S-BAND PHASED ARRAY TELEMETRY RECEIVER

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**Summary**  A phased array receiver operating at S-band has been developed to automatically track a moving telemetry transmitter by electronic beam steering. Each array module consists of an antenna, mixer, IF amplifier and local oscillator. Beam steering is accomplished by a unique method of controlling the output phase of the local oscillator.

The antenna beam may be moved in a continuous scan through 120° in azimuth and elevation. Tracking rates as high as 100° per millisecond are achieved with no moving parts.

**Introduction**  The requirement for vacating the 215-265 MHz telemetry band has created the requirement for improved receiving and tracking systems to offset the additional propagation losses encountered at the higher frequencies. Two antenna configurations may be used to fulfill the requirements for ground based tracking receivers in the UHF telemetry bands. Parabolic reflectors with conical scan or monopulse feeds have been designed and tested. Such antennas are motor driven and the narrow beam requires a high precision servo system to acquire and track the target. The reflector antennas have slow tracking rates due to excessive size and weight of the antenna mount.

A second antenna system is an array of antenna elements connected through variable phase shifters to a combined output. Beam steering is accomplished by shifting the phase of the signal received by each antenna element. Maximum energy is received when all signals are in phase.

If each antenna signal is converted to an intermediate frequency by mixing with a local oscillator signal, beam steering may be accomplished by controlling the phase of each local oscillator. This eliminates the loss of a phase shifter placed in the signal path.

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**Receiving System** The receiving array is composed of a number of identical antennas attached to miniature superheterodyne receivers or receiving modules. The array may be arranged in linear or planar configuration and the number of elements or modules is determined by the required gain.

In a linear array of \( n \) isotropic equally spaced elements, the phase between successive elements required to steer the antenna beam is

\[
\phi = \frac{2\pi d}{\lambda} \ n \ \sin \ θ \ (\text{referenced to } n=1)
\]

where
- \( d \) = element spacing
- \( \lambda \) = operating wavelength
- \( θ \) = angle between the beam maximum and the normal of the array axis
- \( n \) = number of elements in the array.

If the reference is in the center of the array the phase becomes

\[
\phi = \frac{2\pi d}{\lambda} \ (n-1) - \frac{(n-1)}{2} \ \sin θ \ (n=1, \ 2, \ 3 \ldots \ x)
\]

The phases shift symmetrically about the reference in the array center and the phase shift between adjacent elements is equal for uniformly spaced elements.

**Receiver Module** The receiving modules are identical units containing an antenna element, preselector filter, mixer, local oscillator, and IF preamplifier.

**Antenna Element** The antenna elements may be any type of radiator such as dipoles, spirals, horns, slots, etc. Dipoles are commonly used for linearly polarized arrays and spirals or crossed dipoles are used for circular polarization.

An experimental S-band receiver module with a spiral antenna is shown in Figure 1. The antenna is a two-wire Archimedean spiral printed on teflon fiberglass. The spiral is fed by a split-tube balun in the center and is cavity-backed to produce radiation from one side.

The spiral antenna receives right hand circularly polarized signals over a wide band of frequencies. The antenna gain is approximately 3.0 db over isotropic.

The phase of the signal received by a spiral antenna may be shifted by rotating the antenna about its axis. One degree of mechanical rotation produces a corresponding change in phase of one electrical degree. This provides a convenient and accurate
method of adjusting the initial boresight phase of the receiver modules by mechanical rotation of the antennas to trim the phase of the array.

**Preselector Filter**  An RF bandpass filter is connected between each antenna and its associated mixer to suppress spurious signals and image frequencies. The filter also prevents reradiation of any local oscillator energy from the mixer. This filter provides at least 60 db rejection from dc to 2.15 GHz and from 2.35 to 11.0 GHz. It has an insertion loss of 0.35 db in the passband of 2.2 to 2.3 GHz.

**Mixer**  The microwave signal mixer is a stripline hybrid ring connected to form a balanced mixer. The mixer is designed to provide maximum isolation between the local oscillator and signal arms. The ring provides greater than 40 db isolation between opposite ports when terminated in 50 ohms at the local oscillator and signal frequencies. The signal frequency VSWR is less than 1.2:1.

The Schottky barrier diodes are selected in matched pairs. One diode is reversed and the output connected in parallel. The noise figure of the receiver module is less than 8.0 db.

**IF Preamplifier**  The IF preamplifier is a high performance unit designed to provide 35 db gain with a noise figure of 2.0 db. The transistors are connected in an overcoupled circuit which has a 3.0 db bandwidth of 100 MHz at a center frequency of 265 MHz. A voltage-variable attenuator is used to vary the gain of the IF amplifier to adjust the amplitude distribution of the array. This attenuator stage provides continuous gain adjustment from 0 to 35 db with negligible change in phase.

**Local Oscillator**  The local oscillator of each module consists of a VHF driver amplifier and a step recovery diode (SRD) frequency multiplier. Input to the driver is supplied by a common crystal controlled source operating at 165.4 MHz. Output from this master oscillator is divided equally by the number of array elements and applied to each driver amplifier.

Output from the driver amplifier is applied to the input of the SRD multiplier which multiplies the frequency by twelve to an output frequency of 1985 MHz. The phase of the multiplier is shifted by controlling the bias current of the SRD. A continuous phase shift of greater than $720^\circ$ in input is obtained as shown in Figure 2. Variation in the output power with phase control is less than $\pm1.0$ db.

Phase shift due to ambient temperature changes is minimized by a temperature network in the bias circuit. The heat sensitive elements of this network are embedded near the SRD to sense the temperature of the diode. The compensated output phase shift is less than 0.3 electrical degrees per degree centigrade ambient temperature change.
Output from the SRD multiplier is passed through a narrow bandpass filter to suppress the unwanted harmonics. This is a four section stripline interdigital filter centered at 1985 MHz. Rejection of the 11th and 13th harmonics is greater than 40 db.

**Steering Control**  The voltages required to scan the beam are produced by a resistive matrix connected according to the form of the array. The matrix for a planar array of equally spaced elements is a quadrille of equal value resistors. Isolation resistors are added to the sides of the matrix so the voltage applied in one axis is independent of the voltage applied in the other axis.

Voltages from the matrix are applied through current sources to the bias circuit of each SRD multiplier. In a balanced array, the center of the matrix is the fixed reference and the voltages across the matrix vary in a $+3V/2$, $+2V/Z$, $+V/2$, $-V/2$, $-2V/2$, $-3V/2$ relationship. These voltages applied to the multipliers produce the $+30/2$, $+20/2$, $+0/2$, $-20/2$, $-30/2$ phase shift required to scan the beam.

In large arrays with wide scan angles the steering voltages pass through a steering logic circuit which “steps” the matrix voltages so that the SRD multipliers never shift phase more than 360 electrical degrees. When the matrix output increases above the voltage required to shift the phase by 360°, the logic circuit steps the bias voltage by an equivalent of 360°. For example, if the required phase shift is 400°, the receiver element phase will shift through 360°, and then step back to 40° which is the exact equivalent of 400°. Thus, the SRD multipliers are always operated over the most linear 360° portion of their phase shift characteristic.

The circuit switches within a millisecond in either direction of phase shift. There is no “dead zone” or “zone of indecision” in the logic switching. As the phase of a module increases, the SRD multiplier may shift 363 degrees before switching occurs. However, the logic will step the phase back to 3.0 degrees so that no switching phase errors occur.

**Automatic Tracking System**  The receiver array may be connected in several configurations to automatically track a moving signal source. Figure 3 is the block diagram of the array connected in a monopulse tracking configuration. The array is divided into four groups of modules and the sum of each group designated A, B, C, and D. The IF outputs of A and C are applied to a “magic tee” hybrid which produces the sum (A+C) and difference (A-C) signals. Another hybrid combines the output of B and D into (B +D) and (B -D). The sum signals are applied to a third hybrid which produces the total sum of A+B+C+D and the difference of (A+C)-(B+D) which is the azimuth difference signal. Similarly a fourth hybrid combines the difference signals to (A+B)-(C+D) which is the elevation difference signal. The azimuth and elevation signals are applied to a 90° hybrid which adds the difference signals in quadrature.
The sum signal and quadrature difference signals are applied to a dual channel receiver operating in the 215 to 315 MHz band. The dual channel receiver demodulates the sum channel to produce the TM data. The sum channel is also used as a reference in a tracking error demodulator to produce azimuth and elevation error voltages. These error voltages are applied to the steering control circuit which moves the antenna beam to maintain the Az and El nulls and the sum channel maximum.

The antenna beam position may be controlled manually by means of azimuth and elevation control dials or the beam may be scanned by a search and lock circuit. This circuit produces a triangular waveform which is applied to the horizontal axis of the steering matrix causing the antenna beam to scan in azimuth. A similar triangular function is applied to the vertical axis to scan the beam in elevation. Application of both functions produces a raster scan of the beam through the sector covered by the array. Both scan function frequencies and amplitudes may be controlled to vary the scan rate and the search angles. The beam may be scanned through 120° in 0.5 milliseconds in either axis.

When the beam intercepts the desired signal, the error voltage is applied to the scan circuit to stop the scan at the point of crossover and add the error output to maintain track. If the signal drops below a readable level for a specified interval, the scan circuit becomes unlocked and the beam starts to search until the signal is reacquired.

**Experimental Results**  A thirty-six element (6 x 6) receiver shown in Figure 4 was constructed to demonstrate beam steering by phase controlling the SRD multiplier local oscillators. The receiver operates at 2290 MHz with an 8.0 db noise figure. The dipole antennas are spaced approximately 0.5 λ in azimuth and elevation.

Figure 5 shows the control unit which contains the steering matrix, logic circuits and power supplies. The top panel contains the switches and indicator lights for the various power supplies. The second panel contains the beam steering controls and beam position meters. The beam may be positioned by the azimuth and elevation controls and the position indicated by the azimuth and elevation meters.

High speed scan may be obtained by the application of function generators through coaxial connectors to the steering matrix.

The third rack contains the printed circuit logic cards or “stepper” circuits. These circuits step the phase of each module by 360° to the equivalent phase. A logic card was provided for each module in the experimental array to provide a number of beam steering tests. Arrays with symmetrical phase shift about the center use a common stepper for
complimentary modules such as 1 and 10 or, 5 and 6 in a ten element array since these modules have identical control voltages with opposite polarity.

Figure 6 is the broadside pattern of the array in the plane of a diagonal. The antenna patterns with the beam steered to angles of 20° and 40° from boresight are shown in Figures 7 and 8. The low sidelobes are due to the taper achieved by the diagonal or diamond array. The gain was practically constant as the beam was scanned ±60°.

Similar patterns were recorded while the beam was scanned rapidly from one side of boresight to the other by the application of square waves to the beam steering input. Rapid scans of ±60° were made without beam distortion at rates up to 1.0 KHz.

An experimental 1 x 8 array was constructed to demonstrate monopulse tracking in azimuth with circular -polarization. The modules were combined in groups of four on each side of boresight. The combined output from each side were applied to a hybrid ring junction to obtain the sum and difference of the signals received by each group.

Figure 9 is the broadside (θ = 0) pattern of the eight receiver elements. The solid line is the sum pattern which is approximately 12 degrees wide at the 3 db points. The dashed line shows the amplitude of the deference signal from the hybrid. The sharp null and symmetrical pattern is an indication of uniform amplitude and phase characteristics of the receiver modules.

Figures 10, 11 and 12 are the sum and difference patterns with the beam scanned 15°, 30° and 45° from broadside.

The sum and difference signals were applied to a phase detector to produce an azimuth error signal. This signal was amplified and connected to the steering matrix. The beam was scanned in azimuth by a triangular wave function generator connected to the matrix.

A portable S-band signal source was acquired and tracked from -60 to +60° in azimuth with a tracking accuracy of less than 1.0 degree. Additional tests are being conducted to determine the tracking accuracy with a high velocity target.

**Conclusions** Phased array receivers using SRD phase shift local oscillators have been designed to receive telemetry signals in the UHF bands. The SRD phase shift system provides a simple and accurate method of high speed scanning, acquisition, and tracking.

The modular array is very flexible in beam shape or gain. Increased gain in a given plane is obtained by adding identical modules. Maximum gain with minimum sidelobes may be obtained by adjusting the gain of the modules to produce an amplitude taper across the face of the array.
Figure 1 - Receiver Module

Figure 2 - Phase Shift Control
Figure 3 - Monopulse Tracking Block Diagram

Figure 4 - Thirty-Six Element Receiver
Figure 5 - Steering Control

Figure 6 - 6 x 6 Receiver Diagonal $\theta = 0^\circ$
Figure 7 - 6 x 6 Receiver Diagonal $\theta = 20^\circ$

Figure 8 - 6 x 6 Receiver Diagonal $\theta = 40^\circ$

Figure 9 - Broadside Pattern $\theta = 0^\circ$