NASA CR- 159977

Aerospace Report No.
ATR-78(7735)-1

COMMUNICATION SATELLITE TECHNOLOGY:
State of the Art
and
Development Opportunities

(NASA-CR-159977) COMMUNICATION SATELLITE TECHNOLOGY: STATE OF THE ART AND DEVELOPMENT OPPORTUNITIES (Aerospace Corp., Los Angeles, Calif.) 275 p HC A12/MF A01 CSCL 22B G3/15
N80-25358
Unclas
22049

Prepared by
THE AEROSPACE CORPORATION

July 1978

Prepared for
Goddard Space Flight Center
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Contract No. NAS 5-24489

Aerospace Report No.
ATR-78(7735)-1

COMMUNICATIONS SATELLITE TECHNOLOGY:

State of the Art
and
Development Opportunities

Compiled by
J. B. Woodford

July 1978

THE AEROSPACE CORPORATION
El Segundo, California
Washington, D. C.

Contract No. NAS 5-24489

Prepared for
Goddard Space Flight Center
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Report No.
ATR-78(7735)-1

COMMUNICATIONS SATELLITE TECHNOLOGY:
State of the Art and Development Opportunities

Prepared

J. B. Woodford, Principal Director
Data Systems and Telecommunications Directorate

Approved

J. Meltzer, General Manager
Eastern Technical Division

PRECEDING PAGE BLANK NOT FILMED

CONTENTS

CONTENTS (continued)

INTRODUCTION

This report is composed of material that was assembled and interpreted by The Aerospace Corporation during an intensive short-term effort aimed at identifying and defining new opportunities in communication satellite technology. In particular, Aerospace's mission was to support an in-house study at Goddard Space Flight Center (GSFC) to assess the role of the National Aeronautics and Space Administration (NASA) in the development of technology for communication satellites. The Aerospace and GSFC studies were conducted concurrently. All material in this report has been received by NASA as working papers in draft form.

In the design and conduct of the Aerospace study, technology efforts that had a high risk or that required a long period to reach fruition were noted as being especially appropriate for the government to pursue since the private sector of the communication satellite community finds such programs difficult to justify. The study was particularly directed at evaluating those factors that tend to limit the ready availability of satellite communications to an increasingly wide group of users. Current primary limitations on this wide utilization are the availability of frequency and/or synchronous equatorial satellite positions and the cost of individual user earth terminals. The former could be ameliorated through the reuse of frequencies, the use of higher frequency bands, and the reduction of antenna side lobes. The latter limitation will require innovative hardware design, careful system design, and large-scale production.

The parameters and ground rules of the study include the aforementioned, stringent 2.5-month time period and preselected technologies which had been identified primarily with communication satellites (e.g., satellite antennas, satellite receivers, satellite transmitters, propagation, low-cost earth terminals, system architecture, multiple access methodology, error correcting coding, on-board data processing, and bandwidth-compressing image processing). A look at all current activities in each of the areas was desired together with a traceable documented summary of the state of the art, an assessment of the possible progress to be made, and the identification of attractive opportunities for additional emphasis. The study focused on technologies that could be brought to the point of actual demonstration within 5 years and that could be appreciably accelerated by the additional funding. The technology reported upon was limited to unclassified programs. However, in all cases where applicable technology was known to exist in classified programs, the same technology was found to exist in an unclassified form.

Because of the need to cover these diverse areas in a very limited time and because, of necessity, use was to be made of existing Aerospace expertise, independent teams tackled each area and produced drafts of their own work. This report was edited to be a compendium of the work, and a measure of consistency of format was sought in order to facilitate utilization by the reader. Individual writing styles and different approaches to the treatment of the material were left as they appeared in the drafts. Therefore, the body of this report is a series of monographs on the topics mentioned above which relate to various facets of communication satellite technology.

CHAPTER I

ANTENNAS

Prepared by

C. B. Coulbourn
Communications Department

F. L. Hennessey
Radar and Microwave Department

CONTENTS FOR CHAPTER I

LIST OF ILLUSTRATIONS FOR CHAPTER I

LIST OF ILLUSTRATIONS FOR CHAPTER I (continued)

CHAPTER I

ANTENNAS

The biggest potential benefit from new antenna technology as applied to satellite communication systems is in the area of multibeam systems. The system capacity can be increased directly as the number of independent beams in a fixed frequency band serving a given area is increased. The requirement that these links be free of mutual interference imposes a requirement on sidelobe suppression significantly more stringent than that which has been imposed on satellite antenna systems in the past. At the same time, the desire to increase the number of beams in a given area implies that the antennas must be large enough in terms of a wavelength so that dedicating a separate antenna to each beam becomes impractical. For these reasons the various antenna technology areas considered here are evaluated primarily on the basis of their suitability for improving the designer's ability to reliably produce many narrow (say 1° or less) beams with very low (-30 dB or less) sidelobes from a single aperture. All of the technology areas recommended for early development are directly applicable to satellite-borne multibeam antennas.

The following paragraphs are devoted to deployable reflectors, fixed reflectors, lenses, arrays, and feed systems appropriate to multibeam antennas. While each of these subjects is treated separately, there is some overlap in that the basic characteristics of large directive antennas apply to all types discussed.

A. REFLECTORS

1. OVERVIEW

A considerable amount of recent effort in the area of directive antenna technology has been applied to reflectors. The basic reason for this is that in the communications satellite, the reflector simultaneously provides the advantages of very lightweight, extremely wide frequency bandwidth capability and simplicity of design. During the development of communication satellite technology, weight was a prime consideration, and so expertise in this area has built up. Basic considerations having to do with reflectors are summarized in Figure I-1. The restricted volume available to the communication antenna when it is packaged for launch has led to considerable development in the area of mechanically deployable reflector antennas.

ADVANTAGES

- SIMPLE
- WIDE BAND
- LIGHT WEIGHT

LIMITATIONS

- LAUNCH ENVELOPE
- THERMAL DISTORTION
- OFF-AXIS BEAM DISTORTION
- MANUFACTURING TOLERANCES
- FEED BLOCKING

STATE-OF-ART APPROACHES (FIXED)

- GRAPHITE-EPOXY CONSTRUCTION
  - COEFFICIENT OF THERMAL EXPANSION $\rightarrow 10^{-7}$ IN/IN/OF
  - SURFACE ROUGHNESS $\frac{\epsilon}{D} \rightarrow 2/10^5$

  SOURCES: GD, TRW, FORD, OTHERS

STATE-OF-ART APPROACHES (DEPLOYABLE)

- FLEX-RIB/MESH (LMSC)
- RIGID RIB/MESH (HARRIS)
- EXPANDABLE TRUSS/MESH (GD)
- SEGMENTED, FOLDED RIGID SURFACE (TRW, GD)

Figure I-1. Reflectors - Basic Considerations

The principal areas in which there is still much opportunity for significant advance are those of deployable antennas that can operate at frequencies below about 8 GHz, can be packaged inside a shuttle bay, and can open up in orbit to have diameters greater than 100 feet. Most experience suggests that such antennas will be constructed of a collapsible structure supporting a mesh reflector surface. At frequencies much greater than 10 GHz, the mesh reflector surface is less applicable. Giant steps have been taken in the last 5 or 6 years with the development of graphite fiber reinforced plastics (GRFP) which have made possible a thermal stability in orbit far greater than that achievable with conventional materials. Use of this material results in solid, rigid reflector surfaces which are, however, less amenable to packaging in very small volumes. Using mechanical deployment schemes that permit folding these rigid structures utilizing relatively rugged mechanisms may help with this problem. It seems likely that a determined development effort could make common the use of 30-ft diameter antennas folded to fit inside the shuttle while maintaining tolerances on orbit suitable for operation at frequencies of the order of 100 GHz.

2. STATE-OF-THE-ART OF REFLECTORS

Specific examples of the current state-of-the-art in reflector technology are listed in Figure I-2. This listing includes both fixed and deployable antennas. The largest of the fixed antennas is the 12-ft diameter GFRP solid reflector used on the Voyager. The largest of the deployable antennas that has actually been orbited is the 30-ft diameter flex-rib used with the Lockheed ATS-6. The criterion for evaluating these reflectors is surface roughness, which is most conveniently expressed in terms of the rms deviation from an ideal surface. (Figure I-3 is the familiar plot of gain loss vs. rms surface error lifted from Ruze.) Using this plot, one finds that the .055" rms roughness that is characteristic of the ATS-6, 30-ft dish under average thermal conditions leads to about 1 dB of roughness loss at the 8.25-GHz frequency at which the dish was evaluated. Similarly, the worst case thermal .005" rms measured on the General Dynamics 8-ft diameter GFRP reflector implies slightly less than 1-dB loss at its 94-GHz frequency.

The Lockheed flex-rib deployable reflector illustrates (Figure I-4) the pioneering approach to deployable reflectors. The 30-footer is presently in orbit and remains close to the edge of the state of the art. The ATS-6 design uses aluminum ribs with a woven mesh for the reflector surface. Its principal limitations result from the fact that

IN-ORBIT

• ATS-6 (LMSC)	30 ft diameter flex rib - 48 aluminum* ribs, gold plated nylon woven* mesh, ~.055'' rms, 53% efficiency at 8.25 GHz (D ≈ 250) degrades ~2 dB in worst thermal, 182 lbs uncontrolled* deployment, launch package ~ 4 ft dia x 6 in. high.
• INTELSAT IVA (HAC)	53 in. diameter GFRP offset parabola. 37 feed cluster for shaped beam.
• JAPANESE CS (FORD WDL)	Offset single feed with reflector shaped to control pattern 1 m diameter 17.5 - 31 GHz bare GFRP.
• VOYAGER (FORD WDL)	12 ft diameter GFRP solid reflector, nondeployable, rms <.010'' dual shaped X-band cassegrain 109 lbs
• FLTSAT (TRW)	16 ft UHF

SPACE-QUALIFIED

• TDRSS (HARRIS)	16 ft diameter rigid rib - 18 GFRP ribs, moly gold knitted mesh controlled by quartz back-up cords, ~.018'' rms doubly curved, controlled deployment, 34 lbs, ~ 3 ft dia x 8 ft long launch package, highest frequency 15 GHz (D = 240λ)
• USAF TECH DEVELOPMENT (GD)	8 ft diameter fixed GFRP, coated with Al and SiO MFG. rms .003'', worst thermal .005'', 45 lbs, D = 750λ at 94 GHz.

FIRM PLANS FOR LAUNCH

• INTELSAT V (FORD WDL)	8 ft and 6 ft diameter offset parabs, 88 horn feed, 4 times frequency re-use electrical design complete. C-band.

DEVELOPMENT PROGRAMS WITH HARDWARE

• DAT 1973 (HARRIS)	50 ft rigid rib - 24 aluminum ribs with knitted Chromel-R double mesh, .050'' rms MFG., (D ≈ 500 λ at X-band) 562 lbs.
• GFRP FLEX-RIB (LMSC)	Presently building 22-rib, 50 ft reflector using GRFP for rib and using knitted mesh.
• GFRP FIXED REFLECTOR(TRW)	9 ft diameter GFRP sandwich construction with .005'' rms suitable for about 100 GHz.

PAPER STUDIES

LMSC, HARRIS, GRUMMAN, OTHERS	Study hoop-column designs for reflector and lenses from 100 ft to 1000 ft diameter.
ON-ORBIT ASSEMBLY (GD) (MARTIN)	Study 100 m diameter deployable space-fed array for space-based radar.

*Indicates things the supplier says he would change in upgrading technology.

Figure I-2. Reflectors - Examples of Current Status

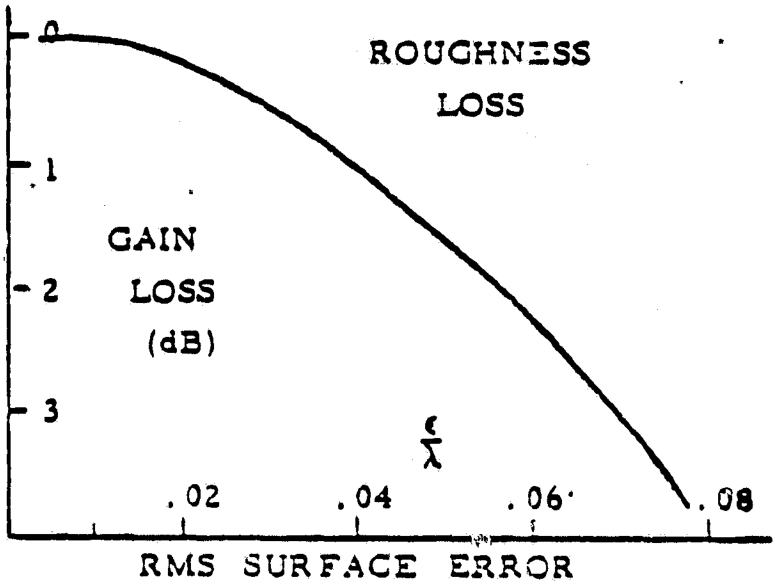
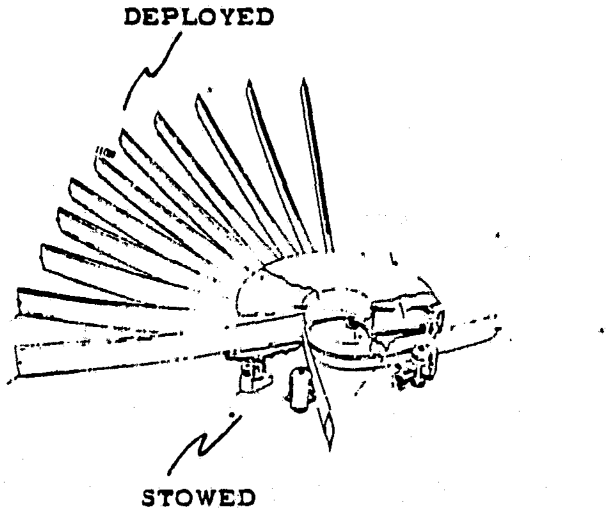


Figure I-3. Roughness Loss Curve

APPROACH

FLEXIBLE RIBS WRAP AROUND HUB AT LAUNCH, ARE DRIVEN OUT TO RADIAL POSITION IN ORBIT WITH MESH STRETCHED BETWEEN RIBS



STRONG POINTS

- PROVEN AT 30 FT (UNCONTROLLED)
- COMPACT, RUGGED AT LAUNCH
- POTENTIALLY THERMALLY STABLE IF RIBS CAN BE GFRP AND IF MESH CAN BE KNIT

WEAK POINTS

- "FLATS" BETWEEN RIBS
- DEPLOYMENT CONTROL COMPLEX

CURRENT EFFORTS

- GFRP RIBS, MOLY-GOLD MESH, DRIVE CONTROLS

Figure I-4. Deployable Reflectors - Specific Approach - Flex Rib (LMSC) the mesh is a structural element in this design, and the tension in the mesh is used to shape the ribs to the desired contour. This leads to somewhat greater thermal sensitivity than is the case when the ribs are made of a more thermally stable material, and the mesh is installed in such a way that it does not affect the rib shape. Lockheed is currently working on GFRP-wrapped ribs that are thermally quite stable. A soft knitted mesh is substituted for the woven mesh used previously. The firm is also working on a 50-ft diameter design that should be a significant improvement over the original approach.

The Harris approach to deployable reflectors (Figure I-5) used aluminum ribs with a knitted Chromel-R double mesh stretched over the tops and bottoms of the ribs. Ties between the two surfaces were adjusted to provide a double curvature in the reflector surface which eliminated the systematic error that resulted when a single reflector surface was stretched between ribs. Later designs by Harris have substituted GFRP ribs for the aluminum and quartz cords stretched between the ribs in place of the back mesh. The front reflecting surface is now made of a gold covered molybdenum. The ties from the front to the back surface again provided the desired double curvature with a soft front surface shaped by a very thermally stable GFRP and quartz backup. This construction is the one that has been used with the 16-ft tracking and data relay satellite antenna that was listed under the flight-qualified items in Figure I-2.

The third of the three leading approaches to deployable reflectors is the General Dynamics expandable truss illustrated in Figure I-6. This approach was first developed for a portable ground installation for NASA/Goddard in a 15-ft diameter reflector. In this case also, the original application included using aluminum tubes in the backup truss with a Chromel-R reflector surface. More recent designs by General Dynamics have used GFRP tubes in the truss and different knitted materials for the reflecting surface. General Dynamics has also used drop cords tying the reflector surface to the backup structure to increase the control over the reflector surface.

In summary, the leading approaches to deployable reflectors have different advantages for different applications. The Lockheed approach provides an extremely compact, rugged launch package but has the disadvantage of controlling the mesh surface only along the ribs, leading either to a systematic departure from the ideal doubly curved surface that can become too large or to the need for a very large number of ribs. The Harris approach has demonstrated the best control of the reflector

APPROACH

- RIGID TUBULAR GFRP RIBS
- SINGLE HINGE AT HUB
- FRONT SURFACE REFLECTING SOFT MESH, BACK SURFACE STIFF QUARTZ CORDS
- TIES BETWEEN MESHES SHAPE REFLECTOR

STRONG POINTS

- THERMALLY STABLE
- CONTROLLED DEPLOYMENT
- DOUBLY CURVED REFLECTOR
- TDRS 16 FT EXPERIENCE

WEAK POINTS

- RELATIVELY LARGE LAUNCH PACKAGE

CURRENT EFFORTS

- DOUBLY HINGED RIBS

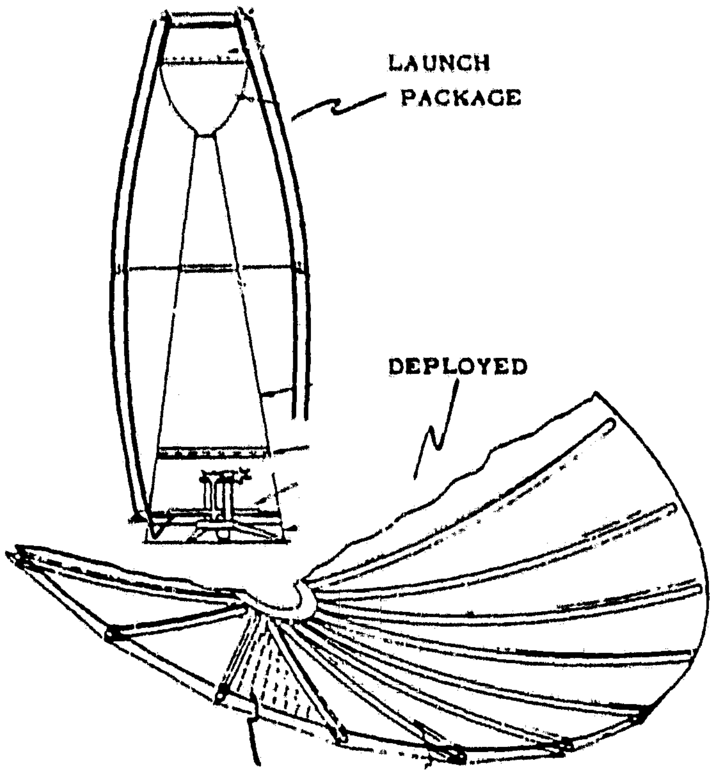


Figure I-5. Deployable Reflectors - Tubular Rib Umbrella (Harris)

APPROACH

- TUBULAR TRUSS BACK-UP STRUCTURE WITH HINGES
- COLLAPSES INTO SMALL CYLINDER AT LAUNCH
- DEPLOYMENT DRIVEN BY CARPENTER TAPE HINGES
- KNIT MESH SURFACE CONTROLLED BY DROP CORDS TO TRUSS STRUCTURE

STRONG POINTS

- GFRP TUBES WITH TITANIUM HINGES VERY THERMALLY STABLE
- SMALL, RUGGED AT LAUNCH
- CAN BE SUPPORTED AT EDGE FOR OFFSET FEED
- TDRS USER 4 FT EXPERIENCE
- DOUBLY CURVED SURFACE

WEAK POINTS

- UNCONTROLLED DEPLOYMENT

CURRENT EFFORTS

- GRAPHITE - TITANIUM HARDWARE
- COMPUTER ANALYSES OF DEPLOYMENT

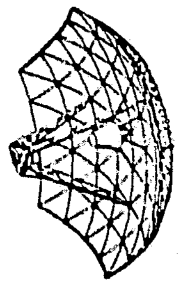


Figure I-6. Deployable Reflectors - Expandable Truss (General Dynamics) surface to date, but it requires a relatively large launch package with attendant problems during early flight. The General Dynamics approach provides a launch package almost as compact as that of Lockheed's and the potential for achieving surface tolerances similar to those of Harris. The Harris approach provides a very well controlled deployment in which a motor-drive controls the rate at which the antenna opens up on orbit, which eliminates any risks associated with a sudden shock when the structure opens up and imposes no significant force on the space vehicle. The demonstrated Lockheed deployables are uncontrolled, but Lockheed's latest efforts use a motor-controlled deployment to eliminate the shock associated with the earlier technique. The General Dynamic approach is uncontrolled but may be amenable to being controlled with some modifications in the design approach.

3. TECHNOLOGY LIMITS OF REFLECTORS

The traditional technology limits for large reflectors in space was imposed by the thermal environment. The extreme thermal variations between the sun and shadow in space led to a warping of the reflector surface that limited the usefulness of the reflector. The remarkably low thermal coefficients that have been shown to be practically achievable with graphite composites have led to the excellent thermal stabilities typified by many of the illustrations in Figure I-2. Current limitations have to do primarily with overall size and weight. Deployable reflectors using mesh surfaces can be expected to achieve tolerances of the order of .050" rms in 50-ft diameters and still package in the shuttle envelope. Development is necessary if a reflector much larger than 50 ft is desired. For extremely tight tolerances (e.g., .005" rms) applicable to frequencies in the millimeter range, the solid graphite reflectors are the preferred approach. Development is necessary in this area when the diameter of the reflector becomes larger than about 15 ft.

4. TECHNOLOGY OPPORTUNITIES OF REFLECTORS

Most of the work on reflectors suitable for space has emphasized the need for antenna gain. For the extremely low sidelobes that are necessary for multibeam satellite communication systems with isolation of the order of 30 dB between beams operating at the same frequency, the criterion for evaluating the surface roughness is associated with the scattered sidelobes rather than with peak gain loss. The specific kind of roughness becomes important where sidelobes are concerned. (See Figures I-7 through I-9). These figures show calculated patterns in

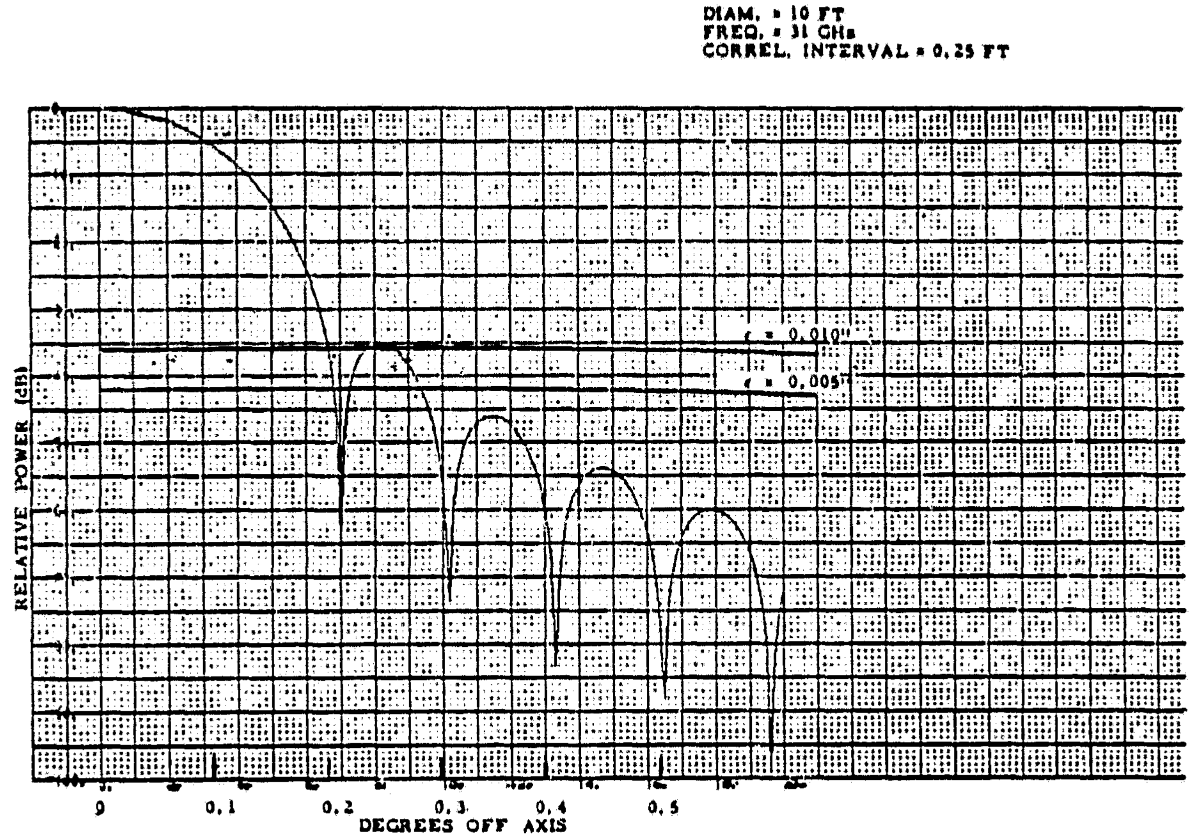


Figure I-7. Scattered Sidelobes vs. Surface Roughness (After Ruze) (Correlation Interval = 0.25 ft)

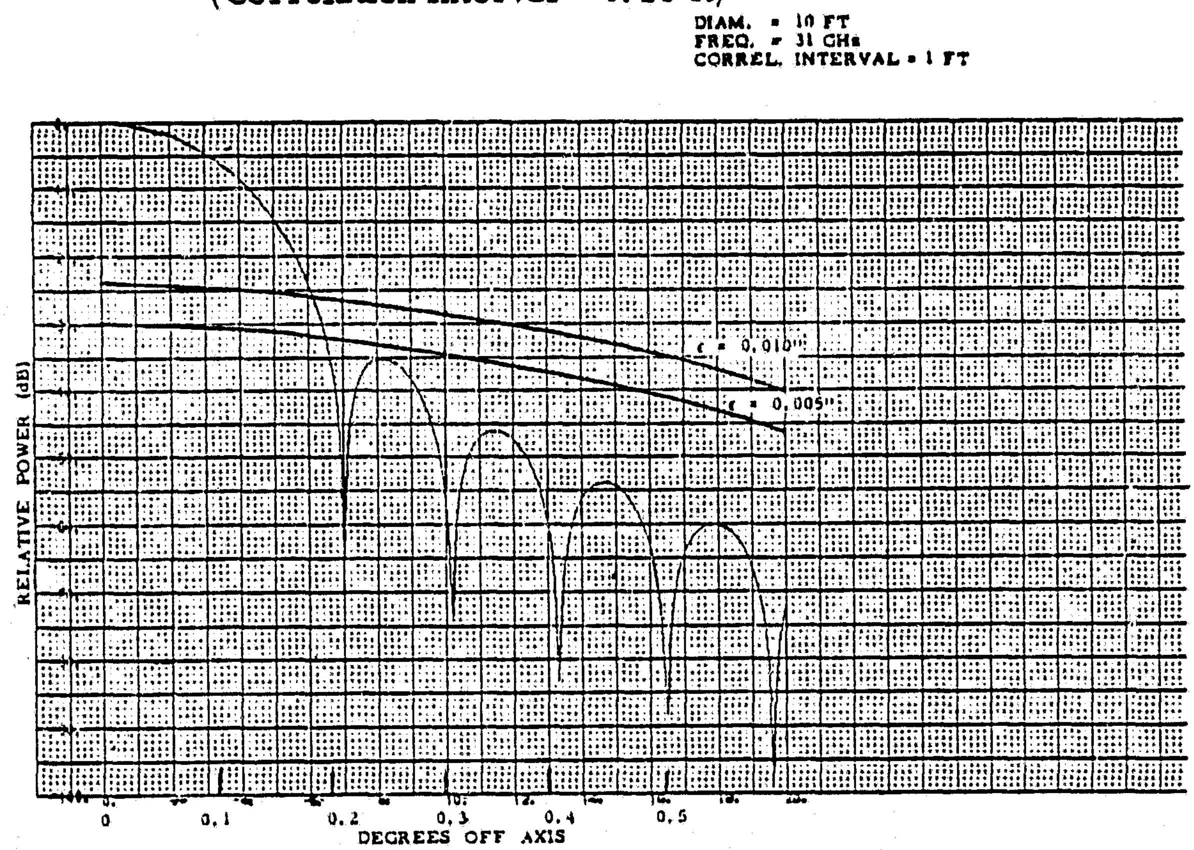


Figure I-8. Scattered Sidelobes vs. Surface Roughness (After Ruze) (Correlation Interval = 1 ft)

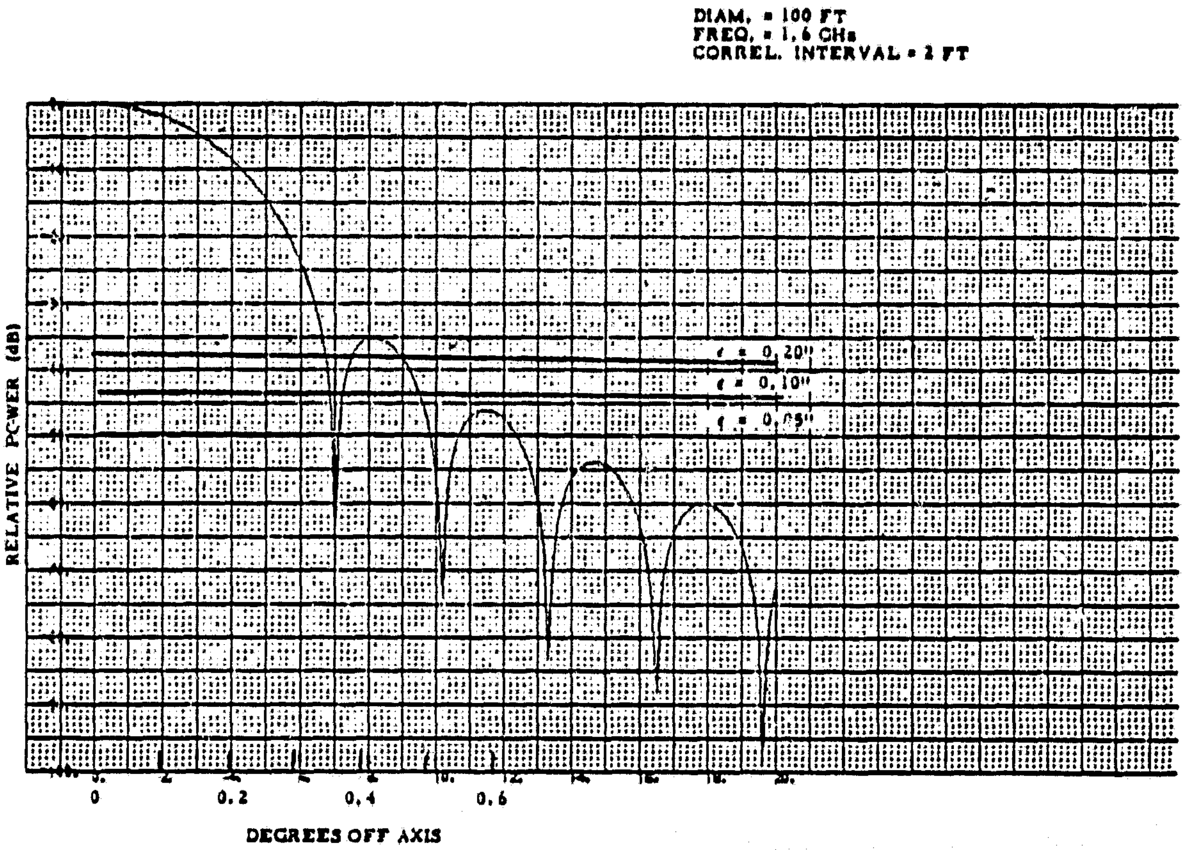


Figure I-9. Scattered Sidelobes vs. Surface Roughness (After Ruze) (Correlation Interval = 2 ft)

which the basic aperture distribution is designed to provide 35-dB sidelobes. The effect of surface roughness on the overall sidelobe level is illustrated here following an analysis presented by Ruze. It can be seen that for surface roughness ordinarily considered to be very good, the sidelobes (caused by the roughness) can be the limiting factor in terms of the isolation that is possible between two beams in a multibeam system.

5. CURRENTLY DEMONSTRATED REFLECTORS

The current state-of-the-art for reflectors is presented in a graphical form in Figure I-10. This figure shows the surface RMS (and the corresponding rf frequency for which it provides reasonably efficient performance) as a function of diameter for currently demonstrated reflectors. Each of these reflectors has been mentioned above. The O's on the chart indicate orbiting reflectors, the Q's represent reflectors that have been qualified for use in space, and the D's represent reflectors that have been developed and for which the complete hardware is in existence. The line on the chart corresponds to a ratio of rms roughness to overall diameter of four parts in 10^5. Experience to date suggests that achieving significantly better surface roughness than this in practical, flyable hardware will be very difficult.

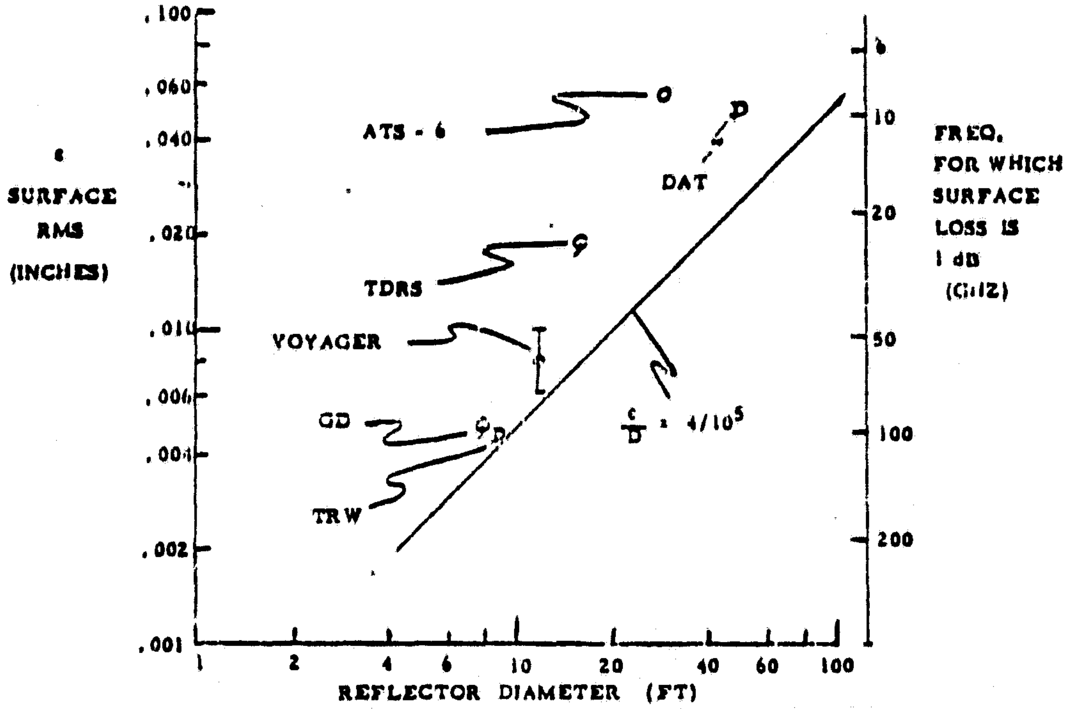


Figure I-10. Current State-of-the-Art of Reflectors

B. PHASED ARRAYS

By using phased arrays, a designer, in principle, has almost unlimited control over all antenna design parameters. He can precisely control phase and amplitude of the excitation of each element to achieve any physically realizable tradeoff between gain factor and sidelobe lèvel. He can fit his array to any arbitrary contour. He can build in adjustments to achieve rapid, inertialness beam scan, or arbitrary beam shaping. His array will have built into it the characteristics of graceful degradation. By placing an amplifier at each element, or group of elements, he can use multiple low-power solid-state amplifiers to generate an arbitrarily high transmit power.

The bandwidth of arrays, while not unlimited, is sufficient for known communication applications. By using modulo 2π phase shifters and feeding the array elements in parallel, percentage bandwidths can be achieved which approximately equal the beamwidth in degrees. By using true time delay control networks, the bandwidth will be wider. Thus, for a 10-percent bandwidth and a 1-degree beam typical for a communications satellite, time-delay control networks would be necessary.

Array theory is well developed, well documented, and mature. Necessary design tools are available.

Even so, none but the simplest array configurations is being used on communication satellites. The reason is that known array implementation techniques require extremely large numbers of components. A 1-meter square array operating at 20 GHz would typically require 18,000 elements spaced one-half wavelength apart. These elements would each have to be properly excited. Phase and amplitude control networks would be required, the exact number depending on the number of subarrarys which in turn depends primarily on the maximum required scan angle. Power control and distribution network losses could be high. Large numbers of amplifiers with closely matched amplitude and phase transfer characteristics would be needed.

The opportunities for making phased arrays practical for communications satellite applications are believed to primarily involve advancement of the technology of microwave integrated circuits (MIC). Low-cost MICs are required for the following functions.

- Power amplifiers operating at all assigned space-to-earth satellite communication frequencies. Matched amplitude and phase characteristics are necessary.
- Low-noise amplifiers operating at all assigned earth-to-space satellite communication frequencies. Matched amplitude and phase characteristics over large dynamic ranges are necessary.
- Phase control and time-delay control networks are required to operate at all assigned satellite communication frequencies.
- Passive components including power dividers, hybrids, and filters are required at all assigned satellite communication frequencies.

In addition to MICs, techniques for integrating arrays, feed networks, amplifiers, and control networks onto one photoetched (or otherwise produced) assembly are needed. Good examples of such hardware are the monolithic phased arrays developed by Ball Brothers Research Corporation in Boulder, Colorado.

The required effort and potential payoff for these technology advancements are both enormous.

1. STATE-OF-THE-ART OF PHASED ARRAYS

As noted earlier, most of the phased arrays that have been used on satellites are of simple configuration. This section illustrates this fact with summary descriptions of many of the phased arrays used on operational spacecraft.

One of the more complex satellite phased arrays was developed by Lincoln Laboratory for the LES-6. The characteristics of this array are summarized in Figure I-11 and descriptive diagrams are provided in Figures I-12, I-13, and I-14. This array consists of eight colinear slot pairs and eight colinear dipole pairs, each evenly spaced about the periphery of the cylinder-shaped LES-6 vehicle and parallel to the vehicle axis. Each dipole element is space $\lambda/8$ at the transmit frequency above a slot element. The dipoles provide the axial component of a circularly polarized wave, and the slots provide the circumferential component. A 90-degree phase difference is provided in the feed network.

The radiated beam from the array is despun by alternately exciting adjacent pairs of feed elements. The switch network (Figure I-13) is used for this purpose. The beam produced by any two adjacent elements can be steered to one of two directions by adjusting the relative phase of excitation of the two elements: the phase of one element can be made to lead or lag the phase of the other by 90 degrees by selection of the 2P 2T switch setting. The total number of switched beam positions is thus 16. The relationship of feeds and beam direction is shown in Figure I-14.

Another of the more sophisticated satellite phased arrays is used on the Synchronous Meteorological Satellite (SMS) developed by FACC. The characteristics of this electronically despun antenna are summarized in Figure I-11. Thirty-two columns of Yagi-Uda array elements, dual tuned to UHF and S-band, are equally spaced around the periphery of the cylindrical spacecraft, Figure I-15. The S-band beam is despun by using the variable power dividers (Figure I-16) to gradually shift power from the beam leaving earth to the beam approaching earth. For example, as the satellite spins, variable power divider Number 1 gradually transfers power, at the appropriate time, from Element 1 to Element 5 then to Element 9 then to Element 13, etc. Likewise, variable power divider Number 2 gradually transfers power, at the appropriate time, from Element 2 to Element 6 then to Element 10, etc. The gain and phase at various pointing angles, α, from nadir versus scan (rotation) angle is shown in Figure I-17. The UHF beam is also despun, but by simply switching to the odd-numbered elements pointing closest to earth. Several fixed-beam arrays have been flown on various satellites. The characteristics

Program/Sponsor	Manufacturer	Description	References
LES-6	Lincoln Laboratory	Freq: ~250 MHz TX ~300 MHz Rc ~255 MHz Beacon Gain: Scan Mode 8.4 to 10.2 dB Peak 6.9 to 8.6 dB, $\pm 9^\circ$ Gain, Omni Mode: -.7 dB to -2.8 dB Half-Power Beamwidth: Scan Mode: $\approx 30^\circ$ Omni Mode: $\approx 35^\circ$ x 360° Array Type: 8 Colinear Pairs of Slots Plus 8 Colinear Pairs of Dipoles About Periphery, Periphery, Fed in Quadrature Feed Network: Separate Switch Network for Slots and Dipoles; Two Elements at a Time, Scan Mode; All Elements, Omni Mode.	Lincoln Laboratory Tech Report 451
Synchronous Meteorological Satellite, SMS	FACC	Freq: S-Band, 1700 MHz Tx and 2000 MHz Rc, UHF 468 MHz Tx, and 402 MHz Rc Gain: 18.5 dB at 1687 MHz Half-Power Beamwidth: $\approx 20^\circ$ (S-Band) Array Type: 4 x 32 Element-Belt Around Satellite, 4 Elements on at a Time; Every Other Element Operates at UHF Feed Network: S-Band, Corporate Network of Switches and Variable Power Dividers, UHF, One Element Switched on at a Time Element Type: Double-Tuned, 4-Element Yagi-Uda Array	F. J. Dietrich Article

Figure I-11. Steerable Phased Array Antennas - In-Orbit

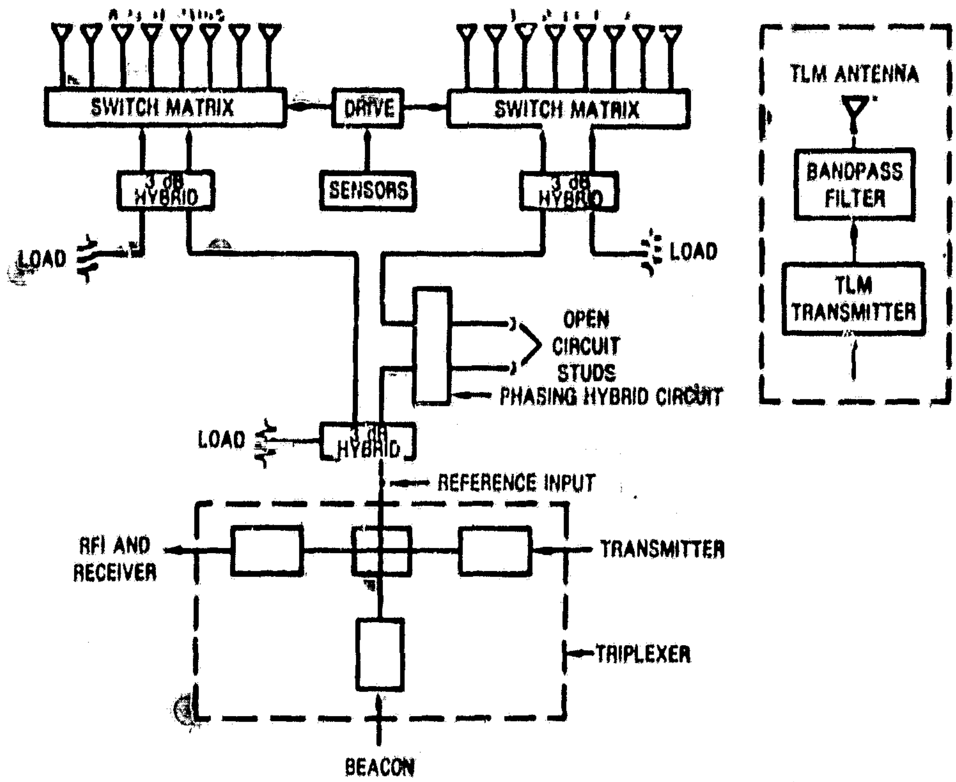


Figure I-12. LES-6

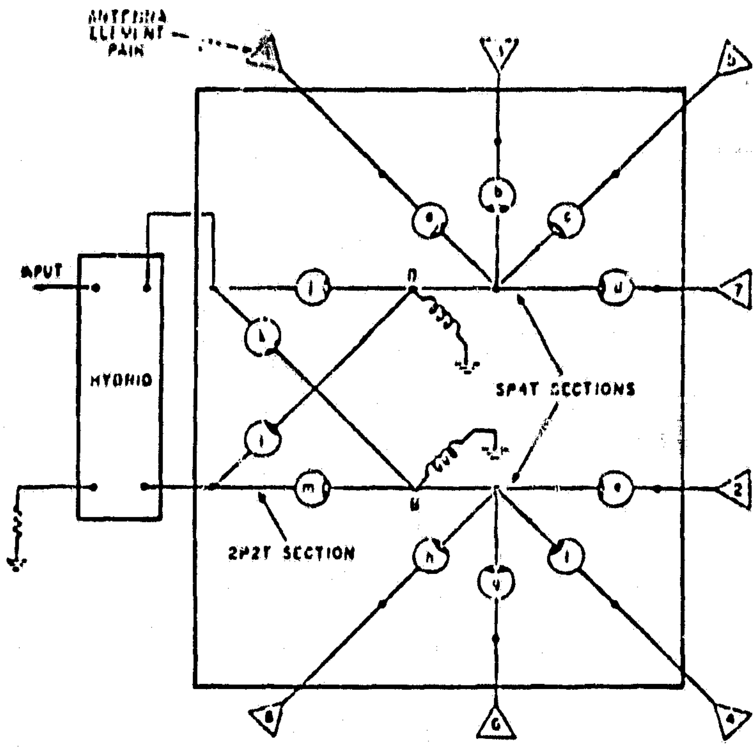


Figure I-13. Switch Matrix and Details as Given in a SPST Unit

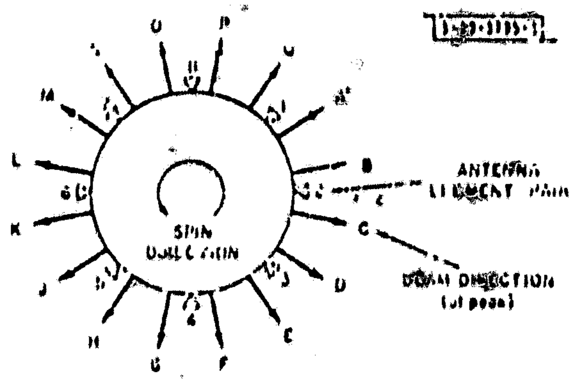


Figure I-14. Radiation of Beam Directions to Antenna Positions

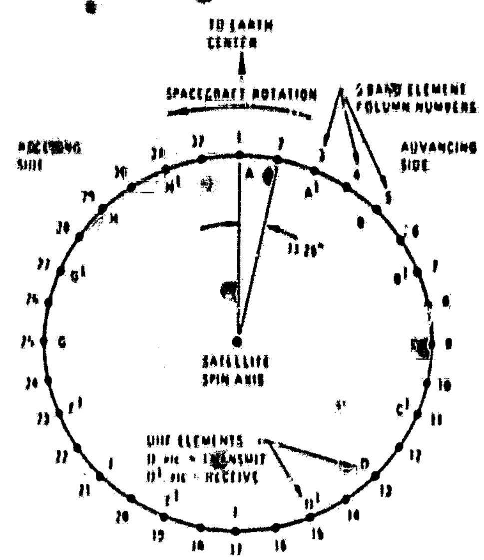


Figure I-15. Array Geometry

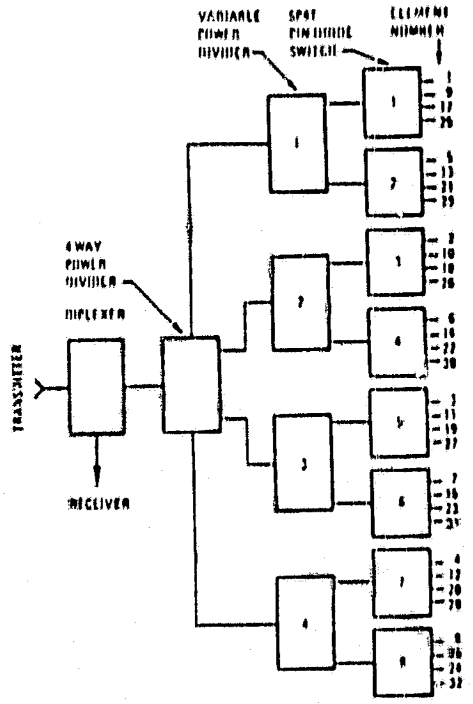


Figure I-16. Synchronous Meteorological Satellite

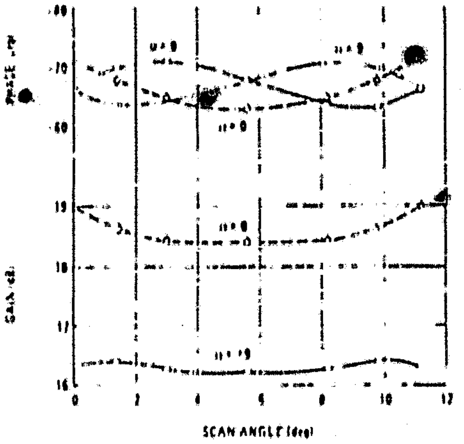


Figure I-17. Calculated Gain and Phase Ripple for Amplitude-Steered Array at 1687 MHz with Equal Earth Edge Gains of these are given in Figure I-18. The arrays on NATO III and Skynet II, both developed by FACC, are essentially the same, except for the number of elements.

Ball Brothers has recently developed a large L-band phased array for SEASAT. The characteristics of this array, made up of 8 panels which fold together fc , launch, are summarized in Figure I-19. This array has very good efficiency. A gain of 34.9 dB has been measured, which is only 2.1 dB less than the theoretically perfect gain, for this size aperture (i.e., 3 dB).

2. TECHNOLOGY LIMITS OF PHASED ARRAYS

No commonly recognized technology limits which define ultimate performance are known; however, practical limits for a given application do exist. A description of each follows.

- The numbers of elements and associated hardware represent the most usual limitations of phased arrays. To illustrate this limitation, Figure I-20 lists the comparatively large number of elements which would be required for various sizes of K-band arrays.
- The ultimate gain of a subarray fed from any single amplifier is limited by loss in the feed system. This is illustrated in Figure I-21, where gain vs. side dimensions of a square K-band array is given. As the array dimensions increase, the length of feedline and associated insertion-loss, increases accordingly. In Figure I-21, the array gain is decreased by the insertion loss of RG-12U aluminum waveguide plus 1 dB of miscellaneous losses. The length of feedline equals $(\ell + w) \div 2$ where ℓ equals one dimension of the array and w equals the other dimension. For the square array of Figure I-21, ℓ equals w.
- Uncompensated aperture distortions as well as phase errors in the feed system limit the ultimate achievable gain.
- Amplitude unbalance in the feed system limits ultimate gain.

3. TECHNOLOGY OPPORTUNITIES OF PHASED ARRAYS

To advance the state-of-the-art of phased array antennas, the following programs are suggested. Each program is briefly described,

Program/Sponsor	Manufacturer	Description	Reference
NATO III	FACC	Freq: 2.22 GHz Tx 1.78 GHz Rc Gain: -7 dB Beamwidth - Near Omni Polarization: RHCP Type: 64 Cavity-Backed Flat Turnstile-Element Array Weight: 10.4 lbs, Array and BFN	
OSO	Ball Brothers	Freq: 136 MHz Tx 149 MHz Rc Pattern: Omni	B. B. Data Sheet
Atmosphere Explorer	Ball Brothers	Freq: 2289.5 MHz Tx 2108.25 MHz Rc Pattern: Omni	B. B. Data Sheet
Apollo-Soyuz Test Project	Ball Brothers	Freq: 162 and 324 MHz Beamwidth: 70° Gain: 7 dB Typical	B. B. Data Sheet
Canadian Communications Technology Satellite	Ball Brothers	Freq: S-Band Pattern: Omni	B. B. Data Sheet
SKYNET II	FACC	Freq: 2.24 MHz, Tx 1.795 MHz, Rc Gain: ≥ -7 dB Beamwidth: ±75° x 360° Polarization: RHCP Type: 54 Cavity-Backed Flat Turnstile-Element Array Weight: 9.7 lbs	

Figure I-18. Phased Array Antennas - In Orbit

Program/Sponsor	Manufacturer	Description	Reference
SEASAT	Ball Brothers	Freq: 1275 ± 11 MHz Gain: 35 dB Half-Power Beamwidth: ≈1.5° x 6.4° Array Type: 16 x 64 Element Micro-strip Array, Made Up of 8 Each 8 Ft. x 4.5 Ft. Panels which Fold Together for Stowage Feed Network: Corporate Structure, 4 Feed-Points Per Panel .6 dB Loss, Input to Panel .2 dB Loss, Panel to Element Input VSWR: <1.8:1	R. Munsen

Figure I-19. Phase Array Antennas - Space Qualified

Side Dimension Feet	Number of Elements
1	1,849
5	43,681
10	173,889
50	4,322,241
100	17,272,336
150	38,862,756
200	69,089,344

Figure I-20. Numbers of Elements vs Array Dimension Half-Wavelength Spacing at 20.45 GHz

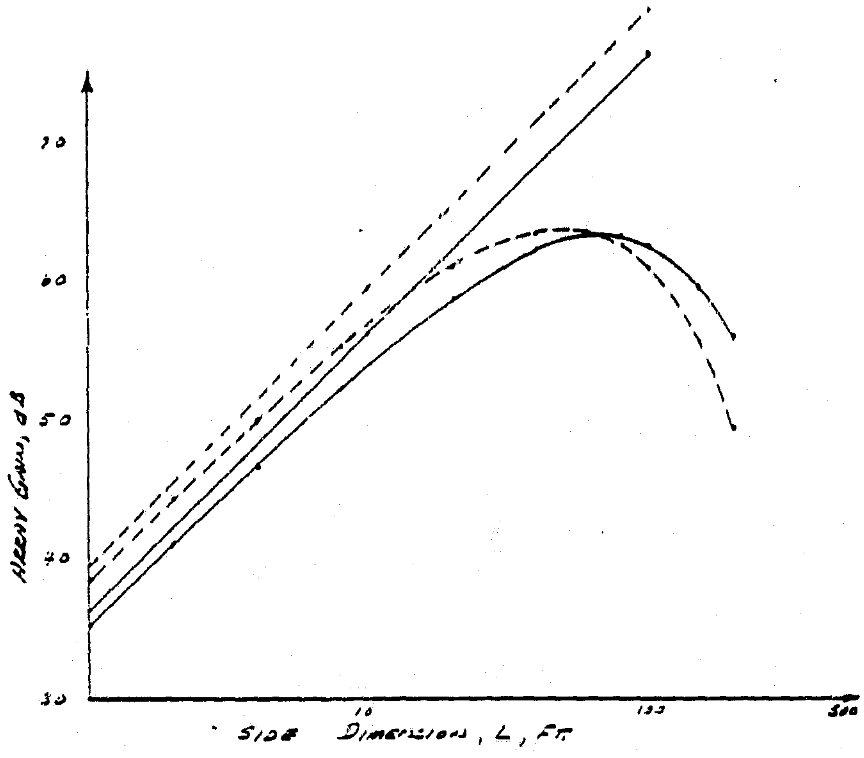


Figure I-21. Gain vs Side Dimension of Uniformly-Illuminated Square Waveguide Array and the tasks necessary to conduct it are delineated. Basically, what is desired is to advance the technology of:

- MIC power amplifiers.
- Low-noise amplifiers.
- Phase control and time-delay control networks.
- Integrated phased array systems.

a. Microwave Integrated Circuits for Communications Satellite Applications at Ku Band

(1) Background

The potential performance capabilities of multiple-beam antennas and of phased arrays in general are not being exploited as they should be. One of the major reasons for this is the lack of suitable microwave components needed for antenna control.

As in optics, multiple-beam antennas utilizing a focusing aperture require a beam-forming network to control distribution of power to the various feed elements. In general, for each independent beam (beams which transmit different information), a separate beam-forming network is required. Each beam-forming network normally contains one less variable power divider than the number of feed elements. Each variable power divider of the DSCS III type contains two phase shifters. Hence, a very large number of phase shifters may be needed for a single multiple-beam antenna. Small size of the phase shifters is therefore essential.

Substantial insertion loss is expected in a beam-forming network containing many variable power dividers. Perhaps the most practical way to overcome the effects of this loss is to amplify a transmit signal after transmission through the beam-forming network, and amplify a receive signal before transmission through the beam-forming network. If this approach were followed, then large numbers of power amplifiers for transmitters and large numbers of low-noise amplifiers for receivers would also be needed for systems of expanded capability.

(2) Design of Suitable Microwave Components

a. Task 1. Formulate designs for microwave integrated circuit (MIC) phase shifters operating over the bands of 19.7 to 21.2 GHz and of 29.5 to 31 GHz. Each should provide at least 180 degrees of phase shift adjustment with 6-bit resolution and with insertion loss independent, within .1 dB, of phase setting. Insertion phase must also be independent of frequency to within a few degrees. Separate designs are permitted for each frequency band. Consideration should also be given to size, weight, reliability, lifetime, rf efficiency, dc efficiency (of control power), setting accuracy, insertion loss, and cost.

Five prototypes should be provided and complete design documentation, including descriptions of computer programs, developed under this contract.

b. Task 2. This task is a repeat of Task 1, except that a constant time-delay device is required. At least one-half wavelength of time-delay adjustment, with 6-bit resolution, is required. The setting must be independent of frequency, over the bands defined in Task 1, to within 1 percent of a wavelength.

c. Task 3. Designs should be formulated for a MIC power amplifier to operate over the frequency range of 19.7 to 21.2 GHz. The device should provide a gain of at least 20 dB with an output power level of 2 watts at the 1-dB compression point. The dc to rf efficiency should be at least 10 percent. Design emphasis should also be given to achieving a flat gain response, small size, low weight, high reliability, long lifetime, high gain stability, and low cost.

Five prototypes should be provided and complete design documentation, including descriptions of computer programs developed under this contract.

d. Task 4. Formulate designs of a MIC low-noise preamplifier to operate over the frequency range of 29.5 to 31.0 GHz. The preamplifier should have a noise figure of under 6 dB and provide a small signal gain of 30 dB. Output power should be at least 5 mw at the 1-dB compression point. The difference in insertion phase between any two units should be no more than 5 deg over a dynamic range of at least 60 dB. Design emphasis should also be directed towards the achievement of low weight and size, high reliability, long lifetime, low IM generation, flat gain response, and low cost.

Five prototypes should be provided and complete design documentation, including descriptions of computer programs developed under this contract.

(3) Estimated Time and Cost

The estimated time is 12 man-months and approximate cost is $300K for each of the tasks.

(4) Candidate Contractors

The candidate contractors are Hughes, RCA, Watkins-Johnson, Aertech, Avantec Amplica, and Hewlett-Packard.

b. <u>An Integrated Phased Array System</u>

(1) Background

Phased array antennas have the potential for providing generally excellent performance as well as good flexibility for communication satellites. They can form fixed low-sidelobe beams, electronically steerable beams, shaped beams, or multiple beams. The theory of arrays is well developed. However, phased array antennas are seldom used for satellite systems, primairly because of the very large number of parts required in an array, and the resulting weight and complexity.

Integration of an entire phased array system perhaps on a single or double-layer printed circuit board offers a viable solution to this drawback.

(2) Design of an Integrated Phased Array System for Communication Satellites

a. <u>Task 1</u>. Design a .5-meter square phased array to operate over the frequency range of 29.5 to 31.0 GHz. It must provide a beam capable of being steered anywhere within a solid angle of ±9 deg, and it must provide a G/T of TBD. The amplitude transfer characteristic must be linear to within 5 percent over a dynamic range of TBD. Sidelobes must be at least 30 dB below peak of the main beam when the beam is pointed anywhere within the required ±9 deg. Linear polarization with cross-polarization components down by at least 30 dB is required.

A goal is to package the entire phased array system on a single two-sided printed circuit board. The system is considered to include array elements, feed system, beam steering-control devices, and low-noise amplifiers. Chip packages of integrated circuit and semiconductor devices should be used where possible.

The integrated phased array system shall be designed to operate over the temperature range of TBD.

b. Task 2. Build and test one feasibility model of the integrated K-band phased array system. Tests shall be sufficient to completely characterize performance over the entire specified temperature range.

Deliverables include the antenna model, monthly oral status presentation, a complete and comprehensive final report, engineering sketches, and a description of the code of any computer program developed under this contract.

(3) Estimated Time and Cost

The estimated time is 8 man-months and the estimated cost is $200K for each task.

(4) Candidate Contractors

The candicate contractors are Ball Brothers, Hughes Ground Systems Group, General Electric Space Division, and TRW System Group.

C. LENSES

1. INTRODUCTION

Interest in microwave lenses for satellite applications has increased tremendously during the past few years, primarily as a result of the advent of multiple-beam antennas (MBA) for space communications. Popular MBA configurations require many feeds (i. e., one per beam). While many feeds result in severe blockage in a normal center-fed reflector antenna, they present absolutely no problem when a lens is used, since blockage is no longer involved. MBAs must radiate beams at large scan angles to cover large fields-of-view. Unfortunately, as the scan angle increases for center-fed or offset-fed parabolic antennas, the beam shape is degraded. Certain types of lenses provide the capability to accomplish unlimited scanning with very low beam distortion. A Luneburg lens is an example of such a lens.

Unfortunately, the design technology of microwave lenses suitable for satellites application is immature. Most lenses capable of providing wide-angle scanning, such as the Luneburg lens, are heavy. Others provide scanning in only one plane. Broadband lenses, such as the bootlace, are typically heavy and provide limited scan capabilities. Structurally attractive devices such as waveguide lenses have limited bandwidth capability and provide relatively poor scan characteristics. It appears that a combination of some but not all of the desirable characteristics of good scan, good structure, deployability, good bandwidth, and high efficiency can be found in at least one of many types of lenses known; however, no lens is known which has the desired combination of all.

As a consequence, many opportunities exist for advancing the technology of lens design. The most significant of these are described below.

- Lenses with bandwidths on the order of 5 to 10 percent are required for current and next generation communication satellites; lenses with bandwidths of up to 38 percent are expected to be needed for future-generation systems. These bandwidths are not defined in the usual sense; rather they are bands over which good polarization characteristics and low sidelobes can be maintained, for frequency reuse.
- Satellite-compatible lens designs are required for scanning beams up to 50 beamwidths from the antenna axis without excessively degrading either beam shape or polarization characteristics.
- Good structural characteristics of ruggedness, light-weight, low distortion, deployability, and reliability are required.
- Reasonable cost is necessary.

2. STATE-OF-THE-ART OF LENSES

No microwave lens is known that has either been flown on a satellite, or has yet, in fact, been space qualified. However, the DSCS III satellite which has on it two transmit waveguide lenses and one receive waveguide lens is currently undergoing space qualification with firm plans for launch during 1979. A summary of characteristics of these lenses (each lens forms part of a multiple-beam antenna) is shown in Figure I-22 and a picture of the DSCS III satellite, with lenses, is shown in Figure I-23. Engineering models of both types of lenses have been built, and their performance and structural characteristics thoroughly and successfully tested.

Each of the DSCS III lenses is zoned (i.e., stepped) waveguide type. The steps of the transmit lens are positioned so as to achieve minimum weight, and the steps of the larger receive lens are positioned to maximize bandwidth. The resulting shape of the receive lens is convex.

Spacecraft	Manufacturer	Characteristics	Reference
Rc MBA/DSCS III	General Electric Space Division	Dia.: 45 in. F/D: 1 Wt.: 40 lbs Oper. Freq.: 7.95-8.32 Type: Waveguide, Phase Compensated W.G. ID: .927 in. sq. No. Zones = 7 Polarizations Independent	Aerospace General Electric
Tx MBA/DSCS III	General Electric Space Division	Dia.: 28 in. F/D: 1 Wt: 8.54 lbs Oper. Freq.: 7.25-7.59 Type: Waveguide, Minimum Weight W.G. ID = 1.029 in. sq. No. Zones = 2 Polarizations Independent.	Lincoln Laboratory

Figure I-22. Lenses, Firm Plans for Launch

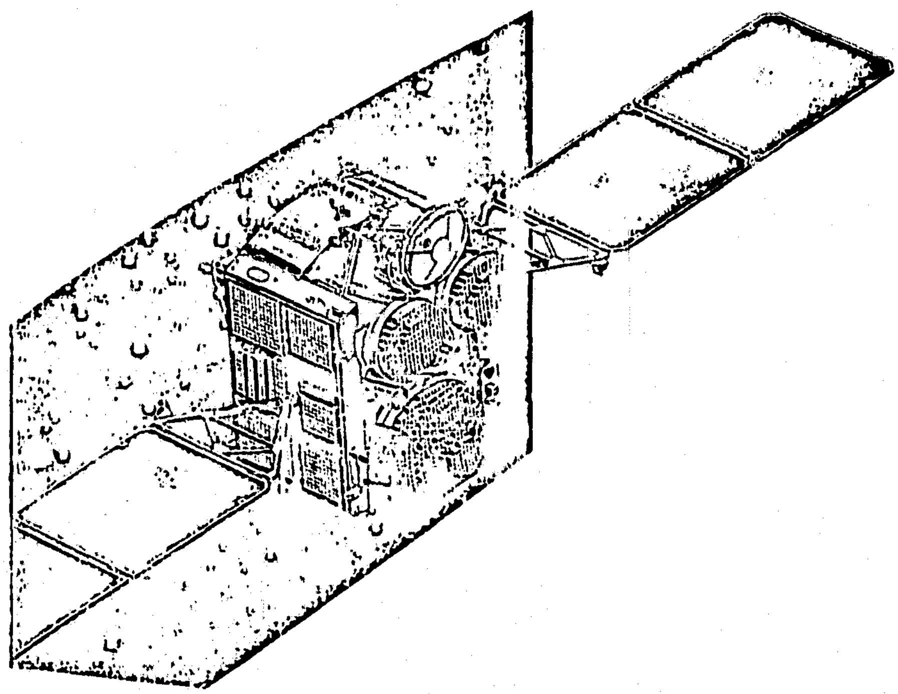


Figure I-23. DSCS III Satellite

A forerunner of the DSCS III lenses is the waveguide lens developed for LES-7 by Lincoln Laboratory. A summary of characteristics of this lens is given in Figure I-24 and a photograph of it is presented in Figure I-25. This lens also forms part of a multiple-beam antenna; the multiple feeds, each of which forms a separate beam, can be seen in the figure. The LES-7 lens was designed for minimum weight by positioning each step so that minimum lens thickness required for structural integrity remained after each step "flyback". This lens was thoroughly tested and shown to provide excellent performance; however, a model has neither been space qualified nor flown.

Hughes Aircraft Ground Systems Group has developed a waveguide lens consisting of stacked sections of circular waveguide with a half-wave plate phase shifter inserted in each guide. By properly combining phase shifts due to the half-wave plates with those due to insertion delay of the waveguides, Hughes has designed a very wide band waveguide lens. A summary of characteristics of this lens is given in Figure I-24 and a picture of it is shown in Figure I-26. The swirling effect over the face of the lens results from the systematic orientation of half-wave plates.

Ford Aerospace and Communications Corporation has developed and tested two models of a dual-band transverse electromagnetic bootlace, lens. The dual bands are at 4 and 6 GHz. Each lens consists of an array of orthogonal pairs of printed-circuit cards. Each printed-circuit card has photoetched on it two slot radiator feed-elements, one at each end, connected by a serpentine transverse electromagnetic line of prescribed electrical length. The first lens model made is 5 feet in diameter and contains 397 orthogonal feed pairs. Though it provides good performance, tests indicated that smaller size lens elements would provide better performance. Thus, smaller size lens elements were subsequently used for the second lens model, which is 3 feet in diameter and contains 367 orthogonal pairs of elements. The characteristics of this lens are provided in Figure I-24 and a photograph of it is shown in Figure I-27. Measurements of the performance reportedly showed that beam-to-beam isolation of 27 dB is feasible over 500-MHz bands at 4 GHz and at 6 GHz.

In the early 1970s, Rockwell developed a lens to provide a single beam for radar applications. The lens is a constrained, or bootlace, type, which provides focussing by means of true time-delay elements. It consists of an array of slots on each lens surface, with each pair of opposing slots interconnected by a printed-circuit delay line of proper electrical length. The delay lines were computed and plotted under computer control, so that no manually generated drawings were required.

Program/Sponsor	Manufacturer	Characteristics	Reference
LES-7	Lincoln Laboratory	Dia: 30 in. F/D: 1.0 Wt: 7 lbs Oper. Freq.: 7.68 GHz. Type: Waveguide, Min. Weight Type W.G. ID = 1.0 in. sq. N. Zones = 3 Polarization Independent Matl: Titanium	Lincoln Laboratory AD BM Potts
Company	Hughes Aircraft Ground Sys. Group	Dia: 46 in. F/D: 1.56 Oper. Freq.: 7-9 GHz Type: Waveguide Lens, Equal Group Delay W.G. ID: 1.061 in. dia.	HAC Ajioka Article
Comsat Labs.	Ford Aerospace	Dia.: 3 ft Wt: (40.59 lbs Projected for 5-ft dia. Flt Mod) Oper. Freq.: 3.7-4.2 GHz: 5.9-6.4 GHz Type: Bootlace with 367 Printed Circuit Elements Polarization: Independent	Comsat Rept Ford, MBA for Data Comm Sats
USAF	Rockwell	Dia.: 28.7 F/D: .36 Wt.: (30 lbs Projected for 44.5-dia. Lens w/F/D = 1) Freq: 8.7-10.2 GHz Type: Constrained (Bootlace) Polarization: Linear	Rockwell Rept. No. T75-469/ 034A

Figure I-24. Microwave Lenses - Laboratory Demonstration Models

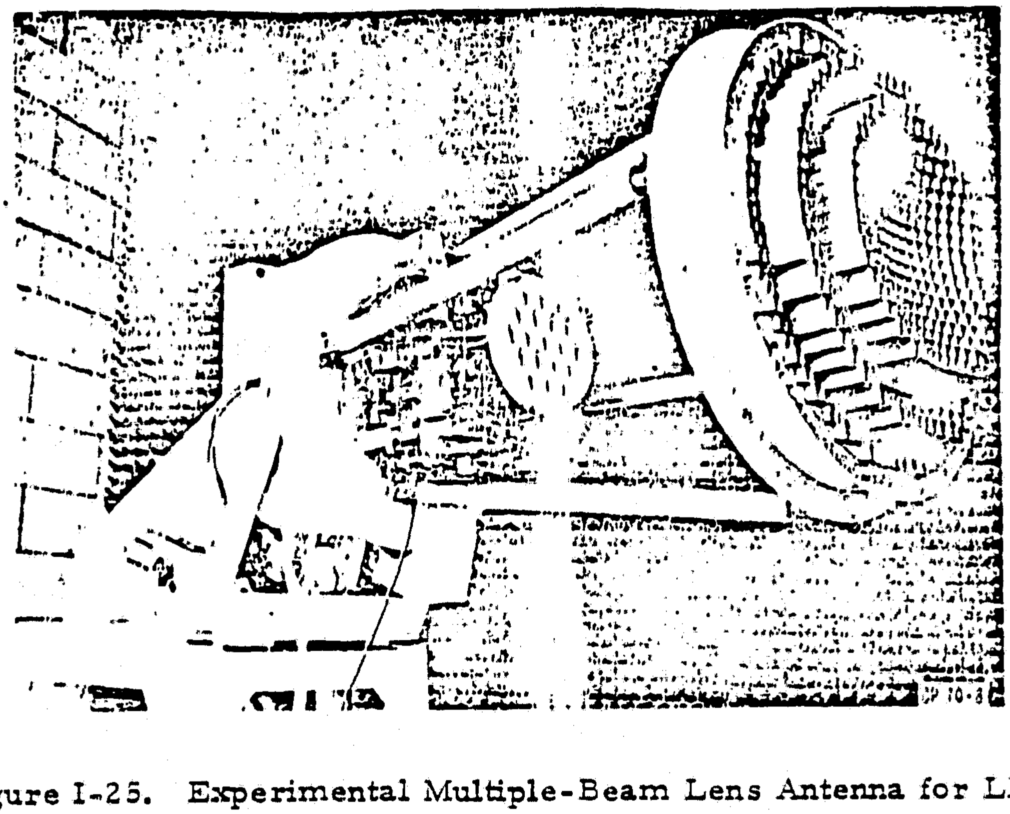


Figure I-25. Experimental Multiple-Beam Lens Antenna for LES-7

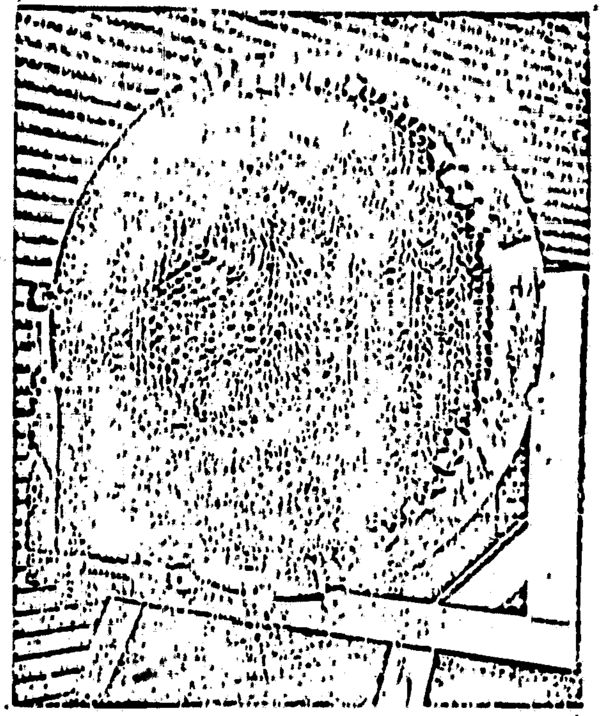


Figure I-26. X-Band Equal-Group-Delay Lens (Hughes Ground Systems Group)

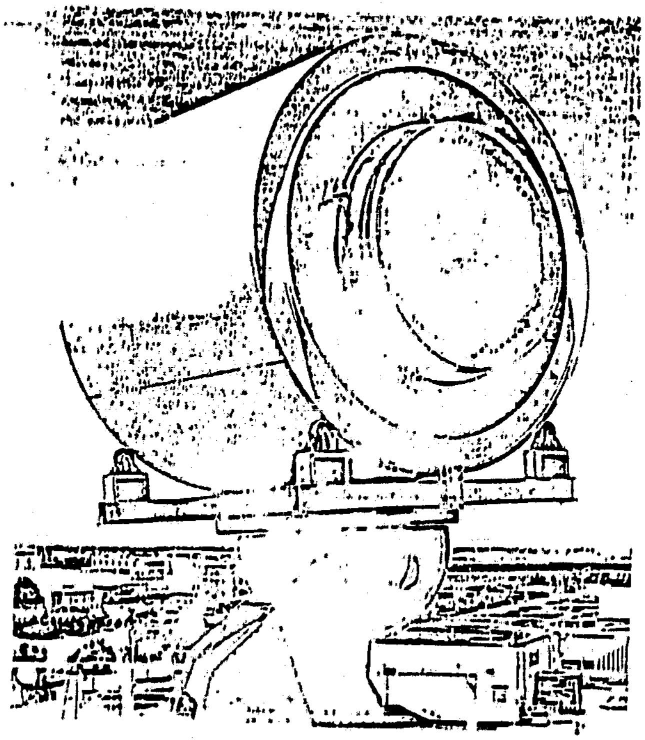


Figure I-27. FACC Transverse Electromagnetic Lens

Design goals of wide bandwidth and low sidelobes were achieved. A summary of characteristics of this lens is given in Figure I-24, and a photograph of the lens is shown in Figure I-28.

Examples of additional satellite-oriented lens development carried out during the past few years are summarized in Figure I-29. General Electric, LMSC and TRW have each built models of and tested metallic delay lenses of the general type built by Kock at Bell Labs (Figure I-30). It is believed that only limited success was achieved by any of the workers, primarily because of the anisotropic characteristics of the artificial dielectric material, which is composed of a periodic arrangement of flat metallic dots. The University of Illinois Electromagnetics Laboratory analyzed, in depth, the performance of such an artificial material and may have arrived at a solution of the anisotropic problem; however, their theoretical work has yet to be experimentally verified. The Space and Communications Group of Hughes Aircraft Company has done extensive work on helix lenses consisting of helix-element arrays on each lens surface; with back-to-back pairs interconnected by lengths of transverse electromagnetic line. All elements on one face are wound with one sense (clockwise or counterclockwise), and all elements on the opposite face are wound with the opposite sense. Focussing is achieved by adjusting the rotational orientation of each of the interconnected back-to-back helix pairs. The Ground Systems Group of Hughes has, in addition to developing the broadband lens whose characteristics were summarized earlier, built and tested a number of other types of waveguide lenses, operating at the uplink military communication band (i.e., 7.9 to 8.4 GHz). Ball Brothers is developing a printed circuit lens and has reported that initial measurements indicate successful performance (design details of this lens are proprietary). Grumman Aircraft has built sections of a so-called wire-wheel active bootlace lens to demonstrate mechanical feasibility; however, so far as is known, neither have active elements been incorporated nor electrical performance been measured.

3. TECHNOLOGY LIMITS OF LENSES

Because serious interest in lenses for satellite application is recent, the design technology of such lenses is very immature (as compared to a center-fed parabola whose design technology is very mature), and obvious technology limits are not well documented. However, general technology limits can be identified with reasonable accuracy. A summary of technology limits, on this basis, follows.

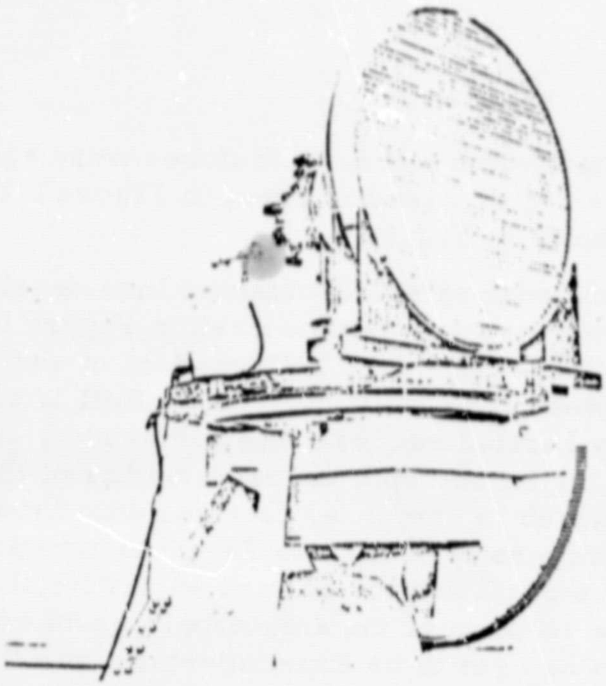


Figure I-28. Constrained Lens Mounted for Pattern Tests (Rockwell Electronics Group)

Company/Agency	Activities	Reference
General Electric, Space Systems Division	Limited Development and Test of Metallic Delay Lens Covering 7.2-8.4 GHz	A. Horvath
LMSC	Limited Development and Test of Metallic Delay Lens and Waveguide Lens Operating at 7.2-8.4 GHz	G. Chadwick
TRW Systems	Limited Development and Test of Metallic Delay Lens Covering 7.2-8.4 GHz	J. Duncan
University of Illinois	Theoretical Analysis of Metallic Delay Lenses	Y. T. Lo
Hughes Aircraft Space and Comm. Group, and Ground Systems Group	Limited Development and Test of Constrained Lens Using Helix Elements and of Various Types of Waveguide Lenses Operating at 7.2-8.4 GHz	D. Nakatani J. Ajioka
Ford Aerospace	Development and Test of 5-Foot Bootlace Lens Operating at 4-6 GHz, Similar to 3-Foot Model Described Earlier.	W. Scott
Ball Brothers	Initial Design and Test of Printed Circuit Lens	R. Munson
Grumman Aerospace	Conceptual Design and Partial Construction of Wire-Wheel Active Bootlace Lenses of 30-3000 Meter Diameter	Grumman Ref's

Figure I-29. Microwave Lenses - Additional Activities

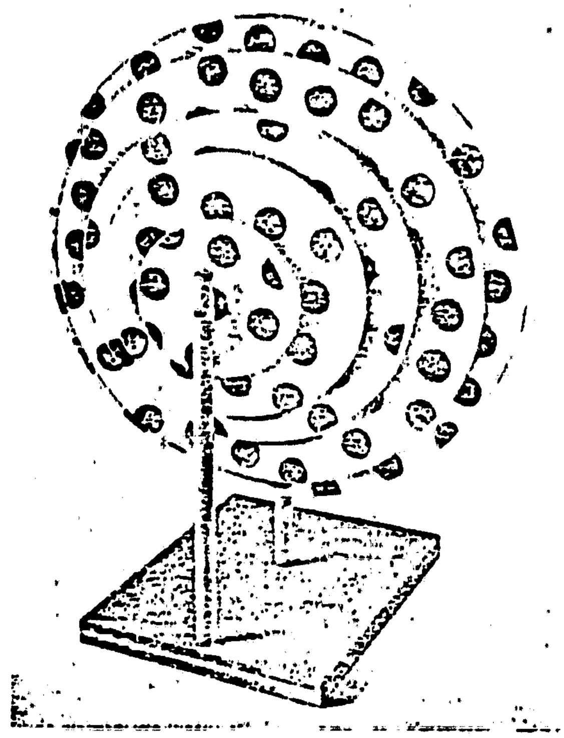


Figure I-30. Kock Lens (Bell Labs)

- Overall lens efficiency should equal and perhaps exceed the efficiency of a center-fed reflector. Although a lens has additional transmission loss, it has zero blockage loss and less sensitivity to surface inaccuracies. A graph comparing electrical phase error (which results in efficiency loss) of lens position/warpage and parabolic surface error is shown in Figure I-31.
- A lens should provide much better beam-scan characteristics than a center-fed reflector, because a lens has more degrees of design freedom.
- The ultimate weight of a lens is expected to exceed that of a reflector because the lens necessarily has greater thickness.
- The complexity of the deployment mechanism of a lens is expected to approach that of a center-fed reflector, once the maturity of lens deployment mechanisms reaches that of reflector deployment mechanisms.

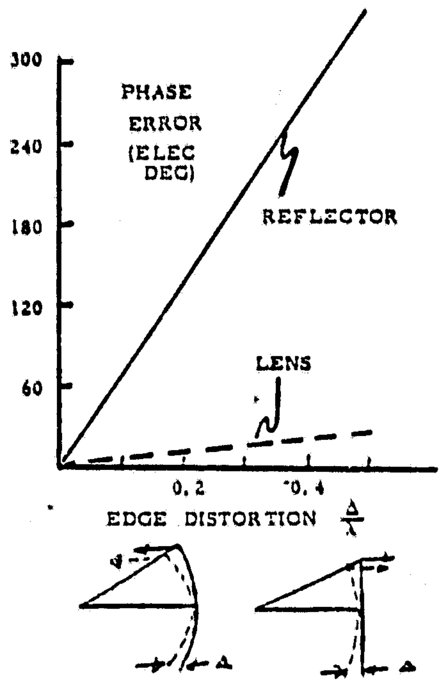


Figure I-31. Electrical Phase Error as a Function of Quadratic Edge Distortion (Edge Angle = 30°)

4. TECHNOLOGY OPPORTUNITIES OF LENSES

Because the state of design of lenses for use on satellites is very immature, a great number of opportunities exists for expanding the present state-of-the-art. Those opportunities having the greatest chance for substantial payoff follow.

- Establish lens designs that are capable of providing beams that maintain good characteristics when scanned up to 50 beamwidths off-axis and when operated over a 10-percent bandwidth. The first few sidelobes, including coma lobe, are to be maintained below 27 dB; sidelobes more toward the edge are to be maintained below 35 dB. Cross polarization components are to be maintained below 30 dB.
- Develop computer programs that can economically compute beam shapes from the leading lens candidate designs. Apertures up to 1000 wavelengths should be addressed. Program accuracy should hold for beams scanned up to 50 beamwidths, but no more than 9 deg, off-axis. The program should also accurately predict relative levels of the first few sidelobes as well as main beam gain.
- Develop mechanical designs, of the leading lens candidates that are deployable as well as otherwise suitable for use on satellites.

The characteristics of weight, design, ruggedness, reliability, and ratio of deployed-diameter-to-stowed volume must be considered.

A sample program covering preliminary efforts in connection with the above opportunities is provided in the following paragraphs. It is likely that many such tasks will be necessary before the maturity of lens design reaches the present-day maturity of parabolic reflector design.

a. <u>Lens Design for Five-Foot Diameter, 30 GHz, Multibeam Antenna for Satellite Applications</u>

(1) Background

Efficient frequency reuse utilizing spatial isolation is possible at frequencies above 20 GHz if sidelobes can be kept about 30 dB below beam peak. Center-fed reflectors cannot satisfy the sidelobe requirement because of blockage and coma. However, center-fed lenses provide a symmetry that gives them an advantage both in electrical performance and in mechanical convenience. The fact that a single lens has two surfaces provides an advantage over a single reflector in that an added parameter is available to the designer. The traditional problem with lenses for satellites has been weight. As frequencies become higher and with the advent of the Shuttle, this disadvantage is somewhat reduced.

(2) Design Study for Five-Foot Diameter Lens Satellite Antenna for 30 GHz

a. <u>Task 1</u>. Investigate alternative design approaches including but not limited to real dielectrics, artificial dielectrics, waveguide lenses, and bootlace lenses (passive and active).

b. <u>Task 2</u>. Investigate methods of controlling coma lobes and sidelobes, the methods including but not limited to primary pattern control, choice of F/D, control of amplitude across aperture by resistive loading in lens, selection of lens surfaces to improve off axis performance (e.g., Abbé sine condition), surface matching techniques.

c. <u>Task 3</u>. Select and justify a preferred design based on performance, size, weight, development risk, and long-term cost.

d. Task 4. Propose a hardware program leading to an experimental demonstration of flight type equipment.

(3) Estimated Time and Cost

The estimated time is 9 months and the estimated cost is $400K.

(4) Candidate Contractors

The candidate contractors are Ford, Hughes, TRW, General Electric, Lockheed MSC, and Rockwell.

D. MULTIPLE-BEAM ANTENNAS

1. INTRODUCTION

The multiple-beam antenna (MBA) has recently become of great interest for communication satellite applications. Since they form multiple beams from a single aperture, the phase and amplitude of each beam can be independently controlled, leading to the following characteristics:

- Conservation of radiated power by shaping beam contours to cover only a defined region;
- Interference rejection by means of turning off any beams pointing in the direction of interfering sources;
- Frequency reuse by feeding each beam independently;
- In-orbit reconfiguration by utilizing ground commandable amplitude and phase-control elements; and
- Beam steering, one of the by-products of in-orbit reconfiguration.

Because the interest in MBAs is recent, the technology is immature and the opportunities for advancing the state-of-the-art extensive. Those opportunities having the greatest probability of substantial payoff follow.

- New types of lenses and reflectors that maintain well-shaped beams at large scan angles. It is important to note that these scan angles are ordinarily large in terms of the number of half-power beamwidths scanned but not in terms of absolute angle. For a synchronous satellite, scan angles are no greater than the earth-disk field-of-view, ±9 deg. The lenses and reflectors must have structural characteristics that are compatible with satellite environment and, if of large diameter, they must be deployable.

- Miniature and efficient beam control devices. These include adjustable power distribution networks (variable power dividers) and adjustable phase control networks.
- MBA system design technology advancements. The relationship between beam crossover level, pencil beam efficiency, broad coverage gain ripple, and null characteristics needs to be better understood so that optimum system tradeoffs can be made.
- Techniques for achieving desired isolation between independent beams in frequency reuse systems. These are needed to more fully exploit the frequency reuse capability.

The advances in design technology of lenses, reflectors, and rf components are identified in other sections of this report. The MBA system design technology is unique to this section.

2. STATE-OF-THE-ART OF MBAs

A review of the characteristics of most multiple-beam antennas that have flown, are being developed, or are the subject of research programs is presented in this section. Most of the earlier MBAs have very little if any flexibility and simply provide shaped contour converage. Later models, however, have the flexibility necessary for in-orbit reconfiguration. The frequency reuse capability, also not present in early models, is evident in later models of commercial satellites.

The Telesat and ANIK satellites developed by Hughes used MBAs to form shaped beams. No capability for frequency reuse nor in-orbit reconfiguration is provided. A summary of the antenna characteristics is given in Figure I-32 and the satellite itself is depicted in Figure I-33. Westar is similar to Telesat except for the coverage region--Westar covers CONUS, Alaska, and Hawaii; Telesat covers Canada.

Comstar and Intelsat IVA, developed by Hughes, also provide shaped coverage through the use of multiple beams. In addition, these two satellites provide frequency reuse as well as the capability for limited in-orbit reconfiguration. Pictures of the two satellites are shown in Figures I-34 and I-35, respectively.

Program/Sponsor	Manufacturer	Description	Reference
Telesat (Anik)	Hughes Space and Comm Group	Freq: 6 GHz Rc; 4 GHz Tx Sector Gain: 32 dB Rc; 28 dB Tx (estimated) Max Scan: ≈1 Beamwidth Type Antenna: Offset-Fed Parabola Polarization: Vert Lin Rc; Horiz Lin Tx Freq. Reuse: None Coverage: Shaped to cover Canada Refl. Diam.: 60 in. Focal Length: 30 in. Reconfigurability: None Refl. Const.: Mesh on Open Frame No. Beams/Horns: Three, Common for Tx and Rc	HAC, DA of Comm Sat Ant
Westar	Hughes Space and Comm Group	Same as for Telesat (Anik) Except: Coverage: Shaped to cover Conus, Alaska, Hawaii No. Beam/Horns: Four, Common for Tx and Rc Sector Gain: 31 dB Rc; 27 dB Tx (estimated)	HAC, DA of Comm Sat Ant
Comstar, *Vertically-Polarized Shaped-Beam Ant.	Hughes Space and Comm Group	Freq: 3720-4160, Tx; 5945-6385, Rc Sector Gain: 24.5 dB Type Ant: Offset-Fed Parabola Polarization: Vertical Linear Freq. Reuse: Yes, with 33-dB Isolation by Polarization Diversity Coverage: Conus and Alaska Refl. Dimen.: 50 in. x 70 in. Focal Length: 35 in. Reconfigurability: None Refl. Constr: Mesh on Open Frame with Polarization Screen over Aperture No. Beams/Horns: Five, each used for Tx and Rc	HAC DA of CSA

Figure I-32. Multiple-Beam Antennas - In-Orbit

Program/Sponsor	Manufacturer	Description	Reference
*Comstar, Horizontally-Polarized Shaped-Beam Ant.		Same as the Vertically-Polarized Antenna Except for the following: Freq: 3740-4180 GHz Tx; 5965-6405 GHz Rc Polarization: Horizontal Linear Coverage: Conus, Puerto Rico, Hawaii No. Beams/Horns: Six, each used for Tx and Rc	
Intelsat IV A Transmit MBAs 1 each for Odd Ch's 1 each for Even Ch's	Hughes	Freq: 3707-4153 MHz Area Gain: 24 dB Max Scan: ≈3 Beamwidths Type: Offset-Fed Reflector Polarization: RHCP (1) Freq. Reuse: Yes, Between East and West Sector Coverage; 27 dB Isolation by Spatial Separation Refl. Dimen: 53 in. x 53 in. Quasi-Square Focal Length: 50 in. Reconfigurability: Limited, Two On-Off Beams, Odd Ch. Ant. Refl. Constr: Mesh on Open Frame No. Beams/Horns for Odd Ch. Ant. 19 for Eastern Coverage 18 for Western Coverage No. Beams/Horns for Even Ch. Ant. 9 for Northeast Coverage 10 for Northwest Coverage	HAC, ICC 1976 Design Aspects of Comm Sat Ants March 1976

(1) Later models, F2 and F3, achieve 27 dB isolation for frequency reuse by means of polarization diversity between Global Horn and Shaped Beam antennas.

Figure I-32. Multiple-Beam Antennas - In-Orbit (continued)

Program/Sponsor	Manufacturer	Description	Reference
Intelsat IV A Receive Ant.	Hughes Space and Comm Group	Freq: 5932-6378 MHz No. Beams/Feed Elements: 17 for East Coverage 17 for West Coverage Max Scan: ≈3 Beamwidths Type Feed-Refl: Offset Polarization: LHCP Freq. Reuse: Between East and West Sectors, 27 dB by Spatial Separation Refl. Dimen: 35 in. x 35 in. Quasi-Square Focal Length: 33.33 in. Reconfiguratility: Limited Construction: Mesh on Open Frame Area Gain: 22 dB	Design Aspects of Comm Sat Ant's March 1976

Figure I-32. Multiple-Beam Antennas - In-Orbit (continued)

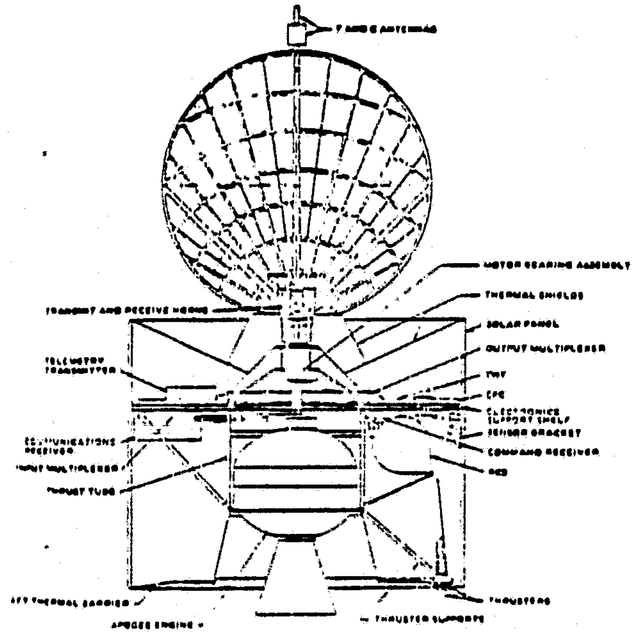


Figure I-33. General Layout, Telesat (Hughes Space and Comm. Group)

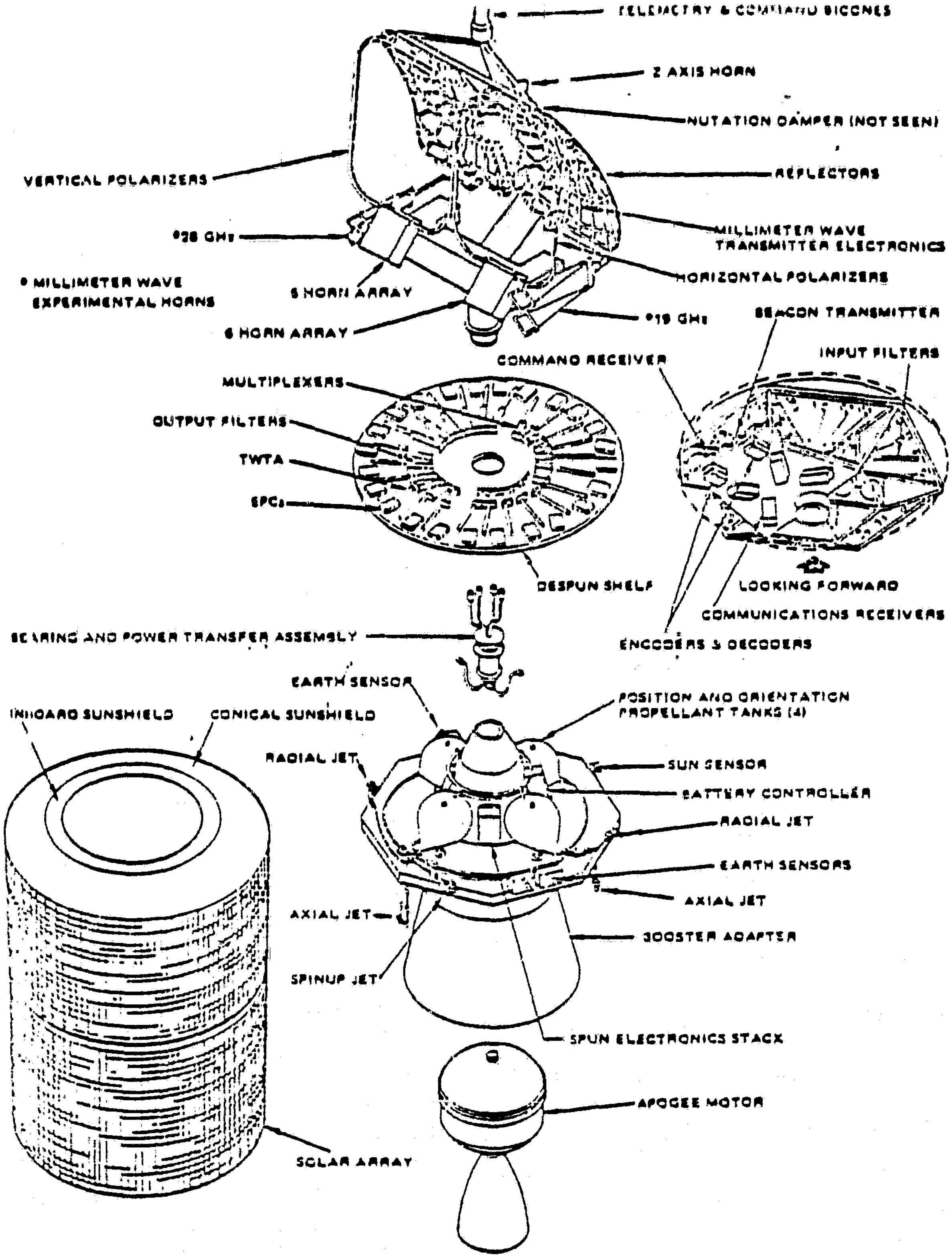


Figure I-34. Principal Spacecraft Elements and Their Arrangement, COMSTAR I (Hughes Space and Communications Group)

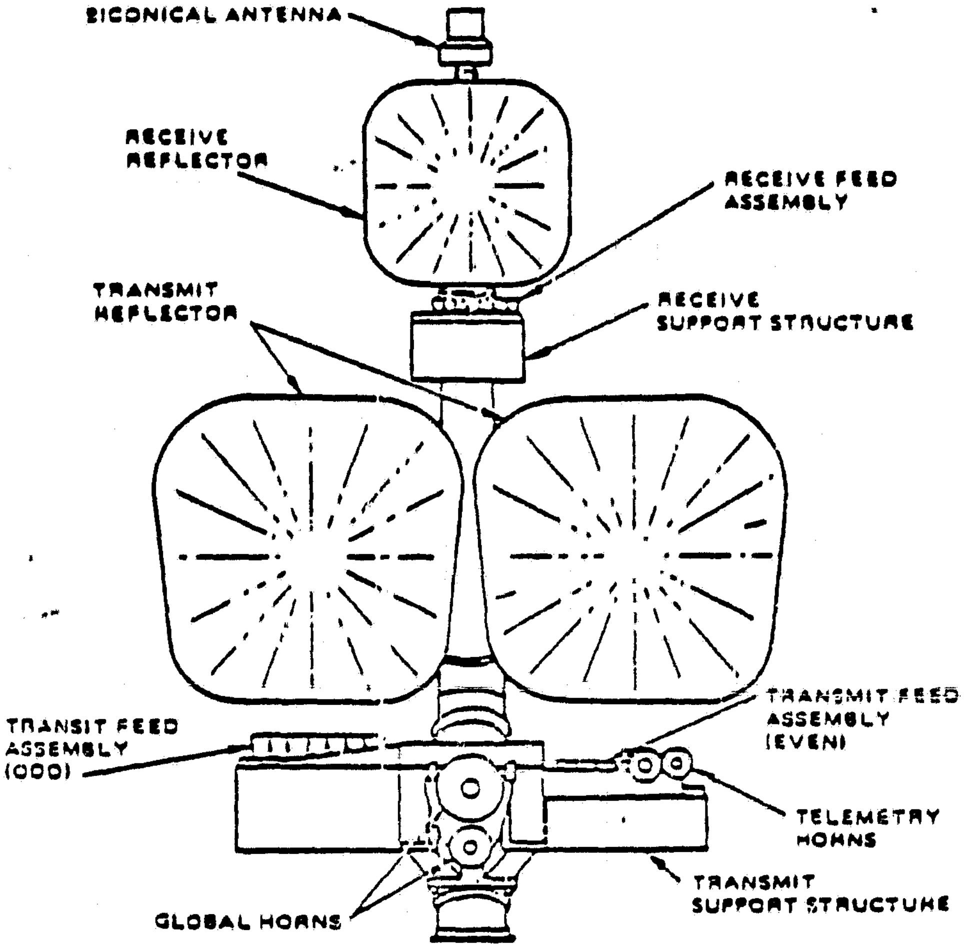


Figure I-35. General Arrangement of Antenna Hardware on Mast, Intelsat IVA (Hughes Space and Communications Group)

The DSCS III satellite is currently being developed by General Electric Space Division. It has three MBAs, each of which has full capability for in-orbit reconfiguration. Two 19-beam transmitting MBAs can each form shaped beams of arbitrary contour, subject to the constraints of singlet beamwidth and maximum coverage angles. One 61-beam receiving MBA has the same capabilities, but with added resolution afforded by a narrower singlet beam. Frequency reuse is not provided. At the present time, this capability does not appear to be especially needed for military communications. Characteristics of the DSCS III MBAs are summarized in Figure I-36.

Intelsat V, currently under development at FACC, features one MBA for transmitting and one for receiving. It makes extensive use of the capability of frequency reuse, achieving isolation between beams by means of beam separation and also by means of polarization diversity. It provides very limited in-orbit reconfiguration capability; a small number of feed horns can be switched in or out to permit tailoring the contoured patterns to better cover desired regions from different points in synchronous orbit. The characteristics of the Intelsat V antennas are summarized in Figure I-37.

TRW is performing a conceptual design study, under NASA contract, of an MBA system which provides coverage of CONUS, Alaska, and Hawaii. This system provides improved frequency reuse capability. The characteristics are summarized in Figure I-38, and the design baseline is illustrated in Figure I-39. Each of two nested reflectors consists of a grid of parallel strips oriented orthogonal to the parallel strips of the second nested reflector, and each of the two reflectors has a different focal point, as indicated in the figure. Two such nested antenna "pairs" would be utilized on one satellite. Footprints of the two antenna pairs are presented in Figure I-40 and illustrate the frequency reuse pattern. Reflectors 1 and 2, referred to in the figure, are nested, and reflectors 3 and 4 are nested. All vertically polarized beams from reflector 1 are shown separated by at least one beamwidth, so that they are sufficiently isolated from one another. An isolation of about 28 dB can be achieved. Beams from reflector 2 are orthogonally polarized and also separated from each other so that an isolation of at least 28 dB can be achieved. Beams from the second nested-pair antenna system provide similar sets of footprints, as shown, with an isolation between any two beams of at least 28 dB. When all footprints are combined, they cover a solid area, with any beam still isolated from any other beam by at least 28 dB. The three methods used to achieve the beam-to-beam isolation are:

Program/Sponsor	Manufacturer	Description	Reference
DSCS III, Transmit Two Each	General Electric Space Division	Freq: 7250-7590 GHz Gain, Pencil Beam: 26 dB over $\pm.75^{\circ}$ Earth Coverage: 16 dB over $\pm 8.8^{\circ}$ Max Scan: 2 Beamwidths Type Ant.: Lens fed by cluster of feeds Polarization: LHCP Freq. Reuse: None Coverage: $\pm 2^{\circ}$ Min (Singlet Beam), $\pm 9^{\circ}$ Max (Earth Coverage) Lens Dia.: 26.8 in. Focal Length: 28 in. Reconfigurability: Complete Beam Shaping Flexibility Lens Construction: Waveguide No. Horns: 19 Beam Control: Ferrite Adjustable Power Dividers	DSCS III Chart A. Horvath
DSCS III, Receive	General Electric Space Division	Freq: 7950-8320 GHz Gain, Pencil Beam: 29 dB over 1.5° Earth Coverage: 14.5 dB over $\pm 8.8^{\circ}$ Max Scan: 4 Beamwidths Type Ant: Lens Fed by Cluster of Feeds Polarization: RCHP Freq. Reuse: None Coverage: $\pm 1^{\circ}$ Min (Singlet Beam), $\pm 8.8^{\circ}$ Max (Earth Coverage) Lens Dia.: 44 in. Focal Length: 45 in. Reconfigurability: Complete Beam Shaping Flexibility Lens Constr: Waveguide, Phase Compensated N. Horns: 61 Beam Control: Adjustable Ferrite Power Dividers Plus Adjustable Ferrite Phase Shifters	DSCS III Chart A. Horvath

Figure I-36. Multiple-Beam Antennas - Firm Plans for Launch - DSCS III

Program/Sponsor	Manufacturer	Description	Reference
Intelsat V, Rc Ant	Ford Aerospace and Comm Group	Freq: 5.93-6.26 GHz, Zone Beams, 5.93-6.3 GHz, Hemi Beams Gain: 25 dB, Zone Beams 22 dB, Hemi Beams Type Ant: Offset-Fed Parabola Polarization: RHCP, Zone Beams; LHCP, Hemi Beams Freq. Reuse: Yes, 27 dB Isolation between orthogonally Pol. Beams; 27 dB isolation between Spatial Separated Beams Coverage: East Hemi, West Hemi, East Zone, West Zone Refl. Dia.: 5 ft F/D: 1 Reconfigurability: Limited Switching to Tailor Coverage No. Beams/Horns: 88 Horns, 78 Active and 10 Dummies	MBAs for Data Comm Sats
Intelsat V, Tx Ant	Ford Aerospace and Comm Group	Freq: 3.7-4.04, Zone Beams 3.7-4.07, Hemi Beams Gain: 25 dB, Zone Beams 22 dB, Hemi Beams Type Ant: Offset-Fed Parabola Polarization: LHCP, Zone Beams; RHCP, Hemi Beams Freq. Reuse: Yes, 27 dB Isolation between Orthogonal Pol. Beams ~27 dB Isolation Between Spatially Separated Beams Coverage: East Hemi, West Hemi, East Zone, West Zone Refl. Dia.: 8 ft. F/D: 1 Reconfigurability: Limited Switching to Tailor Coverage No. Beams/Horns: 88 Horns, 78 Active and 10 Dummies	MBAs for Data Comm Sets

Figure I-37. Multiple-Beam Antennas - Firm Plans for Launch - Intelset V

Program/Sponsor	Manufacturer	(1) Description	Reference
Ku-Band MBA NASA/Langly	TRW Systems	Freq: 11.7-12.2 GHz Tx 14.0-14.5 GHz Rc Type Ant: Offset-Fed Dual Parabolas [illegible] Polarization: Orthogonal Linear Frequency Reuse: Yes, with 28-dB Isolation from Polarization Diversity; 28 dB from Spatial Separation of Beams Coverage: Conus, Alaska, Hawaii Refl. Dia.: 198 cm Focal Length: 98.04 cm Sidelobes: 34 dB Down Reconfigurability: None Refl. Constr: Each Surface to be Photoetched Polarization Grid, ≈.001 Inch Tolerance No. Beams/Horns: About 17	

(1) Performance Projections Supported by Analysis

Figure I-38. Multiple-Beam Antennas - Conceptual Design Study

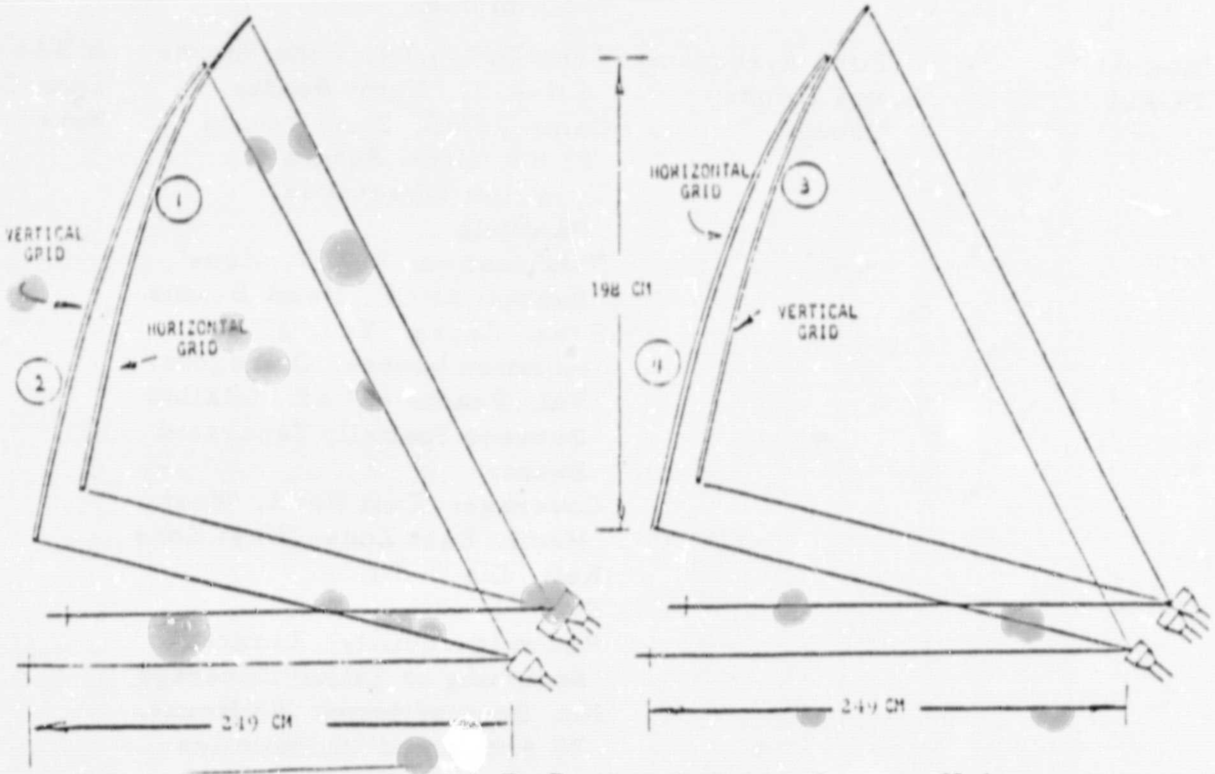


Figure I-39. 4-Reflector Antenna System Using Front-to-Back Orthogonally Polarized Wire Grid Reflectors

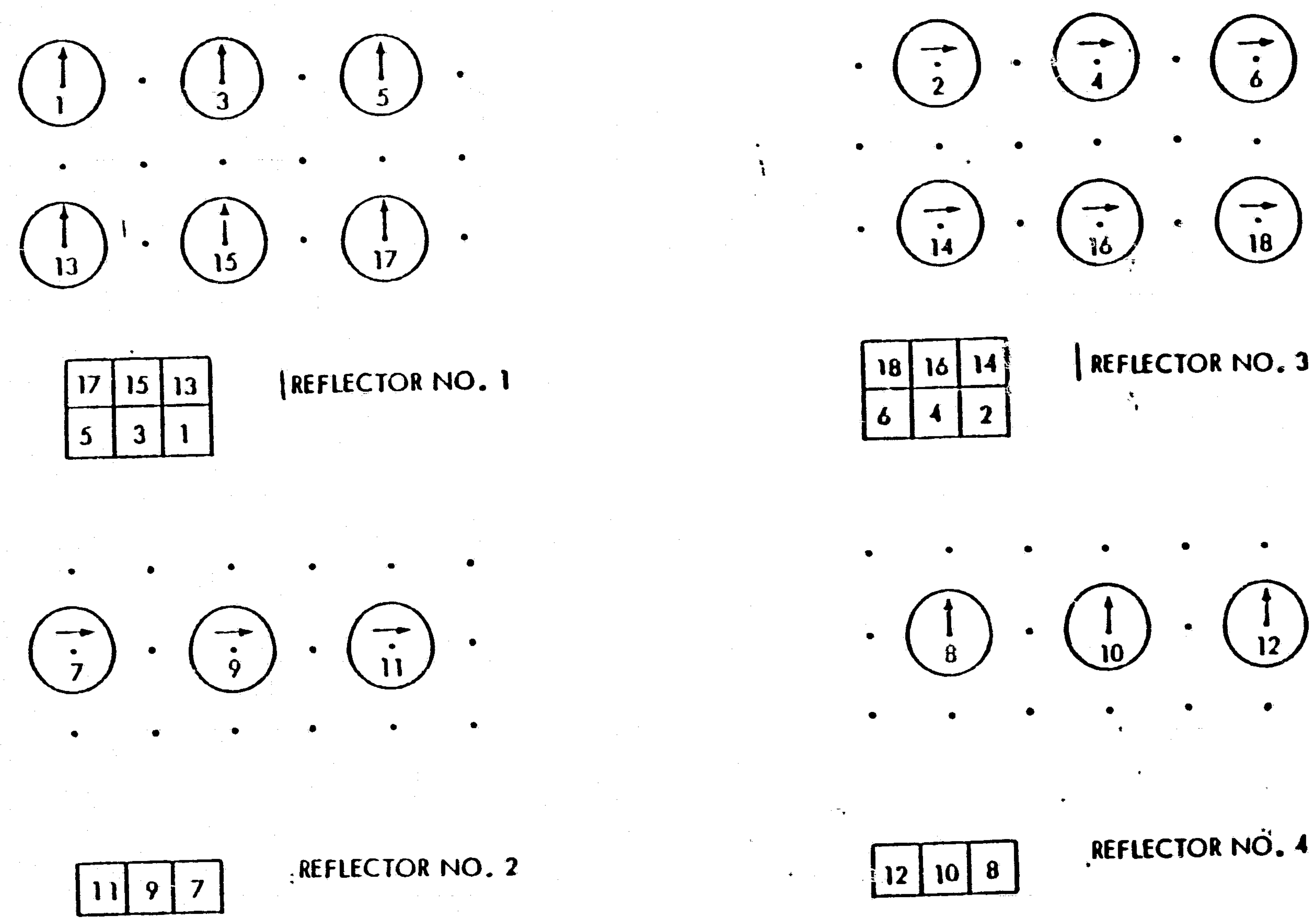


Figure I-40. Spot Beam Antenna - 4-Reflector System

- spatial separation of beams;
- polarization diversity; and
- use of physically separated antennas (nested pair 1 and 2 being physically separated from nested pair 3 and 4).

3. TECHNOLOGY LIMITS FOR MBAs

The most significant theoretical limit of performance of multiple-beam antenna is the relationship between beam crossover level and loss in efficiency of the involved singlet beams. As the crossover level between two contiguous beams approaches 0 dB, the efficiency of each beam worsens. This relationship has been illustrated, for the case of three contiguous beams by Hughes as shown in Figures I-41 through I-43. Figure I-41 shows a triangular lattice of MBA footprints with a crossover point, between three contiguous beams identified. These beams may have any one of the patterns illustrated in Figure I-42. In Figure I-42:

- uniform taper means constant illumination over the aperture; resulting beam has 17.6-dB sidelobes;
- P = 1 taper has an aperture illumination defined by $1 - (r/a)^2$ (resulting beam has 24.6-dB sidelobes); and
- P = 2 taper on .25 pedestal has an aperture illumination defined by $1/4 + (1 + (r/a)^2)^2$; resulting beam has 31.7-dB sidelobes.

The maximum singlet beam efficiency is shown in Figure I-43 as a function of crossover level of the beams formed by each of the three different aperture tapers. Notice that as the crossover level approaches zeros, the beam efficiency worsens. Also, the lower-sidelobe beams suffer greater efficiency losses for the same crossover levels within the range of 1 to 7 dB. This characteristic illustrates a basic theoretical performance limit of multiple beam systems and must be taken into account during the design phases.

If a center-fed reflector is used, additional performance limits are applicable. When a beam is scanned off-axis, as the outlying beams from an MBA must be, its gain drops and coma lobe increases. Figure I-44 illustrates the gain loss versus scan angle for antennas of different F/D ratios, and Figure I-45 gives the level of coma lobe. Notice that both scan loss and coma lobe are better behaved with larger F/D systems.

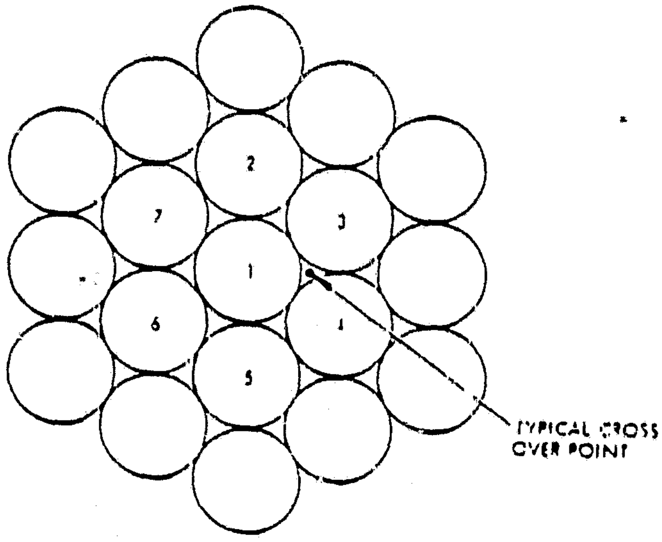


Figure I-41. Arrangement of Beams on a Triangular Lattice Showing Numbering System and Crossover Point

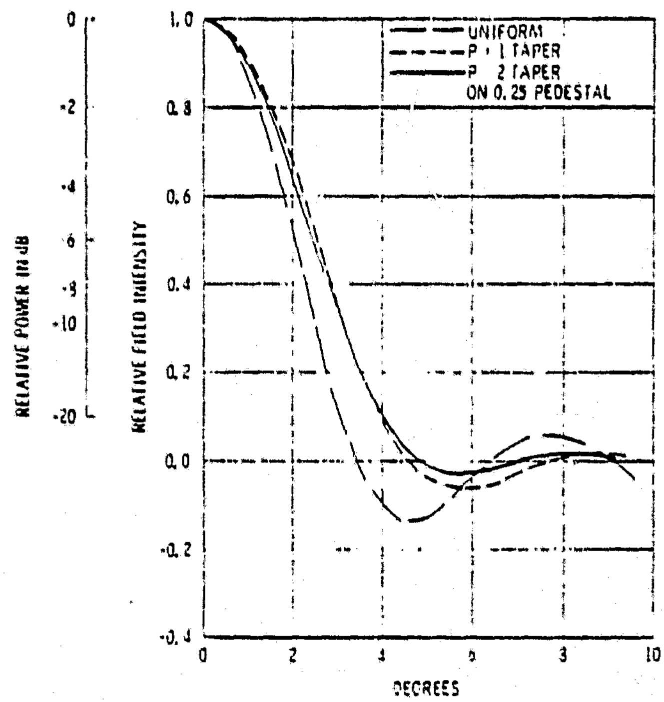


Figure I-42. Beam Shapes Used in Efficiency Calculations

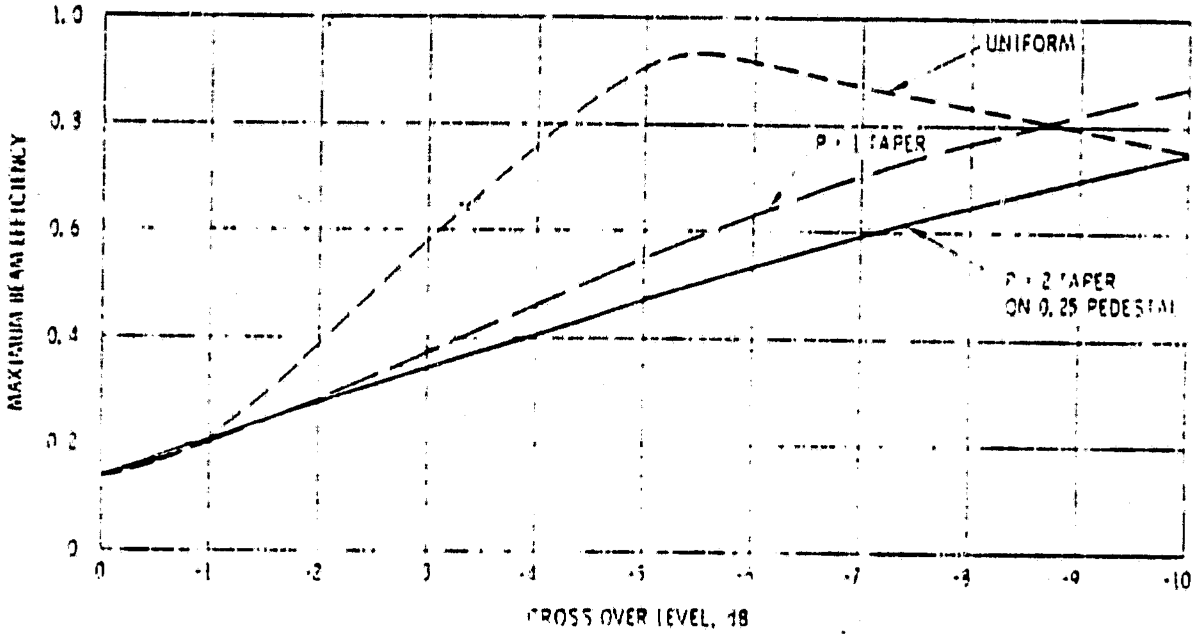


Figure I-43. Maximum Beam Efficiency Versus Crossover Level of the Beams of Figure I-42

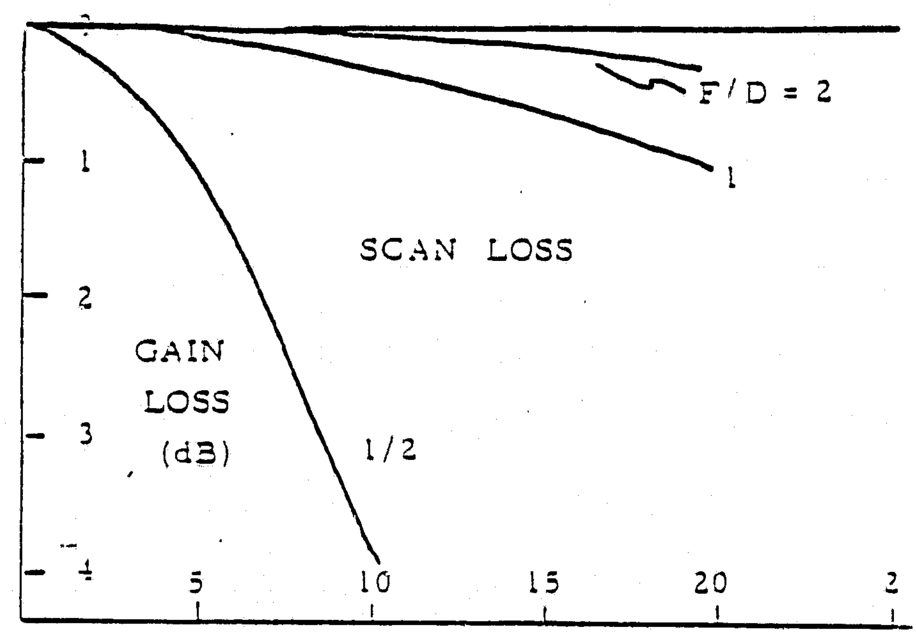


Figure I-44. Number of Beamwidths Scanned Off Axis for Simple Parabola (From Ruze)

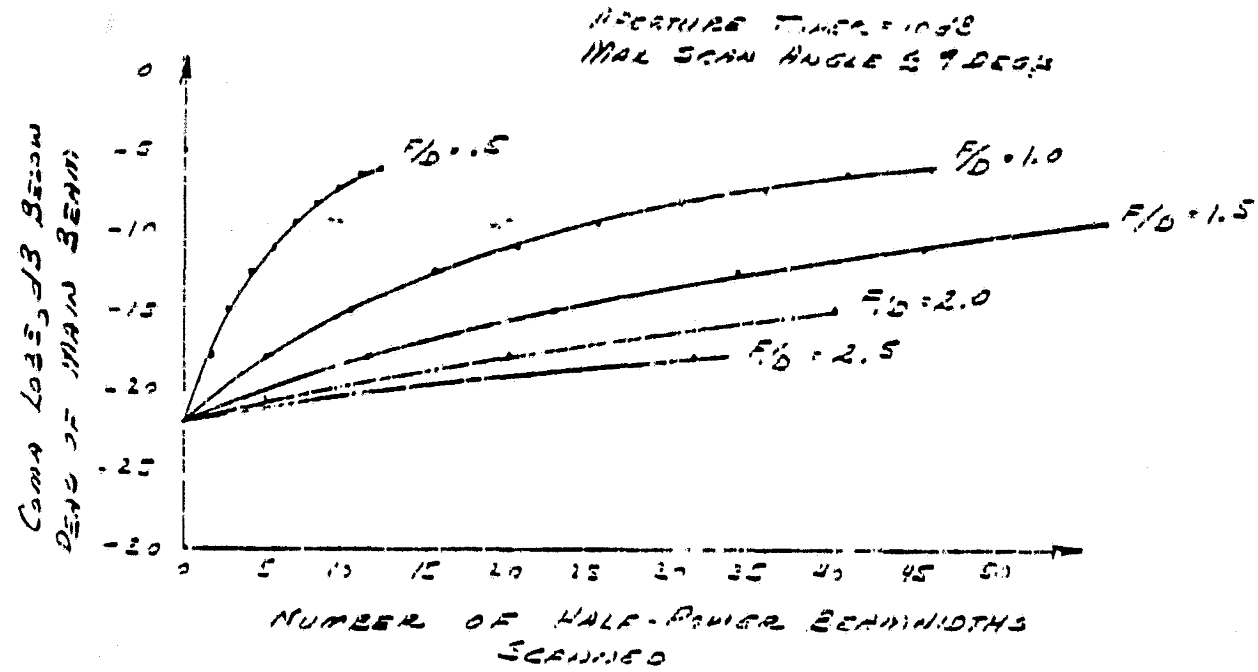


Figure I-45. Coma Lobe vs Scan Angle of Center-Fed Parabola

However, larger F/D systems suffer much more from blockage effects, as illustrated in Figure I-46. In this set of curves, gain loss and sidelobe levels are plotted as a function of F/D ratio for two cases: when CONUS is covered from synchronous orbit, and when earth is covered from synchronous orbit.

As a consequence of the effects illustrated in these figures, center-fed reflectors are not normally selected to be MBAs. Rather, offset-fed reflectors, which still suffer from beam steering but have no blockage, are used. Lenses are also preferred since they have no feed blockage, and certain types, in fact, have no beam steering degradation.

4. TECHNOLOGY OPPORTUNITIES FOR MBAs

Opportunities having the greatest probability of substantial payoff for advancing the state-of-the-art of MBAs were listed earlier and are:

- Develop new types of lenses which maintain well-shaped beams at large scan angles;
- Develop variable power dividers and variable phase shifters with smaller size, lower loss, and better control characteristics;

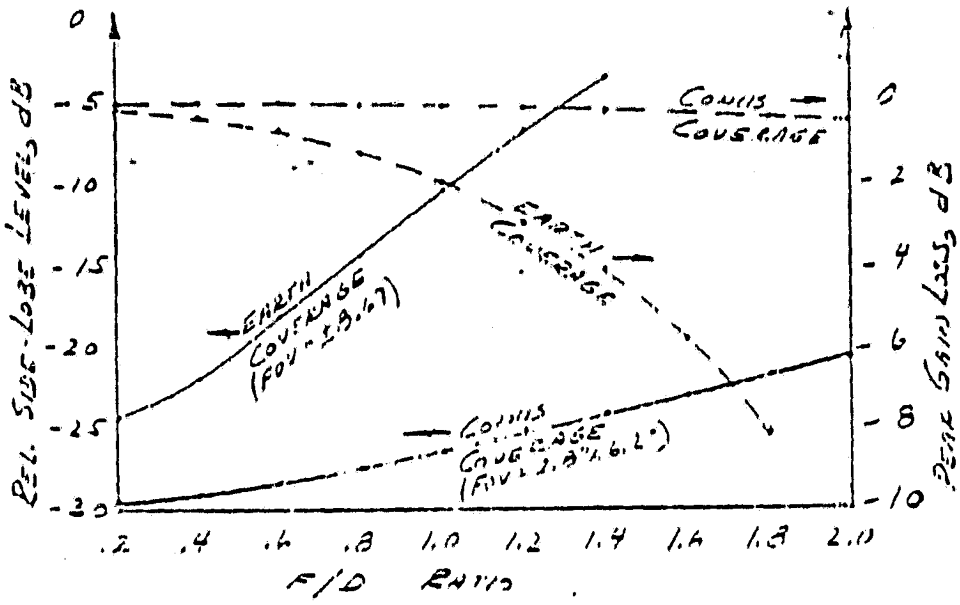


Figure I-46. Effects of Blockage, Center-Fed Reflector
(Ref. Hannan, P. W. 1961)

- Improve MBA system design technology; and
- Improve techniques for achieving high isolation between beams from an MBA.

A suggested program for addressing the requirements of the last two items above is provided in the following paragraphs.

a. Twelve-Meter Wide-Angle Scanning Antenna for Operation at 29.5 - 31.0 GHz

(1) Background

There is currently much activity directed toward increasing the capacity of satellite communication systems by means of increasing antenna gain. There is also much activity directed toward increasing effective bandwidth by means of incorporating frequency reuse.

A major problem in the design of such systems concerns degradation of beam shape at large scan angles when parabolic reflector antennas, of the type commonly found on satellites, are used. At large scan angles, the coma lobe of beams from these antennas increases in level to a point only 10 to 15 dB below beam peak, regardless of the level of sidelobes of the on-axis beams. The level of coma lobes, of course, limits the beam-to-beam isolation needed for frequency reuse.

Large aperture antennas, with apertures of 1000 or more wavelengths in diameter, are also very costly to analyze by computer.

(2) Design Study of a Twelve-Meter Wide-Angle Scanning Antenna for Operation at 29.5 - 31.0 GHz

a. Task 1. Develop a computer program capable of computing the far field pattern of beams whose position varies from on-axis to, nominally, nine degrees off-axis. Such an angle is equivalent to some 100 or more half-power beamwidths. The computer program should be economical and suitable for multiple-lens systems. The output of this task consists of a complete description of the computer program, including examples illustrating its use.

b. Task 2. Formulate conceptual designs of large-aperature antennas capable of scanning over 9 deg, and calculate gain and patterns as a function of scan angle. Advance the design to the point where size, weight, surface tolerance, deployment method, and stowed size can be identified. Assuming the use of Shuttle, rate each type of antenna on the basis of its suitability for communication satellite application. Consider performance, size, weight, development risk, and long-term cost.

c. Task 3. Propose a hardware program leading to an experimental demonstration of flight-type equipment.

(3) Estimated Time and Costs

The estimated time is 9 months and estimated costs are $400K.

(4) Candidate Contractors

Candidate contractors are Hughes, Ford, TRW, Lockheed MSC, General Dynamics, Harris, and Grumman.

E. TECHNOLOGY OPPORTUNITIES FOR COMMUNICATION SATELLITES

The following list contains recommended development areas with potential benefits to commercial satellite communications systems.

- Lenses suitable for satellite multibeam antennas with 30-dB sidelobes, including the identification of acceptable lens materials and the design for sidelobe control for coma lobes;
- Reflectors with surface roughness suitable for 30-dB sidelobes (offset feeds), including both fixed for frequencies >30 GHz and deployable for frequencies <2 GHz;
- Auto track systems to continuously correct the pointing of all beams in a satellite multibeam antenna;
- Adaptive systems suitable for rejecting a small number of strong interfering sources;
- Multiple offset reflector designs for sidelobe control in multibeam systems; and
- Multiple-beam feed networks for arrays of elements arranged on a triangular grid to be used as full aperture antennas or as feeds for reflectors or lenses.

The following numbered paragraghs contain descriptions of the suggested programs within the recommended development areas.

1. LENS DESIGN FOR FIVE-FOOT DIAMETER SATELLITE MULTIBEAM ANTENNA AT 30 GHz

a. Background

Efficient frequency reuse is possible at frequencies above 20 GHz if individual beams are less than 0.5 deg wide and sidelobes are down about 30 dB. Center fed reflectors cannot satisfy the sidelobe requirement. Center fed lenses provide a symmetry that gives them an advantage over offset fed reflectors both in electrical performance and in mechanical convenience. The fact that a single lens has two surfaces provides an advantage over a single reflector in that an added parameter is available to the designer. The traditional problem with lenses for satellites has been weight. As frequencies become higher and with the advent of the Shuttle, this disadvantage will be somewhat reduced.

b. Design Study for 5-Foot Diameter Lens Satellite Antenna for 30 GHz

(1) Task 1

Investigate alternative design approaches including but not limited to real dielectrics, artificial dielectrics, waveguide lenses, and bootlace lenses (passive and active).

(2) Task 2

Investigate methods of controlling coma lobes and sidelobes including but not limited to primary pattern control, choice of F/D, control of amplitude across aperture by resistive loss in lens, selection of lens surfaces to improve off-axis performance (e.g., sine condition), and surface matching techniques.

(3) Task 3

Select and justify a preferred design based on performance, size, weight, development risk, and long-term cost.

(4) Task 4

Propose a hardware program leading to an experimental demonstration of flight type equipment.

c. Estimated Time and Cost

The estimated time is 9 months. The estimated cost is $400K.

d. Candidate Contractors

Candidate contractors are Ford, Hughes, TRW, General Electric, Lockheed MSC, and Rockwell.

2. OFFSET FED REFLECTOR DESIGN FOR 100-FOOT DIAMETER DEPLOYABLE SATELLITE ANTENNA AT 1.6 GHz

a. Background

Surface tolerance requirements imposed by the need to suppress sidelobes to about the 30-dB level for frequency reuse are far more stringent than any such requirements imposed on deployable reflectors in the past. The effect of random surface errors on sidelobes has been defined by Ruze (and others) and has been shown to be not only a function of the roughness, but also of the distribution of the roughness (characterized by a "correlation interval"). When large parts of the reflector are displaced a small amount from the ideal surface, the effect on sidelobes is much worse than when many small areas are displaced the same amount, although the effect on gain is essentially the same. All of the demonstrated techniques for deploying large reflectors have a discrete number of control points for shaping the surface. The more experienced deployable reflector contractors (Harris, LMSC, GDA) have sophisticated structural analysis computer programs for predicting the surface under various loads. Little has been done, though, to evaluate the effect on sidelobes of the particular method of construction. Before attempting frequency reuse, it is desirable to quantify these effects.

b. Design Study for Offset Fed 100-Foot Reflector Suitable for Producing 30 dB Sidelobe Multibeams at 1.6 GHz

(1) Task 1

Design 100-foot diameter deployable offset fed reflector for covering CONUS with contiguous pencil beams from synchronous orbit. Define the feed cluster.

(2) Task 2

Calculate the on-orbit surface for the specific control techniques defined in Task 1.

(3) Task 3

Calculate the radiation patterns over all of CONUS for representative feeds (i.e., on-axis, outer edge, several in-between) taking into account the feed characteristics and the specific reflector surface geometry to define the expected isolation between beams.

c. Estimated Time and Cost

The estimated time is 6 months and the estimated cost is $200K.

d. Candidate Contractors

Candidate contractors are Harris, Lockheed MSC, and General Dynamics.

3. ADAPTIVE SYSTEMS SUITABLE FOR REJECTING A SMALL NUMBER OF STRONG INTERFERING SOURCES

a. Background

The usual approach to frequency reuse with communication satellites makes the basic assumption that enough interference suppression can be provided by controlling antenna pattern sidelobes and polarization so that the quality of the desired signals will not be significantly degraded. Interference rejection of about 30 dB is a typical design goal which has proven to be adequate in the past. This basic rationale applies in a typical benign environment in which all potential interferers radiate low level signals in the direction of the communication satellite. If a few interferers radiating very strong signals crop up they will show up in the sidelobes of many different beams in a multibeam system and can degrade the service to many different users. Some protection against such interference can be provided with adaptive nulling circuitry which can maximize the signal-to-interference ratio for selected users by creating nulls in the antenna pattern in the direction of the strong interference sources. A great deal of progress has been made in the adaptive processing field in the last ten years,* and although adaptive nulling finds most of its application in military systems there is a significant potential benefit to commercial systems, particularly when the satellite antenna sidelobes cover parts of the earth outside the political control of the nations being serviced by the communication system.

b. Assessment of the Utility of an Adaptive Nulling System for CONUS Coverage Multibeam System

(1) Task 1

Perform a paper design for a multibeam satellite antenna covering all of CONUS with about 100 contiguous pencil beams at 30 GHz, plus

*IEEE Trans. on Antennas and Propagation, Special Issue on Adaptive Antennas, September 1976.

beams covering Hawaii and Alaska. Characterize the sidelobe coverage for eight typical beams over all of the region intercepted by the earth.

(2) Task 2

Define an adaptive processing network suitable for maximizing the signal-to-interference ratio by combining one of the eight beams with auxiliary antennas (can be other pencil beams or add-on antennas) and varying the amplitude and phase coefficients for the different inputs on the basis of a suitable algorithm. Implement a computer simulator that will accurately reproduce the behavior of the adaptive processor when the satellite is receiving a user signal on the peak of one of the beams and a few strong interfering sources are located in the sidelobe region. Vary the beam used and the interferer locations. (Similar computer simulators are available at some companies and agencies.)

(3) Task-3

Quantify the improvement in signal to interference achievable with adaptive processing as a function of the number and strength of the interferers and as a function of the number of auxiliary channels.

(4) Task 4

Estimate the size, weight, and cost of adaptive circuitry compatible with those configurations in Task 2 deemed to provide useful system benefits in Task 3.

c. <u>Estimated Time and Cost</u>

The estimated time is 9 months and the cost is $400K.

d. <u>Candidate Contractors</u>

Candicate contractors are Airborne Industry Laboratory, Harris, Lockheed MSC, General Electric, and Lincoln Laboratories.

4. AUTOTRACK SYSTEMS TO CONTINUOUSLY COMPENSATE FOR POINTING ERRORS IN MULTIBEAM SATELLITE ANTENNAS

a. Background

When the individual beams in a multibeam satellite antenna become very narrow (less than about 1 deg), attitude errors in the platform and thermal distortion in the structure can introduce significant pointing errors, particularly for users near the edge of coverage of one of the beams. The relative merits of various methods of compensating for the errors depend on the type of multibeam antenna and on the particular source of the pointing error. Methods of autotracking to compensate for such errors should be evaluated.

b. Autotrack Systems for Multibeam Antennas

(1) Task 1

Define three specific multibeam systems each providing CONUS coverage with 1/2 deg beams at 30 GHz, using three different approaches to the antenna design.

- Lens fed by a feed cluster, each feed giving rise to one beam;
- Reflector fed by an offset feed cluster; and
- An array made up of N subarrays fed by a transmission line multibeam network (such as a Butler matrix) with N inputs, each input giving rise to one beam.

(2) Task 2

Assume that each antenna system is subject to pointing errors greater than 0.1 deg., and assume that a cooperating emitter is located on the earth near the center of the coverage region. Calculate the accuracy with which the pointing error can be determined by receiving a pilot signal from the emitter.

(3) Task 3

Evaluate alternative methods of correcting for the pointing error determined without using the satellite attitutde control system. Candidate approaches to be considered along with others are:

- Gimballing complete antenna system;
- Laterally translating the feed system;
- Gimballing the reflector only; and
- Electronic compensation (such as phase scanning the array).

(4) Task 4

Select a preferred approach on the basis of performance, size, weight, cost, complexity, and reliability, and estimate how the selection of the preferred approach would change if the same problems had been posed for an antenna operating at 1.6 GHz.

c. Estimated Time and Cost

The estimated time is 4 months and the estimated cost is $150K.

d. Candidate Contractors

Candidate contractors are Ball Brothers, Ford, General Dynamics, General Electric, Hughes Aircraft Corporation, Harris, Lockheed MSC, Rockwell, and TRW.

5. MULTIBEAM TRANSMISSION LINE FEED SYSTEMS FOR ARRAYS ON A TRIANGULAR GRID

a. Background

When very good pattern control is required in all planes of an antenna array, as is the case with a multibeam array exploiting frequency reuse, there is an advantage in distributing the elements over the aperture by placing them on a triangular grid rather than on a rectangular grid. This arrangement alleviates the geometry change observed with the rectangular grid in going from the planes parallel to the rows of the array to the diagonal planes. When adjacent beams in a multibeam rectangular array cross over at the points 3 dB below peak, the diagonal plane cross-over level is about 6 dB down. The corresponding worst case point when the elements are distributed on a grid made up of equilateral triangles is only about 4-1/2 dB down implying significantly better service for the users who happen to be located at the worst points in the communication satellite pattern coverage. However, the transmission line feed systems required to generate multiple lossless beams from a triangular grid array have not received the attention that has been given to the rectangular array. While Butler matrix type networks made up of equal power dividing four port hybrids are well known and have been widely used for some 20 years, the comparable networks for triangular matrices are more complex and need demonstration. Unless this is done, the multibeam array will be at a significant disadvantage relative to optical designs (which can use the triangular arrangement quite readily) even at frequencies low enough to make the arrays a competitive approach.

b. Multibeam Triangular Array Feed Networks

(1) Task 1

Design a feed network suitable for feeding an N-element array with the array elements distributed over a planar aperture arranged on a grid of equilateral triangles, with N input ports, each giving rise to a single beam. It shall be a design goal that adjacent beams should cross over between the 3 and 5 dB levels, and that all beams shall be as close to orthogonal as possible (that is, network losses due to energy coupled into undesired ports shall be minimized).

(2) Task 2

Fabricate laboratory models at 1.6 GHz of the power dividers required by the design determined in Task 1. Measure insertion losses and calculate the efficiency of 1.6 GHz multibeam arrays suitable for covering CONUS with beams about 1 deg. wide. Recommend a preferred design for this application specifying type of element, type of transmission line, and deployment method.

c. Estimated Time and Cost

Estimated time is 6 months, estimated cost is $100K.

d. Candidate Contractors

Candidate contractors are Lockheed MSC and Airborne Industry Laboratories.--

ORGANIZATIONS/PERSONS CONTACTED FOR CHAPTER I

Airborne Instrument Laboratory; J. J. Taub, P. F. Seilman (April 7, 1978).

Ball Aerospace (P. O. Box 1062, Boulder, CO); R. E. Munson.

Ball Brothers (Boulder, CO): R. E. Munson (April 12, 1978).

COMSAT Laboratories (Clarksburg, MD); D. DiFonzo (March 10, 1978 and April 25, 1978).

Defense Communication Agency; R. Donovan (March 10, 1978), R. Donovan, J. Riley (March 14, 1978).

Ford Aerospace and Communications Corporation; E. W. Mathews, W. G. Scott, A. Wickert (March 21, 1978).

General Dynamics (5001 Kearny Villa Road, San Diego, CA); J. Fager, R. Thomas (March 23, 1978).

General Electric Space Division; A. Horvath (March 7 and 9, 1978).

Grumman; J. Shultz (April 6, 1978).

Harris (Melbourne, FLA); H. E. Bartlett, W. McCaslin, B. C. Tankersley (March 13, 1978).

Hughes Aircraft Ground Systems Group (Fullerton, CA); J. Ajioka (March 28, 1978).

Hughes Space and Communications Group (El Segundo, CA); D. Nakatani, T. Kinaga (April 10, 1978).

Lincoln Laboratory; L. J. Ricardi (March 15, 1978).

Lockheed MSC (Sunnyvale, CA); G. Chadwick (March 21, 1978).

Rockwell (Seal Beack); G. Freeman (March 31, 1978).

TRW Systems; J. Duncan, C. C. Chen, M. Chen (March 24, 1978).

University of Illinois; Y. T. Lo (March 13 and 24, 1978).

Westinghouse Advance Technology Laboratories (Baltimore, MD); M. Lorenzo (April 5, 1978).

BIBLIOGRAPHY FOR CHAPTER I

AIL, "AGIPA for Fleet Satellite Communications," Deer Park, New York.

Ajioka, J. S., "A Limited Scan Technique Using Focal Spot Transformation," (November 1975).

________________, "Spherical Reflectors," (March 1977).

Ajioka, J. S., and V. W. Ramsey, "Group Delay Waveguide Lens," Hughes Aircraft Company, Ground Systems Group, Fullerton, California.

Allen, J. L., "A Theoretical Limitation on the Formation of Lossless Multiple Beams in Linear Arrays," IRE Transactions on Antennas and Propagation (July 1961).

Archer, D., "Lens-Fed Multiple-Beam Arrays," Microwave Journal (October 1975).

Assaly, R. N., et al., "LES-6 Antenna System," Lincoln Laboratory, MIT, Lexington, Mass., Technical Report 465 (March 1969).

Bilenko, H. W., A. N. Wickert, and C. C. Han, "Computer-Aided Array Feed Design for Multiple-Beam Lens Antenna," 1975 AP-S International Symposium Digest, University of Illinois (1975).

________________, "Computer-Aided Design of Multimode Horn Antennas," 1974 Northern California Symposium (1974).

Chuang, C. A., and C. C. Han, "Active Element Pattern of a Rectangular Waveguide in a Periodic Planar Array," 1976 International IEEE/AP-S Symposium and USNC/URSI Meeting, University of Massachusetts (October 1976).

Coulbourn, C. B., Jr., Increased Bandwidth Waveguide Lens Antenna, The Aerospace Corporation, TOR-0076(6403-01)-3, El Segundo, California (December 1975).

Covault, C., "Major Advances Expected from ATS-F," Aviation Week and Space Technology (May 1974).

Cuccia, C. L., et al., "Transponder and Antenna-Design Problems at Millimeter Wavelengths for 20-30 GHz Communications Satellites," Procedures of Symposium on Advanced Satellite Communications Systems, Genoa, Italy (December 1977).

Das, S.,"Multi-Beam Antennas Improve Satellite Communication," FCC, MSN (December 1977).

Dietrich, F. J., "An Amplitude-Steered Electronically Despun Antenna for the Synchronous Meteorological Satellite," 1972 IEEE National Telecommunications Conference, Houston (December 1972).

________________, "Design Considerations for High Gain Intersatellite Antennas," 1970 IEEE/G-AP Symposium and Fall USNS/URSI Meeting, Columbus, Ohio (September 1970).

Dietrich, F. J., D. F. Ford, and H. L. Hillesland, "A Millimeter-Wave Intersatellite Communication Antenna," 1970 International Conference on Communications, San Francisco (June 1970).

Dietrich, F.J., and R. K. Long, "An Efficient, Moderate-Size Vertical-Incidence Ionosonde Antenna for 2-20 MHz Polarization Studies," IEEE Transactions on Antennas and Propagation, AP-17 (September 1969).

Dion, A. R., "Minimum Directivity of Multiple-Beam Antennas," IEEE Transactions on Antennas and Propagation (March 1975).

________________, Variable-Coverage Communications Antenna for LES-7, Lincoln Laboratory, MIT, Technical Report 471 (October 1969).

________________, A Wideband Waveguide Lens, Lincoln Laboratory, MIT, Technical Note 1977-8 (February 1977).

Dion, A. R., and L. J.. Ricardi, "A Variable-Coverage Satellite Antenna System, Proceedings of the IEEE, 59 (February 1971).

Duncan, J. W., S. J. Hamada, and P. G. Ingerson, "Dual Polarization Multiple-Beam Antenna for Frequency Reuse Satellites," AIAA Paper 76-248, AIAA/CASI 6th Communications Satellite Systems Conference, Montreal, Canada (April 1976).

Edelson, B. I., "The Second Decade of Satellite Communications," Microwave Journal.

Edelson, B. I., and P. L. Bargellini, "Technology Development for Global Satellite Communications," AIAA Paper 76-234, AIAA/CASI 6th Communications Satellite Systems Conference, Montreal, Canada (April 1976).

Edelson, B. I., and W. L. Morgan, "Orbital Antenna Farms," AIAA Journal (September 1977).

Ford Aerospace and Communications Corporation, Multiple-Beam Frequency Reuse Antenna, Final Report, Palo Alto, California.

Gregorwich, W. S., "An Electronically Despun Array Flush-Mounted on a Cylindrical Spacecraft," IEEE Transactions on Antennas and Propagation Conformal Arrays (January 1974).

__________, "A Mechanically Despun Antenna for the Skynet IDCSP/A Communications Satellite," Communication Satellites for the 70's: Technology (ed., Feldman and Kelly) MIT Press (1971) pp. 241-254.

__________, "A Multipolarization Dual-Band Array," IEEE/AP-S 1975 International Symposium, University of Illinois (June 1975).

__________, "A Novel VHF Turnstile Antenna for the SMS Satellite," IEEE 1972 National Telecommunications Conference, 36F1-36F4 (1972).

__________, "An Omnidirectional Telemetry Antenna for Spacecraft," IEEE 1971 National Telemetering Conference (1971) pp. 94-99.

Gregorwich, W. S., "A Survey of Antenna Array Technology for Surveillance Systems," (February 1977).

——————, "A Tangential Turnstile Antenna for Spacecraft," IEEE/AP-S 1974 International Symposium (1974) pp. 207-209.

Gregorwich, W. S., A. Hessel, and G. H. Knittel, "A Waveguide Simulator Study of a Blindness Effect in a Phased Array."

Gregorwich, W. S., and P. K. Kawata, "A Broadband Conformal Array for Communications Satellites," 1977 Antenna Applications Symposium, University of Illinois (April 1977).

——————, "A Conformal Array for Communication Satellites," IEEE-Antennas and Propagation International Symposium, University of Maryland (May 1978).

Gregorwich, W. S., and C. W. Westerman, "A Near-Isotropic Microwave Antenna for Communications Satellites," Communications Satellite Technology (ed., Dr. P. L. Bargellini) MIT Press (1974) pp. 533-540.

Han, C. C., "Optimization in the Design of a 12 GHz Low Cost Ground Receiving System for Broadcast Satellites," ICC Conference Record, Seattle (June 1973) p. 36-8.

——————, "Reduction of Ground Antenna Near-In Sidelobes in the Direction of Geostationary Orbit," IEEE/G-AP International Symposium Digest, University of Colorado (August 1973) pp. 310-313.

Han, C. C., and D. F. Ford, "Multifunction C-Band Antenna Feed for ATS F&G Satellites," 21st Annual Symposium Digest, USAF Antenna Research and Development Program, University of Illinois (October 1971).

Han, C. C., and D. F. Ford, et al., "A General Beam Shaping Technique--Multiple-Feed Offset Reflector Antenna System," AIAA/CASI 6th Communications Satellite Systems Conference, Montreal Canada (April 1976).

Han, C. C., and A. N. Wickert, "A New Multimode Rectangular Horn Antenna Generating Circularly-Polarized Elliptical Beam," IEEE/G-AP International Symposium Digest, University of Colorado (August 1973) pp. 426-429.

Han, C. C., "A New Multimode Rectangular Horn Antenna Generating A Circularly Polarized Elliptical Beam," IEEE Transactions on Antennas and Propagation (November 1974) pp. 746-750.

Hanson, A. W., "Antenna Design for Pioneer Venus Probes," Hughes Aircraft Company, Space and Communications Group.

Harris Electronic Systems Division, "Harris Family of Deployable Antennas," Melbourne, Florida, Proprietary Data.

Hughes, Comparison of Design Approaches for Multi-Beam 7-9 GHz Space Antennas, Air Force Report No. SAMSO-TR-72-284, Hughes Aircraft Company, Culver City, California (December 1972).

Hwang, Y., and R. G. Kouyoumjian, "The Diffraction of an Edge Formed by Two Uniform Impedance Surfaces," IEEE/AP-S Symposium and USNC/URCI Meeting, University of Massachusetts (October 1976).

Jamieson, A. R., Offset Fed Zoned Reflectors for Multiple-Beam Antenna Systems, Technical Report 77-20, Electromagnetics Laboratory, University of Illinois.

Kawata, P. K., and A. E. Smoll, "CS Omni Array Pattern Analysis with Measured and Perturbed Excitations," Antenna Engineering Department (July 1977).

Klein, C. A., H. W. Bilenko, and C. C. Han, "Design of Shaped Beam Satellite Antenna Through Minimax Pattern Optimization," IEEE/AP-S Symposium and USNC/URCI Meeting, University of Massachusetts (October 1976).

Koloboff, G. J., "Amplitude Steered Pseudophased Antenna Array," NASA Technical Brief B74-10255 (January 1975).

Kreutel, R., "A Multiple-Beam Torus Reflector Antenna for 20-30 GHz Satellite Communications Systems," AIAA/CASI 6th Communications Satellite Systems Conference, Paper 76-302 (April 1976).

Kummer, W. H., Final Report for Advanced General Purpose Forces Satellite Antenna Study, SAMSO-TR-No. 74-71, Hughes Aircraft Company, Culver City, California (December 1973).

Lang, K. C., and B. J. Forman, "Experimental Study of Scanning Characteristics of an Offset Cassegrainian Reflector Antenna," Hughes Aircraft Company, Space and Communications Group, El Segundo, California.

Lo, Y. T., and G. A. Deschamps, Multiple-Beam Antenna Study, Final Report, Electromagnetics Laboratory, Technical Report 77-6, Parts 1, 2, and 3, University of Illinois.

Luh, H. S., "The Effect of Tolerance on the Isolation of Frequency Reuse Antennas," IEEE Transactions on Antennas and Propagation (January 1975).

________________, "On Computation of the Radiation Pattern of a Zone Waveguide Lens," IEEE Transactions on Antennas and Propagation (May 1974).

________________, "On Radiation Pattern of a Multi-Beam Antenna," IEEE Transactions on Antennas and Propagation (January 1976).

________________, "Polarization Separation by an Adaptive Filter," IEEE Aerospace and Electronics Group.

Luh, H. S., et al., "A Constrained Lens Antenna for Multiple-Beam Satellites," AIAA Paper 74-465, AIAA 5th Communications Satellite Systems Conference, Los Angeles (April 1974).

________________, "A Constrained Lens Antenna for Multiple-Beam Satellites," Communication Satellite Developments Technology (ed., Wm. Schmidt and G. LaVean), 42, Progressing Astronautics and Aeronautics, MIT Press (1976).

Luh, H. S., and W. G. Scott, "Testing of Multiple-Beam Lens Antenna for Advanced Communication Satellites," AIAA/CASI 6th Communications Satellite Systems Conference, Montreal, Canada (April 1976).

Luh, H. S., T. M. Smith, and W. G. Scott, "Dual Band TEM Lens Development," IEEE/AP-S International Symposium, University of Maryland (May 1978).

MacLellan, D. C., et al., "Lincoln Experimental Satellites 5 and 6," AIAA Paper No. 70-494, AIAA 3rd Communications Satellite Systems Conference, Los Angeles (April 1970).

Matthews, E. W., "Variable Power Dividers in Satellite Systems," Aeronutronic Ford, Palo Alto, California, and MTT-S, Cherry Hill, New Jersey (1976).

——————, "Multi-Beam Antennas for Data Communications Satellites," IEEE and ACM 5th Data Communications Symposium, Snowbird, Utah (September 1977).

Matthews, E. W., L. F. Brokish, and G. F. Will, "The Communications Antenna System on the Japanese Experimental Communications Satellite," AIAA 7th Communications Satellite Systems Conference, San Diego (April 1978).

Matthews, E. W., and M. A. Ikemoto, "A Multi-Channel Rotary Joint for Spacecraft Applications," 1972 MIT Symposium (1972).

Matthews, E. W., W. G. Scott, and C. C. Han, "Advances in Multi-Beam Satellite Antenna Technology," EASCON, Washington, D. C. (October 1976)

Mayer, R. D., R. A. Stonier, and G. H. Schennum, New Technology Report (A Frequency Selective Surface or Electrically Polarized Discriminator from a Metallized Film) JPL S/C #953969.

Mayhan, J. T., Adaptive Nulling with Multiple-Beam Antennas, Lincoln Laboratory, MIT, Technical Note 1976-18 (September 1976).

Mittra, R., et al., "A Review of Performance Characteristics of Satellite Antennas and Some Observations on Future Directions in Satellite Antenna Design," (undated).

Munson, R. E., "Antenna Data Sheets," Ball Aerospace Systems Division, Boulder, Colorado.

Nakatani, D. T., et al., "Design Aspects of Commercial Satellite Antennas," Hughes Aircraft Company, Space and Communications Group, El Segundo, California, Communication Satellite Antenna Technology, University of California at Los Angeles (March 1976).

Nakatani, D. T., and J. S. Ajioka, "Lens Designs Using Rotatable Phasing Elements," Hughes Aircraft Company, El Segundo, California.

Nakatani, D. T., and S. L. Flateau, "Multiple-Beam Antenna Design for Satellite Communication Systems," Hughes Aircraft Company, El Segundo, California.

Nakatani, D. T., and G. G. Kuhn, "Comstar I Antenna System," Hughes Aircraft Company, El Segundo, California.

Norris, A. P., and B. S. Wescott, "Computation of Reflector Surfaces for Bivariate Beamshaping in the Elliptic Case," Journal of Physics A -- Mathematical and General, 9 (December 1976).

Palmer, W. B., Deployable Antenna Reflector, 1976 IR&D Final Report, Report No. MEL-76-B-113, TRW Systems, Defense and Space Systems Group, Redondo Beach, California, Proprietary Data (December 1976).

Panicali, A. R., Y. T. Lo, and Georges A. Deschamps, "A Reflector Antenna Corrected for Spherical, Coma, and Chromatic Aberrations," Antenna Laboratory Report No. 70-14, Department of Electrical Engineering, University of Illinois.

"Parabolic Expandable Truss Antenna (PETA)," General Dynamics Convair Division, San Diego, California.

Powell, R. V., "A Future for Large Space Antennas," JPL, preprint (April 1978).

Powell, R. V., and A. R. Hibbs, "An Entree for Large Space Antennas," AIAA Journal (December 1977).

Reudink, D. O., and Y. S. Yeh, "A Scanning Spot-Beam Satellite System," The Bell System Technical Journal, 56(8) (October 1977).

Richards, W. F., and Y. T. Lo, Anisotropy, Birefringence, and Dispersion in Artificial Dielectrics, Final Report 2, Technical Report 77-17, Electromagnetics Laboratory, University of Illinois.

Schennum, G. H., "Design of Frequency Selective Surfaces Using a Waveguide Simulator Technique," IEEE International Antenna and Propagation Symposium, University of Illinois (June 1975).

________________, "Development of a High Power Frequency Selective Cassegrainian Sub-Reflector (FSS)," IEEE International Antenna and Propagation Symposium, Ohio State University (September 1970).

________________, "A Dual-Frequency Coaxial Feed for a Prime Focus Antenna," IEEE International Antenna and Propagation Symposium, University of Colorado (August 1973).

________________, "Frequency-Selective Surfaces for Multiple-Frequency Antennas," Microwave Journal (May 1973).

________________, "Mariner-Jupiter/Saturn Dual-Frequency High Gain Antenna," IEEE Northern California Antenna and Propagation Symposium (May 1976).

________________, "MJS Dual-Frequency High Gain Antennas," IEEE Northern California Antennas and Propagation Symposium (May 1976).

________________, "Use of Equalizers to Reduce the Cross Polarization Response in a Waveguide Array," 1977 Antenna Applications Symposium, University of Illinois (April 1977).

Schennum, G. H., C. C. Han, and H. J. Gould, "Reduction of Mutual Coupling in a Waveguide Array," IEEE Antennas and Propagation International Symposium, University of Maryland (May 1978).

Schroeder, K. G., "Characteristics and Applications of Multi-Beam Spacecraft Antennas," AIAA Paper No. 72-530, AIAA 4th Communications Satellite Systems Conference, Washington, D. C. (April 1972).

Schultz, J. L., "Large Communication-Satellite Antenna," Grumman Aerospace Corporation, Bethpage, New York.

Schultz, J. L., and I. Kadar, "A Frequency Reuse Direct-to-Home TV Broadcast Satellite System," Grumman Aerospace Corporation, Bethpage, New York, 7th AIAA Communications Satellite Systems Conference, San Diego (April 1978) pp. 78-577.

Sciambi, A. F., Jr., "High Power Monopulse Tracking Feed," MTT-S Symposium (June 1976).

Scott, W. G., "Antenna Pattern Topology," 1969 IEEE/G-AP International Symposium, University of Texas, Austin (December 1969).

______________, "Antennas in Modern Communication Satellites."

______________, "Polarization Ellipse Orientation on the Antenna Radiation Sphere," 1971 IEEE/G-AP International Symposium, University of California at Los Angeles (1971).

______________, "Multi-Beam Antennas in Communication Satellites," Northern California Symposium on Antennas and Propagation, Santa Clara Valley Chapter of IEEE/AP-S, Palo Alto (May 1976).

______________, "Design of a Wide-Band Frequency Reuse Multiple Beam Lens Antenna," Lecture presented as part of a UCLA Short Course on Communication Satellite Antenna Technology, Los Angeles (March 1976).

______________, "Ranger Lunar Capsule Antenna," Electronics (November 1962).

Scott, W. G., and C. E. Ermatinger, "The Crossed Ellipse Array--A System for Reduction of Polarization Axial Radio," 1972 IEEE/G-AP International Symposium, Williamsburg, Virginia (December 1972).

Scott, W. G., H. S. Luh, and E. W. Matthews, "Design Tradeoffs for Multiple-Beam Antennas in Communication Satellites," IEEE International Conference on Communications, Philadelphia (June 1976), IEEE Communications Society (March 1977).

Scott, W. G., et al., "Wide-Angle Circularly Polarized Antenna Techniques for Spacecraft," IRE 9th East Coast Conference on Aerospace and Navigational Electronics (October 1962).

Sielman, P. F., L. Schwartz, and T. T. Noji, "Multiple-Beam Communicating Satellites with Remote Beam Steering and Beam Shaping," Paper presented 72-566 at AIAA 4th Communications Satellite Systems Conference, Washington, D. C., (April 1972).

Smoll, A. E., "Reflector Antennas for Communication Satellites," presented at Tutorial Series on Reflector Antennas, San Francisco Chapter IEEE/AP-S, Palo Alto (February 1974).

——————, "Shaped Beam Patterns," Northern California Symposium on Antennas and Propagation, Palo Alto (May 1974).

Smoll, A. E., and C. C. Han, "A Split-Mode Horn/Reflector Antenna--A New Concept in Antenna Design," International Symposium on Antennas and Propagation, University of Illinois (June 1975).

Stein, S., "On Cross Coupling in Multiple-Beam Antennas," <u>IRE Transactions on Antennas and Propagation</u>.

Taormina, F., et al., "Intelsat IVA Communications Antenna--Frequency Reuse Through Spatial Isolation," Hughes Aircraft Company, Los Angeles, California.

Tomita, C. Y., R. W. Wesley, and C. T. Brumbaugh, "Constrained Lens Antenna," Rockwell International, Missile Systems Division, Anaheim, California.

Tsai, L. L., Phase-Delay-Type Artificial Dielectrics, Lincoln Laboratory, MIT, Technical Report 1975-4 (January 1975).

Wesley, R. W., and C. Y. Tomita, X-Band Constrained Lens Radar Antenna, Final Report, Autonetics, North American Rockwell, Technical Report AFAL-TR-71-229 (August 1971).

White, W. D., "Pattern Limitations in Multiple-Beam Antennas." IRE Transactions on Antennas and Propagation.

Wickert, A. N., et al., "The Design of the Communications Antenna for CS," 1976 AIAA 6th Communications Satellite Systems Conference, Montreal, Canada (April 1976).

Witte, R. A., "Pioneer Venus Antenna System," Hughes Aircraft Company, Space and Communications Group, El Segundo, California.

Woods, A. A., and W. D. Wade, "On the Design of Self-Deploying, Extremely Large Parabolic Antennas and Arrays," Lockheed Missiles and Space Company.

CHAPTER II

SATELLITE LOW-NOISE RECEIVERS

Prepared by

W. J. Wilson
Antennas and Propagation Department

CONTENTS FOR CHAPTER II

LIST OF ILLUSTRATIONS

PRECEDING PAGE BLANK NOT FILMED

CHAPTER II

SATELLITE LOW-NOISE RECEIVERS

A. OVERVIEW

Low-noise receivers for communication satellite systems are required in the satellite and the ground terminals. In each application, the lowest system noise is required to mimimize the required transmitter power and/or antenna size (and gain) to achieve the required signal-to-noise ratio. With the satellite receiver, the antenna is looking at the earth background which is at a temperature of ~290K; consequently; the minimum system noise temperature will be ~290K. For satellites, therefore, the use of receivers with noise temperatures much less than 100K will not reduce the system noise significantly. With the ground terminal, the antenna temperature ranges from 20 to 200K due to sidelobe pickup, atmospheric emission (depending on frequency), and weather conditions. (The larger values would occur at higher frequencies (>15 GHz) and in poor weather conditions.) For frequencies below 15 GHz, therefore, ground receivers with noise temperatures of <50K could be usable to obtain maximum performance; for frequencies above 15 GHz, receivers with noise temperatures ~100K would not significantly degrade system performance.

With these considerations in mind, it appears that GaAs FET amplifiers (both uncooled and cooled to 100K) should be used for the low-noise receiver application for all frequencies below 40 GHz. (The 40-GHz limit is due to limitations of GaAs FETs as discussed in Section C.) The other choice is parametric amplifiers for low-noise receivers in this frequency range, but cooled GaAs FETs will provide the required performance, especially in the satellite receiver, with a much simpler device and lower cost. It should be noted, however, that in some applications below 40 GHz, the lowest possible receiver noise may be required which would require a cooled parametric amplifier--but these paramps are reasonably well developed, and NASA support is not required for further improvements.

Above 40 GHz, the choices for low-noise receivers are mixers, image-enhanced mixers, and parametric amplifiers. All these devices can be cooled to improve their noise performance. In this study, it was concluded that development of cooled image-enhanced mixers (cooled to ~100K) would offer the greatest improvement in noise performance and provide the best device, in terms of simplicity, reliability, and cost for comsat application. Paramps above 40 GHz will require the development of pump sources to 300 GHz and low-loss coupling and ferrite circuits, which would be a major development program. Using a cooled image-enhanced mixer followed by a cooled FET IF amplifier could provide a receiver noise temperature of ~400K (F = 3.7 dB) at 90 GHz by 1983--which is a factor of 3 improvement over 1978 room-temperature mixer receivers and nearly equal to the predicted performance of 1983 paramps.

B. STATE-OF-THE-ART OF LOW-NOISE RECEIVERS

A summary of the performance of low-noise receivers in 1978 is shown in Figure II-1; each of the devices will be discussed below.

GaAs FET technology has progressed so fast in the past few years that curret FETs are pushing the theoretical limits, and, in some cases, it has been necessary to modify the theories to keep pace with laboratory developments. Many companies are now developing and/or producing low-noise GaAs FETs. The following is a list of these companies:

- AIL
- Alpha Industries
- Avantek
- Bell Laboratories
- Dexcel
- Hewlett-Packard
- Hitachi (Japan)
- Hughes
- Nippon Electric Company (Japan)
- Plessey (England)
- RCA
- Royal Signals and Radar Est. (England)
- Rockwell
- TRW
- Watkins-Johnson
- Varian

Because of the current interest in this field and the large number of excellent review articles (see Bibliography), determining the state-of-the-art in GaAs FETs has been relatively simple. The detailed performance of 1978 GaAs FETs is summarized in Figure II-2 which was taken directly from a review article by DiLorenzo (1978). Below 10 GHz, GaAs FET performance is excellent and within a few tenths of a dB of the

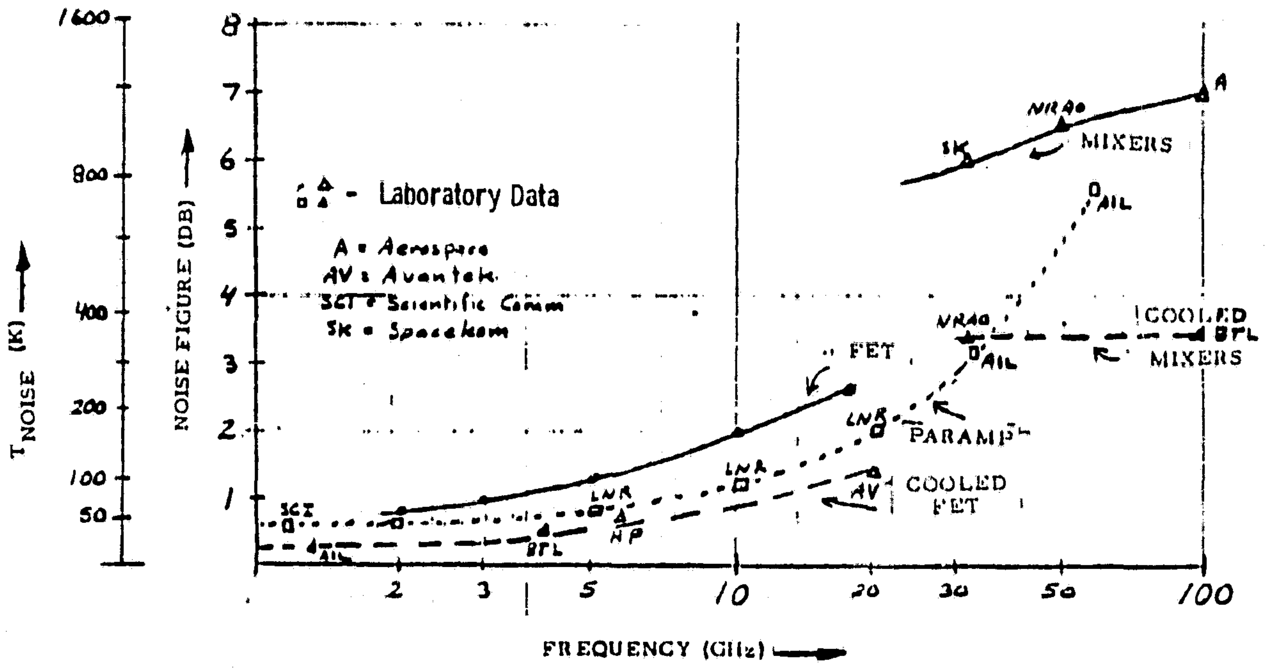


Figure II-1. Low-Noise Receivers - 1978 State of the Art

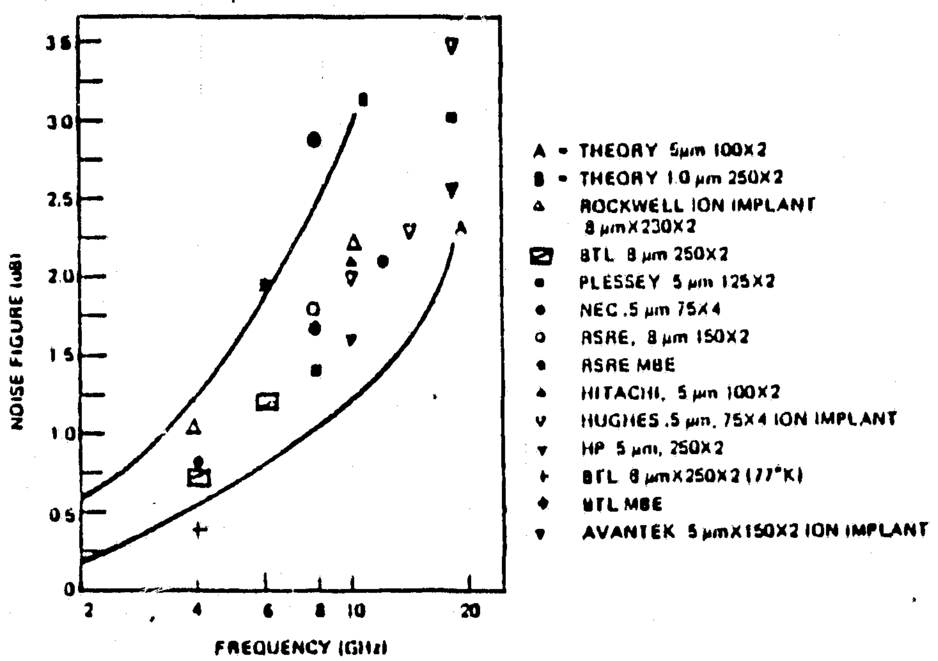


Figure II-2. FET Noise Figures - Experimental Data and Theoretical Curves (Lines A and B) - DiLorenzo (1978) current theoretical limit. A 1978 prediction of a noise figure of 3 dB at 26 GHz has been made (Cooke, 1978), and AFAL has a 1978 development program with a goal of a 6-dB noise figure at 40 GHz.

Cooling of FETs to 77K reduces their noise temperature by a factor of 2 to 3, which makes it possible to build a 20 GHz amplifier, cooled to 77K, that has a noise temperature of 100K (Cooke, (Avantek) private communication). For frequencies <20 GHz, cooled FET amplifiers have very low noise temperatures--better than room temperature parametric amplifiers.

Below 20 GHz, paramps have excellent noise performance and could satisfy the system requirements. Cryogenic paramps, cooled to 20K by closed cycle refrigerators, have much lower noise temperatures (<50K) and could be useful in some critical applications. Between 20 and 40 GHz, very low noise paramps are not available as standard items, but they could be produced with very little development. As a consequence, paramps below 40 GHz are fairly well developed, and significant imporvements are not expected in this area.

Above 40 GHz, the lowest noise receivers are mixers followed by IF paramps, all cooled to 20K by closed cycle cryogenic refrigerators. Their noise temperatures are between 300 and 400K. The best 40- to 90-GHz room temperature mixers (i.e., those followed by FET IF amplifiers) have noise temperatures between 800 and 1200K. A receiver which could be developed within a year, would be an image-enhanced mixer followed by a FET amplifier, both cooled to 77K, which would have a noise temperature of <600K (Whelehan (AIL), private communication). Paramps constructed above 40 GHz have noise figures comparable to mixer receivers; significant improvement should occur when pending developments become reality.

C. TECHNOLOGY LIMITS AND 1983 PREDICTIONS

A theoretical analysis by various persons (e.g., Fukui (Bell Labs), Taub (AIL)) suggests that the minimum noise figure for a GaAs FET with a 0.25 μm gate length is 0.5 dB at 4 GHz, 2.2 dB at 20 GHz, and 4.5 dB at 40 GHz. The minimum noise figure is limited by the GaAs material characteristics, device parasitics (e.g., gate to source capacitance, gate and source resistance and inductance), and device geometry of which the gate length seems to be the most important. Reducing gate lengths to less than 0.1 μm does not seem to be practical from a construction standpoint or a device physics point of view. The theoretical curve for minimum noise figure based on current theories (e.g., Taub (AIL) private communication) is plotted in Figure II-3 along with the laboratory data from Figure II-2. This curve likely represents the state-of-the-art in 1983; the spaces between the data points and the curve indicate where significant improvements can be made. As seen in Figure III-3, the significant improvement (>1 dB) in the noise figure is possible only above 20 GHz where relatively little work has been done. Below 20 GHz, commercial and military interests have pushed and will continue to push developments of low-noise devices so that no additional development support is necessary; however, there are aspects such as cooling and reliability which will require support.

Above 40 GHz, the device which offers the most promise for significant improvement is the image enhanced (IE) mixer. Curves of the 1978 and 1983 IE mixers' performance are shown in Figure II-4 and are based on information obtained from J. Whelehan at AIL. The main limitation on performance of IE mixers in the 40- to 100-GHz frequency range is the circuit design around the diode (e.g., mixer mount), which must properly terminate all the frequencies produced in the mixer. Excellent progress has been made in the circuit area at 35 GHz, where a conversion loss of 2.2 dB was measured (Taub, (AIL), private communication), and this should be applicable to the 40- to 100-GHz mixers with little degradation. Another limitation is the diode noise, but progress on tailoring the epitaxial layer doping profiles may improve this factor--especially for the cooled mixers (Schneider, et al. 1977).

The state-of-the-art curves for 1978 and 1983 for paramps are also shown in Figure II-4 and are based on data from LNR and AIL. Above 40 GHz, there is little difference between the 1983 paramp and cooled IE mixer curve. Given the significant development program required for the paramp (pump sources to 300 GHz and very low-loss circuits and ferrites) vs the straightforward program for the relatively simple IE mixer, development of paramps in this frequency range is not recommended for this NASA program.

D. TECHNOLOGY OPPORTUNITIES FOR LOW-NOISE RECEIVERS

One general problem area which was mentioned by many GaAs FET manufacturers is the need for a U.S. supplier capable of delivering high quality GaAs in large quantities. Currently, there is only one small U.S. supplier of GaAs that is satisfactory (according to most manufacturers) for very low-noise FETs (Crystal Specialties). Many of the larger users of GaAs are dependent on Japanese suppliers for high quality GaAs. A

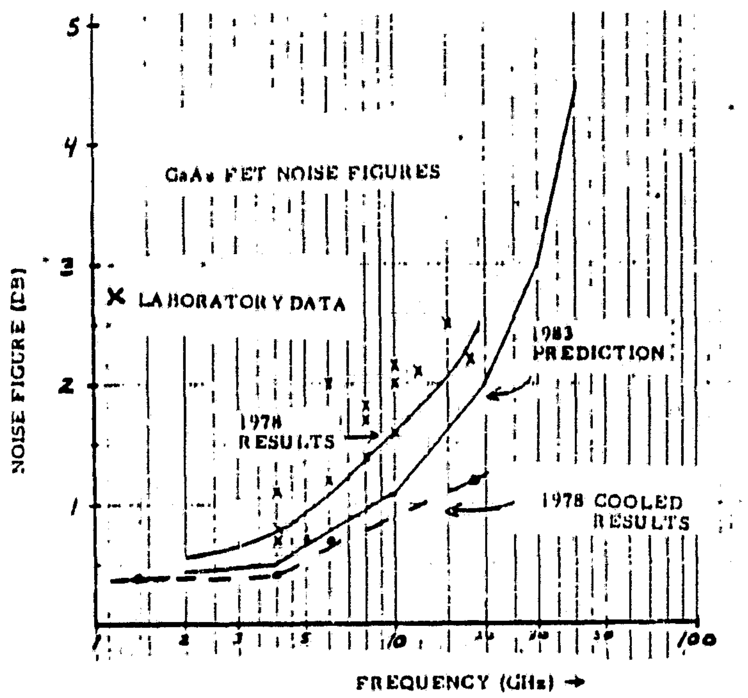


Figure II-3. GaAs FET Noise Figures

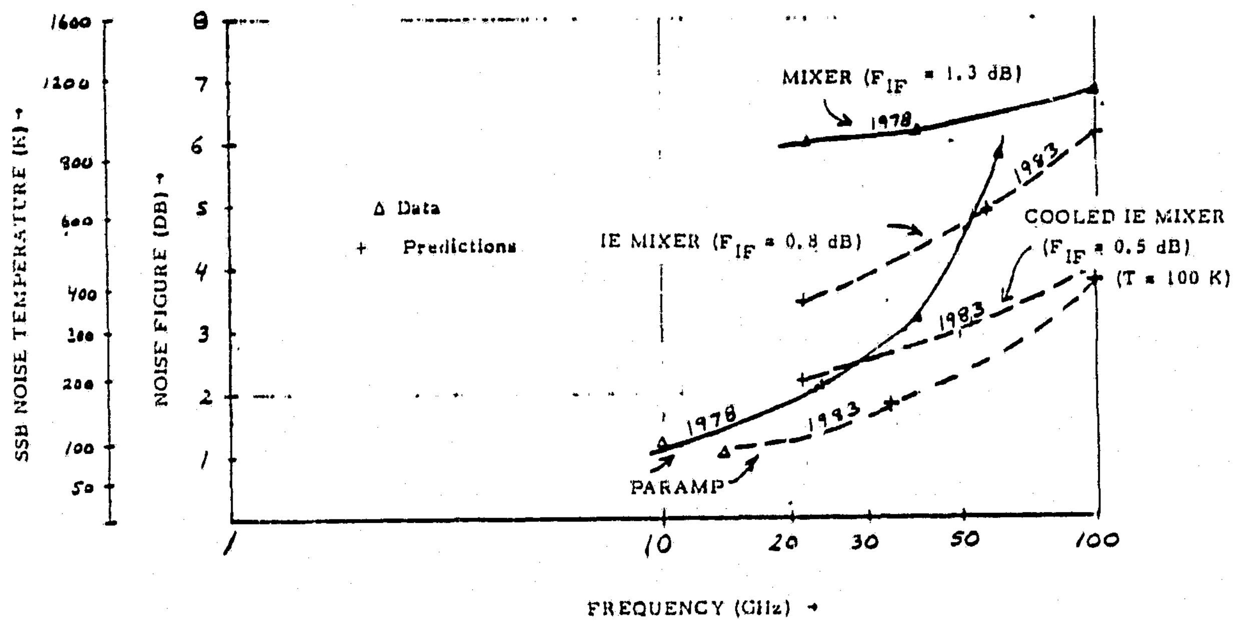


Figure II-4. Paramp and Mixer Receivers

number of FET manufacturers recommended that a research program to produce pure GaAs material with fewer dislocation centers be started. This program would require about $300K/year for approximately 3 years.

Another general area in low-noise receivers is the requirement for low cost, reliable, small refrigerators for cooling the input stages of the amplifiers to about 100K for the low-noise performance. In the satellite, passive coolers should be developed for the same task. Work in the satellite area has been done for IR sensors, and this could be applied to the GaAs FET stages.

Recommendations for the development of specific low-noise devices can be broken into separate frequency ranges: <20 GHz, 20 to 40 GHz, and >40 GHz. These programs could be conducted simultaneously or, depending on the actual frequency range of the satellite system, only the device which is required could be supported.

For frequencies <20 GHz, NASA support for device and amplifier development is not required since very little improvement could be realized. However, a program on cooling FET amplifiers to approximately 100K, to gain the factor of 2 to 3 reduction in noise temperature is necessary as little work is being supported in this area. Development of a cooled FET amplifier would include optimization of the device for cooling in terms of doping levels and epitaxial layer doping profiles, design of proper matching circuits at the cold temperatures, and construction of an amplifier which could be reliably cycled between 300K and 100K. Development of a cooled FET amplifier might require 2 years at a level of $200K/year.

Another program for devices <20 GHz is an extensive reliability program which will be necessary to obtain space qualified components. Many devices would be tested under dc bias conditions (rf signals would probably not be necessary for these small signal devices) for long periods to determine long-life failures. It would also be necessary to define failures in terms of degradations of gain and noise figure. This program would require about 3 years at the $250K/year level. Devices tested would be those used in the specific designs.

In the 20- to 40-GHz region, a more ambitious program will be required since little development is occuring in this frequency range. The first step would be to develop a device and amplifier at the frequency of interest, (e.g., 30 GHz). A cooled version would also be required, and then reliability studies of the amplifier would be necessary. This program would require about 2 years for the amplifier development at approximately

$400K/year, about 2 years for the cooled amplifier at $200K/year, and 2 to 3 years for the reliability studies at approximately $250K/year. These programs could occur concurrently. It should be noted that AFAL has GaAs FET development programs in this frequency range and that results of these programs should be studied in the design of a NASA-supported program.

Above 40 GHz (i.e., from 40 to 100 GHz), a program to develop image enhanced (IE) mixer receivers is recommended. This would include room temperature and cooled versions. The advantage of image enhanced mixers is that they offer 2- to 3-dB improvements in noise in this frequency range. As discussed earlier, cooled IE mixers offer nearly the best noise performance of any device, and they are basically very simple devices, which could make very reliable and solid state LO's available. The development program would be for 2 years at a cost of $300K/year. An additional year would be required for reliability studies. Because of developments at lower frequencies, achievement of these goals is fairly certain.

If a direct broadcast satellite is chosen for satellite mission, then development of an integrated receiver for the ground stations--which includes a preamp/mixer, local oscillator, and IF amplifier all in one package--should be started. Work is proceeding at about 10 GHz in this area and could be extended to any frequency range. The advantages of this would be a reliable receiver which could be mass produced at a moderately low cost. An estimate for a 90-GHz receiver was made at $500/unit on a volume basis (Cardiasmenos (Alpha Industries), private communication).

ORGANIZATIONS/PERSONS CONTACTED FOR CHAPTER II

The Aerospace Corporation (El Segundo, CA); M. Millea, Electronics Research Laboratory (March 8, 1978).

AIL (Melville, NY); M. Lebenbaum, J. Taub, B. Weisfeld, J. Whelehan, Applied Electronics Division (April 6, 1978).

Alpha Ind./TRG Division (Woburn, Mass.); B. Cardiasmenos, F. Leith, J. Angus (April 7, 1978).

Avantek (Santa Clara, CA); H. Cooke, J. Starret (March 23, 1978).

Bell Telephone Laboratories (Holmdel, NJ); R. Linke (March 8, 1978).

California Eastern Labs (Burlington, CA); J. Arden (March 17, 1978).

Hewlett Packard/Microwave Semiconductor Division (Palo Alto, CA); J. Barrera (March 22, 1978).

Hewlett Packard/Solid State Laboratory (Palo Alto, CA); C. Liechti (March 22, 1978).

Hughes Electron Dynamics Division (Torrance, CA); G. Ladd (March 17, 1978).

LNR Communications, Inc. (Hauppauge, NY); F. Arams (April 4, 1978).

Rockwell International Science Center (Thousand Oaks, CA); R. Kuvas, S. Long (March 22, 1978).

Rockwell International Science Center (Thousand Oaks, CA); L. Bateria, D. Ball, D. Ch'en (April 24, 1978).

Royal Signals and Radar Establishment (Great Malvern, Worcester, WR 143PS, England); A. J. Grant (March 28, 1978 and April 3, 1978 - Letters).

TRW (Redondo Beach, CA); D. Claxton, J. Leverton, M. Andres, A. Benudias (April 11, 1978).

BIBLIOGRAPHY FOR CHAPTER II

Abronson, C., "FET Amplifiers: The Viable Alternative," Microwave System News, 8 (February 1978) p. 29.

Adair, J. E., "Millimeter Wave Radiometry Developments," Microwave Journal, 20 (November 1977) p. 32.

Airborne Inst. Labs., "Low-Noise Paramps for Satellite Communication Earth Stations," Microwave System News, 4 (1974) p. 27.

________________, "A SatCom K_a-Band Paramp," Microwave Journal, 18 (February 1975) p. 11.

Akaike, M., and K. Ohnishi, "A Non-Linear Analysis of Schottky-Barrier Diode Up-Converters," IEEE Trans. MTT, MTT-25 (1977) p. 1059.

Allen, C. M., and P. Lombardo, "Spaceflight-Qualified Miniature S-Band Parametric Amplifier Assembly," National Aerospace and Electronics Conference, Dayton, Ohio (May 1977).

Arams, F. R., and P. Lombardo, "Recent Developments in C-Band and K_u-Band SatCom Receivers," LNR preprint (1978).

Arams, F. R., and H. C. Okean, "State-of-the-Art Low Noise Receivers for Microwave and Millimeter-Wave Communications," Proc. Nat. Telecommunications Conf., Dallas (1978) pp. 48.5-1.

Arden, J. A., "The Care and Feeding of GaAs FETs," Microwave Journal, 19 (September 1976) p. 55.

________________, "The Design Performance and Application of the NEC V244 and V388 Gallium Arsenide Field Effect Transistors (GaAs MESFET)," Application Note, California Eastern Labs. AN 769, (June 1976).

Avantek, "6.5 to 16.5 GHz GaAs FET Amplifier," Microwave Journal, 20 (August 1977) p. 62.

________________, "7 to 15 GHz GaAs FET Thin-Film Amplifier," Microwave Journal, 19 (May 1976) p. 46.

Avantek, "GaAs FET Device and Amplifier Development," Microwave Journal, 21 (January 1978) p. 39.

Barrera, J. L., "GaAs FET Explosion Keeps Gaining Momentum," Microwave System News, 7 (December 1977) p. 73.

________________,"Microwave Transistor Review," Microwave Journal, 19 (February 1976) p. 28.

Bearse, S. V., "Impatts, GaAs FETs and TWTs Deemed Most Likely to Succeed," MicroWaves, 15 (July 1976) p. 14.

________________,"Special Report: GaAs FETs: Device Designers Solving Reliability Problems," MicroWaves, 15 (February 1976) p. 32.

Bernues, F., H. J. Kuno, and P. A. Crandell, "GaAs or Si: What Makes a Better Mixer Diode?" MicroWaves, 15 (March 1975) p. 46.

Besser, L., and S. Swenson, "Take the Hassle out of FET Amp Design," Microwave System News, 6 (September 1976) p. 97.

Bierman, H., " 'Old World' Technology? Don't Believe It!" MicroWaves, 15 (November 1976) p. 35.

Blum, F. A., "FETs: Cost and Integration will be the Next Goal," Microwave System News, 8 (February 1978) p. 40.

Brand, F., "Compound Semiconductors - An Impending Crisis in Materials," Microwave Journal, 21 (February 1978) p. 16.

________________, "Current Status of Microwave Technology: Microwave Solid State Devices," Microwave Journal, 19 (May 1976) p. 18.

Calviello, J. A., and J. L. Wallace, "Novel GaAs Metallized Diode Configuration to Reduce Skin-Effect Contributions at High Frequencies," Elect. Letters, 12 (November 1976) p. 648.

________________, "A Novel GaAs Metallized Schottky Diode for High Performance Millimeter-Wave Application," 6th ARPA/Tri-Service Millimeter-Wave Conference, Adelphi, Maryland (November 1977).

Calviello, J. A., and J. L. Wallace, "Performance and Reliability of an Improved High Temperature GaAs Schottky Junction and Native-Oxide Passivation," IEEE Trans. on Elec. Dev., ED-24 (1977) p. 698.

Cooke, H. F., "Microwave FETs - A Status Report," IEEE Solid-State Circuits Conf., THAM 10-1 (February 1978) p. 116.

__________, "Microwave Field Effect Transistors in 1978," Microwave Journal, 21 (April 1978) p. 43.

Cooper, J. F., and M. S. Gupta, "Microwave Characterization of GaAs MESFET and the Verification of Device Model," IEEE Trans. Solid-State Circuits, SC-12 (1977) p. 325.

Cowan, D. A., P. Mercer, and A. Bell, "Low-Noise and Linear FET Amplifiers for Satellite Communications," IEEE Trans. on MTT, MTT-25 (1977) p. 995.

Cuccia, C. L., "1976 IRDP Millimeter-Wave Spacecraft Technology," Propagation Considerations in 20/30 GHz Satellite Communications, Part I, - The ATS-6 Experience, 7 (1976).

__________, "Status Report: Microwave Communications Update - 1976," Microwave System News, 6 (February/March 1976) p. 43.

__________, "Status Report: Modern Low-Noise Amplifiers in Communication Systems," Microwave System News, 4 (August/September 1974) p. 120.

__________, "Status Report: Modern Low-Noise Amplifiers in Communication Systems II," Microwave System News, 4 (October/November 1974) p. 52.

__________, "Status Report: Solid-State Baseline of Telecommunications into the 1980's," Microwave System News, 6 (April/May 1976) p. 97.

Cuccia, C. L., and P. T. Ho, "The Impact of the FET on the Satellite Transponder - A Technology Perspective," Ford preprint, (1978).

Davis, R. T., and J. Jordan, "FET Scoreboard," Microwave System News, 7 (February 1977) p. 70.

Davis, R. T., "Special Report: Cruise Missile Technology, Millimeter-Waves: A Solution that has Finally Found a Problem," Microwave System News, 7 (September 1977) p. 63.

deLeon, J. C., "InP Gunn-Effect Devices Begin to Surface in the U.S. and GaAs FETs Step Up to K-Bank," MicroWaves, 16 (February 1977) p. 12.

Dickens, L. E., and D. W. Maki, "An Integrated-Circuit Balanced Mixer, Image and Sum Enhanced," IEEE MIT, MTT-23 (1975) p. 276.

DiLorenzo, J. V., "GaAs FET Development - Low Noise and High Power," Microwave Journal, 21 (February 1978) p. 39.

Douville, R. J., "A 12-GHz Low-Cost Earth Terminal for Direct TV Reception from Broadcast Satellites," IEEE Trans. on MTT, MTT-25 (1977) p.1000.

Edrich, J., "A Cryogenically Cooled Two Channel Paramp Radiometer for 47 GHz," IEEE MTT, MTT-25 (April 1977) p. 280.

Emery, F. E., "Low Noise GaAs FET Amplifiers," Microwave Journal, 20 (June 1977) p. 79.

Frey, J., "Effects of Intervalley Scattering on Noise in GaAs and InP FETs," IEEE Trans. Elec. Dev., ED-23 (December 1976) p. 1298.

Gibbons, G., "InP Devices Promising but Challenging," Microwave System News, 8 (February 1978) p. 42.

Glaze, G. E., and G. H. Hobbs II, "FET Amplifier Spans 4 - 12 GHz," Microwave Systems News, 8 (February 1978) p. 49.

Goel, J., and H. J. Wolkstein, "A 4 - 8 GHz Dual-Gate Amplifier," IEEE Solid State Circuits Conf., THAM 10-6 (February 1978) p. 126.

C-2

Grant, A. J., A. M. White, and B. Day, "Low Frequency Noise and Deep Traps in Schottky Barrier Diodes," Proc. 5th Inter. Conf. on Noise in Physical Systems, Bad Havheim (1978).

Hennies, S. R., "A 7 - 18 GHz Amplifier Using GaAs FETs," IEEE Solid State Circuits Conf., THAM 10-5 (February 1978) p. 124.

Henry, P. S., B. S. Glance, and M. V. Schneider, "Local Oscillator Noise Cancellation in the Subharmonically Pumped Down-Converter," IEEE Trans. MTT, MTT-24 (1976) p. 254.

Higgins, J. A., et al., "GaAs FETs Fabrication by Selenium Ion Implantation," Proc. of North American Gallium Arsenide Symposium, Inst. of Phys. Publs. Division, Technohouse, Redcliffe Way, Bristol, BF1 6NS, England (1977)

________________, "Low-Noise GaAs FETs Prepared by Ion Implantation," IEEE Trans. Elect. Devices (June 1978).

Hislop, A., and R. T. Kihm, "A Broad-Band 40 - 60 GHz Balanced Mixer," IEEE Trans. MTT, MTT-24 (1976) p. 63.

Hughes, "Balanced Mixer-Preamp-LO Assembly Opens New Opportunities at 94 GHz," MicroWaves, 15 (October 1976) p. 62.

________________, "Harmonic Generators Over 26.5 - 140 GHz," Microwave Journal, 21 (January 1978) p. 83.

________________, "Hughes Unveils New 38-GHz Radio," Microwave System News, 6 (February/March 1976) p. 13.

________________, "Single-Ended Mixers Extended to 170 GHz: 90 - 140 and 110 - 170 GHz Intervals," Microwave System News, 8 (February 1978) p. 86.

Hundley, R. E., P. Estabrook, and E. J. Crescenzi, Jr., "Small Low Gain Amplifiers for Front End Designs," Microwave Journal, 21 (February 1978) p. 47.

Kelly, A. J., and H. C. Okean, "A Low Noise Millimeter MIC Mixer," IEEE Trans. on MTT, MTT-24 (1976) p. 867.

Kelly, A. J., and H. C. Okean, and S. J. Foti, "Low Noise Microwave and Millimeter Wave Integrated Circuit Mixers," LNR preprint (1978).

Kennedy, W. K., "FET Technology: An Overview," Microwave System News, 8 (February 1978) p. 47.

Kerr, A. R., "Low-Noise Room Temperature and Cryogenic Mixers for 80 - 120 GHz," IEEE Trans. on MTT, MTT-23 (1975) p. 781.

Knamuri, N., and R. Kawasaki, "Design and Performance of a 60 - 90 GHz Broadband Mixer," IEEE Trans. on MTT, MTT-24 (1976) p. 259.

Konishi, Y., "12 GHz FM Broadcast Satellite Receiver," Microwave Journal, 21 (January 1978) p. 55.

Lax, B., "Evolution of Millimeter Waves," Microwave Journal, 19 (May 1976) p. 26.

Lazarus, M. J., and S. Novak, "Improved MicroWave Gunn-Mixer Receivers," Microwave Journal, 20 (March 1977) p. 43.

Leber, A., T. Flattau, and P. Meier, "A Low-Cost Rugged 35-GHz Tactical Radiometric Sensor," AIL preprint (November 1977).

Liechti, C. A., "Microwave Field Effect Transistors - 1976," IEEE MTT, MTT-24 (1976) p. 279.

Liechti, C. A., and R. B. Larrick, "Performance of GaAs MESFETs at Low Temperatures," IEEE MTT, MTT-24 (1976) p. 376.

Lindauer, J. T., and N. K. Osbrink, "GaAs FETs are Closing Fast on the Low Noise, Narrowband Leaders," Microwave System News, 6 (April/May 1976) p. 63.

LNR Communications, "Hybrid Paramp Downconverters Cover 2.2 to 35 GHz," MicroWaves, 15 (January 1976) p. 63.

LNR Communications, "LNAs for K_u-Band Ground Terminals," Microwave Journal, 21 (January 1978) p. 74.

________________, "New Uncooled 15 GHz Paramp Measures 80 K - Approaches Cryo-Paramp Noise Temperatures," LNR News (1978).

Magarshack, J., "FETSs: Improving Performance and Reliability," Microwave System News, 8 (February 1978) p. 38.

Mazur, D. G., et al., "40 and 80 GHz Technology Assessment and Forecast," NASA-CR-135028 (May 1976).

McColl, M., "Conversion Loss Limitations on Schottky-Barrier Mixers," IEEE Trans. on MTT, MTT-25 (1977) p. 54.

McMaster, T. F., M. V. Schneider, and W. Snell, Jr., "Millimeter-Wave Receivers with Subharmonic Pump," IEEE Trans. on MTT, MTT-24 (1976) p. 948.

Medley, M. W., Jr., "Stretch FET Amp Design Beyond Octave Bandwidths," MicroWaves, 16 (May 1977) p. 54.

Microwave Journal Staff, "GaAs FETs - Market and Technology Review," Microwave Journal, 21 (February 1978) p. 22.

Millea, M. F., "Improved MESFET Performance, The Aerospace Corporation, Aerospace IOC, 77(4030)SSE-127 (July 1977).

Miller, R. E., et al., "Noise Performance of Microwave GaAs FET Amplifiers at Low Temperatures," Electronic Letters, 13 (January 1977) p. 10.

Moncrief, F. J., "FETs: Reaching for Higher Power and Frequency," Microwave System News, 8 (February 1978) p. 13.

Narda Microwave Corp., "Solid-State Amps can Replace TWTs," Microwave System News, 7 (October 1977) p. 117.

NASA, "Microwave Space Receivers," A Forecast of Space Technology 1980-2000, NASA SP-387 (1976) pp. 3-45.

Niehenke, E. C., "An Environmentalized Low-Noise Parametric Amplifier," IEEE Trans., MTT-25 (1977) p. 992.

Nussbaum, S., and E. Sard, "Broadbanding a K_a-Band Parametric Amplifier," Microwave Journal, 20 (November 1977) p. 57.

Ohata, K., T. Nozaki, and N. Kawamura, "Improved Noise Performance of GaAs MESFETs with Selectively Ion-Implanted n^+ Source Regions," IEEE Trans. Elect. Devices, ED-24 (1977) p. 1129.

Okean, H. C., et al., "K_a-Band Paramp-Downconverter Satellite Communications Receiver," LNR preprint (1978).

Okean, H. C., and A. J. Kelly, "Low Noise Receiver Design Trends Using State-of-the-Art Building Blocks," IEEE-MTT, MTT-25 (1977) p. 254.

Peterson, C., "GaAs FET -- A Bilateral Device," Microwave Journal, 20 (January 1977) p. 53.

Pierro, J., "Cryogenically Cooled GaAs FET Amplifier With a Noise Temperature Under 70 K at 5.0 GHz," IEEE MTT, MTT-24 (1976) p. 972.

PLAMIC, "GaAs FET Amps Cover 4 - 8 and 6 - 12 GHz," Microwave System News, 7 (September 1977) p. 124.

Pucel, R. A., H. A. Haus, and H. Statz, "Signal and Noise Properties of Gallium Arsenide Microwave Field-Effect Transistors," Adv. Electron Phys., 5 (1975) p. 195.

Pucel, R. A., D. J. Masse, and C. F. Krumm, "Noise Performance of Gallium Arsenide Field-Effect Transistors," IEEE Solid State Circuits, SC-11 (1976) p. 243.

Rees, H. D., and K. W. Gray, "Indium Phosphide: A Semi-Conductor for Microwave Devices," IEEE Solid State and Elect. Devices, 1 (September 1976) p. 1.

RYT Industries, "GaAs FET Amplifier Offers 1.55 dB Noise Figure 3.7 - 4.2 GHz" Microwave System News, 7 (November 1977) p. 87.

Schneider, M. V., and W. W. Snell, "Harmonically Pumped Stripline Down-Converter," IEEE Trans. on MTT, MTT-23 (1975) p. 271

Schneider, M. V., R. A. Linke, and A. Y. Cho, "Low-Noise Millimeter-Wave Mixer Diodes Prepared by Molecular Beam Epitaxy (MBE)," Applied Physics Letters, 31 (August 1977) p. 219.

Sechi, F. N., and R. W. Paglione, "Design of a High-Gain FET Amplifier Operating at 4.4 - 5.0 GHz," IEEE Trans. Solid State Circuits, SC-12 (1977) p. 285.

Sekido, K., and J. A. Arden, "Recent Advances in FET Device Performance and Reliability," Microwave System News, 6 (May 1976) p. 71.

Snell, W. W., and M. V. Schneider, "Millimeter-Wave Thin Film Down-Converter," IEEE Trans. on MTT, MTT-24 (1976) p. 804.

Turner, J., "The Versatile FET Expands Its Horizons," Microwave System News, 8 (February 1978) p. 71.

Vendelin, G. D., "Five Basic Bias Designs for GaAs FET Amplifiers," MicroWaves, 17 (February 1978) p. 40

Vernon, F. L., Jr., et al., "The Super-Schottky Diode," IEEE Trans. on MTT, MTT-25 (1977) p. 286.

Wade, P., "Ask Tough Questions About GaAs FET Specs.," MicroWaves, 16 (October 1977) p. 82.

Walker, M. G., F. A. Marki, and H. M. Abrumowitz, "MESFET Amplifiers go to 18 GHz," Microwave System News, 6 (April/May 1976) p. 39.

Watkins-Johnson, "W-J Producing FETs with Liquid Phase Epi," Microwave System News, 7 (November 1977) p. 17.

Weinreb, S., et al., "Multiband Low Noise Receiver for a Very Large Array," IEEE-MTT, MTT-25 (1977) p. 243.

Weissglas, P., "Microwave Semi-Conductors: What's Ahead?" Microwave System News, 8 (February 1978) p. 35.

Whelehan, J., "Low-Noise Millimeter-Wave Receivers," IEEE-MTT, MTT-25 (1977) p. 268.

Whelehan, J., E. Kraemer, and H. Paczkowski, "Millimeter-Wave Paramp with a Solid State Pump Source Operating in the 55 - 65 GHz Range," Microwave Journal, 16 (November 1973) p. 38.

Wilson, W. J., "1975 State-of-the-Art of 5 GHz to 250 GHz Receivers," The Aerospace Corporation, Aerospace Technical Memorandum No. ATM-75(5030)-1, (May 1975).

Wollins, B., "Power (9.5 W) and Low Noise (0.7 dB NF) GaAs FETs in Lab Now, Say Researchers at Cornell Conference," MicroWaves, 16 (October 1977) p. 18.

Wrixon, G. T., "Select the Best Diode for Millimeter Mixers," MicroWaves, 15 (September 1976) p. 56.

Yuan, L. T., "Design and Performance Analysis of an Octave Bandwidth Waveguide Mixer," IEEE Trans. on MTT, MTT-25 (1977) p. 1048.

CHAPTER III

SATELLITE TRANSMITTERS

Prepared by

S. W. Lewinter
Communications Department

CONTENTS FOR CHAPTER III

LIST OF ILLUSTRATIONS FOR CHAPTER III

CHAPTER III

SATELLITE TRANSMITTERS

A. OVERVIEW

Radio frequency (rf) power sources suitable for use in satellite transmitters employ a variety of technologies, ranging from the relatively mature to those currently undergoing intensive development. Salient electrical parameters characterizing any rf power amplifier include power output, efficiency, gain, frequency band, bandwidth, and linearity. For a space mission, reliability, long life, stability, and suitability in the space environment are paramount considerations.

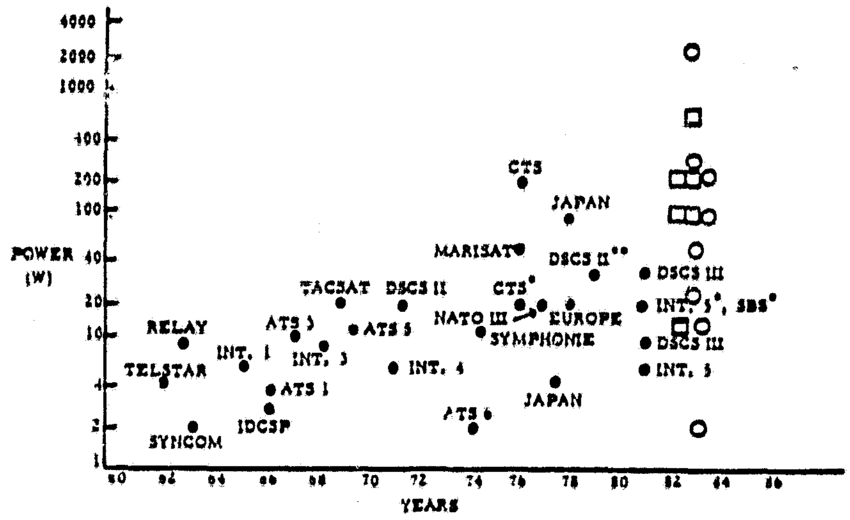
Several types of power sources were considered in this study. These include traveling-wave tube amplifiers (TWTA), gallium arsenide field effect transistors (GaAs FET), IMPATT diodes, electron bombarded semiconductor (EBS) devices and power combiners. The latter are not power sources as such; rather, they are a class of techniques for achieving relatively high-power output using low-power devices.

The applicability of each technology is determined by the requirements of the system. In turn, technology both constrains and defines the major outlines of a system design. The selection of a particular type of power source and its associated characteristics is an interactive process which may depend, for example, on new developments in antennas or the method of modulation that is preferred. While much has been said about solid-state devices replacing tubes, the facts seem to be that for the foreseeable future each will have a role to play in satellite communications.

B. TRAVELING-WAVE TUBE AMPLIFIERS

1. HISTORY OF TWTAs

TWTAs have been with us for at least 20 years (Figures III-1 and III-2). They have been extensively developed; their theory is well understood; and they have been successfully used in space missions for a number of years. The requirements placed on TWTAs used for space communication in recent years have increased significantly. For applications demanding less power output, the newer solid-state devices will suffice. However, for the higher power, higher frequency applications, it appears that TWTAs must maintain a significant role. To maintain this role,



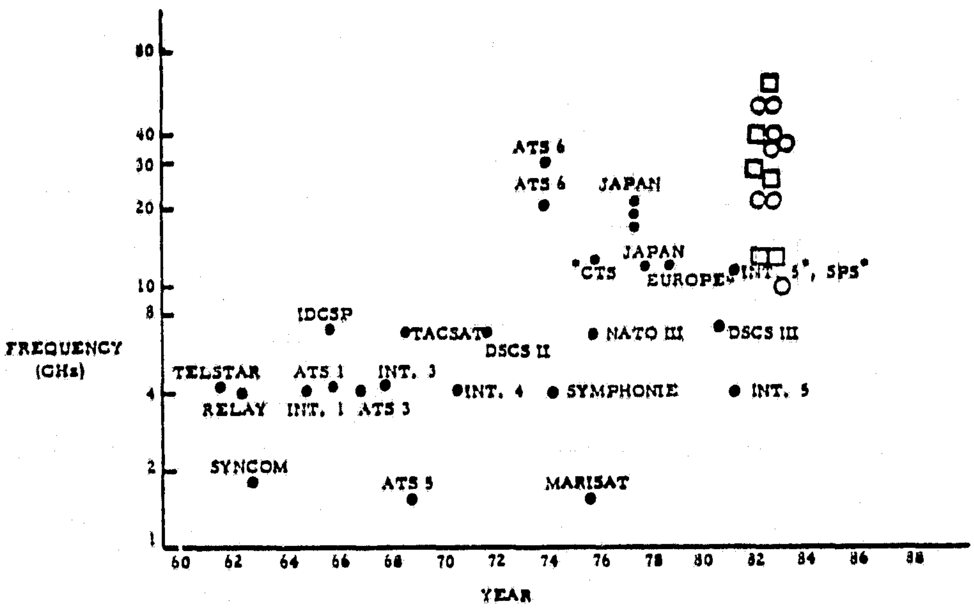
*THESE SATELLITES USE A EUROPEAN TWT (20W, 11-12 GHz) - ALL OTHERS USE U.S. TUBES

**LATER MODEL DSCS II WILL USE 40W TUBE

□ HUGHES PROJECTIONS

○ WATKINS-JOHNSON PROJECTIONS

Figure III-1. History of Space TWTAs - Power (W)



*THESE SATELLIES USE A EUROPEAN TWT

□ HUGHES PROJECTIONS

○ WATKINS-JOHNSON PROJECTIONS

Figure III-2. History of Space TWTAs - Frequency (GHz) manufacturing techniques, processes and procedures must be improved, and quality control must be more stringent. Above all, the United States must reassert its technological leadership, which in this field may now belong to the Europeans. Critical design requirements for space communication TWTAs include:

- Long life (typically 7 to 10 years),
- Higher frequencies,
- Higher efficiencies (in some cases), and
- Higher power.

2. STATE-OF-THE-ART OF TWTAs

Power and frequency trends are depicted on the accompanying chart (Figure III-3). Higher efficiency requires maintaining tight tolerances and using a more complicated mechanical design (e.g., triple collectors). Long life is achieved by low cathode current density, low outgassing of components, and high component stability. Unfortunately, the trend toward higher frequencies and higher power necessitates higher cathode current density, which results in the need for improved cathodes. Similarly, there is a need to develop attenuator materials having higher stability and compatibility with the support structure. Materials and processes are needed to minimize outgassing of traveling-wave tube components. Finally, it must be noted that the high-voltage power supply required by a TWT is often as much of a reliability problem as the tube itself.

Recognizing the key role played by TWTAs in the operation of satellite communications systems, there has been a considerable effort within The Aerospace Corporation to maintain current awareness and knowledge of all aspects of TWTA technology, production, test, and reliability issues. In mid-1976 an ad hoc TWTA Committee was formed which included representatives from the Air Force Space and Missile Systems Organization (SAMSO) and The Aerospace Corporation. A program plan was prepared which resulted in individual programs in the areas of reliability analysis and failure assessment, materials, theoretical studies, performance requirements, and manufacturing processes. Other government agencies (e.g., NASA/Lewis Research Center) and TWTA vendors were involved, as appropriate. The Aerospace Laboratory provided support by investigating failures in TWTs and resolving design and quality control problems. Much of the material, in particular the identification of required TWTA technology programs presented in this report, is the result of consultation with key people within The Aerospace Corporation who have been associated with these efforts.

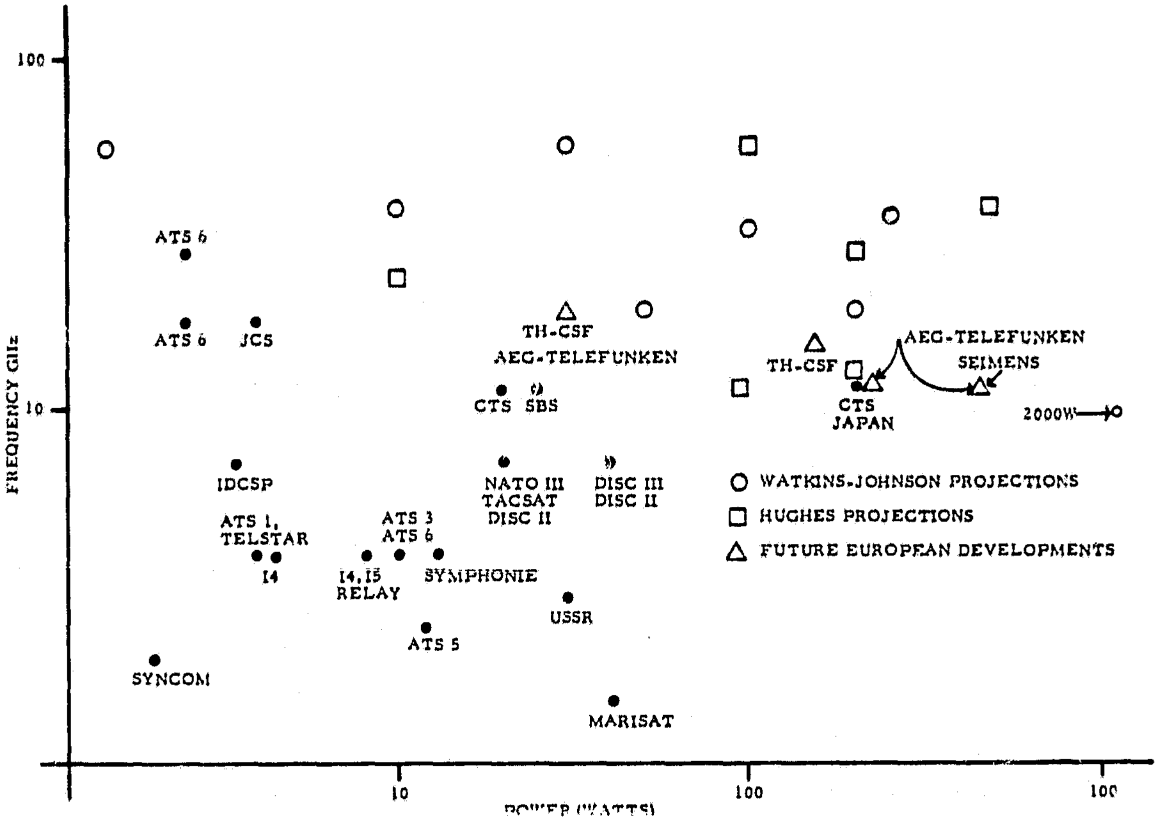


Figure III-3. State of the Art - TWTs

3. TECHNOLOGY OPPORTUNITIES

The technology opportunities are listed under the following three general study areas.

- Applications
  - Output power stage in high-power transmitter
  - Driver stage for high-power transmitter
  - Linear amplifier above approximately 25 GHz
- Technology Limits
  - Life of cathode
  - Trade-off between power and frequency
    - Helix tube upper frequency limited to approximately 60 GHz
    - Coupled cavity tube frequency limit to approximately 94 GHz
  - Limited bandwidth of coupled cavity tube
  - Effect of high-power TWTA on thermal balance
- Approach to development
  - Upper frequency limits not likely to be significantly extended
  - Cathode developments
  - Internal attenuator developments
  - Collector developments
  - Encapsulation developments
  - Accelerated life test method
  - Benefit from European developments
  - Near-term payoff possible

Technology development programs required to further the state-of-the-art of TWTAs are listed below.

- Cathode developments
  - Oxide cathodes fairly well understood
  - Dispenser cathodes
    - Addition of rhenium, osmium
    - Operation at lower temperatures
    - Develop meaningful accelerated tests
  - Cold cathodes
- Internal attenuator developments
  - Investigate tungsten carbide
  - Other materials

- Collector developments
  - For use with higher power, higher frequencies
  - Withstand on-off cycles
  - Triple collector development
- Encapsulation developments
  - Corona effects
  - Materials research
  - Minimize dependence on insulating materials
- Reliability assurance
  - Develop meaningful accelerated life tests
  - Begin testing early in the program.

To augment the validity of the above-mentioned findings, the two principal suppliers of space TWTAs in this country were visited. Discussions were held with key technical people in these organizations (i.e., the Watkins-Johnson Co. and the Hughes Corp.). Comsat Laboratories were also visited, because of the exposure of that organization to commercial communications satellites via the INTELSAT programs and their working relationship with European suppliers of TWTAs. These visits were documented by trip reports which were appended to the Draft Final Report and which are listed at the end of this chapter. A late input of European developments was also obtained from a paper presented at the AIAA 7th Communications Satellite Systems Conference held in San Diego during April 1978. (Paper No. 78-558 "European Capabilities in the Field of Microwave Tubes for Space Use," D. R. Madden, J. J. Smidt.)

C. GaAs FET POWER AMPLIFIERS

1. HISTORY OF GaAs FETs

Gallium arsenide microwave field-effect transistors (GaAs FET) became a practical reality during the early 1970s. Within a few years, their development had progressed to the point where GaAs FETs were replacing uncooled parametric amplifiers in earth stations at 4 and 7 GHz as low-noise devices. Space applications came shortly thereafter, initially as low-noise devices in the Communication Technology Satellite (CTS) and in the Japanese Communication Satellite (CS). Now the list of applications for GaAs FETs in space is expanding to include the role as a power amplifier. Interest in extending the application of GaAs FETs in this manner is particularly keen in view of the potential for their displacing the last significant application for vacuum tubes in space: the traveling-wave tube amplifier. Historically, solid-state devices offer orders of magnitude advantages over tubes in terms of reliability, size, weight and power. The interest in GaAs FETs as a replacement of TWTAs is largely based on the premise that similar benefits will accrue via their use.

While these hopes are in part well founded, the reliability of present day power GaAs FETs for a long life mission in space is not yet established. Certain GaAs FET electrical parameters (e.g., power output, efficiency) are likely to remain surpassed by TWTA for the foreseeable future. On the positive side, the potential reliability of GaAs FETs for a long life mission is orders of magnitude greater than for TWTAs. Better understanding of materials and metallization, better thermal design, and development of manufacturing technology are needed. Used with appropriate power combining technology, the GaAs FET will become a formidable competitor to TWTA, eventually displacing the latter for most space applications at frequencies above 4 GHz and below 25 GHz.

It should be emphasized that the future direction of power GaAs FET applications may not lie in a one-for-one plug-in replacement of TWTAs. Advances in antenna technology and the use of satellite-switched time division multiple access may reduce considerably the requirements for high power in space, except for broadcast applications.

2. STATE-OF-THE-ART OF GaAs FETs

The state-of-the-art of power GaAs FETs is depicted in Figure III-4. Three curves of power output versus frequency are shown: one curve corresponds to actual performance achieved in the laboratory today, and the other two curves represent the bounds of predictions for 1983. It must be borne in mind that today's most spectacular laboratory results are embodied in products that are not suitable for space missions. They are obtained from devices that are overstressed and therefore have limited life. One relatively conservative goal for a 5-year development program is, therefore, to upgrade today's laboratory products into devices that can be produced with good yield and high reliability. A more ambitious program would be to achieve the results shown as predictions for 1983 with a significant level of reliability assurance.

Curves similar to those just described were constructed to correspond with GaAs FET developments that were announced 1 year ago and 6 months ago, respectively. In conjunction with today's status and the 1983 range of predictions, a family of curves showing GaAs FET power output versus time was constructed (Figure III-5).

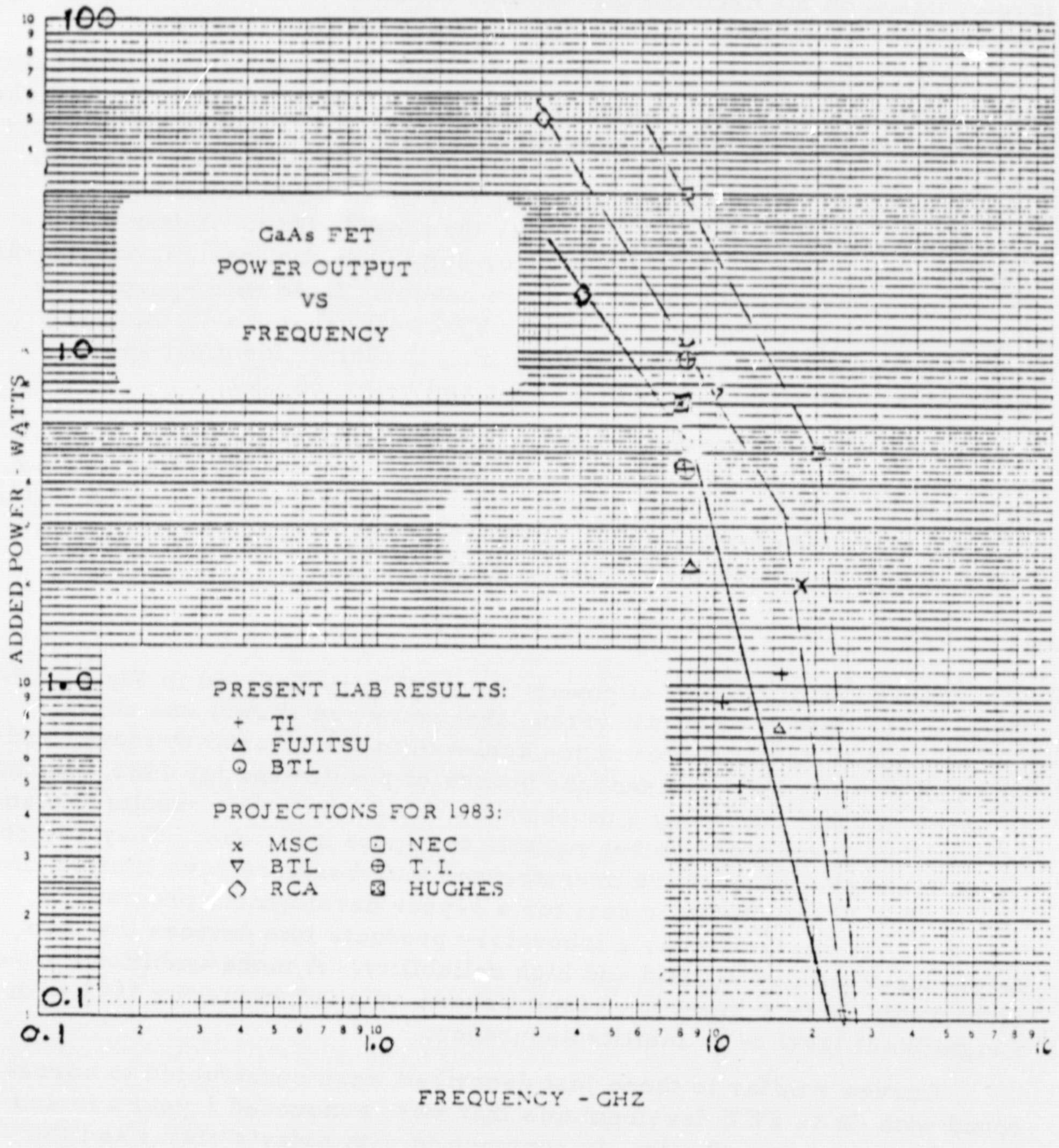


Figure III-4. GaAs FET Power Output vs Frequency

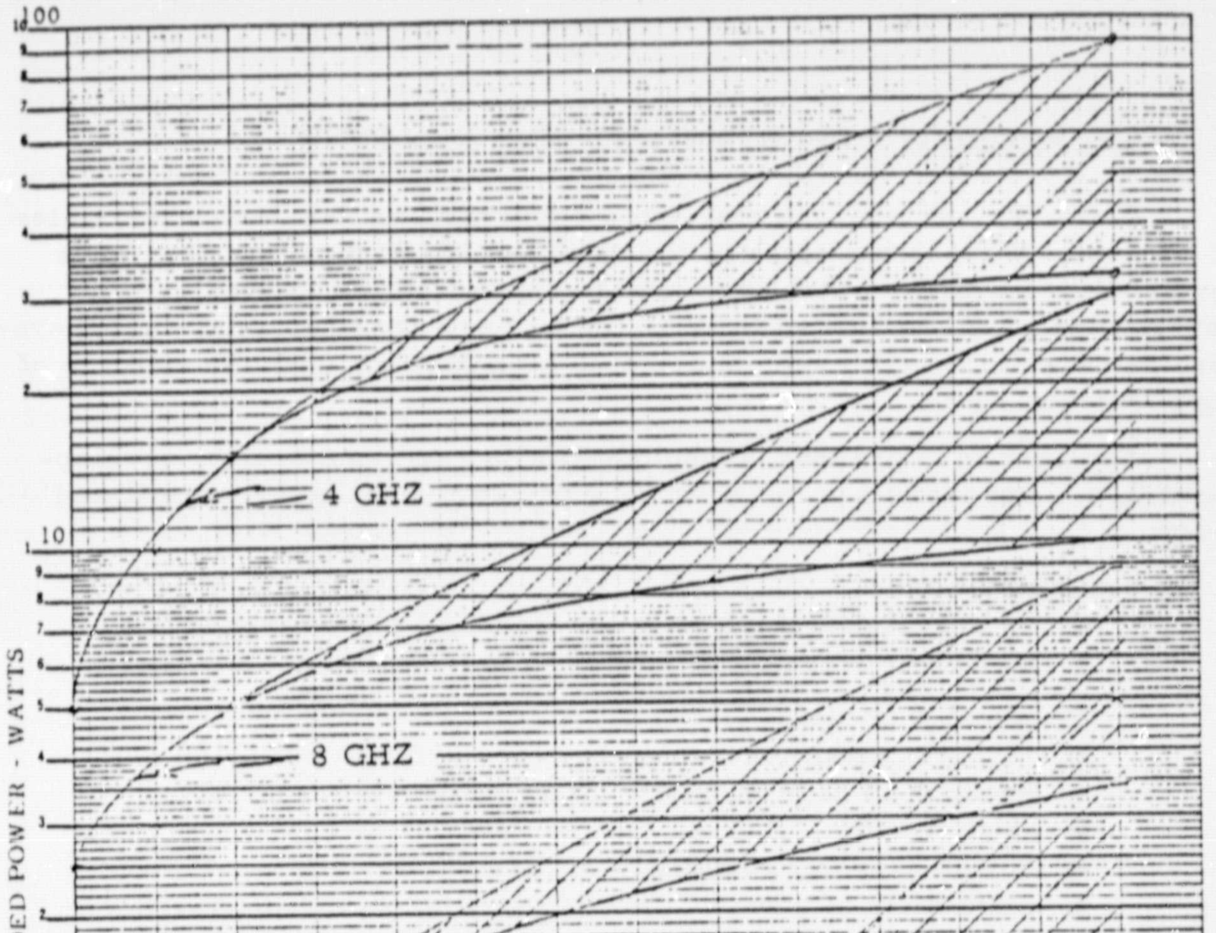


Figure III-5. Output Power GaAs FET Device Packages

3. TECHNOLOGY OPPORTUNITIES FOR GaAs FETs

From the curves, one may infer opportunities to advance the state-of-the-art. What is not clear is the extent to which these performance levels will be achieved through normal commercial incentives, what developments will be funded through the defense agencies, and what therefore remains to be achieved, and should be achieved, with the addition of support from NASA.

Applications, present technology limits, and approach to development (i.e., opportunities for advancing the state-of-the-art) are listed below.

- Applications
  - As output power stage in low-medium power transmitter
  - As driver stage for high-power transmitters
- Technology limits
  - ~25 GHz maximum frequency for useful output (>100 MW)
  - Production of high-purity GaAs substrate material
  - Metallization schemes that do not limit life
  - Power handling capability of thermal designs
  - Reliability of power GaAs FETs requires demonstration
- Approach to development
  - Maximum useful frequency of power GaAs FETs likely to remain below 30 GHz
  - Near-term payoff potential in materials, metallization, and thermal design programs
  - Development pace rapid with present funding levels
  - Reliability for space missions requires demonstration

The level of effort required in a 5-year program depends strongly on the specific goals and how far these goals must advance today's state-of-the-art. The following list contains required GaAs FET power amplifier technology programs.

- Materials programs
  - Substrate problems
  - Buffer layers
  - Surface stability
  - Passivation
  - Higher voltage operation

- Device processing
  - Submicron lithography development
  - Throughput and yield increase
- Metallization
  - Aluminum problems
  - Investigate alternative metal systems
  - Reliability must be demonstrated
- Thermal design
  - Improve device packaging
  - Decrease thermal resistance
- Combining technology
  - In-package combining
  - External circuit combining
- Reliability demonstration
  - RF life testing necessary

Examples of two development programs are shown in Table III-1. The first has the objective of developing a reliable 10-watt power amplifier at 12 GHz using GaAs FETs. The second program is for a 5-watt amplifier at 60 GHz using IMPATT diodes. (IMPATT diode amplifiers are separately treated in this report.) These program estimates are subjective in the sense that they assume an unspecified level of support from a mix of customer and internal company funding sources, with only the funding increment required for the specific identified goals being tabulated. Obviously, the mix of future funding sources is indeterminate at this time.

In reviewing the efficiency obtainable from power GaAs FETs, no consistent trend was found in present day devices. The efficiency decreases with increasing frequency, although the extent to which this degradation occurs is a function of the gate dimensions and the device packaging. At any one frequency, the efficiency of commercial GaAs FETs varies widely. This is shown in Table III-2 for a variety of devices at 8 GHz. Note that power-added efficiencies (at saturation) range from 15 to 30 percent. It should be emphasized that the overall amplifier efficiency is considerably less than the power-added efficiency of the output stage. This is due principally to the low gain of the power GaAs FET, necessitating a substantial driver chain, and to a lesser extent, to the losses in the power conversion equipment. Typically, a power GaAs FET will have a gain of 4 dB at saturation. Assuming a cascade of GaAs FETs, each having 30-percent power-added efficiency

Table III-1. Example Development Programs - Solid State Power Amplifiers

1. 12 GHZ GaAs FET AMPLIFIER
   10 WATTS POWER OUTPUT

	ENGINEERING (MAN-YEARS)
MATERIALS WORK (SUBSTRATE FABRICATION PROCESSES)	1
METALIZATION DEVELOPMENT	1
DEVICE THERMAL DESIGN & PACKAGING	2
RELIABILITY ENGINEERING	3
COMBINER DEVELOPMENT	2
PROCESS DEVELOPMENT (MANUFACTURING ENGINEERING)	3
TOTAL (PLUS SUPPORT)	12

2. 60 GHZ Si DD IMPATT DIODE AMPLIFIER
   5 WATTS POWER OUTPUT

DEVICE THERMAL DESIGN & PACKAGING	3
METALIZATION DEVELOPMENT	1
COMBINER DEVELOPMENT	3
MILLIMETER WAVE COMPONENT (CIRCULATORS, ETC) DEVELOPMENT	2
RELIABILITY ENGINEERING	3
TOTAL (PLUS SUPPORT)	12

Table III-2. Efficiency and Power Output of Commercial GaAs FETs at 8 GHz

Manufacturer	Type No.	Output Power		Power Added Efficiency
		@ saturation mW	@ 1 dB comp. mW	%
Texas Inst.	MSX801	250		30
Texas Inst.	MSX802	500		30
Texas Inst.	MSX803	1000		30
NEC	V868A		250	24
NEC	V868B		500	20
NEC	V868C		1000	10
MSC	88001	310	260	25
MSC	88002	600	515	21
MSC	88004	1100	940	19
MSC	88010	2800	2500	19
Dexcel	3630A-CR	700	500	15
Dexcel	3615A-P200	300	250	16
Plessey	GAT4/020		100	10

and each having 4-dB gain, the overall rf output to dc input efficiency, neglecting power conversion, would be 18 percent. (Note: The driver stages would generally have higher gain and lower efficiency than the power output stages. This example is offered by way of illustration only.) Assuming the power converter has 85-percent efficiency, the rf output to dc bus power efficiency would be about 15 percent. Hence, an approximate rule-of-thumb may be to consider the overall amplifier efficiency to be about half the power-added efficiency of the final stage.

It is, therefore, apparent that the highest efficiency GaAs FETs available today result in overall amplifier efficiencies that are considerably less than TWTAs. Present development trends in GaAs FETs are oriented toward producing devices having higher power output and improved reliability. Efficiency, gain, and bandwidth are receiving less attention, although it is clear that all parameters are interdependent. There is no present basis for projecting major improvements beyond the efficiencies realizable in the better GaAs FET devices available today. In addition, there should be little or no incentive to design GaAs FET power amplifiers with high efficiency as the major goal. The need for highest efficiency results in considerable measure from limitations in present spacecraft payloads and from an application in which the solid-state amplifier is to function as a plug-in replacement to an existing TWTA. For future spacecraft designs, these considerations are secondary.

Bandwidth is related to power output. Higher output power would tend to imply higher operating temperatures for the device, which would tend to reduce reliability. To relieve thermal stresses, the power generating surfaces can be dispersed either by paralleling several elementary devices within one device package or by using a wider gate within one GaAs FET device. Either way, the parasitic elements (chiefly shunt capacitance) that limit the device's bandwidth become more significant. To some extent, the effect of shunt capacitance can be relieved by using internal matching sections between discrete elementary devices. This is an approach that would generally be applied insofar as manufacturing technology permits. A more advanced approach, which has been suggested but not yet acted upon, is to design a distributed amplifier using many elementary devices within one package. The latter goal would appear to be beyond near-term attainment, in view of the lack of work in this area.

Figure III-6 shows percentage bandwidth as a function of power output for X-band GaAs FETs. The solid region of the curve represents a region that has already been achieved or can be achieved by 1983 without major difficulty. The dotted region represents extrapolations that

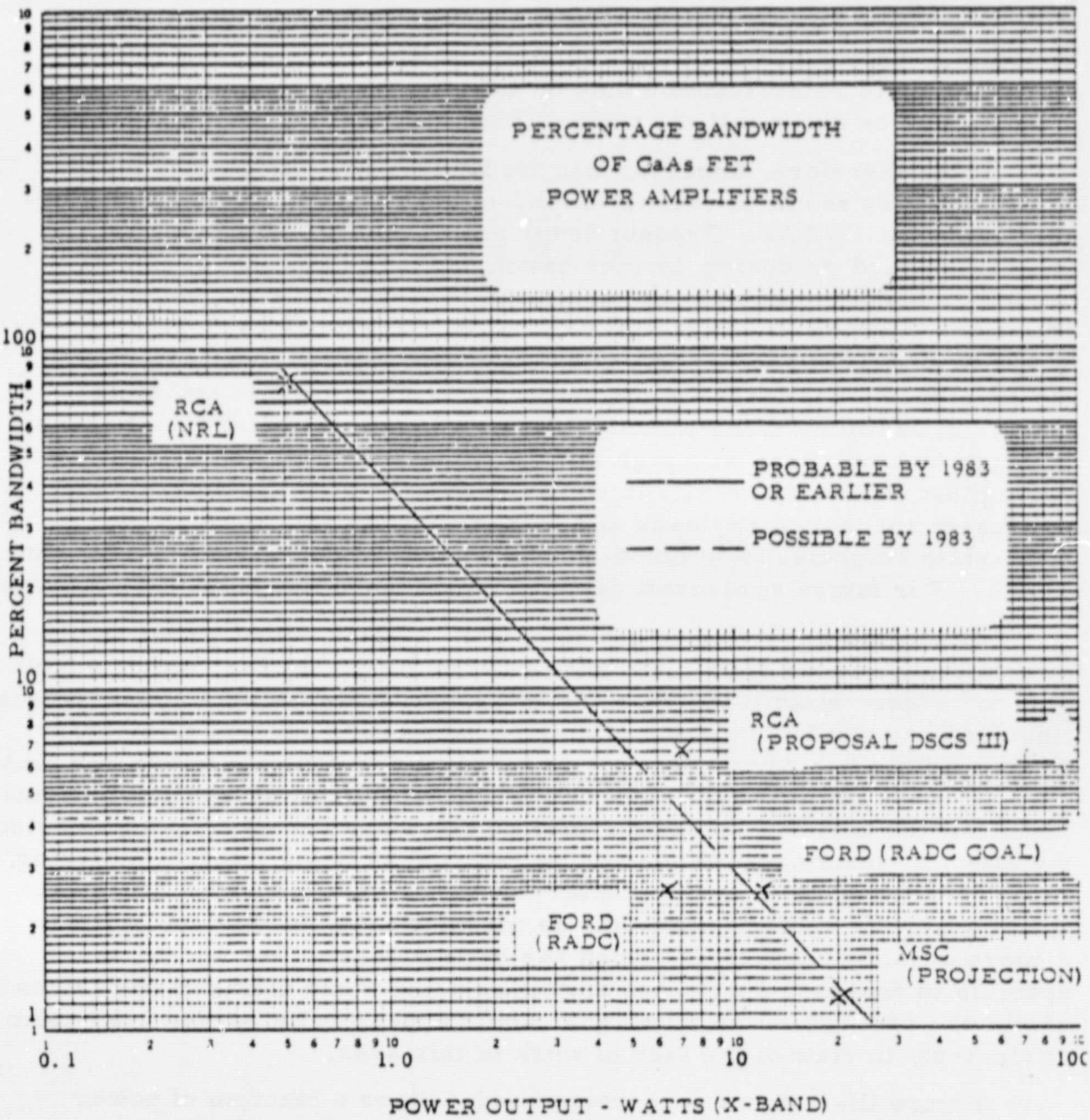


Figure III-6. Percentage Bandwidth of GaAs FET Power Amplifiers would require considerably more effort. To achieve 10 watts output would result in an amplifier with about a 250-MHz bandwidth at X-band. This would be entirely adequate for any present communications satellite system requirements, but wider bandwidth would be desirable for future systems. To some extent, bandwidth limitations will be relieved without any special effort when these devices are scaled to higher frequencies. In the absence of a specific system requirement for wider bandwidth than can be achieved at a given operating frequency, it does not appear worthwhile to stress bandwidth as a specific parameter requiring development funds.

At least a dozen major companies in this country and abroad are actively pursuing power GaAs FET development. Several universities have programs underway on special aspects of GaAs FET technology. There are other laboratories, in government and industry, that are actively working in the field. Finally, these are systems houses and user organizations that are building amplifiers and designing novel system approaches that rely on GaAs FET technology. The result is an outpouring of literature in one relatively narrow field that has seldom been equaled.

References abound, and in the short time available for this study, these could only be partially and imperfectly skimmed. Although an overview of this field has been maintained by The Aerospace Corporation from a time long predating the initiation of this study, the earlier findings were often nullified by rapid advances in technology. A list of the more important references used in the study is included in the Bibliography at the end of this chapter. To supplement findings gleaned from the literature, key investigators in several organizations in the forefront of this technology were visited or interviewed by telephone. Reports from contact visits and telephone calls were included in the Draft Final Report for this document; a list of those organizations/persons contacted appear at the end of the chapter.

D. IMPATT DIODE AMPLIFIERS

An IMPATT diode exhibits negative resistance at microwave frequencies. It can, therefore, be used as an oscillator or as an rf amplifier. The frequency at which the device is useful can be as low as 1 to 2 GHz or as high as several hundred gigahertz (although any given IMPATT diode will be usable over only a small portion of that range).

The IMPATT diode derives its negative resistance properties from a combination of carrier generation by impact ionization and transit time effects. It employs a p-n junction or Schottky barrier, biased in the avalanche region of its volt-ampere characteristics. The doping profile provides the desired combination of carrier generation and transit time delay.

IMPATT diodes most commonly are made using silicon or gallium arsenide. Single-drift and double-drift devices are available. The latter are generally more efficient and capable of higher power output. A double-drift IMPATT diode is roughly equivalent to a series-connected pair of single-drift devices. It has a drift region on both sides of the junction, one for holes and the other for electrons. The resultant increase in impedance levels relative to single-drift devices facilitates matching into microwave circuits. The tendency toward parametric instability is also reduced by the double-drift structure.

1. HISTORY

IMPATT diodes were introduced about 10 years ago. Within a relatively short time, they were hailed as the obvious replacement for TWTs. For a combination of reasons, they never assumed that role. Although their potential reliability was thought to be comparable to most solid-state devices, it is only recently that their reliability has begun to approach values that would be required for long life in space. One reason for the difficulty in achieving reliability is the nature of the avalanche phenomenon upon which IMPATT diodes depend. Efficient charge carrier multiplication requires a relatively high current density across the junction, which in turn raises the junction temperature. As a result, the current densities required for reasonable efficiencies produced junction temperatures that were too high for reliable long life operation. It was characteristic of IMPATT diodes that they seemed to operate best at the point where they were just below burnout. Now, with designs employing efficient diamond heat sinks, good reliability may be obtainable. However, it is still true that these devices tend to be applied by amplifier designers in a manner that results in excessive junction temperatures.

A second difficulty with IMPATT diodes is common to most negative resistance devices. There is no inherent isolation between input and output, so that a complete amplifier must include low loss, low voltage-standing-wave-ratio circulators between stages. Careful design is required to achieve broadband characteristics. It is extremely important to control the load presented to the diodes. Certain kinds of mismatches may result in near instantaneous burnout.

2. STATE-OF-THE-ART OF IMPATT DIODES

IMPATT diode amplifiers can operate in a negative resistance mode or in an injection locked mode. Because the injection locked mode has significantly higher efficiency, IMPATT diode power amplifier developments have concentrated in this area. The injection locked amplifier is highly nonlinear, with characteristics approaching that of a hard limiter. It is, therefore, usable with angle modulated systems (such as frequency modulated or quadraphase shift keying) where only one carrier at a time is present. With multiple carriers, intermodulation would generally be considered excessive. Hence, frequency division multiple access systems cannot usually share a single IMPATT diode power amplifier.

A lock-in bandwidth of about 3 percent is the approximate limit for the injection locked mode when the amplifier is driven by an unmodulated carrier. For a fixed carrier frequency near band center modulated by a digital bit stream, limited measurements made at TRW suggest that the bit error rate becomes significant as the width of the rf spectrum approaches the steady-state continuous wave lock-in range.

Because of these special peculiarities of IMPATT diode amplifiers, they never assumed the role of a TWTA replacement. Nor is it likely that they will assume such a role in the future, except for special cases. Although IMPATT diodes and associated amplifier circuitry are now relatively well understood, other solid state devices, principally GaAs FETs, have more desirable characteristics as a TWTA replacement at frequencies up to about 20 GHz. The IMPATT diode is capable of significantly higher power output than the GaAs FET (i.e., at 10 GHz, by a factor of six to one in laboratory devices). However, the development of power combining technology, together with the more rapid growth in GaAs FET capability largely nullify this advantage of IMPATT diodes. The outstanding example of IMPATT diode application in a space mission was their use in the COMSTAR beacons. However, they were used as oscillators rather than amplifiers in this application.

3. TECHNOLOGY OPPORTUNITIES FOR IMPATT DIODES

The IMPATT diode amplifier appears to have a significant future role in space at frequencies above 15 to 20 GHz--not as a replacement for the TWTAs but in systems that can be designed to accommodate their more restrictive characteristics. Digital systems employing time division multiple access clearly represent a future trend. For these applications, the IMPATT diode amplifier is well suited. Power-combining techniques suitable for use with IMPATT diodes have been developed at frequencies up to 40 GHz. These techniques appear to be extendable to 60 GHz in the relatively near term. With a more intensive development effort, extrapolations to 86 GHz appear reasonable.

The technology characteristics and development approaches for IMPATT diodes are identified in the following list.

- Applications
  - Output power stage in low-medium power transmitters
  - Driver stage for high-power transmitters
- Technology limits
  - Major applications above 10 GHz
  - Upper frequency limit 200 to 300 GHz
  - GaAs most useful below 15 GHz
  - Si most useful above 15 GHz
  - Highly nonlinear, angle modulation, single carrier only
  - Injection locked mode required for efficient operation
  - 3- to 4-percent bandwidth near limit
- Approach to development
  - Near-term payoff potential in materials, metallization, and thermal design programs
  - Develop DD read fabrication technology
  - Develop manufacturing technology: high yield, reliability
  - Develop appropriate device packaging

The required IMPATT diode technology programs are listed below.

- Develop double drift read profile devices
  - GaAs
  - Si
- Investigate modified junction
  - Now use circular junctions
  - Try ring junctions or cross junctions
  - Other
- Develop improved cooling techniques
  - Investigate miniature heat pipes
- Develop manufacturing technology
  - Higher yield
  - Improved reliability
  - Lower cost

- Develop an integrated matching circuit
  - Diode itself should form the first step of the matching circuit
  - Package may include a section of radial transmission line

The present state-of-the-art in terms of power output versus frequency is shown in Figure III-7. A projection of what can be accomplished by 1983 is also included. By means of similar curves constructed at particular instants in past time, a trend of power output versus time was established. A family of curves for different frequencies was derived in this way, as shown in Figure III-8.

Because of the limited range of application of IMPATT diode amplifiers, one would expect that little of the anticipated growth in technology will be achieved through commercial funding sources. (Note that the GaAs FET is of much more interest to a wider range of users.) It appears that, in this country, advances in IMPATT diode technology will require support by the defense agencies and by NASA, with seed money being provided by internal company funding. It should be mentioned that Japan is doing significant work with IMPATT diodes, principally because of their commitment to Ku band space systems. NEC is the leading Japanese company in this endeavor. An example of a specific development program appropriate for an IMPATT diode application was included in Table III-1.

Although the GaAs FET now occupies center stage in the arena of microwave solid-state development, considerable interest is still evident in IMPATT diode work, and the literature in this field is constantly expanding. A list of the more important literature references used in this study is included in the Bibliography at the end of this chapter. Visits made to organizations at the forefront of numerous developments in IMPATT diode technology are also listed at the end of the chapter.

E. POWER COMBINERS

1. HISTORY

Interest in the development of efficient power combiners results from the power limitations of solid-state amplifiers. Power combining can take place within the device package, or it can be accomplished by external microwave circuitry. In-package combining was discussed briefly under the section dealing with GaAs FETs. Although in-package combining can, in principle, be accomplished with IMPATT diodes also,

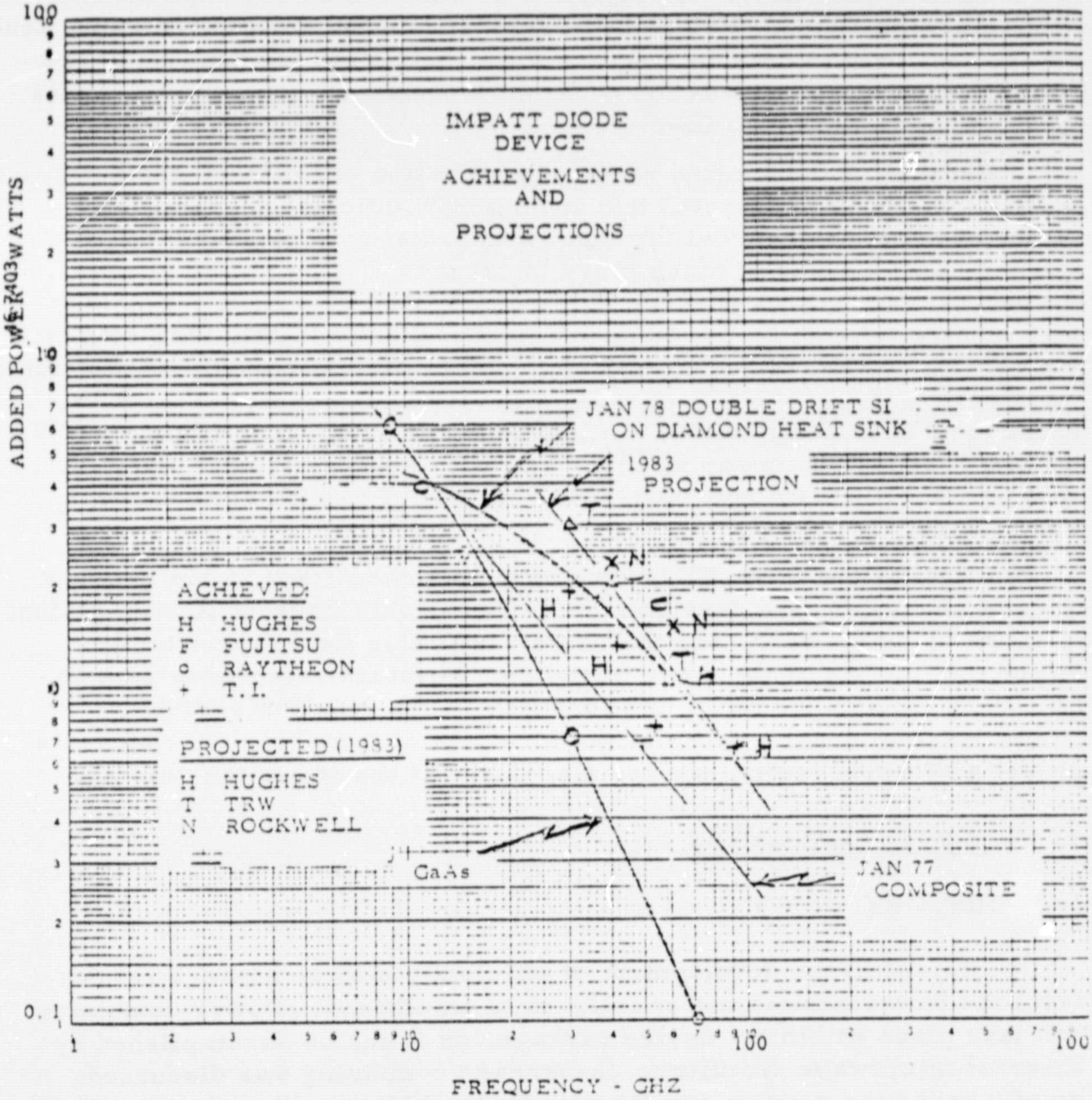


Figure III-7. IMPATT Diode Device - Achievements and Projections

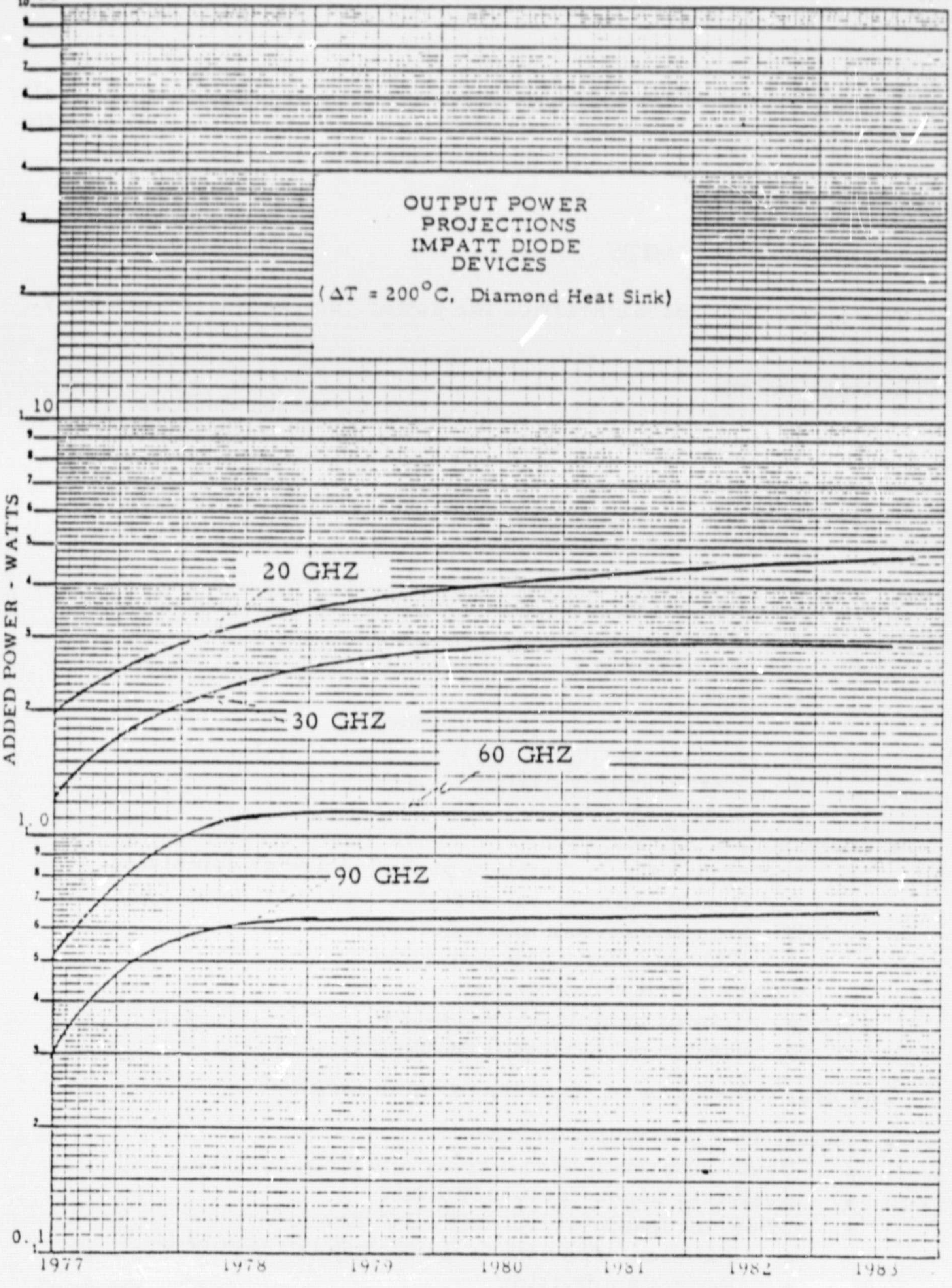


Figure III-8. Output Power Projections - IMPATT Diode Devices there is usually little incentive to do so as the junction capacitance usually limits the upper usable frequency of these devices. Moreover, it is difficult to obtain proper load sharing between multiple negative resistance devices in one package.

2. TECHNOLOGY LIMITS

The technology characteristics for power combiners, by category, are:

- Applications
  - Provide high power output using low power devices
  - Provide increased reliability through redundancy
- Technology Limits
  - In-Package Combining
    - Thermal concentration
    - Bandwidth constraints
    - Circuit parasitics
    - Reliability
  - Circuit combining
    - Combining efficiency
    - Number of devices combined
    - Bandwidth constraints
    - Heat transfer design
    - Failure modes
- Approach to Development
  - Optimum balance between package/circuit combining
  - Develop combiners using higher order modes
    - Accommodates more devices
    - Extends upper frequency limit
  - Attack thermal problems
    - Use of miniature heat pipes
    - Improved packaging geometry

The characteristics of in-package combining are:

- Paralleling of several devices
  - Useful approach with bipolar and FET devices
  - Restricts upper frequency limit
  - Often not feasible with IMPATT diodes
    - Junction capacitance limits upper frequency
    - Poor load division

- Use of in-package matching
  - May extend upper frequency limit
  - Eases bandwidth restrictions
- Reliability aspects
  - Package vulnerable to single failure
  - No way to assure graceful degradation
  - Thermal concentration tends to reduce MTTF
  - Integrated circuit techniques may help

The characteristics of circuit combiners are:

- Resonant combiners (Raytheon, TRW)
  - Power combined in single cavity
  - Coupling between devices through EM field
  - Applicable to two terminal devices
  - Combining efficiency typically 85 to 90 percent (4 to 6 devices)
  - Graceful degradation may be dependent on failure mode
- Nonresonant combiners
  - Binary tree approach (RCA, Ford Aerospace)
    - Uses cascaded 3 dB hybrids
    - Combines 2^N devices with N levels
    - Low-risk approach
    - Can provide good heat sinking
    - Losses per level are cumulative
    - Practical limit approximately 4 levels ($2^N = 16$ devices)
    - Graceful degradation assured
  - Single multiport divider/combiner (Raytheon, Westinghouse)
    - May use N-way hybrids
    - May use radial transmission line
    - Difficult thermal design
    - High combining efficiency (87 percent, 12 way, X-Band)
    - Graceful degradation assured

An important requirement for any combiner is so-called "graceful degradation." Failure of one (or more) devices whose power is being combined should not cause complete failure of the combiner. Circuit combiners of the hybrid tree or radial line type will inherently possess a graceful degradation characteristic. Cavity combiners, which are often used with IMPATT diodes, will degrade gracefully if the diode fails in some specified manner. For example, if it is known that an IMPATT diode looks like a short circuit upon failure, a coupling circuit to the cavity can be designed so that if a short is substituted for the diode, little degradation occurs. However, if the diode fails in an atypical manner, the complete amplifier may be disabled.

3. TECHNOLOGY OPPORTUNITIES

A projection of the power output versus time that can be achieved (with funding) is shown in Figure III-9 for several frequencies using GaAs FETs and IMPATT diodes. The growth in capability includes the twofold effect of device improvement and improvement in the combiner circuitry.

In assessing combiner status and future growth projections, several organizations involved in this work were visited; they are listed at the end of this chapter. A Bibliography also appears at the end of the chapter.

F. ELECTRON BOMBARDED SEMICONDUCTOR AMPLIFIERS

1. HISTORY

Electron bombarded semiconductor (EBS) devices are a hybrid between a vacuum tube and a semiconductor device. They employ a focused electron beam to bombard a target diode or group of diodes. Hole-electron pairs are generated, and charge multiplication takes place in the semiconductor material. A power gain is achieved which is intermediate between that of a TWTA and a more conventional solid-state amplifier. Although possessing some of the disadvantages of the TWTA, the low power in the electron beam relative to the output power (typically 10 to 15 percent of the output power) relieves the usual TWTA cathode problems considerably. Likewise, the power supply of an EBS device is intermediate in complexity between a TWTA power supply and a solid-state amplifier power supply.

EBS amplifiers are limited to the frequency range from VHF to about 4 GHz. They can provide relatively high power, compared to a solid-state amplifier employing bipolar transistors, in that frequency band. However, bipolar amplifiers, particularly with some circuit combining, may now be approaching equivalent power levels.

A unique characteristic of the EBS amplifier is its high linearity. In this respect, it is superior to either a conventional TWTA or a conventional solid-state amplifier. However, the importance of this extreme linearity characteristic for space communication is not apparent. Where intermodulation effects cannot be kept within bounds by normal design methods, its use may be considered.

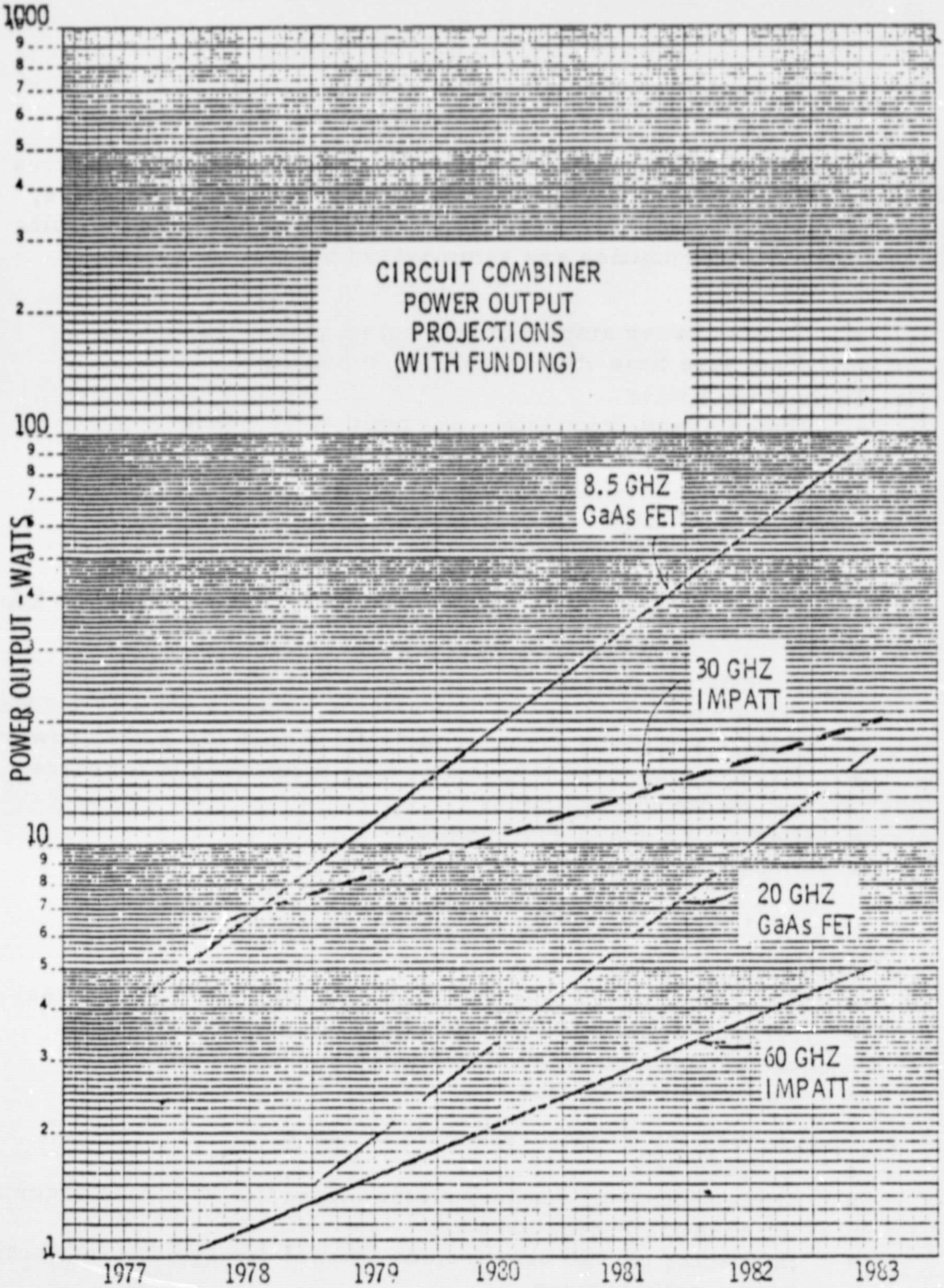


Figure III-9. Circuit Combiner Power Output Projections (With Funding)

2. TECHNOLOGY LIMITS

At present, the only company known to be working on EBS devices is Watkins-Johnson. A vist was made to the development group there, and a trip report is available from NASA. The major technology limits and development opportunities are summarized below.

- Applications
  - Linear power amplifier in medium power transmitters
  - Fast rise time video amplifier/modulator
- Technology limits
  - Upper useful frequency - approximately 4 GHz
  - Demonstrated performance (1.6 GHz)
    - 50 watts continuous wave
    - 12 dB gain
    - 200 MHz bandwidth (1 dB)
    - 29 percent efficiency
  - Power supply more complex than SSA, simpler than TWTA
  - Untested in space
- Approach to development
  - Scale present design to 200 watts continuous wave (1.6 GHz)
  - Use larger diode areas or multiple diodes for higher power
  - Develop improved output matching techniques to increase bandwidth and efficiency
  - Design for space environment
  - Resolve reliability issues

The reliability status of EBS devices is indicated as:

- On-going life test results
  - Total test time - approximately 200,000 hours (8 devices)
  - Stress level - 20 to 40 watts/MM^2 (comparable to high power continuous wave devices)
  - Zero failures to date
- Open issues for 7- to 10-year life in space
  - Cathode life
  - Compatibility of semiconductor target life with tube processing (heating during bakeout)
  - Hardening of EBS target diode against damage due to electron beam bombardment
  - Metalization, electromigration effects

3. TECHNOLOGY OPPORTUNITIES

An estimate of technology growth during the next 5 years is shown in Figure III-10. The conservative goal would be to redesign an EBS device of the sort already demonstrated, so that it would be suitable for the space environment, and upgrade its reliability. More ambitious goals would involve scaling these devices to larger size and developing improved output coupling circuits.

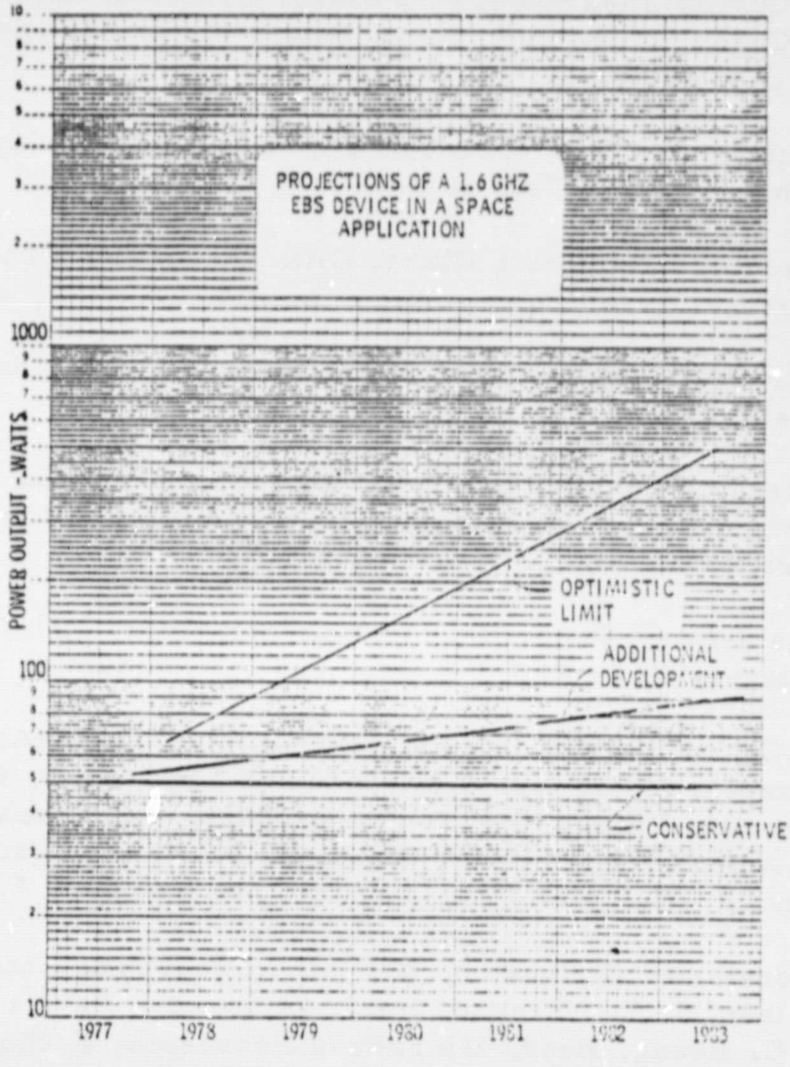


Figure 10. Projections of a 1.6-GHz EBS Device in a Space Application

ORGANIZATIONS/PERSONS CONTACTED FOR CHAPTER III

Bell Telephone Laboratories (Murray Hill, NJ); J. V. DiLorenzo, Manager, Microwave Materials and Process Group (March 10, 1978).

Comsat Corporation (Washington, DC); S. Metzger, Chief Scientist (April 6, 1978).

Comsat Laboratories (Clarksburg, MD); W. J. Getsinger, Manager, Microwave Circuits Department; R. Strauss, Director, Reliability and Quality Assurance; P. Koskos, Assistant Director, Reliability and Quality Assurance; H. L. Hung, Circuit Design Engineering (April 6, 1978).

Cornell University, Department of Electrical Engineering (Ithaca, NY); Professor G. C. Dalman (March 9, 1978).

Dexcel, Incorporated (Santa Clara, CA); Y. Satoda, President (March 8, 1978).

Hughes Aircraft Company (Torrance, CA); G. Ladd, Manager, Microwave Semiconductor (March 17, 1978).

Hughes Electron Dynamics Division (Torrance, CA); L. Mohrfeld, Manager, Product Marketing; T. Appleby, Manager, Helix Tubes (April 13, 1978).

Microwave Semiconductor Corporation (Somerset, NJ); I. Drukier, Manager, GaAs FET Development and Production (March 9, 1978).

Raytheon Central Research Laboratories (Waltham, MA); B. Bierig, Manager, Microwave Semiconductor Laboratory; B. Steele, Materials Processing; D. Masse, Materials Characterization; M. Adlerstein, Device Technology; R. Bera, Combiner Development; R. Wallace, Program Management (April 7, 1978).

RCA Laboratories (Princeton, NJ); M. Nowogrodzki, Manager, Division Liaison; S. Y. Narayan, Head, Microwave Device Technology; H. C. Huang, Head, Microwave Processing Technology; R. Ernst, Combiner Circuitry; F. Sterzer, Manager, Microwave Technology Center (April 10, 1978).

ORGANIZATIONS/PERSONS CONTACTED FOR CHAPTER III (continued)

Texas Instruments Incorporated (Dallas, TX); B. Wisseman, Manager, Advanced Microwave Components (March 16, 1978).

TRW Incorporated (Redondo Beach, CA); J. E. Raue, Manager, Millimeter Wave Development (March 21, 1978).

Watkins-Johnson Company (Palo Alto, CA); J. Schram, Head, Space TWT Engineering Section; R. Knight, Head, EBS Engineering Section; L. Roberts, Staff Scientist; M. Lin, Applications Engineer, Microwave Amplifiers; D. Bates, Engineering Manager (March 14, 1978).

Westinghouse Advanced Technology Laboratories (Baltimore, MD); J. Schellenberg, S.S. Radial Power Combiner; M. Cohn, MM Wave Components and MIC Assemblies; D. Lampe/M. White, CCD's; D. Mergerian, Integrated Optics; M. Lonky, CMOS/MNOS; B. Moore, SAW Filters; J. Walker, Laboratory Tour; H. Schrank, Multi-Beam Phased Array Antenna Technology; T. Foster/B. Gardenghi, "L" Band T/R Modules; B. Hubbard, Ground Stations (April 5, 1978).

BIBLIOGRAPHY FOR CHAPTER III

Bates, D. J., et al., "Periodic EBS Status Report," Watkins-Johnson Company (August 1977).

Brand, F., "Compound Semiconductors, An Impending Crisis in Materials," Microwave Journal (February 1978) pp. 16-18.

Briefing Document, "Microwave GaAs FET Review," Prepared by Air Force Avionics Laboratory (March 1978).

Briefing Document, Watkins-Johnson Company, "Electron Bombarded Semiconductor Amplifier" (1977).

Cuccia, C. L., and P. T. Ho, "The Impact of the FET on the Satellite Transponder - A Technology Perspective," AIAA 7th Communications Satellite Systems Conference (April 1978).

DiLorenzo, J. V., "GaAs Development - Low Noise and High Power," Microwave Journal (February 1978) pp. 39-44.

Drukier, I., and J. Silcox, "Power GaAs FET Reliability," Microwave Semiconductor Corporation (February 1978).

Ernst, R., R. Camisa, and A. Presser, "Graceful Degradation Properties of Matched N-Port Power Amplifier Combiners," International Microwave Symposium Digest, 1977 IEEE MTT-S, pp. 174-177.

"Final Report, 10 Watt X-Band Solid State Amplifier Study, Phase Zero, for DSCS-III," General Electric Company Space Division (April 1978) (Contract No. F04701-77-C-0036).

Hasegawa, F., et al., "GaAs Power MESFETs with a Simplified Recess Structure," IEEE International Solid-State Circuits Conference (February 1978).

Knight, R. I., and D. J. Bates, "Electron Bombarded Semiconductor VHF/UHF Amplifiers," Watkins-Johnson Company (September 1977).

Liechti, C. A., "Microwave Field Effect Transistors - 1976," IEEE Transactions on Microwave Theory and Techniques (June 1976) pp. 279-300.

Madden, D. R., and J. J. Smidt, "European Capabilities in the Field of Microwave Tubes for Space Use, " AIAA 7th Communications Satellite Systems Conference (April 1978).

Microwave Journal Staff Report, "GaAs FETs Market and Technology Review," Microwave Journal (February 1978) pp. 22-30.

____________, "X-Band Planar Combiner Module Using GaAs FETs, Microwave Journal (February 1978) p. 34.

Raue, J. E., "60 GHz Device and Circuit Development Activities Planned for 1978/79," unpublished TRW document (March 1978).

____________, "High Performance Millimeter Wave Receiver and Transmitter Component Development," AIAA 7th Communications Satellite Systems Conference (April 1978).

Schellenberg, J. M., "Transistor Combinatorial Techniques," Westinghouse Electric Corp., Report No. AFAL-TR-77-205 (November 1977).

Schellenberg, J. M., and M. Cohn, "A Wideband Radial Power Combiner for FET Amplifiers," 1978 IEEE International Solid-State Circuits Conference Record (February 1978) pp. 164-165.

Silzars, A., D. Bates and A. Ballonoff, "Electron Bombarded Semiconductor Devices," Proceedings of the IEEE (August 1976).

Solman, F. J., et al., "The Ka-Band Systems of the Lincoln Experimental Satellites LES-8 and LES-9," AIAA 7th Communications Satellite Systems Conference (April 1978).

Wade, P. C., "A 1-W, 2-6 GHz Amplifier Utilizing a Discretely Packaged GaAs FET," IEEE International Solid-State Circuits Conference (February 1978).

CHAPTER IV

IMAGE COMPRESSION

Prepared by

A. G. Tescher
Optical Systems Department

CONTENTS FOR CHAPTER IV

LIST OF ILLUSTRATIONS

PRECEDING PAGE BLANK NOT FILMED

CHAPTER IV

IMAGE COMPRESSION

A. INTRODUCTION

The vast amount of NASA/LANDSAT digital imagery has created a significant storage and transmission problem. Image compression is a potential solution. Unlike other topics in this Aerospace/NASA study the image compression area must be more speculative because only a few actual implementations have been carried to hardware design.

In this chapter, an overview is given on applications, theoretical backgrounds, and algorithms. In addition, references are given to projects and organizations involved with image compression. Image quality is also considered. New technologies are addressed, and prospects for potential algorithms are given. A majority of the projects have not been carried beyond limited computer experimentation. Specifically, the results have been exposed to rather limited, if any, evaluation by the potential user community.

B. ALGORITHM OVERVIEW

The following general considerations are applicable for image compression algorithms. For generalized adaptive systems (i.e., implementations for which local rate fluctuation is permitted through a post buffer) single or multipass systems are possible, where the algorithm scans through the image once or several times, respectively. For the latter, a frame buffer is required creating a prohibitive constraint for an on-board application.

The algorithm types likely to be useful for potential implementations are differential pulse code modulation (DPCM) and the family of transform coding techniques. The DPCM is relatively straightforward and could be a candidate for on-board compression. The transform coding implementation is significantly more complicated and is not likely to be acceptable except in a ground-based system.

Table IV-1 provides an overview of various algorithms and conservative estimates for implementable rates. The rates are in bit per pixel, and the numbers are given for algorithms that generate reconstructed images with negligible degradation. For higher compression rates, the resulting degradation may not be acceptable to the user community. The primary recommended coding algorithms are DPCM and transform coding.

Other algorithms are listed for completeness. The last listed algorithm (frame replenishment) although quite efficient, is only appropriate for video techniques for which significant degradations are acceptable.

Table IV-1. Algorithm Overview

	PRIMARY APPLICABILITY AND RATE (bpp)		
ALGORITHM TYPES	INTRA FRAME	MULT/SPECTRAL	INTER-FRAME
DPCM	2-5	?	?
HYBRID CODING	2-4	?	?
TRANSFORM CODING	1-2.5	?	?
RM TECHNIQUES	1-2.5	?	?
BLOB	N.A.	?	N.A.
CLUSTER CODING	N.A.	?	N.A.
FRAME REPLENISHMENT	N.A.	N.A.	0.2-1

N.A. - Not Applicable

Some organizations and individuals involved with image compressions are listed in Table IV-2, and a Bibliography appears at the end of the chapter. Although the list in the table is incomplete, it demonstrates the university and industry activity. Special considerations should be given to the Defense Advanced Research Projects Agency (DARPA) project in combination with Naval Ocean Systems Center (NOSC) which developed the so-called hybrid coding algorithm for remotely piloted vehicle application. Although the actual development is not likely to be acceptable for high quality image compression required by LANDSAT applications, it demonstrates the problems associated in developing a device. Also, the DARPA/NOSC device is the only technique available that has been carried through hardware development.

Table IV-2. Organizations Active in Image Compression

Organization	Individual	Areas of Effort
Aerospace Corporation	A. G. Tescher	Entropy coded DPCM and transform techniques, buffer feedback
Bell Telephone Labs.	B. G. Haskell	Adaptive interframe coding
CDC	A. E. LaBonte	Micro-adaptive picture sequencing (maps)
DARPA	H. Federhen	Remotely piloted vehicle applications
Jet Propulsion Lab.	E. Hilbert	RM techniques, cluster coding
NASA/AMES	S. C. Knauer	Three-dimensional transform (Hadamard)
NOSC	H. J. Whitehouse	Hybrid coder, transform coders, remotely piloted vehicle hardware
Purdue University	T. Huang	BLOB, transform coding
RCA	W. Schaming	Transform techniques, remotely piloted vehicle hardware
Stanford University	J. Goodman	Optical implementations
SUNY of Buffalo	A. Jain	Transform techniques
Texas Instruments	D. Buss	Device technology, CCD
TRW	A. Habibi	Hybrid codings, transform coding, DPCM, cluster coding
University of Kansas	R. Haralick	Transform techniques
USC	W. K. Pratt	Transform coding

C. SPECIAL CONSIDERATIONS FOR IMAGE COMPRESSION

The primary difficulty with image compression is that it is an inter-disciplinary field. Figure IV-1 indicates that a comprehensive image compression development must rely on numerous related technologies.

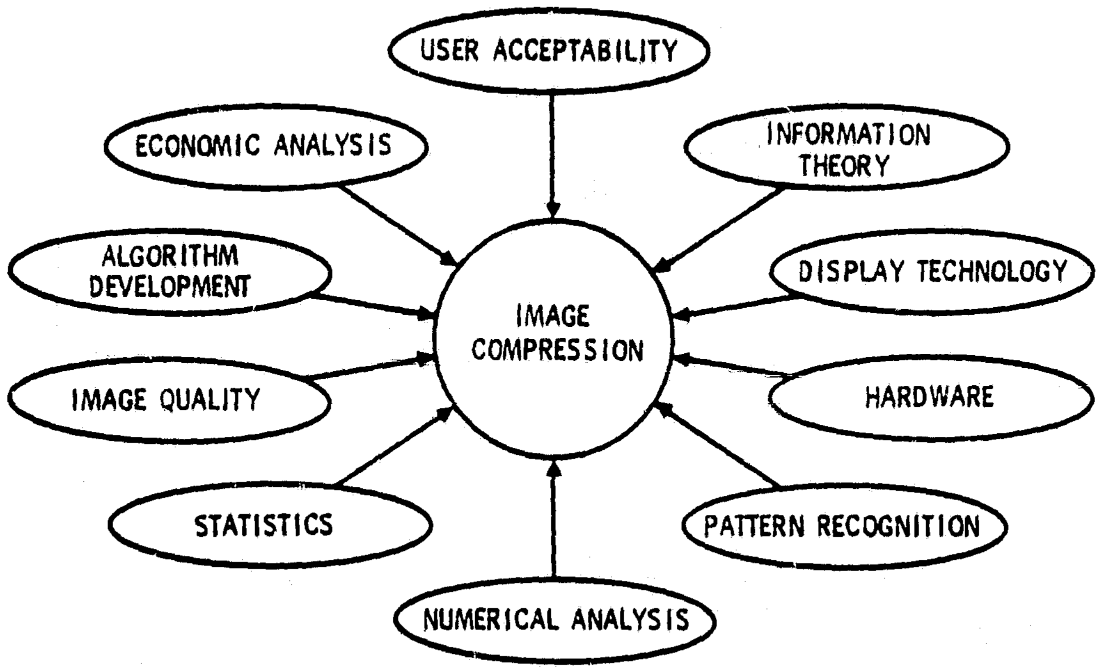


Figure IV-1. Image Compression Technology

The image quality consideration is fundamental; it is evaluated through user acceptability. When the final destination is the human observer, heavy emphasis must be placed on display technology. Image compression is part of information theory which, in turn, uses statistics. Algorithm development is heavily dependent on the results of numerical analysis. For machine evaluation techniques, pattern recognition provides many useful inputs. The overall cost benefits of a successful image algorithm should be determined through economic analysis.

D. IMAGE QUALITY CONSIDERATIONS

The imagery, which is the input in digital form to the image compression algorithm, is derived through several steps from an analog image. The digital image generation is performed through what is referred to here as a conceptual sampler, which is shown in Figure IV-2. This figure emphasizes the fact that in a typical digital image generation, numerous degradations are introduced into the image and these degradations, including system noise, represent information to the compression algorithm. Consequently, an information preserving algorithm is equivalent to the requirement that the system noise be also preserved. Unless the image quality requirements associated with the compression algorithm allow for noninformation preserving techniques, only limited compression can be achieved. What can be achieved is dependent on the original image quality. For a noisier image, less compression is possible.

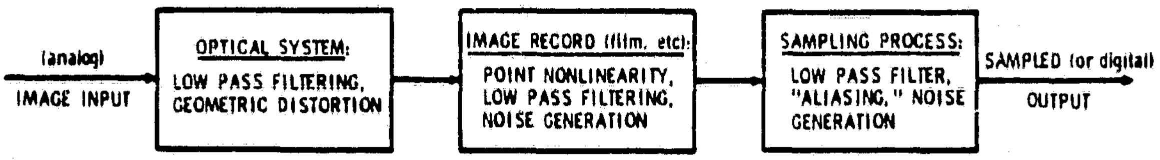


Figure IV-2. Conceptual Sampler

The following issues must be addressed relative to image quality procedures. For information preserving techniques, user evaluation is not involved. However, for any noninformation preserving procedure, the eventual user of the same information must be consulted. It is important to permit techniques of the second category. They can be high quality procedures, but they do not guarantee that each input element (pixel) is regenerated identically.

E. FUTURE PROSPECTS

Image compression in a proper implementation could achieve a considerable amount of bandwidth compression for on-board implementations and for ground-based development. A few algorithms are listed in Figure IV-3. Among those listed, only DPCM and transform techniques are recommended for consideration. Figure IV-3 also provides time estimate ranges required to develop the appropriate algorithms for actual hardware implementations. The ranges are rather speculative.

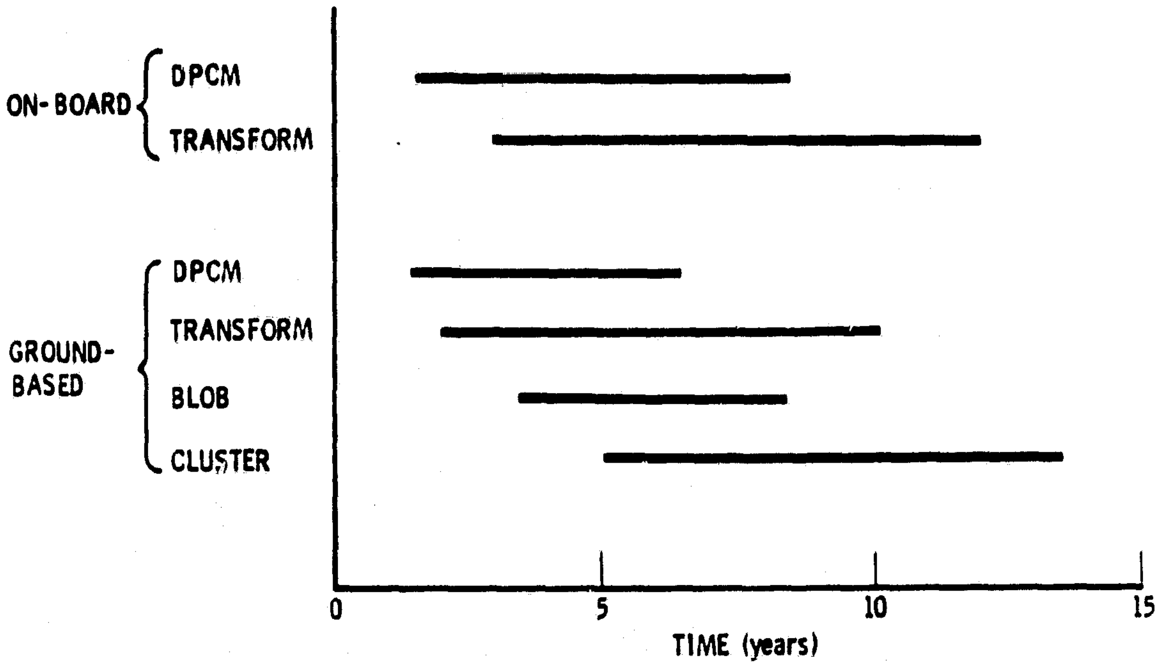


Figure IV-3. Future Prospects and Estimates of Development Time

Several special comments must be made. The indicated algorithms in actuality refer to a class of algorithms rather than to a specific design. Significant research and development effort is required before the specific algorithm is available. The DARPA/NOSC remotely piloted vehicle development, for example, required several years of study before a breadboarded design was available. The indicated time range in Figure IV-3 depends on the level of effort. The shortest period indicated assumes a high level of development activity.

To achieve the required image quality, the desired algorithm is expected to be highly adaptive both in algorithm parameters and in local rate fluctuation. The field of rate-adaptive compression techniques is relatively new and only a limited amount of information is available for algorithm development.

The additional complexity associated with compression technology is the speed at which the algorithm is to be implemented. Since available channel rates are likely to be significantly higher that rates at which individual computations can be performed, a high-speed system heavily depends on a large number of multiplexed independent algorithms. Design of a multiplexed system introduces additional complexity and requires significant development effort.

F. RECOMMENDATIONS

A clear need exists in the NASA community for image coding algorithms for on-board implementations and ground-based systems. The development effort should address both of these considerations. It is proposed that an adaptive DPCM coding system be developed that would be adaptive through implementation of entropy coding. This type of system is sufficiently simple for on-board implementation, yet it is also sufficiently efficient to permit high accuracy coding for the range of 2.5 to 3.5 bits per pixel. Although this type of system is not information preserving, it is expected that with sufficient coordination, the user community is likely to accept the appropriate degradations. It should also be emphasized that although DPCM systems have been experimented with for many years, an adaptive rate controlled system of the type proposed is still likely to take considerable effort to develop.

For a high degree of compression, although with added complexity, rate adaptive techniques using transform coding should be actively pursued. The potential achievable rates with these systems may be as low as 1 bit per pixel. Although immediate on-board implementation is not likely, should an efficient design be obtained for ground-based implementation, subsequent on-board consideration might be appropriate. Although there are several years of experience with transform coding, immediately implementable algorithms are not available.

In addition to algorithm development, a coordinated study-project with user communities should be encouraged to determine what degradations are acceptable to them. These studies should consider two areas. First, it should be determined what the impact is, if any, of the coder induced degradation on the eventual use of the imagery. For example, what is the degradation in terms of classification accuracy of a compressed multispectral data versus the one which was transmitted without any compression algorithm. Second, it should be determined what the inherent inaccuracy is in the basic information. It is degraded by sensor noise, quantization effects, and other noise components introduced by the imaging system. If this system noise information is available, it can serve as a design guideline on what is permitted as noise introduction by the compressor.

The hybrid technology relevent and appropriate to image coding should be monitored, encouraged, and possibly funded. Although it is premature to state whether an all-digital system is more likely to be implemented than one using analog components, potential advantages of analog processes are quite likely. Specific areas are appropriate to transform implementations through either optical or CCD device technology and focal plane processors.

In general, since hardware implementations that are directly applicable to image coding are essentially nonexistent, should an algorithm/coder development begin it is important to carry the design through at least breadboard development to obtain reasonable experience.

BIBLIOGRAPHY FOR CHAPTER IV

Applications of Digital Image Processing, Proceedings of the International Optical Computing Conference 1977, SPIE Vol. 119, San Diego, California (August 1977).

NSF Workshop on Image Compression, Boulder, Colorado (December 1977).

Special Issue on Image Compression, IEEE Trans. on Comm. COM-25 (11) (November 1977).

Tescher, A. G., Transform Image Coding in Image Transmission Techniques, Academic Press (to be published).

________________, ed., Efficient Transmission of Pictorial Information, Proceedings of the International Optical Computing Conference 1975, SPIE Vol. 66, San Diego, California (August 1975).

________________, ed., Advances in Image Transmission, Proceedings of the International Optical Computing Conference 1976, SPIE Vol. 87 (1976).

CHAPTER V

SYSTEM ARCHITECTURE

Prepared by

L. M. Nirenberg
Communications Department

S. J. Curry
Communications Department

C. T. Wolverton
Command and Telemetry Department

CONTENTS FOR CHAPTER V

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Continued)

LIST OF ILLUSTRATIONS (Continued)

CHAPTER V

SYSTEM ARCHITECTURE

A. MULTIPLE ACCESS SATELLITE COMMUNICATIONS ARCHITECTURE

1. INTRODUCTION

The purpose of this portion of the study is to briefly describe the nature of multiple access (MA) satellite communications architecture and to identify architectural issues that affect hardware and software design.

To achieve the above purpose requires a brief description of MA systems. We assume that there are M earth stations (ESs) desiring to communicate to each other by using digital modulation to send blocks of bits (called "packets"). The connectivity of M^2-M possible different communication links is provided by a satellite in geostationary orbit. There are M users seeking access to the satellite's basic resource: bandwidth. Bandwidth is allocated according to assignments to users of periodic, disjoint time slots, disjoint frequency bands, and orthogonal signals of fixed bandwidth (Time, Frequency, and Code divisions of the basic resource). A multiple access algorithm (MAA) is that procedure whereby each user uses Time, Frequency and Code to communicate through the satellite to other users. A multiple access system is a combination of hardware and software that supports the MAA.

The MAA architecture, or functional organization, is illustrated in Figure V-1. The MAA must schedule users on the channel by assigning them Time, Frequency, or Code. The scheduler generates assignments after having received reservations from the users informing the scheduler of traffic status. The process by which reservation and schedule information is produced is performed by the control function. Finally, the communication function is provided by communication links that enable the actual physical transfer of information.

These functions are illustrated in Table V-1 for three well-known MAAs (Ref. 1). Using fixed assignment schemes such as TDMA (time division multiple access) and FDMA (frequency division multiple access), there are no reservations and a fixed schedule (independent of system state) of time slots and frequency bands, respectively. For these fixed assignment MAAs, control is provided by frame synchronizations to distinguish time slots in TDMA, and frequency guard bands to distinguish frequency bands in FDMA. In the random access/reservation MAA, users make their traffic requests by sending whenever a new packet arrives at the ES. This random access produces reservations, which are scheduled in turn according to a first-in first-out rule. The system is controlled by each user listening to the rebroadcast satellite downlink to update its own queueing (schedule) tables.

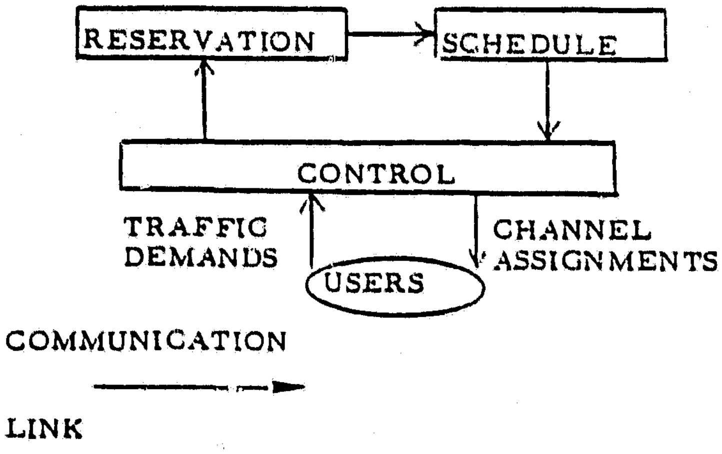


Figure V-1. Multiple Access Algorithms: Basic Functional Organization

At this point it is appropriate to introduce the notion of system (or network) performance. Network performance is a subjective concept, since ultimately the users generating and receiving traffic are human. Fortunately, there is a variety of quantitative measures of performance. Examples of these are given in Table V-2 and are self-explanatory. Perhaps the most important performance measure is the delay - throughput trade-off. This trade-off expresses the fundamental fact that as message throughput, ρ, increases, the delay, D, between message generation and reception also increases. Throughput in this context is defined by

$$\rho \equiv \frac{\Lambda}{R}$$

where

$\Lambda \equiv$ average number of bits per second sent over satellite channel by all users

$R \equiv$ bit rate available from satellite bandwidth and the modulation/coding scheme used

We see that, intuitively, if Λ were to exceed R, then there would be more bits generated per second than the number transmittable per second, thereby resulting in an ever increasing queue and delay at the ES transmitters. This relationship between D and ρ, expressed as $D(\rho)$, depends only on the MAA and the statistical characteristics of the user traffic. Special qualities such as fairness to users of the channel assignments and stability* of the MAA

*An MAA is stable if small increases in ρ produce small increases in D.

Table V-1. Examples: Basic Functions of Three Simple MAAs

	TDMA	FDMA	RANDOM ACCESS/RESERVATION
RESERVATION	NONE	NONE	RANDOM ACCESS MODE
SCHEDULE	FIXED	FIXED	FIRST IN, FIRST OUT
CONTROL	FRAME SYNC	GUARD BANDS	RE-BROADCAST, QUEUE TABLE UPDATE

Table V-2. Specific Network Performance Measures

- ACCESSIBILITY

  PROBABILITY THAT NETWORK OVERLOAD WILL CAUSE
  - FAILURE TO ACCESS SYSTEM
  - FAILURE OF DATA TRANSFER

  DURING A GIVEN TIME PERIOD OF A DAY

- ACCURACY
  - PROBABILITY OF DATA LOSS
  - PROBABILITY OF INCORRECTLY DELIVERED DATA

- EFFICIENCY

  PROBABILITY THAT x PERCENT OF ALL NETWORK REQUESTS ARE SATISFIED WITHIN y SECONDS OF REQUEST INITIATION

- RELIABILITY

  PROBABILITY THAT EQUIPMENT FAILURE IN A GIVEN YEAR WILL CAUSE
  - A FAILURE TO ACCESS THE NETWORK
  - INCORRECT NETWORK CONNECTION

are accounted for in the $D(\rho)$ function. These ideas are qualitatively illustrated in Table V-3, where the D vs R relationship is also shown. Table V-3 summarizes the basic performance and functional issues associated with MAAs.

An interesting observation is that the very best schedules for all users would be obtained if there were no need to first communicate traffic requirements or to have any information flow to organize the use of the channel. In other words, if a magic genie could instantly know the traffic status of all users he could then provide the most efficient schedule for them to use. This model enables a simple queueing analysis to be used to get the best system performance (Ref. 2).

The fundamental design-performance issues regarding satellite MA systems are illustrated in Figure V-2. It also shows the basic functional subsystems of any satellite MA system: modulation system of the ES, the satellite functions, and the MAA. The left-hand input to each system is a design issue, and the right-hand outputs are performance issues. So in the case of the modulation function, its design issues of receiver front end design, Time/Frequency/Code channelization, modulation scheme and coding all combine to produce the fundamental communication link performance. The satellite function, driven by on-board processing capability, antenna systems and available power, produces computational support for the MAA and communication link support. Finally, the overall network performance is determined by (1) the MAA and its prime supporting functions of communication link performance and computational ability, and (2) the user traffic the MAA must support. In Tables V-4 and V-5 are succinct elaborations of the relationship between design and performance issues in the MAS architecture.

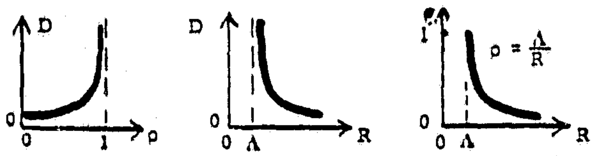
It should be clear from the above discussion how basic architectural issues impact technology areas such as ES and satellite design. In the sequel, we will elaborate on the impact of three of these areas: (1) network performance due to the location of the MAA controller function, (2) network performance due to modulation scheme and ES design, and (3) synchronization requirements due to the use of time-slot channelization. Before we present these discussions, we will review the state of the art of MA systems for satellite communications.

To aid in conducting this study, we contacted several organizations involved in related efforts. A list of these organizations appears at the end of the chapter.

2. STATE OF THE ART OF MULTIPLE ACCESS SYSTEMS FOR SATELLITE COMMUNICATION

A brief description of seven satellite systems that use some form of demand assigned MA system is given in Table V-6. Three systems are in the active planning stage, and four are operational (on orbit). In the present

Table V-3. Multiple Access Systems: Multiple Access Algorithm (MAA)

MAA DESCRIPTOR	IMPACT ON MAA PERFORMANCE
● RESERVATION FUNCTION ACQUIRES REQUESTS FOR SCHEDULING ● SCHEDULER ASSIGNS CHANNEL RESOURCES TO USERS ● CONTROLLER - THE MECHANISM FOR DISTRIBUTING RESERVATION AND SCHEDULE INFORMATION	RESERVATION FUNCTION, SCHEDULER, AND CONTROLLER ALL INTERACT TO PRODUCE THE FUNDAMENTAL MAA PERFORMANCE MEASURE FOR THE PARTICULAR TRAFFIC TYPE SERVED: DELAY VS. THROUGHPUT (D VS ρ) TRADE-OFF 
● COMMUNICATION LINK PERFORMANCE	FOR FIXED P_e AND OFFERRED USER TRAFFIC A THE AVAILABLE DATA RATE R DRIVES THE DELAY VS. THROUGHPUT TRADE-OFF: 
● USER TRAFFIC PARAMETERS - MESSAGE STATISTICS - MESSAGE PRIORITIES - MESSAGE DELAY CONSTRAINTS - NUMBER OF USERS - RECONFIGURABILITY	● D VS. ρ TRADE-OFF ● MAA STABILITY ● FAIRNESS TO USER

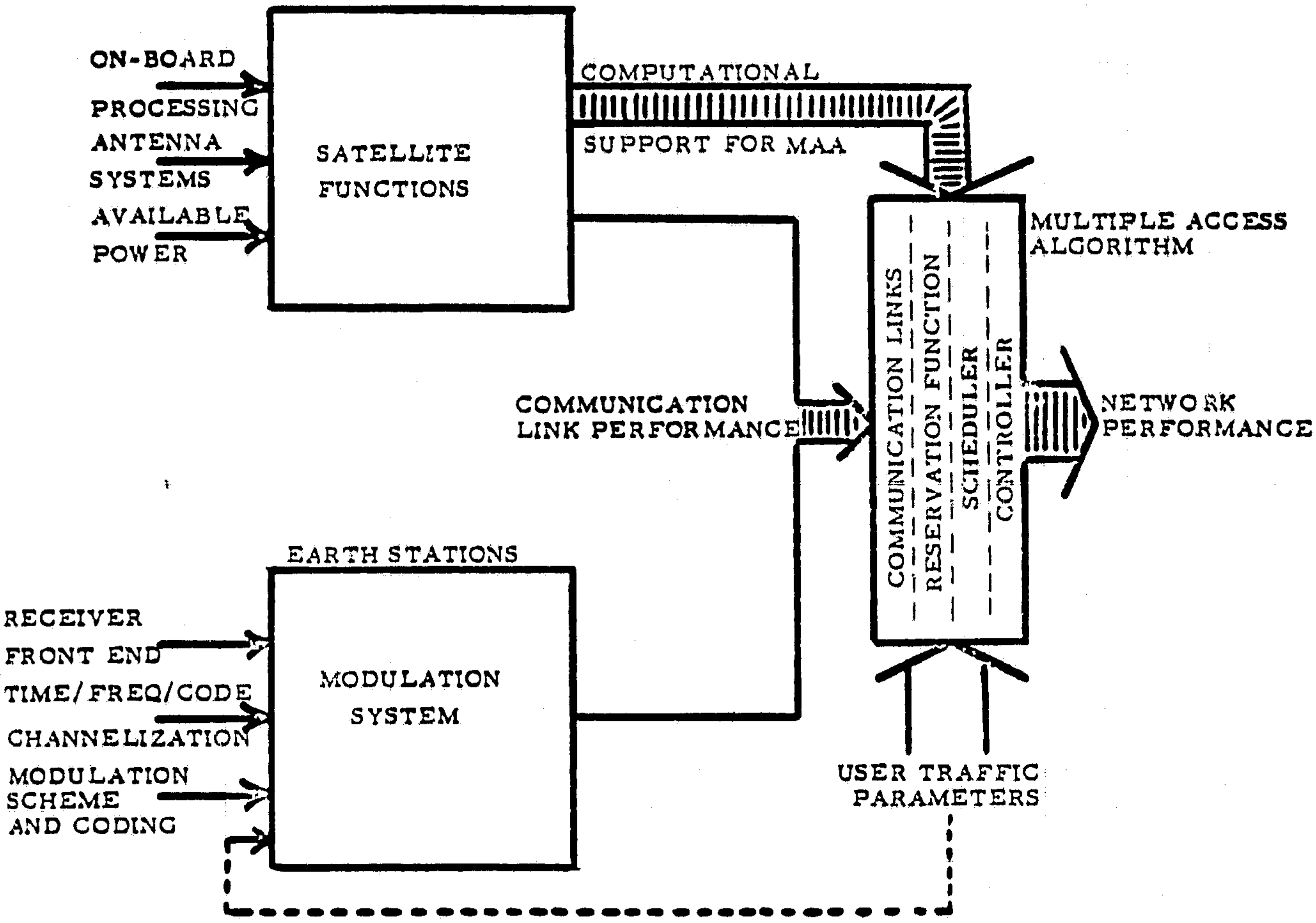


Figure V-2. Satellite Multiple Access Systems: Design-Performance Relationships

Table V-4. Multiple Access Systems: Satellite Functions

DESIGN PARAMETER	BENEFIT TO MAA	AFFECTED AREA OF NETWORK PERFORMANCE	COST TO SYSTEM
ON-BOARD PROCESSING	• COMPUTATIONAL SUPPORT: -RESERVATION FUNCTION CAN QUEUE REQUESTS -SCHEDULER -COMPUTE SERVICE ORDER AND RESOURCE ALLOCATION -CONTROLLER DISTRIBUTE SCHEDULE AND ACKNOWLEDGMENT INFORMATION	• REDUCTION IN DELAY TO DELIVER SCHEDULE INFORMATION SINCE CONTROL DISTANCE LESS THAN THAT OF A GROUND CONTROLLER -OR- • INCREASED THROUGHPUT	SPACECRAFT LOGIC
	• COMMUNICATION LINK PERFORMANCE IMPROVEMENT -ENHANCEMENT OF LINK CAPACITY BY DECODE/RECODE (UPLINK POWER REDUCED; RECEIVE ANTENNA'S SIZE REDUCED)	• REDUCTION IN DELAYS -OR- • INCREASED THROUGHPUT	SIGNAL PROCESSING H/W, LOGIC
ANTENNA SYSTEMS -MULTIPLE BEAMS -ANTENNA SWITCHING	• COMMUNICATION LINK PERFORMANCE IMPROVEMENT -USE OF A SPATIAL DEGREE OF FREEDOM TO INCREASE AVAILABLE RESOURCE -INCREASE IN LOCAL CHANNEL CAPACITY DUE TO INCREASED DIRECTIVITY	• REDUCED MESSAGE DELAYS -OR- • INCREASED THROUGHPUT	WEIGHT, POWER REQUIREMENTS INCREASE; ON-BOARD PROCESSING REQUIRED
POWER	• COMMUNICATION LINK PERFORMANCE IMPROVEMENT -INCREASE IN CHANNEL CAPACITY (AVAILABLE DATA RATE)	• REDUCED MESSAGE DELAY -OR- • INCREASED THROUGHPUT	POWER

Table V-5. Multiple Access Systems: Earth Stations/ Modulation Systems

DESIGN PARAMETERS	BENEFIT TO MAA	AFFECTED AREA OF NETWORK PERFORMANCE	COST TO SYSTEM
• RECEIVER FRONT END -REDUCE NOISE TEMP. -INCREASE RECEIVED AVERAGE POWER	• COMMUNICATION LINK PERFORMANCE IMPROVEMENT -MAINTAIN DESIRED P_e AT HIGHER DATA RATE	• REDUCED MESSAGE DELAYS -OR- • INCREASED THROUGHPUT	COOLER LNR LARGER ANTENNAS
• TIME/FREQ./CODE/ CHANNELIZATION	• COMMUNICATION LINK PERFORMANCE IMPROVEMENT -MODULATION TYPE DEPENDS ON CHANNELIZATION -CHANNELIZATION DIRECTLY AFFECTS DELAY	• REDUCED MESSAGE DELAYS -OR- • INCREASED THROUGHPUT	H/W DESIGN AND COMPLEXITY
• MODULATION SCHEME AND CODING	• COMMUNICATION LINK PERFORMANCE -CHOICE OF MODULATION/CODING AFFECT ERROR RATE P_e, MODULATION EFFICIENCY (DATA RATE USED/REQUIRED BANDWIDTH), AND REQUIRED E_b/N_o -SYNCHRONIZATION SYSTEM DIRECTLY AFFECTS THROUGHPUT	• REDUCED MESSAGE DELAYS -OR- • INCREASED THROUGHPUT	H/W DESIGN AND COMPLEXITY

Table V-6. Some Current Satellite Demand Assigned Multiple Access Systems

SYSTEM	SPONSOR	STATUS	MULTIPLE ACCESS ALGORITHM	REF.
INTELSAT-IV (SPADE)	INTELSAT/ COMSAT	OPERATIONAL	•RESERVATION TDMA/SCPC/DA/FDMA •CIRCUIT SWITCHING •DISTRIBUTED CONTROL	3
MARISAT	COMSAT, RCA, ITT, WU	OPERATIONAL	FM/SCPC (VOICE), TDMA (TELEX) } RESERVED CIRCUIT SWITCHING •CENTRALIZED CONTROL	34
MAROTS	EUROPEAN SPACE AGENCY	OPERATIONAL	•RANDOM ACCESS/RESERVATION/TDMA •CIRCUIT SWITCHING •DISTRIBUTED CONTROL	35
SS-TDMA	INTELSAT/ JAPAN/KDD	DESIGN	•SS-TDMA, DEMAND ASSIGNED •CENTRALIZED CONTROL	30
AFSATCOM II	AF/SAMSO /AEROSPACE	DESIGN	•ALGORITHMS CONSIDERED FOR SPECIAL MODES: TDMA, TDMA WITH POLLING + RESERVATIONS, S-ALOHA •CENTRALIZED CONTROL	13
SATELLITE BUSINESS SYSTEMS	IBM, AETNA, HUGHES	DESIGN	•RESERVATION TDMA •CIRCUIT SWITCHED •CENTRALIZED CONTROL	36
SATNET	ARPA/BBN/ COMSAT/LINKA-BIT	OPERATIONAL EXPERIMENT	•RESERVATION TDMA •ROUND ROBIN TDMA •CPODA/TDMA •PACKET SWITCHED •HYBRID CONTROL	7

context, "circuit switched" means channel assignments are made irrespective of the users' amount of traffic, while "packet switched" means particular channel assignments allow transmission of particular numbers of packets, previously reserved. The control structures will be explained below.

All but one of these systems described use simple forms of MAAs and as such do not fully represent the state of current research (Ref. 3). The exception is SATNET, which uses the most advanced MAA architecture (in the author's opinion); thus it will be briefly described.

The SATNET experiment is sponsored by DARPA to accomplish these goals (Ref. 4):

- Define and refine demand assignment multiple access protocols for broadcast packet satellite networks.
- Obtain data through experiment and simulation for the design and planning of future satellite networks.
- Demonstrate the actual operation of a packet satellite network with elaborate demand assignment multiple access algorithms.

Toward these goals, DARPA obtained use of 64 kbps channel in transponder No. 10 of an INTELSAT IV-A Atlantic satellite. The network consists of four ESs, three standard INTELSAT ESs and a smaller, unattended ES built by Comsat Laboratories. A summary of pertinent ES characteristics is presented in Table V-7. Furthermore, the SATNET experiment, in keeping with the goal of obtaining data to support the design and planning of future satellite networks, is intensely concerned with the problem of serving users with mixed rates and different traffic demands. Accordingly, the "small" ES, while able to transmit at the full 64 kbps information rate of the other three ESs, is able to receive at only one-fourth of that rate, 16 kbps. The traffic types forming the mixture are "bursty" and "non-bursty," and each type of traffic is associated with a priority, indicating the significance of the messages, and a delay constraint (a time interval within which the message must be received to preserve its usefulness). Bursty traffic is characterized by messages with a large variance on both interarrival times and message duration, while non-bursty traffic is defined as messages with very small variance on interarrival times and message duration. Examples of bursty traffic are computer-to-computer and computer-to-terminal traffic. Examples of non-bursty traffic are packetized speech and packetized facsimile. Finally, bursty traffic users can tolerate large variations in message delays, while non-bursty users cannot.

The SATNET experiment is studying three types of MAA: Reservation TDMA (Ref. 5), a type of polling applied to TDMA called Round-Robin (Ref. 6), and a very advanced MAA called "Contention Based Priority Oriented Demand Assignment," or CPODA. The first two MAAs are well

Table V-7. SATNET Experiment: Earth Station Parameters

TYPE OF ES	LOCATION	G/T (DB/°K)	ANTENNA DESCRIPTION	(UNCODED) INFORMATION RATES TRANSMIT	RECEIVE
SMALL, UNATTENDED	CLARKSBURG, MD	29.7	FIXED REFLECTOR, MULTIPLE-BEAM TORUS	64 Kbps	16 kbps
STANDARD INTELSAT	- ETAM, W. VA. - GOONHILLY, GREAT BRITIAN - TANUM, SWEDEN	40.7	97' DISH	64 kbps	64 kbps

Table V-8. The SATNET Experiment: Basic Function of CPODA Scheduler

QUALITATIVE EXAMPLE OF SERVICE ORDERING

MESSAGE PRIORITY	MESSAGE DELAY CONSTRAINT	ORDER OF SERVICE
HIGH	SHORT	1
LOW	SHORT	2
HIGH	LONG	3
LOW	LONG	4

covered in the literature. CPODA, specially designed by researchers (Ref. 7) at Bolt, Baranek and Newman, Inc., and Linkabit, Inc., to handle the general traffic mix described above, is the most promising MAA of the three, so only CPODA will be described here.

The goal of the CPODA algorithm is to obtain best use of satellite channel capacity, subject to user message delay constraints, user priorities, and a mix of user data rates. The approach taken is simply described. Based on a reservation system, the CPODA algorithm schedules channel time for each transmitter according to some desired function of message priority and delay. Only enough time is assigned to a sender for its currently queued messages.

The CPODA scheduler seeks to assign time slots to users in such a way that both message delay-constraints are accounted for in some "fair" way. In Table V-8 this point is illustrated. It is deemed fair to schedule a high-priority, short delay-constraint message before a message with low priority and long delay-constraint.

The reservation and control functions of CPODA are more readily explained with the aid of Figure V-3. There we see that the CPODA MAA has a basic time-frame structure. Each CPODA frame consists of an information subframe (ISF) and a control subframe (CSF). The duration of each CPODA frame is fixed. The duration of the CSF plus the duration of the ISF must always equal the duration of the CPODA frame, allowing the duration of ISF and CSF to vary according to this constraint.

The CSF is used to send control information and to make reservations. Scheduling, accomplished during the ISF, is executed by sending schedule information during the CSF on control packets.

The basic access control problem is: how to inform users of the schedule? The CPODA MAA must account for mixed information rates (recall that the small station cannot receive high rate control information). Also, CPODA must recognize that centralized control incurs two round-trip delays and distributed control incurs one round-trip delay, but is sensitive to noise, two points that will be expanded upon below. The current control function uses distributed control to schedule large ESs and uses one or more large ES to act as a central controller to inform small ESs of their schedule.

Reservations are made in two modes, contention and piggyback. In the contention mode, users that are not currently scheduled use random access during the CSF to inform the scheduler of new packets and their priorities and delay constraints. Once a user is scheduled and transmitting packets during the ISF, reservations may be placed by adding reservation information as overhead on transmitted packets (piggybacking). Naturally, this reservation mode reduces the number of users contending during the CSF to make reservations.

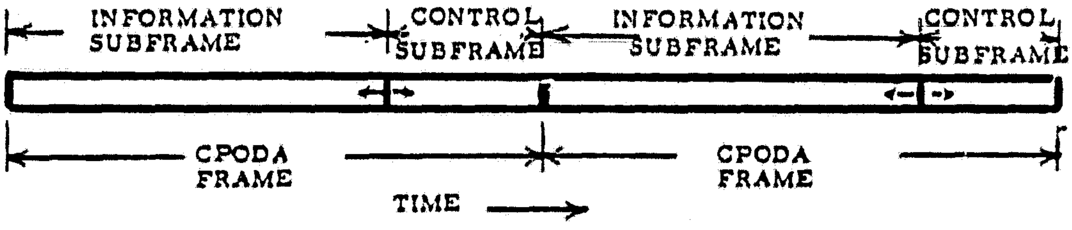
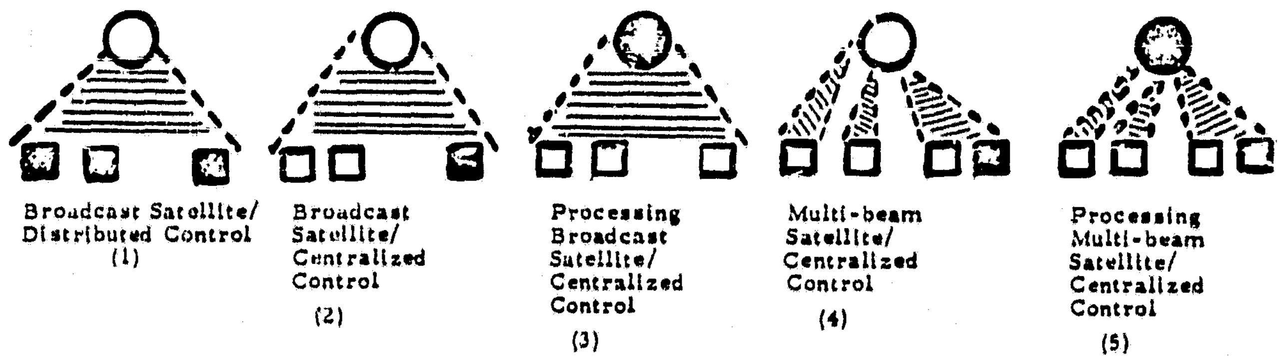


Figure V-3. CPODA: Information and Control Structure



- SIMPLE COMPARISON OF CONTROL ARCHITECTURE
  - (1), (3) AND (5) HAVE SAME SCHEDULE DELAY (1 ROUND TRIP TIME)
  - (2) HAS A SCHEDULE DELAY OF 2 ROUND TRIP TIMES
  - (4) REQUIRES SATELLITE SWITCHING TO YIELD A SCHEDULE DELAY OF 2 ROUND TRIPS
- LINK PERFORMANCE IS DIRECTLY AFFECTED BY
  - CONTROLLER LOCATIONS
  - ON-BOARD PROCESSING CAPABILITY

Figure V-4. Basic MAA Control Architecture

Finally, the duration of the ISF adapts to traffic load, increasing or decreasing as the traffic increases or decreases, respectively.

The CPODA algorithm is currently used in SATNET. Measurements of performance have been made, but are not analyzed as yet.

3. IMPACT OF MULTIPLE ACCESS SYSTEM ARCHITECTURE ON TECHNOLOGY

At this point we have enough background to discuss examples showing how MA system architecture can affect hardware requirements. We will discuss aspects of the impact of controller architecture on hardware requirements, the relationship between MAA, modulation type, and ES design, and the effect of time-domain channelization on synchronization requirements.

a. Impact of Controller Architecture

First we discuss controller architecture with the aid of Figure V-4. We show five basic system architectures resulting from combinations of satellite on-board processing capability, satellite antenna systems, and controller location. Each architecture in the figure is denoted by a number, and the dark shading indicates the location of the controller (a circle stands for the satellite and a square is the ES).

Architecture 1 consists of a broadcast, transponding satellite with distributed control. A reservation request from any user ES is sent to the satellite and rebroadcast to all users who, using identical scheduling algorithms residing in each ES, create the next schedule for the reserved messages. There is a one-hop or one-round-trip delay time incurred (as a minimum) to schedule any user. We also see that scheduling conflicts are avoided only if all ESs correctly receive reservation requests. So communication link performance affects the scheduling function, and the overall communication link is affected by the uplink and downlink individually.

Architecture 2 uses a broadcast satellite with centralized control. A user's reservation must make one hop to inform the controller of a request, and the user must wait another round-trip time to get schedule response. Naturally, the communication link, if noisy, will affect the scheduler.

Architecture 3 uses a broadcast satellite with on-board processing (OBP) ability. The communication links (up and down) can be improved using OBP. Having the controller and scheduler on the satellite enables the user to wait only for his request to reach the satellite and schedule information to return before he sends his message, resulting in a one-round-trip delay, minimum.

Architecture 4 is functionally the same as 2 if OBP and beam switching are present in the satellite. Architecture 5 is functionally the same as (3) if OBP and beam switching are present in the satellite. The use of spot beams can improve communication link performance at the cost of OBP requirements.

As summarized in Figure V-4, architectures 1, 3, 5 have the same minimum schedule delay of one round-trip time, and architectures 2 and 4 have a two round-trip time delay. Further, communication link performance is directly affected by controller location, OBP, and antenna directivity.

It appears from this simple discussion that Multiple Access System Architecture directly affects the hardware areas of antenna systems and communication links, as well as network performance as measured by the component of message delay due to scheduling.

b. Relationship Between MAA, Modulation Type, and ES Design

In this section, discussion is facilitated by defining these basic quantities:

- D = Message delay
- R = Satellite available bit rate (bps)
- P_e = Probability of bit error on the transmission link
- E_b = Energy per bit per received carrier
- C = Average received radiated power
- N_o = One-sided receiver white noise power spectral density
- Λ = Total offered traffic (bps)

We assume for simplicity that we are using a transponding satellite that is downlink limited.

The purpose here is to relate the performance of the MAA, the modulation system, and the ES design as constrained by the key ratio C/N_o.

We begin by noting that for any given MAA and traffic type we have the relationship

$$D = h_{MAA}(R);\ R > \Lambda \tag{1}$$

where $h_{MAA}(\cdot)$ is a function depending on the MAA, and we are constrained to have $R > \Lambda$ to ensure $D < \infty$ as noted in Section 1. Now the communication link is characterized by

$$P_e = g_{MOD}\left(\frac{E_b}{N_o}\right) \tag{2}$$

where $g_{Mod}(\cdot)$ depends on the particular modulation scheme used on the link. Formula (2) holds for any type of Time/Frequency/Code channelization. Also, for any Time/Frequency/Code channelization, we can write (2) as

$$P_e = g_{Mod}\left(\frac{C}{N_o R}\right) \tag{3}$$

because

$$\frac{E_b}{N_o} = \frac{T_b C}{N_o} = \frac{C}{N_o R} \tag{4}$$

where

$$T_b = \frac{1}{R} = \text{duration of 1 bit on channel}$$

$$D = h_{MAA}\left(\frac{C/N_o}{g^{-1}_{MOD}(P_e)}\right) ; \frac{C}{N_o} \geq \Lambda \frac{E_b}{N_o} \tag{5}$$

Formula (5) should be interpreted as follows. First, $g^{-1}_{MOD}(\cdot)$ is simply the inverse function of $g_{MOD}(\cdot)$, which of course exists since P_e is monotonically decreasing in E_b/N_o. Second, (4) implies

$$\frac{C}{N_o} = R \frac{E_b}{N_o} \tag{6}$$

which, when combined with the constraint $R > \Lambda$ in (1), gives the constraint on C/N_o in (5). Finally, (5) and (6) are two relationships that together show how D varies with C/N_o for fixed traffic, P_e, modulation, and MAA. The process leading to (5) and (6) is illustrated in Figure V-5.

It is useful to consider a particular example to demonstrate these ideas. Suppose we consider the standard fixed assignment MAAs frequency division multiple access (FDMA) and time division multiple access (TDMA). We assume that all ESs have the same type of single-packet message traffic characterized by Poisson arrival statistics and b bits per packet. Then defining

$$H(\rho) \equiv \frac{2 - \rho}{2(1 - \rho)} \tag{7}$$

$\tau \equiv$ round-trip propagation delay time

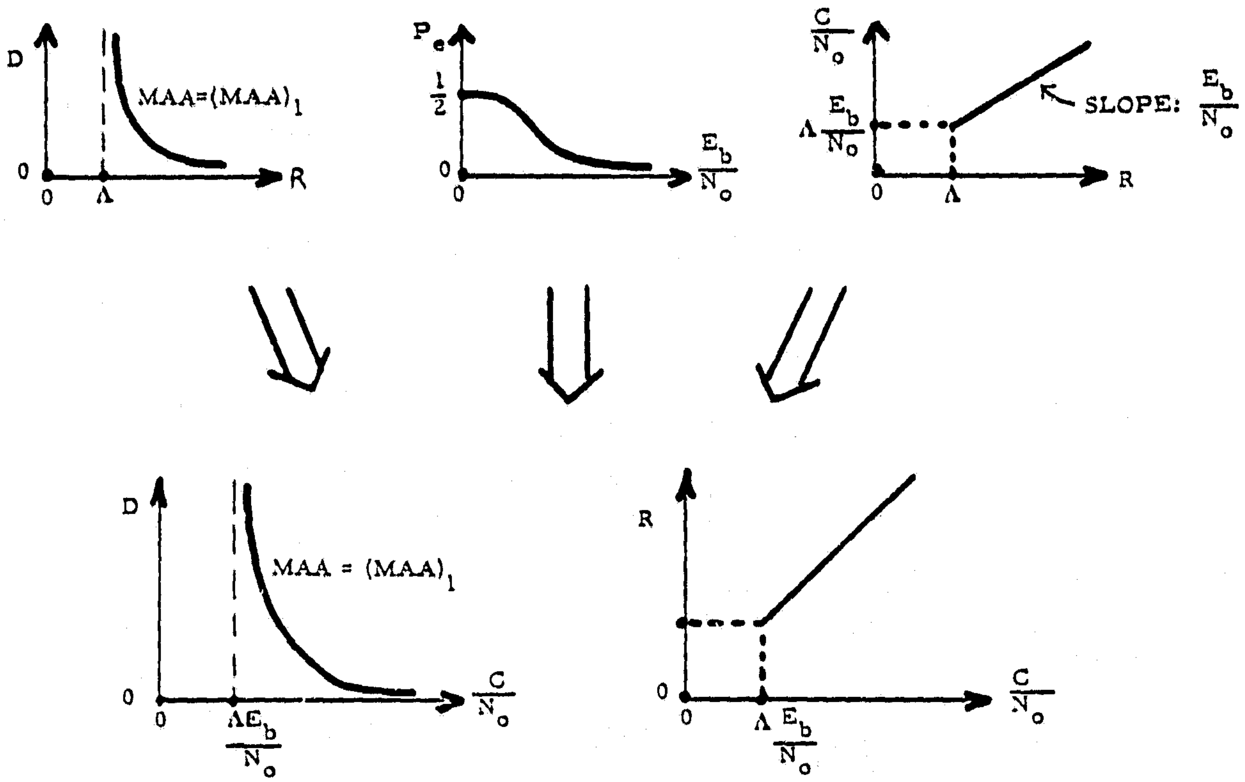


Figure V-5. Relationship Between MAA, Modulation Type, and ES Design we have (Ref. 2)

$$D = h_{MAA}(R) \tag{8}$$

where

$$h_{MAA}(R) = \begin{cases} \frac{Mb}{R} H\left(\frac{\Lambda}{R}\right) + \tau; & MAA = FDMA \\ \frac{Mb}{R}\left[H\left(\frac{\Lambda}{R}\right) - \left(\frac{1}{2} - \frac{1}{M}\right)\right] + \tau; & MAA = TDMA \end{cases} \tag{9}$$

(Observe that the average delay for TDMA is considerably smaller than for FDMA as M increases.) Now let us further assume we use binary coherent phase shift keyed modulation and no coding. Then we have (Ref. 8)

$$P_e = g_{MOD}\left(\frac{E_b}{N_o}\right) = \frac{1}{\sqrt{2\pi}} \int_{\sqrt{\frac{2E_b}{N_o}}}^{\infty} \exp\left(-\frac{v^2}{2}\right) dv \tag{10}$$

Formula (10) can be accurately inverted by using the formula (Ref. 9)

$$\frac{E_b}{N_o} = g^{-1}_{MOD}(P_e) = \frac{1}{2}\left(Z - \frac{a_1 + a_2 Z + a_3 Z^2}{1 + a_4 Z + a_5 Z^2 + a_6 Z^3}\right)^2 \tag{11}$$

where

$Z \equiv \sqrt{-2 \ln (P_e)}$
$a_1 = 2.515517$
$a_2 = 0.802853$
$a_3 = 0.010328$
$a_4 = 1.432788$
$a_5 = 0.189269$
$a_6 = 0.001308$

$|\text{error}| < 4.5 \times 10^{-4}$ for $P_e \in [0, 0.5]$

Assuming M = 1000 ESs, b = 1000 bits/pkt, and each ES's packet generation rate of $\lambda = 0.1$ pkt/sec, we get $\Lambda = Mb\lambda = 10^5$ bps. We also consider $P_e = 10^{-7}$ and $P_e = 10^{-5}$, corresponding to $E_b/N_o = 11.3$ dB and 9.6 dB, respectively. Using these values in (5) and (6) produces the curves shown in Figures V-6 and V-7, where for convenience we have plotted $D - \tau$ instead of D. These curves plainly show the system architect how to trade off D for C/N_o and R for given traffic, P_e, and fixed assignment MAA.

c. <u>Effect of Time Domain Channelization on Synchronization Requirements</u>

The use of time-slot channelization in the various forms of TDMA systems requires that each user ES know precisely the beginning and end of each time slot so that the ES can correctly extract the bits destined for it. Similarly, each ES must know when to begin transmission so that its bit stream in its assigned slot arrives at the satellite transponder without overlapping bursts from any other ES. The problem of determining the correct times to receive and transmit time slots is called the "time synchronization" problem. In the present context, another term, "network synchronization," will refer to the problem of keeping unconflicted schedule information known to all ESs.

The purpose of this section is to show that insofar as time synchronization is required by time-slot channelization, present systems demonstrate the ability to maintain time synchronization at rates exceeding 50 Mbps. In fact, Table V-9 (taken from Ref. 10) shows 16 currently operating TDMA satellite communication systems. The identifier and sponsor of the system are given, along with the name of the class of time synchronization method used (see Ref. 10 for descriptions of these methods). Also, the number of preamble symbols, guard times, and frame times are listed, as well as the modem type and bit rate. In Table V-9 there are at least 13 systems operating with time synchronization systems supporting TDMA using bit rates of at least 50 Mbps. All systems listed in this table operate with at least 90% frame efficiency (total preamble + guard time in a frame)/(frame duration) < 0.10.

We conclude that the technology required to support high rate TDMA time synchronization is mature and need not be an area of major research and development for current purposes.

4. RECOMMENDATIONS TO ADVANCE THE STATE OF THE ART

The purpose of this section is to indicate actions that could be taken to advance our ability to design and build effective multiple access systems. The approach recommended here is intended to reduce the gap between the theory of multiple access algorithms and architecture and the practice of satellite communication systems.

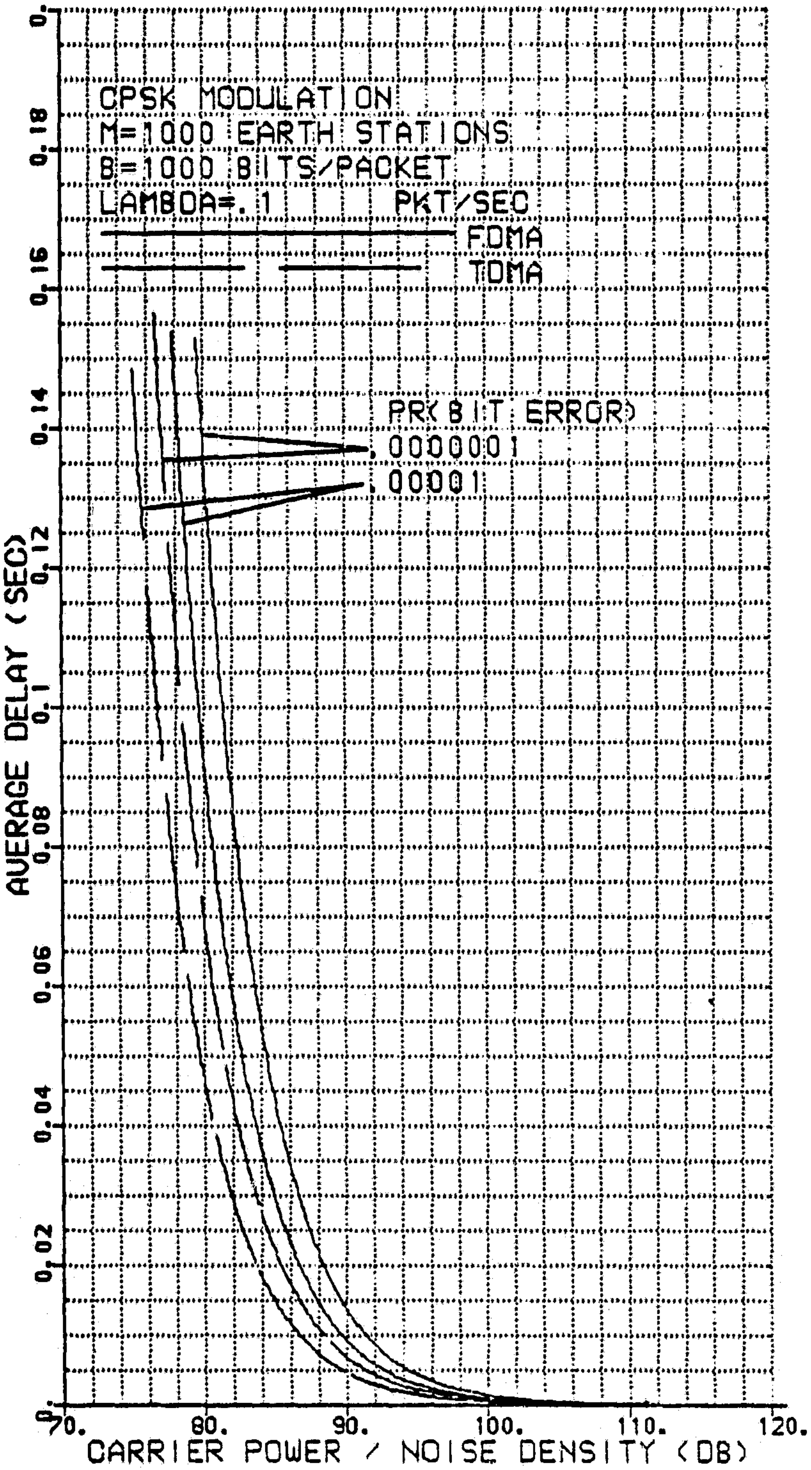


Figure V-6. CPSK Modulation

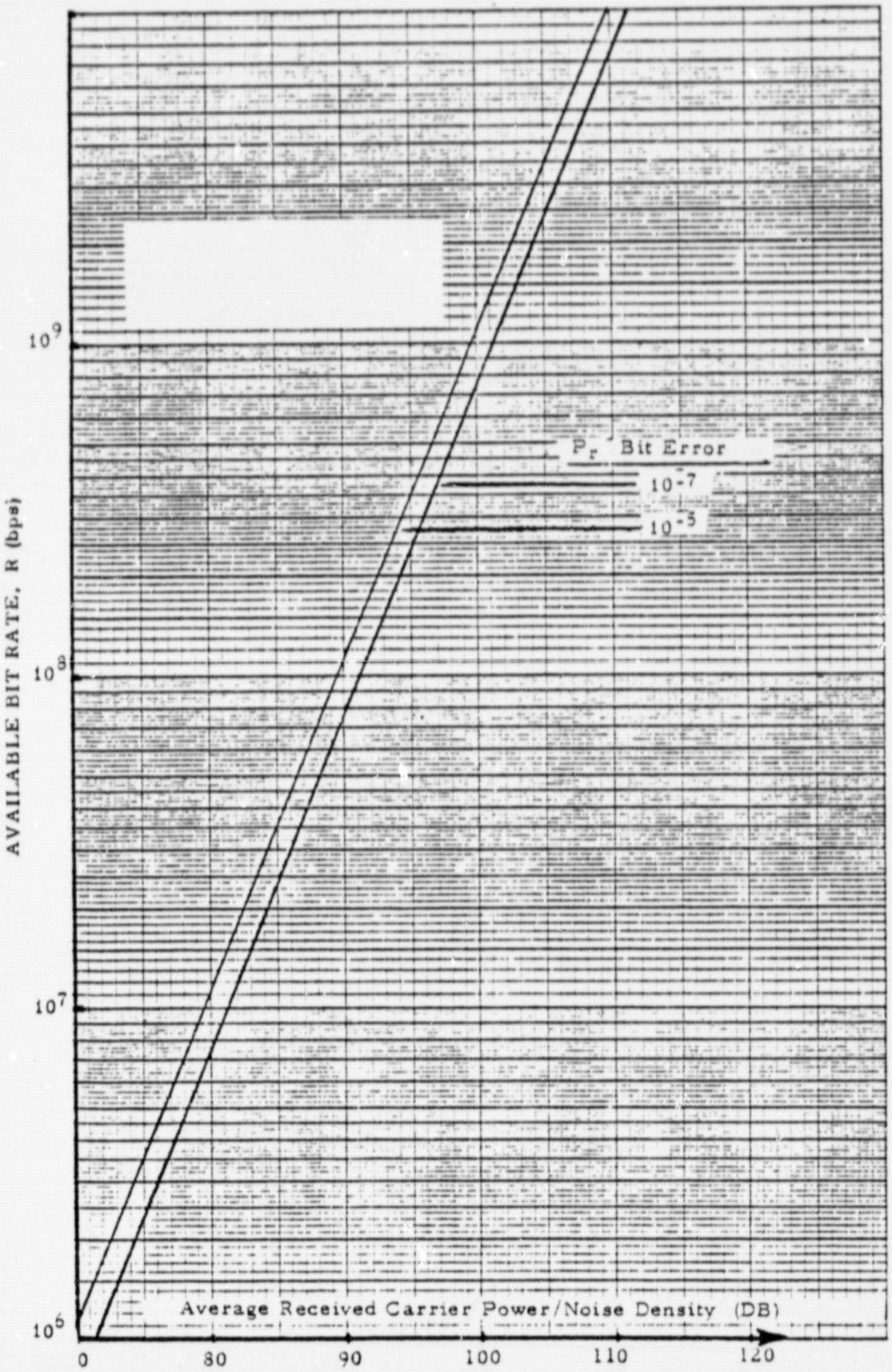


Figure V-7. Relationship Between R, C/N_o and P_e for CPSK Modulation

Table V-9. Summary of TDMA Synchronization Systems

● INTELSAT SYSTEMS

IDENTIFIER	CLASS OF SYNCHRONIZATION	PREAMBLE (# OF SYMBOLS)	GUARD TIME (ns)	FRAME (μs)	MODEM	RATE (Mb/s)
MATE	REFERENCE BURST WITH SELF-RANGING	82	220	125	2φ CPSK	6.176
MAT 1 TDMA-1	REFERENCE BURST WITH SELF-RANGING BURST-INCOHERENT (SERIAL) DETECTION	52	100	125	4φ CPSK or 4φ DCPSK	50
INTELSAT TDMA	REFERENCE BURST WITH SELF-RANGING	72	60	750	4φ CPSK	61
TDMA-2	REFERENCE BURST WITH SELF-RANGING	30	60	125	4φ CPSK	50
TDMA TEST-BED	REFERENCE BURST + SELF-LOCK, OR FEEDBACK OR SLAVE	72	35	750	4φ CPSK	120

● JAPAN

IDENTIFIER	CLASS OF SYNCHRONIZATION	PREAMBLE (# OF SYMBOLS)	GUARD TIME (ns)	FRAME (μs)	MODEM	RATE (Mb/s)
SMAX (ECL)	REFERENCE BURST, CLOCK COHERENT	36	0	125	4φ PSK	13.664
TTT (KDD)	REFERENCE BURST WITH LOW-LEVEL RANGING	38	< 100	125	4φ DPSK	50
T/F (KDD)	REFERENCE/FEEDBACK (SPOT BEAM)	45 (2φ)	60	125	8φ CPSK	90
Fujitsu	REFERENCE BURST, SATELLITE-SWITCHED, SYNC. WINDOW		50	750	2φ DCPSK	40
NTT	REFERENCE BURST, CLOCK COHERENT	63	10	328	2φ CPSK	100

Table V-9. Summary of TDMA Synchronization Systems (Continued)

● EUROPE

IDENTIFIER	CLASS OF SYNCHRONIZATION	PREAMBLE (# OF SYMBOLS)	GUARD TIME (ns)	FRAME (μs)	MODEM	RATE (Mb/s)
FRANCO-GERMAN	REFERENCE BURST WITH SELF-RANGING BURST-COHERENT (PARALLEL) DETECTION	40	80	750	2φ DPSK 4φ DPSK	100,50
ESTEC/ESA	REFERENCE BURST, SATELLITE SWITCHED		130 90	750	4φ DCPSK	60, 180
ESA TDMA	LOW-LEVEL M-SEQUENCE		<100		4φ CPSK	90,100

● CANADA

IDENTIFIER	CLASS OF SYNCHRONIZATION	PREAMBLE (# OF SYMBOLS)	GUARD TIME (ns)	FRAME (μs)	MODEM	RATE (Mb/s)
TELESAT TDMA	REFERENCE BURST	48	196	250	4φ CPSK	61.248
CENSAR	CENTRALIZED	31	< 30	125	2φ DPSK	65 32.5

● USA

IDENTIFIER	CLASS OF SYNCHRONIZATION	PREAMBLE (# OF SYMBOLS)	GUARD TIME (ns)	FRAME (μs)	MODEM	RATE (Mb/s)
DSCS (DCA)	LOW-LEVEL SPREAD-SPECTRUM, COHERENT DETECTION	18	100	832	4φ CPSK	40, 20, 10

Toward this end, a series of system engineering studies should be undertaken to clarify certain key architectural issues and to accurately model the interplay of the multiple access system functional (architectural) requirements and the design parameters of the supporting hardware and software.

a. Key Architectural Issues

As indicated in the discussion of the SATNET experiment, a prime area of interest is MAAs that can yield desirable delay-throughput trade-offs while supporting traffic consisting of a diverse mixture of message lengths, rates, priorities, and delay constraints. There are basic papers in MAA research (Refs. 6, 11) concerning a mixed user class, but much more work needs to be done to account for the great diversity of communications requirements (Ref. 12).

Another key architectural issue is network synchronization. Here we are fundamentally concerned with enabling all users to maintain conflict-free schedules. Effective network synchronization should enable users to readily measure network scheduling states, to readily enter or leave the network, and to avoid and if necessary detect and correct schedule conflicts. It appears that there is only one generally available work on this network synchronization problem (Ref. 7), and this work results from the SATNET experiment.

The final architectural issue of importance here is interoperability of terrestrial and satellite communication networks. The enormous sunk-costs of present terrestrial equipment and satellite network ground stations strongly argue for their continued use to fully amortize their value. Therefore, the existence of this equipment constrains the development of satellite communication networks in ways that require further study.

b. Interplay Between System Architecture and Hardware

Two important aspects of the interplay between architecture and hardware need further exploration. The first, described above, is the relationship between MAA, modulation system, and ES design. The second aspect concerns the impact of on-board processing. There are at least four significant factors regarding on-board processing that would affect overall network performance:

- Communication link performance
- Location of MAA control and schedule functions
- Multi-beam antenna switching
- Capability to store and forward packets

c. Specific Recommendations

To achieve the understanding of key issues outlined above, we recommend the creation and exercise of a satellite communication network simulator, followed by a series of specialized studies to explore issues that appear significant in the first simulation experiments.

The satellite communication network simulator should be a software package that enables accurate modeling of MAAs of interest as well as basic system architectures and hardware. An internal subroutine would produce measurements of network performance. Naturally, certain restrictions on generality should be made to permit an initial program to be written and debugged in a reasonable time. For example, modulation could be restricted to N-CPSK and coding restricted to convolutional. User traffic models could be classified by the method described earlier (bursty, non-bursty, priority, and delay-constraint). Earth stations could be modeled according to the antenna systems, front ends, power levels, and channelizations (see Introduction). The MAAs will require fairly sophisticated programming methods to treat them generically, and this can be avoided by restricting the admissible class of MAAs. Work at The Aerospace Corporation (Ref. 13) uses a technique whereby MAAs are constructed as a combination of sub-algorithms that are common to all MAAs and those sub-algorithms, changeable by an expert programmer, that are unique to the particular MAA of interest. Finally, all these subsystems must be tied together in the program according to the architectural designs under consideration (e.g., according to the impact of a particular on-board processor).

Such a simulation study would require a sophisticated computer programmer, preferably expert in discrete event simulation, and a satellite communication system engineer who is familiar with MAAs. It is expected that a simulator could be written, debugged, and exercised by this team over a 1-year period to produce useful understanding of the architecture-hardware interplay.

Based on ongoing results from this basic study, areas of particular interest may be discerned, and these can be investigated with separate studies.

B. SURVEY OF ERROR CORRECTING CODES

1. OVERVIEW

It has been recognized for some time that error correcting codes can be used on a satellite communication channel to provide a significant reduction in transmitter power requirements. It was later realized that some of the algorithms used for error correction can also be used to increase data throughput in a bandlimited channel. Such codes are attractive with regard to hardware requirements because:

- Encoders can be implemented with very simple hardware, and thus can be placed on-board a satellite.
- Decoders require complex hardware, but can usually be located on the ground. This is true in satellite-to-ground links, where coding can be used to reduce the satellite transmitter power requirements or to increase the link margin.

For example, a rate 1/2, constraint length 7 convolutional code used with a maximum likelihood (Viterbi) decoder saves approximately 5 dB of transmitter power on a Gaussian channel. This is currently the most popular choice for error correction equipment, and has been used on military communication links at data rates up to about 10 Mbps.

Figure V-8 summarizes the performance of various combinations of modulation and coding techniques on a Gaussian channel. All these codes can be implemented as ground equipment with reasonable complexity. Table V-10 defines the data points on the figure. There are some general conclusions that can be drawn from this figure:

- In the power-limited region, currently known coding techniques are within 3 to 4 dB of the Shannon limit. Although it is possible that better algorithms could be devised, the additional payoff in coding gain would be small compared to that already realized by current techniques.
- In the bandwidth-limited region, there is room to improve throughput.
- Coding for a Gaussian channel is a fairly mature technology in the sense that the gap between uncoded PSK and the Shannon limit has been reduced drastically. There remains the question of hardware implementation limits, which is discussed later. It should be noted that the use of a powerful code places performance stress on the modem. For example, use of the concatenated codes shown in Figure V-8 would require the modem to operate at a signal-to-noise ratio of -0.4 dB, which is outside the capability of most modems. Thus, to more closely approach the Shannon limit in the power-limited region would require modem development in addition to better coding techniques.

The following sections discuss the state of the art of error correction coding for both satellite-based and ground-based equipment. Technology gaps and development opportunities are identified. The areas which appear

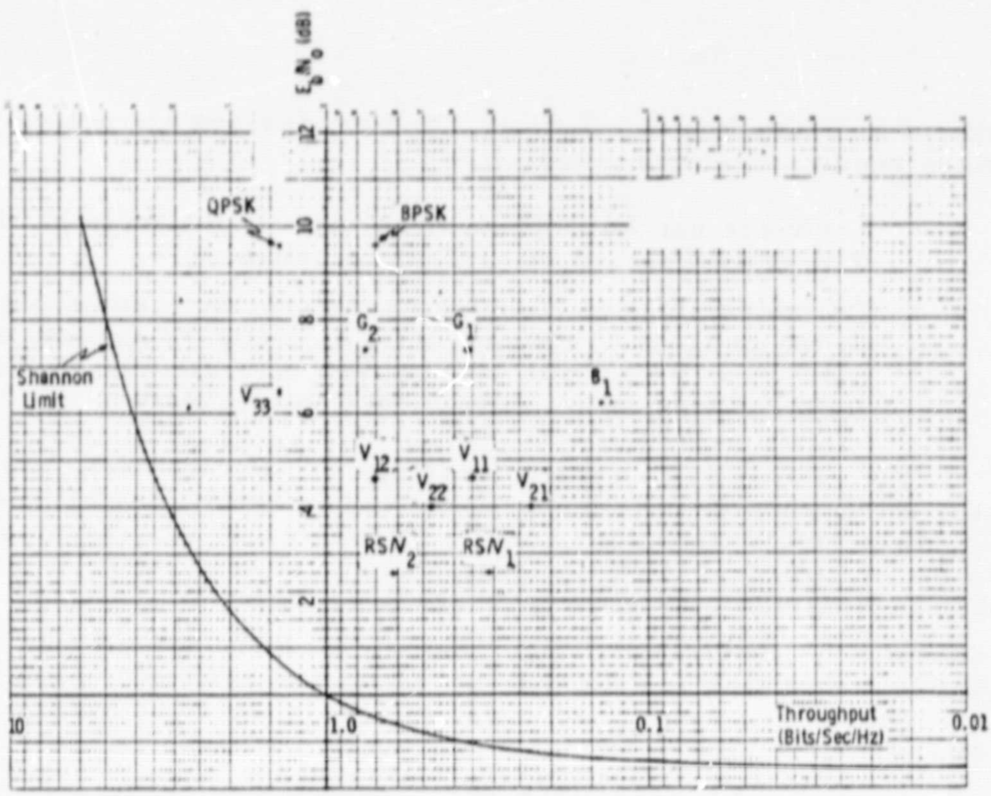


Figure V-8. Coding Algorithms on Gaussian Channels (BER = 1×10^{-5})

Table V-10. Coding/Modulation Performance for Gaussian Channel

	Code	Modulation	Throughput (Bits/Sec/Hz)	E_b/N_o (dB) (For BER = 1×10^{-5})	Reference
B_1	Biorthogonal (32, 6)	BPSK	0.14	6.2	Linkabit (14)
G_1	Golay (23, 12)	BPSK	0.36	7.3	"
G_2	"	QPSK	0.73	7.3	"
V_{11}	K=7, R=1/2 Viterbi	BPSK	0.35	4.5	"
V_{12}	"	QPSK	0.70	4.5	"
V_{21}	K=7, R=1/3 Viterbi	BPSK	0.23	4.0	"
V_{22}	"	QPSK	0.47	4.0	"
RS/V_1	Concatenated*	BPSK	0.31	2.6	Odenwalder (15)
RS/V_2	"	QPSK	0.62	2.6	"
V_{33}	K=8, R=2/3 Viterbi	8PSK	1.4	6.5	Odenwalder (16)

* Inner Code - K=7, R=1/2 Viterbi Decoder
Outer Code - Reed-Solomon (255,223) with 8 bits/symbol

to provide the most potential for development are broadly classified as bandwidth-efficient modulation and coding techniques, and satellite-based demodulation and decoding. Specific recommendations for furthering the state of the art are presented.

2. STATE OF THE ART

a. Ground-Based Decoders

Since the encoding function is simple and easy to implement, the state of the art is determined by implementation of the decoder. The primary benchmarks for decoder design are considered to be:

- Performance, as measured by the required bandwidth and signal-to-noise ratio. This is determined primarily by the decoding algorithm since hardware implementation losses are typically negligible.
- Maximum data rate, determined by logic speed and decoder architecture.
- Complexity, which has a direct effect on weight, power consumption, and reliability.

The last two items are closely related since data rate can be increased by doing the various decoding operations in parallel, but at the cost of complex hardware.

There have been no general decoder hardware studies to define the trade-off between performance, speed, and complexity. There have been several decoder designs implemented or proposed which can be used as data points in surveying the state of the art. These are illustrated in Figure V-9, which plots coding gain vs. data rate. In Table V-11 each data point is defined according to decoder type and number of integrated circuits required for implementation (Ref. 15).

The decoders shown in Figure V-9 represent the state of the art. All use convolutional codes, and it is generally recognized that convolutional codes are superior to block codes for a Gaussian channel when the comparison is done on equal bandwidth basis.

Recently, Acampora and Gilmore (Ref. 17) have developed an analog Viterbi decoder, which has the capability of operating at data rates as high as 200 Mbps. This speed surpasses that of any digital convolutional decoders yet produced, and it is achieved by using analog adders for the path metric computations. Although it is an intriguing approach, it is too early to predict whether the analog decoder will be able to compete with existing digital decoders.

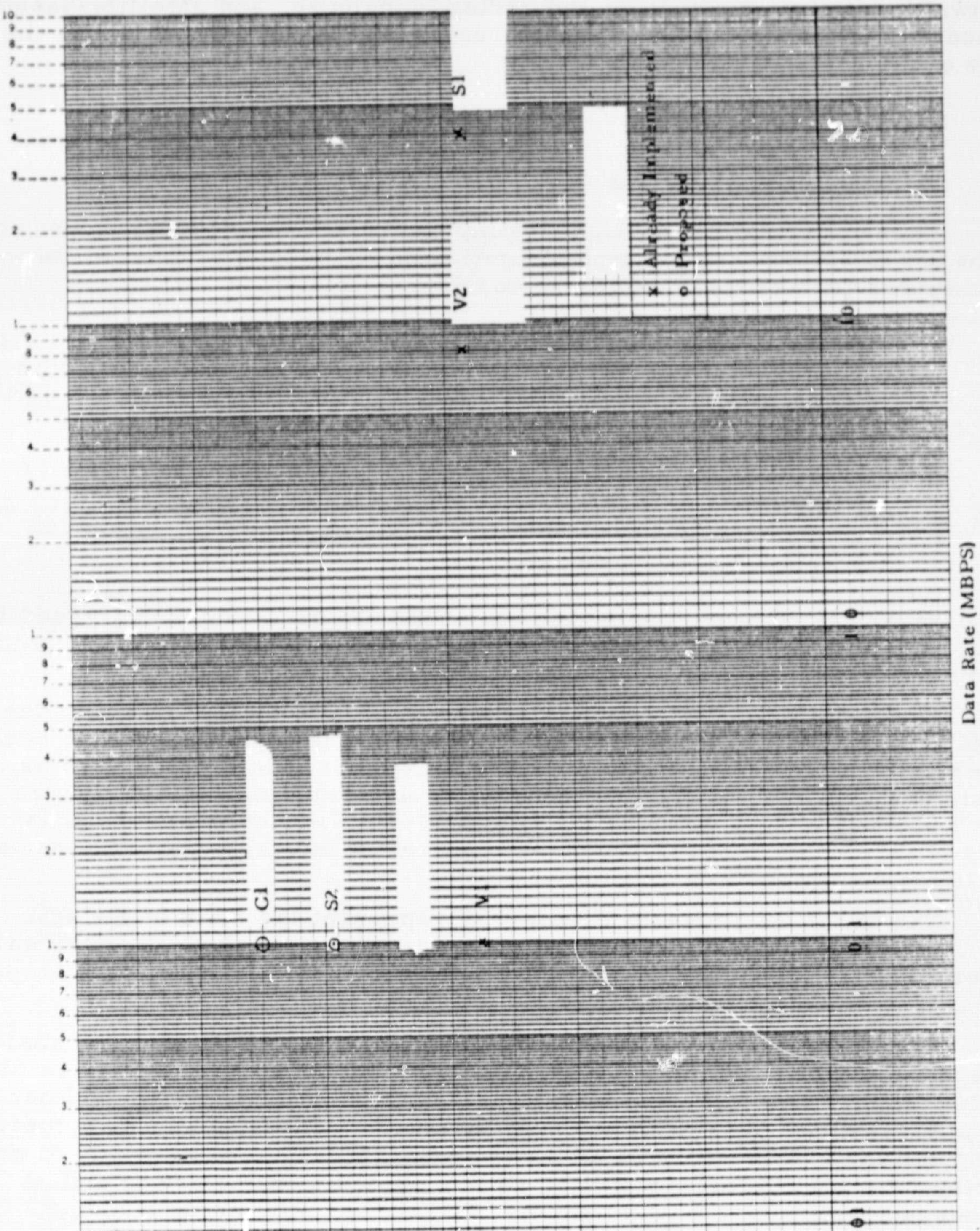


Figure V-9. Decoder Speeds

Table V-11. Decoder Design Characteristics

	Decoder Type	Max. Data Rate	Logic Type	No. of IC's	Remarks
V1	Viterbi, K=7, R=1/2	100 kbps	T^2L	60	Serial processing
V2	Viterbi, K=7, R=1/2	8 Mbps	T^2L	250	Parallel processing
S1	Sequential, R=1/3	40 Mbps	MECL, T^2L	700	10^8 computations/sec, 64K buffer, hard decisions
S2	Sequential, R=1/3	100 kbps	T^2L	400	10^6 computations/sec, 64K buffer, soft decisions
C1	Concatenated Viterbi K=8, R=1/3	100 kbps	T^2L	333	Requires 64K buffer

b. Satellite-Based Decoders

On-board error correction at present is limited to decoding of simple block codes at very low data rates. Convolutional decoding of any type has not been done. Thus, there is no experience in on-board decoding which would be applicable to a communication channel.

c. Satellite-Based Demodulators

On-board demodulators have been used in military programs for relatively low rate data, and the techniques could be applied to high-rate communications data. Comsat Laboratories is in the process of developing a differential quadraphase shift keying (QPSK) demodulator intended for on-board use (Ref. 18). It uses direct demodulation (there is no conversion to an IF frequency) to save weight and power. The differential phase comparison is done by using a delay unit with a precise delay of one band interval. This delay is temperature compensated, which was the main implementation problem. They estimate that the demodulator can be used at data rates up to 120 Mbps. Of course, differential demodulation has a performance degradation of about 3 dB compared to coherent QPSK. Thus, it places a power penalty on the uplink, thereby making on-board demodulation less useful.

3. TECHNOLOGY LIMITS

a. Ground-Based Decoding

There is a theoretical limit on coding gain, illustrated as the Shannon limit in Figure V-8. In addition, hardware complexity limits coding gain. It can be shown that for any of the known coding algorithms, for a fixed bandwidth the decoder complexity grows exponentially with coding gain. Thus, there is no practical way to achieve all the coding gain promised by the Shannon limit. Studies have indicated that the best approach to increasing coding gain is not to build a more complex decoder, but rather use a concatenated code (which is a two-stage coding process, or a code within a code) (Ref. 15).

There is also a hardware constraint on the data rates that can be decoded, but it is not a serious one. Although a digital convolutional decoder is limited to data rates in the range of 10 to 40 Mbps with current logic speeds (Refs. 15 and 17), higher data rates can be obtained by operating encoders and decoders in parallel, as shown in Figure V-10. The only high speed equipment in this system configuration is the multiplexers and demultiplexers, which can be implemented at data rates up to 1 Gbps. This is the approach chosen for the Space Shuttle (Ref. 19). Thus, high speed decoding does not require the development of faster logic, although it is expected that as faster logic becomes available it will be incorporated into decoder designs.

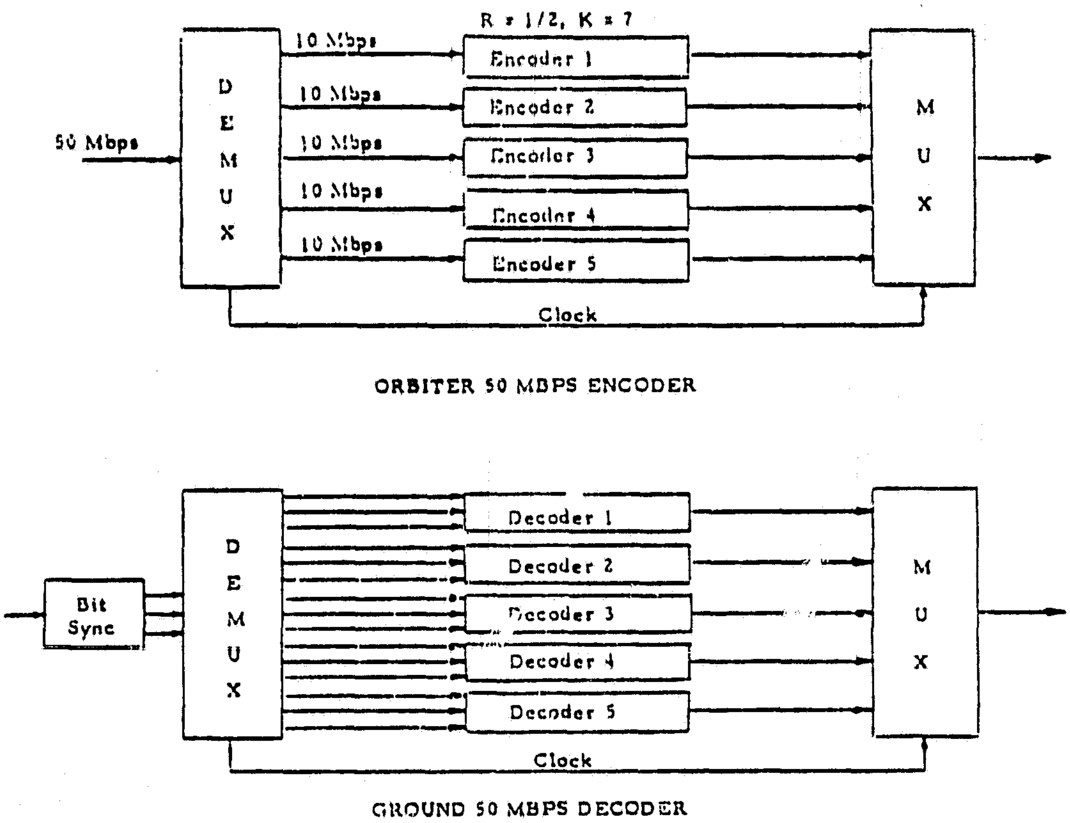


Figure V-10. Functional Configuration for 50 Mbps Operation Using Multiplexed 10 Mbps Viterbi Decoders (From Ref. 19)

b. On-Board Demodulation/Decoding

Throughout our discussion of on-board decoding, demodulation will also be considered since the two subjects are so closely related. For on-board demodulators and decoders, the primary constraint is hardware complexity. Since there are no on-board decoders at present, the use of such equipment in the 1983 era would be a significant advancement in satellite communications technology.

None of the coding experts contacted in the course of this study has defined the maximum data rate that could be achieved with on-board demodulation/decoding by 1983. The following general conclusions are probably conservative, but represent a reasonable goal for an initial on-board decoder:

- If the decoder is implemented in software based upon a microprocessor (assuming a suitable microprocessor will be space qualified by 1983), the data rate would be limited to about 1 kbps (Ref. 20).

- If the decoder is implemented in hardware, a data rate of about 100 kbps should be possible. This estimate is based upon the fact that a serial processing Viterbi decoder can be implemented at 100 kbps using about 60 T^2L IC's.
- On-board demodulators can be implemented at data rates as high as 120 Mbps (Ref. 18).

4. DEVELOPMENT OPPORTUNITIES

This section summarizes the development opportunities that have been suggested by various people who work in the area of error correcting codes. These suggestions were obtained from the literature and from personal contacts. Personnel contacted are included in a list at the end of the chapter.

a. On-Board Demodulation/Decoding

On-board demodulation/decoding is a subject which is just beginning to receive serious consideration. Lindsey (Ref. 21) has done the most complete analysis of the effects of satellite nonlinearities and bandlimiting on the transmission of PSK. The performance curves shown in Figures V-11 and V-12 are based upon this reference.* The following notes apply to these figures:

- The transmit filter is wide enough so that intersymbol interference is not significant.
- For the case of the nonlinear repeater (designated NL on the figures), the repeater model consists of a soft limiter followed by a traveling-wave tube. Measured AM/PM characteristics of a particular traveling-wave tube are assumed.
- Figures V-11 and V-12 show that for binary phase shift keying (BPSK), on-board demodulation results in very little power saving on either the uplink or downlink. For QPSK or 8-level PSK, on-board demodulation provides a definite improvement over the nonlinear repeater.

Other authors have also made predictions on the power reductions afforded by on-board processing, and these predictions in some cases differ markedly from Figures V-11 and V-12. For example, Lee (Ref. 18) predicts

*Figure V-11 shows the case of 0-dB backoff from saturation, and Figure V-12, 3-dB backoff.

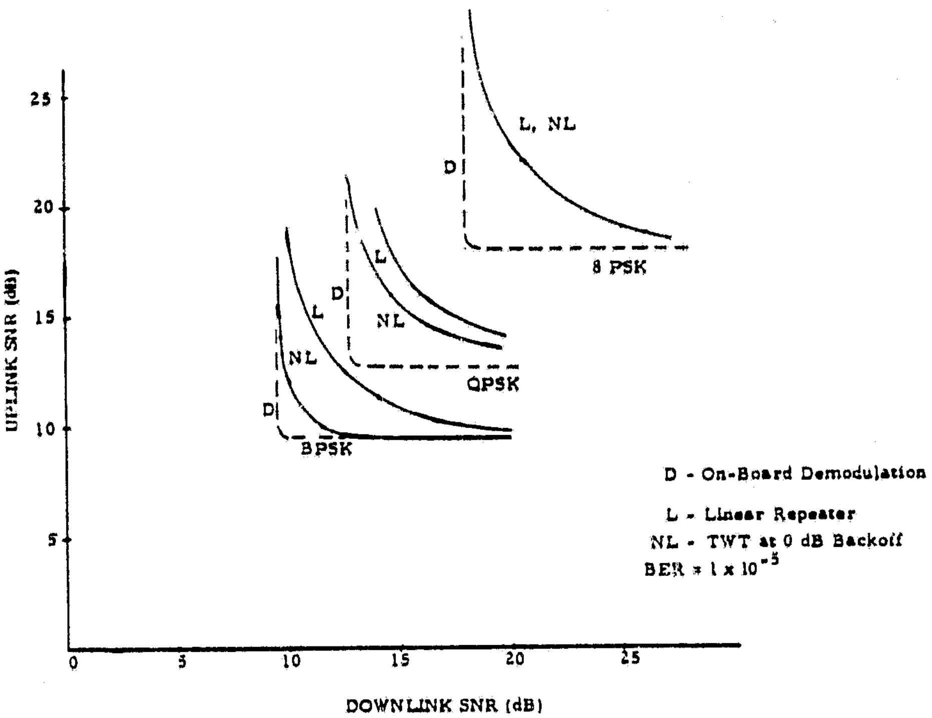


Figure V-11. On-Board Demodulation (Based on Ref. 21)

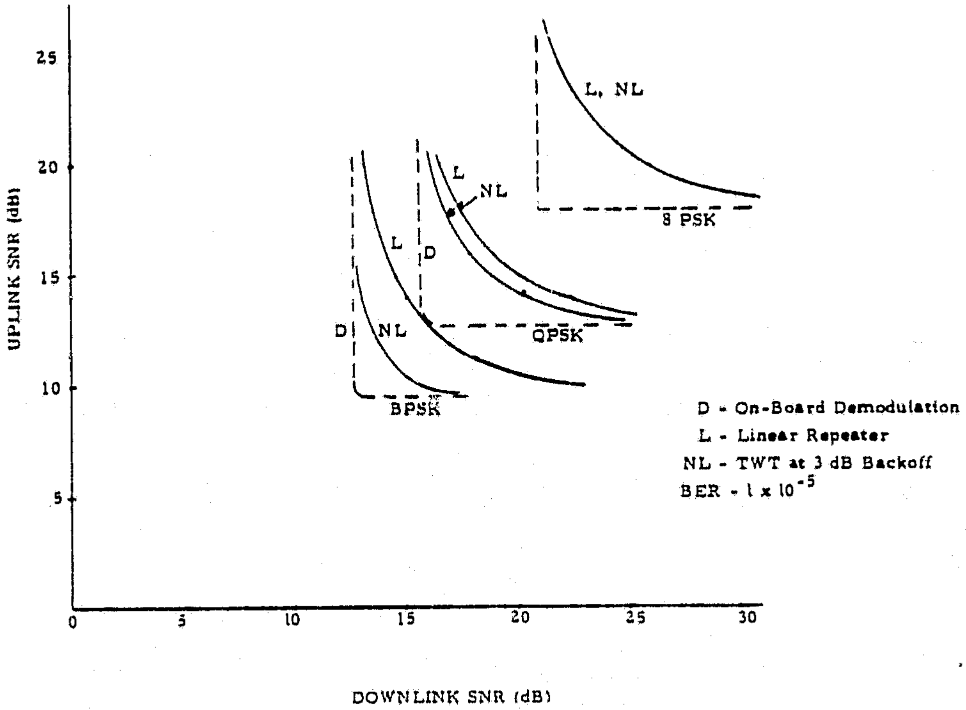


Figure V-12. On-Board Demodulation (Based on Ref. 21) much larger gains for the case of QPSK. Time did not permit these differences to be sorted out during the course of this study. However, they should be resolved to arrive at a solid prediction of the performance of on-board demodulation.

Another topic which needs attention is the best choice of modulation/demodulation technique for on-board processing. Comsat Laboratories (Ref. 18) has developed a differential QPSK demodulator which is suitable for satellite implementation. However, it suffers about 3 dB degradation on the uplink compared to a coherent demodulator, and thus gives away some of the uplink performance provided by on-board demodulation. Lindsey and Omura of LinCom are currently studying on-board modulation techniques for DCA, and their report will be made public by October 1, 1978.

In connection with on-board decoding, the following additional topics for further study have been suggested:

- μ-processor based decoders for low-rate uplink channels (Ref. 20).
- A Marisat-type system for the application of on-board demodulation and decoding.
- Feed-forward linearizing modems that compensate for the effects of satellite nonlinearities.
- Stability problems resulting from on-board analog signal processing. (Mentioned by Dr. Huth at Axiomatix; also see discussion of stability problems in building an analog demodulator in Ref. 18.)

b. Bandwidth Conserving Modulation/Coding Techniques

Combinations of modulation and coding techniques which conserve bandwidth should be studied for applications where bandwidth is scarce. The idea is to use a bandwidth-conserving modulation technique, such as 8-level PSK, and to make up the power loss by using coding. For example, 8-level PSK combined with rate 2/3 Viterbi decoding requires the same bandwidth as QPSK, but gets by with 3 dB less transmitter power (Ref. 16).

Another approach to conserving bandwidth was studied by LinCom (Ref. 21). This approach involves using a Viterbi demodulator to compensate for intersymbol interference in a bandlimited channel. Although the LinCom study contains performance predictions obtained from simulations, some open questions remain:

- How does the Viterbi demodulator compare to classical equalization techniques?

- Under what circumstances would the Viterbi demodulator need to be adaptive, and can the adaptive feature be implemented?

Figure V-8 shows the importance of studying techniques that conserve bandwidth, since there is considerable room to improve throughput at any given signal-to-noise ratio.

c. Coding on Non-Gaussian Channels

Satellite channels are conventionally modeled as Gaussian. However, in some cases this is not valid because of co-channel interference. Interference on an uncoded binary PSK signal has been studied (Ref. 22), but coding techniques to overcome this interference do not appear very promising, except for the following situations:

- Conventional spread spectrum techniques, such as frequency hopping, combined with coding can be used, but these techniques have been studied extensively for military communication systems.
- If the interference is of a burst nature, such as that produced by a pulsed radar, then there are burst correcting codes which are applicable.

The study did not uncover any promising coding studies for non-Gaussian channels.

d. Other Coding Topics

Other miscellaneous candidates for further study include the following:

- Better decoding algorithms for block codes.
- The relative advantages of sequential and Viterbi decoding for packet data transmission and for multiplexed codes.
- Analog Viterbi decoding (Ref. 17). One of the decoder configurations given in this reference is particularly interesting because it is a complete departure from the usual decoder block diagram.

C. ON-BOARD PROCESSING

1. INTRODUCTION

The on-board processing functions considered in this survey can be grouped into three categories as indicated in Figure V-13a. The rf switching involves routing multiple received signals (possibly after conversion to some convenient frequency) to appropriate downlink modulators. Digital processing involves operations on signals at i.f. and subsequently at baseband. Control functions are those functions which are necessary to enable the system to perform the communications mission but are not directly involved with signal processing.

Primary benefits resulting from processing on the spacecraft are summarized in Figure V-13b. The rf switching, which is essentially a form of circuit switching, provides the first level of increased network flexibility. With the addition of digital processing, full flexibility, including the ability to route individual messages (or packets), can be achieved. If rf switching is used in conjunction with multiple beam antennas or if baseband digital processing is employed, uplink power efficiency is increased. Demodulation of the uplink followed by remodulation (possibly accompanied by decoding, encoding, etc.) separates uplink and downlink signal designs allowing optimization of each. Spread-spectrum processing, essentially a specialized form of demodulation, increases system survivability in the face of either intentional or circumstantial interference. With substantial processing, especially digital, performed on-board, the possibility exists for modification (either by uplink command or dynamically by an on-board controller) of the processor functions and configuration. Finally, with increased on-board control, the dependence on command links is reduced.

Most of the technologies necessary to implement the processing functions discussed are either currently available or under active development. However, the complexity of envisioned processors leads to significant reliability and power/weight problems. Thus, these problems and approaches to solving them are the key issues in on-board processing. This study focuses on two approaches: digital processor architectures and processor technologies, as summarized in Figure V-14.

2. DIGITAL PROCESSOR ARCHITECTURES

A general conceptual block diagram of a full digital processor is shown in Figure V-15. The i.f. inputs from a multiple beam receive antenna are demodulated, data detected, deinterleaved, and decoded. The resulting information bits are buffered for routing, reformatting, encoding, etc. in preparation for downlink transmission via a transmit multiple beam antenna. It should be noted that in a given application not all of these functions are necessarily performed. The question of interest here is how one actually structures a processor which performs some or all of the functions indicated.

RF SWITCHING

DIGITAL PROCESSING

- DIGITAL FILTERING
- DEMOD/REMOD
- DEINTERLEAVE/INTERLEAVE
- DECODE/ENCODE
- BASEBAND SWITCHING

CONTROL FUNCTIONS

- MULTIPLE ACCESS ALGORITHMS
- ANTENNA CONTROL
- ATTITUDE CONTROL
- COMMAND/TELEMETRY

Figure V-13a. On-Board Processing Functions

INCREASED CONNECTIVITY

- CIRCUIT SWITCHING
- MESSAGE SWITCHING

INCREASED COMMUNICATIONS EFFICIENCY

- REDUCED LINK SIGNAL-TO-NOISE RATIOS
- SEPARATED UPLINK/DOWNLINK DESIGNS

INCREASED RFI AND AJ PROTECTION

INCREASED FLEXIBILITY

- SATELLITE RESOURCE MANAGEMENT
- DYNAMIC RECONFIGURATION

REDUCED COMMAND LINK DEPENDENCE

Figure V-13b. On-Board Processing Benefits

- RELIABILITY
- POWER/WEIGHT
- DIGITAL PROCESSOR ARCHITECTURES

  DEDICATED DEVICES
  CUSTOM MICROPROCESSOR
  GENERAL PURPOSE COMPUTER

- TECHNOLOGIES

  MICROWAVE SWITCH MATRIX
  LOGIC DEVICES
  MEMORIES
  MICROPROCESSORS
  COMPUTERS

Figure V-14. On-Board Processing Key Issues

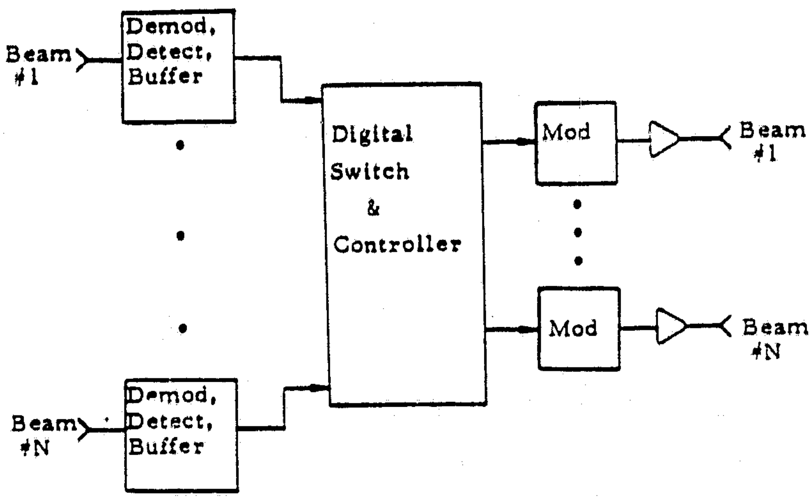


Figure V-15. Digital Processors - Concept

Raytheon (Sudbury, MA) has sized a processor to perform the survivable satellite system (SSS) communication functions. These include demodulation, deinterleaving, decoding, and downlink multiplexing of multiple input channels. Their design is based on their fault tolerant computer (FTC) design developed with SSS application in mind. Although the FTC is used in their design (mainly the memory), the communications functions are performed by special purpose modules, as shown in Figure V-16. This is an example of what will be referred to here as a hardware processor, meaning that dedicated functional modules are employed. Digitized inputs are processed by members of three pools of modules: demodulators, interleaver/deinterleavers, and encoder/decoders. Numbers in parentheses in the figure indicate the number of members of each pool. These are chosen to provide the desired reliability. Failed modules are excluded from the pool subsequent to failure. After all digital processing, the resulting data are applied to the appropriate downlink modulator. All routing is under the direction of the bus controller as indicated.

Lincoln Laboratory is breadboarding elements of a processor with a different mission (general purpose UHF anti-jam communications), but also using a hardware architecture. As shown in Figure V-17, after removal of frequency hop modulation the multiple inputs are presented to pools of demodulator modules. These in turn go to a deinterleaver/decoder pool and thence to an encoder/interleaver pool. Finally, communications output processor (COP) modules time division multiplex selected input data streams for downlink transmission. Routing is controlled via the interfacing buses. Although the multiplicity of modules is intended to provide expanded capability rather than reliability, presumably the approach can be extended to that end.

A processor for performing functions essentially equivalent to those needed for SSS has been implemented at Rockwell (Seal Beach, CA) using what is referred to here as a hybrid architecture since it employs a customized microprocessor, as shown in Figure V-18. Inputs are digitized and stored after which all digital processing is performed by a custom designed microprocessor employing pipelining to achieve the required speed. Reliability is achieved by redundancy. The processor currently is implemented in low-power Schottky TTL.

The last architecture type indicated in Figure V-14, viz., a general purpose computer, can be used for low data rates such as those typical for command links. See the discussion of on-board computers in the next section for details.

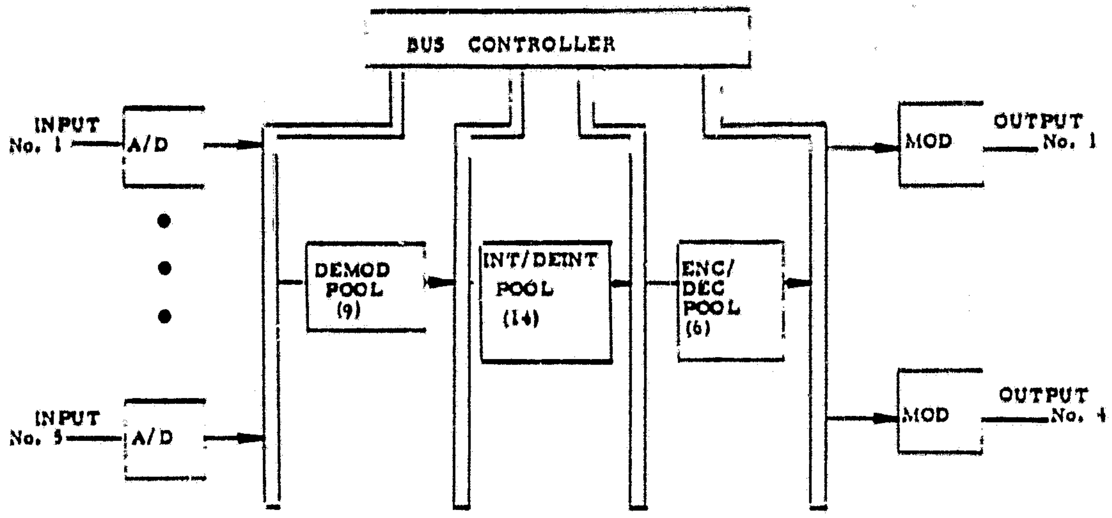


Figure V-16. SSS Signal Processor (Raytheon)

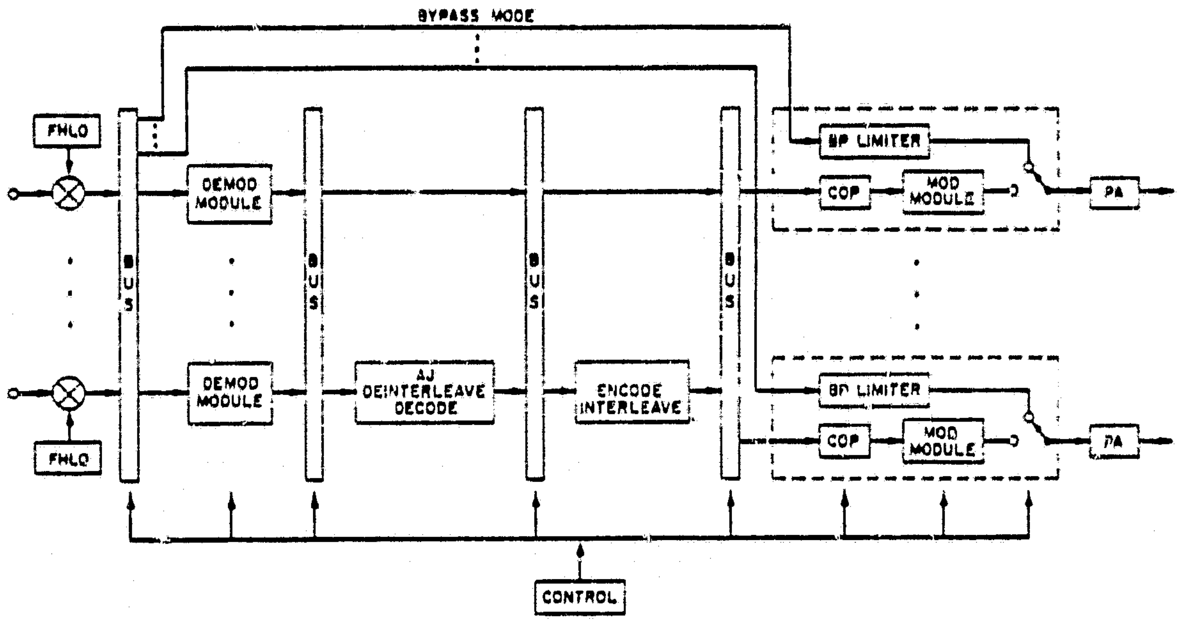


Figure V-17. Strawman UHF Signal Processor (Lincoln Lab)

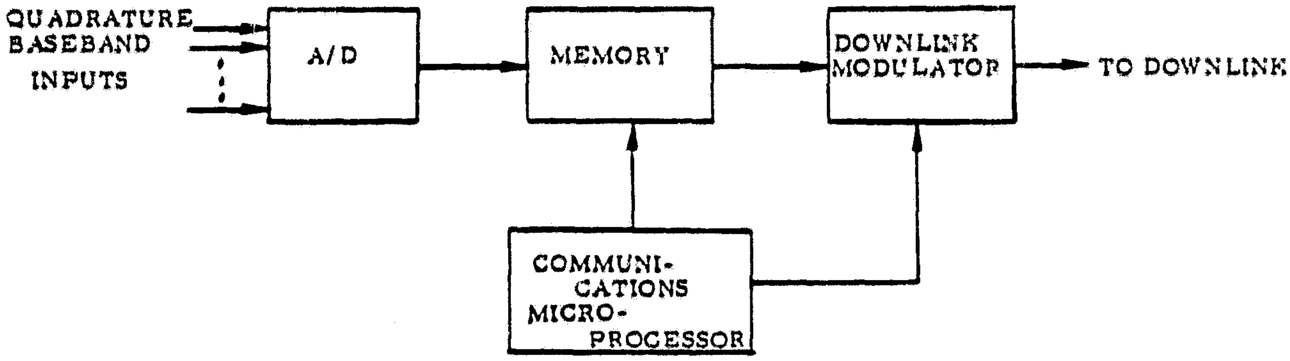


Figure V-18. Hybrid Processor Example -- SSS On-Board Signal Processor (Rockwell)

The status of on-board processing is summarized in Table V-12. The only on-orbit communication processors are LES 8/9, which perform only demodulation, modulation, and formatting functions, and FLEETSAT, which performs only an anti-jam demodulation function. The Defense Support Program (DSP) satellite is not a communications satellite but does include a data compression function. The AFSATCOM single channel transponder (SCT), being developed for inclusion aboard DSC III and being considered for GPS, performs only one demodulation function. In addition to the activities at Raytheon and Rockwell, sizing of a standard microprocessor-based SSS processor is being done at The Aerospace Corporation. Finally, a variety of general processing studies are in process as noted.

The processing capabilities of the three architecture types considered are indicated in Table V-13. A software soft decision Viterbi decoder has been implemented on a PDP-11 and is capable of processing about 150 bps. A custom decoder has been designed for the Space Shuttle and will operate at about 100 kbps. The microprocessor-based decoder performance indicated is only intended to illustrate the fact that increased speed can be achieved by simply paralleling computational elements. The time to compute a 1024 point FFT using a minicomputer is estimated using representative add and multiply times of available space-qualified computers. The times for microprocessor-based processors and custom devices again are indicative of the effects of increased parallel processing (as well as shorter operation times).

It should be noted that projected increases in general purpose computer operation speeds (see Figure V-19) would considerably extend the applicability of software processors.

An overview of on-board digital processors as discussed here is given in Figure V-20, and an assessment of the current status and the prospects for the 1980's is indicated in Figure V-21. The most complex on-orbit communications processor is LES 8/9. Although the only currently funded

Table V-12. Digital Processor Activity Summary

ORGANIZATION OR SATELLITE	STATUS	DEMOD	DECODE	BASEBAND SWITCHING	OTHER	TECHNOLOGY
LES 8/9 (Ref. 23)	ON ORBIT	75 BPS MFSK 5/150 KSPS DQPSK 10/100 KBPS DPSK		TDM ON DOWNLINK	BASEBAND SAMPLING, CHIP COMBINING	TTL
FLEETSAT (Telecon with TRW)	ON ORBIT	PN	—	—	—	ANALOG
DSP (Discussion with Aerospace)	ON ORBIT (DEVEL.)		—	—	DATA COMPRESSION	DTL (TTL, CMOS/SOS MEMORY)
AFSATCOM SCT (Discussion with Aerospace)	DEVEL. FOR DSCS III (GE) GPS (RI)	75 BPS MFSK	—	—	—	TTL
SSS (Discussions with Aerospace, Raytheon, Rockwell)	STUDIES (AEROSPACE RAYTHEON, RI)	12-75 BPS MFSK 9-75 BPS	SOFT VITERBI	TDM ON DOWNLINK	DEINT, ACQUISITION	VARIOUS
GENERAL UHF (Ref. 24)	STUDY, BREADBOARD (LL)	SEVERAL	SOFT VITERBI	YES	DEINT	—
GENERAL (Refs. 25, 26, 27)	STUDIES (MITRE, FACC, CLARKSON)	YES	YES	YES	—	—

Table V-13. Processing Capabilities

	MINICOMPUTER	MICROPROCESSORS	CUSTOM DEVICE
VITERBI DECODER (BPS)	150 (SERIAL) (Ref. 20)	1K (~ 8 PARALLEL)	100K (T^2L, SERIAL) (Discussion with Aerospace)
N=1024 FFT (μSEC)	500,000 (100 μS/BUTTERFLY)	10,000 (~ 10 PARALLEL, 10 μS/BUTTERFLY)	100 (512 PARALLEL 10 μS/BUTTERFLY)

BASED ON

4 REAL MULTIPLIES

6 REAL ADDS

10 MEMORY CYCLES

TIMES FROM REF. 28

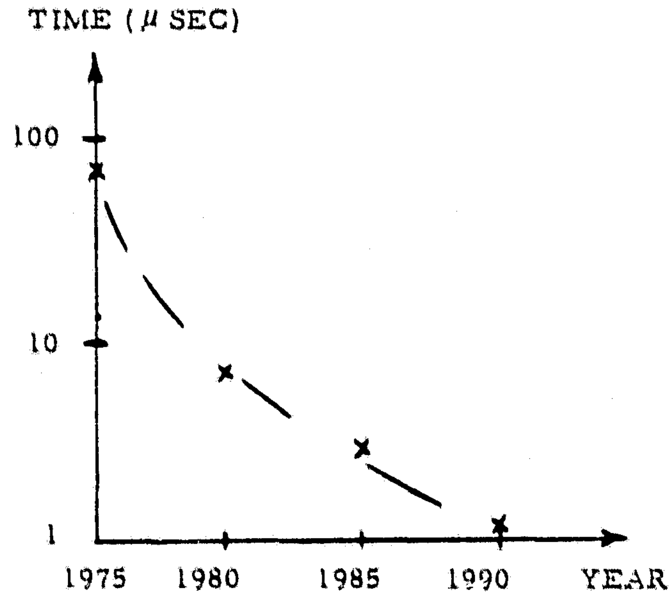


Figure V-19. Projected Computation Time for FFT Butterfly (On-Board General Purpose Computer)

APPLICATIONS

- REGENERATIVE REPEATING
- BASEBAND SWITCHING

APPROACHES

- SPECIAL PURPOSE DEDICATED PROCESSOR (HARDWARE)
- CUSTOM DESIGNED MICROPROCESSOR (HYBRID)
- GENERAL PURPOSE COMPUTER (SOFTWARE)

CURRENT STATUS

- ON ORBIT - LES 8/9, FLEETSAT, DSP
- DEVELOPMENT - AFSATCOM SCT (GE)
- BREADBOARD - SSS (ROCKWELL)
- STUDIES - SSS(AEROSPACE, RAYTHEON), GENERAL (LINCOLN LAB, MITRE, FACC)

Figure V-20. Digital Processors - Overview

- MOST COMPLEX ON-ORBIT SIGNAL PROCESSOR IS LES 8/9
- ONLY FUNDED SIGNAL PROCESSOR IS AFSATCOM SCT
- AVAILABLE TECHNOLOGY WILL SUPPORT FUNCTIONS ENVISIONED FOR EARLY 1980s

- USEFUL SYSTEM STUDIES FOR MULTIPLE FIXED AND MOBILE USERS (2-4 MAN YEARS EACH)
  - PROCESSOR ARCHITECTURE TRADE-OFFS (CAPABILITIES, RELIABILITY, POWER/WEIGHT, AVAILABILITY)
  - DISTRIBUTION OF PROCESSING BETWEEN SPACE AND GROUND
- COULD LEAD TO EXPERIMENTAL SATELLITE TRANSPONDER ($ 3M)
  - CURRENT TECHNOLOGY
  - SOFT DECISION VITERBI DECODING
  - BASEBAND SWITCHING
  - OPTIMIZED ARCHITECTURE
  - MULTIPLE BEAM ANTENNA

Figure V-21. Digital Processor Architecture Assessment

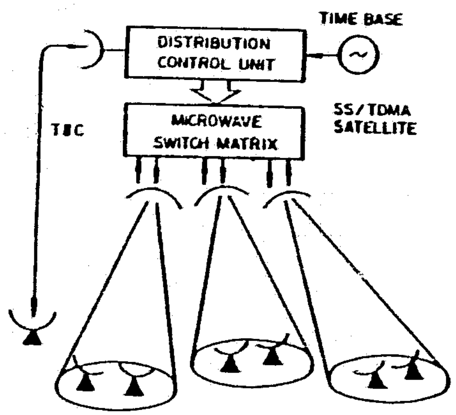
processor, the AFSATCOM SCT, is much less complicated than LES 8/9, currently available device technologies will support the processing functions envisioned for the 1980's. The principal problems are reliability and cost, which the commercial users are especially reluctant to attack. Although development in the military arena is proceeding, there seems to be a definite need for development in the commercial arena. This need could be met by NASA in a two-phase program as outlined in Figure V-21. After an assessment has been made of potential processing requirements of commercial users, systems studies should be conducted which investigate the advantages and disadvantages of processor architecture types and consider how much of the processing burden should actually go in the spacecraft. Following these and other related studies, an experimental processing transponder could be developed for inclusion on a scheduled bus.

3. PROCESSOR TECHNOLOGY

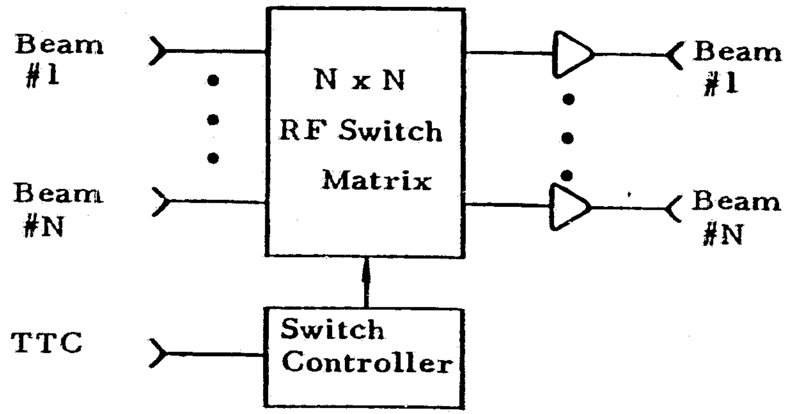
The status and prospects of the following technologies that impact on-board processing functions are discussed in this section: microwave switch matrices, LSI technology, and space-borne minicomputers.

a. Microwave Switch Matrices

Microwave switch matrices (MSM) are high speed rf switches implemented using either PIN diodes or FETs (field-effect transistors) as gating devices. Their application is illustrated in Figure V-22, which illustrates



SS/TDMA SYSTEM



SS/TDMA SATELLITE

Figure V-22. RF Switching -- Concept

the satellite switched/time division multiple access (SS/TDMA) concept. Both uplink and downlink multiple beam antennas are employed. Uplink beam i is connected via the MSM to downlink beam j only during some interval of a TDMA frame. Thus, users in uplink beam i can only send to users in downlink beam j during that time interval.

Current activities in this technology are summarized in Table V-14. Although most of the activities are at the experimental stage, the TRW 4 × 4 MSM is being developed for inclusion on TDRS. This MSM and others that are in advanced stages are implemented using PIN diodes. Since these require high power, FETs are being investigated for this application by Hughes and FACC. Because this is presently a highly competitive area, detailed performance values are difficult to obtain.

Figure V-23 is an overview of microwave switch matrix technology, and Figure V-24 is an assessment of prospects for the 1980's. Since an MSM will be on-orbit with the launch of TDRS and industry is vigorously pursuing the technology, there seems to be no need for stimulation by NASA. As indicated, there are open questions concerning the maximum dimension MSM that is necessary and/or feasible and how to optimally schedule the switching. However, answers to these questions should arise naturally out of the ongoing activities.

b. LSI Technology

The past and projected progress in large scale integration is indicated by the curves in Figure V-25 of chip density and RAM capacity. Note that the extrapolation of past progress results in hitting the technological limit for MOS technology in the middle 1980's.

Two technologies currently receiving considerable attention are CMOS/SOS and I^2L (integrated injection logic). Both offer high density at low power levels. The primary problem presently is radiation hardening of the devices. Although the prospects for hardening the two device types are comparable (see Table V-15), the development of hardened devices is following different paths. I^2L is being developed for commercial applications and the hardening is to a large extent a by-product of projected improvements in the commercial devices. Additional hardening might therefore involve only minor modifications to commercial product lines. CMOS/SOS on the other hand is being developed primarily for military applications, and hardening is a product of the customized design. If this trend continues, the cost squeeze on custom CMOS/SOS may result in I^2L becoming dominant. In any event, this is another arena in which it appears that commercial interests are providing sufficient stimulus and NASA funding is not necessary.

Table V-14. Microwave Switch Matrix Activity Summary

ORGANIZATION	STATUS	DIMENSION (DEVICES)	POWER (W)	WEIGHT (LB)	LOSS/ ISOLATION (DB)	SWITCH SPEED (NSEC)	FREQ./ BANDWIDTH
TRW (Discussion with TRW)	DEVEL. FOR TDRS	4 X 4 (PIN DIODES)	—	—	—	—	4 GHZ
KDD (Discussion with FACC)	DEVELOPED	8 X 8 (PIN DIODES)	—	—	-/40	5-10	4 GHZ
THOMSON-CSF (FOR COMSAT) (Ref. 29 and discussion with Comsat Labs)	EXPERI-MENTAL, SPACE QUAL VERSION IN DEVEL.	16 X 16 (PIN DIODES)	≈5	5	27/50	50	4 GHZ/ 500 MHZ
HUGHES (Discussion with Hughes)	BREAD-BOARD	8 X 8 (SINGLE GATE FET)	—	—	10/50	~1	4 GHZ
FACC (Discussion with FACC)	BREAD-BOARD	4 X 4 (DUAL GATE FET)	—	—	—	<1	4 GHZ

APPLICATION
● MBA BEAM SWITCHING FOR SS/TDMA
APPROACHES
● PIN DIODES
● FETS
CURRENT STATUS
● NONE ON ORBIT
● DEVELOPMENT - TDRS (TRW)
● EXPERIMENTAL - (THOMSON - CSF, HUGHES, FACC, KDD)
PROJECTION
● SS/TDMA PREVALENT IN 1980s (Discussion with Comsat Labs)
RELATED ACTIVITY
● DETERMINE EFFICIENT SWITCHING SCHEDULES (Ref. 30)

Figure V-23. Microwave Switch Matrix

● MSM DEVELOPMENT PROCEEDING
● FURTHER PROGRESS WILL BE STIMULATED BY COMMERCIAL NEEDS
● SS/TDMA IMPLEMENTATION WILL EXIST IN 1980 WITH LAUNCH OF TDRS
● OPEN QUESTION: MSM DIMENSIONALITY REQUIRED AND/OR FEASIBLE

Figure V-24. RF Switching Technology Assessment

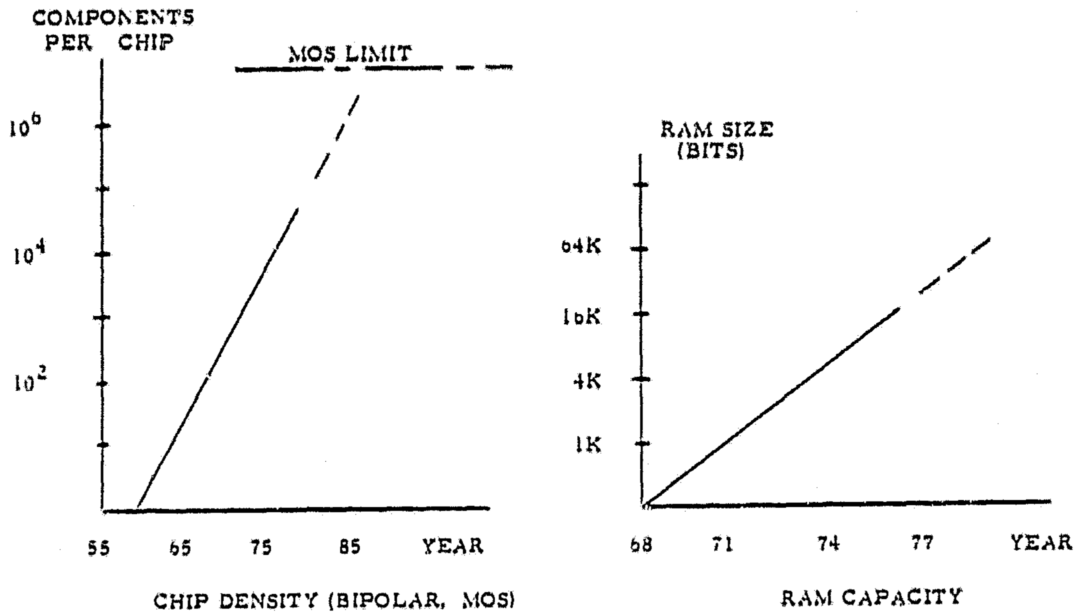


Figure V-25. LSI Chip Density Progress

Table V-15. CMOS/SOS and I^2L Comparison (Ref. 31)

	CMOS/SOS		I^2L	
	CURRENT	PROJECTED (1980's)	CURRENT	PROJECTED (1980's)
DENSITY (GATES/mm^2)	200-300	—	150-300	—
PROPAGATION DELAY (NSEC)	4-20	—	7-50	—
SPEED X POWER (PJ)	0.5-30	—	0.2-2.0	—
HARDENING -				
TOTAL DOSE (RADS)	5×10^5-10^6	10^6-10^7	10^5-10^6	10^6-10^7
DOSE RATE (RAD/SEC)	10^{10} - 10^{11}	5×10^{10}-10^{11}	10^9-10^{10}	1-5×10^{10}

The status of memory technologies is indicated in Table V-16. Although the comparison of parameters for the technologies is based on 4K RAMS, larger ones are available in some technologies. A status summary of microprocessors for space applications is given in Table V-17. Again, no need for NASA funding to stimulate development in these areas is foreseen.

c. <u>On-Board Computers</u>

A summary of the status of space-borne computers is given in Table V-18. A wide spectrum of technologies and applications is represented. As indicated in the discussion on processor architectures, faster computers might increase the attractiveness of using a software architecture in some applications. Considering the large number of commercial concerns in this arena, further stimulation does not appear necessary.

Table V-16. RAM Semiconductor Technologies (4K) Ref. 32)

	BIPOLAR				MOS			
Technology	ECL (Fairchild F10470)	I^2L (Fairchild 93481)	ST^2L (Signetics 82S400)	T^2L (Fairchild 93470)	CMOS (Harris 6514)	HMOS (Intel 2147)	NMOS (Mostek 4027-2)	VMOS (AMI 4017)
Static Or Dynamic	Static	Dynamic	Static	Static	Static	Static	Dynamic	Static
Access Time (ns)	30	120	70	50	170	70	150	55
Operating Power (mw)	1000	450	600	900	30	500	462	500
Cents Per Bit	.854	.586	1.09	.793	.725	.915	.332	.610

Table V-17. On-Board Microprocessors, Status Summary

DEVICE	STATUS/ APPLICATION	WORD LENGTH	TECHNOLOGY	CYCLE TIME (μSEC)
RCA 1802	Space Qualified in 1979	4	CMOS	1.5
AMD 2900	Shuttle (IUS)/ Guide, Control	4	TTL	—
INTEL 8086	To be Space Qualified	8	N-MOS	—
RI PPS-4	GPS/NAV	4	P-MOS	5

Table V-18. On-Board Computers, Status Summary

COMPUTER	STATUS/ APPLICATION	WORD LENGTH	PROCESSOR	MEMORY	SPEED ADD/ MPY (μSEC)
NASA NSSC-I (Ref. 33)	LANDSAT, IUE/ TELE,CONTROL	18	TTL-LSI	CORE	5/38
NASA NSSC-II (Ref. 33)	SPACELAB, SPACE TELESCOPE	16, 32, 64		N-MOS	2/8
RCA SCP-234 (Discussion with Aerospace)	DMSP/ATTITUDE CONTROL	16	TTL-MSI	CMOS	3/10
CDC-469 (Discussion with Aerospace)	HEAO	24	P-MOS LSI	PLATED WIRE	1/-
TI-990 (Discussion with Aerospace)		16	I^2L LSI		
RAYTHEON FTC (Discussion with Raytheon)	DEVELOPMENT	32	CMOS/SOS LSI	CMOS/SOS	
LITTON 4516E (Discussion with Aerospace)	AMaRV	—	CMOS	CMOS	2/4
DELCO 362F (Discussion with Aerospace)	TITAN IIIC	—	—	CORE	3/5
TELEDYNE MECA (Discussion with Aerospace)	IUS	—	CMOS	CMOS	2/6
NORDEN PDP11 (Discussion with Aerospace)	DEVEL	—	—	CORE	3/12
AUTONETICS DF224 (Discussion with Aerospace)	SPACE QUAL.	—	P-MOS	PLATED WIRE	2/6

ORGANIZATIONS/PERSONS CONTACTED FOR CHAPTER V

American Satellite Corp. (Germantown, MD); G. Cacciamani (March 1978).

Axiomatix (Marina Del Rey, CA); G. Huth (March 17, 1978).

Bolt, Baranek, and Newman (Cambridge, MA); R. Binder, N. T. Hsu, I. Richer (March 23, 1978).

Clarkson College of Technology (Potsdam, N.Y.); Prof. M. Arozullah (March 1978).

Comsat Headquarters (Washington, DC); R. C. Gibbons, E. Hoversten, T. McGarty (March 27, 1978).

Comsat Laboratories (Clarksburg, MD); K. Betaharon, G. Dill, Y. Lee, L. Palmer (April 5, 1978).

Defense Communications Agency (Arlington, VA); J. Edell, P. Jain, R. Sherwin (March 28, 1978).

Digital Communications Corp. (Gaithersburg, MD); J. Puente, L. Golding (March 3, 1978).

FACC (Sunnyvale, CA); L. Cuccia, R. Davies (March 1978).

Hughes Aircraft (El Segundo, CA); R. Gasperi, H. Yee (March 1978).

Jet Propulsion Laboratories (Pasadena, CA); R. J. McEliece (April 26, 1978).

Lincoln Laboratory (Lexington, MA); J. De Rosa (March 8, 1978); and A. Dion, B. Hutchinson, C. Niessen, T. Seay (March 24, 1978).

LinCom Corp. (Los Angeles, CA); W. Lindsey (March 28, 1978).

Linkabit Corp. (San Diego, CA); J. P. Odenwalder (March 16, 1978).

MITRE Corp. (Bedford, MA); W. Brandon, J. Katz, J. Ruddy, J. Segal, B. White (March 21 and 23, 1978).

Motorola Government Electronics Division (Scottsdale, AZ); P. Leahy (March 20, 1978).

ORGANIZATIONS/PERSONS CONTACTED FOR CHAPTER V (continued)

Naval Electronics Systems Command (Washington, DC); R. McGlothlin, J. Nooney, Cmdr. J. Waylan (March 27, 1978).

Raytheon Co. (Sudbury, MA); F. Howes, J. Stiffler (March 24, 1978).

Rockwell International (Seal Beach, CA); H. Maddox (March 15, 1978).

SAMSO, U.S. Air Force (El Segundo, CA); Capt. D. Wilhelm (March 1978).

Satellite Business Systems (McLean, VA); W. Schmidt (April 20, 1978).

TRW DSSG (Redondo Beach, CA); R. Cagnon, J. Lewis, W. Nations, D. Vandervoet, A. Wartella (March 1978).

UCLA (Los Angeles, CA); W. Chu, I. Rubin (March 21 and April 20, 1978).

REFERENCES FOR CHAPTER V

1. M. O. Scholl, Multiplexing Techniques for Data Transmission Over Packet Switched Radio Systems, UCLA-ENG-76123, School of Engineering & Applied Science, UCLA (December 1976).

2. L. Kleinrock, "Performance of Distributed Multi-Access Computer-Communication Systems," Proceedings of the IFIP Congress, Toronto (1977).

3. J. G. Puente and A. M. Werth, "Demand-Assigned Service for the Intelsat Global Network," IEEE Spectrum (January 1971) pp. 59-69.

4. Capt. D. Wilhelm, "SAMSO Management Plan for Packet Satellite Program," prepared for Deputy for Advanced Space Programs, Directorate of Plans, Advanced Concepts Division, SAMSO/YAPC, Los Angeles (March 1977).

5. L. G. Roberts, "Dynamic Allocation of Satellite Capacity Through Packet Reservation," AFIPS Conference Proceedings, 42 (1973) pp. 711-716.

6. R. Binder, "A Dynamic Packet-Switching System for Satellite Broadcast Channels," Proceedings of the IEEE International Conference on Communications, 3 (June 1975).

7. I. Jacobs, et al., "CPODA-A Demand Assignment Protocol for SATNET," Proceedings, Fifth Data Communications Symposium (September 1977).

8. J. M. Wozencraft and I. M. Jacobs, Principles of Communication Engineering, John Wiley and Sons, Inc., New York (1965).

9. M. Abromowitz and I. A. Stegum, Handbook of Mathematical Functions, National Bureau Standards, Applied Math. Series 55 (1965).

10. P. P. Nuspl, et al., "Synchronization Methods for TDMA," Proceedings of the IEEE, 65 (1977) pp. 434-444.

11. R. Binder, A Simple Mixed-Traffic Technique for Ground-Based Aloha Channels, Technical Report B75-6, University of Hawaii, Honolulu, Hawaii (January 1975).

12. Bernstein, et al., User Demand Modeling Study, Vol. 1: Analysis and Findings, System Development Corp., Report to SAMSO, SAMSO-TR-77-22, distribution limited to U.S. Government agencies.

13. C. T. Wolverton, T. Moeller, and L. M. Nirenberg, Satellite Multiple Access Study, TOR-0078(3417)-1, The Aerospace Corp., El Segundo, CA (15 June 1978).

14. Applications Information, Linkabit Corp. (20 September 1973).

15. J. P. Odenwalder, et al., Hybrid Coding Systems Study, Linkabit Corp. Report No. NASA CR 144486 (September 1972).

16. J. P. Odenwalder, et al., Study of Transfer Optimization for Communication Satellites, Report No. NASA CR No. 114561, Linkabit Corp. (3 January 1973).

17. A. S. Acampora and R. P. Gilmore, "Analog Viterbi Decoding for High Speed Digital Satellite Channels," advance copy of paper for IEEE publication.

18. Y. S. Lee, "Simulation Analysis for Differentially Coherent Quaternary PSK Regenerative Repeater," COMSAT Technical Review, 7 (2), 447-474 (Fall 1977).

19. B. H. Batson and G. K. Huth, "Convolutional Coding at 50 Mbps for the Shuttle KU-Band Return Link," International Telemetering Conference Proceedings, XII (1976) pp. 175-183.

20. J. Conan and R. Oliver, "Hardware and Software Implementation of the Viterbi Decoder," paper presented at unidentified conference, copies available from S. Curry, Aerospace Corp.

21. W. C. Lindsey, et al., Investigation of Modulation/Coding Trade-Off for Military Satellite Communications, Vol. II, TR-7807-1276, LinCom Corp. (19 July 1977).

22. A. S. Rosenbaum, "Binary PSK Error Probabilities with Multiple Cochannel Interferences," IEEE Trans. Comm. Tech., COM-18 (June 1970).

23. LES 8/9: Communications Capabilities, Project Report SC-21, MIT Lincoln Laboratory (15 March 1976).

24. L. Metzger, On-Board Satellite Signal Processing, Vol. 1, Technical Note 1978-2, Vol. 1, Lincoln Laboratory (January 1978).

25. Application of Advanced Signal Processing Concepts to Future Satellite Communication Systems, Proposal to NASA GSFC, MITRE Corp. (June 1977).

26. Application of Satellite Store and Forward Techniques to Data Packet Communications, Proposal to NASA GSFC, FACC (June 1977).

27. "Design of a Microprocessor-Based High Speed Space-Borne Message Switch," Submitted to NASA GSFC, Clarkson College (June 1977).

28. R. Turn, Computer Systems Technology Forecast, P-5344, Rand Corp. (January 1975).

29. X. Rozec and F. Assal, "Microwave Switch Matrix for Communications Satellites," Proceedings of the International Communications Conference (June 1976) pp. 35-13 to 17.

30. Y. Ito, et al., "Analysis of a Switch Matrix for an SS/TDMA System," Proceedings of the IEEE (March 1977) pp. 411-419.

31. R. Donovon, M. Simons, and R. Burger, "Radiation Hardened LSI for the 1980's: CMOS/SOS vs I^2L," IEEE Trans. on Nuclear Science, NS-24 (6), 2336-40 (December 1977).

32. D. Theis, Memory Technology Update, TOR-0078(3475-20)-2, The Aerospace Corp., El Segundo, CA (28 December 1977).

33. NASA Standard Equipment Announcement.

34. D. W. Lipke, et al., "Marisat-A Maritime Satellite Communications System," COMSAT Tech. Review, 7 (Fall 1977).

35. G. R. Stette, "A Multiple Access and Access Control System for MAROTS," EUROCON 77, Conference Proceedings on Communications.

36. C. Kittiver and F. R. Zitzmann, "The SBS System - An Innovative Domestic Satellite System for Private Line Networks," Paper presented at AIAA/CASI Sixth Communication Satellite Systems Conference, Montreal, Canada, April 5, 1976.

BIBLIOGRAPHY FOR CHAPTER V

Binder, R., J. McQuillan, and R. Rettberg, "The Impact of Multi-Access Satellites on Packet Switching Networks," EASCON '75 Convention Record, IEEE, New York, 63-A to 63-F (1975).

Campanella, S., F. Assal, and A. Berman, "On Board Regenerative Repeater," Proceedings of the International Communications Conference, 121-125 (June 1977).

Chiao, J.T., and F. Chetnik, "Satellite Regenerative Repeater Study," Canadian Proceedings of the Communication and Power Conference, 222-225 (October 1976).

Cuccia, L., "Modern Transponder Technology for Baseline Designs of Data Processing and Switching Communications Satellites," IAF (1976).

Cuccia, L., R. Davies, and W. Matthews, "Baseline Considerations of Beam Switched SS-TDMA Satellites Using Baseband Matrix Switching," Proceedings of the International Communications Conference, 126-131 (June 1977).

DeRosa, J., "A Digital Processing Satellite for Widely Disseminated Telecommunications," INTELCOM 7 Proceedings, I, 307-311 (October 1977).

Demand Assignment Techniques Study (DATS) for Military Satellite Communication Applications, Collins Gov't. Telecommunications Group, Final Report to MILSATCOM Systems Office, DCA, Collins Report No. 523-0767775-00221M (25 June 1977).

Dill, G., Y. Tsuji, and T. Muratani, "Application of SS/TDMA in a Channelized Satellite," Proceedings of the International Communications Conference, 51-1 to 51-5.

Edelson, B., and W. Morrow, "Orbital Antenna Farms," Astronautics and Aeronautics (September 1977).

Huang, R., and P. Hooten, "Communication Satellite Processing Repeaters," IEEE Proceedings, 59 (2) 238-252 (February 1971).

Hsu, N. T., and L. N. Lee, "Synchronization Techniques for CPODA," Proceedings of the International Communications Conference, June 4-7, 1978, Toronto.

Jarett, D., "Meeting the Twin Challenges of Demand and Conservation of Spectrum and Orbit through Technology," EASCON 77, Paper 25-1 (September 1977).

Katz, J., and K. Schneider, "Processing Methods to Suppress Effects of Uplink Multipath in Satellite Systems," Proceedings of the International Communications Conference, 138-143 (June 1977).

Koga, K., T. Muratani, and A. Ogawa, "On a Satellite Regenerative Repeating System," Proceedings of the Canadian Communication and Power Conference, 93-96 (October 1976).

Koga, K., T. Muratani, and A. Ogawa, "On-Board Regenerative Repeaters Applied to Digital Satellite Communications," IEEE Proceedings, 65 (3) (March 1977).

Lam, S. S., "Delay Analysis of a Packet-Switched TDMA System," NTC 76 Conference Record, IEEE, New York, 16.3-1 to 16.3-6.

Lewis, J., et al., Mobile Multiple Access Study Final Report, TRW, Redondo Beach, CA (16 August 1977).

McGarty, T., and T. Warner, "Multiple Beam Satellite System Optimization," IEEE Trans. on Aerospace and Electronic Systems, AES-13 (5) (September 1977).

Raymond, J., and R. Pease, "A Comparative Evaluation of I^2L," IEEE Trans. on Nuclear Science, NS-14 (6) 2327-35 (December 1977).

Rubin, I., A Group Random Access Procedure for Multi-Access Communication Channels, Proceedings of the National Telecommunications Conference (December 1977).

Rubin, I., Integrated Random Access Reservation Schemes for Multi-Access Communication Channels, School of Engineering and Applied Science, UCLA Rept. No. UCLA-ENG-7752 (July 1977).

Rubin, I., "On Message Delays in FDMA and TDMA Communication Channels," Paper presented at Conference on Information Sciences and Systems, Johns Hopkins U., March 1978.

Rubin, I., Reservation Schemes for Dynamic Packet Access-Control of Multi-Access Communication Channels, School of Engineering and Applied Science, UCLA, Report No. UCLA-ENG-7712 (January 1977).

Schmidt, W., "SS/TDMA: Transponder or Beam Switched?," Paper presented at AIAA 5th Communications Satellite Converence, 1974.

Townsend, R., "A Satelliteborne Adaptive Array Employing Ground Implemented Beam Formation," Proceedings of the International Communications Conference, 323-327 (June 1977).

Van Trees, H., E. Hoversten, and T. McGarty, Communications Satellites, Projections for the 1980s, COMSAT Corp. (1 November 1976).

Van Trees, H., and T. McGarty, A Mobile Satellite Communication System, COMSAT Corp., Preliminary Report (February 1977).

CHAPTER VI

PROPAGATION EFFECTS

Prepared by

H. M. Wachowski
Radar and Microwave Department

CONTENTS FOR CHAPTER VI

PRECEDING PAGE BLANK NOT FILMED

CHAPTER VI

PROPAGATION EFFECTS

A. OVERVIEW OF THE FIELD

This chapter discusses the potential significance and relative importance of various propagation effects that could become a limiting factor in future communications satellite system design. Before deciding on whether a particular propagation effect will limit future system performance, numerical data, obtained experimentally or analytically, must be available on the magnitude of the effect. Our present level of understanding of these effects and the confidence with which their magnitude can be predicted varies with the particular effect. Those effects that are least understood or for which inadequate numerical data are available will be identified as possible subjects of future experimental research. Some of the material in this chapter was obtained during visits or phone conversations with individuals listed at the end of this chapter. A list of references also appears at the end of the chapter.

The most important effect of the propagation medium on a space-to-ground link is the attenuation that an electromagnetic wave suffers in traversing the medium, and, indeed, this effect has received the greatest attention, both theoretically and experimentally. Numerous papers devoted to various aspects of the attenuation problem are in the technical literature. Tropospheric and ionospheric attenuation are well understood for clear weather conditions and for normal, undisturbed ionospheric conditions. For frequencies of major interest in future communications satellite systems, however, rain attenuation is very important and must be allowed for by providing an adequate system margin.

Until relatively recently, the magnitude of the rain attenuation on a space-to-ground path has been theoretically estimated on the basis of an assumed drop size distribution and an assumed spatial distribution of rainfall intensity within the rainstorm. Alternatively, the attenuation has been measured using a ground-based radiometer and a narrow-beam antenna tracking the sun through the rainfall, or just measuring the temperature of the sky through the rainfall. The former approach is unsuited to the problem of determining cumulative probabilities for path attenuation levels; a further weakness is the usual lack of knowledge of storm structure and drop size distribution. The latter approach is limited in dynamic range and is subject to considerable error in converting from a measured noise temperature to a path attenuation. By far the best method for determining rain attenuation statistics is to receive a signal radiated by a beacon on a synchronous satellite.

This method has been used in recent years using beacons on the ATS-5, ATS-6, CTS, COMSTAR, SIRIO, and ETS-2 satellites. The geometrically fixed propagation path permits the accumulation of long-term statistics. A good data base is already available at various frequencies up to 30 GHz, but measurements are needed at higher frequencies. The rain attenuation area will remain open until long-term statistics have been gathered at a sufficient number of frequencies, elevation angles, and geographic locations to permit reliable prediction at an arbitrary combination of these parameters.

Closely related to the rain attenuation problem is the problem of establishing design criteria for the use of space diversity receiving systems. Space diversity is the classic approach to the rain attenuation problem and depends on the very low probability that rain will fall simultaneously at each of two or more spaced receiving sites. In recent years some space-to-ground experiments have been conducted on space diversity (e.g., Hodge, ATS-6, OSU, Westinghouse, Vogel, Texas). However, it appears that the required design criteria can be established at much lower cost by statistically analyzing long-term weather records at various locations near the receiving site to determine the probability of simultaneous rainfall at these locations. Thus, although much data are needed at many geographic locations, these data can be obtained without conducting costly measurement programs on satellite-to-ground links.

The depolarization caused by the propagation medium can become a serious problem in systems designed to receive signals simultaneously in orthogonal polarizations. Rainfall is known to cause depolarization because of the nonsphericity of raindrops. Depolarization has also been observed at times when no rain was falling, and this has been attributed to high altitude ice crystals. Rain, however, is by far the principal cause. The magnitude of the depolarization is affected by the distribution of raindrop canting angles. Numerous theoretical and experimental studies have been made, most notably by Bell Telephone Laboratories (Hogg, Chu, Semplak, and others) and by T. Oguchi in Japan. Theory and some very limited experimental data both predict that the cross-polarization discrimination of circularly polarized waves is much poorer (by about 10 dB) than that of linearly polarized waves. This result should be checked experimentally on space-to-ground links. Because experimental results obtained on terrestrial links cannot be used to predict the magnitude of depolarization on space-to-ground links, a much larger data base than is presently available is needed on space-to-ground paths. Since it is essential that the effects of high altitude precipitation particles and hydrometeors be accounted for, there appears to be no acceptable substitute for more depolarization experiments on space-to-ground links similar to those made with the ATS-6 or the ETS-2 satellites.

Amplitude and phase scintillations caused by ionospheric irregularities have been under investigation for many years, and the Space Physics Division of the Air Force Geophysics Laboratory has published very complete surveys of the results at frequencies up to UHF. Up to 1972 it was thought that amplitude scintillations did not occur at L-band and above, based on an assumed $1/f^2$ dependence. However, in 1972 scintillation occurrences were noted on some INTELSAT transmissions in the 4 to 6 GHz band. Various candidate mechanisms were examined and eliminated, leading to the surprising conclusion that the ionosphere (including, possibly, the plasmasphere region between the ionospheric F-region and synchronous altitude) was responsible. The $1/f^2$ law is not applicable. Although a definitive model accounting for observed scintillations has not been developed, the scintillations appear to be caused by diffraction through and around F-region irregularities. This effect is observed between 30°N and 30°S magnetic latitude, especially around the equinoxes, and starting about 1 hr after sunset and persisting to local midnight. Cumulative distributions for amplitude scintillations have been obtained for many geographic locations, but very little data have been obtained on phase scintillations. Phase is more difficult to measure experimentally. A data base for phase scintillations at VHF, UHF, and L-band has been obtained by SRI International using the Wideband satellite, which was designed specifically for this purpose. Since phase scintillations can cause loss of phase lock in coherent PSK receivers if they are fast enough, this problem area is of concern for future system designers. A statistical data base is required at frequencies up to at least X-band. It would be very advantageous to make such measurements at or near the next maximum in the solar cycle, which occurs in 1981.

It is known that atmospheric effects have a rapidly rising magnitude as grazing incidence is approached. Future communications satellite systems that may be required to operate out to very low elevation angles can experience serious problems if the low elevation angle effects are not properly considered during system design. To date, very little data in this area have been obtained on space-to-ground paths. Deep fades can occur due to tropospheric irregularities and multipath, and refractive defocusing becomes significant near grazing incidence. There is a need for further experimental effort in this problem area to produce an adequate data base to establish design criteria.

In future systems involving intersatellite links, problems may occur if the system geometry is such that the propagation path between two satellites traverses the ionosphere. The total path length in the ionosphere would be quite large, and no data have ever been obtained on a path of this type. A pair of satellites such as LES-8 and LES-9 are needed for this type of experiment. Because of the complete lack of data, propagation effects on such a path could pose a problem in the design of future intersatellite links.

A final general comment applicable to all the problem areas discussed above is appropriate here. For experiments requiring long-term measurements over a space-to-ground link, it is essential that the propagation experiments be assigned a high enough priority to ensure that adequate data are obtained for statistical analysis. Some earlier propagation experiments (e.g., those aboard ATS-6) suffered because of low priority relative to other experiments on the satellite. As a result, some carefully designed and otherwise successful experiments produced rather sparse data. At the other extreme, satellites whose primary mission is to perform propagation measurements, such as Japan's ETS-2 satellite or SRI International's Wideband satellite, have been very successful in advancing the current state of knowledge for various propagation effects.

B. AN ASSESSMENT OF THE PRESENT STATE OF KNOWLEDGE

For each of the propagation effects in the previous discussion, the current level of knowledge and understanding of the effect and of our ability to reliably predict its magnitude will be described. This discussion is based upon an examination of the technical literature and upon information gained from personal discussions with various specialists in the field of propagation. A list of the people contacted and a comprehensive reference list are provided at the end of the chapter.

1. RAIN ATTENUATION

The subject of rain attenuation has had a long history. In the initial phases of investigation of this phenomenon, theoretical estimates of the attenuation coefficient (dB of attenuation per unit length of propagation path) were obtained on the basis of a simplified electromagnetic analysis applied to an assumed drop size distribution. Total attenuation along a propagation path through a rainstorm was then obtained by integrating this attenuation coefficient along the path, assuming a specific spatial distribution of rainfall intensity through the storm. This approach is subject to serious error for a given space-to-ground path because of a lack of knowledge of the actual spatial structure of the storm. Furthermore, this approach is not suited for obtaining statistical data on rain attenuation along a space-to-ground path in the form of cumulative probability distributions. Measurements made on terrestrial links are of little use here because they reveal nothing about the contributions of the upper regions of the rainstorm. Upward-looking measurements of antenna noise temperature using ground-based radiometers were a major step forward in coping with this problem, but the dynamic range of measurable path attenuations is limited to 10 or 15 dB, and a significant error can be incurred in converting from a measured noise temperature to a path attenuation. The ideal approach to the problem of determining rain attenuation along space-to-ground paths is to receive signals radiated by a beacon on a geosynchronous satellite. Since the path is for all practical purposes fixed, long-term measurements make it possible to derive a reliable cumulative probability distribution for rain attenuation along that fixed path. Fortunately, this method is being applied to an increasingly greater extent in recent years with the launch of such satellites as ATS-5, ATS-6, CTS, COMSTAR, SIRIO, and ETS-2. Reference 1 presents an excellent review of the rain attenuation problem and measurement methods.

To design future systems involving specific space-to-ground path geometries, statistical data must be available at a sufficient number of frequencies, elevation angles, and geographic locations to permit reliable interpolation for arbitrary combinations of these parameters. The development of methods for making these interpolations is an important current research goal. References 2, 3, and 4 describe some recent contributions to this area.

In general, the basic physics relating to the problem of rain attenuation is well understood. However, since rainfall is, in essence, a nonstationary random process, a physically deterministic approach is inappropriate; long-term measurements are required over fixed space-to-ground links. Such measurements have been and are being gathered at various microwave frequencies up to the 30-GHz region and, in the case of the Japanese ETS-2, at 34.5 GHz (Ref. 5). A statistical data base is gradually being formed which, together with interpolation methods, will lead to a reliable means of predicting on a statistical basis the amount of link margin required on an arbitrary space-to-ground link for a given outage time specification. At higher frequencies, however, much remains to be done to reach a correspondingly satisfactory state. There is a need for long-term measurement programs at frequencies up to at least the 94-GHz atmospheric window. The rain attenuation problem increases in severity with increasing frequency throughout this range. A higher outage time will have to be accepted on single links. The problem can be alleviated by conventional space diversity techniques or, as a second alternative, by providing a back-up capability at a lower frequency that is relatively unaffected by rain. The latter technique has been studied by RAND Corporation (Ref. 6). The basic premise of this study is that outage time due to rainfall should be kept compatible with total delay and outage time due to all other causes. During periods of rainfall, high-priority message traffic would automatically be switched to the back-up link, while during clear periods all traffic would use the millimeter-wave link. For such a system, a link availability specification relative to rainfall outage would typically be 99.9 percent, allowing a system design with much lower link margin than would have been necessary for a specification of 99.99 percent or higher. In any event, one of the first steps that must be taken before future communications satellite systems can be intelligently planned in the 40- to 94-GHz region is the accumulation of long-term attenuation statistics at several frequencies in this region.

2. SPACE DIVERSITY

The technique of space diversity relies for its success on the fact that regions of intense instantaneous rainfall within a rainstorm are quite localized and limited in extent, making it highly unlikely that each of two receiving stations separated by a suitable distance will be troubled by the same high-intensity rain cell. Thus, the use of two or more spaced receivers results in a much lower outage time for the combination, compared to that of a single receiver. However, in contrast to the problem of developing a prediction model for rain attenuation along a space-to-ground path, the solution of which requires long-term measurements along such paths, a prediction model and associated design criteria for a space diversity receiving system can be developed without resort to costly satellite experiments. The parameter of primary important here is the probability that rainfall will occur simultaneously along neighboring propagation paths to spaced ground sites.

This probability can be determined by either of two methods not involving satellites: (1) long-term weather records for the sites in question can be statistically analyzed, or (2) long-term upward looking radiometric measurements can be made simultaneously for the spaced sites. The site spacing should range through a set of values, allowing diversity gain to be determined as a function of this spacing. The first of these two methods has been the subject of an Aerospace Corporation study (Ref. 7). An application of the second method is described in Ref. 8, where an interesting comparison is made between results obtained by the radiometric method operating continuously and those obtained by measurement of 30-GHz beacon signals from the ATS-6 satellite, operating part-time according to a schedule. The cumulative statistics for simultaneous observations (radiometer and beacon) agree remarkably well up to a fade level of 10 dB. Deeper fades cannot be accurately measured by the radiometric method due to its inherently limited dynamic range. The cumulative statistics for the full 13-month continuous observation period of the radiometers differ significantly from those obtained from the beacon measurements, obtained over only about one-sixth of the total available time. The beacon measurements caught only one in four of all the 3dB fades, and slightly less than one of every two 10 dB fades. These results clearly demonstrate the necessity of carrying out long-term, continuous observations.

It is concluded that either of the two nonsatellite methods of establishing space diversity criteria provides an acceptable alternative to long-term satellite measurements, at significantly reduced cost. One method is usable only if long-term rainfall statistics are available for the geographic area of interest. Otherwise such statistics would have to be gathered over a sufficiently long time. The other method is limited to fade levels up to about 10 dB. According to data presented in Ref. 8, a fade level of 10 dB for a two-station diversity system in England with a spacing of 12.3 km corresponds to a link availability of 99.9 percent, which would be adequate for many applications. A diversity experiment using satellite beacon sources (e.g., the 19- and 28-GHz beacons aboard COMSTAR) would be cost effective only if it could be carried out with a minimal ground equipment investment. References 9, 10, and 11 describe some recent diversity experiments using satellite beacons.

3. DEPOLARIZATION

It is essential for the design of future dual-polarization space-to-ground links that a reliable statistical prediction model be available for the extent of depolarization suffered by a signal in traversing the atmosphere. The available data base provided by depolarization measurements made to date on space-to-ground links is insufficient for the development of such a prediction model. Orthogonal circular polarizations should be considered as well as orthogonal linear polarizations. It is known that the depolarization phenomenon is caused by the nonsphericity of raindrops (and of high-altitude ice crystals), and that its magnitude is affected by the distribution of raindrop canting angles. Major contributions to the theoretical understanding of rain-induced depolarization have been made by T. Oguchi in Japan and by several investigators at Bell Telephone Laboratories. Reference 12 gives a convenient compilation of theoretical formulas and presents some generally favorable comparisons between calculations based on these formulas and measurements made on short terrestrial links. The formulas predict that the cross-polarization discrimination for circular polarization will be much worse (by about 10 dB) than that for linear polarization. This prediction has been confirmed experimentally on the basis of some very limited data obtained on a terrestrial path, where orthogonal circular and linear pairs of signals were transmitted and measured simultaneously, thus making possible a valid direct comparison. This experiment (Ref. 13) is crucial in settling the question of relative depolarization sensitivity for the two types of orthogonal polarizations, at least for terrestrial paths. A suitably modified version of the experiment (preserving the simultaneity aspect) should be performed on at least one space-to-ground link. One cannot generalize from the results of depolarization measurements made on terrestrial links to a communications satellite link since the terrestrial results do not consider the precipitation particles at higher altitudes or ice crystals at still higher altitudes. Semplak conjectures (Ref. 14) that the magnitude of the depolarization effect will decrease with increasing frequency because at the higher frequencies the small raindrops become relatively more important, and these small drops are more nearly spherical than the larger drops. This point has apparently never been checked experimentally. On the other hand, the theory and experiment described in Reference 12 reveal that the depolarization effect is relatively insensitive to rainfall rate.

Much effort is currently being devoted to the goal of providing a statistical data base for the prediction of depolarization effects on space-to-ground links. The results of depolarization measurements made on 20- and 30-GHz transmissions from ATS-6 have been reported recently, both by American (Ref. 15) and European observers (Refs. 16 through 21). References 22 and 23 present some preliminary results at 19 and 29 GHz using the COMSTAR satellite. References 5, 24, and 25 discuss current and future depolarization measurements by Japanese investigators using the CS, ECS, and ETS-2 satellites covering frequencies at L-, S-, C-, X-, and K-band. Depolarization measurements are also being made on the 11.6 GHz downlink from Italy's SIRIO satellite (Ref. 26), and further measurements at 20 and 30 GHz are planned for ESA's Heavy Satellite scheduled for 1981 launch. ESA's OTS satellite, scheduled for 1978 launch, will have propagation experiments at 11 and 14 GHz. All of this recent, current, and planned future activity allows for an optimistic appraisal of the expected advance in the current state of knowledge of depolarization effects. A large body of measured data is gradually being formed for linear polarizations at various frequencies up to 34.5 GHz. Any additional future activity should concentrate on the following gaps that still exist in the overall picture: (1) measurements are needed for linear and circular polarizations at frequencies above 34.5 HGz, (2) a set of simultaneous measurements for linear and circular polarizations should be performed at a number of frequencies from S-band up to 34.5 GHz to determine whether the cross-polarization discrimination for circular polarization is significantly worse than for linear polarization, and (3) if the results of (2) indicate that the cross-polarization discrimination for circular polarization is not severe enough to eliminate circular polarization from further consideration in planning future dual-polarization space-to-ground links, then long-term cross-polarization discrimination measurements should be made at frequencies below 34.5 GHz. The simultaneous measurements recommended in (2) would ideally be performed using a four-step switching sequence, corresponding to sequentially transmitting two orthogonal linearly polarized signals followed by two orthogonal circularly polarized signals.

References 16 and 18 emphasize the role of high altitude hydrometeors in causing depolarization. It is in fact conjectured that hydrometeors above the melting band are more strongly depolarizing than rainfall, at least when they are aligned by an electric field. Thus, it is to be expected that strong depolarization will be observed from time to time during periods of no rainfall. No information is currently available on the level of depolarization caused by high altitude hydrometeors in the case of circularly polarized waves.

4. PHASE SCINTILLATIONS

Although a great deal of experimental effort has been devoted to developing a data base for the phenomenon of amplitude scintillations caused by ionospheric irregularities, the companion area of phase scintillations is relatively unexplored experimentally up to the present time. Reference 27 is a fairly recent survey of the state of knowledge in this area up to early 1977. The discovery of ionospheric scintillation in the 4- to 6-GHz band in 1972 was a great surprise, since the ionospheric irregularity models that had been developed on the basis of observations at lower frequencies predicted that ionospheric scintillations in the GHz range would be unobservable. It became clear that a new model would have to be developed, a research goal that has not yet been satisfactorily achieved. It also became essential that long-term statistics be gathered at GHz frequencies so that scintillation effects could be properly taken into account in future communications satellite system designs. Reference 28 presents some cumulative amplitude distributions at 4 and 6 GHz at several locations in the equatorial zone, using INTELSAT transmissions. Ionospheric scintillations are usually confined to the auroral and equatorial regions although they may occasionally be observed at mid-latitude stations. For example, at the AIAA 7th Communications Satellite Conference in San Diego in April 1978 Fugono reported a scintillation event at 1.7 GHz at a receiving site in Japan, using transmissions from the ETS-2 satellite. This can be considered as a rare event, however, and principal interest in ionospheric scintillations should be directed to receiving sites in the equatorial and auroral regions. Because so little attention has been paid to phase scintillations, and especially in view of the trend toward the use of coherent PSK techniques in satellite communications, the remainder of this section will be devoted to the problem of phase scintillations.

Phase scintillations are far more difficult to measure experimentally than amplitude scintillation. In addition to signals at the frequencies for which scintillation data are desired, the satellite must also radiate a coherently related signal at a higher frequency to serve as a phase reference. The Japanese ETS-2, for example, uses the 34.5 GHz signal as a phase reference. Apart from this and other very recent satellites that are beginning to measure phase, the only other satellite which has provided a significant data base for phase scintillations in the GHz range is the Wideband satellite designed by SRI International for the Defense Nuclear Agency (DNA). This satellite was launched in May 1976 and data have been continuously recorded at three different receiving stations since that time. Its sole objective is to make amplitude and phase scintillation measurements at VHF, UHF, and L-band (1.239 GHz), using an S-band signal (2.891 GHz) as phase reference. The experiment has been eminently successful in achieving its goal, thus providing a convincing demonstration of the effectiveness of a dedicated satellite in providing data on propagation effects. The ETS-2 is another example of such a satellite. In addition to the Wideband experiment (Ref. 29), DNA has sponsored a great deal of work on scintillation effects in natural and disturbed ionospheres. The interest of DNA in the phenomenology and statistics of ionospheric scintillations stems from a concern over the capability of planned future space-to-ground links to function during periods of scintillation. To this end, analytical and experimental studies have been performed under DNA sponsorship at such organizations as SRI International, Mission Research Corporation, Science Applications, Inc., and ESL, Inc. Reference 30 is an example of a recent study to develop a physical model to explain observed ionospheric scintillations and to serve as a basis for predicting scintillation effects at other frequencies. Reference 31 contains a proposal for a future experiment to extend the results of the Wideband satellite and to provide additional clues on the structure of the irregularities responsible for scintillations at GHz frequencies.

The Wideband satellite is in a sun-synchronous orbit at 1000 km altitude. The experimental results reveal that phase scintillations are quite severe at L-band, and that they are sometimes observed even when amplitude scintillations are too weak to be detected. No experimental data are available above L-band. Because of the current lack of a definitive model of the irregularity structure giving rise to scintillations, there is a need for phase scintillation measurements at GHz frequencies up to possibly X-band. From personal discussions with specialists in this field at the Air Force Geophysics Laboratory, DNA, COMSAT Laboratories, and Mission Research Corporation, it was found that the majority felt that phase scintillations could possibly be a limiting factor in future coherent PSK system design, and that, therefore, long-term observations of this effect are necessary at several GHz frequencies up to X-band on a space-to-ground path. It was found in simulation studies at Mission Research Corporation that phaselock receivers having certain assumed characteristics will lose lock during scintillation events, and that increased amplitude margins will not prevent this loss of lock. Phase scintillation statistics gathered by Wideband were used in these simulations.

Scintillation events are more likely to occur during periods of increased solar activity. Since the peak of the 11-year solar cycle will occur in 1981, the early 1980s would be an exceptionally favorable time to make such measurements. It is recognized that some types of coherent PSK receivers are more sensitive to phase scintillation than others, depending on their implementation. It may turn out that at S-band and above, phase scintillations will not be a limiting factor in system design, but long-term measurements will be necessary before this can be decided.

5. LOW ELEVATION ANGLE EFFECTS

The magnitude of most propagation effects increases rapidly as the elevation angle of the incoming signal at the receiving station approaches zero. In addition, some new effects (e.g., multipath, ducting, and refractive defocusing) that are not factors in propagation at higher elevation angles also have an impact on the received signal. For space-to-ground links that must operate at or near grazing incidence, these low-angle effects will degrade system performance. The increased effects are due not only to the increased length of the propagation path through the atmosphere, but also to the greatly enhanced influence of random temporal variations in atmospheric structure due to turbulence in the lower levels of the troposphere. A review of the technical literature revealed that very little experimental effort has been devoted to low-angle effects on space-to-ground links. Reference 32 describes a significant MIT Lincoln Laboratory program during which angle-of-arrival and amplitude scintillations were measured over a 1-year period at X-band (7.3 GHz) and UHF (0.4 GHz) at Haystack and Millstone. Transmissions from the IDCSP satellites were used. These satellites were in near-synchronous 12-day orbits, ideally suited for low-angle measurements because the line of sight changed very slowly as the satellites rose or set. Except for this one concentrated study, measurements of low-angle effects have only been reported in a few instances as a small part of a broader overall study. References 15 and 33 are examples of such studies. These studies reveal a great deal of rapid amplitude scintillations at low angles, caused by tropospheric irregularities. Corresponding phase fluctuations have apparently not been measured on any program to date.

In many communications satellite applications the system geometry is such that low elevation angles are not encountered, and the enhanced propagation effects at such angles are of no significance. However, it is reasonable to expect that mission requirements for some future systems will lead to system configurations involving link operation down to near-grazing incidence. A long-term measurement program on such a link would be required to establish the statistics of these effects. The average attenuation will rise due to the increased path through the troposphere. Amplitude and phase scintillations will be very pronounced, especially at the higher frequencies. Reference 33 gives peak-to-peak fluctuations of 20 dB at 30 GHz and 8 dB at 2 GHz, all at an elevation angle of 0.38 deg. At 2.82 deg the corresponding values are 18 dB and 4 dB. An additional effect, refractive defocusing, is due to the rapid rise in ray bending as the elevation angle approaches zero. It can add, typically, 1 to 2 dB of loss to the total path loss. As an additional consequence of these low-angle effects, the contours of constant received power density on the ground do not coincide with the constant gain contours of the satellite antenna on the earth's surface. The former are shifted away from the horizon and toward the subsatellite point by a significant distance which, in some applications, would have to be allowed for in the overall system design.

6. INTERSATELLITE LINKS

Because of the likelihood that intersatellite links will find increasingly frequent application, the consideration of possible propagation effects on such links is appropriate here. If the separation between the two geosynchronous satellites is such that the intersatellite propagation path does not pass through any part of the earth's atmosphere, then it can be assumed that propagation effects will be negligible. For greater separations, however, the path can pass through the ionosphere and, in fact, in more extreme cases, it can even graze the upper levels of the troposphere. The total length of path through the ionosphere will be much greater than it would be along a space-to-ground path. It can be expected that ionospheric effects will be considerably enhanced, especially if the intersatellite path geometry is such that its minimum distance from the earth's surface is about equal to the height of the level of maximum ionospheric electron density. This potential problem area was brought up by

Mr. J. A. Klobuchar of the Space Physics Division at the Air Force Geophysics Laboratory during a personal discussion. Since it is probable that NASA and other organizations concerned with future communications satellite systems will be faced with this type of intersatellite link problem, it is concluded that an experimental measurement program is needed to establish the statistics of the propagation effects to be encountered (primarily amplitude and phase fluctuations). Unfortunately, such an experimental program will require two satellites; therefore, it will be very costly unless it can be done in conjunction with a satellite program that will have appropriate pairs of satellites with suitable radiating sources. The LES-8 and LES-9 pair of satellites is an example; however, only one frequency is available on the intersatellite link, and it is doubtful if these satellites can be made available for such a measurement program.

C. FUNDAMENTAL LIMITATIONS

Propagation effects and their causes are essentially nonstationary random phenomena, and their quantitative characterization must of necessity be statistical in nature. This in turn leads to requirements for long-term measurement programs. The time required for measurement of a particular effect depends upon two factors: (1) the temporal character of changes in these effects, especially the long-term, slow changes in the underlying cause mechanisms and (2) the probability level to which the cumulative probability distributions are to be carried out. With regard to the first factor, rainfall and ionospheric irregularity formation are good illustrative examples. It is known that rainfall patterns, even in an average, statistical sense, are not repeatable from year to year: dry years are typically interspersed with wet years in an unpredictable fashion. The formation of ionospheric irregularities is influenced by solar activity, which follows an 11-year cycle. Thus, in both of these examples, measurements performed over, say, a 1-year period would be inadequate and could not reliably serve as a basis for predicting the magnitude of corresponding effects in future years. With respect to the second factor, Crane (Ref. 34) draws some significant and interesting conclusions. He points out that a 1- to 2-year measurement period is adequate for determining the cumulative attenuation distribution function out to the 0.1- to 0.01-percent outage time level, but that 10 to 15 years would be required to extend the function out to the 0.001-percent level. This is clearly impractical, and it is highly questionable whether a cumulative outage level of 0.001 percent is meaningful in a practical sense, not only because of the prohibitive experimental effort required, but also because operational outages and delays due to other causes will exceed by far this percentage level. Thus, a 0.001-percent rainfall outage specification is incompatible with outages from other causes and should not be used. This point is also emphasized in Reference 6. Again, according to Crane, because rainfall is a nonstationary random process, it may never be adequately described at the level of a few minutes a year: 0.001-percent outage time amounts to about 5 min a year. Thus, we have here a fundamental limitation imposed by nature. Long-term measurements of rainfall attenuation on space-to-ground links should be limited to the determination of the cumulative attenuation distribution function out to at most the 0.01-percent level. Rare events, as represented by 0.001-percent outage, cannot be properly handled.

In the case of propagation effects affected by ionospheric structure and subject to changeable solar activity and the 11-year solar cycle, it is clear that measurements performed over 1- to 2-year periods should be repeated several times during the cycle. At the very least, they should be performed at the maximum and minimum parts of the cycle.

A final and very serious fundamental limitation in the propagation area is one which, unfortunately, is imposed by the experiment planner himself. In the past, propagation experiments have often suffered due to the low priority assigned to these experiments, relative to other experiments aboard the satellite. It is a truism that, no matter how ingeniously an experiment is planned, no matter how precisely the experimental equipment is designed and constructed, the experiment will in the end be of little value if it is not allowed to run its course unhampered for a sufficiently long time period to produce adequate data for statistical analysis. Without a high priority for propagation experiments, the time and money spent on future experimental satellite programs will produce a meager return on investment in the propagation area.

D. OPPORTUNITIES FOR ADVANCING THE STATE OF KNOWLEDGE

The section on the present state of knowledge discussed some problem areas involving propagation effects which require further experimental effort. It is recommended that funding for future experimental programs in the propagation area be concentrated in these areas. They are repeated and listed in summary form here.

- Rainfall attenuation statistics are needed in the 40- to 94-GHz range. The cumulative distribution functions should be determined out to at most the 0.01 percent outage level.
- Design criteria for space diversity systems should be established by either of two nonsatellite techniques: simultaneous ground-based radiometric measurements at spaced ground sites, or statistical analysis of long-term weather records for the sites in question. A satellite experiment can only be justified if a suitable satellite and ground stations are already available.

- Depolarization measurements for linear and circular polarizations are required at frequencies above 34.5 GHz; simultaneous measurements for linear and circular polarizations are needed at a number of frequencies from S-band to 34.5 GHz. If the cross-polarization discrimination for circular polarization is found to be acceptable, then long-term cross-polarization discrimination measurements should be carried out at frequencies below 34.5 GHz also.
- Phase scintillation measurements are required for receiving sites in the auroral and equatorial regions at several frequencies from L- to X-band. This is especially desirable near the peak of the solar cycle, which will occur in 1981.
- Long-term measurements of amplitude and phase scintillations at low elevation angles are required at frequencies from L-band to at least 30 GHz and, for the longer term, up to 94 GHz, or some experimentally established upper frequency limit above which the low-angle effects are severe enough to rule out their use in future communications satellite links at low elevation angles.
- Long-term measurements of amplitude and phase fluctuations should be made on intersatellite links passing through the ionosphere.

ORGANIZATIONS/PERSONS CONTACTED FOR CHAPTER VI

Air Force Geophysics Laboratory (Hanscom AFB, MA); J. A. Klobuchar, Space Physics Division (March 27, 1978).

COMSAT Laboratories (Clarksburg, MD); Dr. G. Hyde, Manager, Propagation Studies Department, and Dr. D. J. Fang, L. Palmer, F. Tseng, C. Devieux, D. Rogers, and D. Kennedy (April 5, 1978).

COMSAT Laboratories (Palo Alto, CA); Dr. R. R. Taur (March 27, 1978).

Defense Nuclear Agency, Headquarters (Alexandria, VA); Maj. R. Bigoni (April 17, 1978).

Ford Aerospace and Communications Corporation (Palo Alto, CA); C. L. Cuccia (March 28, 1978).

Mission Research Corporation (Santa Barbara, CA); Dr. R. L. Bogusch, F. W. Guigliano, and D. L. Knepp (April 24, 1978).

REFERENCES FOR CHAPTER VI

1. D. C. Hogg and T. S. Chu, "The Role of Rain in Satellite Communications," Proceedings of the IEEE, 63 (1975), pp. 1308-31.

2. D. J. Fang and J. Jih, "A Model for Microwave Propagation Along an Earth-Satellite Path," COMSAT Technical Review, 6, 379 (1976).

3. J. Goldhirsh, "Extrapolation of Rain Attenuation Statistics to Other Locations," Proceedings of the First Open Symposium of URSI Commission F, La Baule, France (28 April-6 May 1977), pp. 305-10.

4. J. Goldhirsh, "Prediction Methods for Rain Attenuation Statistics at Variable Path Angles and Carrier Frequencies Between 13 and 100 GHz," IEEE Transactions on Antennas and Propagation, AP-23 (1975), pp. 786-91.

5. N. Fugono and R. Hayashi, "Propagation Experiment in 1.7, 11.5 and 34.5 GHz with Engineering Test Satellite Type II (ETS-II)," AIAA Paper No. 78-623, presented at AIAA 7th Communication Satellite Conference, San Diego, CA (23-27 April 1978).

6. N. E. Feldman and S. J. Dudzinsky, Jr., A New Approach to Millimeter-Wave Communications, R-1936-RC, RAND Corporation, Santa Monica, CA (April 1977).

7. E. E. Reber and D. V. McDonald, On Rainfall and Space Diversity for Millimeter-Wave Earth-Satellite Communications Systems, TR-0073(3230-01)-1, The Aerospace Corporation, El Segundo, CA (15 March 1973).

8. J. E. Allnutt and P. F. Shutie, "Space Diversity Results at 30 GHz," Proceedings of the First Open Symposium of URSI Commission F, La Baule, France (28 April-6 May 1977), pp. 371-74.

9. W. J. Vogel, et al., "ATS-6 Attenuation and Diversity Measurements at 20 and 30 GHz," NASA TN D-8197, 20- and 30-GHz Experiments with the ATS-6 Satellite, edited by L. J. Ippolito (April 1976).

10. D. B. Hodge, D. M. Theobold, and R. C. Taylor, "Initial Results of the Ohio State University 20- and 30-GHz ATS-6 Propagation Measurements," NASA TN D-8197, 20- and 30-GHz Experiments with the ATS-6 Satellite, edited by L. J. Ippolito (April 1976).

REFERENCES FOR CHAPTER VI (continued)

11. ATS-6 Millimeter Wave Propagation Experiment: Final Data Analysis Report, FIS-75-0050, Westinghouse Electric Corporation (September 1975).

12. T. S. Chu, "Rain-Induced Cross-Polarization at Centimeter and Millimeter Wavelengths," Bell System Technical Journal, 53, 1557 (1974).

13. R. A. Semplak, "Simultaneous Measurements of Depolarization by Rain Using Linear and Circular Polarizations at 18 GHz," Bell System Technical Journal, 53, 400 (1974).

14. R. A. Semplak, "The Effect of Rain on Circular Polarization at 18 GHz," Bell System Technical Journal, 52, 1029 (1973).

15. C. W. Bostian, et al., "Results from the ATS-6 20-GHz Depolarization Experiment at Virginia Polytechnic Institute and State University," NASA TN D-8197, 20- and 30-GHz Experiments with the ATS-6 Satellite, edited by L. J. Ippolito (April 1976).

16. J. Fimbel and P. Ramat, "Mesures de l'affaiblissement et de la dépolarisation à 20 GHz à partir du satellite ATS-6," Proceedings of the First Open Symposium of URSI Commission F, La Baule, France (28 April-6 May 1977), pp. 333-38.

17. R. G. Howell and J. Thirwell, "20 GHz Cross-Polarization and Dual Frequency Attenuation and Scintillation Measurements Using the ATS-6 Satellite," Proceedings of the First Open Symposium of URSI Commission F, La Baule, France (28 April-6 May 1977), pp. 339-44.

18. P. A. Watson, et al., "20 GHz Attenuation and Cross-Polarisation Measurements Using the ATS-6 Satellite with Simultaneous Radar Observations," Proceedings of the First Open Symposium of URSI Commission F, La Baule, France (28 April-6 May 1977), pp. 345-50.

19. T. Pratt and D. J. Browning, "Cross-Polarisation Measurements for a 30 GHz Satellite Earth Path in Central England," Proceedings of the First Open Symposium of URSI Commission F, La Baule, France (28 April-6 May 1977), pp. 361-65.

20. P. F. Shutie, J. E. Allnutt, and E. C. Mackenzie, 'Depolarisation Results at 30 GHz Using Transmissions from the ATS-6 Satellite," Proceedings of the First Open Symposium of URSI Commission F, La Baule, France (28 April-6 May 1977), pp. 367-69.

21. J. Dijk and E. J. Maanders, "Copolar and Cross-Polar Signals Received at 30 GHz from ATS-6," Proceedings of the First Open Symposium of URSI Commission F, La Baule, France (28 April-6 May 1977), pp. 375-80.

22. J. M. Harris and G. Hyde, "Preliminary Results of COMSTAR 19/29-GHz Beacon Measurements at Clarksburg, Maryland," COMSAT Technical Review, 7, 599 (1977).

23. H. W. Arnold and D. C. Cox, "Some Results from 19 and 28 GHz COMSTAR Beacon Propagation Experiments," AIAA Paper No. 78-619, presented at AIAA 7th Communications Satellite Conference, San Diego, CA (23-27 April 1978).

24. H. Kaneda, K. Tsukamoto, and H. Fuketa, "Experiments in the Japanese CS Program," AIAA Paper No. 78-616, presented at AIAA 7th Communications Satellite Conference, San Diego, CA (23-27 April 1978).

25. T. Ishida, et al., "Program of Experimental Communication Satellite (ECS) of Japan," AIAA Paper No. 78-614, presented at AIAA 7th Communications Satellite Conference, San Diego, CA (23-27 April 1978).

26. G. Perrotta, "The Italian SIRIO 12-18 GHz Experiment: The Forerunner of 20-30 GHz Preoperational Satellites," AIAA Paper No. 78-631, presented at AIAA 7th Communications Satellite Conference, San Diego, CA (23-27 April 1978).

27. R. K. Crane, "Ionospheric Scintillation," Proceedings of the IEEE, 65 (1977), pp. 180-99.

28. R. R. Taur, "Ionospheric Scintillation at 4 and 6 GHz," COMSAT Technical Review, 3, 145 (1973).

29. C. L. Rino, et al., Wideband Satellite Observations, DNA 4399F, SRI International, Menlo Park, CA (June 1977).

30. D. L. Knepp, Multiple Phase-Screen Propagation Analysis for Defense Satellite Communications System, DNA 4424T, Mission Research Corporation, Santa Barbara, CA (September 1977).

31. E. J. Fremouw, et al., Design Considerations for a Microwave Scintillation Experiment, DNA 4092F, SRI International, Menlo Park, CA (15 March 1977).

32. R. K. Crane, Low Elevation Angle Measurement Limitations Imposed by the Troposphere: An Analysis of Scintillation Observations Made at Haystack and Millstone, 518, MIT Lincoln Laboratory (18 May 1976).

33. D. B. Hodge, D. M. Theobold, and D. M. J. Devasirvatham, "Amplitude Scintillation at 2 and 30 GHz on Earth Space Paths," Proceedings of the First Open Symposium of URSI Commission F, La Baule, France (28 April-6 May 1977), pp. 421-25.

34. R. K. Crane, "Prediction of the Effects of Rain on Satellite Communication Systems," Proceedings of the IEEE, 65 (1977), pp. 456-74.

CHAPTER VII

LOW-COST TERMINALS

Prepared by

Ernest I. Pritchard
Satellite Systems Division

James J. Murphy
Communications Department

Orin J. Mead
Advanced Orbital Systems Division

CONTENTS FOR CHAPTER VII

LIST OF ILLUSTRATIONS

CHAPTER VII

LOW-COST TERMINALS

A. LOW-COST SMALL EARTH STATIONS

1. OVERVIEW

The information in this chapter has been traced whenever possible to the appropriate reference documents. Verbal information has been gained from telephone calls or visits to earth terminal suppliers, earth terminal subsystem suppliers, common carriers, communication satellite system operators, and experiments using small earth terminals.

A list of the organizations and persons contacted during the course of this study appears at the end of this chapter. References to documents cited and a bibliography are also presented here.

The objectives of this study are (1) to develop a traceable evaluation of the current state of the art in low-cost earth terminals, (2) to list technological opportunities in low-cost earth terminals, and (3) to estimate the resources needed to develop these technologies.

On the basis of guidance furnished by the National Aeronautics and Space Administration (NASA), the study approach is as follows:

- To elicit information on the current state of the art for communication satellite low-cost earth stations from the industry.
- To elicit from the industry concepts of technological opportunities in the next five years which could be carried out with NASA funding. From analyses of data obtained from the industry or from the literature, gaps in the low-cost earth station technology which could benefit from NASA funding in the next five years were sought. Low-cost terminals for frequencies from 0.9 to 100 GHz are of interest; however, microwave frequencies of 0.9, 1.6 to 1.5, and 30 to 20 GHz are emphasized.

The professionals contacted and the documentation reviewed generally agreed that it is important to lower the cost of earth stations and, in particular, the cost of small-capacity earth stations which serve one to a few users per terminal. The National Academy of Sciences takes the view that small terminal users would come forward if prices could be reduced (Ref. 1). Such a reduction in cost depends on the use of multiple-beam, high-gain satellite antennas. Communications Satellite Corporation (Comsat) planners state that the growth of the mobile communications area will depend on the development of appropriate low-cost terminals, which in turn will depend on a satellite with larger, higher-gain antennas; more powerful amplifiers; and adequate on-board switching with the port terminals (Ref. 2).

This chapter covers complete integrated terminals and ground terminal subsystems. In this discussion of low-cost terminals, it seems appropriate to define the ground station categories used in this study:

- A high-performance ground station costs $1 million or more per station and is typified by the International Telecommunications Satellite Consortium (INTELSAT) Standard Station A.
- A medium-performance ground station costs less than $1 million and is typified by military terminals costing several hundred dollars each or by the Satellite Business System (SBS) terminal.
- A small low-performance (not necessarily low cost) station is typified by the two-way television and 56-kbps ground terminals currently operating with the U.S. domestic satellite (DOMSAT) systems.
- A small low-cost ground station typically costs less than $100,000, such as the small terminals that are compatible with the Palapa satellite, many of the receive-only stations compatible with the U.S. DOMSATs, Marine satellite (MARISAT) terminals, and Communications Technology Satellite (CTS) terminals.

All ground terminals are, of course, linked to specific communications satellite systems. For a perspective on the ground terminals, it is useful to consider a communication satellite system in being or planned (Table VII-1). This table is based on data from Ford Aerospace and from Refs. 1 and 3. U.S. carriers currently use Western Union's WESTAR, RCA SATCOM, COMSTAR, ANIK, and INTELSAT; all are 6- to 4-GHz systems. It has been announced that INTELSAT-V and Advanced WESTAR will continue this C-band service. In addition, INTELSAT-V will operate at 14 to 11 GHz, and Advanced WESTAR will operate at 14 to 12 GHz. The SBS spacecraft will also operate at 14 to 12 GHz. Both the SBS and Advanced WESTAR service at this frequency range is totally digital and operates exclusively in the time division multiple access (TDMA) mode (Refs. 3, 4, and 5).

The 8- to 7-GHz band is used by the military. Above 14 GHz, there is no satellite with which a U.S. civilian ground station could uplink. The

Table VII-1. Modern Communication Satellite Systems

Up-Link Frequency (GHz)	5.9-6.4	7.925-8.425	14.0-14.5	14.0-14.5	27.5-30.0	30.0-31.0	34.8	36.0-38.0
Down-Link Frequency (GHz)	3.7-4.2	7.25-7.75	10.95-11.2	11.7-12.2	17.7-20.2	20.2-21.2	31.65	36.0-38.0
Satellite Systems	Westar Symphonie RCA Satcom Intelsat IV Intelsat IVA Anik ATS-6 Anik-C Intelsat V Indonesia Sat AT&T Com-star Japan CS Advanced Westar	DSCS-II DSCS-III NATO2B, 3 Skynet 2B Fltsatcom	Canadian Technology Satellite Intelsat V	European Orbiting Test Sat. Japan Broadcast Satellite Anik-B SBS Advanced Westar	Japan Comm. Satellite (CS)		Japan Experimental Comm. Satellite (ECS)	LES-8 LES-9
	Brazil Sat. Arabian Sat. Iranian Sat. Intelsat VI	AFSATCOM-II			AT&T Japan Comm. Satellite (CCS)	Military Comsats Japan Mobile		

LES-8 and LES-9 ground terminals are relatively small with 3- and 4-ft-diam antennas. These ground terminals operate at 38 to 36 GHz.

In the near future, the Mutual Broadcasting System will broadcast its radio programs via WESTAR satellite to more than 500 low-cost terminals (Ref. 6). Both Associated Press (AP) and United Press International (UPI) have conducted experiments with WESTAR also. A telephone discussion with Don Snodgrass of Rockwell International Collins revealed that the Public Broadcasting System is purchasing 162 ground stations with 10-m antennas for two video and five audio channels apiece. National Public Radio is also purchasing 4.5-m antenna terminals. Holiday Inns is investigating and apparently initiating first-run movie distribution through satellite links to its motels for viewing on television (Ref. 7). Reference 8 shows that RCA American Communications now serves, through its satellite network, between 115 and 120 receive-only stations owned by cable television (TV) systems throughout the continental United States. The cost of earth stations for the Mutual Broadcasting Corporation radio program distribution system is quoted at $6350 for the basic unit (Ref. 9). Television receive-only stations start at $10,000 each when linked with the powerful CTS satellite (Ref. 10) and start at about $22,000 a unit when linked with the WESTAR or RCA SATCOM (Ref. 11). At current prices, the small-terminal industry needs Government support in order to compete successfully with the Japanese, according to Rockwell International Collins.

In summary of the overview information stated thus far, there is a need to support the industry with low-cost terminal technology in the near future at 6 to 4 GHz, both to compete with foreign competition and to bring in new users by getting additional small station users started. With the SBS and Advanced WESTAR TDMA systems at 14 to 12 GHz, the ground terminal costs are estimated to be $345,000 per terminal (Ref. 5). The large terminal costs are apparently due to the complexity of the terminal and its controller. The TDMA mode of operation adds to this complexity relative to the frequency division multiple access (FDMA) mode. The Goddard Space Flight Center (GSFC) study team has uncovered evidence that the Advanced WESTAR terminal for Ku-band is approximately the same price and that the SBS terminal has increased even more in cost. For driving down the TDMA terminal costs, including the high-power amplifier operating in the burst mode, the modem control and synchronization equipment are technology needs. Little effort was devoted to this problem in this Aerospace study, and no specific approaches to technology development were found or defined. It was noted, however, that studies of future mobile systems at L-band showed terminal concepts for TDMA in the price range of $2,000 to $15,000, with quantity production assumed (Refs. 12 and 13). The satellite effective isotropic radiated power (EIRP) was significantly higher (50 to 55 dBW) for these studies compared to the satellite EIRP for SBS (at about 40 dBW), thus facilitating lower-cost ground terminals since ground terminal performance is lower.

The CTS experiences to date and the advanced system studies described indicate that the key element to lower-cost terminals is the high-power (EIRP), high-performance [high antenna gain over noise (G/T)] satellites. Where then are the opportunities for these satellites in the future? From the population of satellites in the geostationary arc visible in the United States, shown in Figure VII-1 (Ref. 14), it is seen that by 1981 the arc will be well filled at the 6- to 4-GHz frequency band and well on its way to being filled at the 14- to 12-GHz band. The opportunities then for future systems which would include the powerful high-performance satellites are at the higher frequency (e.g., 30 to 20 GHz) or at the lower frequencies (0.9 GHz, L-band, or S-band). At the lower frequencies, care would have to be exercised not to crowd out existing mobile systems such as MARISAT and MAROTS. The study was thus led to concentrate on small earth station technology work at the higher frequencies, including both mobile and fixed systems. Civil communication satellite system studies of the 30- to 20-GHz area were found (Refs. 1, 15, 16, and 17). Studies for military systems were also found (Refs. 18 through 22). Reference 16 considers a large space antenna concept (13 × 15 m) and a small earth station antenna concept (8 ft in diameter). However, these studies were not generally oriented toward low-cost ground terminals, again leaving a gap to be filled. System and cost optimization work is needed.

The technology opportunities described for the antenna, receiver, and transmitter subsystems apply to the 30- to 20-GHz frequency band as well as frequencies of interest. Reference 23 covers the technology base for 20- to 30-GHz earth terminals. Much of the technology is Japanese, developed for their communication satellite (CS) system (Figure VII-2).

Figure VII-3 indicates an absence of low-cost small earth terminals in the 30- to 20-GHz area. Technology opportunities are described at the end of this chapter as NASA options to help fill this gap. Reference 24 also reviewed the communication satellite systems technology in a thorough manner and found no small earth station technology available in the 30- to 20-GHz frequency band.

2. STATE OF THE ART FOR LOW-COST SMALL EARTH STATIONS

The current state of the art in communication satellite mobile systems is represented by the MARISAT system. The entire shipboard terminal, including the inside and outdoor units, can be purchased from Magnavox for $63,500 plus installation (Ref. 25). The Scientific Atlanta terminal can be purchased from Comsat Corporation for $62,000 plus installation (Ref. 11 and the Comsat contact listed in the ORGANIZATIONS/PERSONS CONTACTED section appearing at the end of this chapter). Each of these installations has a 4-ft-diam antenna operating at L-band.

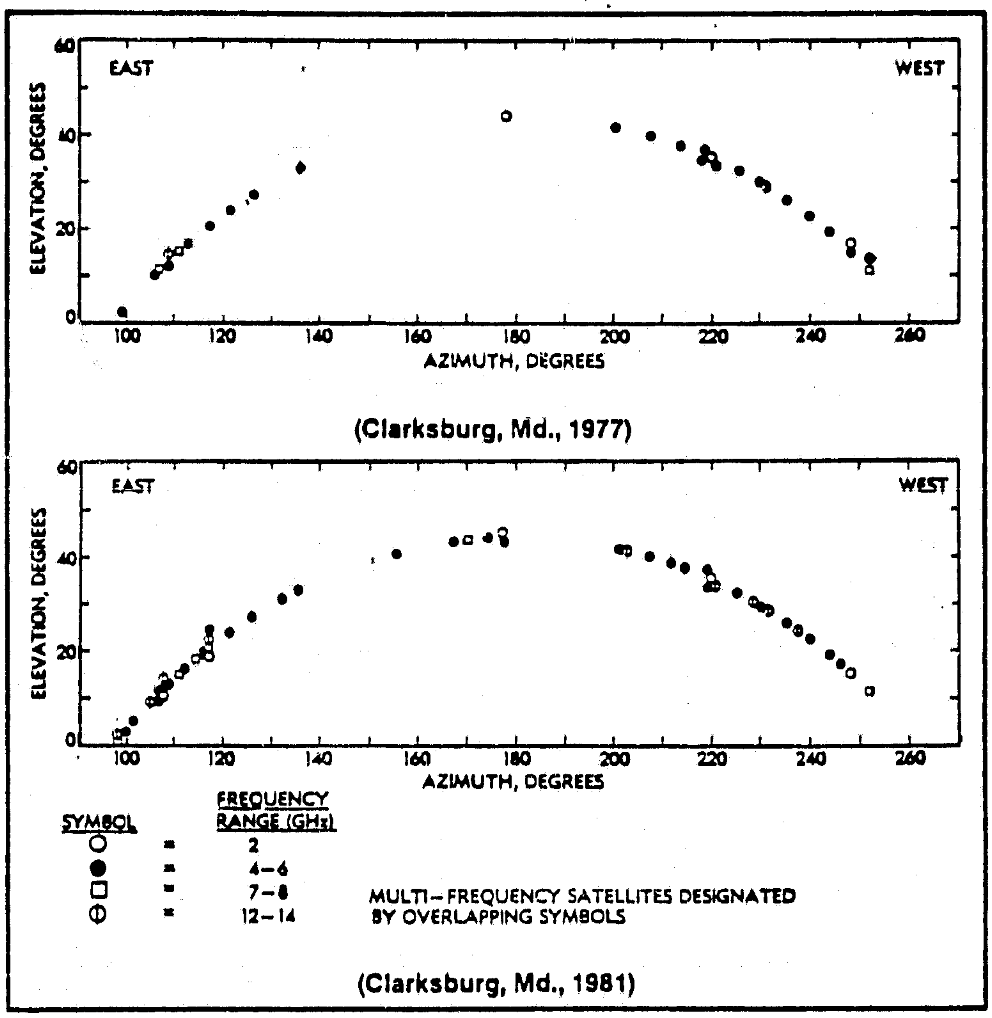


Figure VII-1. Visible Geostationary Arc

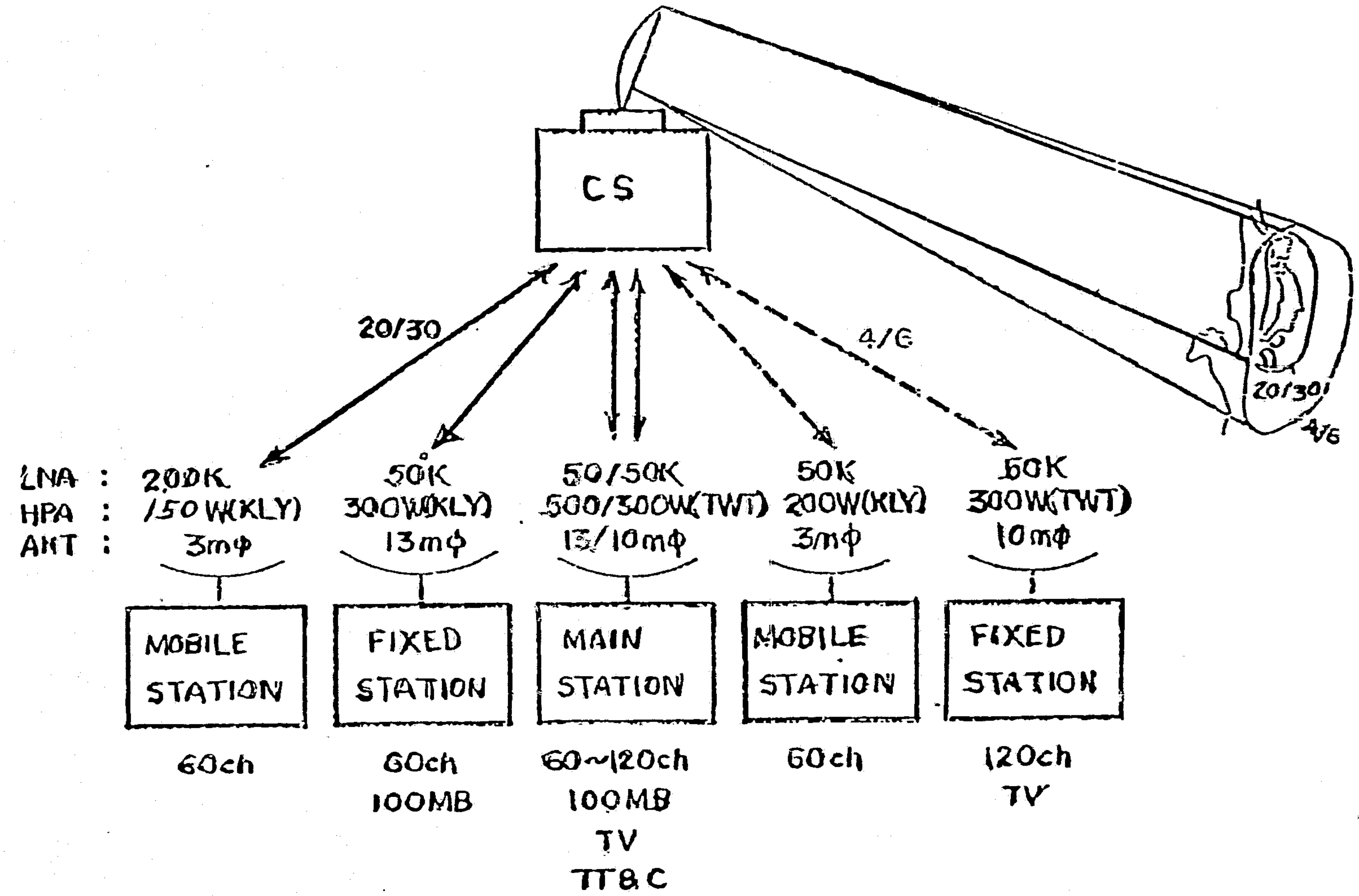


Figure VII-2. The Terminals To Be Used with CS

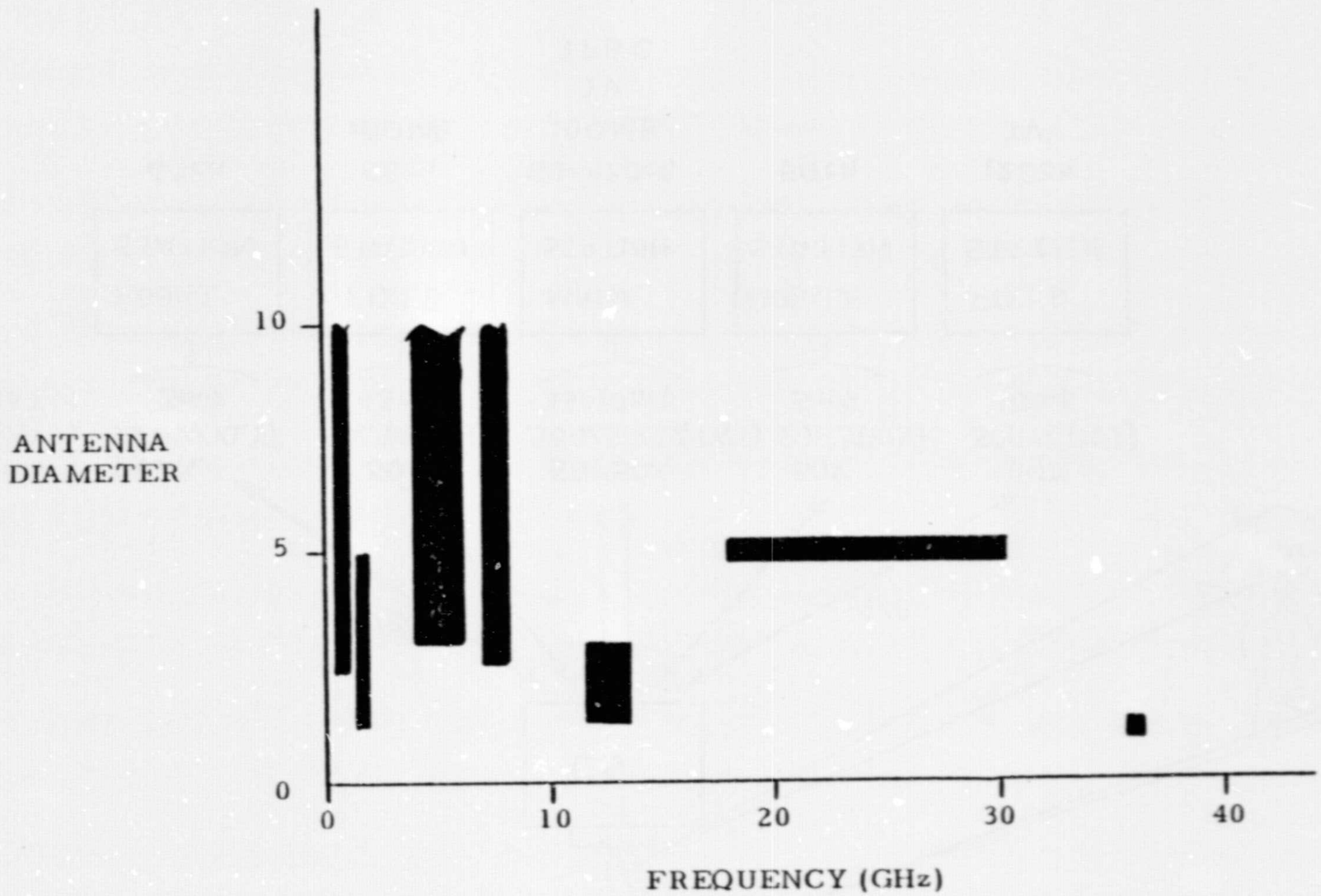


Figure VII-3. U.S. Small Earth Terminals

The LES-8 and LES-9 military experimental satellites operate in K-band at 38 to 36 GHz. Mobile terminals for LES-8 and LES-9 have 3- and 4-ft-diam antennas and are on the order of $250, 000 (Lincoln Laboratory contact listed in the ORGANIZATIONS/PERSONS CONTACTED section appearing at the end of this chapter).

A U.S. Army Satellite Communication Agency Manpack satellite terminal (AN/PSAC-1) operating at frequencies of 225 and 400 MHz, featuring selective call notification, digital voice, and data with 7000 voice channel frequencies, costs $23, 000 each for 200 units (Ref. 12).

A Motorola microdigital private line mobile radio with one frequency modulated (FM) voice channel at 800 MHz and 35 W of rf power and used in conjunction with a ground-based mobile network costs $1, 600 (Ref. 12).

One or two mobile receive-only terminal experiments were run, using the ATS-6 satellite. John Marishek of GSFC is familiar with these, but no terminal costs are available.

The status of U.S. technology in small earth stations of a nonmilitary or civilian variety is summarized in Table VII-2. Mobile terminals as well as fixed terminals are included. The 0.9- and 1.6- to 1.5-GHz bands are applicable to mobile systems only. The 2.6- to 2.5-GHz frequency band has only been used experimentally so far in the United States. The 6- to 4-GHz frequency band or C-band is the INTELSAT communications band as well as the U.S. DOMSAT band. The 14- to 12-GHz band has only been used in the United States so far, by the CTS satellite. No U.S. systems have used the 30- to 20-GHz frequency band thus far. The table shows which of the small terminals of each type and frequency are currently available from industry in the United States. Shown in parentheses are the references reporting the availability of these various small terminals. Also shown, by the symbol N, are the areas where no terminals were found. The basic technology is evidently available for terminals from L-band to 14 to 12 GHz. The obvious gaps are at 0.9 GHz for the mobile terminal and 30 to 20 GHz for all kinds of terminals.

The state of the art is different in different parts of the world. The Japanese have ground terminals down to 3-m in diameter, operating in the 30- to 20-GHz area (Ref. 23). The Europeans have reported experimenting with small terminals down to 3-m in diameter in the 6- to 4-GHz band, using the Symphonie satellite (Ref. 24).

The Europeans and Japanese are interested in and planning for direct broadcast to home television. The United States, indeed the North American continent, has no plans for direct broadcast. Therefore, the terminals associated with direct broadcast are not included in the technology list. None are available here, and no plans were uncovered for producing any.

Table VII-2. Status of U.S. Technology in Small Earth Stations, Nonmilitary

Frequency (GHz)	Type of Terminal				
	Thin Line	Receive Only		Two-Way TV	Mobile
		Radio(1)	TV(1)		
0.9	—	—	—	—	(N)
1.6/1.5	—	—	—	—	A (33, 63, 58)
2.6/2.5	A (53)(2)	N	A (66)	A (66, 53)	—
6/4	A (58, 92, 93, 94, 95(2))	A (77, 94)	A (58, 62, 94, 95)	N	—
14/12	A (56)	N	A (39, 49, 56, 93, 96)	A (49, 56, 96)	—
30/20	(N)	N	N	(N)	(N)

N = None found available.
A = Available from industry.
— = Not applicable.
(( )) = Reference number.
(N) = None found available, technology opportunity options.

(1) Distribution and one-way special services.
(2) TV also.

Table VII-3 displays current costs to the users charged by U.S. DOMSAT carriers for various services that they offer. Single telephone circuits leased for a short haul (Atlanta to Chicago) cost $415.00 per month. Longer-haul service (New York City to Los Angeles) costs $740.00 per month for circuits. Radio broadcast via satellite takes twice as much bandwidth and costs twice as much. These charges include telephone-to-telephone service and radio station-to-station service. These rates are quoted by American Satellite Corporation.

At higher data rates, two-way service for a 56-kbps system leases for $10,000 per month, including door-to-door service with an earth station at either end. For this service, the satellite transponder charges are a little under $2000 per month and the station costs represent 84 percent of the user charge. Other cases also quoted by the American Satellite Corporation are shown for more stations or higher data rates. The remaining figure shows costs associated with TV distribution for a system where the carrier furnishes the uplink to the satellite and the satellite transponder service. The customer purchases and operates a ground terminal for receipt of the TV signal. The carrier's charge (RCA) is $134 per hour for protected service before 5 PM, and after 5 PM in peak hours $295 per hour. This is a contract rate quoted for a minimum of five hours a day of service. If we assume a case with a use rate of eight hours a day, four hours of peak time operation and four hours at off-peak operation, and amortize a 100 ground terminal network over three years, the station costs are 79 percent of the cost of operating the distribution network. If the terminals are amortized over seven years (the average life of a normal DOMSAT), then the station costs are 62 percent of the cost of operating the network. Twenty percent of the station cost is assumed to go for maintenance.

These examples show clearly that the station costs are a very large portion of the cost of using satellite systems with small earth terminals.

3. TECHNOLOGY LIMITS FOR LOW-COST SMALL EARTH STATIONS

The technology limits on the cost of small, low-cost earth station costs are probably represented in the limit by the cost of materials and parts, since mass production methods could be used (theoretically) to fabricate the units. Thus, the cost per pound of TV electronics and radios will eventually apply. Cost of antennas is expected to be more like the cost per pound of automobile or TV antennas.

4. TECHNOLOGY OPPORTUNITIES FOR LOW-COST SMALL EARTH STATIONS

Technology opportunities derived from this study for entire small earth terminals, disregarding for the moment the terminal cost picture, are depicted in Table VII-2. They are denoted by "N." Most of the opportunities are in the 30- to 20-GHz band. Thin-line and two-way TV for fixed terminals

Table VII-3. Typical Current Monthly Tariff (End-to-End Service)

- SINGLE CIRCUIT VIA SATELLITE (4 KHz BANDWIDTH)

ATLANTA —— CHICAGO	\$415
N.Y.C. —— L.A.	\$740

- RADIO BROADCAST VIA SATELLITE (8 KHz BANDWIDTH)

ATLANTA —— CHICAGO	\$830
N.Y.C. —— L.A.	\$1480

- FOR HIGHER DATA RATES TWO-WAY SERVICE 78-84% OF THE LEASE COSTS ARE FOR DEDICATED EARTH STATIONS

56 KBPS, 2 STATIONS	\$10K[1]	(84% STATION COSTS)
56 KBPS, 3 STATIONS	\$16.2K	(78% STATION COSTS)
112 KBPS, 2 STATIONS	\$12.4K	(85% STATION COSTS)
224 KBPS, 2 STATIONS	\$17.2K	(87% STATION COSTS)

- FOR TV DISTRIBUTION (BLACK AND WHITE OR COLOR), 62% TO 79%[2] OF THE SYSTEM COSTS ARE FOR RECEIVE-ONLY EARTH STATIONS

  \$134/HR BEFORE 5 PM EST

  \$295/HR AFTER 5 PM EST

  GROUND TERMINAL R.O. STATION - \$60,000 ONE-TIME COST

(1) EQUIVALENT COST FOR FRACTION OF TRANSPONDER - 1.8K/MONTH

(2) EIGHT HOURS PER DAY OPERATION, 100 STATIONS AMORTIZED OVER THREE TO SEVEN YEARS, 20% FOR MAINTENANCE

were selected primarily because of their many potential applications. The mobile 30-to 20-GHz terminal was also selected because of the apparently large potential use rate for mobile systems worldwide, which may saturate the 0.9-GHz band. Some of the mobile services will require special privacy arrangements, which use up bandwidth.

In Table VII-4, technology opportunity options for small low-cost U.S. earth stations are considered and listed by frequency and type of terminal. Areas where low-cost technology would apply to these stations are listed as "L." Many of these are expected to develop without Government support. Most of the contacts made with small station manufacturers referred to the industry as highly competitive. The areas where low-cost technology development by the Government could make a significant change in systems costs and therefore rate of user acceptance are shown by "Ⓛ." The four opportunities for small earth stations technology listed in Table VII-2 are also shown here as low-cost technology opportunities. Also appearing is the thin-line service at the 6- to 4-GHz band, where it is important to get costs down so that the service is affordable in relatively poor, remote areas.

In the case of the technology opportunities for 30- to 20- and the 0.9-GHz opportunity for mobile terminals, the essence of the rationale for proposing these technology opportunities gets down to the question of which comes first, the satellite or the low-cost ground terminal. In these areas, the opportunity currently presented is to work on the technology for low-cost ground terminals at the same time or even perhaps ahead of the satellite technology and satellite design. Historically, it has not worked this way. Now, however, with the combination of a more mature industry, additional satellite weight capability, and technology which can lead to more powerful satellites, it is time to consider changing the procedure to firm up the low-cost earth terminal technology along with the space segment technology in a manner that will encourage the orderly and coordinated application of low-cost terminal technology.

Table VII-5 shows an integrated strawman schedule and resources for technology opportunities in the low-cost ground terminal area. The summaries for these opportunities appear in Tables VII-6 through VII-13. The schedule shows the ground terminal subsystem technology work and the system studies for the terminals starting immediately. System studies on the 0.9-GHz mobile transceivers have already been accomplished; therefore, these can also start immediately. The systems using the 6- to 4-GHz low-cost terminals are in existence or firmly planned; therefore, that opportunity can start immediately. Mobile transceivers in the 29- to 19-GHz area would be initiated after the system studies were over. Low-cost terminals in the 20- to 30-GHz area would be initiated after the system optimization studies are completed and on a schedule compatible with making use of the results of the subsystem technology developments for antennas, direct modulation and demodulation, and frequency translators. The last item on the schedule would be initiated in approximately five years and aim at a flight test of a 30- to 20-GHz transponder/antenna, possibly on a multipurpose

Table VII-4. Technology Opportunity Options for Small Low-Cost U.S. Earth Stations

Frequency (GHz)	Type of Terminal				
	Thin Line	Receive Only		Two-Way TV	Mobile
		Radio(1)	TV(1)		
0.9	—	—	—	—	(L)
1.6/1.5	—	—	—	—	L
2.6/2.5	AL	—	AL	AL	—
6/4	(L)	L	L	—	—
14/12	AL	—	L	L	—
30/20	(L)	AL	AL	(L)	(L)

(1) Distribution and One-Way Special Services.

NOTE: L = Low-cost technology may develop without government support.

(L) = Low-cost technology opportunity option.

AL = Additional low-cost technology opportunity which could develop if applications arise

— = Not applicable.

Table VII-5. Low-Cost Ground Terminals Strawman Integrated Schedule and Resources, Technology Opportunities ($ in Millions)

Technology Opportunity	Year 1	Year 2	Year 3	Year 4	Year 5	Estimated Total Cost
Antennas[1]	(0.2)	(0.4)	(0.4)	(0.4)		1.4
Direct Modulation, Direct Demodulation	(0.4)	(0.4)	(0.5)			1.3
Translators	(0.4)	(0.5)				0.9
Microprocessors[2]						
Communication Satellite System Optimization Studies:						
Mobile (29/19 GHz)	(0.5)					0.5
Fixed Thin-Line System (30/20 GHz)		(0.5)				0.5
Mobile Transceivers[3]						
29/19 GHz Prototype		(1.0)	(2.0)	(1.0)		4.0
0.9 GHz Prototype	(0.2)	(0.5)	(0.8)			1.5
Low-Cost Terminals						
6/4 GHz	(1.0)	(1.0)				2.0
30/20 GHz Prototype			(1.0)	(2.0)	(2.0)	5.0
Initiate Flight Tests of Transponder/Antenna					▬	——[4]
TOTALS:	2.7	4.3	4.7	3.4	2.0	17.1

(1) Two contractors.
(2) Technology available by 1980 (Ford Aerospace/Array, NASA technology program).
(3) Mobile antenna data are available, further study not needed.
(4) Not estimated.

Table VII-6. Direct Modulation/Demodulation

Applications:	1. Low-cost earth stations 2. In and out equipment for spaceborne regenerative repeaters in digital systems
Technology Limits:	Direct modulation and direct demodulation is not currently done in ground terminals. Limitations are not known.
Opportunities:	Reduced cost on microwave (MW) or millimeter wave (MMW) earth terminals through the replacement of frequency conversion and I.F. equipment. Noise may also be reduced. Linearity relative to MW or MMW center frequency may also improve.
Approach:	The primary motivation for development of direct modulation and demodulation is to save terminal equipment costs. The contractor will therefore estimate cost savings, compared to conventional equipment, as a part of his proposal and again at the end of the development task. The development task is to include a breadboard and prototype unit, the testing of these units, and the delivery of the prototype to NASA. Direct Demodulation - For direct demodulation the first requirement will be the development of low noise RF preamplification in order to achieve the appropriate S/N. In addition, the contractor will propose, develop, and test signal processing techniques demodulating (1) digital PSK, (2) FM/FDM signals, and (3) digital FSK signals. The equipment is intended for use with ground stations at 4, 12, and 20 GHz. Direct Modulation - For direct modulation the contractor will propose, develop, and test signal processing techniques for modulating the HPA RF carrier with (1) digital PSK, (2) FM/FDM signals, and (3) digital FSK signals. The equipment is intended for use with ground stations at 6, 14, and 30 GHz(1). Estimated cost for analytical, breadboard, prototype, and engineering test model programs is $1.3M, two to four years.
References:	LNR Communications Inc., Hauppauge, New York

(1) Emphasis is on 30/20 GHz.

Table VII-7. Low-Cost Frequency Translators (20 → 12 → 4 GHz) (6 → 14 → 30 GHz)

Applications:	Efficient frequency converters for earth terminal up and down links in the C-band, Ku-band, and 20/30. Techniques are also applicable to satellite equipment.
Technology Limits:	The current technology limit is based on S to Ka band power upconverters. Upconverters to higher frequencies (e.g., 80 GHz) are possible.
Opportunities:	Transition from use of one band to another will be eased. Small thin line and receive-only terminals can be adaptable to more than one frequency, potentially reducing terminal costs. Multi-frequency terminals have advantages for all-weather operation. These converters could provide sufficient frequency agility to permit cross-strapping between uplinks in one band and downlinks in another band, and vice versa.
Approach:	The primary motives for developing frequency translator technology are to save earth station unit costs and to allow stations to be adapted or transitioned at low cost from one satellite (frequency) to another. The frequency converters themselves are to be designed for low cost. The approach is to have the contractor propose, design, develop, and demonstrate frequency translators for a specific small 6/4 GHz earth terminal. Translation from 6 → 14 GHz and 12 → 4 GHz is to be demonstrated with a satellite. Translation from 6 → 30 GHz and 20 → 4 GHz is to be demonstrated either on the ground or with a satellite. $900K, two years.
References:	LNR Communications Inc., Hauppauge, New York

Table VII-8. Direct Mobile Terminal to Mobile (or fixed) Terminal Communication Via Satellite at 900 MHz or L-Band (Prototype)

Application:	Trucking communications, highway patrole cars, various emergency mobile elements, as well as passenger cars and aircraft.
Technology Limits:	Current satellites EIRP and mobile antenna gain limitations result in insufficient margin to accommodate natural fading environment due to buildings, trees, weather.
Opportunities:	Enablement of adequate communication capacity by means of a multi-element antenna at the mobile terminal; adaptively aiming toward satellite.
Approach:	1. Use of downlink beacon to orient multi-element antenna toward satellite. 2. A 1 x 1 m^2 array flush (or near flush) mounted on roof of car, cab, truck, aircraft. The feasibility and cost of adaptive nulling to prevent interference from adjacent satellites will be investigated by the contractor. 3. Microprocessor controlling the coherent addition of antenna elements receiving beacon. 4. Alternating uplink/ downlink carrier frequencies from mobile terminals within the assigned 900 MHz or 1.6/1.5 GHz bandwidth would require frequency reuse control similar to the one currently configured in cellular systems (References 86, 87, 88). 5. The contractor will first do a one-year feasibility study for a mobile terminal making use of systems data from References 8, 11, 86, 87, and 88 and additional available systems data. The contractor will design, breadboard, construct and test prototype mobile transceiver units demonstrating produceability, cost, and operation.

Table VII-9. Mobile Communication System Optimization Study at 29 to 19 GHz

Applications:	Mobile systems (land, sea, air) remote land vehicles, aircraft, small boats, public safety, and crime control. This is two-way voice service.
Technology Limits:	Not Applicable.
Opportunities:	System requirements for mobile communication systems at these frequencies have not been optimized considering advanced technology, higher power spaceborne transponders and antennas. The availability required is generally less for mobile systems than fixed systems, so that margins for rain attentuation should be less of a problem. System tradeoff data are needed.
Approach:	NASA and the contractor will postulate service definitions and system requirements imposed by regulations. Cost goals are to be set. The contractor will accomplish tradeoffs considering satellite bandwidths, mobile transceiver bandwidths, random access vs demand access, satellite EIRP and G/T against mobile transceiver requirements and system availability, satellite antenna gain vs number of beams, FDMA vs TDMA, and equipment technology projections. Minimizing service costs to the user is the goal. The contractor will design the optimum mobile terminals and define the optimum satellite transponder antenna concept. Requirements for use in further hardware type development, cost estimates for the terminals, satellite costs and user costs are to be made. The project is estimated to cost \$0.5M and take one year.

Table VII-10. Thin-Line Communication Satellite System Cost Optimization Study at 30 to 20 GHz

Applications:	Special thin-line services (several circuits for voice, data, FAX) for health, education, teleconferencing, data collection, remote site communications. Two-way communications at 56 kbps and television applications should be considered.
Technology Limits:	Not applicable.
Opportunities:	System data is not available for communication satellite systems optimized for costs in the 30/20 GHz frequency band. It will be very important to do optimizations at these frequencies since bandwidths greater than 500 MHz can be made available. Especially important will be the FDMA vs TDMA trades under these conditions. Data on other system trades will also be needed.
Approach:	NASA and the contractor will postulate service definitions and systems requirements imposed by regulations for the services to be studied. Cost goals are to be set. The contractor will accomplish system cost trades such as satellite bandwidth and earth station bandwidth vs cost, FDMA vs TDMA, random access vs demand access, satellite transmit power vs ground station receiver performance, satellite antenna gain and number of beams, transmit power vs sidelobe supression required. Cost to the user is the criteria in these studies. The contractor will design the optimum low-cost earth station concept and the corresponding satellite transponder/antenna concept. He will also define the optimum system requirements for use in a later hardware technology development effort. The user costs, satellite costs, and terminal costs are to be estimated. The project is estimated to cost $0.5M and take one year.

Table VII-11. Mobile Transceivers at 29 to 19 GHz (Prototype)

Applications:	Mobile systems (land, sea, air) remote land vehicles, aircraft, small boats, public safety, land crime control. This is two-way voice service.
Technology Limits:	To be defined in system studies preceding this effort.
Opportunities:	The opportunity is for development of receiver technology and design innovations. Telephone service can be made available to vehicles in remote areas for commercial airline and passengers and small boats. The service is not normally available now. This is an opportunity for the terminal concept to influence communication satellite system transponder and antenna design so that the space link is compatible with low-cost mobile terminals.
Approach:	The approach for low-cost terminals should stress design for manufacturability, inexpensive materials and parts, standardization and modularization. The contractor will design to a unit cost goal using innovative approaches to the terminal and its subsystems. The tasks will include design and test of a breadboard model and the design, fabrication, and test of a prototype NASA low-cost technology mobile 29/19 GHz transceiver and antenna. Resources required are estimated at $4M for a three-year effort.

Table VII-12. NASA Low-Cost Technology, Small, Two-Way 6- to 4-GHz Terminal

Applications:	Special thin-line services (several circuits for voice, data, FAX) for health, education, teleconferencing, data collection, remote site communications.
Technology Limits:	Current state of the art starts at $40,000 per terminal (FOB). Technology limits would be close to material and parts costs (estimated $2-5K).
Opportunities:	The major user of thin-line service (other than experimental users) on the North American continent are the Canadian and Alaskan remote area services provided through ANIK. Low-cost unattended thin-line stations operating with U.S. Domsats at 6/4 GHz should open up additional North American, Central American, and South American users.
Approach:	The principles of low-cost small terminals stress design for manufacturability, small sizes, inexpensive materials and parts, use of microprocessors and chips, standardization(1) and modularization. The contractor will apply low-cost principles and innovative approaches to the terminal and its subsystems. Risk using innovative low-cost technology in terminal subsystems is acceptable. Trading terminal performance for cost is acceptable. The contractor shall estimate cost savings as a part of his proposal and at the end of the development task. The design approach will stress design to the lowest unit cost. The tasks will include design and test of breadboard models (where appropriate) and the design, fabrication, and test (including FDMA satellite link demodulation with a U.S. Domsat) of a prototype NASA low-cost technology, small, two-way, 6/4 GHz terminal. Resources are estimated at $2M; two years.
References:	Ford Aerospace, Rockwell International/Collins (References 83, 35).

(1) With other terminals or ground systems.

Table VII-13. NASA Low-Cost Technology, Small, Two-Way 30- to 20-GHz Terminal (Prototype)

Applications:	Special thin-line services (several circuits for voice, data, FAX) for health, education, teleconferencing, data collection remote site communications. If tradeoffs show it to be economically advantageous, the same terminal subsystems could be adaptable to 56 kbps and television applications.
Technology Limits:	Cost limits would be close to materials and parts costs. Technology limits are to be defined in a system study preceding this effort.
Opportunities:	The opportunity to develop a low-cost terminal in advance of the implementation of high space systems presents itself here. The opportunity would be defined in a system study listed as a separate technology opportunity. It is an opportunity to have the lower cost user equipment (terminals) drive the satellite transponder/antenna design to be compatible. This is especially attractive with the higher satellite weights and larger sizes obtainable with the Space Transportation System. Prospects for a future system at 30/20 GHz are helped by the fact that the space-to-earth and earth-to-space bands available are up to 2.5 GHz wide. At these higher frequencies, the ground terminal antenna diameter can be smaller than at the lower frequencies for equivalent performance.
Approach:	Using ground station characteristics from system studies listed as separate technology opportunities, and applying the principles of low-cost, small terminals stressing design for manufacturability, small size, inexpensive materials and parts, use of microprocessors and chips, standardization and modularization, the contractor will design, develop, and test 30/20 GHz small ground terminals. Innovative approaches to the terminal design and its subsystems are invited if they result in cost reductions. The application of technology opportunities developed in the antenna area, direct modulation and demodulation, frequency translators, and microprocessors are to be applied to the design as appropriate. Two prototype terminals would be produced and tested initially using a transponder and antenna in a high altitude (mountain top or aircraft supported) installation. Three year, $5M project.

NASA satellite or on a multimission commercial satellite venture. The flight of the 30- to 20-GHz transponder/antenna would be used to demonstrate and test the system, using the low-cost ground terminals whose prototypes have been developed from these technology opportunities.

B. GROUND ANTENNA TECHNOLOGY STUDY

1. INTRODUCTION

A wide variety of ground antenna structures have been employed to track and/or communicate with orbiting satellites. Most of these structures belong to one of three general categories, examples of which follow:

- Single Element Structures -- Electromagnetic horns, end-fire yagi's, log periodic dipoles, and helices
- Multielement Arrays -- Crossed dipoles, helices, waveguide slots, disc-on-rods ("cigars"), crossed log periodic dipoles
- Reflector Systems -- Paraboloids (e.g., focal fed, offset, and Cassegrainian), spherical, Gregorian, and "shaped"

The most widely used, of those listed, are the crossed dipole and helical arrays, the front-fed paraboloid, and the Cassegrainian antenna.

Where tracking is a requirement, the antenna structures are generally installed on either an x-y or elevation-over-azimuth type pedestal. Tracking techniques include amplitude monopulse, phase monopulse, conical scan, step track, pseudo-conical scan, program track, and others. For shipboard applications and low orbiting satellites, tracking becomes a formidable problem in that the antenna must not only track the satellite, but also overcome motions associated with the pitch and roll of the ship.

In the case of equatorial synchronous satellites that are used as communication transponders or relay links, tracking in many instances is not required. The antenna structures are usually mounted, or installed, on polar mounts capable of adjustment in both the hour and declination angles. The design of the antenna is generally optimized to (1) provide a good G/T, (2) exhibit a beamwidth that permits nominal satellite drift, and (3) have sidelobes that are suppressed to minimize interference from adjacent satellites.

The following paragraphs address ground antenna technologies associated with synchronous communication-type satellites. The theoretical considerations include the design aspects of earth terminal antennas: Specifically, (1) the performance characteristics of an ideal ground terminal antenna are formulated; (2) antenna gains as a function of half-power beamwidths and aperture efficiencies are examined; and (3) the present requirements of sidelobe characteristics are reviewed. Surface accuracy requirements of a reflector-type antenna are reviewed, and comments on fabrication technology are given. Studies that NASA might fund to enhance technology are recommended. Calls and visits were made during the period in which the following information was researched for this document. A list of the contacts made appear at the end of this chapter.

2. THEORETICAL CONSIDERATIONS

a. RF Performance of Ideal Antenna

The ideal RF performance requirements for an earth station antenna are high gain, zero pointing loss, and zero sidelobes.

The ideal radiation pattern dictated by these requirements would exhibit uniform response over a small angular cone. For nontracking systems, the cone angle would be large enough to account for satellite drift. The plot of the response through the antenna beam in rectangular coordinates would appear as a square wave pulse. It can be shown analytically that a rectangular pulse-shaped radiation pattern requires an antenna aperture that is infinitely large. With an aperture of finite size, these ideal requirements can only be approximated. The gain of the antenna is maximized in the direction of the satellite and minimized elsewhere. The aperture is sized to provide the desired gain consistent with a given pointing loss and sidelobe criteria.

Special note is made of the fact that for nontracking earth antennas in the 20- to 30-GHz region, where high-gain antennas are manageable, the utilization efficiency of the geostationary satellites is highly dependent on the allowable satellite drift. The smaller the satellite drift, the higher the gain that can be specified for the earth station antenna.

b. Typical RF Performance vs Aperture Size

The relationships between antenna gains and aperture diameters are shown in Figure VII-4 for aperture efficiencies of 100, 70, and 55 percent. Corresponding half-power beamwidths for gains ranging from 24 to 58 dBi are plotted in Figure VII-5. These beamwidths are typical of those that would be achieved with a paraboloidal reflector exhibiting an aperture efficiency of 55 percent. Sidelobe levels for the typical -10-dB edge illumination taper would be approximately -18 to 22 dB, depending upon aperture blockage, surface accuracy, strut blockage, and other factors. A more detailed discussion of sidelobes is presented in the following paragraph.

c. Sidelobe Suppression Requirements

Present Rules and Regulations (25.209) of the Federal Communication Commission (FCC) states (Ref. 26):

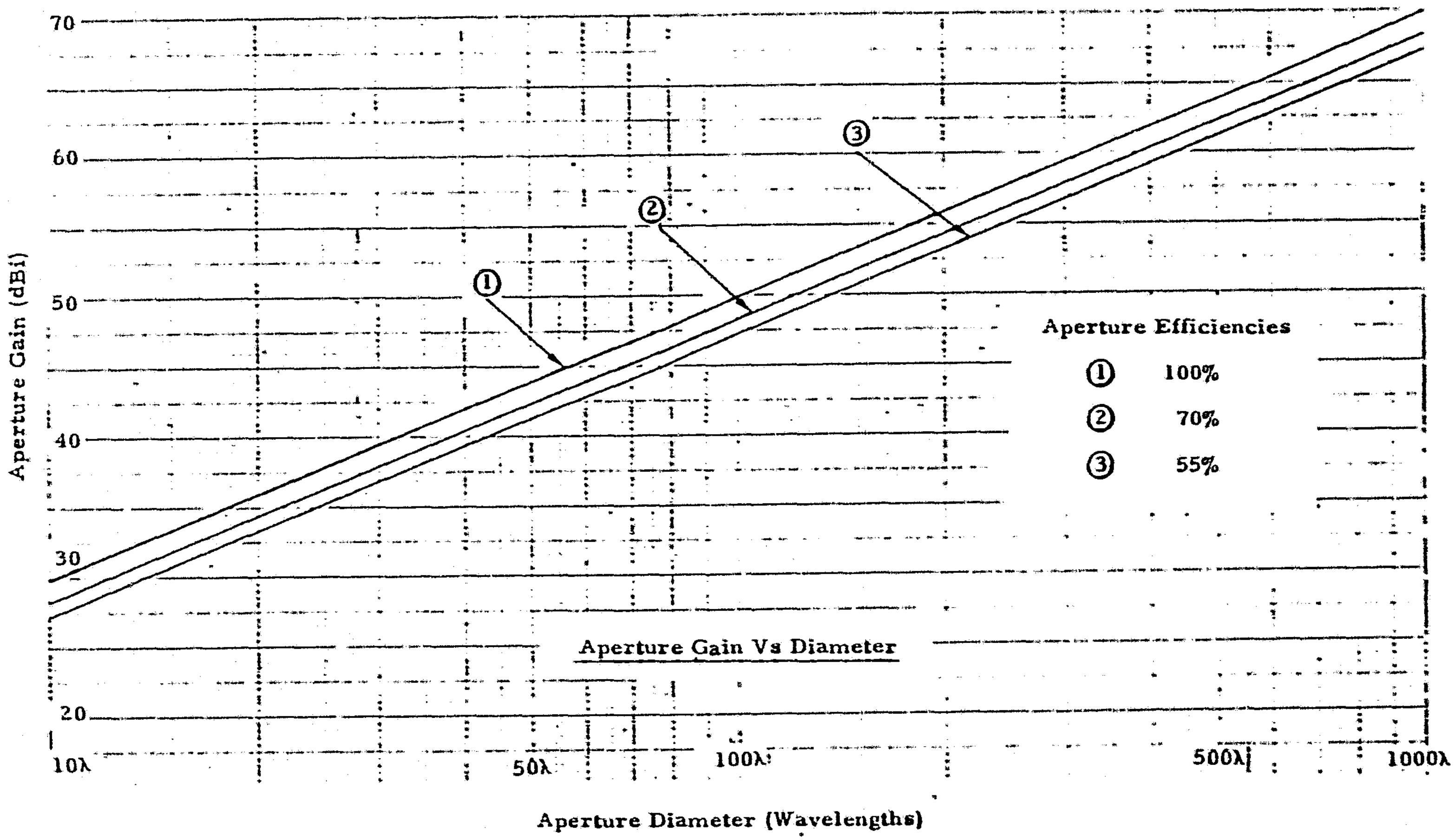


Figure VII-4. Antenna Gain vs Aperture Diameter

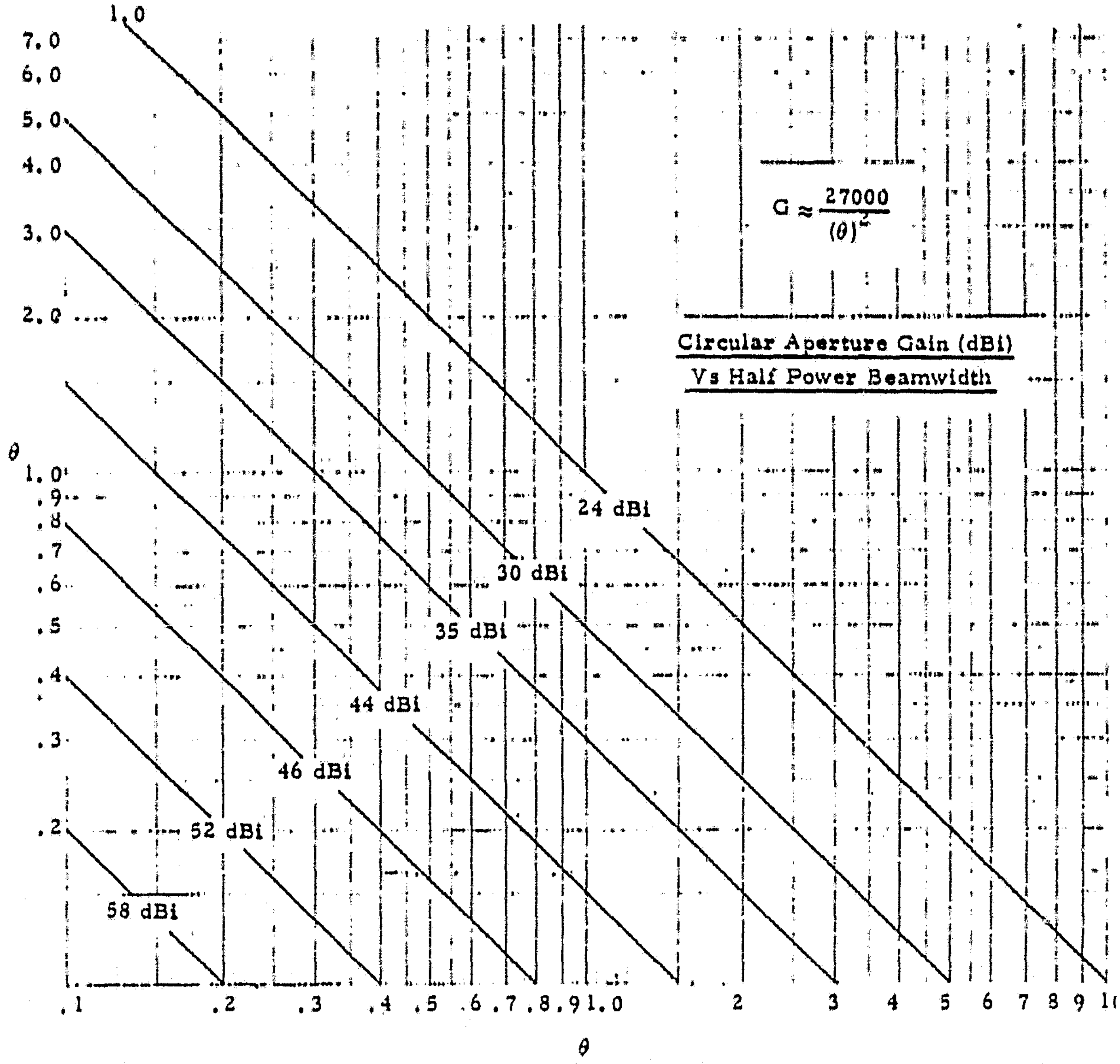


Figure VII-5. Circular Aperture Gain vs Half-Power Beamwidth

Any antenna to be employed in transmission at an earth station in the Communication-Satellite Service shall conform to the following standard:

Outside the main beam, the gain of the antenna shall lie below the envelope defined by:

$$32-25 \log_{10} (\theta) \text{ dBi} \quad 1^\circ \leq \theta \leq 48^\circ$$

$$-10 \qquad \text{dBi } 48^\circ < \theta \leq 180^\circ$$

where θ is the angle in degrees from the axis of the main lobe, and dBi refers to dB relative to an isotropic radiator. For the purposes of this section, the peak gain of an individual sidelobe may be reduced by averaging its peak level with the peaks of the nearest sidelobes on either side, or with the peaks of two nearest sidelobes on either side, provided that the level of no individual sidelobe exceeds the gain envelope given above by more than 6 dB.

The above FCC requirement for sidelobe suppression is plotted in Figure VII-6. The Consultative Committee on International Radio (CCIR) (Ref. 27) recommends (Recommendation 465-1) that this figure be used as the criteria in the frequency range from 2 to 10 GHz, where the antenna diameter to wavelength ration D/λ exceeds 100. It is also suggested that the figure could be provisionally adoped for the frequency range of 10 to 30 GHz. In the case of apertures, less than 100 wavelengths in diameter, CCIR recommends that the formulae

$$G = 52-10 \log_{10} (D/\lambda) -25 \log \theta \text{ dB} \tag{1}$$

be used rather than $32-25 \log_{10}\theta$.

The principal reasons for sidelobe suppression are to minimize interference from (1) adjacent satellites and (2) nearby earth stations operating at the same frequency. Most important is the discrimination against interference from satellites. In most instances, adjacent earth terminals can be appropriately located to provide adequate isolation. This is particularly true in the case of large-aperture high-gain terminals. For small aperture terminals, if adequate isolation cannot be achieved by proper location, it can probably be improved to an acceptable value through the use of judiciously placed microwave absorber material.

3. SURFACE ACCURACY

Theoretical analyses of random deviation in the surface of a paraboloid have been treated extensively by Ruze (Refs. 28 and 29). In Ruze's analyses, he assumes a positionally dependent phase error across the aperture. It is

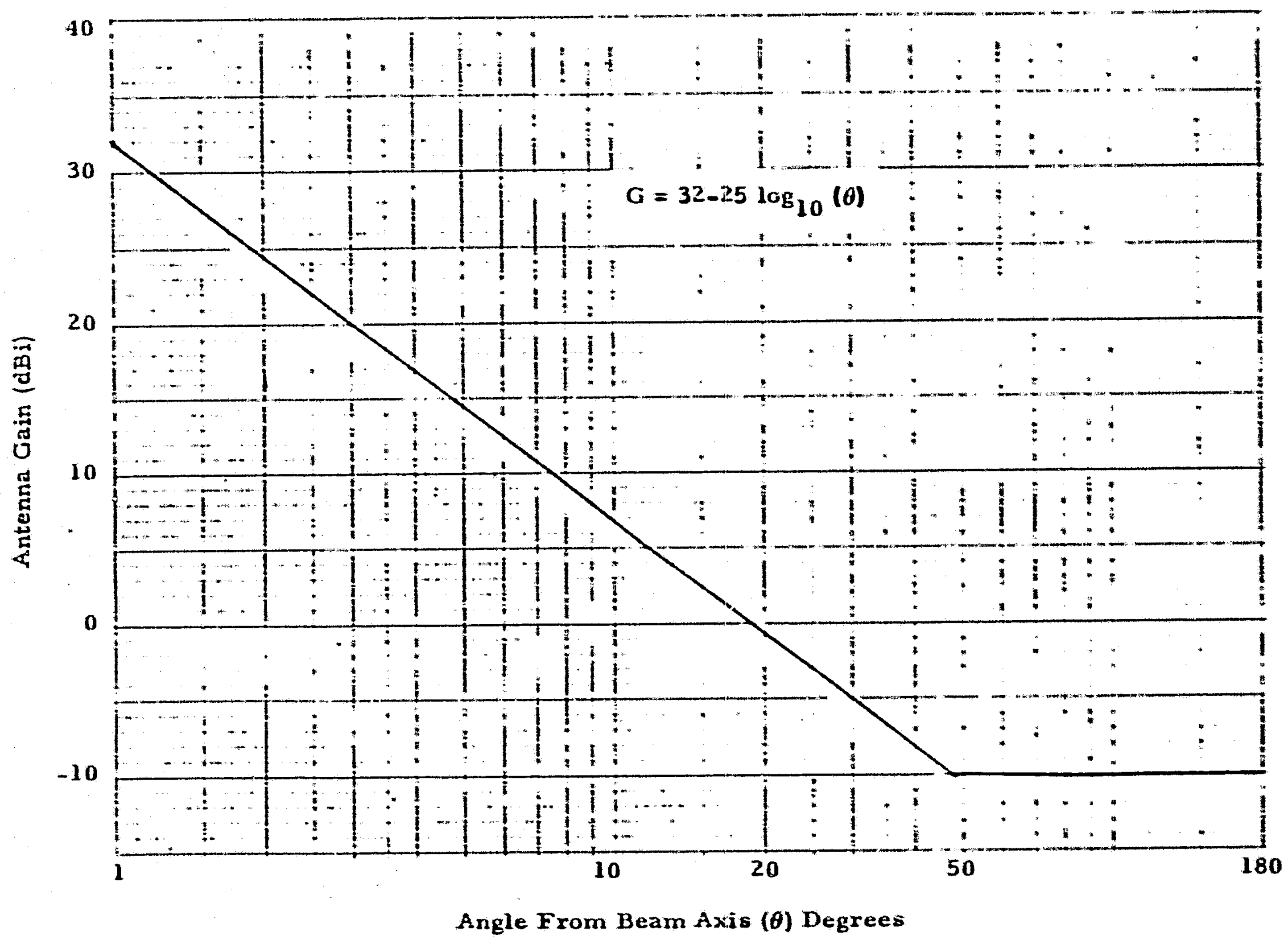


Figure VII-6. Sidelobe Suppression Requirement for $1^{\circ} < \theta \leq 180^{\circ}$

reasoned that in a reflector-type antenna, if there is a deviation, or error, resulting from tolerances at one position in the reflector, one could expect that in the immediate vicinity of that point there would exist other errors in the same direction. Ruze addresses this phenomenom by defining a correlation interval c as the distance on the average that the errors become essentially independent.

Doidge (Ref. 30), utilizing Ruze's work, presents the following simplified solutions for relatively flat parabolas:

$$c/\lambda \ll 1 \quad \eta = 1 - 12\pi^4 (c\lambda)^2 \sigma^2 \tag{2}$$

$$c/\lambda \ll 1 \quad \eta = \exp\left[-\frac{16\pi^2\sigma^2}{\lambda^2}\right] \tag{3}$$

where

η = surface efficiency

c = correlation interval

σ = rms surface deviation

λ = wavelength

Equation (3) is ordinarily used to predict gain loss. The reasons for this are that it (1) is the worst case, (2) agrees closely with assumptions made by Ruze, and (3) closely satisfies the conditions that exist in practice. The rms loss based on Equation (3) was computed as a function of rms error in wavelengths. The results are shown in Figure VII-7.

In the case of a Cassegrainian or dual reflector antenna, the surface tolerances of both surfaces must be included in the analysis. The total surface efficiency η_T is the product of the two separate efficiencies, namely:

$$\eta_T = \exp\left[\frac{-16\pi^2}{\lambda^2}\left(\sigma_1^2 + \sigma_2^2\right)\right] \tag{4}$$

where

σ_1 = rms surface deviation of main reflector

σ_2 = rms surface deviation of sub-reflector

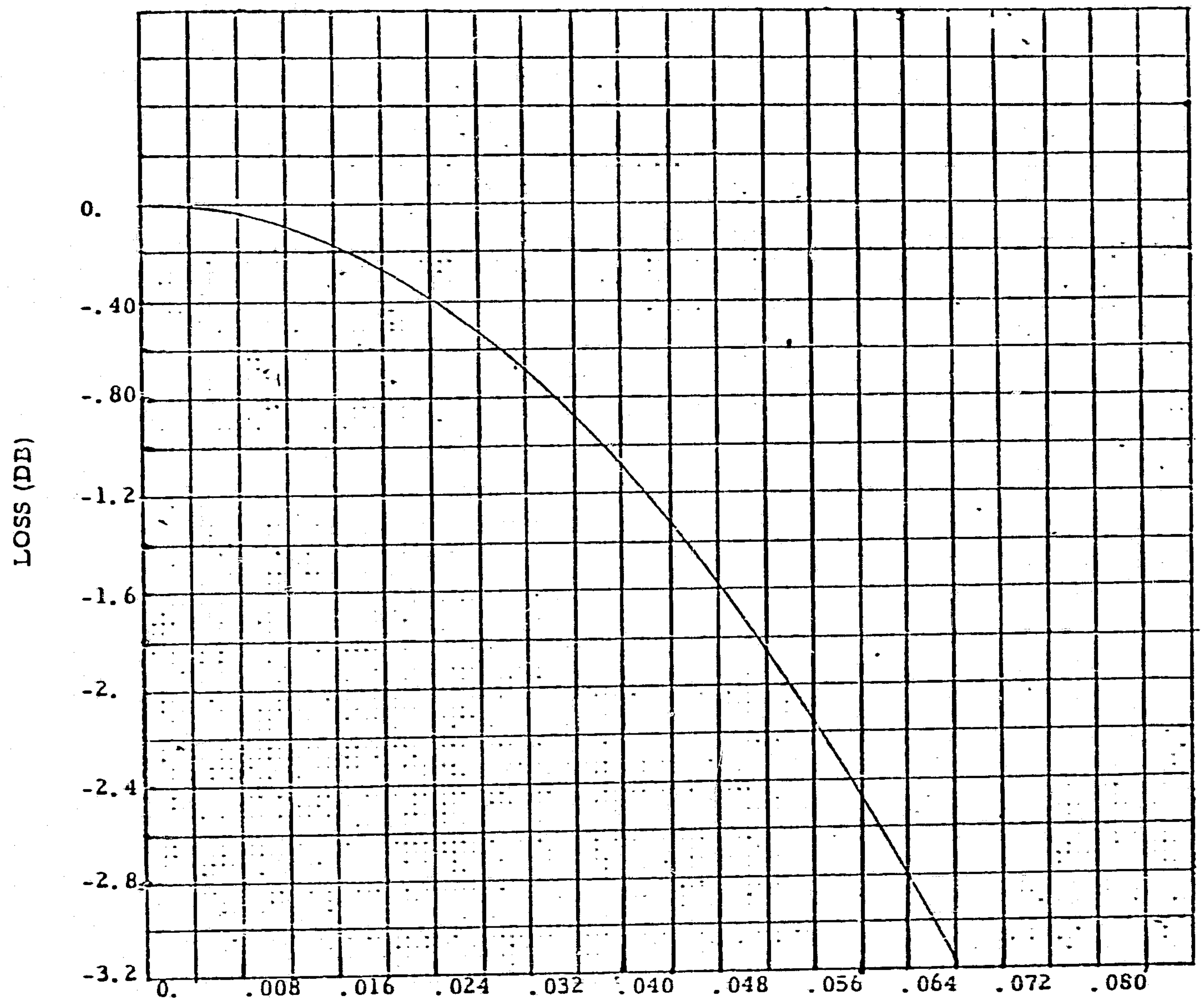


Figure VII-7. Gain Loss vs RMS Surface Error

4. REFLECTOR FABRICATION TECHNIQUES

Most reflectors belong to one of the following categories:

- Spun aluminum
- Mesh
- Fiberglas
- Metallic surface reflector with truss backup structure
- Graphite composite

The manufacturing method chosen is primarily dictated by the required rms and specified wind environment. Brief comments on each of these follow in the same order. (Funding by NASA to fabrication techniques does not seem warranted at this time. The appropriate technology appears to be in existence. It is only a question of choosing the manufacturing process to match the production requirements.)

a. Spun Aluminum

Aluminum spinning is the process by which a flat sheet of aluminum is rotated with and rolled against a male mold. A rolled edge is usually provided at the periphery of the reflector to improve its structural integrity. The technique is particularly applicable for low-cost ground terminals, particularly in the small X-band, Ku-band, and perhaps in the 20- to 30-GHz region. An rms surface accuracy of 0.020 is readily achievable in diameters of up to about 8 ft. In the case of 6-ft-diam reflectors, rms values of 0.010 can be obtained. It is noted that at 20 and 30 GHz, 6-ft-diam reflectors have respective gains of 49 and 52.5 dBi (Figure VII-4). The half-power beamwidths for an aperture efficiency of 55 percent are 0.4 and 0.6, deg, respectively (Figure VII-5).

b. Mesh

The mesh reflector is fabricated by forming mesh over a mold and attaching it to a series of concentric tubular rings that are welded to a backup support structure. In ground antennas, mesh-type reflectors have not found much use above 4 or 5 GHz. Mesh reflectors, 33 ft in diameter, have been fabricated, in quantity, and have exhibited rms values of less than 0.060. The 0.060 was static and a manufacturing error. It did not include dynamic errors attributed to wind, gravity, acceleration, or other factors.

c. Fiberglas

Fiberglas reflector surfaces with an imbedded metallic screen have been used in a variety of antennas. In large structures, the surface is usually backed up with a honeycomb sandwich. In small reflectors, the fiberglass itself is made thick enough to be self-supporting. For large quantity, small, low-cost ground terminals, Fiberglas is considered a viable contender.

d. Metallic Surface Reflectors with Truss Backup Structure

These types of reflectors are widely used in industry. As a rule, the main support consists of a central cylindrical hub. Radial trusses extend outward from the hub to the periphery. Reflector pie-shaped panels are attached to the trusses. The panels are usually fabricated using slotted channels in conjunction with crossed tubular supports. The skin itself may be stretched, formed, or segmented. The number of panels used is a function of the required rms. Thirty-two-foot diameter reflectors (with 24 panels) have been fabricated with rms surface accuracies of less than 0.030. Tolerances between 0.010 and 0.020 are possible for reflectors smaller than 20 ft in diameter.

e. Graphite Composite

Graphic composite technology has advanced significantly during the past 10 years. Although the process is costly compared to many other methods of fabrication, it is expected to be competitive in the 20- to 30-GHz region. Based on telephone discussions with General Dynamics, it appears that sealing problems exist for an outdoor environment but that this problem is 80 percent solved and will be solved totally within the next five years.

According to John Fager (Ref. 31), uncoated graphite will perform similarly to copper, up to the K-band range. At frequencies above K-band, a vapor deposition of aluminum or other high-conductance metallic film is needed to prevent gain degradation.

According to Dennis Dunbar, in 1980 graphite epoxy sheets (before stamping) will be about $30/lb.

General Dynamics has built and measured the rms of an 8-ft-diam solid graphite reflector for operation to 200 GHz. The rms surface accuracy is reported to be 0.00212 in.

If the results of a NASA-funded sidelobe suppression study indicated that the present rms values, required to achieve tolerable gain losses, were totally unacceptable for low sidelobe performance, then graphite composite reflectors may be the answer.

5. TECHNOLOGY AREAS NEEDING DEVELOPMENT

In the course of the investigation of low-cost ground terminals, three areas have been identified that require advancement in technology:

- Adaptive ground antennas
- Mobile antennas
- Sidelobe suppression techniques

Of those listed, the advancement of sidelobe suppression techniques is considered the one deserving the most emphasis by NASA. The rationale for this is that considerable studies have been and will be pursued with regard to satellite adaptive nulling techniques. Much of the information gained from these studies will be directly applicable to ground antennas. The mobile antenna effort should await future studies that define specific scenarios for mobile stations.

Although the advancement of sidelobe suppression is most highly recommended for NASA funding, comments on each are presented in the following paragraphs.

a. Adaptive Ground Terminal

Airborne Instruments Laboratory (AIL), a division of Cutler-Hammer, identified ground antenna adaptive nulling as a potential candidate for funding, particularly in the millimeter wave area. Although adaptive nulling has considerable merit, it is somewhat incongruous with the present ground rule concept of low-cost ground terminals.

It is hoped that adequate sidelobe discrimination can be obtained by standard design techniques to provide the required discrimination at these higher frequencies. For example, at 30 GHz, a small 6-ft-diam reflector has a gain and half-power beamwidth of approximately 53 dBi and 0.36 deg, respectively. Figure VII-8 is a computed radiation pattern of such an antenna. In a direction 1.5 deg from the axis of the beam lies the peak of the fourth sidelobe. The relative level of energy from this sidelobe is -37 dB, relative to beam maximum or approximately 16 dBi. This relatively high gain easily satisfies the 32 to 25 log requirement in this direction. Satellites closer than 1.5 deg are not anticipated in the near future.

b. Mobile Antenna

The higher the frequency, the better it is for the mobile antenna designer. For trailer-type portable terminals, satisfactory technology is considered in existence. In the case of automobiles or vans, the antenna would be located on the roof of the vehicle. For shipboard application, the antenna should be located to facilitate the maximum field of view. With aircraft, the optimum location is the top of the fuselage.

The following observations are made with regard to the mobile antenna. In the comments that follow, it is assumed that the trailer-mounted, erectable antenna terminal is in effect a fixed terminal rather than a mobile one. The antennas for such a terminal can be rather large erectable types, in that they are not space-limited:

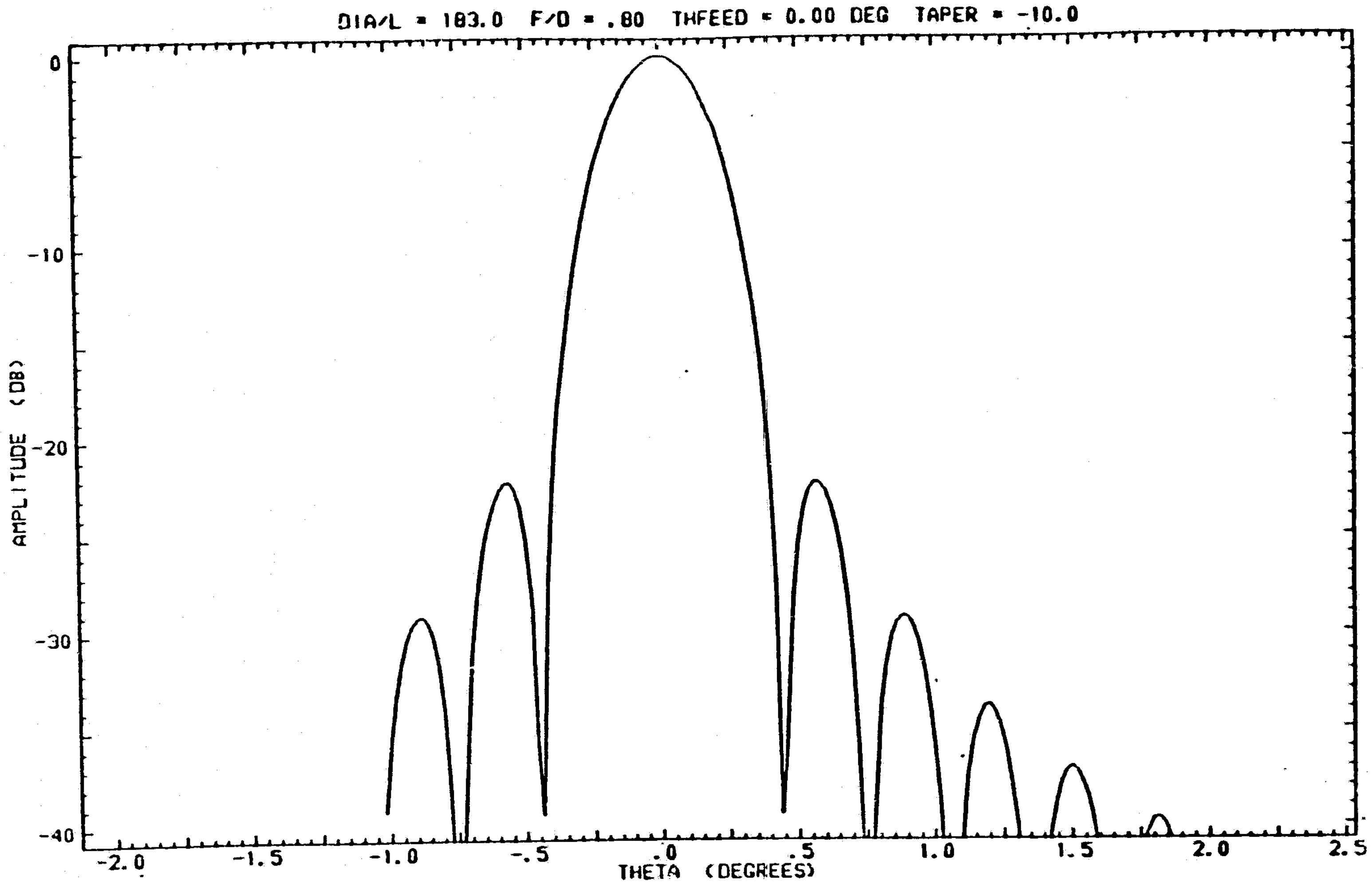


Figure VII-8. Radiation Pattern of a Paraboloid, 6 ft in Diameter at 30 GHz

- Antennas with omnidirectional, spherical-type coverage have problems with reflections from their surrounding environment. For installations on top of an aircraft fuselage, such coverage might find use for a receive-only system.
- If one wishes to optimize the limited physical space available, the 20- to 30-GHz region appears to be a good frequency.
- Two (of many) conceivable choices for the antennas are (1) paraboloids and (2) arrays.

  In the case of paraboloids, the available space probably limits the diameters to 2 or 3 ft maximum. With these sizes, some means of enhancing sidelobe suppression are needed to minimize interference with adjacent satellites. Some of this technology will come from the recommended sidelobe suppression study. In some instances, it may prove feasible to array 3 or 4 small paraboloids and perhaps monopulse track the satellite.

  In the case of planar or conformal arrays, the technology is in existence. For beams electronically scanned far from the normal axis of the array, some type of adaptive nulling may be required in the direction of other satellites. It is believed that any premature development would have to be redone if the frequency, gain, sidelobe requirement, or operational scenario were to change.

c. <u>Sidelobe Suppression Technology</u>

Several companies, including Aerospace, have identified the need for advancement of sidelobe suppression technology. Accordingly, it is recommended that NASA sponsor research to improve antenna sidelobe performance by at least 5 dB below that required by $32-25 \log_{10}(\theta)$, as shown in Figure VII-6.

For aperture antennas of many wavelengths, there are no theoretical limits with regard to sidelobe suppression. An amplitude distribution can be calculated to provide any desired sidelobe level, assuming the aperture is equiphase. For a given aperture diameter, sidelobe suppression is at the expense of beam broadening and gain loss.

From a practical viewpoint, however, many factors influence the achievable sidelobe performance. In the case of paraboloids, these can be grouped as follows:

- Feed phase characteristics
- Feed amplitude taper

- Reflector surface accuracy
- Edge diffraction at the periphery of the reflector
- Edge diffraction at the periphery of the subreflector in the case of a Cassegrain antenna
- Primary feed blockage
- Primary feed spillover
- Secondary blockage
- Multiple reflections and/or diffraction from feed and support structure

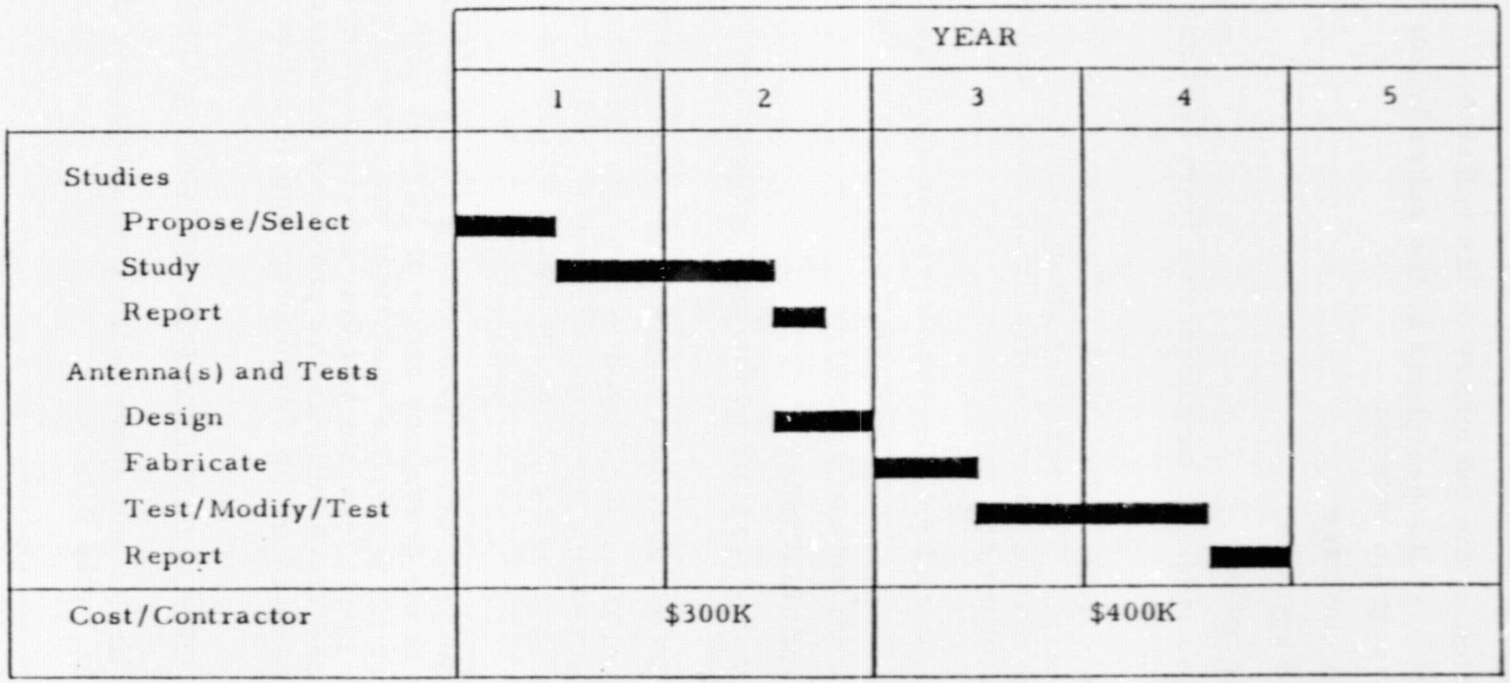
An investigation should include detailed analyses as well as developmental experimental tests. The analyses should address all factors influencing reflector performance, particularly those cited, and should answer questions such as the following:

- What is the effect of rms surface error on sidelobe level?
- Is it possible to shape the reflector to account for the measured phase response of a feed?
- What is the optimum taper?
- Is pattern shaping feasible at the high frequencies to minimize pointing loss?
- What is the lowest practical sidelobe level achievable?
- If an increased taper were used to improve sidelobes at the expense of decreasing aperture efficiency, could the gain be increased by increasing the overall size without increasing sidelobes?

The experimental program envisioned would involve building two different type models in the frequency range of 20 to 30 GHz. The model would be used to either (1) verify the analytical tools developed or (2) demonstrate that analysis is not feasible and that development must be pursued experimentally. Figure VII-9 outlines the projected schedule. The projected program is presented in the Technology Opportunities section (Table VII-14).

6. TECHNOLOGY OPPORTUNITIES FOR GROUND ANTENNAS

The technology limits and opportunities for advancing the state of the art are summarized in Table VII-14.



3 to 5-Year Program

Figure VII-9. Low Sidelobe Antenna Technology Two Contractors

Table VII-14. Advancement of Low Sidelobe Antenna Technology

Application: Small and large earth station antenna installations. Techniques are also applicable to space antennas. Emphasis is on small antennas for low-cost terminals.

Technology Limits: Industry is finding it extremely difficult to satisfy present FCC requirement of 32-25 log θ. Theoretical limit is no sidelobes.

Approach: Decide on frequency band(s) and beam widths of interest. Investigate analytically the parameters affecting sidelobes, and methods of reducing them. Verify analytical designs experimentally by building and testing one or more small terminal antennas which can be replicable, $1.5M for two concepts, 2 to 4 year program.

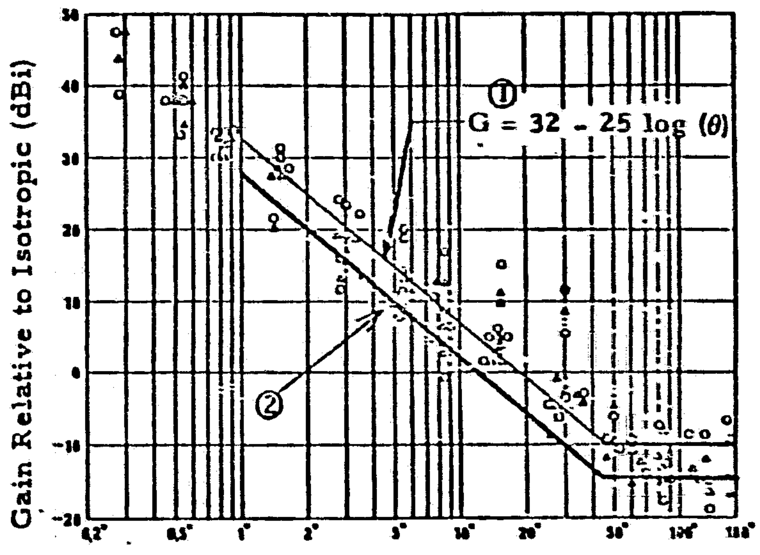
References: C.C.I.R. XIIIth Plenary Assembly, Geneva, 1974, Volume IV, Ford Aerospace Visit Report.

Opportunities:

1. Primary focus feed concept
2. Offset feed concept
3. Conventional
4. Offset Cassegrain feed concept(1)

Concepts with minimum sidelobe design features for each of the 4 types. Low sidelobes needed to reduce interference between single or multiple beam adjacent satellites.

(1) If multiple beams on ground station are of interest.



DATA FROM SOME LARGE EARTH ANTENNAS AT 4 AND 6 GHz
Δ: 4 GHz, o: 6 GHz

1 Existing requirement per FCC regulations, paragraph 25.209.

2 Projected achievement with NASA funding for apertures >100 λ

ORGANIZATIONS/PERSONS CONTACTED
FOR CHAPTER VII

Anslie Corporation (Braintree, MA); E. Sandquist.

American Satellite Corporation (Germantown, MD); G. Cacciamani and R. French.

American Satellite Corporation (Los Angeles, CA); R. Mason.

Andrew California Corporation (Claremont, CA); T. Glab.

California Microwave, Inc. (Sunnyvale, CA); G. J. Watts.

Communications Research Center, Department of Communications (Ottawa, Ontario, Canada); W. T. Kerr.

Communications Satellite Corporation (Washington, DC); R. Barthle and D. Lipke.

Communications Satellite Corporation, Comsat Laboratories (Clarksburg, MD); G. Welti.

Comtech Laboratories, Inc. (Smithtown, NY); D. Bond.

Datron Systems (Chatsworth, CA); N. Hannon.

Diamond Antenna and Microwave Corporation (Winchester, MA); A. Anderson.

Electronic Space Systems Corporation (ESSCO) (Concord, MA); S. L. Hensel, Jr.

Fairchild Space and Electronics Company (Germantown, MD); N. Edwards, S. Miller, and J. Weiss.

Ford Aerospace and Communications Corporation, Western Development Laboratories Division (Palo Alto, CA); C. L. Cuccia, H. K. Berland, C. Hellman, D. Ford, and A. Wichert.

General Dynamics, Convair Division (San Diego, CA); R. Abramoff, J. Fager, J. Fisher, R. Henry, R. Stubblefield, and S. Minner.

ORGANIZATIONS/PERSONS CONTACTED FOR CHAPTER VII (continued)

Harris Corporation, Electronic Systems Division, Electro-Optics Department (Melbourne, FL); H. E. Bartlett, W. McCaslin, and B. C. Tankersley.

Hughes Aircraft Company, Space and Communications Group (Los Angeles, CA); F. Utrecht and P. McShaine.

ITT/DSE (Nutley, NJ); E. M. Bradburd.

Lincoln Laboratory, Massachusetts Institute of Technology (Lexington, MA); D. J. Frediani and C. W. Niessen.

LNR Communications Inc. (Hauppauge, NY); F. Arams and C. E. Salamone.

Lockheed Missiles and Space Company, Inc. (Sunnyvale, CA); G. Chadwick.

Magnavox, Government & Industrial Electronics Co., Advanced Products Division (Torrance, CA); J. Hoerber.

MELCO U.S.A., Inc. (Mitsubishi Electric) (Compton, CA); M. Nomura.

Motorola Government Electronics Division (Scottsdale, AZ); K. Porter.

Motorola (Scaumburg, IL); M. Cooper, R. Hays, and J. Mikulski.

NASA, Goddard Space Flight Center (Greenbelt, MD); J. Chitwood and J. Marishek.

NASA Headquarters (Washington, DC); S. Hubbard.

NASA Lewis Research Center (Cleveland, OH); P. L. Donoughe and D. L. Wright.

The Rand Corporation (Santa Monica, CA); N. Feldman.

RCA America Communications, Inc. (Los Angeles, CA); S. Smart.

RCA American Communications, Inc., Kingsbridge Campus (Piscataway, NJ); J. Boning, J. Redman, and B. Ralph.

RCA American Communications, Inc. (New York, NY); L. G. Donato and B. Louie.

RCA, Government Systems Division, Western Region Office (Los Angeles, CA); S. Jacks.

ORGANIZATIONS/PERSONS CONTACTED FOR CHAPTER VII (continued)

RCA Laboratories, David Sarnoff Research Center (Princeton, NJ); J. Clark, F. Sterzer, H. Staras, and K. Power.

Rockwell International, Collins Transmission Systems Division, Commercial Telecommunications Group (Dallas, TX); D. Snodgrass.

Rockwell International, Space Division (Downey, CA); G. G. Freeman.

Satellite Transmission Systems, Inc. (Hauppauge, NY); D. Hershberg.

Scientific-Atlanta, Inc. (Atlanta, GA); T. J. Kelly and K. F. Leddick.

SPAR Technology Limited, Division of SPAR Aerospace Products, Ltd. (Montreal, Quebec, Canada); C. H. Wicks.

TRW Defense and Space Systems Group (Redondo Beach, CA); J. Lewis, H. Raymond, and W. White.

Western Union Corporation (Upper Saddle River, NJ); J. Aconis, G. Frank, G. Milne, J. Ramasastry, and W. Heiser.

Western Union Corporation (Los Angeles, CA); R. Hess, J. Metzler, and H. Slobodian.

Westinghouse Defense and Electronic Systems Center (Baltimore, MD); M. Lorenzo.

Westinghouse Electric Corporation (Annapolis, MD); M. Geller and H. Nunnally.

Whittaker, Trasker Systems Division (Chatsworth, CA); J. Marlowe.

REFERENCES FOR CHAPTER VII

1. Federal Research and Development for Satellite Communications, Davenport Report of the Committee on Satellite Communications of the Space Applications Board, Assembly of Engineering, National Research Council. National Academy of Sciences, Washington, DC (1977).

2. H. L. Van Trees, E. V. Hoversten, and T. P. McGarty, Communications Satellites, Projections for 1980s, Communications Satellite Corporation, Washington, DC (1976).

3. J. Rainasastry, W. Heiser, E. Levine, R. Markham, "Western Union's Satellite - Switched TDMA Advanced Westar System," AIAA Paper No. 78-602, Seventh Communications Satellite Systems Conference, April 1978.

4. Executive Summary SBS, Hughes Aircraft Company, Culver City, CA (22 February 1978).

5. "IBM Reaches for a Golden Future in the Heavens," Fortune (September 1977).

6. "Small Aperture Terminals Offer New Communications Possibilities," Communication News (February 1978).

7. "Holiday Inns Go Satellite," Satellite Communications (April 1978).

8. "Satellite Networks," RCA American Communications (Received May 1978).

9. California Microwave, Inc., Sunnyvale, CA, Data package (21 April 1978).

10. SPAR Aerospace Products, Ltd., Montreal, Quebec, Data package.

11. Scientific Atlanta, Inc., Atlanta, Georgia, Data package.

12. Mobile Multiple Access Study Final Report, TRW, Cleveland, OH (16 August 1977) (NASA GSFC Contract NAS5-23454).

13. H. L. Van Trees and T. P. McGarty, A Domestic Mobile Satellite Communication System, Preliminary Report, Communications Satellite Corporation, Washington, DC (February 1977).

14. W. L. Morgan, "Space Stations," Satellite Communications (April 1978).

15. D. H. Staelin, "Broadband Communications Satellites" (3 April 1978).

16. D. H. Staelin, "Communications Satellites Wideband Switched Network" (3 February 1978).

17. 20/30 GHz Satellite Communications System Study Program Final Report, WDL-TR-7499, Ford Aerospace and Communications Corporation, Dearborn, MI (29 April 1977) (Nondisclosure and restricted use).

18. "20/30 GHz Utilization for DSCS," Briefing chart.

19. "Satellite Switched TDMA Space Experiment at 20/30 GHz," Briefing chart presented at TRW, January 1977.

20. "Advanced 30/20 GHz SSTDMA Milsatcom System," Briefing chart presented at TRW, January 1977.

21. "20/30 GHz Milsatcom Candidate System Architecture," Briefing chart presented at TRW.

22. DSCS-II Attitude Control and Narrow Beam Antenna Pointing Control, Sections 1 and 2.

23. C. L. Cuccia, "The Technology Base for 20/30 GHz Earth Terminals," Vol 6, Millimeter Wave Spacecraft Technology, Ford Aerospace/RDP G-635, PAAB, Ford Aerospace and Communications Corporation, Dearborn, MI (27 January 1976) (Proprietary).

24. R. G. Gould and Y. F. Lum, Communications Satellite Systems, An Overview of the Technology, IEEE Press, New York (1975).

25. Satellite Transmission Systems, Inc., New York, Data package.

26. "Satellite Communications," Rules and Regulations, Part 25, Federal Communications Commission, Washington, DC (March 1974).

27. "Fixed Service Using Communication Satellites," CCIR Thirteenth Plenary Assembly, Vol IV, International Telecommunication Union (1974).

28. J. Ruze, Physical Limitations on Antennas, Technical Report No. 248, Electronics Research Laboratory, Massachusetts Institute of Technology, Cambridge, MA.

REFERENCES FOR CHAPTER VII (continued)

29. J. Ruze, "The Effect of Aperture Errors on the Antenna Radiation Pattern," NUOVO Cumento Supplement, Vol 9 (1952), pp 364-380.

30. F. G. Doidge, "Antenna Gain As It Applies to Satellite Communication Earth Stations," Paper presented at the United States Seminar on Communications Satellite Earth Station Technology, Washington, DC, 1966.

31. J. A. Fager, "Application of Graphite Composites to Future Spacecraft Antennas," Paper 76-238 presented at the AIAA/CASI Sixth Communications Satellite Systems Conference, Montreal, Canada, April 5-8, 1976.

BIBLIOGRAPHY FOR CHAPTER VII

18/30 GHz Fixed Communications System Service Demand Assessment, NASA Lewis RFP 3-834505, National Aeronautics and Space Administration, Lewis Research Center, Cleveland, OH (1977).

18/30 GHz Fixed Service Satellite Communications System Study, NASA Lewis RFP 3-824766, National Aeronautics and Space Administration, Lewis Research Center, Cleveland, OH (1977).

Andrew California Corp., Claremont, CA, Data package.

Arams, F. R., and P. Lombardo, Recent Developments in C-Band and Ku-Band Satcom Receivers, LNR Communications, Inc., Hauppauge, NY.

Audiosat Developmental Test Report, Western Union Corp., Mahwah, NJ (15 July 1977).

Brenner, A. S., "Cellular Systems for Mobile Operations," Motorola, Inc., Communications International Division, Chicago, IL.

Briskman, R. D., "The COMSTAR Program," Comsat Technical Review (Spring 1977).

"Broadcast Networks Turn to Satellite Distribution," Communications News (February 1978).

Canada, Government of, Information package containing brief resumes of Canadian Hermes (CTS) Experiments, list of Canadian experimenters, November 1977

Chitwood, J., Advanced Ground Receiving Equipment Experiment (AGREE), National Aeronautics and Space Administration, Goddard Space Flight Center, Greenbelt, MD.

Communication System Technology Assessment, NAS 3-2364, Fairchild Camera and Instrument Corp., Mountain View, CA (1977).

Communications Systems Technology Assessment Study, Final Report (Draft), Task VII, Fairchild Camera and Instrument Corp., Mountain View, CA (March 1978)(Contract No. NAS 3-20363).

Communications Systems Technology Assessment Study, Final Report (Draft), Vol. VI, Fairchild Camera and Instrument Corp., Mountain View, CA (March 1978)(Contract No. NAS 3-20363).

"Communications Technology Satellite," CTS 3100-27, National Aeronautics and Space Administration, Lewis Research Center, Cleveland, OH.

"Communications Technology Satellite (CTS) Transportable Emergency Terminal Experiment," Briefing charts.

"Comparison of Circuit Call Capacity of Demand-Assignment and Preassignment Operation."

Comtech, Data package.

Cuccia, C. L. (Ford Aerospace), "Japan Bids for Leadership in Space Communications," Microwave Sys. News (March 1978).

"The Development of a Prototype Low Noise and Low Cost (Mass Producible) 12 GHz FM Receiver for Television Reception from Broadcasting Satellites," Statement of Work, National Aeronautics and Space Administration, Goddard Space Flight Center, Greenbelt, MD.

Donoughe, P. L., "U.S. Experiment Principal Investigators," National Aeronautics and Space Administration, Lewis Research Center, Cleveland, OH, 3 pp.

Donoughe, P. L., and H. R. Hunczak, "CTS (HERMES) - United States Experiments and Operations Summary," NASA Technical Memorandum, NASA TM-73830, National Aeronautics and Space Administration, Lewis Research Center, Technical Paper presented at Symposium on HERMES, 29 November - 1 December 1977.

Durrani, Sajjad H., "Network Architecture," Memo for the Record, 13 February 1978.

Electronic Space Systems Corp., Concord, MA, Data package.

Fairchild Camera and Instrument Corp., Mountain View, CA, Data package.

Final Report, Technology Requirements for Post-1985 Communications Satellites, NASA CR-114680, Lockheed Missiles and Space Company, Sunnyvale, CA (October 1973).

"GaAs FETs Market and Technology Review," Microwave J. (February 1978).

Gould, R. G., and Y. F. Lum, Communications Satellite Systems, An Overview of the Technology, IEEE Press, New York (1975).

"Japan Expands Technology Program," Aviation Week (October 17, 1977).

Kelley, R. L., Low Cost Ku Band Earth Terminals for Voice/Data/Facsimile, Fairchild Camera and Instrument Corp., Mountain View, CA.

Kelly, A. J., C. Okean, and S. J. Foti, "Low Noise Microwave and Millimeter Wave Integrated Circuit Mixers," LNR Communications, Inc., Hauppauge, NY.

Konishi, Y. (NHK), "12 GHz FM Broadcast Satellite Receiver," Microwave J. (January 1978).

Lebow, I. L., K. L. Jordan, and P. R. Dronilhet, "Satellite Communications to Mobile Platforms," Proc. IEEE (February 1971).

LES-8/9 Ground Terminal Information

Linker, D. M., and L. Lazarus, "Specifying 4.5 Meter Satellite Earth Station Hardware for Domsat and CATV Application," LNR Communications, Inc.; also, Communications News (April 1977).

Lippe, D. W., D. W. Swearingen, J. F. Parker, E. E. Steinbecker, T. O. Calost, and H. Dodd, "MARISAT, A Maritime Satellite Communications System," Comsat Technical Review (Fall 1977).

"LNR Awarded $4 Million Contract for Spacecraft Amplifiers," LNR News, LNR Communications, Inc. (July 1977).

"LNR Awarded Ku-Band Amplifier Contract for TDRSS Satellite Ground Stations, LNR Amplifiers Now Used in Both Spacecraft and Ground Segments of TDRSS," Press-type release from LNR, January 1978.

LNR Communications, Inc., Hauppauge, NY, Data package.

Mason, J., "Computerized Switching and a Technique Called Frequency Reuse Get More Talk Into New Mobile Bands," Popular Science (January 1978).

McGarty, T. P., and T. H. Warner, "Multiple Beam Satellite System Optimization," IEEE Trans. Aerospace and Electron. Sys. AES-13 (5) (September 1977).

"Microwave Systems News," Technology Forecast Articles (January, February, March).

Mitsubishi Electric Co., Japan, Data package.

Morgan, W. L., "Satellite Utilization of the Geosynchronous Orbit," Comsat Technical Review (Spring 1976).

"Multiple Beam Satellite System Optimization," IEEE Trans. Aerospace and Electronics Systems (September 1977).

"National Aeronautics and Space Administration Communications Program Review," Briefing charts, (January 1978.)

"New Earth Station Antenna Features Low Sidelobes," Communications News (February 1978).

"New Uncooled 15 GHz Paramp Measures 80°K -- Approaches Cryo-Paramp Noise Temperatures," News from LNR Communications, Inc.

Oga, K, Akira, "Earth Stations for Norway's Domestic Satellite-Communications System."

Okean, H. C., J. A. DeGruyl, L. J. Steffek, A. J. Kelly, and S. J. Foti, "Electronically-Tunable, Low Noise Ka-Band Paramp-Downconverter Satellite Communications Receiver," LNR Communications, Inc.

Okean, H. C., and A. J. Kelly, "Low-Noise Receiver Design Trends Using State-of-the-Art Building Blocks," IEEE Trans. Microwave Theory and Techniques, MTT-25 (4) (April 1977).

Okean, H. C., and L. J. Steffek, "Octave Input, S-TO Ka-Band Large Signal Upper Sideband Varactor Upconverter," LNR Communications, Inc., Farmingdale, NY.

"Providing for Flexibility in a Receive-Only Earth Station," Communications News (February 1978).

Raine, H. L., "The Communications Technology Satellite Flight Performance," Paper No. IAF-76-223, International Astronautical Federation Twenty-Seventh Conference, 1976.

"Report of the United Nations Panel Meeting on Satellite Broadcasting Systems for Education," Paper No. A/AC.105/128, United Nations General Assembly, Committee on the Peaceful Uses of Outer Space, Tokyo, 26 February - 7 March 1974, 5 April 1974.

Rockwell International, Collins, El Segundo, CA, Data package.

"Satellite Communication Technology Study Interim Review" (14 April 1978).

"Satellite Link Solves BP Alaska's Needs," Communications News (February 1978).

Satellite Transmission Systems, Inc., New York, Data package.

"Small Dish Earth Station Gives Domestic/International Service," Communications News (February 1978).

"A Small Efficient X-Band Terminal," Ford Aerospace, Dearborn, MI.

"Small Transportable Stations for Satellite Communications," Ford Aerospace WDL, Dearborn, MI.

Stern, M., and V. Graziano, "A New Portable and Mobile Radiotelephone System Goes to Washington (and Baltimore)," Telephony, July 18, 1977.

"Suggested Areas for Research and Development," Fairchild Camera and Instrument Corp., Mountain View, CA.

Technical Evaluation of the Health/Education Telecommunications Experiment, Submitted to Office of Telecommunications, Department of Health, Education, and Welfare by Engineering, Federation of Rocky Mountain States (14 April 1976).

Turner, E. L., "Advanced Communications Technology, Satcom Terminals Operation," Briefing charts, Ford Aerospace, Dearborn, MI, 1977.

"U.S./Canadian Satcom Proves Effective With Small Antennas," Aviation Week (13 December 1976).

"Updated List of U.S. Experiments," National Aeronautics and Space Administration, Lewis Research Center, Cleveland, OH, 2 pp.

Western Union, Briefing charts, mostly regarding WESTAR, Western Union Corp., Mahwah, NJ.

Westinghouse Electric Corp., Pittsburgh, PA, Data package.

Wright, D. L. (National Aeronautics and Space Administration, Lewis Research Center), and J. D. Kiesling (Fairchild Camera and Instrument Corp.), Communication Satellite Services for Special Purpose Users.

"X-Band Planar Combines Module Using GaAs FETs," Microwave J. (February 1978).