. Satellite communications have thus provided a measurable financial return from the large international investment in space technology.

The global system has shown the economic viability of satellite communications. Although Intelsat is an international organization whose members are sovereign nations, it operates in a commercial fashion. The 95 member nations each own investment shares in Intelsat proportional to their current usage of the system. The five largest shareholders for the current year (1977) are:

United States	30.9 %
United Kingdom	10.7 %
France	5.4 %
Brazil	4.9 %
Japan	4.6 %

The minimum share held by any country is 0.05 %.

During Intelsat's 12 year history (1965–76) a total investment of \$650 M has been made. With current annual operating revenues of \$140 M, Intelsat meets its financial goal of 14 % return on invested capital.

Through technological progress and economies of scale, circuit charges have been reduced during a 12 year period (1965–77) from a unit charge (per half-circuit-year) of \$32000 to \$7380.

The total investment in Earth stations operating in the global system is approximately equal to the space segment. The total cost to operate a standard 'A' (40.7 dB G/T) Earth station in the Intelsat system may be as low as \$1000 per circuit year for a station with heavy traffic (1000 or more circuits) (Edelson, Wood & Reber 1976). A standard 'B' Earth station (31.7 dB G/T) would be cost effective for light traffic streams (e.g. 24 circuits).

8. Future trends

Technological developments are directed toward expanding the capacity and reducing the cost of satellite communications. The most significant improvements are expected to be achieved by enlarging the spectral bandwidth available at each location in the geosynchronous orbit through techniques known as 'frequency reuse' and by employing additional frequency bands of operation. Also, important advantages may be obtained by increasing the effective isotropic radiated power (e.i.r.p.) and the received carrier-to-noise ratio in the channel bandwidth, and by efficiently encoding or processing the source information. Other associated technologies are being developed to use more fully these advanced capabilities and attain cost advantages; among them are digital processing, bandwidth-efficient modulation techniques, flexible multiple-access systems, processing satellite repeaters, and intersatellite links.

(a) *Frequency reuse*

Probably the most dramatic increase in satellite system capacity and cost effectiveness will be provided by reusing the allocated spectrum at a given orbital location. This can be accomplished by using multiple, disjoint, directive antenna beams to provide the desired composite area coverage and/or dual polarization in overlapping coverage areas. (Both techniques, as previously mentioned, are to be employed on Intelsat V.) The degree of frequency reuse which may be achieved in the former case is dependent upon the relative spacing of the individual coverage areas of each beam, the number of beams, and the amount of interbeam interference that is tolerable. Dual polarization provides twofold frequency use. A number of technologies are needed to implement systems of this type; among these are technologies to produce large, dimensionally precise structures supporting the antenna reflectors or lenses and complex feed horn assemblies, and technologies to provide precise spacecraft pointing capabilities.

In order to provide a practical means of interconnecting a large number of beams in all of the requisite combinations, with reasonable bandwidths in the interconnecting filters, a technique known as 'satellite-switched time-division multiple access' (or s.s./t.d.m.a.) has been proposed. This technique incorporates two concepts:

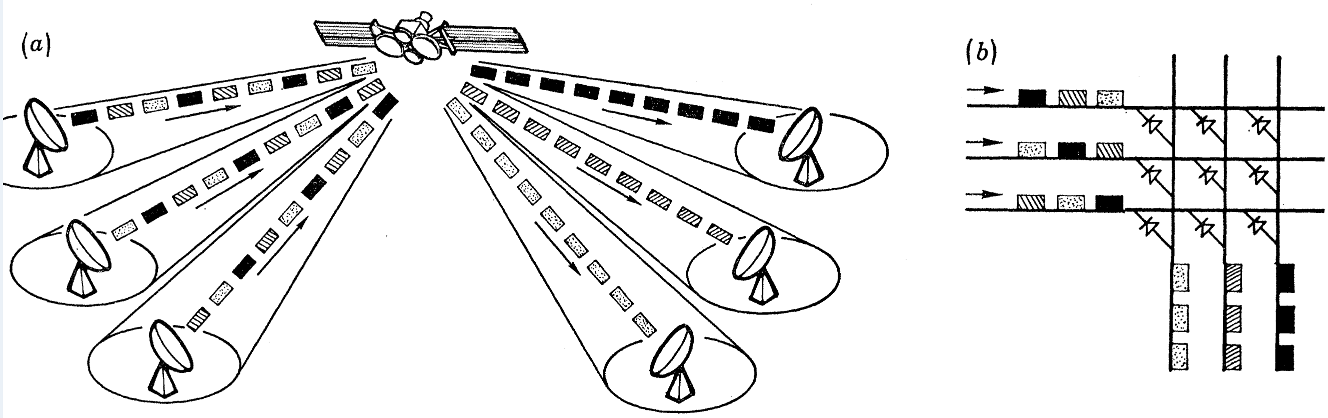

FIGURE 12. Satellite-switched t.d.m.a.: (*a*) system concept; (*b*) onboard matrix switch.

(i) *t.d.m.a.*

A given bandwidth channel in the up- and down-links is shared by a number of digital transmissions from different Earth stations by synchronizing the transmissions with respect to each other so that they appear sequentially at the input to the satellite.

(ii) *Switching*

A switching capability in the satellite permits the interconnections between different up- and down-link beams to be dynamically changed in synchronism with the signal bursts from the respective Earth stations as shown in figure 12. These provisions ensure the desired connectivity and flexibility for reallocation of capacity, while maintaining the relatively wide channel bandwidths needed for efficient use of the channel and for effective equipment use.

(b) *New frequency bands*

Another way of increasing the available spectral bandwidth is to extend the usage to the fixed satellite service bands between 10.95 and 14.5 GHz and between 17.7 and 31 GHz. A frequency range of 500 MHz is available for each of the up-link and down-link paths at 14/11 GHz and 3500 MHz at 30/50 GHz. In addition, unlike those in the 6/4 GHz bands, these large segments of available bandwidth are relatively free from interference from terrestrial communications systems in most locations. The effects of precipitation on transmission in terms of signal attenuation and effective receiver noise temperature increase are quite severe in these bands, particularly at 30/20 GHz (attenuation of the order of 27/18 dB, respectively, for 0.1 % of the time at Washington, D.C.), and appropriate margins and/or space diversity of the Earth stations must be selected to ensure the desired link availability.

For equivalent antenna aperture sizes, significantly higher gains and narrower beamwidths are achievable in these frequency bands. This factor may be used, at least in some cases, to offset the degradation due to rain. Multiple frequency reuse systems can be realized with smaller satellite antenna dimensions and provide additional spectrum availability. A number of satellites have provided capabilities in these new frequency bands for experimentation and for the collection of propagation statistics. These include the U.S. ATS-6 (shown in figure 13, plate 2) and the Canadian CTS experimental satellites, and an experimental package on the U.S. commercial Comstar satellite. Future experimental satellites such as the Italian Sirio satellite, the European Space Agency OTS satellite, and the Japanese broadcast satellite will provide additional data.

(c) *Increased spacecraft e.i.r.p.*

One of the associated benefits of multiple-beam antenna systems providing frequency reuse is the higher antenna gain of each beam, both up-link and down-link, and the higher e.i.r.p. that is available for a given output power of the final amplifier. In addition, higher power stages (such as t.w.t.as) are being developed and tested. The use of high output power tubes may well be cost effective for certain applications. Solar arrays on body-stabilized satellites may be sun orientated to provide very high levels of prime power needed for future communications satellites (several kilowatts). Increased spacecraft e.i.r.p. can be used in thermal-noise-limited environments to provide higher carrier-to-noise (C/N) ratios into small Earth stations. Coupled with highly bandwidth-efficient modulation methods, high power and higher C/N can provide high capacity per unit bandwidth. Higher e.i.r.p. can be used with smaller Earth stations to provide a range of tradeoffs for cost effectiveness of systems with a large number of Earth stations.

An interference-limited environment will be approached as multiple frequency reuse is more extensively employed, as the geosynchronous orbit becomes more heavily populated, and as the number of terrestrial interference sources increases. In this situation, higher spacecraft e.i.r.p. is much less effective than frequency reuse systems in providing increases in overall capacity, particularly into Earth stations with medium to large antenna apertures.

Both the ATS-6 and CTS satellites have dramatically demonstrated the impact of high e.i.r.p.'s on the size and capability of the associated Earth stations. CTS, for example, uses a

200 W t.w.t.a. at 12 GHz in conjunction with narrow spot-beam coverage and has provided good-quality colour television reception into an Earth terminal with a 1.2 m antenna.

(*d*) *Digital techniques*

There is a strong trend evident in satellite communications systems toward the use of digital techniques for a variety of purposes, including modulation, multiple access, signalling and switching, bandwidth compression, and coding. Digital transmission techniques will be applied not only for data originating in digital form, such as computer data, but also for efficient transmission of signals originating in analogue form, such as voice or television. In some instances satellite systems may in fact lead terrestrial systems in the use of digital transmission techniques, but in any event the future holds a requirement for the acceptance of common standards and hierarchies and synchronization of extensive interlocking global terrestrial and satellite digital networks.

One of the most important advantages of digital transmission is that voice, television, facsimile, and data may be efficiently combined for transmission using time-division multiplexing after changing the analogue signals to digital form. Examples of analogue-to-digital conversion techniques for high-quality speech channels include pulse code modulation (p.c.m.), whose standard rate for global transmission is 64 kbit/s, and adaptive differential p.c.m. and continuously variable slope delta modulation at rates of 16 to 32 kbit/s. Digital processing of the analogue signals allows significant reductions in channel bit rate for these services. Digital speech interpolation systems have been developed to give at least a two-to-one increase in channel density for groups of more than 24 voice channels by exploiting the speech activity factor (<0.4). Similarly, reduction in the redundancy of television signals has allowed standard high quality colour television to be transmitted at rates of 16–32 Mbit/s.

Digital modulation techniques include phase shift keying (p.s.k.), amplitude shift keying (a.s.k.), and frequency shift keying (f.s.k.). The most common method used in satellite communications is p.s.k., which allows operation at a wide variety of carrier-to-noise ratios, depending upon the number of independent phases selected for the signal set (e.g. from 2 to 16) and the coding employed. (For example, bandwidth efficiency in the range of 0.5–3.2 (bit/s)/Hz can be achieved with a C/N from 5 to 27 dB, respectively.) This allows the modulation parameters to be selected to match a wide range of channel transmission characteristics. P.s.k. may be used in conjunction with f.d.m.a., t.d.m.a., and single-channel-per-carrier multiple-access methods. In the latter cases, the total communications capacity of individual satellite transponders can be shared on demand among a large population of user terminals, providing an additional increment in cost effectiveness.

(*e*) *Other future technologies*

Two additional technological areas are expected to be employed to improve the cost effectiveness of systems with extensive Earth segments: satellite onboard processing and intersatellite links. Onboard processing may take the form of repeaters which employ demodulation of the received digital carrier and remodulation for transmission to the Earth. Both coherent and differentially coherent demodulation of p.s.k. signals have been considered with and without bit timing recovery for use in signal regeneration. A major advantage of such a regenerative repeater is that it eliminates the up-link noise component in the retransmitted signal. This is particularly beneficial for links using small terminals whose up-link noise may be a substantial portion of the total noise introduced in the satellite link.

Further into the future, the demodulated up-link bit stream may be time-division demultiplexed and routed through a digital switch to the down-link beam selected by an address contained in the bit stream. The signals for each down-link beam would be time-division multiplexed and modulated on a digital carrier for transmission to the Earth station of interest. This 'switch in the sky' could also be used to solve the connectivity problem of the multibeam frequency reuse satellite discussed earlier.

Intersatellite links are being investigated to interconnect Earth stations which are operating into separate satellites without requiring additional antennae or double hops. A major application of intersatellite links would be to allow communications between widely spread Earth stations that do not have mutual visibility to a single satellite. With three or more satellites, properly positioned, worldwide connectivity could be achieved between single-antenna Earth stations with a time delay no more than approximately twice that of a single-hop link. Other applications include interconnection of satellites of different networks, e.g. domestic to international, and connection of single-antenna Earth stations in a network which uses multiple satellites to meet its total capacity requirements. Both radio frequency (primarily millimetre wave) and optical (laser) intersatellite links are being considered. The former is closer to operational availability, but the latter seems to have better long range promise for achieving very high capacity (1 Gbit/s or more) with reasonable size and weight.

(*f*) *Future satellite networks*

The trend in the international system appears to be toward greater capacity. It is expected that Intelsat VI will continue and expand the trend initiated by Intelsat IV–A and V by increasing the number of frequency reuses at 6/4 and 14/11 GHz perhaps to as many as 8 or 16. The need for additional spectra for very-high-capacity links that are free from external interference to connect selected locations may also require the provision of a 30/20 GHz capability. Because of the future trend toward terrestrial facilities using digital transmissions and the need for high capacity and more flexible reassignment of capacity, s.s./t.d.m.a. may also be considered for Intelsat VI, along with digital speech interpolation.

In domestic systems the trend is toward the use of large numbers of small Earth terminals located at or near the information sources and/or distribution points. This will allow a wide variety of advanced communications capabilities to be provided economically, for example high-speed data, television, and facsimile services for such applications as computer communications, electronic mail, television distribution, and teleconferencing, in addition to conventional voice and data services. This will essentially eliminate the need for terrestrial interconnect facilities. These services can be shared on a demand and/or scheduled basis between any of the terminals in the network under central control, consistent with the overall capacity of the system. The broadcast capability of the satellite will also be available for efficient point-to-multipoint transmissions.

Economic transmission of combined analogue and digital services of many types will be provided using all-digital transmissions with efficient and flexible allocation of the satellite resources between the many Earth terminals accomplished by using t.d.m.a. Higher frequency bands, e.g. 14/12 GHz, will be used to minimize interference and coordination problems for

Earth stations located on the users' sites. The Satellite Business Systems (S.B.S.) system which is planned to provide domestic service in the U.S.A. incorporates many of these features.

As the demand for increased capacity grows, it is expected that multiple-beam antenna systems will be employed for domestic systems. Regenerative repeaters may also be employed to reduce Earth station costs and provide the option for the satellite t.d.m.a. switch to operate at baseband if this proves advantageous.

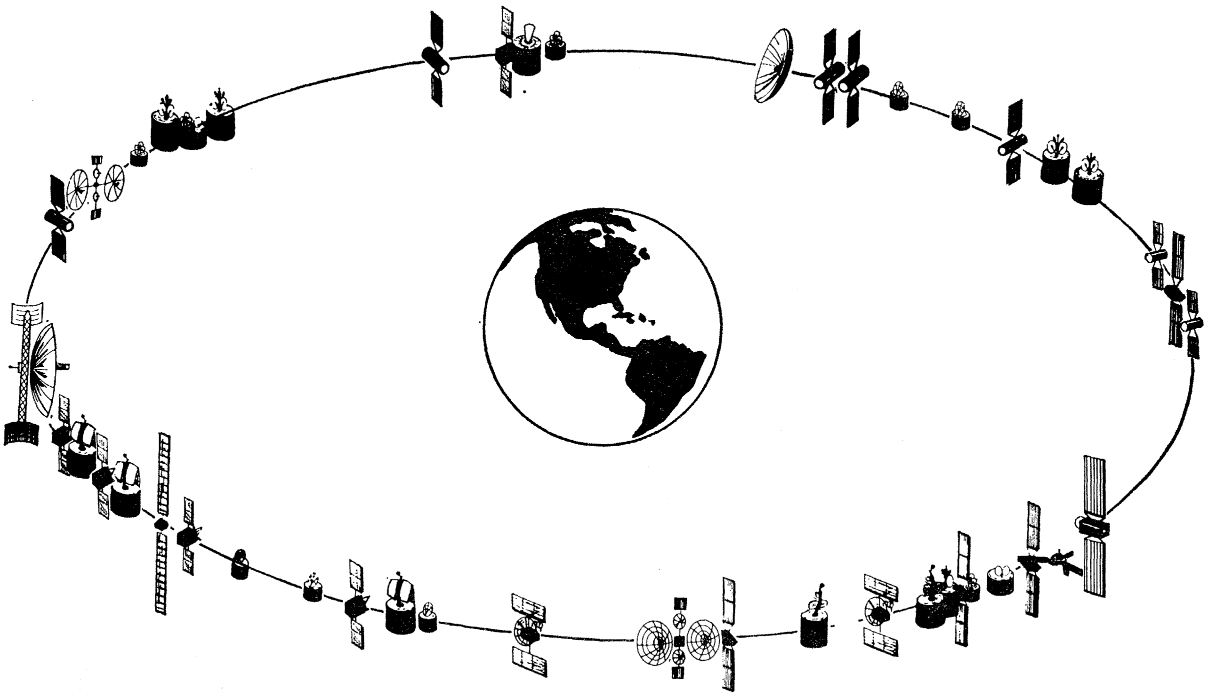

FIGURE 14. Geostationary orbit by 1980.

With the advent of many new domestic systems, the provision of maritime and aeronautical services, the continued growth of the Intelsat system, the potential of broadcast satellite systems, the military satellite networks, and the continuing experimental programme, the geosynchronous orbit is expected to become highly populated, as shown in figure 14. Extensive coordination will be required initially to achieve the desired performance while minimizing deleterious interference. In the longer term the satellite systems may have to be designed to accommodate higher levels of interference from other satellite networks. Multiple frequency reuse may become a requirement to achieve the needed spectral bandwidth when employing relatively small Earth stations.

To provide greater capacity and reduce the Earth segment costs, as the future spacecraft designs become more complex, more economical launch vehicle capabilities must be provided to place these satellites in orbit. Current developments offer promise to fill this need.

9. SHUTTLE IMPACT

The space shuttle under development by N.A.S.A. for use during the 1980s as a general purpose 'space transportation system' will open new avenues for the design of communications satellites. Shuttle launched spacecraft can be much larger and heavier than current designs at

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reasonable cost. The shuttle as presently configured has a payload bay 18 m by 4.5 m. Its capacity into low-Earth orbit is estimated at about 30000 kg. A payload of 2000 kg might be placed in geostationary orbit with an elementary perigee–apogee stage, and twice that amount with a high-energy stage. These weights exceed those that would reasonably be required for any single communications satellite now planned, but might be quite attractive to combine the requirements of several satellites.

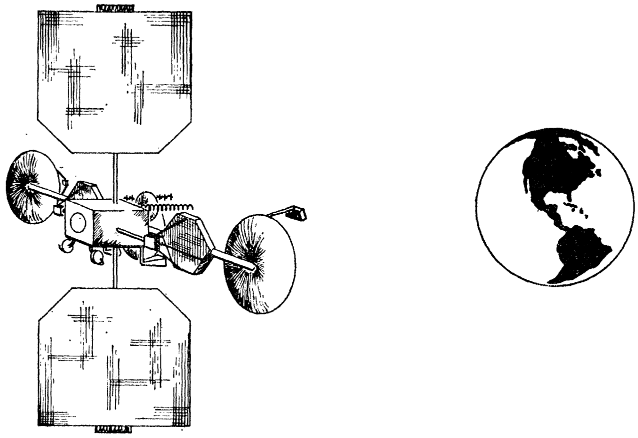

Figure 15. Orbital antenna farm.

The shuttle could place a very large stable platform in a key geostationary orbital location. Such a platform with a common positioning and orientation system, electrical power system, and telemetry and command systems could support several large complex antennae operating at different frequencies and serving different missions. Antennae might be of several types: reflectors, lenses, arrays, or helices. One platform would thus serve as a multi-mission satellite as shown in figure 15: an orbital antenna 'farm' (Edelson & Morgan 1977). Several such platforms in geostationary orbit might be connected into a network by intersatellite links. Such a network might be feasible by 1990.

The interconnection of such a system would appear similar to figure 1. In this case, Clarke's early paper (1945) would have been very prescient, not only in concept, but in specific configuration.

Much of the material used in this paper was derived from Intelsat, Comsat and Comsat General Corporation sources. However, the views expressed, particularly the extrapolation of future trends, are those of the authors. The contributions of several members of the Comsat technical staff to the preparation of this paper, particularly P. L. Bargellini, W. L. Morgan and L. Palmer, are acknowledged and appreciated.

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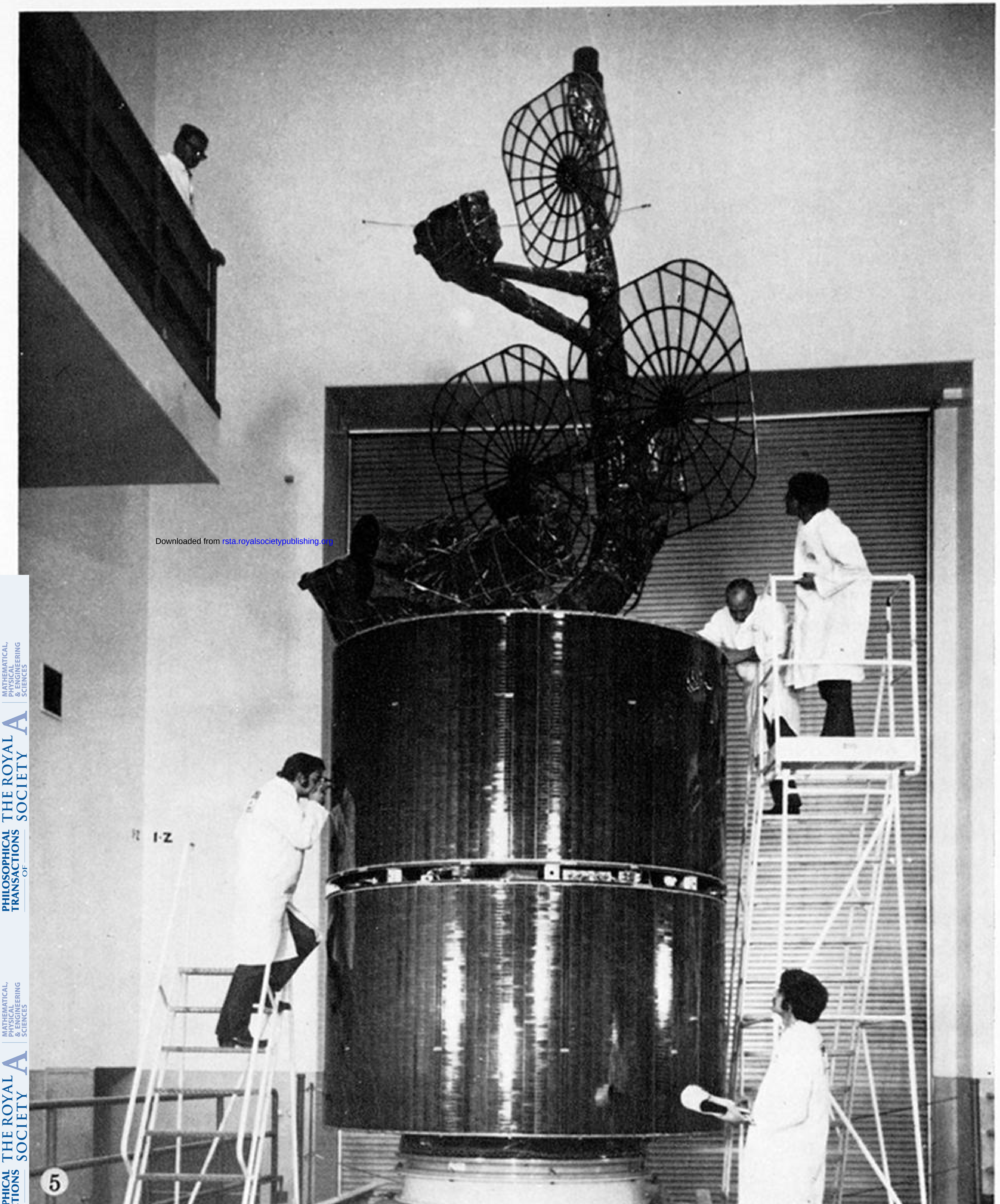


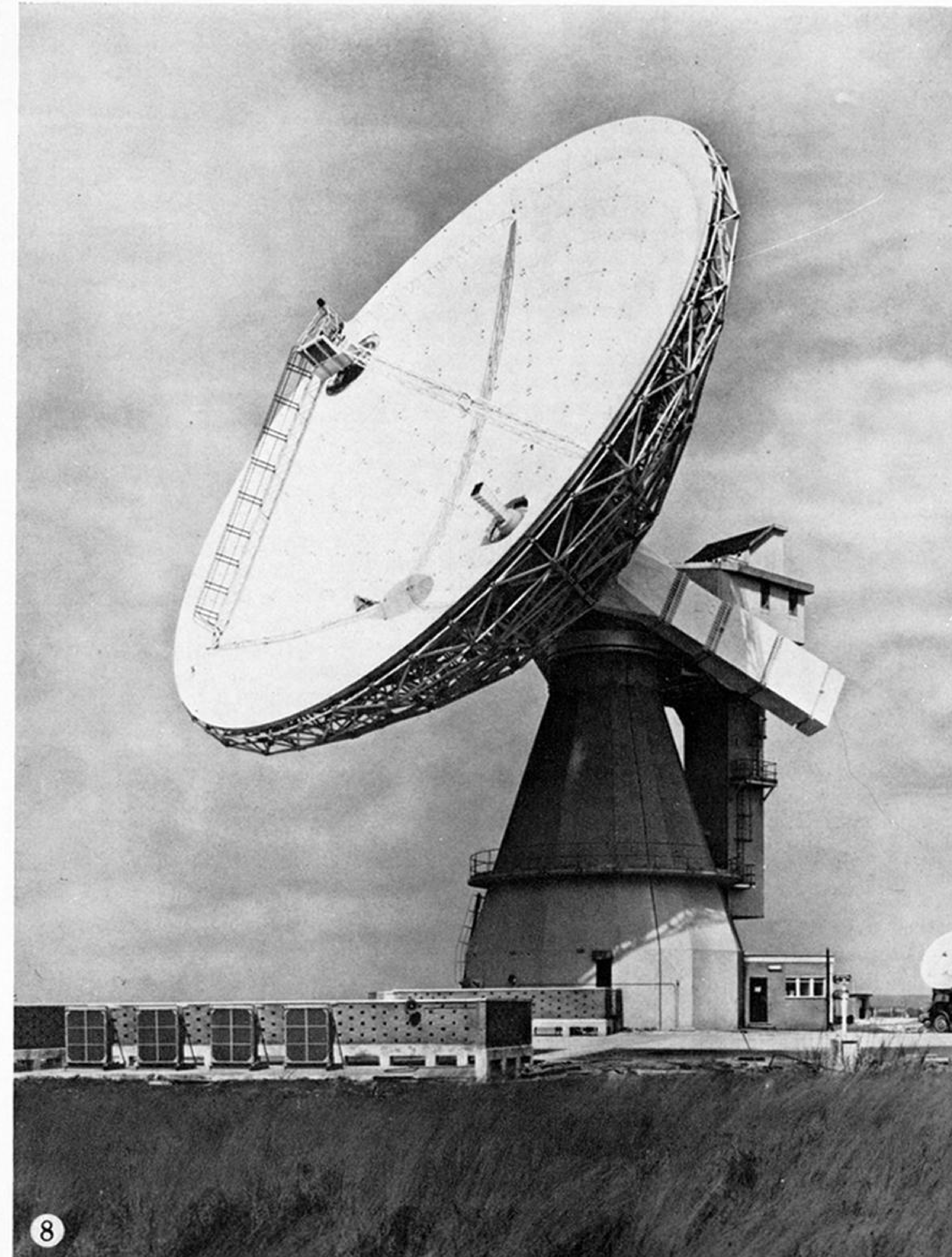
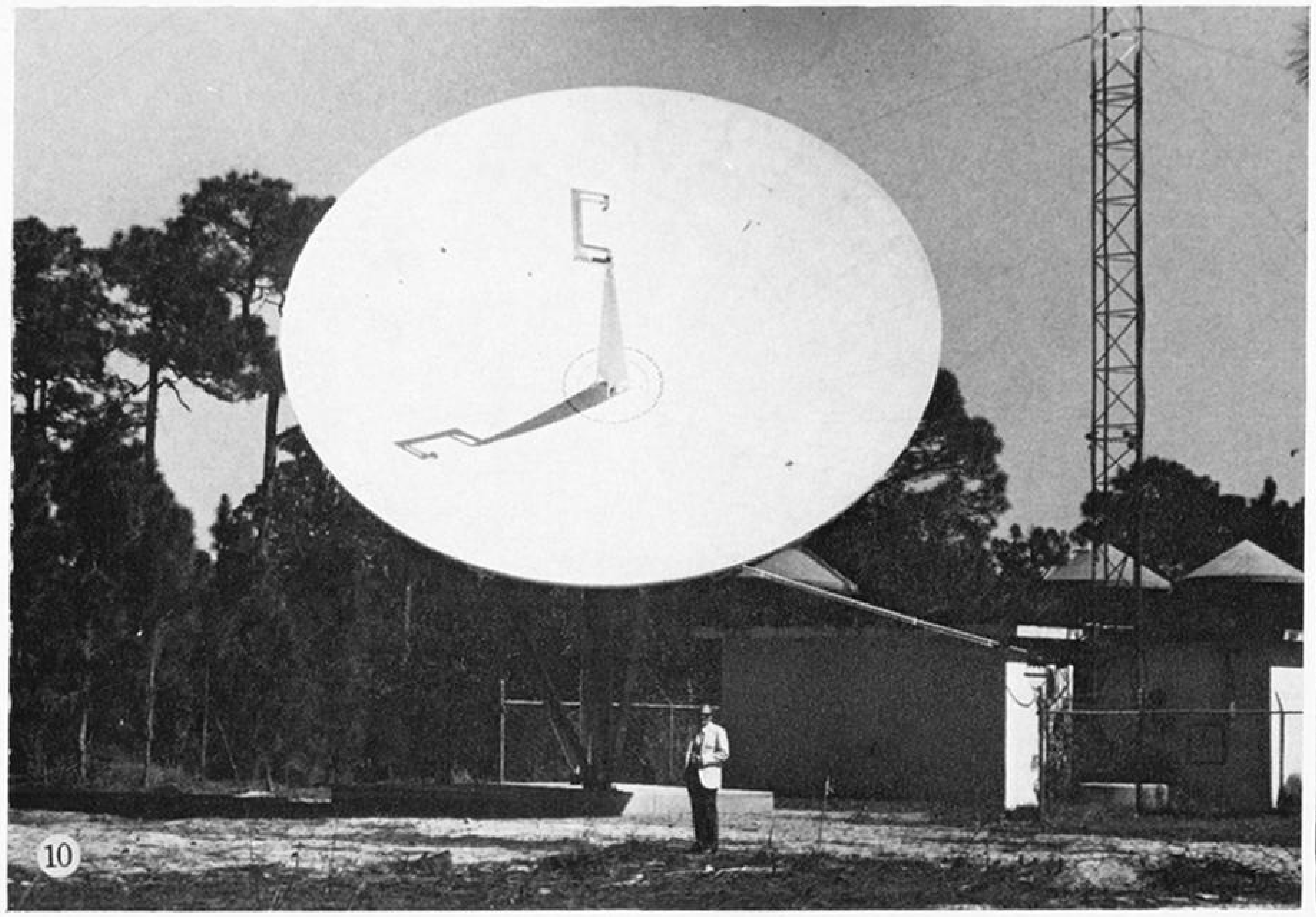
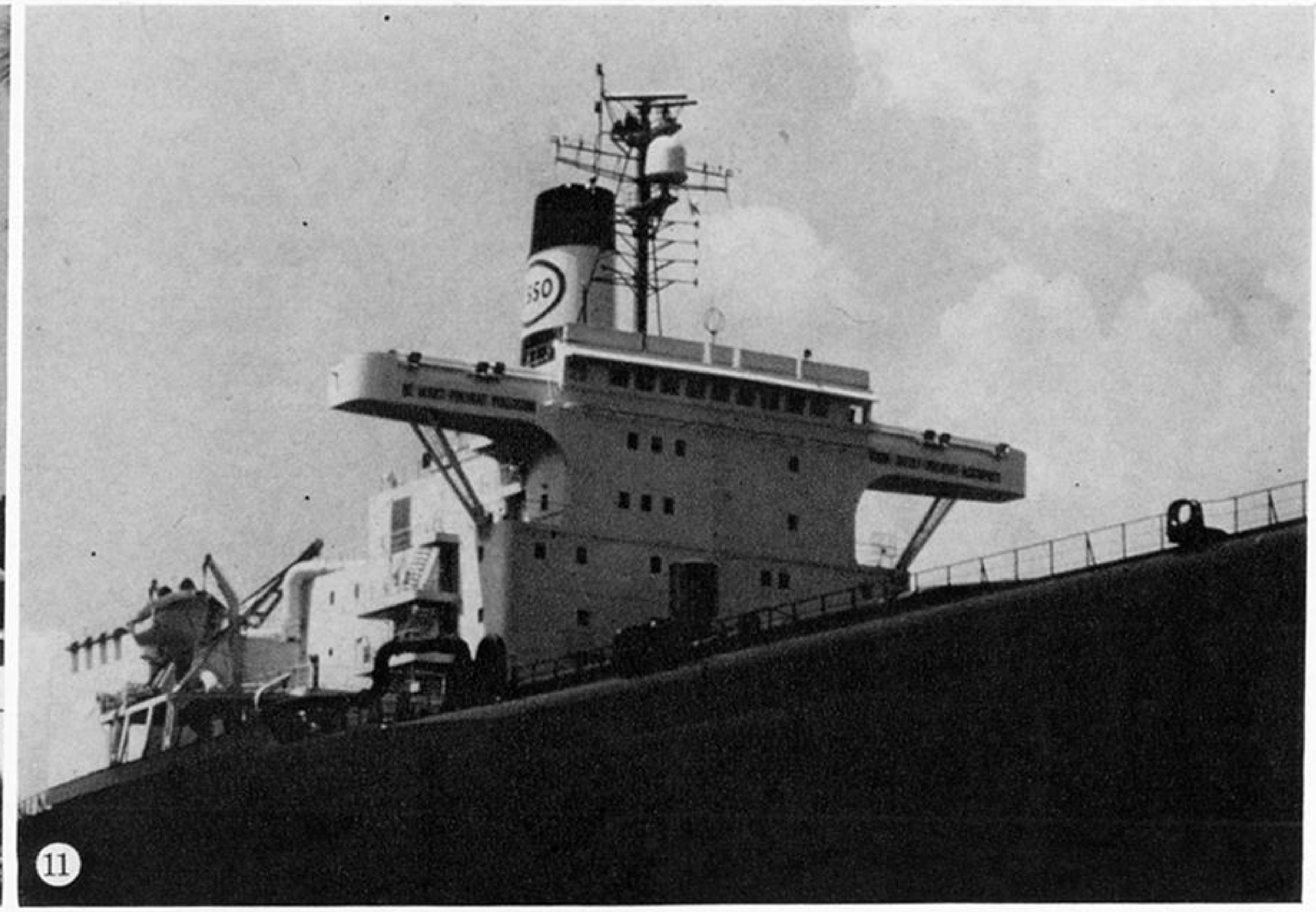


FIGURE 5. The Intelsat IV–A satellite.

FIGURE 8. Standard Earth station, Goonhilly Downs, U.K. (Photograph by courtesy of the Post Office.)





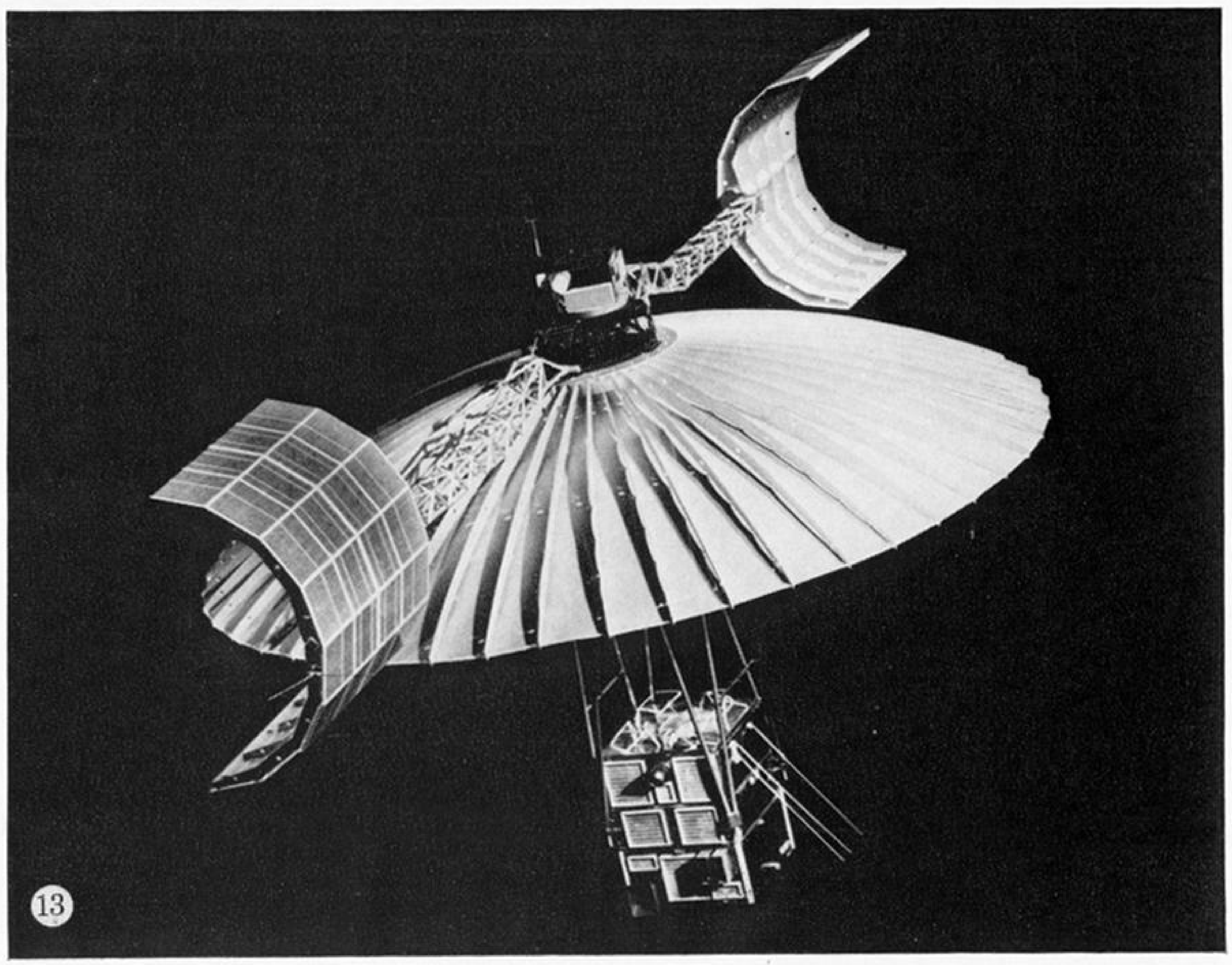


Figure 10. Earth station for domestic service.

Figure 11. Marisat shipboard terminal.

Figure 13. The N.A.S.A. ATS-6 experimental satellite.

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