Historical Perspectives on Commercial and Nonmilitary Government Space Applications of Microwave Systems in the Baltimore/Washington Area

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***Abstract*—The Baltimore/Washington area has made significant contributions to commercial and nonmilitary government space applications of microwaves. These cover a wide swath extending from R&D laboratory items, basically experimental/proof-of-concept, to space-qualified microwave hardware, subsystems, and systems that were launched and operated in space, to operational Earth terminal subsystems. Microwave efforts also included elements in the design of communications satellite systems, satellite payloads and hardware, and satellites for remote sensing, their payload and some hardware, and radiowave propagation on the slant (Earth–satellite) path. Unique contributions include the Applied Technology Satellite-6 (ATS-6), the discovery and characterization of gigahertz ionospheric scintillation, possibly the first electronically steerable phased array and the invention and implementation of the waveguide multimode filter, the first space-qualifiable monolithic-microwave integrated-circuit chips and subsystems, state-of-the-art altimeters, possibly the first Cesium clock for space and the first high Tc microwave filter.**

***Index Terms*— Microwave technology, radio propagation, remote sensing, satellite communications.**

I. Introduction

THE nonmilitary application of microwaves to space began in the Baltimore/Washington area with the onset of the space age, with the establishment first of the U.S. National Aeronautical and Space Administration Headquarters (NASA HQ), Washington, DC, in 1960, and the NASA Goddard Space Flight Center (GSFC), Greenbelt, MD, in 1962. This was followed by the establishment of the Communications Satellite Corporation (COMSAT), District of Columbia (DC), as a public stock-held corporation by act of Congress in 1962 and COMSAT Laboratories (COMSAT Labs), first in DC in 1967, and then in 1969 in Clarksburg, MD. The Johns Hopkins University Applied Physics Laboratory (APL), now in Columbia, MD, opened much earlier, but was initially concerned with military endeavors. In the past three decades, it has increasingly contributed to the nonmilitary side. The contributions of these entities will be detailed below.

Subsequently, other entities such as the International Telecommunications Satellite Organization (INTELSAT) (since 1973), the American Mobile Satellite Corporation (AMSC) (1988), and Orion (1986) have arisen and played a significant role in establishing communications satellite systems deploying microwave payloads in space. Companies like Fairchild, Germantown, MD, the builder of ATS-6, and Hughes Network Systems (originally the Digital Circuit Corporation (DCC), 1973), a major factor in providing microwave very small aperture terminals (VSAT) terminals and networks, have contributed significantly. There are many entities small and large (some of which have come and gone) in this area, active in satellite-related microwave work. All this has made the Baltimore/Washington area second only to the Los Angeles–San Diego area in the U.S. and possibly the world in the application of microwaves to space.

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II. Historic Contributions

NASA

The contributions of NASA HQ have been critical in moving microwave systems and hardware into space. While almost all of the R&D and implementation has taken place at the Centers, at the Jet Propulsion Laboratory (JPL), Pasadena, CA, and at contractors, many of the concepts, some of the preliminary design work, and the force behind the programs have come from HQ. This is especially true of the experimental satellites such as the ATS series, and some of the critical microwave systems technology such as radiowave propagation on the slant path. Another major contribution was their efforts with regard to frequency allocations, Reports and Recommendations at the International Telecommunications Union (ITU) at the Consultative Committee for International Radio (CCIR) (later ITU-R), and World Administrative Radio Conference (WARC) meetings.

The ATS series of satellites first ventured into microwaves with the ATS 5 propagation experiment at Ku-band. The ATS-6 Satellite, shown in Fig. 1, was a major success [1]. GSFC managed the program [2]. The satellite was built at Fairchild, Gaithersburg, MD. One on-board microwave experiment designed at and managed from GSFC was measurement of rain- and cloud-induced attenuation and site-diversity gain at 20/30 GHz using an on-board beacon [3]. Another such experiment employed a 13/18/4-GHz transponder designed and built at COMSAT Labs [4], and is discussed below. It was used for similar measurements at 13 and 18 GHz The results of these measurements were used to develop slant-

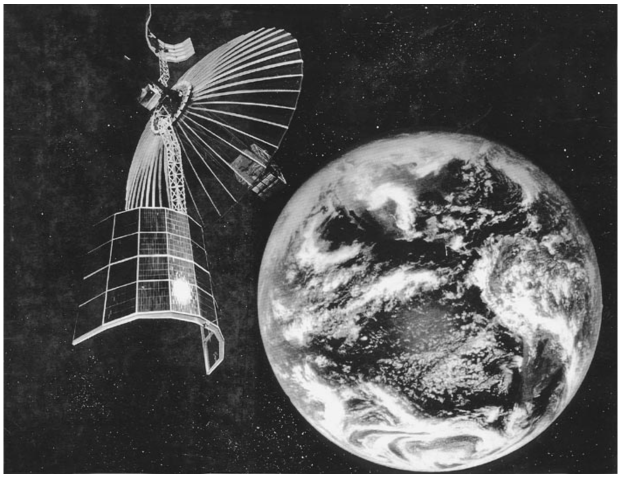


Fig. 1. The ATS-6 Satellite.

path rain attenuation and site-diversity models for locations in CONUS for frequencies above 10 GHz. At L-band, the position location and communications experiment (PLACE) followed the UHF Transit satellite of APL in establishing the technology which led to the global positioning system (GPS) currently in worldwide use. At S-band, the ATS-6 deployed a 9.1-m reflector [5] that allowed two-way video and voice for such applications as connecting remote sites in Alaska and Montana with the University of Washington for medical consultation. Several other services using microwave frequency bands were also demonstrated.

Next came the Communications Technology Satellite (CTS), a joint US/Canadian project, with 200-W Ku-band traveling wave tubes (TWT's) on board. The CTS thoroughly proved the feasibility of Ku-band direct broadcast satellite (DBS) systems in a series of experimental demonstrations starting in 1976. The main contributions from the Baltimore–Washington region, apart from NASA HQ, came from local experimenters at COMSAT Labs and GSFC. Local demonstrations showed that quite usable TV pictures were obtainable using receive apertures under 30 cm across.

The latest in this series is the Advanced Communications Technology Satellite (ACTS), a 20/30-GHz bird. The program was managed out of NASA Lewis Research Center (LeRC) near Cleveland, OH. However, NASA HQ played a major role in defining and designing the ACTS and Congress played a major role in keeping it alive. It carries phased-arrray antennas, on-board processing and beam steering, and operates in both channelized and wide-bandwidth modes. COMSAT Labs designed, fabricated, installed (near LeRC) and operated the network control station. The ACTS has been a major success. It successfully demonstrated the use of the 20/30-GHz bands from space, beam hopping, very high speed (almost gigabit) data rates over the slant path, and a wide variety of hydrometeor attenuation experiments. Local experimenters of note include NASA GSFC, George Washington University (GWU), Washington, DC, and COMSAT Labs., and included high-data-rate service demonstrations and propagation measurements.

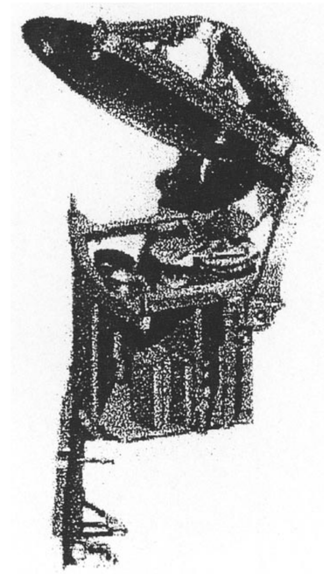


Fig. 2. The TRMM TMI.

NASA GSFC

GSFC has made many contributions to the use of microwaves by satellites. An important one has been the study of radiowave propagation on the slant path at microwave frequencies. As noted above, GSFC has directly participated in ATS and ACTS experiments to collect propagation data. It also sponsored propagation research, including programs at COMSAT Labs. and APL, which are discussed below. These data were collected, analyzed, and modeled at GSFC to provide a basis for prediction of impairments on the slant path through the troposphere due to rain and other hydrometeors, a significant contribution to U.S. efforts in this field.

NASA has contributed much to the field of remote sensing and GSFC has been a prime mover in these endeavors, most recently in the Tropical Rain Measurement Mission (TRMM) Program. There is a need to improve climate modeling, and to do that, the database for rainfall and rain rates must be improved. There is a dearth of good data in tropical regions and over the oceans. The TRMM will be a major factor in overcoming this problem. GSFC has developed, designed, and built several microwave radiometers flown on National Oceanic and Atmospheric Administration (NOAA) weather satellites. The TRMM spacecraft, i.e., observatory, was designed, built, and fabricated at GSFC, with instruments fabricated elsewhere. Two microwave instruments are included in the three-instrument rainfall measurement package, the TRMM microwave imager (TMI) and the precipitation radar. The TMI, depicted in Fig. 2, operates at 10.65, 19.35, 22.235, 37,6, and 85.5 GHz, and is dual polarized, except at 22.235 GHz. It is a nine-channel microwave radiometer with resolution from 45 km at 10.65 GHz to 5 km at 85.5 GHz, sweeping out a 700-km-wide swath. (Information on the TRMM is available on the Internet at http://trmm.gsfc.nasa.gov).

COMSAT

Starting in the mid 1960's, COMSAT was responsible for the design and operation of the INTELSAT 2, 3 4, 4A, (using

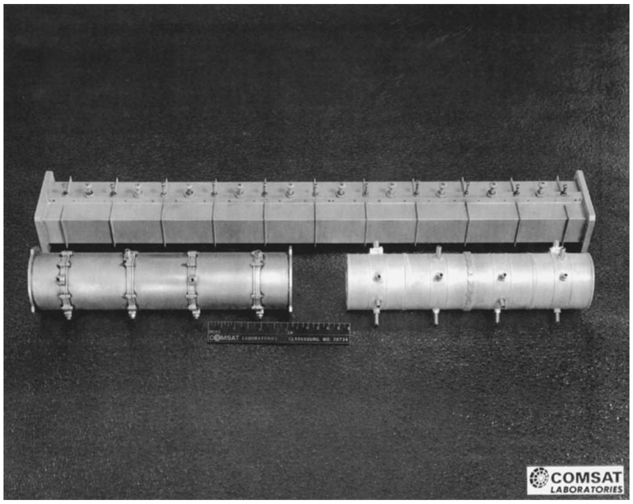


Fig. 3. Size comparison of a Chebyshev filter to two dual orthogonal-mode multimode elliptic-funtion filters.

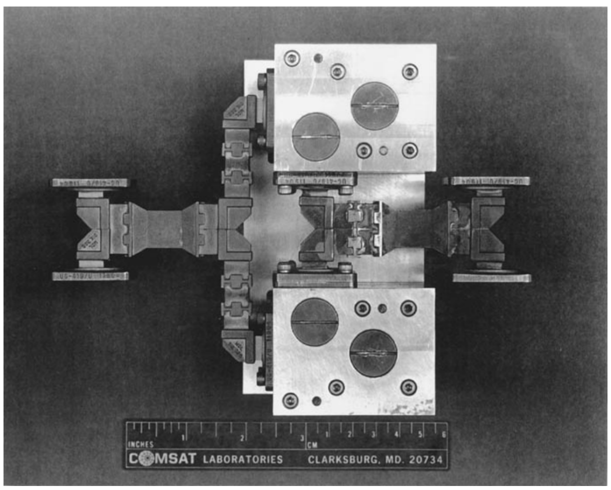


Fig. 4. DBS Multiplexer using TE011 cavities.

Fig. 5. High Tc Filter.

Fig. 6. MMIC switch matrix (MSM).

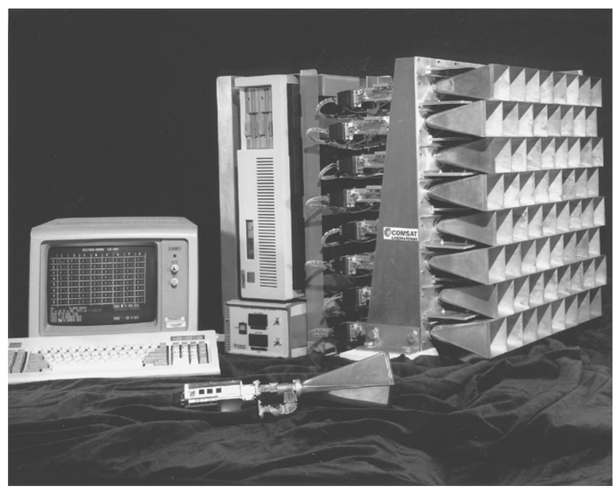


Fig. 7. 64-element Ku-band phased array.

4 and 6 GHz) 5 and 5A (using 4, 6, 11, and 14 GHz) satellites and the L-band (1.5 and 1.6 GHz) Marisat satellites and the satellite communications systems that used them. These efforts established the fixed and maritime mobile satellite services worldwide. Its activities in the ITU have been critical to the allocations of frequency bands and the reports and recommendations required for worldwide operation of these services.

COMSAT Labs

COMSAT Labs' microwave contributions have included both proof-of-concept and flight hardware, subsystems, and systems, as well as Earth terminal antennas and feed systems—too numerous to even list. Outstanding contributions include the first microwave filters for on-board channelization of the microwave bands used by the satellites. These filters minimized guard bands, while providing flat in-band response, sharp skirts, and other desirable properties with a minimum

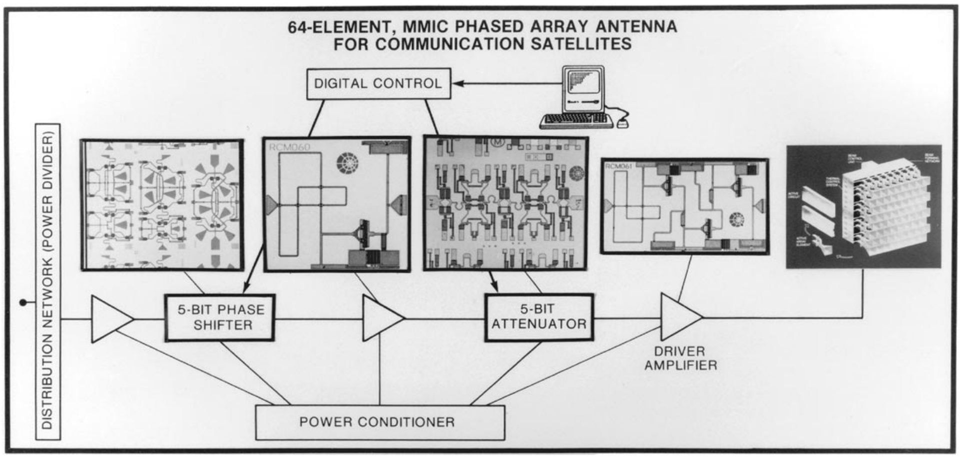


Fig. 8. Active element for one element in the 64-element array.

of loss (very high Q), low mass, and volume. This work, at 4 GHz, has progressed through Chebyshev filters, with 4-MHz guard bands and 36-MHz passbands in 1968, to use of dual orthogonal modes per cavity in 1969 [6], to elliptic function filters, to self-equalized filters in dual-mode cavities to three, and most recently, four orthogonal modes per cavity, thus reducing weight and volume while maintaining all the other desirable characteristics. These filters have been built and flown at frequencies covering the microwave bands. Fig. 3 compares the sizes of a ten-cavity Chebyshev filter used for channelization, as noted above, with two elliptic function dual-mode eight-cavity equivalent filters, each of which performs the same function. (The inventors of the dual-mode cavity filter, Dr. Atia and Dr. Williams, were recognized by the IEEE MTT-S with the 1996 Pioneer Award.) These filter techniques lend themselves to a variety of applications.

In addition to the channelizing multiplexers described above, they have been applied to high-power multiplexing, as is required in DBS feeder link applications at the lower end of the K-band. Fig. 4 shows such a multiplexer employing dual mode TE011 cylindrical cavities [7]. This multiplexer design became the prototype for such devices currently employed in DBS feeder links in North America.

COMSAT Labs also developed the first high Tc superconductor microwave filter [8]. This filter, built at MIT Lincoln Laboratories, Cambridge, in 1991, uses a YBCO superconductor on lanthium aluminate, operating at 77 K. The filter is shown in Fig. 5. Note that it is a stripline configuration. Despite this, the Q is about 50 000, exceeding the Q's of cavity filters by a factor of at least four. The advantage of such filters then lies in their high Q's, their low mass, and their small size. These reflect significant improvement (reduction) in all three critical parameters of good space hardware design, to whit—mass, power, volume. Advances in space-qualified cooling technology have brought such filters to the brink of deployment in space.

The COMSAT Labs' 13/18/4-Ghz transponder on ATS-6 was used by COMSAT Labs to measure rain attenuation on the slant path from locations throughout the U.S. east of the Mississippi. Radiometer measurements of attenuation on the slant path at 12 GHz and at 20/30 GHz were conducted at many sites worldwide. COMSAT Labs built the Comstar 19/28-GHz beacons. Rain depolarization measurements were conducted at 4/6 GHz at several sites around the world. COMSAT Labs participated in 20/30-GHz slant-path rain attenuation measurements using the ATS-6, Comstar beacons, and the ACTS. Using other satellite beacons and signals, in a series of worldwide campaigns funded by INTELSAT, COMSAT Labs accumulated a worldwide database on rain-induced impairments on the slant path used to develop models for predicting such impairments based on climate statistics.

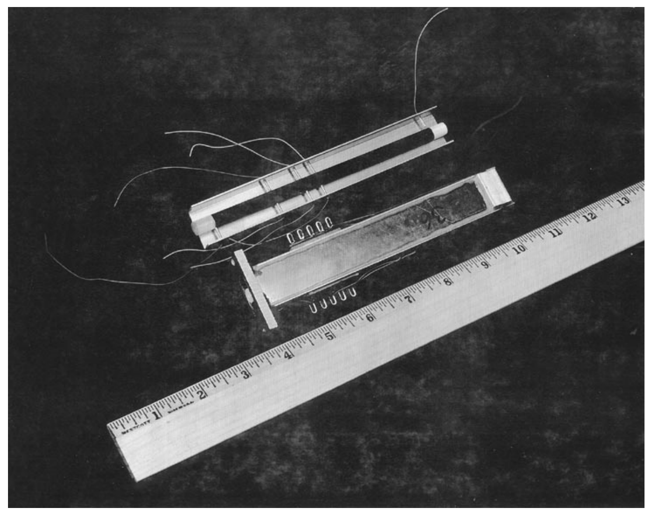
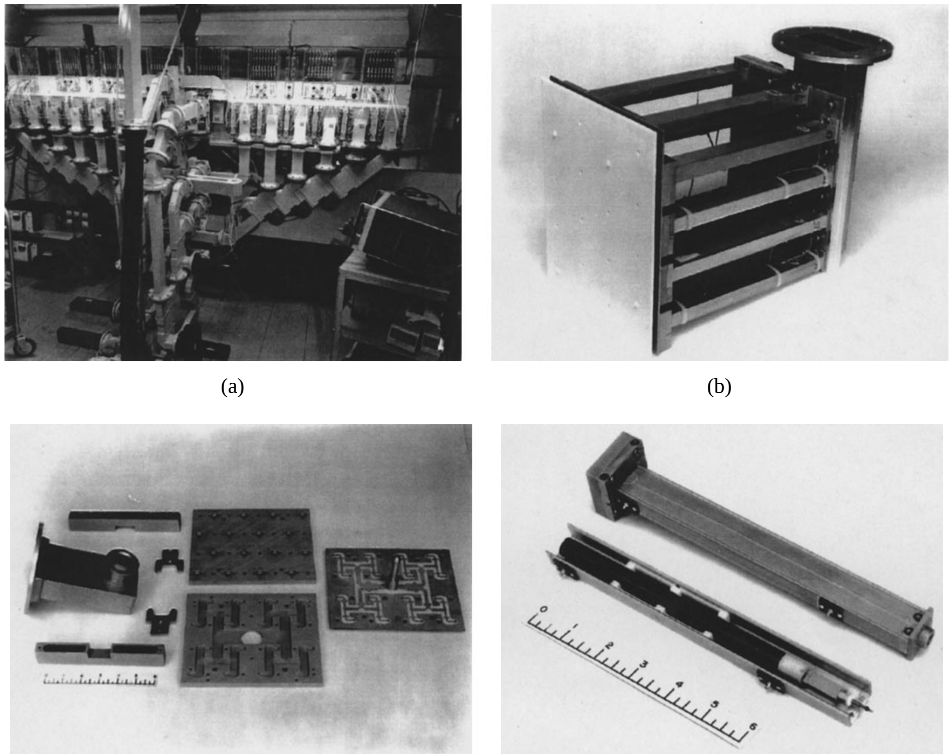


Fig. 9. Electronically controlled broad-band 4-b ferrite phase shifter.

In 1969, Equatorial gigahertz ionospheric scintillations i.e., signal fluctuations [9], were encountered in the INTELSAT system, an unexpected and then unexplained phenomenon of nature; COMSAT Labs measured it worldwide, characterizing it as a function of location vis-a-vis the geomagnetic equator, time of day and year, and the solar cycle. It occurs in signals traversing the ionosphere for a band $\pm 12^\circ$ about the geomagnetic equator, i.e., microwave signals on the slant path to geostationary satellites. Scintillations usually arise at sunset in the ionosphere, when the ionosphere is beginning to undergo diurnal changes, during the equinoctal seasons. Their frequency of occurrence and maximum amplitude follow the solar cycle. COMSAT Labs also conducted measurements



(a) (b) (c) (d)

Fig. 10. Advanced multifunction array radar phased array.

of tropospheric signal fluctuations at 4 and 6 GHz at low elevation angles, worldwide. These fluctuations are much slower than ionospheric scintillations.

These worldwide measurement campaigns were conducted as part of the INTELSAT R&D program. For the past 15 years or so, INTELSAT has continued such efforts, continuing to supplement this already considerable database (see, e.g., [10]).

Microwave antennas and related microwave hardware was another fruitful area of R&D at COMSAT Labs. The torus reflector, invented in the late 1940's at the Naval Research Laboratory (also located in this region) was generalized, optimized, and prototyped for use in Earth terminals [11]. As with the channelization filters, the motivation for efforts to develop microwave antenna hardware lies in the need to make maximum use of the limited bandwidth allocations at microwave frequencies. This entails the use of dual orthogonal polarizations, which essentially doubles the available frequency bands, and multiple frequency reuse through isolation between beams using the same frequencies. To accomplish the use of dual orthogonal polarization, the need was for devices such as high-polarization purity dual orthogonal polarization wideband feeds, polarizers and orthomode transducers. These were developed, as well as multiband dual orthogonal polarization feed systems. Much of this work was done at COMSAT Labs.

Frequency reuse requires the generation of a multiplicity of well isolated beams. This can be achieved through the use of microwave circuits in beam-forming networks (BFN's) feeding arrays of feeds illuminating a reflector or arrays of direct radiating elements in an array, possibly a phased array. As with the dual-polarization case, the solutions lie in microwave circuits and hardware. And these have been developed, with much of the proof of concept work being performed at COMSAT Labs.

COMSAT Labs embarked on the systematic development of GaAs monolithic microwave integrated circuits (MMIC's) for space applications [12]. MMIC's are necessary to achieve low mass and volume and their efficiency (power requirements) is adequate. Gallium arsenide (GaAs) is a good substrate material at microwave frequencies and in space. After the development of devices and individual modules such as field-effect transistor (FET) amplifiers, and MMIC subsystems and systems were developed, many the first space qualifiable designs of their kind. One such first at COMSAT Labs was the development of a MMIC switch matrix (MSM), which could be qualified for space applications (see Fig. 6). The first GaAs MMIC actually flown, a Ku-band amplifier, was produced at COMSAT Labs and space-qualified in 1989, then flown on the ITALSAT. The first GaAs MMIC digital attenuator actually flown was developed at COMSAT Labs for use in phased arrays, but was space-qualified, circa 1989, for use in gain control and flown in the INTELSAT IS 7A. The first large-scale nonmilitary space-qualifiable active Ku-band phased array using GaAs MMIC's was developed at COMSAT Labs. Actually, two such arrays were developed, a 64-element low-power array and a 24-element higher power array [12], [13]. The low-power array and a depiction of one of its element's MMIC complement are shown in Figs. 7 and 8. Such GaAs MMIC technology is being used in the Iridium satellite phased arrays Finally, the invention at COMSAT Labs of a microwave printed-circuit element array and BFN permitted the development of a high-efficiency low-cost flat-plate array [14] suitable for household reception of DBS signals.

APL

In the 1960's, APL set out to develop phased-array technology for radar applications. This led to the advanced multifunction array radar and included such contributions as the first large-scale microwave phased array. This array became an early prototype for the AEGIS program. The earliest development was an 8 × 6 S-band phased array, which employed an electronically controlled broad-band 4-b latching ferrite phase shifter [15], shown in Fig. 9, which was remarkable for its time, 1966. This development was followed by the advanced multifunction array radar, which had 256 elements [16]. It used a continuously variable S-band phase shifter, developed in 1967, also very broad-band. The array and its constituent components are shown in Fig. 10.

APL was and is very active in remote sensing. Early work included the detection of clear air turbulence. Other APL contributions included the Ku-band radar altimeters for the Seasat, Geosat, and ocean topography experiment (TOPEX)/Poseiden satellites used to measure sea state and elevation. The TOPEX altimeter is state-of-the-art, providing the most precise measurements of sea surface to date.

APL also participated in numerous microwave propagation measurements programs mentioned above. Further, they have participated in the characterization of the effects of buildings, vegetation, and terrain on radio waves. These data are essential to the determination of margins needed in the application of satellite-based mobile communications systems and personal communications systems (PCS) at microwave frequencies. Perhaps their most unique contribution has been to show how radar can be used to characterize rain attenuation on the slant path without use of a satellite. Reflection of radar signals at microwave frequencies by rain has been known from the earliest days of radar. But the use of radar to characterize rainfall and rain rates is more recent. It entails modeling rain rates in terms of radar reflectivity. APL has contributed significantly to the development of accurate modeling for this phenomenon. This modeling work is part of the effort that led to using radar on board the TRMM satellite as a remote sensor to measure rain from above.

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Upon graduation in 1953, he joined General Electric, Ont., Canada. In 1955, he joined Sinclair Radio Laboratories, Toronto, Ont., Canada, where he designed antennas and microwave devices until 1958. He then joined Avro Aircraft, where he worked on antennas for the CF-105 Avro Arrow. In May 1959, he joined the RCA Missile and Surface Radar Division, Moorestown, NJ. He participated in the Lunar Excursion Module program from proposal studies through the design efforts. In June 1968, he joined COMSAT Labs, where he worked on communication satellites until retirement in 1989 as Assistant to the Director RF Transmission Laboratories, in 1974 Manager, Propagation Studies Department, and Assistant to the Director, COMSAT Labs, with major responsibilities toward managing the Laboratory's R&D programs. After retirement in June 1989, he consulted for COMSAT Labs and others. His efforts for AMSC dealt with communications systems, antennas (L- and Ku-bands), BFM's testing, in-orbit test (IOT) methods, equipment design, testing and IOT of the AMSC M1 satellite. He has also edited a recent major NASA/NSF-sponsored review of satellite communications systems and technology. In 1996, he prepared a detailed report on laser satellite communications for the IEEE Aerospace Policy Committee. He continues to publish in professional journals in the U.S. and abroad. He has published many papers, authored and co-authored chapters in a handbook and an encyclopedia on antennas and satellite communications and holds patents in these areas.

Dr. Hyde is a Registered Professional Engineer in the Province of Ontario, Canada. He is a member of the IEEE Aerospace Policy Committee, AIAA, and US URSI Commissions B and F. He was a member of the US CCIR SG 5. He is a Fellow of the IEEE, and has also received the 1968 IEEE APS Best Paper Award, and David Sarnoff Fellowship Awards for 1965 and 1966.