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COMMUNICATIONS SATELLITE TECHNOLOGY IN THE NEXT DECADE

R. A. STAMPFL

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GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

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Compiled by
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ABSTRACT

After initial experimentation at lower altitudes, the American commercial communications satellites program has settled on, and is likely to continue exclusive use of, geosynchronous orbits perhaps making use of orbital inclination to the equatorial plane to obtain specific geographical coverage.

System capability during the next decade will exceed current economic and rate regulatory considerations. Hence, reliability and long life will be emphasized to lower communication costs even more than commercial communications satellites have achieved. It is anticipated that system capability will be extended to relay TV channels on a routine basis and provide broadcasting to community receivers for educational purposes. Further, the system capability will provide higher gain, multiple access, and special-purpose links heretofore not served operationally by satellites. One special-purpose link would be intercontinental communication and air-traffic control combined with data collection.

This discussion deals first with the service functions required for satellites: spacecraft power systems, attitude control, and spacecraft propulsion for stationkeeping. The anticipated capability of antenna systems in large reflector structures and multiple beam systems is treated next. The remaining sections concern a variety of multiple-access techniques and the extension of present communication capability into the millimeter wave region.

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PRESENT-DAY TECHNOLOGY

Substantial improvement in solar array and battery reliability can be expected during the next 2 years to ensure a 5-year life expectancy for communication satellites. Solar arrays producing 10 to 12 watts per pound at array efficiencies of 7 to 8 percent on oriented systems will be within the state-of-the-art. Neither basic efficiency nor radiation resistance will improve significantly in 2 years, but weight should be reduced through the use of 8-mil-thick silicon solar cells rather than the present 12 to 14-mil ones. Production quantities can be anticipated in the near future. Nickel-cadmium storage batteries with 50 percent depth of discharge will be used routinely. Power conditioning electronics with efficiency ranges of 85 to 90 percent will make overall power systems of 1 to 2 kw available by 1970.

TECHNOLOGY IN FIVE YEARS

The power-to-weight ratio of deployable solar arrays will double to 20 watts per pound without changing the array efficiency of 7 or 8 percent on oriented systems; 8-mil cells will have replaced thicker cells. If the lithium-doped cell realizes its potential for improved radiation resistance (effectively advancing the technology by an order of magnitude), arrays generating up to 10 to 15 kw should be readily available. Only 5 percent degradation per year at synchronous-orbit altitude will be experienced. Silver-cadmium batteries with the same capacity but only 60 percent of the weight of counterpart thin nickel-cadmium cells should be available and capable of 50-percent depth of discharge. In addition, silver-zinc secondary batteries weighing only 35 percent as much as nickel-cadmium cells may be available. Five years should be enough time to solve the problem of zinc dendrite growth that is currently limiting the cycle life of these cells. Reliable 10-kw static-power converters with a 5-year life are also feasible.

In 10 years, deployable solar arrays generating 25 watts per pound at the same oriented system efficiency of 7 or 8 percent can be made available through the use of lighter structures. If thin-film solar cells prove their flight capability, perhaps 30 to 35 watts per pound at 4 to 5-percent efficiency will be possible. Despite the resulting increase in area, oriented systems ranging from 40 to 50 kw would result from the production of large-area cells. Silver-zinc batteries weighing 35 percent and zinc-oxygen batteries weighing 25 percent of present nickel-cadmium systems will be available. Power conditioning electronics using solid-state static converters should be 85 to 90 percent efficient on the large systems.

Special missions may use radioisotope-thermoelectric generators (RTG), but on a severely limited basis because of their cost, hazard, and political considerations. Furthermore, RTGs require considerable system complexity (e.g., intact reentry for the isotope fuel). Other solar-power schemes, such as solar thermoelectrics, solar-thermionic and solar-Brayton, appear to be too inefficient or complicated for use in space during the next 10 years. Large power systems of 50 kw or higher, for possible use on broadcasting satellites, would apparently require nuclear reactors using thermoelectric, thermionic, or rotating machinery. Development of such systems will require more than 10 years. These anticipated advances in battery technology and nuclear systems presume that support for such development will become available.

SPACECRAFT ATTITUDE CONTROL

INTRODUCTION

Current and projected capabilities of satellite-control systems are summarized in Table 1. The first column lists gravity-gradient systems that have not yet been demonstrated conclusively at synchronous altitude. These completely passive systems are either stabilized in the gravity field of the earth or augmented with a pitch wheel. Accuracies of better than 10 degrees have been

Table 1

Satellite Attitude Stabilization

Present-day technology	0.5°-10° roll & pitch (from local vertical) 15° yaw (about local vertical) Below synchr. altitude	1-10 arc-sec pointing of spin axis	30 arc-sec pointing of spin axis 0.5-1° about the spin axis	0.1-1° all axes
Technology in 5 years	2°-5° roll & pitch 8° yaw passive 0.5°-1° all axes with active pitch wheel	1 arc-sec pointing of spin axis	Less than 10 arc-sec pointing of spin axis 1 arc-min about the spin axis	1 arc-sec all axes
Technology in 10 years	2° roll & pitch 0.5° yaw passive 0.5° all axes with active pitch wheel	Less than 1 arc-sec pointing of spin axis	1 arc-sec pointing of spin axis 1-10 arc-sec about the spin axis	0.1 arc-sec all axes
Limitations	Earth-pointing only Nearly circular orbit required unless pitch wheel is used Magnetic, solar pressure & aerodynamic disturbances & structural dynamics & thermal bending limit accuracy	Alignment of desired device axis with spin axis & thermal structural stability limit accuracy	Alignment of bearing axis with principal axis of inertia of the spinning body Thermal & structural stability limit spin-axis accuracy Attitude sensors & spin-bearing roughness limit pointing about the spin axis	Primary limitations of accuracy are attitude sensors & structural dynamic & thermal stability

achieved in low earth orbit. To date, 20-degree accuracy has been demonstrated in near-synchronous orbit. The pointing accuracies given in the table represent low and medium altitude capability. At synchronous altitude, the numbers may double their values.

Altitude has little effect on the pointing accuracy of spin-stabilized satellites, which have, in fact, been flown at all altitudes. The accuracies listed represent errors in north-south pointing from the equator and assume an equatorial orbit and a spin axis normal to the orbit plane. Sensors used for the alignment of the spin axis may be sun sensors, star mappers, or the communications link itself. Ground observations of sensor data over a long period of time are used to precess and align the spin axis.

The dual-spin-stabilized spacecraft (gyrostats) having a spinning body and a despin platform represent a class of satellites that combine many of the advantages of spinning and three-axis active, stabilized satellites. The spin-axis accuracy is less than that of a spin-stabilized satellite, because the spinning portion is not free to rotate about a principal axis. Since the spin axis is constrained by the bearing axis, inaccuracies will develop from the misalignment of the bearing axis and the principal axis of inertia of the spinning portion. Under the conditions outlined for the spinner, north-south earth-pointing accuracy is determined by the spin-axis pointing accuracy. East-west pointing accuracy is determined by the accuracy of pointing about the spin axis. This latter is limited primarily by sensor accuracy and roughness in the bearings. If an infrared (IR) earth sensor is used, accuracies approaching 0.1 degree can be expected within the next 5 years. In 10 years the accuracy should approach 0.03 degree, probably the ultimate limit because of variations in the earth's IR radiation. If RF sensors are used, the accuracy could be limited only by bearing roughness.

If north-south pointing from the equator is desired on a dual-spin satellite, a gimbal must be supplied on the despin portion to provide this extra degree of freedom. The pointing capability in this direction would be limited by the gimbal and the error sensor. The earth sensor or RF attitude-sensor limitations will be the same as those for east-west pointing.

Three-axis, active attitude stabilization is outlined in the last column of Table 1. The accuracies of these systems are limited primarily by the sensors and, to a lesser extent, by the dynamic and thermal structural stability of the satellite. The earth sensor or RF attitude-sensor limitations will be the same as those listed for the dual-spin satellite. Pointing to any spot on the visible earth can be accomplished at the stated accuracy.

If the accuracies projected in Table 1 are to be achieved, star trackers or precision inertial quality gyros must be used as sensors. The achievement of fractional arc-second accuracies in an earth-oriented direction for communication will require development of an error signal from the RF link. If the accuracies projected in the last column can be exceeded, the three-axis active system can be flown to those accuracies. The numbers stated are best estimates, and variance may be large.

SPACECRAFT PROPULSION STATIONKEEPING

Extensive use of the synchronous altitude over the next 10 years may lead to satellite congestion and may require more precise station-keeping control than is currently in use.

PRESENT-DAY TECHNOLOGY

Long lifetime, active attitude control that includes precise slewing will require precisely controlled onboard propulsion with high specific impulse and low thrust levels.

Most of the basic technology required for these applications has been developed, and the next few years will see it demonstrated in orbit.

Monopropellant hydrazine thrusters in the few-pound thrust range have recently been flown successfully. Millipound-thrust-level hydrazine systems are under development. Electrically heated gas systems (resistojets) have also been successfully employed in orbit. Low-thrust-level (i.e., 10 micropounds), liquid ammonia propellant, resistojet systems have been flown experimentally and will be flown again in the next 2 years. A cesium-contact ion engine system with variable thrust level and thrust vector control is being developed for flight on Applications Test Satellite (ATS)-D. A radioisotope-heated ammonia thruster with 20 millipounds of thrust has been developed and subjected to a continuous operational test for 9 months. Further development has been suspended pending the results of a safety study that may dictate changes in the capsule design. Low-thrust-level, pulsed electric thrusters are in an advanced stage of development and are available for experimental flight test or application.

TECHNOLOGY IN FIVE YEARS

Dual-spin-stabilized spacecraft, because of their fine pointing requirement, will require pulsed thrusters having precise, small impulse capability. Advanced electric thrusters (e.g., the colloid thruster) promising greatly improved performance are under development and will be available for flight testing within 5 years. Technological difficulties lie partly in the thruster-spacecraft interface.

In most cases, the basic thruster systems are far advanced in their development. However, there is still a clear need for experimental investigation of interaction between the thruster system and the spacecraft (e.g., impingement of the exhaust plume on parts of the spacecraft). These routine, yet crucial, investigations are not currently being conducted and may hold pointing and station-keeping capability below the discussed values. These problems can be solved in the next 5 to 10 years if research is started soon.

SPACECRAFT ANTENNA SYSTEMS

While total earth coverage within the line of sight of the satellite is required when many ground receivers are served simultaneously, other applications exist in which point-to-point communication among few stations with limited area coverage is required. The dual requirement for less expensive ground installations and multiple access dictates the development of higher-gain antennas. These antennas must provide multi-beam patterns and a pointing capability. Two classes of antennas are discussed: parabolic dishes and phased arrays.

PRESENT-DAY TECHNOLOGY

The evolution of spacecraft communication antennas originated with the Telstar and the Relay designs which have near-omnidirectional coverage and low gain (0 db) because of the wide range of look angles required in the low-altitude orbit.

SYNCOM was placed in a synchronous orbit that permitted narrowing the fan-shaped beam for full earth disc coverage with a resulting antenna gain of 7 db. No special control or pointing provisions were required. This pattern provides North Pole-to-South Pole coverage of the earth; however, the antenna radiation from the spacecraft is equally distributed in a 360-degree torus around the spacecraft. But since the earth subtends only 18 degrees, most of the energy is wasted in space.

The ATS-I spacecraft is designed with an electronically phased array antenna concentrating transmitted spacecraft RF power in a 20-degree cone (permitting 18-db gain). Internal losses in the antenna electronics limited the effective gain of this approach to 13.5 db.

ATS-III carries a mechanically despun reflector antenna using a parabolic sheet reflector to shape east-west coverage. It uses the SYNCOM antenna concepts mentioned above for north-south beam shaping. The losses in the design are very small, and the resulting gain is very nearly 18 db. Fixed antennas, which illuminate the earth (18 db), are planned for ATS-D and -E. Electromechanically positioned arrays with apertures up to 15 feet in diameter can readily be designed today. Larger apertures (e.g., 30 feet) require development of new structural concepts where the antenna reflector becomes the main component of the spacecraft.

At the present time, only a few beam patterns can be formed simultaneously; these can be pointed up to 5 beam diameters off the bore-sight axis by moving the phase center of the feed. Electromechanical means are applied on ATS to accomplish this end; however, pure electronic steering is equally feasible. The ATS-F antenna reflector uses an aluminum honeycomb-petal structure covered with fine mesh. The petals are side-hinged; thus, deployment in orbit does not require latching of parts.

Currently, parabolic antennas 30 feet in diameter can be launched and deployed in space. The technical problems of folding the antenna for packaging within the shroud and withstanding the launch environment are within the state-of-the-art.

Present technology also permits maintaining the dimensional stability required of the dish to operate at X-band frequencies, despite severe thermal problems. Although technology will permit construction of high-gain antennas in space, the size of the antenna used depends directly on the requirements of the particular spacecraft mission (i.e., there is no limit to the size of an antenna constructed during the next 10 years). Large-antenna technology is being developed in such projects as the ATS-F and -G 30-foot aperture and the LMSC 25-foot unfurlable antenna.

TECHNOLOGY IN FIVE YEARS

Technical problems in the present antenna configuration should be solved for diameters up to 100 feet.

Within 5 years parabolic antennas using lighter construction techniques, such as the electrostatic principle, can be developed and deployed in orbit. In principle, two metalloid fiber meshes could be joined by a ring and then, in space, charged electrostatically with opposite polarity. The parabola would then be formed by electrostatic repulsion. Parabolas with diameters of 200 feet could be launched and deployed.

TECHNOLOGY IN TEN YEARS

The state-of-the-art should permit very large antenna structures to be launched and deployed in space during the next 10 years. The basic principle presently envisioned will probably involve a web-like structure rotating about a central mast. Centrifugal force will slowly deploy the structure, forming a parabolic surface of extremely low density. This type of structure will reduce weight and thermal problems. Parabolas of up to 1 mile in diameter could be formed in orbit.

Surface tolerance (including surface deformation caused by space environment) will allow the reflector to collimate RF energy at 8 GHz, producing a 3-db beamwidth of 0.3 degree with a gain in excess of 50 db. A surface tolerance variation of $\pm \lambda/16$ is expected. Surface tolerances capable of collimating an RF beam at K-band (≈ 16 GHz) can be accomplished within the next 10 years; the capability for lower frequencies can be scaled proportionally. Size limitation is dictated more by available shrouds than by structural dish technology.

PHASED-ARRAY ANTENNA SYSTEMS

An almost unlimited number of beams and channels can be achieved with phased arrays. There are two general types of phased arrays. The first type of antenna uses phasing networks and element space separation. Switching or electronic phasing combines element signals so that beams are formed in the desired direction. External command signals or spacecraft-borne error detectors (horizon sensors) can control beam formation and operation. Examples of this type include conventional phased arrays, lens arrays, and switched multiple-feed arrays. Systems using these principles are highly dependent on satellite pointing and platform stability. This is not the case for the second type, retrodirective arrays, in which pilot carriers or tones are sensed and electronically processed so that phasing to form beams in the desired direction is accomplished automatically.

For multiple access by a large number of subscribers distributed over the visible earth disc, use of these antenna systems is advantageous and offers reduced ground station cost because of the potential of high satellite antenna gain. Table 2 estimates the critical design parameters achievable in the time periods stated. While the principle is well understood today, physical realization in the future will depend upon progress made in component development in the millimeter wave region, reductions in element weight, and increase in elemental power. During the next 5 years some of these antennas will be tested in orbital flight in the ATS program. Table 2 also lists array size, array gain, and other important characteristics for five frequency bands ranging from 2 to 94 GHz.

Two primary limitations for the self-phasing retrodirective (type B) systems in the lower frequency bands (2 to 4 and 6 to 10 GHz) are the availability of small, efficient RF power amplifiers, and the weight per element of the systems. Present solid-state devices are capable of 1/2 watt at 2 to 4 GHz (transistor) and 100 mw at 6 to 10 GHz (varactor up-converter). This limits

Table 2

Antenna Technology Development

	Available with Existing Technology (2 years)					Available with Modest Development (5 years)					Available with Major Development (10 years)				
Frequency band (GHz)	2-4	6-10	15-19	26-40	60-94	2-4	6-10	15-19	26-40	60-94	2-4	6-10	15-19	26-40	60-94
Class A	Controlled Phase Array (Transmitting)														
Array gain (db)	13	30	35	30	-	30	43	30	45	50	40	35	42	55	60
RF bandwidth (MHz)	25	50	200	1000	-	150	250	500	1000	2000	500	1000	2000	1000	6000
ERP* (dbw)	22	38	35	21	-	56	60	38	55	49	70	84	65	67	72
Beam positions	16	64	44*	16	-	200	100	32	16	16	400	300	128	128	64
Weight per element (lb)	0.6	0.8	0.5	0.4	-	0.6	0.8	0.4	0.3	0.25	0.6	0.8	0.4	0.25	0.25
Class B	Retrodirective Phased Array (Transmitting)														
Array size (elements)	100	64	-	-	-	200	100	64	64	16	400	300	100	100	64
Array gain (db)	33	30	-	-	-	36	43	33	40	45	40	55	45	50	60
RF bandwidth (MHz)	10	125	-	-	-	150	250	500	1000	2000	500	1000	2000	4000	6000
Power per element (watts)	0.5	0.1	-	-	-	1	1	0.5	0.15	0.1	5	5	2	1	0.5
ERP* per channel (dbw)	50	38	-	-	-	47	4[illegible]	38	30	20	56	67	45	44	47
Weight per element (lb)**	0.5	0.5	-	-	-	0.4	0.4	0.2	0.2	0.2	0.3	0.3	0.2	0.2	0.1

*Effective radiated power
**One-way communication; i.e., two independent beams per 10-MHz channel
*One-dimensional steering, ±30° coverage

equivalent radiated power, while the weight per element limits the number of elements allowable.

Continued development of solid-state devices and small, efficient traveling-wave tubes indicates that 1-watt amplifiers will be available with modest development for use in 100 to 200-element systems. With a major development effort, 5-watt devices should be small and light enough for 300 to 400-element systems. The RF bandwidth in these bands is expected to increase to 500 to 1000 MHz, and could be wider if traveling-wave tubes are employed. Multiple-beam systems employing separate independent transponders could simultaneously relay many channels of video signals or provide extensive redundancy if required. In the 6 to 10-GHz band, systems employing 25 independent video channels could be realized in 5 years, and 100 or more channels in 10 years.

The use of integrated microwave circuits and increased refinement in IF and signal processing circuitry would lower subsystem weight. However, increased RF power requirements would maintain the weight per element at currently achievable levels. The actual weight varies drastically with the complexity of the transponder system, the number of independent beams required, and the technique utilized.

Similar limitations hold for the type A systems at the lower frequency bands. Furthermore, platform stability must be achieved to overcome limits on high-gain performance.

The present technology of millimeter wave sources and amplifiers prohibits a retrodirective system from being considered in the near future. However, development of the limited space-charge accumulation (LSA) diode and of small, efficient traveling-wave tubes could produce systems with the required ERP for synchronous operation.

The projections given above are in terms of transmitter applications, but the array figures are equally applicable to steerable receivers. The sensitivity and noise characteristics would be coincident with the state-of-the-art in the low-noise receivers described below.

Table 3 and Figures 1 and 2 estimate the state-of-the-art to be achieved by low-noise receivers in the time periods indicated. Table 4 and Figure 3 give estimates for transmitter components of both ground and spacecraft systems. Another important advance may be achieved by use of large scale integrated circuitry (LSI). While this technology is still in its infancy, it can profitably be applied to current logic design; high-frequency applications will probably be developed in the next decade. Applying LSI techniques will permit highly redundant design and associated switching logic to be used in retrodirective arrays for the design of electronic components.

Comparing the efficiencies of parabolic and phased-array antennas (dc to RF) is of substantial technical interest. A general analysis encompassing the complete systems will be followed by a discussion of the specific points of comparison.

MULTIPLE-ACCESS TECHNIQUES

Present-day ground station access to commercial communication satellites is limited to a few high-gain stations that serve as gateways to and from highly developed ground communications networks. Where such networks do not yet exist, direct satellite access from many less expensive stations may be advantageous.

The most likely way to achieve cost-effectiveness for the communication satellite system is to maximize the RF output power of the spacecraft transmitter. But, at the very least, this requires operation of the final RF amplifier at or near saturation levels and gives rise to most multiple-access problems.

Table 3

Microwave and Millimeter Wave Receiver Systems Technology

	2 Years							5 Years							10 Years						
Frequency (GHz)	1-3	4-6	7-8	15-19	26-40	55-65	90-100	1-3	4-6	7-8	15-19	26-40	55-65	90-100	1-3	4-6	7-8	15-19	26-40	55-65	90-100
Spacecraft Receivers																					
1. System noise temperature (°K)	800	900	950	1000	8K	10K	13K	500	600	700	900	1. 8K	2. 8K	4. 5K	400	500	600	700	800	900	1. 2K
2. Bandwidth (GHz)	0. 3	0. 5	0. 6	1. 0	2. 0	4. 0	6. 0	0. 5	0. 6	0. 7	2. 0	4. 0	6. 0	6. 0	0. 5	0. 6	0. 7	4. 0	6. 0	6. 0	6. 0
3. Front end type	TDA	TDA	TDA	TDA	MIX	MIX	MIX	TDA	TDA	TDA	TDA	MIX*	MIX*	MIX*	MIX* PAR	MIX* PAR	MIX* PAR	MIX* PAR	MIX* PAR	MIX* PAR	MIX* PAR
Ground Receivers																					
1. System noise temperature (°K)	50	50	50	170	250	1000	6000	50	50	50	75	100	300[4]	900	50	50	50	50	60	300[4]	75
2. Bandwidth (GHz)	0. 025	0. 025	0. 075	0. 1	0. 2	0. 2	0. 6	0. 050	0. 050	0. 10	0. 25	0. 30	0. 50	1. 0	0. 10	0. 10	0. 20	0. 30	0. 35	0. 45	0. 50
3. Type	MAS	MAS	MAS	MAS	PAR	PAR	MIX	MAS	MAS	MAS	MAS	MAS	MAS	PAR	MAS	MAS	MAS	MAS	MAS	MAS	MAS
4. Cooled amplifier = △	△	△	△	△				△	△	△	△	△	△		△	△	△	△	△	△	△

Notes: 1. TDA = Tunnel diode amplifier; MIX = mixer; MAS = maser; PAR = paramp; MIX* = Schottky mixer
2. Spacecraft system noise temperatures assume spacecraft antenna looking at the earth
3. Ground-system noise temperatures assume good weather and low-elevation angles
4. Sky temperature limited

Table 4

Microwave and Millimeter Wave Transmitter Technology

	2 Years							5 Years							10 Years						
Frequency (GHz)	1-3	4-6	7-8	15-19	26-40	55-65	90-100	1-3	4-6	7-8	15-19	26-40	55-65	90-100	1-3	4-6	7-8	15-19	26-40	55-65	90-100
Spacecraft transmitter																					
Solid-state																					
Power output (w)	10	5	1	0.400	0.200	0.030	0.010	30	20	15	5	1	0.500	0.100	0.150	100	70	50	30	20	10
Bandwidth	← 1% →							← 2% →							← 4% →						
Tube																					
Power out (w)	25	20	15	12	10	0	0	100	100	70	40	20	5	2	1000	1000	700	200	40	20	10
Bandwidth (MHz)	300	300	500	600	1000			300	400	700	1500	3000	4000	5000	500	600	800	2000	4000	5000	6000
Ground transmitter																					
Power output (w)	30	30	30	4	1.5	3.0	0.3	40	40	40	10	3	5	1	60	60	60	20	8	4	2
Bandwidth (MHz)	300	300	400	300	400	600	800	300	400	500	500	500	700	1000	400	500	600	600	800	1000	1500

Note: Ground transmitter powers are not the maximum available RF powers. These powers reflect feasible communications systems. In the 1 to 20-GHz frequency range CW ground-transmitter power does not limit communications capability

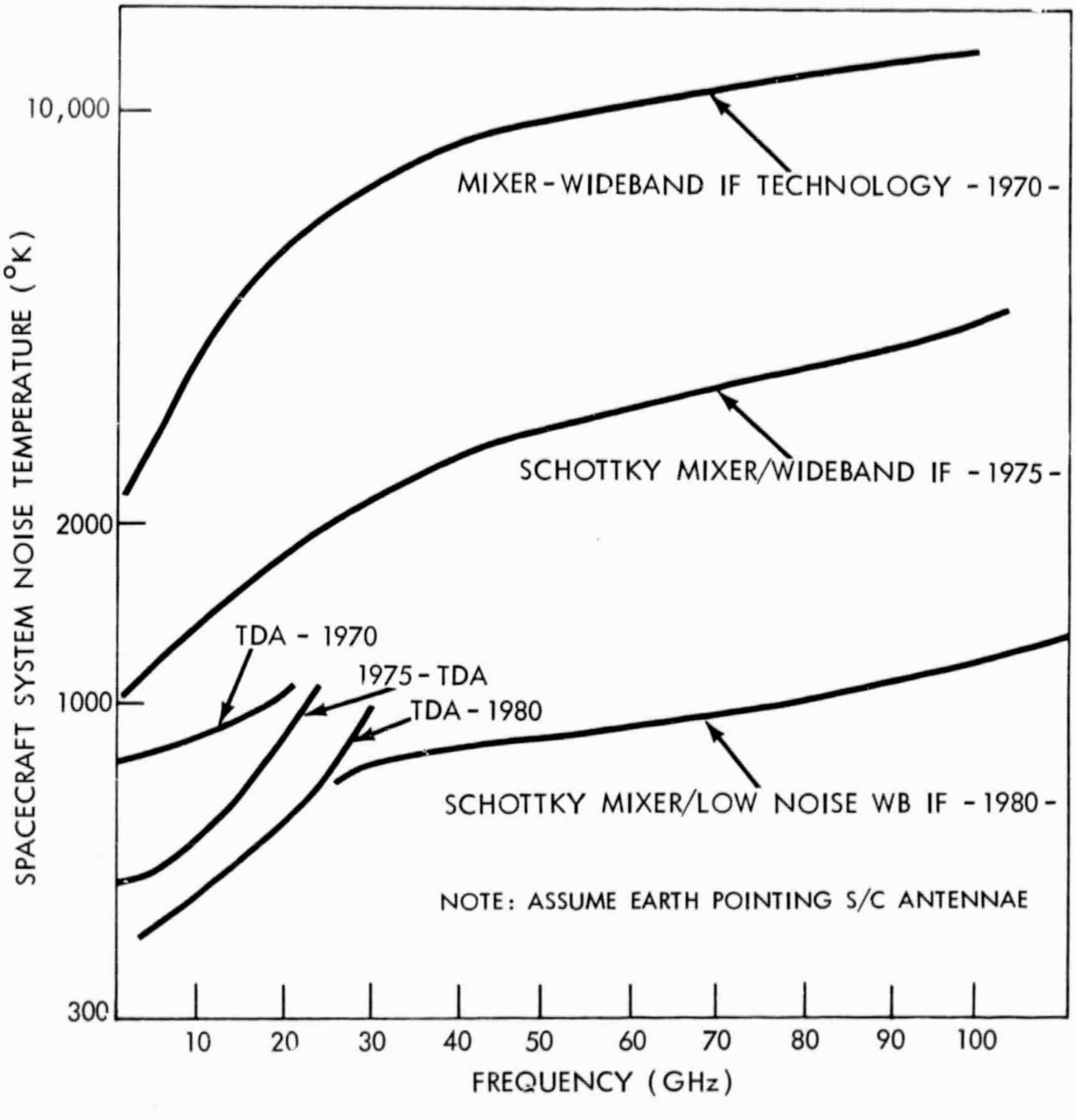

Figure 1—Spacecraft receiver technology for 1970, 1975, and 1980.

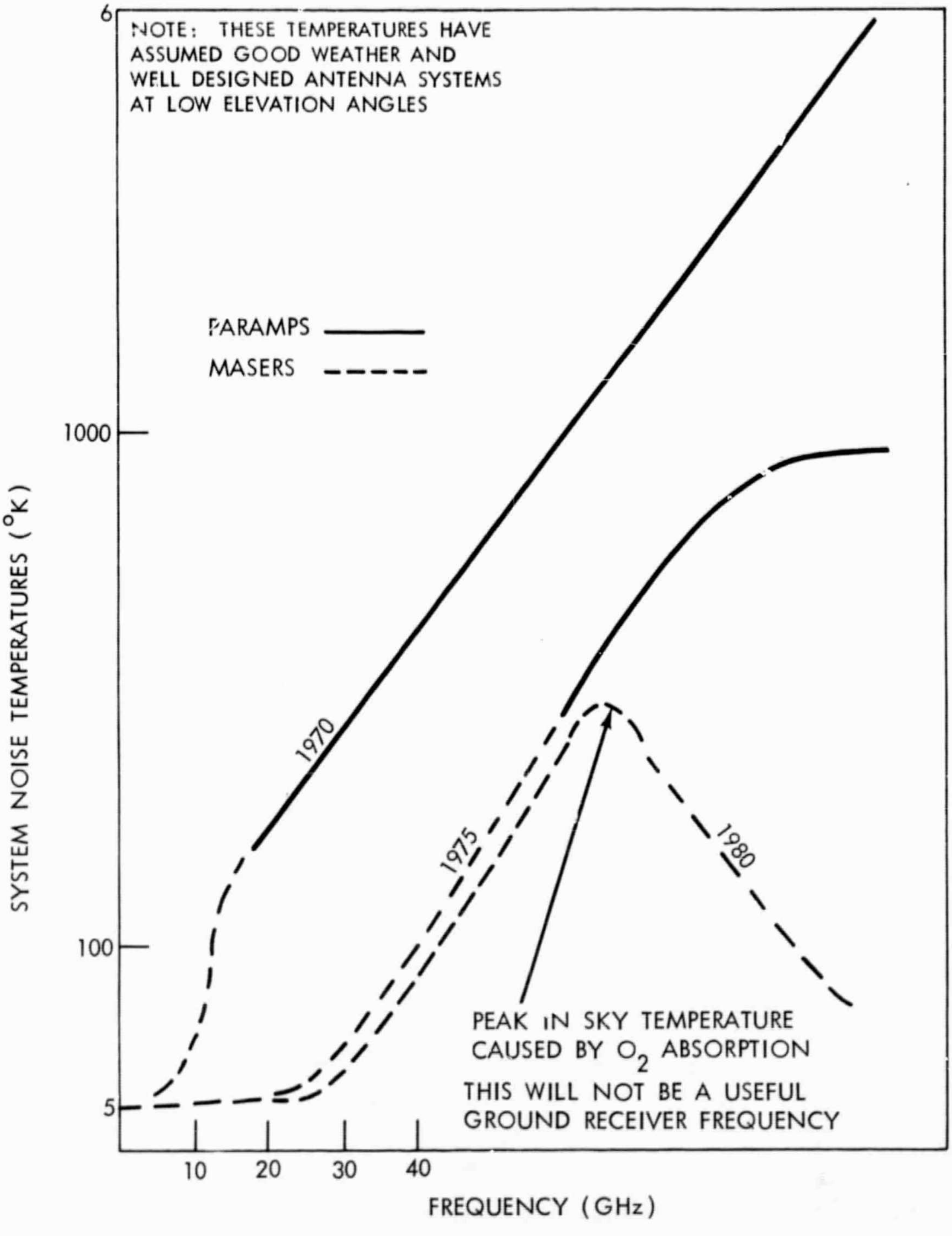

Figure 2—Ground receiver technology for 1970, 1975, and 1980.

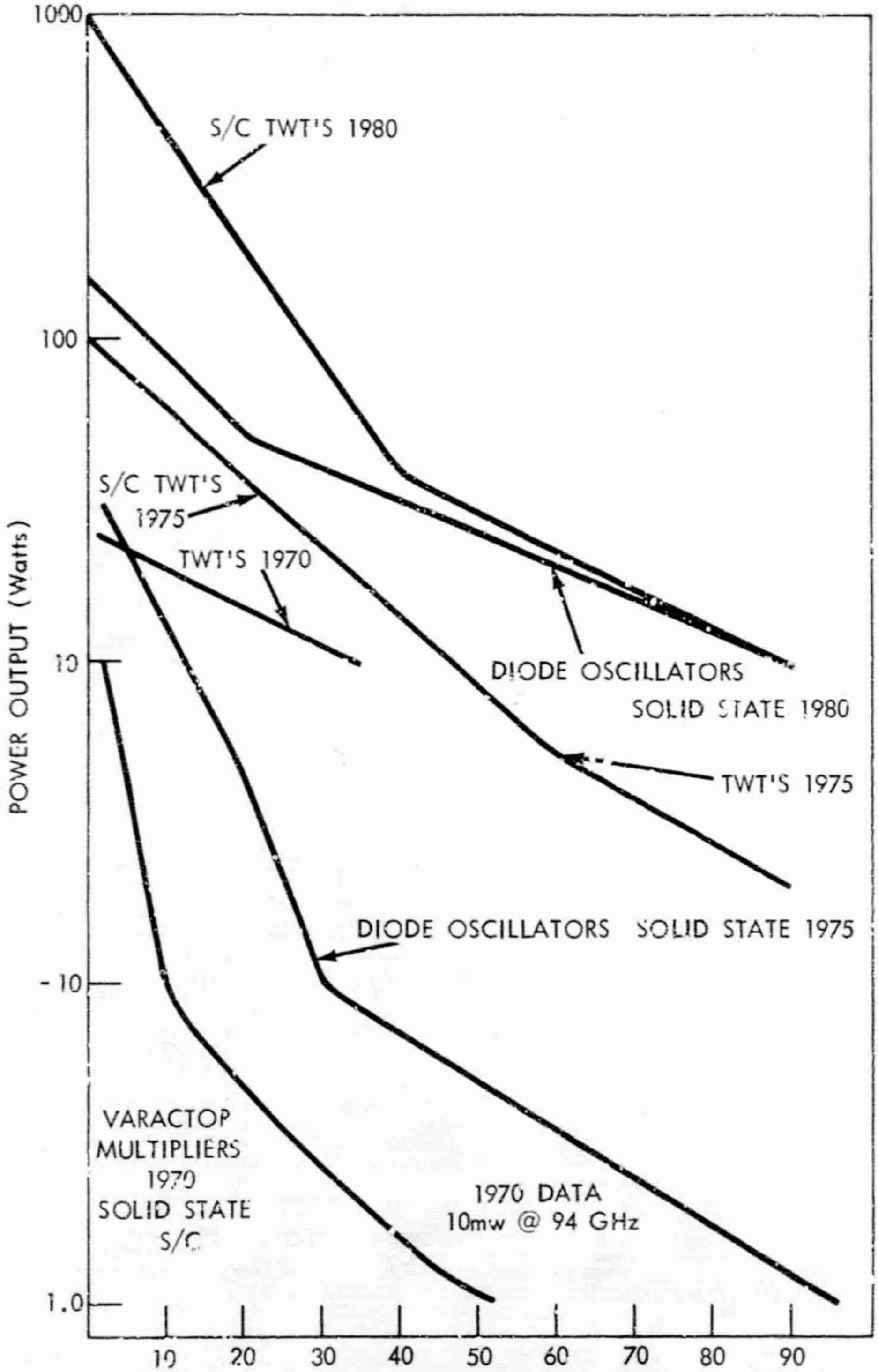

Figure 3—Spacecraft technology in 1970, 1975, and 1980.

Table 5, a modified version of Table 5 of the reference cited*, lists comments on the major multiple-access techniques. The following techniques are considered:

FDMA—Frequency Division Multiple Access

SSB/PMMA—Single Sideband/Phase Modulation Multiple Access

TDMA—Time-Division Multiple Access

SSMA—Spread-Spectrum Multiple Access

PAMA—Pulse-Address Multiple Access

The number of projected maximum capability ground stations having access is given for 1970, 1975, and 1980. The figures indicate the number of independent ground terminals transmitting "simultaneously" to a single spacecraft. The number of voice channels transmitted by a single terminal could range anywhere from one to the capacity of the system.

FREQUENCY DIVISION MULTIPLE ACCESS

Progress in frequency division multiple channel access technology is likely to be slow until the late 1970's. While three-channel access has already been operationally achieved with a single hard-limiting transponder, little further progress is expected before 1970.

In 1975, 20-channel access could be achieved by using components (integrated circuits) available in the 1970's to develop a multiple IF and/or transponder in order to provide an onboard level control capability and to ensure continuing optimum-level operation of the transmitter output.

In 1980 large-scale integrated circuit technology should make practical individual, 5-watt solid-state transponders with overall efficiencies of

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*"Modulation Techniques for Multiple Access of a Hard-Limiting Satellite Repeater," J. W. Schwartz, J. M. Aein, and J. Kaiser. Proc. IEEE, Vol. 54, No. 5, pp. 763-777.

Table 5

Summary of the Characteristics, Advantages, and Disadvantages of the Multiple-Access Techniques

	Characteristics	Advantages	Disadvantages
FDMA	Signals have constant envelopes and have spectra confined to nonoverlapping frequency bands (at the repeater input) constituting the access channels. Multiple-access demodulation is accomplished by a filter tuned to the selected frequency band. Compressive techniques might be required to combat intermodulation noise generated by hard-limiting. Message information can be conveyed by any form of angle modulation.	FDMA makes use of existing technology and hardware to a greater extent than the other techniques. Network timing is not required and repeater loading can be determined by relatively simple procedures.	More than one signal present in the repeater at one time produces intermodulation noise which reduces the usable repeater output power. Problems which may arise from different power spectral densities in different portions of the repeater band can make it difficult to operate with disparate receiving sensitivities at the various user stations. Uplink power coordination is required to make full use of the repeater capacity.
SSB/PMMA	Message information is transmitted to the spacecraft as a single-side band signal. Within the S/C transponder the SSB signal is converted to baseband and caused to phase modulate the transmitted carrier. Demodulation is accomplished by a wideband phase demodulator, resulting in a baseband of SSB signals. Conventional SSB demodulators are then used to demodulate the message.	SSB/PMMA makes use of existing technology and hardware although to a lesser extent than FDMA. It is the simplest technique for achieving a great number of accesses.	Strict frequency and level control must be exercised to avoid interfering with adjacent channels. Some loss is encountered in system capacity because of the residual carrier component in transmitted spectrum. Achieving stations intermix is more difficult with this technique than with TDMA.

Table 5 (continued)

	Characteristics	Advantages	Disadvantages
TDMA	Carriers are on-off gated in such a way that signals from different links are never present in the repeater at any one instant, but pass through in sequence. Multiple-access demodulation is accomplished by time-gating. Message information can be conveyed by any form of angle modulation within each carrier burst.	This technique avoids the problems of mutual interference among signals passing through a limiter simultaneously. The highest capacity, in theory, can be obtained for a given satellite power due to the absence of intermodulation noise. User stations with different receiving sensitivities or with disparate transmitting powers can be accommodated more readily than when constant-envelope carriers are used. Up-link power need not be coordinated, and each user station can use the highest peak power available to it to counteract interference in the up-link without degrading the other links thereby.	Network timing is required. Analog message information often must be converted to digital form.
SSMA	Carriers have constant envelopes and the spectrum of each extends over most, if not all, of the repeater band. The spectrum of a carrier is spread by angle modulation giving rise to a selected	The spread spectrum of the carriers provide a processing gain to counteract interference in the up-link. For carriers with wide-band phase codings, the hard-limiting repeater can	Each carrier occupies a wide bandwidth. Link synchronization is required, and can introduce considerable difficulty. Sophisticated methods are required to determine repeater

Table 5 (continued)

	Characteristics	Advantages	Disadvantages
SSMA (continued)	pattern of phase or frequency shifts. Multiple-access demodulation is accomplished by synchronizing the receiver to the desired carrier and duplicating the pattern of phase or frequency shifts. Message information can be conveyed by any form of angle modulation.	be made to appear similar to an ideal AGC transponder. The essentially unlimited number of distinct carrier waveforms makes it possible to make fixed address assignments. The network can operate without a central timing source and with a minimum of discipline when the repeater is being used to less than full capacity.	loading. Up-link power coordination is required to make full use of the repeater capacity.
PAMA	Carriers are low duty cycle pulsed waveforms. A particular carrier is distinguished by the time pattern of the pulses and possibly by their spectra or by phase modulation within the pulses. Multiple-access demodulation is accomplished by synchronizing the receiver to the desired carrier and time-gating, and possibly by frequency filtering or phase demodulation. Message information can be conveyed by a variety of methods.	Pulse waveforms can make use of high peak power to combat up-link noise. The large number of waveforms makes it possible to make fixed address assignments. Network timing is not required and link synchronization is rapid. The network can operate with a minimum of discipline when the repeater is being used to less than full capacity.	Information capacity is relatively low and coding is required to achieve tolerable error rates for maximum data rates.

10 percent, permitting communication of up to 100 channels. As before, onboard level control to optimize the output stage offers the advantage of very simple network operation.

SINGLE SIDEBAND/PHASE MODULATION

Four-channel access has been achieved experimentally in the ATS program. The present limitation on this technique is simply the frequency-control method. The situation is not expected to change significantly before 1970.

Within 5 years technology will make possible the operation of 1200 channels per transponder, using improved methods of frequency control (essentially on a per-channel or access basis), greater output power, and larger spacecraft antenna gains. The primary consideration in that time period will be economy of operation rather than the maximum number of channels that can be handled. The technique of accessing and level control is a closed-loop system; i.e., the transmitting station monitors its signal as it is received and returned by the satellite and automatically makes continuous adjustments in the frequency and level of the transmitted signal.

Using individual transmitted beams from the spacecraft (multiple antennas and/or steerable arrays) to achieve small area coverage will require the development of other techniques. Onboard spacecraft processing of the received signals and strict network operating procedures would be needed. A well-developed system could be in operation by 1980, if planning starts in the near future.

TIME-DIVISION MULTIPLE ACCESS

A 10-channel system has been experimentally demonstrated at Goddard Space Flight Center (GSFC) with the Relay II medium-altitude satellite. System design can be readily modified to accommodate synchronous orbit satellites. By 1975, the only limit in the performance of TDMA will be the extent to which logic circuits operating reliably at high rates are used. By this time a 100-megabit system should be a reality and will permit 1000 channels per transponder to be designed. Advances achieved by 1980 will depend on advances in LSI technology. Logic-circuit bit rate will determine the maximum number of channels. By then a 300-megabit system should be in operation, permitting 3000 channels per transponder.

SSMA and PAMA are not considered for commercial applications because of their complexity and prime value for anti-gram and security system design. After 1980 anti-gram characteristics may become important because of crowding of the spectrum and satellite spacing at synchronous altitude.

ORBITAL SPACING

Orbital spacing can be discussed only very generally. Current proposals for domestic satellite communication systems recommend spacings ranging from 2 to 10 degrees for synchronous satellites employed in wideband FM systems with a design capacity of one or more television channels and up to 1200 voice and data channels. None of these proposed systems requires major technological developments. Since the initial domestic satellite systems are likely to share the common carrier terrestrial frequency bands, mutual interference must be minimized.

Minimum satellite separation for systems sharing the same carrier frequencies is determined by the protection ratio of interference or unwanted signal power to wanted signal power in the worst telephone channel. The protection ratios required to meet CCIR recommendations range approximately from 27 to 34 db. This range covers interference of multiple-carrier frequency-modulation systems with small and large numbers of channels; two single-carrier frequency-modulation systems, with small and large frequency deviations; a single-sideband with a frequency-modulation system; and a single carrier frequency-modulation system with a digital system. These comprise all conceivable cases of mutual interference likely to be encountered during the next decade.

The protection possible depends primarily on the radiation pattern of the earth-station antenna. Typical earth-station antennas of current design range in diameter from 9 to meters (30 to 90 feet). In theory, these antennas will afford interference protection through angular discrimination of 35 db for satellite separations of 5 degrees and 2 degrees, respectively.

Recent experimental results with both the ATS and Intelsat systems show that separation of 2 degrees offers interference protection ratios of 30 to 32 db, using paraboloid antennas with 40- and 85-foot diameters. Additional interference protection may be realized with polarization discrimination, larger diameter antennas, greater side-lobe suppression, and improved beam-pointing accuracy and stability. These techniques can also minimize multipath fading. Progress in these areas during the next 5 to 10 years can be expected to reduce the angular separations of satellites to approximately 1 degree without compromising system performance. Smaller separations may be acceptable for short periods of time; i. e., 1 or 2 percent of the time for voice and telegraphy signals. However, because of the wider bandwidth requirements, TV signals will demand 2- to 4-degree separations.

MILLIMETER WAVE PROPAGATION

Millimeter wave propagation cannot be exploited today because of the lack of components (see Tables 2 through 4) and lack of detailed propagation parameters to design specific systems. Crowding of satellites and channels will demand use of more spectral bands. In addition, very wide-band applications will find this region attractive. In the next 2 years, the ATS-E millimeter wave propagation experiment will probe the atmosphere at 15.3 and 31.65 GHz to measure accurately the parameters that influence communications link performance. Parameters that influence millimeter wave propagation are molecular absorption, particle scattering, and atmospheric turbulence. Molecular absorption produces well-defined pass and stop bands. The stop bands are located at 22 GHz and 60 GHz, corresponding to the H_2O and O_2 molecular resonances, respectively. The pass bands are located from 10 to 20 GHz, from 27 to 43 GHz, and from 80 to 105 GHz. Attenuation due to particle scattering, the second factor in atmospheric absorption, is less well defined, but is a function of wave length and particle size (i.e., raindrop size). The third factor, atmospheric turbulence, produces wavefront distortions that are equivalent to random gain variations in the receiving aperture.

Future prospects for millimeter-wave communications will, of course, depend on advances in component technology in the areas of solid-state power sources and millimeter-wave tube developments. Recent advances in LSA diodes may offer millimeter-wave power sources for communications links by 1975 (Table 4). These devices could be used for 2-GHz bandwidth communications links at 19 and 37 GHz as well as for satellite-to-satellite experiments at 60 GHz. Use of the 60-GHz frequency for satellite-to-satellite links is particularly attractive because of reduced earth interference and simultaneous employment of small, high-gain satellite antennas.

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