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COMSTAR Experiment:

An Overview of the Bell Laboratories 19- and 28-GHz COMSTAR Beacon Propagation Experiments

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Radio beacons on the COMSTAR communication satellites transmit continuously at 19 and 28 GHz to permit the long-term measurement of the properties of earth-space propagation needed in designing future high-capacity satellite communication systems. An extensive receiving facility has been established at Crawford Hill, New Jersey, for measuring attenuation, depolarization, coherence bandwidth and scatter of the beacon signals by atmospheric processes. The facility includes a precision 7-meter antenna and multichannel receiving electronics designed to obtain optimum benefit from the COMSTAR beacons. Other Bell Laboratories receiving facilities in Georgia and Illinois are accumulating statistics on signal attenuation and diversity improvements for other climatic conditions.

I. INTRODUCTION

Propagation experiments using the 19- and 28-GHz beacons on COMSTAR satellites represent a significant milestone in the quest for design information for future satellite communication systems. The experimental results also contribute to knowledge of meteorological processes. Earth-space propagation information above 10 GHz is a key component in the exploration of concepts for high-capacity domestic satellite communication systems.[1,2]

Future high-capacity satellite communication systems will probably use frequencies above 10 GHz because of the large segment of unused frequency spectrum available and because of spectrum crowding at the lower frequencies. In particular, frequency bands over 2000 MHz wide are allocated at 19 and 28 GHz, and 500 MHz bands are available at 12 and 14 GHz for common-carrier satellite communication systems; at 4 and 6 GHz the allocated frequency bands are only 500 MHz wide. Even now satellite systems at 4 and 6 GHz are severely constrained by requirements for avoiding interference with the extensive terrestrial radio networks that share these same frequency bands.

New systems will probably reuse frequencies on two orthogonal polarizations to double the usable bandwidth and may reuse frequencies among spot antenna beams covering small areas of high traffic concentration. Thus, knowledge of the decrease in cross-polarization isolation produced by rain and ice is needed and satellite antenna sidelobe control will be important. Sidelobe levels of earth station antennas and the scattering of energy from one antenna beam to another by rain will limit how close communication satellites can be spaced in the geosynchronous orbit. Other characteristics of future systems operating above 10 GHz compared to present 4 and 6 GHz systems are as follows: (*i*) they most likely will use smaller earth station antennas; (*ii*) they will experience more rain attenuation and may use transmitter power control or site diversity to cope with it; (*iii*) interaction with the ionosphere will be significantly less; (*iv*) they may use wider bandwidths and thus be more sensitive to delay dispersion, and (*v*) some systems probably will use digital modulation. Some system calculations that were used as a guide in selecting representative values of experimental parameters, such as earth station antenna size, are presented by Tillotson in Ref. 1.

It is well known that rain affects radio propagation more severely at frequencies above 10 GHz.[2] However, present knowledge of rainstorm characteristics and atmospheric processes is not adequate for predicting all earth-space propagation characteristics from terrestrial propagation measurements, surface rain measurements, or radar measurements. Thus, the complete information needed for satellite communication system design can be obtained only from measurements made along earth-space paths. The complication and expense of placing radio sources in synchronous orbit has meant that continuously transmitting beacons were not available in the 1960s for measuring earth-space propagation characteristics. Advantage was taken of a natural extraterrestrial radio source, the sun,[3] and of thermal emission from rain itself[3,4] for indirectly measuring the attenuation of earth-space radio signals above 10 GHz. The sun trackers and radiometers used for these measurements provided the only continuous attenuation data available in the late 1960s and early 1970s.[5] This data base has several limitations. The sun azimuth and elevation change continuously during the day and, of course, the sun is not available during the night. Radiometer measurements of thermal emission from rain have a range restricted to about 12 dB because of rain scatter and uncertainty in effective rain temperature.[3,4] Also, these indirect measurement techniques cannot provide any information on depolarization or on bandwidth limitations imposed by the propagation medium. The NASA experimental ATS-5 and ATS-6 satellites carried beacons transmitting at 15 GHz and at 20 and 30 GHz, respectively. These beacons did not transmit continuously and were often not available during rainstorms because of scheduling and total power constraints on the satellites. Therefore, continuous long term statistics could not be collected using these sources. In fact, availability of the ATS-5 and -6 beacons was so limited that a significant depolarizing phenomenon went undetected until continuously transmitting satellite beacons became available.[6] Propagation information is needed for the satellite bands at 12, 14, 19, and 28 GHz; however, expense, power and weight limitations restrict the number of satellite beacon sources that can be provided reasonably. Beacons transmitting within the 19- and 28-GHz bands were a logical choice for sources for earth-space propagation experiments because attenuation and other atmospheric interaction is greater at the higher frequencies, extrapolation is reasonable from measurements made at two frequencies, and it is safer to extrapolate from large numbers to small numbers. The 19- and 28-GHz beacons were put on the COMSTAR satellites then to satisfy the fundamental need for continuous long-term measurements of propagation parameters such as attenuation, depolarization, coherence bandwidth and differential phase.

In support of this measurement effort, an extensive receiving facility has been established at Crawford Hill, New Jersey.[7] The facility is described in Section III of this paper and in the next two papers.[8,9] of this issue. An interim receiving facility at Crawford Hill is described in the fourth paper.[10] Bell Laboratories receiving facilities have been established near Atlanta, Georgia (Palmetto), and near Chicago, Illinois (Grant Park), for accumulating attenuation and diversity statistics for other climatic conditions. These measurements are described in the fifth paper.[11] Other experimenters outside Bell Laboratories are also making use of the beacons for accumulating propagation information.[19,20] This paper describes the COMSTAR beacons and the experimental measurements at Crawford Hill.

II. THE COMSTAR 19- AND 28-GHz BEACONS

The need for measurements in different climatic regions of the U.S. along with the need for continuous measurements suggest that satellite beacons providing signals for propagation experiments should have U.S. coverage antennas. Such antennas provide about 30-dB gain. Beacons placed on operational satellites such as COMSTAR logically can make use

Table I — COMSTAR satellite beacon parameters

Station-keeping tolerance		<±0.1° E-W and N-S
Antenna pointing tolerance		<±0.1°
Carrier frequencies		19.0400 GHz and 28.5600 GHz
Variation:	Diurnal	$<\pm 1 \times 10^{-6}$
	Aging	$<\pm 1 \times 10^{-6}$ per year
	Maximum Rate	$<\pm 5 \times 10^{-11}$ per second
	Jitter	90% of carrier power in bandwidth $<\pm 8 \times 10^{-10}$
EIRP		
19 GHz		>+52 dBm per polarization
28 GHz		>+56 dBm
Variation*:	Diurnal	<±0.3 dB
	Aging	<±0.5 dB per year
	Maximum Rate	<±0.1 dB per minute
Polarization		
19 GHz		Switched between two orthogonal linear
28 GHz		Linear, aligned with most nearly vertical 19-GHz signal
Orientation†		4° for satellite at 128°W 21° for satellite at 95°W
Crosspolarized components‡		>32 dB below copolarized level at worst case within U.S.
Polarization switch (19 GHz only)		
Rate		1000.0 Hz ± 0.1 Hz
Stability		$<1 \times 10^{-7}$ per 10 min.
Switching time		<10 us
Asymmetry		<±5%
Phase modulation (28 GHz only)		Coherent with carrier
Frequency**		264.4 MHz
Sideband level		<7 dB below carrier

* A circuit malfunction has reduced the power output of the 19 GHz beacon at 128°W by 2 dB since launch.

† Polarization orientation is the angle (<45°) that the received polarization is rotated from vertical or horizontal at Crawford Hill.

‡ >36 dB and >41 dB below 19- and 28-GHz copolarized levels, respectively, toward Crawford Hill.

** A satellite scheduled for a later launch has a modulation frequency of 528.9 MHz.

of the excess power generated by solar cells at the beginning of satellite life. Since this power is limited, low beacon power is desirable; for COMSTAR, about +30 dBm each from the 19- and 28-GHz beacons could be produced without having a detrimental effect on the primary communication mission of the satellite. Since a reliable measuring range of over 30 dB is desirable with simple, relatively inexpensive earth stations and since a range of 60 to 70 dB at 30 GHz is desirable for extrapolating attenuation data to lower frequencies, receiving system signal margin must be obtained by narrowing receiver noise bandwidth. Narrow-band measuring systems, however, require very stable oscillators. These considerations, along with the needs for measuring depolarization and delay dispersion, resulted in the COMSTAR beacons with parameters summarized in Table I.

The spin stabilized COMSTAR satellites illustrated in Fig. 1 were built by Hughes Aircraft Corporation and are owned and controlled in orbit by COMSAT General Corporation. They are leased to the AT&T and

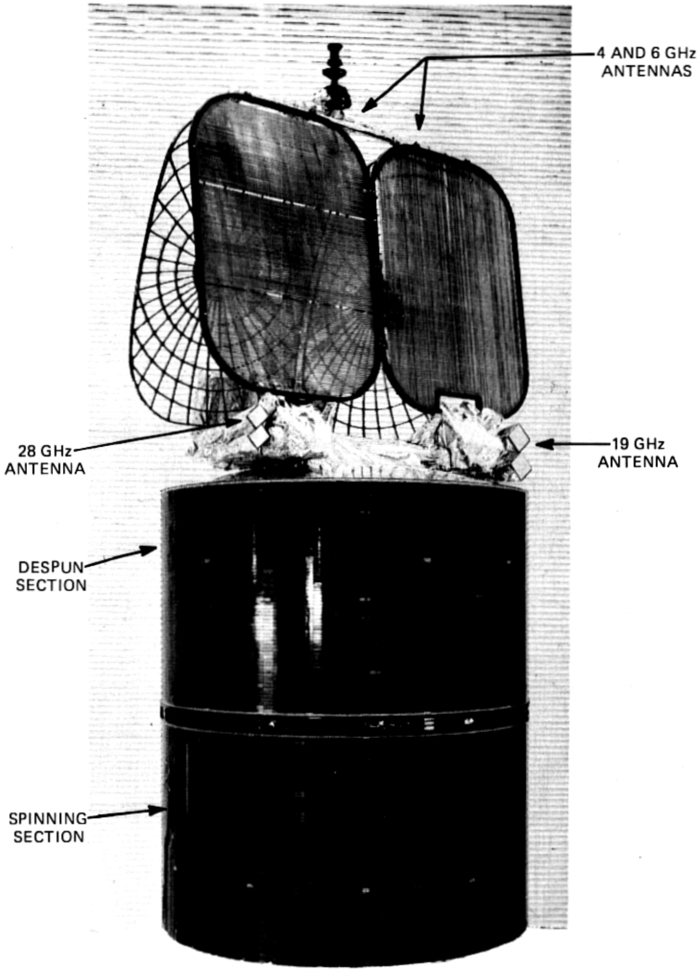

Fig. 1—COMSTAR satellite. Lower solar-cell-covered cylindrical portion is 9 feet high by 8 feet diameter. Overall height is 20 feet.

GT&E Companies for domestic U.S. communication service.[12] The lower half of the solar-cell-covered drum spins at between 50 and 60 revolutions/minute while the upper half, which supports the antenna platform, is despun to keep the antennas pointed towards the earth. The two large antennas are used by the 4- and 6-GHz communications system, one for each of two orthogonal linear polarizations. The 19- and 28-GHz beacon antennas are on opposite sides of the satellite, just below the communication antennas.

There are to be three beacon-equipped COMSTAR satellites in synchronous orbit. The first satellite was launched in May 1976 and is at

Fig. 2—28-GHz beacon coverage from satellite at 95°W longitude. Maximum antenna gain is 30 dB. Coverage for 19-GHz beacon is similar.

128°W longitude; the second was launched in July and is at 95°W; the third is to be launched in the spring of 1978.

The beacons were built by COMSAT Laboratories and are described in more detail in Ref. 13. The 19.04- and 28.56-GHz beacon signals and the 264.4-MHz signal that phase-modulates the 28.56-GHz signal are derived from a common 132.2-MHz quartz crystal oscillator. A common frequency multiplier chain multiplies the oscillator output to 2.38 GHz. The signal path splits into separate frequency multipliers after amplification at 2.38 GHz. The 28.56-GHz multiplier output is phase-modulated before it and the 19-GHz multiplier output are amplified in separate negative-resistance IMPATT amplifiers. Polarization is switched (19 GHz only) with PIN diodes driven from a separate crystal oscillator and frequency divider. The beacons make use of the surplus dc power capacity of the solar-cell array that is available until the solar cells deteriorate under the radiation environment of space. The projected availability of this surplus power is over two years (satellite lifetime is greater than seven years). The expected lifetime of the all-solid-state beacons is considerably greater than 7 years; however, due to a component failure the 19-GHZ beacon on the 128°W satellite has experienced regular daily power fluctuations since July 1976.

As shown in Fig. 1, a two-horn antenna array transmits the linearly polarized 28-GHz signal. Another two-horn array transmits two orthogonal linearly polarized 19-GHz signals. These two-horn arrays permit control of the polarization independent of the radiation pattern; polarization is determined by rotation of the horn apertures relative to the array centerline* while the pattern is determined largely by the array separation, the aperture dimension perpendicular to the array centerline, and the orientation of the centerline. The same antenna is used for both 19-GHz polarizations so that the received differential phase will not be affected by angular motion of the satellite.† If two antennas with separate phase centers were used, unavoidable residual angular motion of the satellite (~0.1°) would produce differential phase shift as in an interferometer. Although ±0.1° is a small variation, it would cause up to ±10° differential phase shift at 19 GHz between two antennas with phase centers placed as close together as possible. Figure 2 is a beacon antenna-coverage pattern constructed from pre-launch antenna-range measurements. Antenna patterns for the other frequency and polarization are similar.

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* The beacon at 128°W was designed to produce horizontal and vertical polarization at Crawford Hill with the satellite at 119°W. The beacon at 95°W was designed to produce horizontal and vertical polarization at Crawford Hill with the satellite at 129°W. Orbital assignments by the Federal Communications Commission (FCC) and launch scheduling did not permit placing of the satellites in their requested orbital locations.

† M. J. Gans of Bell Laboratories collaborated with engineers at Hughes Aircraft in adapting the two-horn array for the two polarization application.

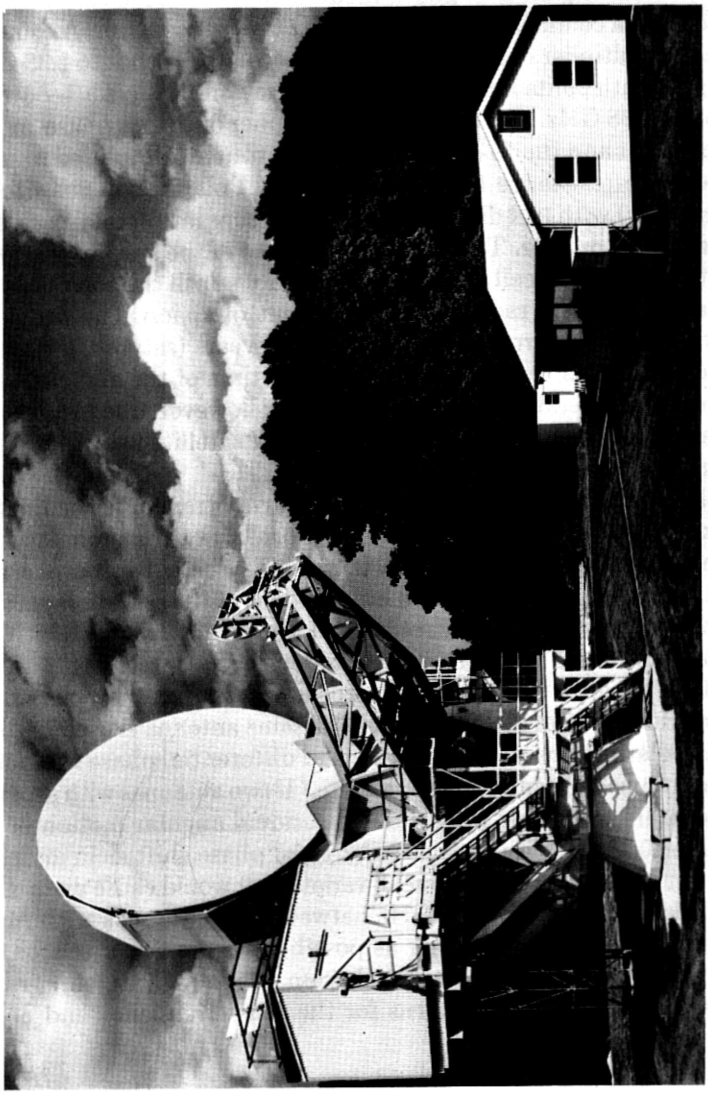

Fig. 3—Crawford Hill main receiving facility showing 7-meter diameter antenna and control building.

III. THE CRAWFORD HILL RECEIVING FACILITY

The Crawford Hill receiving facility was designed to obtain optimum benefit from the COMSTAR beacon emissions[7] while also demonstrating techniques applicable to 19- and 28-GHz earth stations. The facility is located on top of Crawford Hill, New Jersey, about 50 km south-southeast of New York City at 40.392° north latitude and 74.187° west longitude. Crawford Hill is 115 meters above sea level. The main facility shown in Fig. 3 comprises the 7-meter diameter millimeter-wave antenna, receiving electronics, antenna pointing and data collection equipment, and computer programs indicated in the simplified block diagram in Fig. 4. The antenna, antenna feed and receiver front ends could function as communication system components. For example, the antenna size and gain are representative of the needs of typical high-capacity earth stations.[1] The antenna does not have any aperture blockage because of the offset geometry. This clean aperture, combined with a good surface and heavily tapered illumination, result in the low sidelobe levels that would be required for systems working with satellites closely spaced (~1°) in orbit. These low sidelobe levels are also needed in the propagation experiment for measuring the crosstalk produced by the scattering of radio waves by rain. The good surface, long effective focal length and feed design result in the low antenna cross polarization throughout the antenna beam needed by frequency reuse dual polarization systems and required in the experiment for measuring depolarization by raindrops and ice crystals. The simple format for obtaining open loop antenna pointing information from COMSAT also should prove useful in future system operation.[16] The dual-frequency dual-polarization antenna feed uses low loss quasi-optical frequency and polarization diplexers suitable for diplexing high-power transmitters with sensitive receivers. The receiver front ends are low-noise broadband mixers and broadband IF amplifiers that provide a 1-GHz-wide channel suitable for system use from RF through first IF. Following the first IF, the receiver is narrow band and optimized to provide the sensitivity and stability needed for the propagation measurements.

An interim receiving facility shown in Fig. 5 was used before completion of the main facility. Measurements at the interim facility are continuing using the beacon at 128°W. From Crawford Hill the beacon at 95°W is at azimuth = 210.5° and elevation = 38.6°; the beacon at 128°W is at azimuth = 244.7° and elevation = 18.5°. The main receiving facility is briefly described in the following sections. More detailed descriptions of this equipment and a description of the interim facility are contained in the following papers of this issue.[8,9,10]

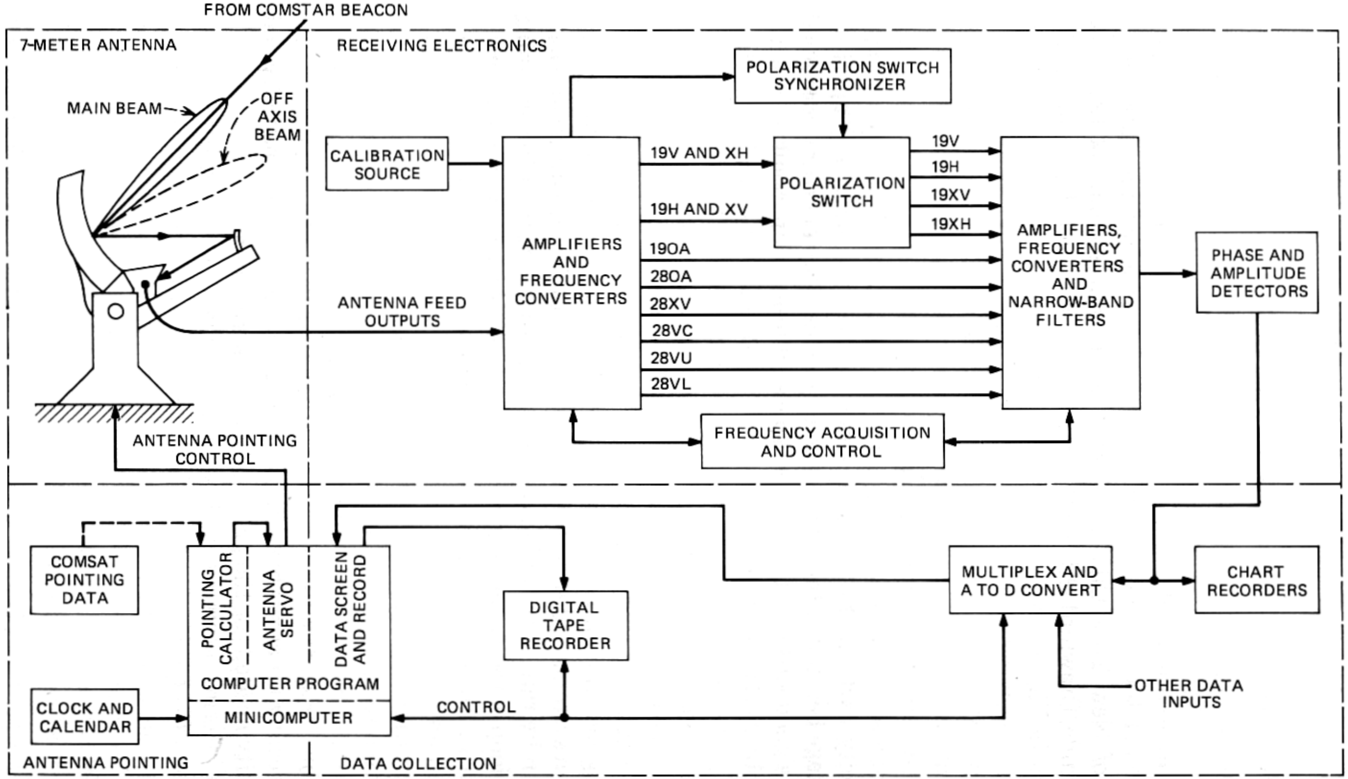

Fig. 4—Configuration of main receiving facility at Crawford Hill comprising 7-meter antenna, receiving electronics, data collection subsystem and antenna pointing components described in the text. Facility simutaneously records COMSTAR beacon signal parameters for two polarizations at 19 and 28 GHz and signals scattered off-axis from the main beam at 19 and 28 GHz.

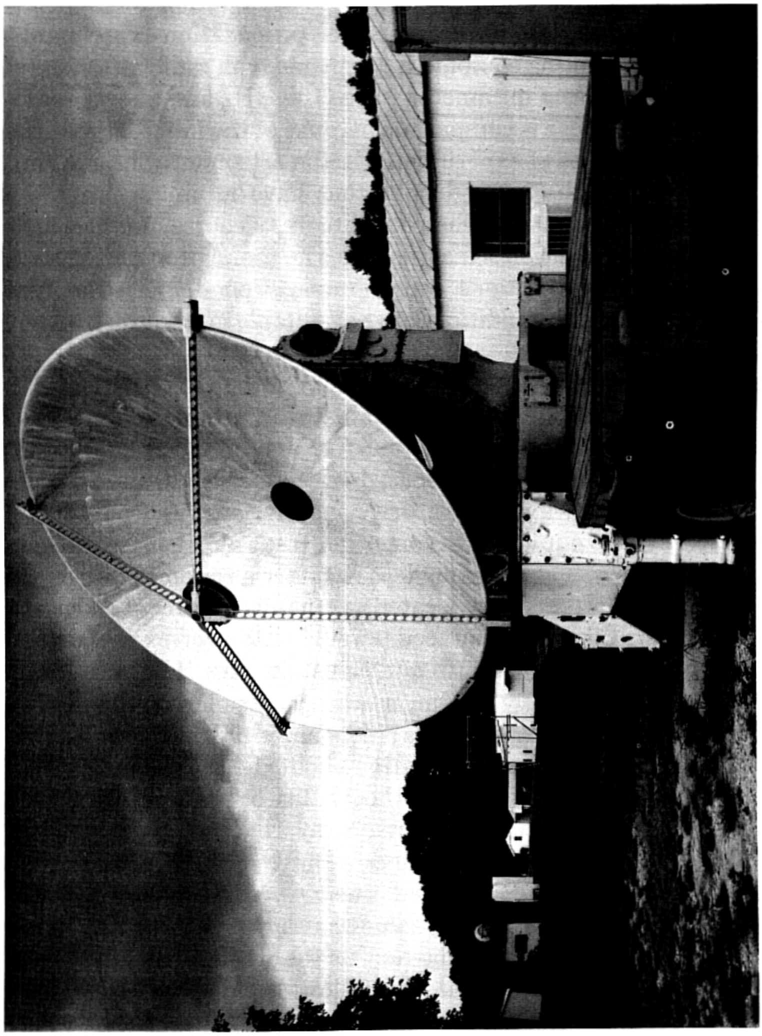

Fig. 5—Crawford Hill interim receiving facility showing 3.7-meter-diameter antenna and instrumentation building. The facility described in Ref. 10 receives beacon signals on two polarizations at 19 GHz.

3.1 7-meter antenna and antenna pointing

The 7-meter diameter millimeter wave antenna[8] shown in Fig. 3 is of novel design and extreme precision. It is designed to operate in the high winds and generally bad weather that are characteristic of summer thunderstorms (and hurricanes). These bad weather events produce most of the propagation degradation such as attenuation and depolarization that are measured in the continuing propagation experiments. The antenna and pointing equipment are shared with radio astronomers who use the facility as a millimeter wave (100 GHz and above) radiotelescope. This joint use is compatible because of the inherent requirements of the two types of experiments. Radio astronomy observations require clear atmospheric conditions that have minimum effect on millimeter wave propagation. These conditions, of course, produce little effect on the satellite beacon signals and thus no useful propagation data. When atmospheric conditions cause propagation degradation that should be measured, the conditions are not suitable for radio astronomy observations.

The millimeter wave offset Cassegrainian antenna consists of a 7-meter diameter parabolic reflector on an altazimuth mount; a convex hyperbolic subreflector; dual-frequency (19 and 28 GHz) dual-polarization quasi-optical main-beam feeds; dual-frequency (19 and 28 GHz) single-polarization off-axis feeds; drive motors, angle encoders, and pointing servos; two equipment rooms; and feeds at other frequencies for radio astronomy. The antenna does not have a radome cover.

All 19- and 28-GHz feeds are located in a small equipment room, the vertex cab, at the Cassegrainian feed point near the vertex of the main reflector, above both the azimuth and elevation axes. The main beam feeds receive simultaneously two linear orthogonal polarizations at both 19.04 GHz and 28.56 GHz; these feeds are mounted on a single frame that permits rotation of the feed polarization about the coaxial main beam axis without affecting polarization orthogonality or beam pointing. The off-axis feeds form a beam that is pointed away from the axis of the main beam. The 0.002-inch Mylar feed window in front of the vertex cab is covered with a nonwetting coating and is nearly vertical to prevent water from collecting on it. The second, somewhat larger, equipment room, the side cab, is to one side of the antenna, on the elevation axis but above the azimuth axis. The antenna has the following characteristics:

Gain	19 GHz	61 dB
	28 GHz	64 dB
Beamwidth:	19 GHz	0.17°
	28 GHz	0.11°
Cross-polarization isolation:	>35 dB throughout main beam	

Sidelobes:	<−40 dB at >1° off-axis	
Pointing error:	<0.0028°	20 mph steady wind
	<0.017°	45 mph steady wind + gusts to 60 mph
	0.001°	angle readout
Slew rates:	2°/sec azimuth; 1°/sec elevation	warm weather

The antenna is fully steerable by the drive system and servo over an elevation of 0° to 90° and an azimuth of 0° to 450° with the azimuth rotation limited by the wrap-up of cables (no slip rings are used).

The antenna is pointed by a minicomputer that compares angle encoder outputs with command pointing angles and calculates velocity commands for the drive system from the resulting error. The commanded pointing angles for the COMSTAR satellites are calculated by the computer from parameters derived from orbital predictions.[16] COMSAT General supplies via teletype a set of coefficients for equations describing antenna azimuth and elevation angles at Crawford Hill. These equations result in a pointing error of less than ±0.008° when updated every 2 weeks, assuming perfect orbital prediction. The antenna follows the ±0.1° diurnal motion of the satellite within about ±0.01°.

3.2 Receiving electronics

The propagation experiments placed strong demands on technology for the receiving electronics.[9] Continuous unattended operation is required so that all significant weather events are included in the resulting data base; thus, a very high degree of reliability is necessary and rapid automatic reacquisition of the beacon signal after dropout due to severe attenuation or momentary power outage is essential. Since relative phases of the many signal components must be precisely measured, the phase stability of all circuits and components demanded careful attention. Also, circuit arrangements had to be devised to ensure that signals to be compared in phase traverse a common path through high-gain amplifiers and other phase-sensitive equipment.

In order to obtain the maximum possible measuring range using the modest power radiated by the satellite beacons, very narrow receiver noise bandwidths are required. This in turn requires excellent stability in the source oscillators in the satellites and the local oscillators in the earth stations. The receiver includes an automatic frequency control circuit with built-in memory to facilitate reacquisition after loss of signal.* Maximum use was made of known correlations among strong and

* The feature also permits easy return to propagation measurements after use of the antenna during clear weather periods for radio astronomy observations.

weak signal components to permit detection of weak cross-polarized signals during severe fading.

The receiving electronics portion of Fig. 4 is subdivided to indicate receiving functions. This part of the facility includes the balanced mixers (frequency converters), oscillators, frequency multipliers, IF amplifiers, bandpass filters, switches, and envelope (amplitude) and phase detectors required to process the following signals: (*i*) the nearly vertically and horizontally polarized 19-GHz main beam signals, 19V and 19H, (*ii*) the corresponding crosspolarized 19-GHz main-beam signal components, 19XV and 19XH, (*iii*) the 19- and 28-GHz off-axis beam signals, 19OA and 28OA, (*iv*) the nearly vertically polarized 28-GHz main-beam carrier, 28VC, upper sideband, 28VU, and lower sideband, 28VL, and (*v*) the corresponding cross-polarized 28-GHz main-beam carrier, 28XV. Included in these functional blocks are the circuits for automatic frequency control, frequency acquisition, polarization switch synchronization and receiving system calibration. The receiving electronics are distributed among the two equipment rooms on the 7-meter antenna and the control building about 15 meters away from the antenna. The equipment distribution optimizes noise performance and phase and amplitude stability while staying within space limitations in the various equipment rooms. Since power line transients and momentary power outages are expected during heavy rain, all oscillators, filter stabilizing ovens and frequency memory registers are powered by batteries charged continuously from the power line. The receiving electronics have the following characteristics:

	19 GHz		28 GHz		
	V,H	XV,XH,OA	VC,XV	VU,VL	OA
Noise figure	≤7 dB		≤7 dB		
Noise bandwidth	16 Hz	16 Hz and 1.6 Hz	24 Hz and 2.4 Hz	24 Hz	2.4 Hz
Channel-to-channel isolation	>65 dB		>68 dB		
Amplitude instability	<0.5 dB		<0.5 dB		
Phase instability	<2°		<5°		
Frequency tracking rate	2 Hz/sec		3 Hz/sec		

Since the 19- and 28-GHz beacon signals are derived from a common oscillator, they have the same frequency fluctuations. Thus, extended measuring range is provided in the 28-GHz channels and in 19-GHz low-signal channels (off-axis and cross-polarization) by: (*i*) using common frequency sources for corresponding 28-GHz and 19-GHz receiver local oscillators (LOs), (*ii*) tracking out frequency fluctuations in the

Table II — Radio link parameters for Crawford Hill, New Jersey

	19.04 GHz		28.56 GHz	
Beacon (95°W) output power	+27.7 dBm		+30.6 dBm	
Polarization switching	−3		—	
Satellite antenna gain	+28.6 dB		+28.2 dB	
EIRP per polarization (average)	+53.3 dBm		+58.8 dBm	
Path loss 22,300 miles	−209.7 dB		−213.2 dB	
Crawford Hill antenna gain	+61 dB		+64 dB	
Clear air absorption (O_2 and H_2O)	−0.6 dB		−0.9 dB	
Signal into receiver (avg. per polarization)	−96 dBm		−91 dBm	
Noise into receiver (clear air)	−156 dBm	−166 dBm	−154 dBm	−164 dBm
Noise bandwidth* (7 dB NF)	(16 Hz)	(1.6 Hz)	(24 Hz)	(2.4 Hz)
Receiver carrier-to-noise (C/N)	+60 dB	+70 dB	+63 dB	+73 dB
(clear air with noise blanking)	(16 Hz)	(1.6 Hz)	(24 Hz)	(2.4 Hz)
Oscillator stability [PLL off (below thresh.)]	−0.2 dB	—	—	—
Measurement range (in rain) (to $C = N$) (ant. temp. 273°)	59 dB	69 dB	62 dB	72 dB

* A single complex pole pair bandpass filter with 10-Hz 3-dB bandwidth has a noise bandwidth of 16 Hz.

beacon and in LOs with a common oscillator in a loop locked in phase to the 19-GHz vertically polarized signal, the signal that experiences the least attenuation, and (*iii*) using very narrow-band filters in the extended range channels.

Differential amplitude and phase stability is maintained by carefully controlling differential temperature between corresponding components in different receiver channels, by using low temperature coefficient components, by choice of IF frequencies and filter bandwidths, and by designing for good circuit linearity.

3.3 Radio link parameters

Radio link parameters affecting dynamic measuring range are summarized in Table II for the beacon at 95°W and the Crawford Hill 7-meter antenna and receiving electronics. The major contributors to the 19-GHz parameters are illustrated in Fig. 6.

Filters with 1.6-, 24-, and 2.4-Hz noise bandwidths are in the channels that receive signals attenuated by rain to lower levels than the vertically polarized (V) 19-GHz signal. The 1-dB difference between clear air carrier-to-noise ratio and measuring range reflects the difference in antenna temperature between clear air and rain.

Refraction in the atmosphere due to temperature and humidity gradients does not have a significant effect on the experiment.[14] For example, the maximum expected surface refractive index variation at Crawford Hill is <±45 ppm for August, the month of maximum spread in refractive index. This refractivity variation corresponds to a ±0.003° elevation angle variation for the 38.6° elevation from Crawford Hill to

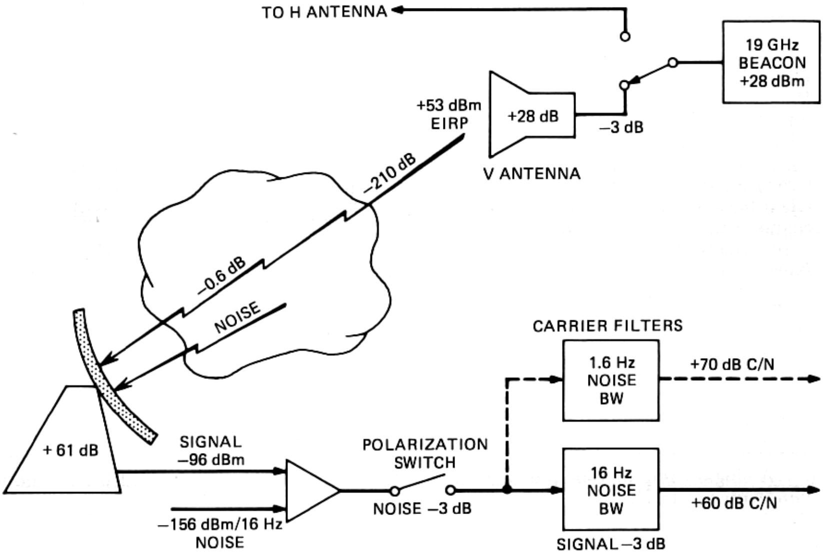

Fig. 6—Radio link summary indicating major parameters that determine the carrier-to-noise ratio of the 19-GHz COMSTAR beacon signals received in clear air with the Crawford Hill main receiving facility.

the satellite at 95°W. The elevation variation would be <±0.008° for the 18.5° elevation to the 128°W satellite. Such angular variations produce <±0.05 dB amplitude variation for the 7-meter antenna and insignificant change in differential phase and cross polarization.

Faraday rotation of linear polarization by the ionosphere is insignificant at 19 and 28 GHz.[14,15] The maximum expected variation in polarization angle is <±0.15° for the extremes of solar flares or magnetic storms. During normal ionospheric conditions the variation is significantly less. If the cross-polarization of the instrumentation system (antennas, beacon polarization switch and receiver) were zero, the rotation variation of ±0.15° would produce a cross-polarized component of <−50 dB. Cross-polarization variation of this magnitude is insignificant in the experiment.

3.4 Data collection

The data collection equipment is common to all receiving channels as indicated in Fig. 4. Data that are critical for maintaining continuity in the data base for long term statistics, e.g., signal attenuation and depolarization, are recorded continuously on analog ink-pen paper-chart recorders. These chart recordings provide a backup in the event of failure of the digital recording system and also provide a "quick look" at the recorded data. The logarithms of signal amplitudes are recorded on the chart recorders with a range of 50 dB.

All receiver outputs are multiplexed along with (*i*) system status indicators such as whether the frequency control loop is tracking or holding in a signal fade, (*ii*) outputs from weather instruments such as rain gauges, thermometers and wind speed recorders, (*iii*) outputs from the on-going interim experiment[10] using the COMSTAR beacon at 128°W, and (*iv*) another propagation experiment[17] using a 12-GHz beacon on the NASA/Canadian Communications Technology Satellite (CTS). These multiplexed signals are digitized, temporarily stored in the mini-computer core memory, screened by the computer for relevance, and stored on digital magnetic tape. Multiplexer and analog-to-digital converter sequencing, digital data buffering and digital tape drive control are handled by the same minicomputer that points the receiving antenna.

The objectives of the data screening procedure* are to minimize the amount of superfluous data stored while not discarding any relevant propagation data. The screening algorithm copes with the multiplicative signal fluctuations caused by the atmosphere and with the additive noise that dominates at low signal level.

All receiver outputs are digitized every ¼ second and temporarily stored as a sample set. A running mean of these samples is accumulated for each channel. This running mean is compared with the mean value last recorded for the channel. If for any channel, the running mean value becomes different from the previous mean value by an amount greater than that expected because of receiver noise and atmospheric fluctuations, the running means for all channels are recorded. These recorded running means then become the previous mean values for testing a new sequence of running means that starts with the next sample set. This procedure detects gradual changes in received signal parameters. A test for rapid or impulsive change in a received signal parameter is also made on the individual sample sets. A data set is recorded at least once each minute regardless of whether there are changes in the data.

Each data set contains the time it was recorded so the time interval spanned is available for further data processing. This data screening procedure, then, records all significant changes in data whether instantaneous or gradual, records data periodically for equipment checking, and within these constraints minimizes the amount of data recorded.

The data handling procedures also include provisions for (*i*) easily stopping and starting data collection when the facility is used for radio astronomy, (*ii*) recovering from primary power interruption,† and (*iii*)

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* The computer programming required for data screening and storage was done by H. W. Arnold.

† The computer programming required for power failure recovery and antenna pointing was done by R. W. Wilson.

recording calibration signals on the data tapes. Weather data and system status are recorded on the magnetic tape periodically.

3.5 Propagation parameters measured

The propagation parameters measured and recorded at the main receiving facility are briefly described in this section. A more detailed parameter description is included in Ref. 9. The measurements are recorded for all events that produce propagation irregularities. These events are all associated with cloudy weather; the most severe are associated with precipitation. Propagation statistics for continuous time intervals spanning at least a year are being compiled from the data.

3.5.1 19-GHz attenuation and depolarization measurements

The measurements made on the polarization switched signals and illustrated in Fig. 7 are:

A19V = co-polarized vertical signal amplitude (TVRV)
A19XV = cross-polarized signal amplitude coupled from vertical to horizontal (TVRH)
A19H = copolarized horizontal signal amplitude (THRH)
A19XH = cross-polarized signal amplitude coupled from horizontal to vertical (THRV)
ϕ19V-H = phase difference between vertical and horizontal signals (TVRV and THRH)
ϕ19V-XV = phase difference between vertical signal (TVRV) and its cross-polarized component (TVRH)
ϕ19H-XH = phase difference between horizontal signal (THRH) and its cross-polarized component (THRV)

where TV indicates transmit vertical polarization from the satellite, TH indicates transmit horizontal, RV indicates receive on vertical polarization on the ground, and RH indicates receive horizontal. Attenuation is obtained by comparing amplitudes of attenuated signals with amplitudes of clear air signals. The measurement of ϕ19V-H requires holding a phase reference from one polarization switch time period to the next. This sets a lower bound on the switching frequency determined by the instabilities of both the satellite and ground station primary oscillators (phase references) and the desired accuracy of the phase measurement.

Attenuation and depolarization of signals with any transmitted polarization can be determined directly from these amplitude and phase measurements without having to assume a rain model.* This procedure

* This capability is desirable since all positions within a U.S. coverage beam cannot have their polarizations set optimally with respect to their local rainfall.

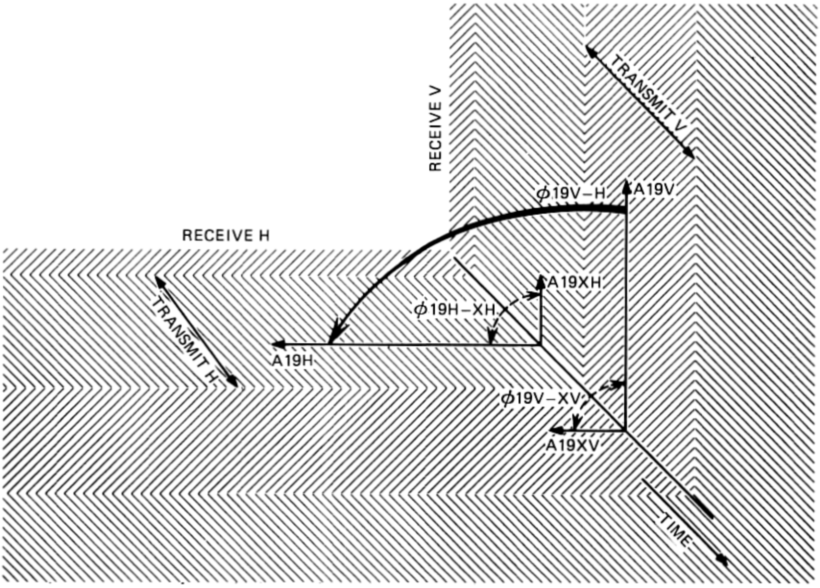


Fig. 7—Three-dimensional diagram illustrating with different crosshatching the transmitter sequencing in time for the vertically (V) and horizontally (H) polarized 19-GHz beacon signals. Also illustrated in two different planes are the reception on V and H polarizations of these signals. The actual signals received are indicated by arrows. Labels of measured signal parameters are as follows. A19V and A19H are copolarized 19-GHz signal amplitudes; A19XV and A19XH are cross-polarized 19-GHz signal amplitudes; ϕ19V-XV and ϕ19H-XH are phase differences between co- and cross-polarized signals; and ϕ19V-H is differential phase between copolarized signals. Note that the measurement of ϕ19V-H requires holding a phase reference between time slots when the beacon transmits V and when it transmits H.

is described in Refs. 7 and 18. These results will be useful for determining (*i*) if there is a fixed polarization orientation with precipitation-related crosstalk low enough to permit doubling capacity by simultaneously using the same frequency on two polarizations, or (*ii*) if (*i*) is not possible, then if a sufficiently low crosstalk can be obtained simply by tracking the linear polarization rotation, or (*iii*) if a more complicated crosstalk minimizing technique will be required, or (*iv*) if crosstalk is low enough to permit use of orthogonal circular polarizations or non-optimally oriented orthogonal linear polarizations for capacity doubling. Determining parameters for signal polarizations different from the transmitted polarizations with sufficient accuracy for use in system design requires measurement accuracy considerably greater than is necessary for using the measured parameters directly in design.[18]

3.5.2 28.56-GHz attenuation and depolarization measurement

Since only one polarization is transmitted at 28.56 GHz, only A28V, A28XV and ϕ28V-XV can be measured. These amplitudes and phases are similar to the 19-GHz measurements made in the transmit V time slot (see Fig. 7). Thus, crosstalk can be determined directly only for the polarization orientation of the measurement. Estimates of crosstalk for other polarization orientations and for other frequencies will be made using these direct measurements, rain models and the extensive 19 GHz measurements.

3.5.3 Amplitude and delay dispersion measurements (usable bandwidth)

The satellite transmits a carrier with frequency f_0 = 28.56 GHz and two sidebands coherently related to $\omega_0 = 2\pi f_0$ with frequencies $\omega_\ell = [(n-1)/n]\,\omega_0$ and $\omega_u = [(n+1)/n]\,\omega_0$. These signals can be represented at the earth station by $s(t) = A(\omega)\cos[\omega t - \omega\tau(\omega)]$ where $\tau(\omega)$ is the dispersive delay at frequency ω and $A(\omega)$ is the dispersive amplitude. If there is no dispersion, $A(\omega)$ and $\tau(\omega)$ are constants; normalized values at the satellite are $A(\omega) = 1$ and $\tau(\omega) = 0$.

Two terms, A_1 and A_2 or τ_1 and τ_2, for series representations of the amplitude or delay, $A(\omega) = A_o + A_1\omega + A_2\omega^2 + \ldots$ and $\tau(\omega) = \tau_o + \tau_1\omega + \tau_2\omega^2 + \ldots$, can be obtained from measurements of differential amplitudes, $A_u = A(\omega_u) - A(\omega_o)$ and $A_\ell = A(\omega_0) - A(\omega_\ell)$ and differential phases, $\phi_u = [n/(n+1)]\omega_u\tau(\omega_u) - \omega_o\tau(\omega_0) = \omega_o[\tau(\omega_u) - \tau(\omega_0)]$ and $\phi_\ell = \omega_o\tau(\omega_0) - [n/(n-1)]\,\omega_\ell\tau(\omega_\ell) = \omega_o[\tau(\omega_0) - \tau(\omega_\ell)]$.

The coefficient A_o can be determined by an absolute attenuation measurement. The absolute delay τ_o cannot be determined since the phase at the satellite is unknown. With only the carrier and one set of sidebands, no higher order dispersion coefficients can be determined.

The measurement of differential phases ϕ_u and ϕ_ℓ requires scaling of ω_u by $n/(n+1)$ to ω_o and of ω_ℓ by $n/(n-1)$ to ω_o as indicated.

Measurement of dispersion (if it exists because of precipitation or index of refraction inhomogeneities) is made over the 528-MHz bandwidth (n = 108) and the 1056-MHz bandwidth (n = 54) permitted by the different satellites with the different sideband frequencies (±264 MHz and ±528 MHz). These measurement bandwidths are large enough to cover system requirements for many years since it is unlikely that transmission rates for individual channels within these bands will exceed 1 gigabit/s in the near future.

3.5.4 Rain signal-scatter measurement

The off-axis beam of the 7-meter antenna points toward a geostationary orbit position that is currently not occupied but could be occupied in the future. Beacon signal scattered by rain or other atmospheric phenomena into the off-axis beam represents a potential interference mechanism between the COMSTAR orbit position and the unoccupied orbital position along the off-axis beam. Measurement of the off-axis beam signal amplitudes determines crosstalk levels and thus limitations on orbital spacing between satellites that may result from scattering of signal by the rain or other atmospheric phenomena.

3.6 Performance

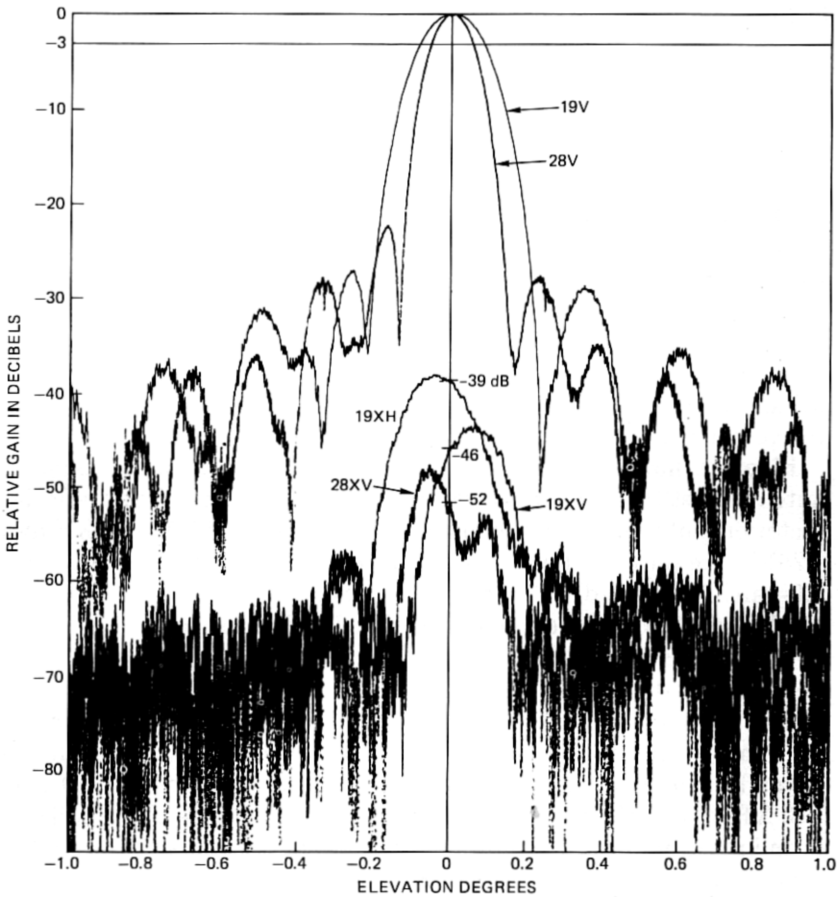
Performance of the individual subsystems in the Crawford Hill propagation experiment is described in the previous sections and in the following papers.[8,9] This section summarizes overall performance of the Crawford Hill main receiving facility working with the COMSTAR beacon at 95°W.

Clear-air signal-to-noise (S/N) ratios measured on cold low-humidity winter days are 60 and 59 dB for 19-GHz H and V polarizations and 61 dB for the 28-GHz carrier. These values are ratios of average signal power to average noise power measured at the narrow-band IF outputs.

Figure 8 shows antenna patterns made by scanning the seven-meter antenna past the beacon and recording the logarithmic amplitude detector outputs. In Fig. 8, the lowest three curves, A19XV, A19XH and A28XV, are the cross-polarized signals from receiver channels with 1.0-, 1.0-, and 1.5-Hz 3-dB IF bandwidths, respectively; the upper curves, A19V and A28V, are the copolarized signals from receiver channels with 10- and 15-Hz 3-dB IF bandwidths. The main beam of the A19H curve lies on top of the A19V curve and A19H sidelobes are all within a few dB of A19V sidelobes. The maximum values of cross-polarization discrimination, i.e., the cross-polarized signal level relative to the copolarized signal level at all points within the 3-dB beamwidths are XRV19 $\leq$ 41 dB; XRH19 $\leq$ 36 dB and XRV28 $\leq$ 45 dB. Differential phase ϕ19V-H is an indicator of the accuracy of alignment of the phase centers of the 7-meter antenna feeds. The differential phase varies $<\pm 1.2°$ over the 3-dB beamwidths. Scans in planes other than the principal planes (azimuth and elevation) are similar.

These antenna pattern measurements illustrate the combined performance of the beacon antennas and the 7-meter antenna. The measurements also demonstrate the capability of the receiver to maintain frequency lock and polarization switch synchronization through deep signal fades (antenna nulls) and to measure the low cross-polarized signal components to levels of the order of 70 dB below the clear-air copolarized signal levels.

Signal amplitudes vary less than $\pm$0.3 dB and differential phase varies less than $\pm 2°$ over several weeks. Most of this variation has a diurnal cycle. Day-to-day repeatability is within measurement resolution. Residual cross-polarized signal levels change with a diurnal cycle that also changes slowly with time, apparently due to change in the orientation of the satellite with respect to the sun. Day-to-day repeatability of cross-polarized signal levels are within $\pm$0.2 dB.

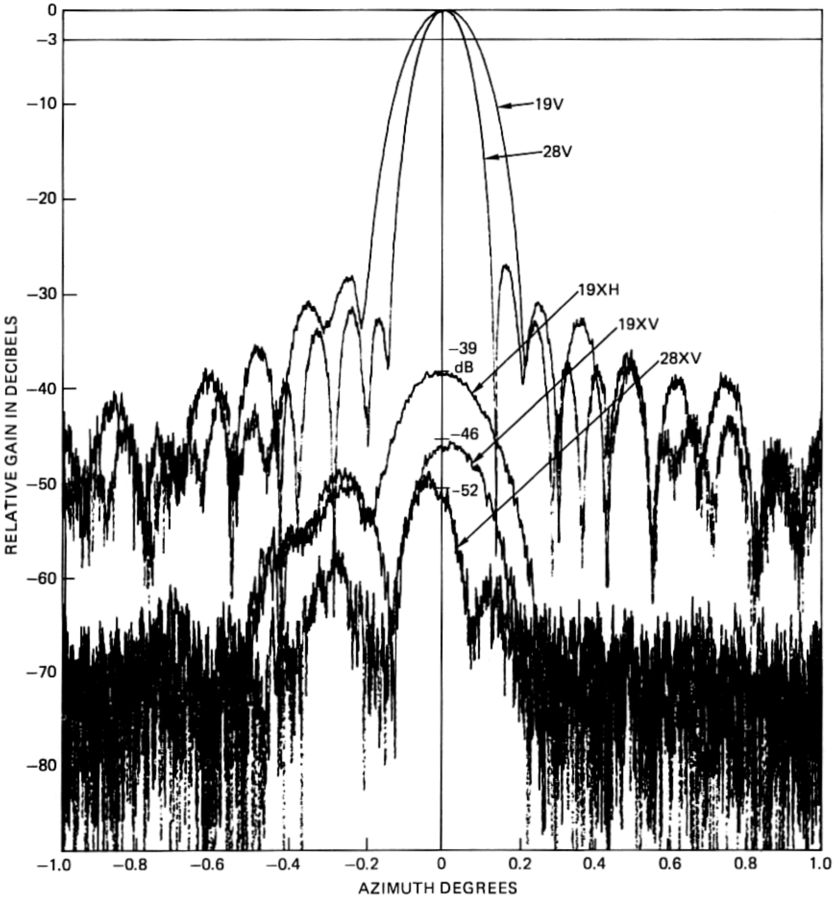


(a) Elevation scan.

Fig. 8—Crawford Hill 7-meter antenna scans of the COMSTAR beacon at 95°W made with the Crawford Hill main facility receiving electronics. Note that the worst first sidelobe is 22 dB down and that all others are at least 27 dB down. Sidelobe levels approach 40 dB down 1° off beam axis. Cross-polarized signals 19XH, 19XV, and 28XV remain more than 38 dB below on axis copolarized signals throughout. Cross-polarization discrimination is better than 36 dB throughout the 3 dB beamwidths. Receiving electronics follow signals through antenna nulls.

IV. CONCLUSIONS

Continuous transmission at 19 and 28 GHz from the COMSTAR beacons in geosynchronous orbit are providing unique opportunities for gathering propagation information needed for designing future high-capacity satellite communication systems. An extensive receiving facility at Crawford Hill, New Jersey, comprising a precision 7-meter-diameter antenna and sophisticated receiving electronics, is providing a detailed look at propagation effects such as attenuation, depolarization, coherence



(b) Azimuth scan.

Fig. 8 (*continued*)

bandwidth and signal scatter that are usually related to atmospheric precipitation. This facility receives on two orthogonal linear polarizations at the two beacon frequencies. In clear weather when atmospheric attenuation is minimal, the signal-to-noise ratio when receiving the beacon at 95°W is 60 dB. Phase differences and amplitudes are measured for all signals and for their cross-polarized components. Cross-polarization isolations are >35 dB throughout the entire antenna beams to the −3-dB beam edges.

Bell Laboratories receiving facilities in Georgia and Illinois are collecting information on signal attenuation and diversity in other climatic regions. Additional propagation information is being collected by non-Bell experiments at other locations.

V. ACKNOWLEDGMENTS

These COMSTAR beacon propagation experiments would not have been possible without the foresight, cooperation and support of a number of people at AT&T, at the Long Lines department of AT&T and at Bell Laboratories. The efforts of all these people are much appreciated by all of us who are now directly involved in these very successful experiments.

E. E. Muller very effectively coordinated the requirements of these experiments with COMSAT General, the overall satellite contractor, with Hughes Aircraft Corporation, the satellite and beacon antenna manufacturer, and with COMSAT Laboratories, the beacon manufacturer.

The contributions of many individuals concerned with particular parts of the experimental facilities are acknowledged in the following companion papers. H. W. Arnold was particularly involved in the overall design, assembly and operation of the Crawford Hill experiment. The efforts of H. H. Hoffman in these areas are also appreciated. The experiment was originally conceived and supported by L. C. Tillotson and D. C. Hogg among others. The continuing support and interest of A. A. Penzias and D. O. Reudink has been helpful. The backing of R. F. Latter and R. C. Harris of AT&T Long Lines and E. F. O'Neill of Bell Laboratories is also appreciated.

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