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## *COMSTAR Experiment:*

# COMSTAR Beacon Receiver Diversity Experiment

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*The design and realization of 19-GHz and 29-GHz beacon receivers for implementation of the remote site diversity reception experiment are discussed. The experiment objectives and constraints are investigated in terms of their impact on equipment realization. Data acquisition and retrieval problems associated with remote sites are also addressed. Finally, some of the results obtained from early operation are presented. These results, obtained from direct measurement of the beacons, correlate very well with earlier radiometer measurements scaled in frequency with appropriate corrections made for the impact of energy scattering due to rain.*

## I. INTRODUCTION

While most current-generation communication satellites operate in the same common carrier bands (4 and 6 GHz) as do terrestrial facilities, operation at significantly higher frequencies—such as the 12- to 14-GHz band, and the 18-, 30-GHz bands—offers a number of important advantages. Among these are expected reduction in interference, reduced spacecraft component sizes, and higher gain spacecraft antenna with the opportunity for independent multiple beams within the continental United States (CONUS).

On the other side of the ledger, radiation at these frequencies is more effectively scattered and attenuated by water droplets, thus threatening system operation with attenuation, depolarization and dispersion effects. These problems are under empirical investigation utilizing beacon sources carried aboard the COMSTAR satellites. This new opportunity follows a fruitful (but limited) period of measurements with radiometers.[1,2,3]

Where uncertainties in radiometer results existed in the past, due to their range limitation and their inability to account for signal loss due to scattering, they can now be overcome using the beacons. Thus the objectives of this new experimental phase are manifold but they can be summarized as follows:

(*i*) Directly obtain continuous, long-term attenuation measurements at (the higher) system frequencies (thus accounting for both absorption and scattering).

(*ii*) Increase the dynamic fade measurement range to at least 30 dB.

(*iii*) Provide for direct comparison of radiometer and beacon measurements obtained simultaneously from the same antenna, thus allowing qualification of radiometer data in hand.

(*iv*) Extend the available site diversity performance data base by operating in different meteorological environments.

Satisfaction of these objectives constrained the design of our receiving stations. In particular, the need for reliable continuous operation requires a capability not only for monitoring the system remotely but also for retrieving data to a central site. The system must provide for unmanned operation over extended periods without loss of data. Finally, the recognition that test sites would be distant (and costly to visit) required that the experiment be implemented to be self-contained and transportable with minimum expense and delays, that equipment failures be very infrequent, and that simple failures not compromise all observations. Consequently, conservative design approaches were used throughout, and provisions were made for operation alarming. The method used to achieve the experimental objectives is discussed in subsequent sections.

Section II presents a discussion of the primary factors which shaped the experimental setup, including such things as anticipated signal-to-noise ratios, the importance of remote test sites, and cost. This is followed in Section III by a detailed description of the data acquisition requirements and their realization. Section IV begins the discussion of the receiver, starting with the preliminary operating objectives. The overall receiver realization is presented in some detail in Section V and includes discussion of the antenna with its auxiliary equipment, the scanning receiver, the 19-GHz receiver, the 28.5-GHz receiver, and the frequency predictor which compensates for satellite drift in the absence of beacon frequency update information. Results obtained during the initial experiment phases are summarized in Section VI.

The Phase I experimental sites are located at Grant Park, Illinois (near Chicago), and Palmetto, Georgia (near Atlanta). Each principal site is equipped with beacon receivers (19 and 29 GHz) and a 13-GHz radiometer. Associated with these sites are remote radiometer sites which

Fig. 1—Beacon/radiometer sites.

provide data for diversity performance evaluation. Figure 1 indicates Manteno, Illinois, approximately 20 miles west of Grant Park, and Temple, Georgia, approximately 20 miles northwest of Palmetto.

## II. PRIMARY EXPERIMENTAL CONSIDERATIONS

Six factors were of prime importance to the design of the beacon reception equipment:

(*i*) The expected power level of the received signals and the required dynamic measurement range.
(*ii*) The spectral width, maximum frequency variations and the rate of drift of the beacon oscillators.
(*iii*) The anticipated satellite stationkeeping excursions.
(*iv*) The requirement for remote unattended and continuously operative stations.
(*v*) The need for coordinated diversity site radiometer data acquisition.
(*vi*) "Minimum" cost procurement and operation.

### *2.1 Preliminary signal-to-noise ratio calculations*

The beacon signal levels and CONUS coverage are detailed in Ref. 4;

the relevant parameters are summarized below:

| | 19 GHz | 29 GHz |
|---|---|---|
| EIRP | 53 dBm | 56 dBm |
| Polarization loss* | 3 dB | — |
| Path loss | 210 dB | 213 dB |
| Fade range | ~35 dB | ~38 dB |
| Min. signal level | <−195 dBm<br>+ $G_A$† | <−198 dBm<br>+ $G_A$† |
| Down converter + preamp noise figure | 6.5 dB | 6.5 dB |

The corresponding noise power in a 100-Hz‡ bandwidth is readily calculated:

$$P_a = N_F + 10 \log \mathrm{KTB}_w + 30 \text{ dBm}$$

$$= 6.5 - 174 + 10 \log 100 \text{ dBm}$$

$$P_a = -147.5 \text{ dBm}$$

Allowing a few dB loss of sensitivity due to satellite stationkeeping variations, antenna misalignment, network loss, etc., implies that achievement of a usable signal-to-noise ratio during deep fades requires an antenna gain of 50 dB or more. In addition, to limit the noise power, it implies a final processing bandwidth significantly less than 100 Hz—which therefore requires the receiver to track the beacon frequency, maintaining lock during fades of at least 35 dB.

### 2.2 Beacon frequency variation

The beacon reference oscillator frequency exhibits a frequency variation less than ±1 part in $10^6$ on a diurnal basis, and ±1 part in $10^6$ per year due to aging. In addition the receiver oscillator has been allocated ±1 part in $10^6$ per year for aging, thus implying a total potential annual variation to be accommodated of ±3 parts in $10^6$ (approximately ±57 kHz at 19 GHz). Consequently, the receiver capture and tracking range was specified to be 100 kHz.

In addition to maximum frequency excursion considerations, the short-term rate of change of frequency must be accommodated. This is a major complication since receiver sensitivity must be obtained by severe band limiting. The receiver configuration chosen utilizes parallel

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* Only one polarization is processed.

† $G_A$, the antenna gain, is determined in Section 2.3.

‡ The beacon design objective was to provide 90 percent of the signal power in a bandwidth of 100 Hz at 19 GHz, or within 150-Hz bandwidth 29 GHz.

processing: a set of 32 narrowband comb-filters for selectivity, and an AFC loop to center the comb set about the instantaneous received frequency. The 32-filter comb set in the 19-GHz receiver spans a total of 1.6 kHz; the AFC loop drives the frequency of the down-converted signal to the center of the comb filter range, allowing only a ±800 Hz band to account for drift errors which are uncompensated by update information which, of course, would be unavailable during periods of severe fading. The maximum estimated drift rate* of approximately 1 Hz/sec implies that, even in the event of deep fades (which preclude feedback frequency updating), there would be no reacquisition delay for outages less than about 15 minutes. Still longer outages could allow drift accumulations greater than 800 Hz, with consequent delay to reacquisition. This compromises data, in that the end of fade would be uncertain. Therefore beacon frequency prediction based upon beacon behavior observed prior to the fade is included in the design. This feature extended the receiver capability for continuous operation in extremely deep fade situations (i.e., no frequency update information) from 15 minutes to over 2 hours.

### 2.3 Satellite stationkeeping

The satellite, while nominally stationary, actually moves within a station of ±0.1° in latitude and ±0.1° in longitude. As a consequence, the ground station antenna must either track this variation or sacrifice absolute gain to provide essentially equal response within the sector traversed by the satellite. Allowing a 1-dB maximum pattern variation due to stationkeeping implies a minimum 3-dB antenna beamwidth of about 0.3°. This corresponds to an antenna gain of about 56 dB, which is consistent with the minimum antenna gain requirement (> 50 dB) necessary to provide the required dynamic range.†

### 2.4 Remote test sites

Practical operation of remote unattended stations requires that equipment be conservatively designed, with broader operating margins than would be necessary if frequent adjustments could be made, and the equipment must have automatic (re-)startup features. In addition, redundant recording equipment is necessary to preclude the loss of interesting data. Finally, representative data should be remotely accessible to allow daily monitoring for both the health of the equipment and the progress of the experiment.

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* Based on COMSAT preflight test curves.

† Antenna selection is discussed in Section 5.1.

### 2.5 Correlation with radiometers

A secondary objective of the experiment was to allow detailed comparison of radiometer and beacon observations, hence the requirement to derive a radiometer signal from the same antenna as that supporting the beacon receivers. A 13-GHz radiometer was chosen; this provides a reasonable match to the dynamic measurement ranges obtained with the beacons and, through frequency scaling, allows calculation of absorption at the beacon frequencies. Scattering losses may be estimated and combined with the measured absorption losses, scaled for frequency differences, and compared with the beacon losses.

### 2.6 Cost

The final restriction, obligatory to all operations, is cost limitation, particularly since multiple sites were to be equipped. It was this consideration that tipped the balance in favor of a fixed, limited gain antenna. This restriction also dictated that standard, readily available components be used in lieu of custom devices.

## III. DATA ACQUISITION

The operation of numerous remote sites, both for beacon reception and for associated radiometer studies, places a high emphasis on data-remoting capabilities (see Fig. 1). It is necessary, of course, to transfer data between associated sites to assess diversity performance; it is equally necessary to transfer data back to Bell Laboratories, Holmdel, for monitoring purposes. The transfer between test sites is accomplished using a 12-bit analog-to-digital converter to drive an FSK telemetry system over dedicated phone lines. At the receiving end, the digital signal is reconverted to analog and processed in conjunction with signals received directly at the main site. Transmittal of summary data back to Holmdel is accomplished on a *dial-up basis* over the DDD network *once* a day.

Data are recorded in a number of different forms: At each site a real-time record of the various received signal levels is kept on stripcharts. At the main sites, Palmetto and Grant Park, stripcharts record the simultaneous levels of both the local and the diversity signals. In addition, at each main site there is a Portable Propagation Recorder (PPR),$^5$ which records the accumulated time during which the signal level is below various fade thresholds, as well as the number of times that a threshold level is traversed. This record is stored in a solid-state memory, the contents of which are accessible by telephone. Finally, to ensure against accessing problems, equipment failure, or holiday weekends, the data are dumped daily onto a local punched paper tape.

For several years prior to the beacon experiment, there existed at Palmetto a computer-directed data-gathering complex supporting other propagation experiments, including the ongoing radiometer tests. This complex, known as MIDAS (Multiple Input Data Acquisition System) uses magnetic tape to store a sampled time record of signal variations. Its sampling rate is five times per second on each channel. For this experiment the Palmetto MIDAS complex records the levels of not only both beacon signals and the on-site 13-GHz radiometer signal at Palmetto but also the 18-GHz radiometer signal from the remote diversity site. In addition it records the instantaneous beacon frequency and the local rain rate as sampled in a tipping bucket gauge. The magnetic tape record is then mailed to Holmdel on a weekly basis for processing.

## IV. RECEIVER OPERATING OBJECTIVES

This beacon receiver was designed to the following objectives:

(*i*) Acquire the signal within 15 seconds either after turn-on or after an extended period of signal dropout. Similarly, in the event of power failure, automatically reacquire the beacon signals without external intervention.

(*ii*) Provide accurate (±0.5 dB absolute and ±0.1 dB relative) fade indications over at least a 30-dB dynamic range, at both 19 and 29 GHz.

(*iii*) For periods up to 1 hour, in the event of loss of signal due to fading, reacquire (virtually instantaneously) when the signal recovers to the fade depth at which it was lost.

(*iv*) Track frequency variations and provide output indications accurate to approximately 1 part in $10^8$.

Each of the above objectives was not only achieved but the realized receiver exceeded the required performance.

The functions identified above are realized in the receiver shown in the simplified block diagram in Fig. 2. Each functional block is treated in some detail following a brief operational summary.

## V. RECEIVER REALIZATION

Initial acquisition of the 19.04-GHz signal is accomplished by a scanning receiver which searches a bandwidth of 95.9 kHz for the 19-GHz tone and the two (polarization) switching sidebands, which are 1 kHz removed from the carrier.

Following acquisition, the two receivers, one at 19 GHz and one at 29 GHz, begin monitoring fades. Associated with the 19-GHz receiver is a frequency predictor which, under normal operating conditions, continuously monitors the received beacon (19 GHz) frequency and the rate

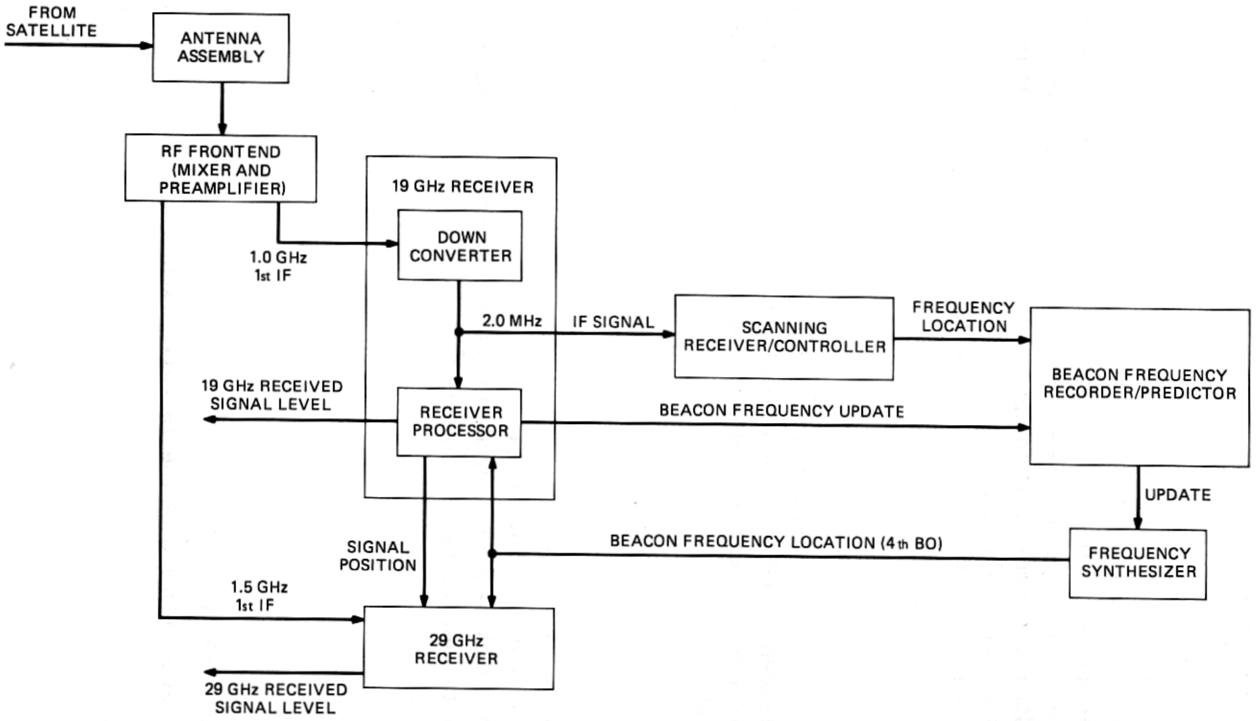


Fig. 2—Simplified receiver block diagram.

at which it is drifting. The coherent relationship between 19- and 29-GHz beacons allows slaving of the 29-GHz receiver frequency to the 19. In the event of loss of the 19-GHz signal for an extended period of time, the predictor extrapolates the last valid frequency measurement using the most recently estimated frequency derivative. This ensures that the local oscillators of the receivers track the beacon frequency and are in best condition to reacquire the signal once it reappears. Note that loss of only the 29-GHz signal has no impact on the frequency tracking of either receiver.

In addition to the basic functions identified previously, there are several other functional units which are separately identified and discussed prior to treatment of the major units. These units are: antenna assembly, frequency multiplier, frequency synthesizers, and comb filters.

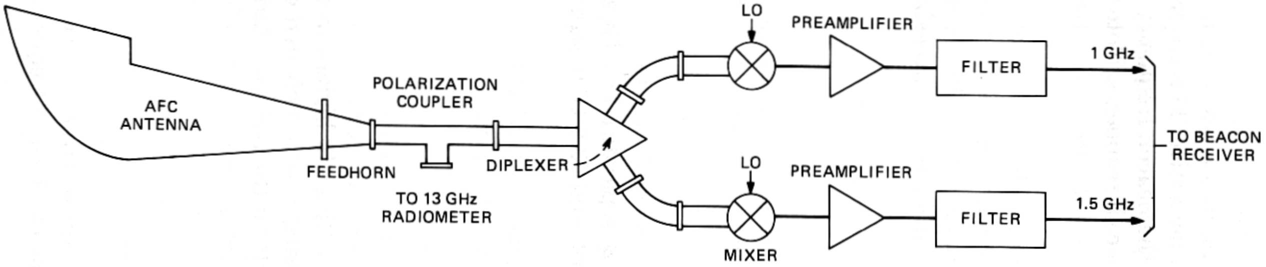
### *5.1 Antenna assembly*

The antenna assembly, shown diagramatically on Fig. 3, includes: antenna mount with azimuth and elevation adjustments, antenna, feedhorn, polarization adapter assembly, polarization coupler and a frequency diplexer.

The functions of the antenna assembly are to: intercept sufficient beacon signal energy for processing, separate a 13-GHz signal for driving a radiometer, and separate the 19- and 28.5-GHz signals for measurement by the beacon receiver.

Recall, from Section 2.3, that a minimum 3-dB bandwidth of 0.3° was necessary to meet the amplitude misalignment objective and that it was this beamwidth constraint that restricted the antenna aperture to 8 feet. The antenna selected is a CH-8 (7.5-foot aperture) conical, horn reflector antenna manufactured by Antennas for Communications Incorporated. Using a specially designed feed horn tapered to WC-65, measurements were made at 19.04 GHz and 26.01 GHz (the highest frequency available from the equipment used for tests) which indicated gains at the two frequencies of 51.0 dB and 53.6 dB for the vertical polarizations and 51.0 dB and 53.4 dB for the horizontal polarization. Scaling to 28.56 GHz implies gains of 54.5 dB for the vertical and 54.2 dB for the horizontal polarizations. Since the satellite could traverse a ±0.1° window, it was important to determine the impact of a fixed orientation on received amplitude. At 28.5 GHz, a 0.1° misalignment results in approximately 1-dB gain decrement. At the time the receiver was installed, the antenna orientation was optimized for the two beacon frequencies and then secured permanently.

The polarization adapter assembly is a rotatable framework attached to the feedhorn which permits continuous adjustment of the angular



| | | | | |
|---|---|---|---|---|
| INSERTION LOSS OR GAIN AT 19 GHz | −0.25 dB | −0.3 dB | +24 dB | −2.4 dB |
| INSERTION LOSS OR GAIN AT 29 GHz | −0.4 dB | −0.2 dB | +22.4 dB | −3.1 dB |

Fig. 3—Antenna assembly and RF front end.

relationship between the feedhorn (antenna) and the polarization coupler. This ensures that the nominal received signal polarization can be accounted for readily, thus placing the polarization coupler in position to couple maximum energy through the vertically polarized port for both 19 and 29 GHz.

The 13-GHz radiometer signal is obtained via a polarization coupler attached to the feedhorn. It is obtained from the "horizontally" polarized port, while the orthogonal port* provides the "vertically" polarized signals (19 and 28.5 GHz) which drive the beacon receiver. This coupler provides considerable flexibility and introduces only 0.1 dB insertion loss at 13 GHz, 0.25 dB at 19 GHz and 0.35 dB at 28.5 GHz. The return loss at each of these frequencies is greater than 30 dB. This technique provides the beacon receiver only one component of the 19-GHz signal; the horizontally polarized component is terminated.

The final item of the antenna assembly is the diplexer. Conceptually, this is a waveguide 120° Y junction with a high-frequency "short" in one output leg and a low-frequency "short" in the second output leg. This readily permits separating the two beacon signals at a loss (insertion) penalty of 0.2 dB at 28.5 GHz and 0.3 dB at 19 GHz.

### 5.2 Frequency multiplier

The receiver utilizes 5 IF frequencies† to obtain the required gain and selectivity prior to detection. The first IF operates at 1.0 GHz; the first beat-oscillators (BO at 18.04 GHz and 27.06 GHz) are obtained from a frequency multiplier built by RDL to Bell Laboratories specifications. This supply is basically a multiplier chain (X288 and X432) which operates upon one precision reference frequency of 62.53888 MHz which is developed within the receiver from a 10.000-MHz reference source.

### 5.3 Frequency synthesizer

Two Rockland frequency synthesizers are used for the fourth BO, one in the main and one in the scanning receiver (see Section 5.5), to down-convert from 2 MHz to 123 kHz. In addition, the digitally controlled synthesizer provides the incrementally adjusted (100-Hz steps) frequency control needed for the scanning receiver; the second synthesizer provides the fine resolution (12.5 Hz) steps needed in the AFC loop of the tracking receiver. These synthesizers were selected because of two features which make them particularly attractive—frequency changes are essentially instantaneous, and the phase is continuous. This is ac-

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* The two signals are orthogonally polarized and are nominally called horizontal and vertical polarizations but are not actually H and V polarized at the receiving sites.

† For the 19-GHz receiver they are: 1 GHz, 20 MHz, 2.0 MHz, 123 kHz, and 10.5 kHz. For the 28.5-GHz receiver the frequencies are scaled in a ratio of 3:2.

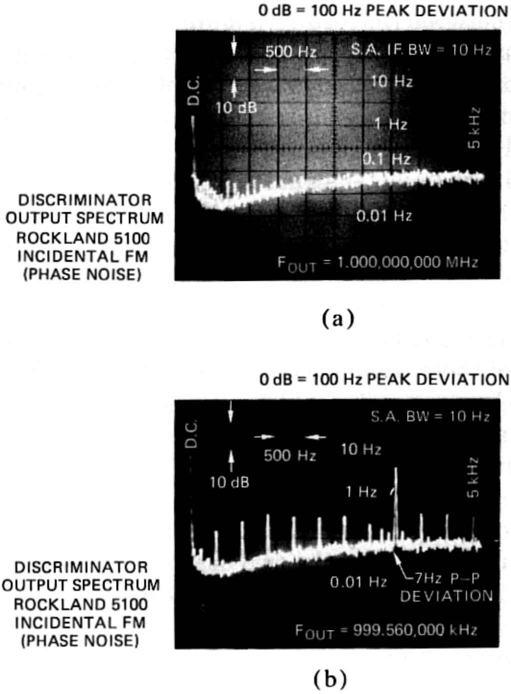


Fig. 4—(a) Discriminator output with synthesizer set to 1.000,000,000 MHz. (b) Discriminator output with synthesizer set to 0.999,560,000 MHz.

complished by using the phase as the driving variable within the synthesizer. A particular signal frequency output is achieved by controlling the rate of change of phase. Thus when a frequency change is called for, the rate at which the output signal phase accumulates is either increased, for a higher output frequency, or decreased for a lower output frequency. No discontinuities occur in the phase of the output signal, and thus there is no need to wait for filter transients to damp in the receiver whenever the synthesizer output frequency is changed. Without this capability, each change in frequency during scanning or tracking would necessitate delays for filter settling.

The synthesizer is driven from a source derived from the 10.000-MHz reference supplying the frequency multiplier discussed above. All BO frequencies in the receiver are derived from this reference, thereby eliminating many potential problems such as relative drift among the frequencies.

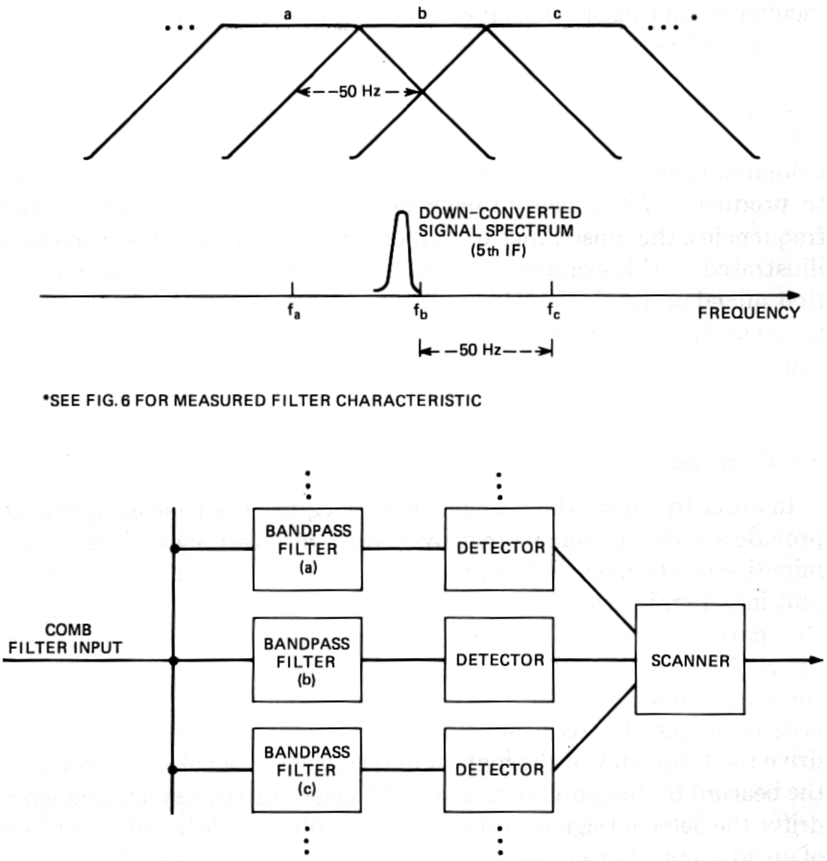
Although the digital frequency control made the system attractive, this approach also implies a certain amount of phase noise arising from the A/D quantization in the synthesizer. This caused some initial difficulties since the synthesizer output could not be used directly due to incidental FM (phase noise) it contained. For example, with the output set for 1.000,000 MHz the phase noise appears random and spectrally smooth, but with slight changes in output frequency a structured noise spectrum became apparent. For example, with an output frequency of 999.560,000 kHz, a spectral analysis revealed a number of tones (with a dominant noise tone at about 3.6 kHz offset), of sufficent amplitude to produce a 7-Hz peak-to-peak deviation (see Fig. 4). (For other frequencies, the noise tones would, of course, vary, but the problem is illustrated by this example.) To reduce this phase noise, the signal was first mixed up to 18.77 MHz (which maintains the same level of phase noise) and then divided by 10—which reduces the phase noise by 20 dB. This ensured that the residual incidental FM would be of no consequence in beacon reception.

### 5.4 Comb filters

In order to reduce the time needed to acquire the beacon signals, to provide a wide frequency range over which accurate signal level determination can be made (while providing narrowband processing for noise limiting), parallel signal processing was incorporated. The first stage of that parallel processing is a set of 32 high-resolution, closely matched filters of 100 Hz bandwidth and spaced by 50 Hz. These comb filters span the range from 9.7 kHz to 11.3 kHz. The output signal from each filter is detected and the frequency synthesizer is incremented to continually drive the frequency of the highest detected signal level (assumed to be the beacon) to the center of this 1600-Hz band. As the beacon frequency drifts, the detected signal level in the center filter tends to fall as the level of an adjacent filter increases. Figure 5 illustrates the condition: output $b > a > c$, which implies that the signal is within the region $f_b - 25$ Hz to $f_b$. If we then note the magnitude of the difference between the output of $b$ and the output of $a$ we can further subdivide the region. If $b - a >$ 1 dB then the signal is located within 12½ Hz of the center of filter $b$. Thus 12½ Hz resolution can be obtained; when the signal drifts further than 12½ Hz from the comb center, the BO is readjusted to drive it back. Parallel processing ensures that if the beacon signal fades below a detectable level (about 38 dB fade, remaining faded for an extended period), upon its recovery to a detectable level, if it lies anywhere in the band covered by the comb set, it will be detected virtually instantaneously. The actual detection process associated with the comb filter outputs is discussed in Section 5.7.

### 5.5 Scanning receiver

The scanning receiver is essentially a scanning spectrum analyzer. Its input is the 2.0-MHz third IF; this signal is twice down-converted to drive



*SEE FIG. 6 FOR MEASURED FILTER CHARACTERISTIC

Fig. 5—19-GHz receiver comb filter characteristic.

two sets of comb filters. The two sets of filters have their outputs processed alternately, thus doubling the allowed settling time per filter while maintaining a rapid scan time (see Section 5.6). Each comb set consists of three 100-Hz filters separated by 1 kHz. The two comb sets are offset from each other by 50 Hz. The filter outputs are linearly detected to estimate power in the band and the entire frequency band of interest is scanned by causing the frequency synthesizer to shift the fourth BO. As the filter outputs are measured, the controller portion of the receiver stores observations, correlating the fourth BO frequency with the power received. At the completion of a scan, the location of the highest detected value is assumed to be the location of the carrier; however, the processor also checks to ensure that sidebands, down 4 dB from the carrier, are found in frequency slots 1 kHz above and below the carrier. If the levels are incorrect by more than 1 dB relative to the carrier, the data is not considered valid. When a valid signal is found, i.e., a carrier of sufficient level to be a candidate and having sidebands appropriately located and energized, the frequency location is stored. This frequency is compared with that of the main receiver and the offset, if large enough, is used for correction of the fourth BO.

Although continuous scanning is desired, it is imperative that spurious responses not input false information to the basic receiver. Thus, update is inhibited without the presence of both carrier and two sidebands; additionally, the absolute signal-to-noise level must be high enough to ensure valid data. If these conditions are satisfied and the frequency difference between the scanning receiver and the main receiver is 187.5 Hz or greater, the scanning receiver output will correct the main receiver tuning. The intent is to ensure that the received signal is maintained as close as possible to the center of the comb filter set to provide maximum accommodation to drift. The 187.5-Hz threshold is somewhat arbitrary but derives from the smallest frequency increment (12.5 Hz) multiplied by 15—which is the maximum count of a four-stage counter.

Under normal operating conditions the scanning receiver continues to operate, but its output is nonfunctional. It *is* functional at initial acquisition, and because the site is remote and unmanned, it must also function in reacquisition should tracking be interrupted for two hours or more.

### *5.6 Equipment design considerations*

Since reliable operation was desired even under worst case conditions, the maximum anticipated frequency drift range of the beacon, ±2 ppm for aging and diurnal variation, was used in determining the maximum range, the design goal was to locate the signal to within 25 Hz, using the commodate any unforeseen variations* which might cause the beacon frequency to drift beyond the receiver window. In spite of this large scan range, the design goal was to locate the signal to within 25 Hz, using the scanning receiver, and to accomplish this in a maximum of 15 seconds. The need to make the receiver relatively inexpensive and to accomplish the realization in a short time frame implied that the filters would have to be LC rather than crystal. Selection of the final IF was based on several considerations. The bandwidth desired was 100 Hz to match the beacon specification of 90 percent of the 19-GHz energy contained within a 100-Hz band (150 Hz for the 29-GHz signal). The achievable filter Q was limited by the coils used. Below about 10 kHz the coil *Q* fell off faster than frequency, thus setting 10 kHz as the lowest operating frequency. Higher frequency operation would be threatened by proportionately

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* This includes ±1 ppm for beacon receiver aging.

greater temperature drift problems. Thus, the best engineering tradeoff between operating frequency and component availability, stability and tolerance suggested a final IF of about 10 kHz.

Conceptually, a single 25-Hz filter/detector system could then be used to find the signal (carrier and sidebands) with the processed results being stored. However, this would result in a long scanning time to allow sufficient filter settling time (60–100 msec per step) and a resultant unacceptable scan time of 3–5 minutes. As an alternative, two sets of filters of 100-Hz bandwidth were constructed. Each set was constructed to simultaneously monitor three slots separated by 1 kHz. This allows immediate recognition of the carrier and its two sidebands. The second set of filters is offset from the first by 50 Hz, permitting 25-Hz frequency accuracy and a full scan in only 15 seconds. Frequency interpolation is possible because the filter responses are well controlled and relative power levels are determined by signal frequency. As can be seen in Fig. 6, if $b > c > a$, where $a$, $b$, $c$ represent the powers in the respective frequency bands, then the beacon signal must lie between 10.5 kHz and 10.525 kHz. The speedup in scan time (relative to the conceptual 25-Hz filter approach) is due to increasing filter bandwidth from 25 to 100 Hz.

Two critical functions in the scanning receiver are linear detection and sample-and-hold. The detectors, well matched and linear to within 0.1 dB over a 60-dB range, are built around the LM318N op amp with 458-type diodes in the feedback path. The sample-and-hold is especially critical since the peak detected sample must be stored for a full scan of 15 seconds. Stable storage with time is most critical when sampling the spectrum in the vicinity of the carrier and its sidebands, i.e., the carrier, the first and third harmonics (a total of 6 kHz) sliding through a 2-kHz window for a total of 8 kHz. With 1/64 sec allotted per step,* this implies a critical storage time of about (8 kHz/100 Hz/step)($\frac{1}{64}$ sec/step) = 1.25 seconds. The critical limiting parameter in the receiver is thermal noise. Ensuring that all other degradations (such as signal droop in the sample-and-hold circuit) contribute small degradation relative to noise requires that droop be limited to no more than 0.05 dB in 1.25 seconds. This corresponds to a maximum droop of no more than 0.6 dB over the 15-second hold time. The current drive capabilities of the op amp, coupled with the slew rate requirements of the sample-and-hold limit the size of the capacitor to about 0.02 $\mu$F. For this size capacitor, a 0.05 dB droop in 1.25 seconds implies a maximum leakage of 1/4 nA. Choice of a polystyrene capacitor for storage ensured that the primary source of this leakage would be the reverse bias of the detector diodes. Back bias on most diodes would result in several nanoamps leakage—much too

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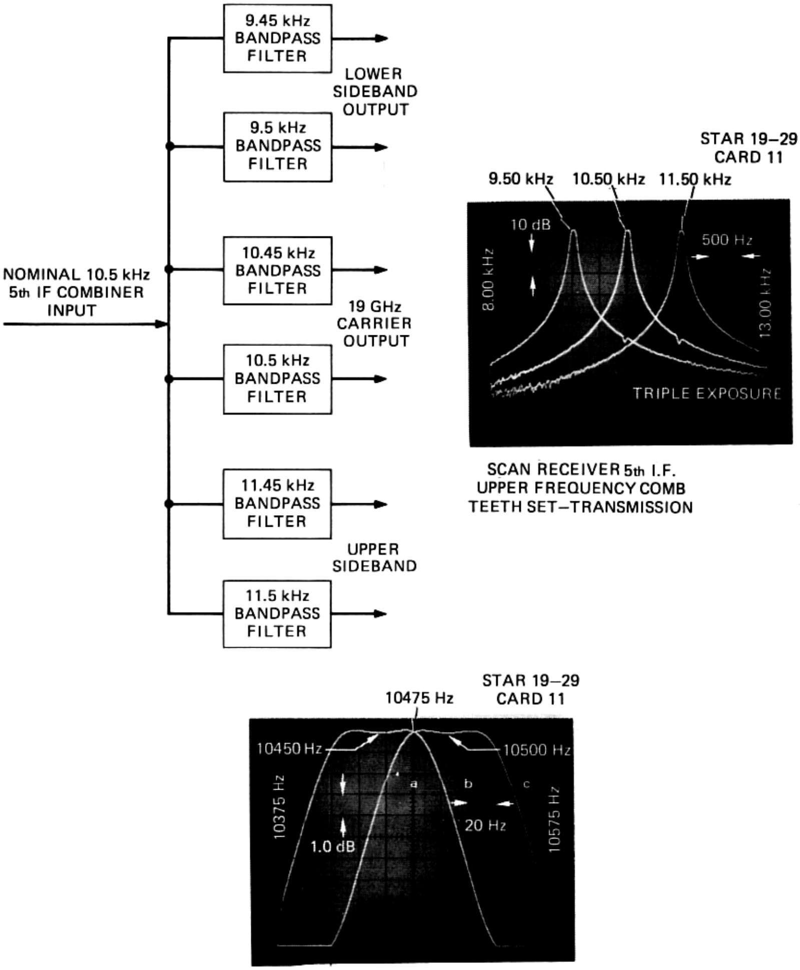
* 15 sec scan time/(960 kHz band/100 Hz steps) = $\frac{1}{64}$ sec/step.



SCAN RECEIVER 5th I.F.
UPPER FREQUENCY COMB
TEETH SET—TRANSMISSION

(5th I.F.) CARRIER COMB
TEETH—TRANSMISSION

Fig. 6—Scanning receiver comb filter characteristics.

large. However, by introducing circuitry (see Fig. 7) to ensure that the bias level across the diodes is virtually zero, i.e., less than 10 mV, the leakage current reduces to less than 1 pA. In a similar fashion, another diode associated with the hold circuit was compensated. This left, as the only current of consequence, the input bias current of the isolation amplifier of the hold circuit. Using a LH0022C, which limits maximum bias current to 50 pa, ensured that droop would not be a problem.

### *5.7 19-GHz receiver*

The 19-GHz receiver shown in Fig. 8 tracks the beacon signal, detects

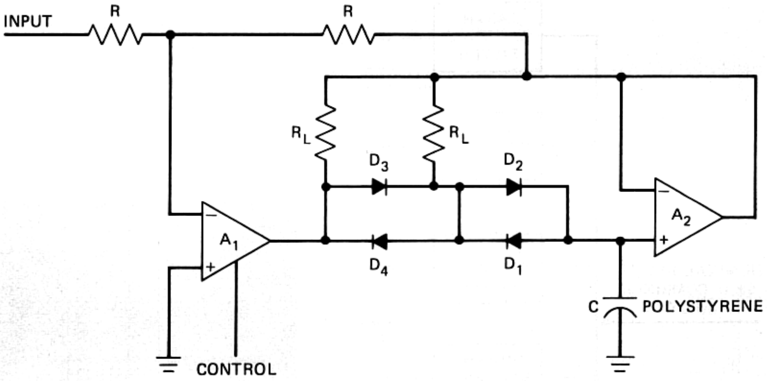


Fig. 7—Leakage compensation in sample-and-hold circuit. The feedback path around $A_2$ ensures that the drop across $D_1$ and $D_2$ is virtually zero, and thus there is no current leakage from C. Resistors $R_L$ are large and serve to provide a path for residual diode leakage current.

its level, and provides the 3/2 frequency-scaled BO for the down-conversion of the 29-GHz signal.

In the interest of keeping waveguide loss to a minimum, the first down-conversion to 1 GHz and amplification of the beacon signal (by about 24 dB) takes place on the polarization adapter assembly which is mounted on the antenna feedhorn. See Fig. 9.* The Space Kom down-converter is a Schottky-diode balanced mixer which, combined with a low noise preamp, yields a combined noise figure of 6.5 dB (due primarily to the mixer). The source of the 18-GHz BO is the frequency multiplier described earlier. The resultant 1-GHz first IF signal, after bandpass filtering to 12 MHz to limit noise and reject images, is then processed by the main 19-GHz receiver. As indicated in Fig. 8 the second down-conversion, to 20 MHz, is accomplished using a double balanced mixer. This mixer requires matched impedance at each port which is constant at 20 MHz as well as 1 GHz. This was realized by following the mixer with a 2-pole Butterworth (constant resistance) LPF with a 100-MHz BW and then 15 dB of gain. To limit unwanted signals, a 2-pole Chebyshev image rejection BP filter with 46 dB of rejection is used prior to the next down-conversion.

After the third down-conversion the signal is split and used to drive the 19-GHz receiver as well as the scanning receiver discussed earlier. The signal has now been amplified from a nominal −110 dBm to −53 dBm. After the fourth conversion to 123 kHz, a 4.0-kHz BW, BP filter (Chebyshev, 0.01 dB ripple) is used to further restrict the bandwidth. Note that the source of the fourth BO used in this down-conversion is

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* Note that the RF front end and temperature-controlled reference noise source for the 13-GHz radiometer are also mounted on the adapter assembly.

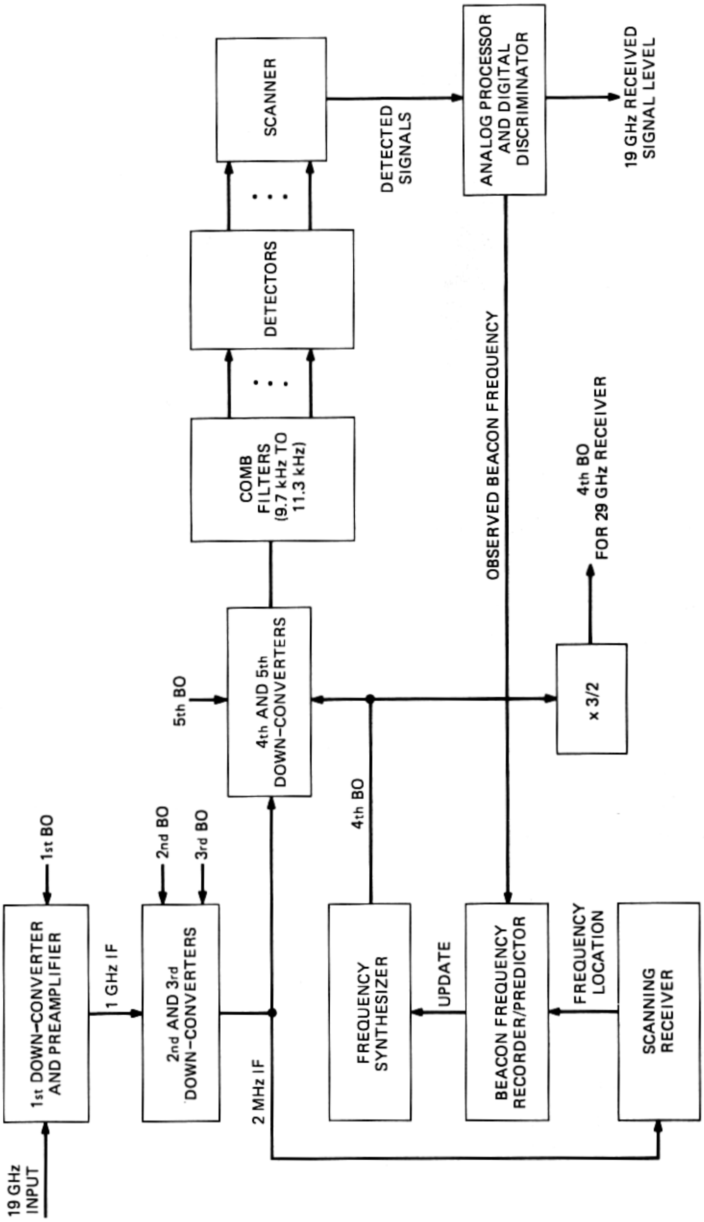

Fig. 8—19-GHz beacon receiver.

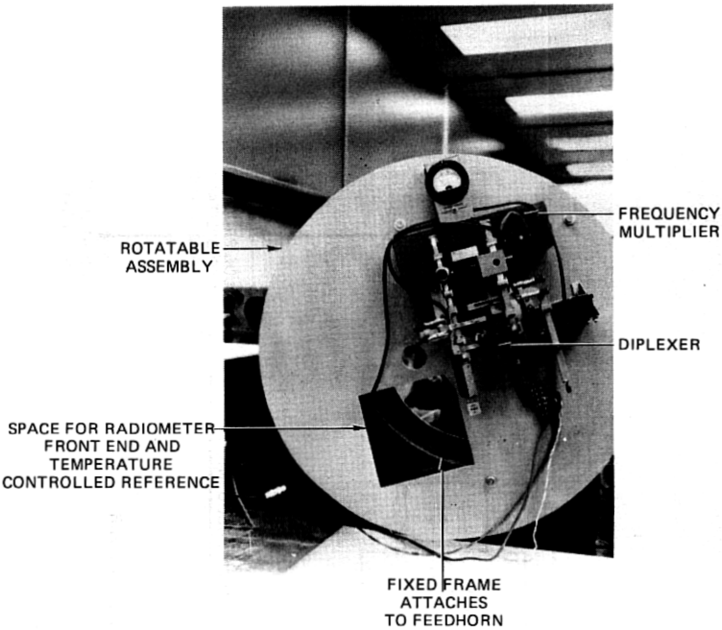

Fig. 9—Polarization adapter assembly.

the digitally controlled frequency synthesizer, which is tuned in 12.5-Hz increments to continually center the received signal at 123 kHz. After down-conversion to 10 kHz the output is passed through a 25-kHz one-pole active Chebyshev low-pass filter. At this point the signal level has been boosted to 14V P-P, and it is this signal which drives the comb filter detectors.

The five down-conversion steps were made along the way to allow progressive tightening of the noise bandwidth without requiring excessively high $Q$. By gradually narrowing the noise band, the filters can be designed with readily achievable $Q$ using standard $L/C$ technology, thus precluding the need for costly, specially designed high-$Q$ crystal filters.

The actual detection process is illustrated in Fig. 10. The fifth IF signal is simultaneously fed to a set of 32 filters of 100-Hz bandwidth on 50-Hz centers spanning a frequency range from 9.7 kHz to 11.3 kHz. Each filter is a 2-pole Chebyshev with a 0.1-dB bandwidth of 50 Hz. Because of the well-controlled filter shape, it is possible to make an accurate determination of signal location from the relative levels in several filters. Each detector output (one detector/filter) is post-detection filtered to 1-Hz bandwidth to further reduce noise. Samples of the post-detection filter outputs are multiplexed together and scanned by a peak detector. A

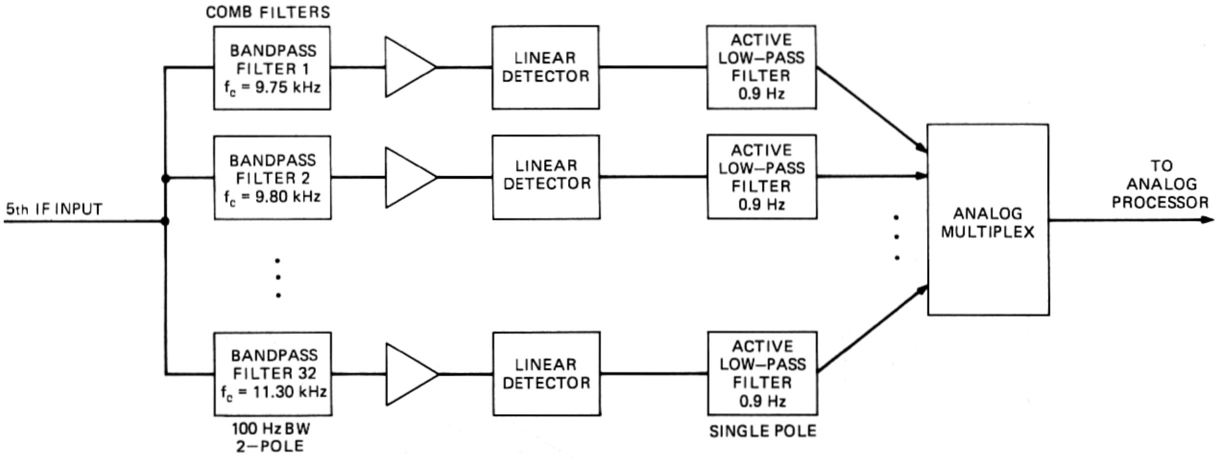

Fig. 10—Parallel processing/detection.

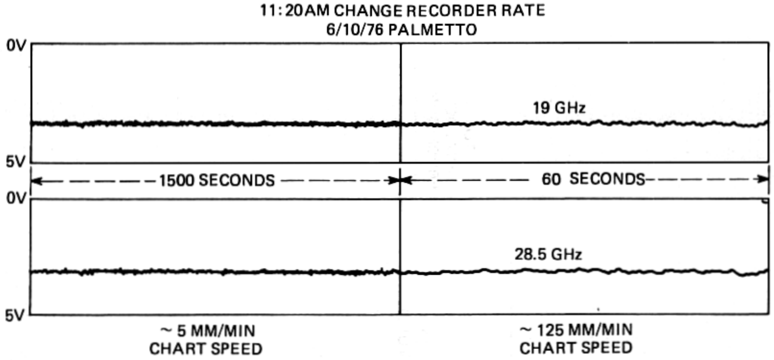

Fig. 11—Periodic amplitude variations. Amplitude scales are linear in voltage; thus the 19-GHz periodic ripple is about 0.2 dB in magnitude. The periodicity was not obvious until the chart speed was increased. At 5 mm/min the variation looked random; however, at 125 mm/min the periodicity becomes apparent.

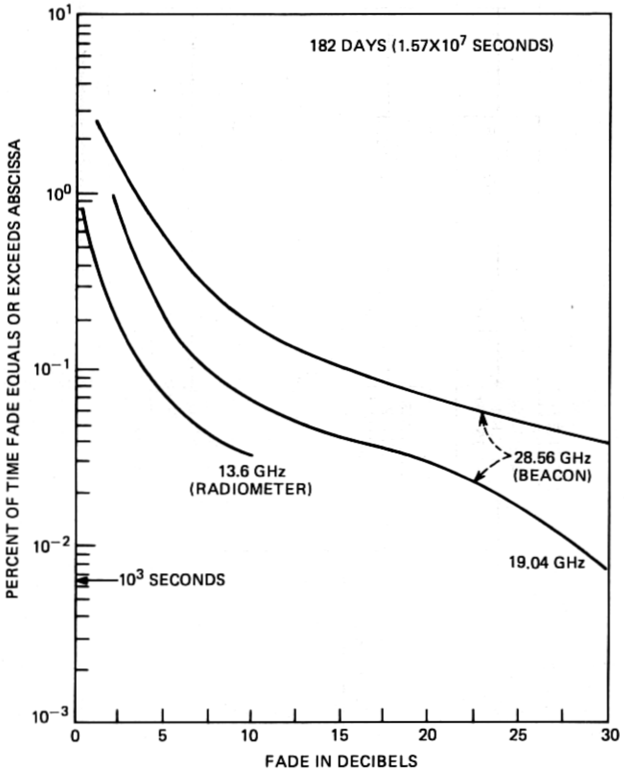

Fig. 12—Grant Park fading.

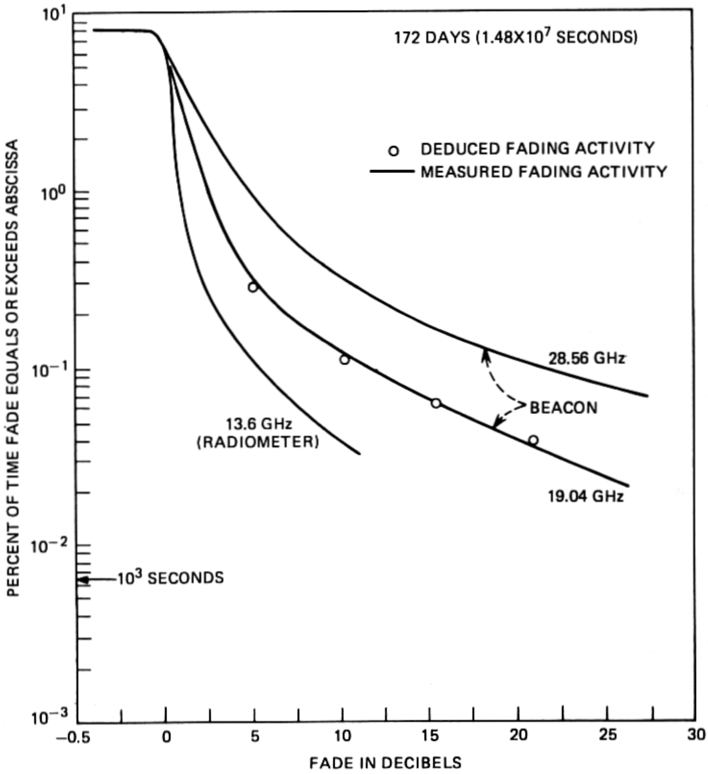

Fig. 13—Fade distribution in Palmetto, Georgia.

sample-and-hold following the peak detector always acquires the most recent sample of the received signal and is updated at each scan of the comb filter outputs. Also, by noting the location of the maximum signal within the comb set, together with the setting of the synthesizer, the beacon frequency is determined. Note that the comb filters have a well-controlled 50-Hz flat bandpass spaced on 50-Hz centers with the center frequency controlled to ±1 Hz, a 75-Hz 1-dB bandwidth, and a 100-Hz 3-dB bandwidth. As discussed in the section on comb filters, it is possible to get 12½-Hz resolution of the beacon frequency and thus to increment the frequency synthesizer so as to continually drive the beacon signal to the center comb position.

### *5.8 28.5-GHz receiver*

Since the 28.5-GHz transmitter is scaled in frequency by 3/2 from the 19-GHz transmitter, the 28.5-GHz receiver local oscillator frequencies are also derived directly from those of the 19-GHz receiver. In this way a single AFC loop is sufficient to center both received signals in their

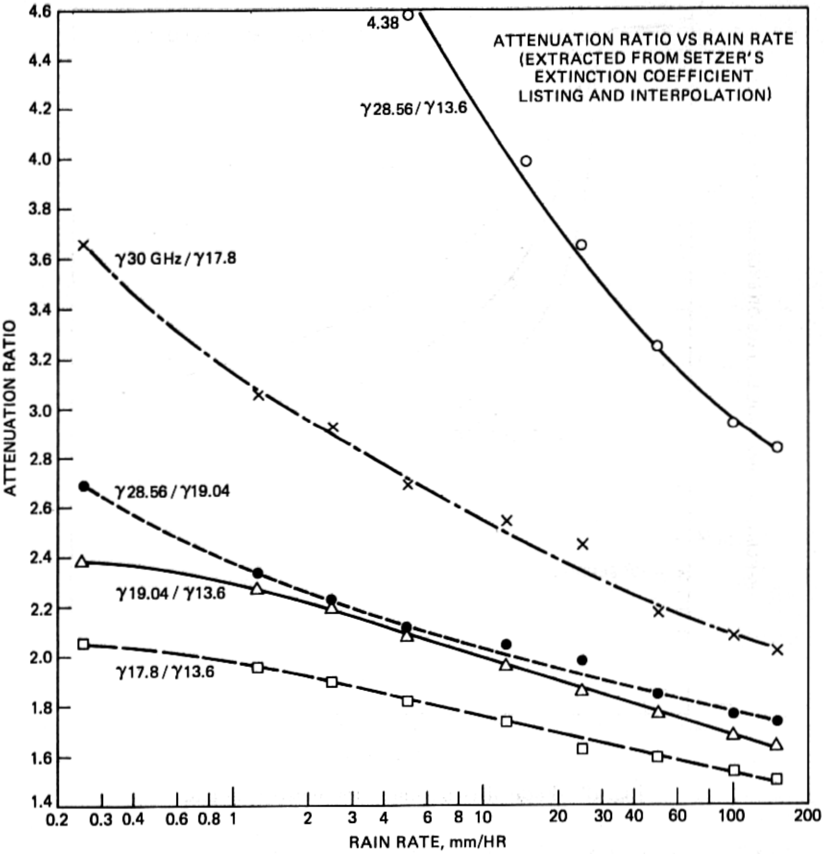

Fig. 14—Attenuation ratios vs. rain rate.

respective filters. Each step in the 28.5-GHz receiver processing is analogous with the 19-GHz receiver except that all frequencies are scaled up.

The signal is down-converted in five steps, using double balanced mixers and filtering to reject images generated in the process. The final processing is done at 12 kHz with a 150-Hz filter. This output is passed through a linear detector followed by a ½-Hz LPF to average out the noise. Note that since the 19-GHz signal will undergo less severe fading than the 28.5-GHz signal, the 19-GHz signal will always recover first and thus provide valid frequency information for detecting the 29-GHz signal before the 29-GHz signal actually recovers.

### 5.9 Frequency predictor

As indicated earlier, there will be occasional periods during which the

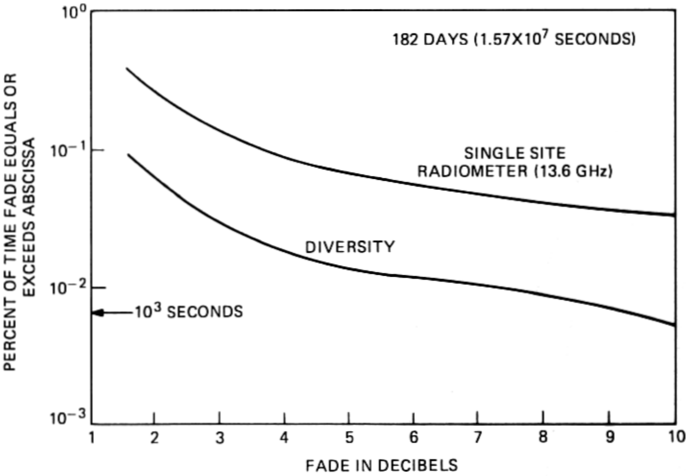

Fig. 15—Diversity results, Illinois.

beacon signal will be attenuated below the level of reliable reception. If these periods are relatively long, say 30 minutes or more, the frequency drift of the beacon may be sufficient to remove it from the range of the receiver. To avoid this potential problem, a frequency drift predictor was incorporated in the receiver. Noting the frequency of the beacon, as indicated by the settings of the synthesizer, and the location of the peak signal in the comb filter set, storing these indications each scan and averaging over a long time period (512 seconds), the average rate of change of frequency can be determined. This drift rate is continually updated as long as the received signal is strong enough for reliable tracking. Whenever the signal level falls below that level, presumably due to heavy rainfall, the drift rate update is stopped. Instead, the most recently calculated drift rate is used to increment the synthesizer and drive the local oscillators to the frequency anticipated by frequency extrapolation. This technique had been found to increase the tracking receiver's capability for immediate acquisition, extending that capability from 15 minutes to over 2 hours.

## VI. EARLY RESULTS

Detailed reduction of the data is, of course, ongoing; there are, however, several items of interest already gleaned.

Immediately following installation of the beacon receiver in Palmetto, a very low level, approximately 0.25-dB peak-to-peak, periodic amplitude variation was detected in both the 19- and 28.5-GHz received signals; see Fig. 11. The frequency of this oscillation, ~54 times per minute, was found to coincide with a 0.04-degree precessing of the satellite arising

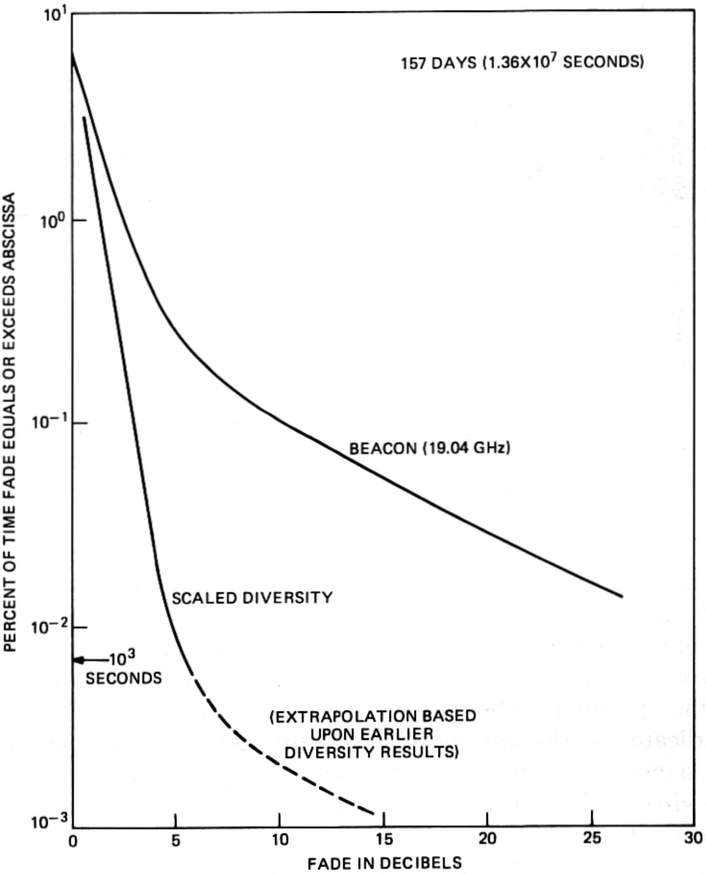

Fig. 16—Diversity results, Georgia.

from spin stabilization. This phenomenon was not detected at the other beacon reception sites in Grant Park or Crawford Hill due to the fact that Palmetto was closer to the edge of the satellite antenna pattern and thus experienced a greater amplitude change as the satellite pattern scanned.

The long-term attenuation (time faded below) of the beacons and of the 13-GHz radiometer, at both Grant Park and Palmetto, are shown in Figs. 12 and 13 respectively. Very good agreement among the three observations was demonstrated by selecting a particular level of occurrence, say 0.1 percent, and determining the attenuation ratio between two of the curves, e.g., the 28.5 GHz and the 13 GHz. From that ratio an equivalent rain rate can be deduced from Setzer's[6] work (attenuation ratios as a function of rain rate were derived from Setzer's results and are summarized in Fig. 14) and an estimate of the attenuation ratio between (say) the 19 GHz and 13 GHz can be obtained for the same rain rate. The X's in Fig. 13 correspond to 19-GHz attenuation deduced in the above manner. Similar results hold if the 13-GHz and 19-GHz signals are used to extrapolate to the 29-GHz attenuation curve.

The preliminary diversity results for Grant Park and Palmetto are given in Figs. 15 and 16. Note that the Grant Park results are biased by the fact that the only appreciable rainfall in the data base occurred during a brief period during the summer of 1976. During this one period of rain the site diversity improvement factor (the ratio of single site time faded below to diversity time faded below) was approximately 12, considerably less than the improvement factors of 50 we have seen in the past for equivalent fade levels.

## VII. ACKNOWLEDGMENTS

The RF front end, as indicated, was the same as that specified by our coexperimenters at Bell Laboratories, Crawford Hill. In particular we benefited from interaction with D. C. Cox and H. W. Arnold. We are also indebted to E. A. Ohm, who designed the polarization coupler and P. Henry, who designed the frequency diplexer. Our ability to meet the design objectives and to be on-site when the satellite came on station is a tribute to the long hours of effort of all concerned. The work got off to a rapid start initially under W. T. Barnett, and the momentum was carried through with support from W. G. Ahlborn, H. J. Bergmann, J. Franzblau, L. J. Morris and E. E. Muller.

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