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AUTOMATIC ELECTRONIC POLARIZATION TRACKING SYSTEM

BY

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GODDARD SPACE FLIGHT CENTER
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ABSTRACT

An automatic electronic method is described that continuously tracks, and measures to better than one-degree, the polarization orientation angle of a linearly polarized signal from a satellite such as ATS-F&G. Comparable systems utilize a mechanically rotating antenna feed.

All linear polarizations are comprised of two circularly polarized components of opposite sense. This system measures the RF phase difference between the two oppositely polarized components to determine the linear polarization orientation angle. This report also describes an error analysis that defines orientation angle errors introduced by antenna ellipticity ratio and thermal noise.

The polarization tracking technique described herein is applicable to the 2 GHz ATS-F&G proposed ground equipment and the 4 GHz Apollo Instrumentation Ship (AIS) SATCOM ground-terminal stations using a 30 foot diameter dish antenna with cassegrainian feed.

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INTRODUCTION

A concept is developed that provides an automatic electronic method for continuously tracking, and consequently accurately measuring to better than one-degree, the polarization orientation angle of a linearly polarized signal transmitted from a spacecraft or other airborne vehicle. A critical requirement for placing a synchronous spacecraft in its proper orbit is the determination of the spacecraft attitude. The attitude is obtained by measuring the polarization orientation angle, as a function of time, during the transfer orbit. This time related data is necessary to control the spacecraft to the required apogee firing attitude, predict the exact firing time, and fire the apogee motor for missions such as the Applications Technology Satellite (ATS-F&G).

Various methods are now available for measuring the polarization orientation angle. For example, the National Aeronautics and Space Administration's (NASA) Space Tracking and Data Acquisition Network (STADAN) Rosman, N.C. No. 2 85-foot diameter dish antenna utilizes a rotating motor-driven 4 GHz antenna feed,(1) in conjunction with a servo loop, that performed this function for the ATS-B spacecraft launched on December 7, 1966. An undesirable feature of this technique is the mechanically rotating antenna feed with its associated operational problems and large size. An electronic-type system, employed by Vogt,(2) is complicated and does not have sufficient accuracy.

The electronic polarization tracking technique, subsequently described, has the following advantages:

(1) Eliminates the mechanical rotating antenna feed,

(2) Determines angular orientation of a linearly polarized vector to better than 1° as a linear function of the radio frequency (RF) phase difference between two coherent circularly polarized signals of opposite sense,

(3) Utilizes a conventional "off-the-shelf" simultaneous-lobing monopulse type autotrack receiver as the polarization tracking receiver, and,

(4) Utilizes a servo loop, similar to the Rosman No. 2 Polarization Tracking System, as a part of the null-seeking tracking loop.

A description of the Rosman No. 2 motor-driven type Polarization Tracking System is given in the attached Appendix 1.

DESCRIPTION OF ELECTRONIC POLARIZATION TRACKING TECHNIQUE

All linear polarizations can be considered as a combination of two circularly polarized waves with the respective electric vectors rotating in opposite directions.[2,3] In order to resolve these two vectors, the receiving antenna must provide two circularly polarized signal output ports with opposite sense (see Figure 1 Block Diagram). It will be shown that the differential RF phase between these two oppositely polarized components is a constant for any given orientation angle, θ_0.

The proposed system utilizes a null-seeking servo loop wherein a continuously-adjustable phase-shifter, in a transmission line, gives an accurate readout of θ_0. The system is relatively insensitive to input signal level changes since a sum-and-difference amplitude ratio is the driving function for the servo. A decided advantage is that a conventional autotrack receiver can be used as the polarization tracking receiver.

The receiving antenna (e.g. 30 foot dish) provides two circularly polarized outputs consisting of left-hand, Σ_{LH}, and right-hand, Σ_{RH}, signal components (see Figure 1 block diagram).

Reference 4 shows that the left-hand (counter-clockwise) circularly polarized wave can be designated by the vector,

$$\Sigma_{LH} = a_x\left(\frac{E_1}{2}\right) + a_y\, j\left(\frac{E_2}{2}\right) \tag{1}$$

The corresponding right-hand (clockwise) rotating circularly polarized wave as,

$$\Sigma_{RH} = a_x\left(\frac{E_1}{2}\right) - a_y\, j\left(\frac{E_2}{2}\right) \tag{2}$$

a_x and a_y are unit vectors in right-handed coordinate system. Then, for zero phase difference between oppositely polarized components,

$$\Sigma = \Sigma_{LH} + \Sigma_{RH}\ . \tag{3}$$

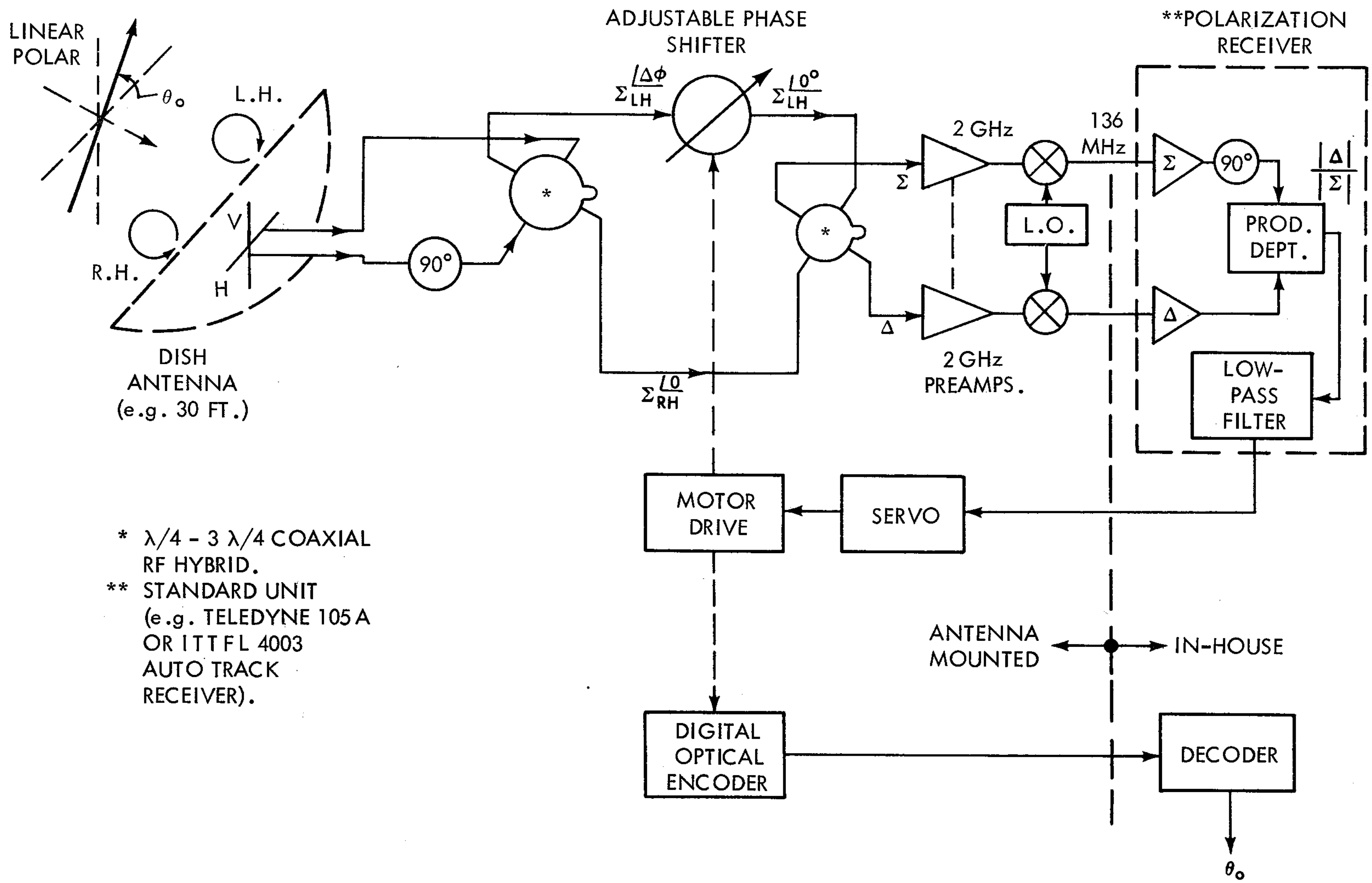


Figure 1. Electronic Polarization Tracking System.

From (3), the electric field vector can be written as:

$$\Sigma = \Sigma_{LH} \exp\left(-j\beta_{LH}\right) + \Sigma_{RH} \exp\left(-j\beta_{RH}\right) \tag{4}$$

β_{RH}, β_{LH} = respective RF phase of RH and LH components from 0° reference.
From (1), (2) and (4),

$$\Sigma = a_x E_x + a_y E_y \tag{5}$$

$$E_x = \left(\frac{E_1}{2}\right)\left[\exp\left(-j\beta_{LH}\right) + \exp\left(-j\beta_{RH}\right)\right] \tag{6}$$

$$E_y = \left(\frac{E_2}{2}\right)\left[j\exp\left(-j\beta_{LH}\right) - j\exp\left(-j\beta_{RH}\right)\right] \tag{7}$$

The angular rotation angle, θ_0, is given by

$$\theta_0 = \tan^{-1}\left[\frac{E_y}{E_x}\right] \tag{8}$$

Factoring out $\exp\left[-0.5\,j\left(\beta_{LH} + \beta_{RH}\right)\right]$ from (6) and (7) obtains

$$E_x = E_1 \exp\left[-0.5\,j\left(\beta_{LH} + \beta_{RH}\right)\right] \cos\left[\frac{\beta_{RH} - \beta_{LH}}{2}\right] \tag{9}$$

$$E_y = -E_2 \exp\left[-0.5\,j\left(\beta_{LH} + \beta_{RH}\right)\right] \sin\left[\frac{\beta_{RH} - \beta_{LH}}{2}\right] \tag{10}$$

Then from (9) and (10),

$$\frac{E_y}{E_x} = -\frac{E_2 \sin\left[\frac{\beta_{RH} - \beta_{LH}}{2}\right]}{E_1 \cos\left[\frac{\beta_{RH} - \beta_{LH}}{2}\right]}$$

or

$$\frac{E_y}{E_x} = -\frac{E_2}{E_1} \tan\left[\frac{\beta_{RH} - \beta_{LH}}{2}\right] \tag{11}$$

Substituting (11) in (8),

$$\theta_0 = \left[\frac{\beta_{LH} - \beta_{RH}}{2}\right] \frac{E_2}{E_1}$$

Letting, $\Delta\phi = \beta_{LH} - \beta_{RH}$,

$$\theta_0 = \frac{\Delta\phi}{2} \cdot \frac{E_2}{E_1} \tag{12}$$

Equation (12) is a significant result since it reveals that the incoming linearly polarized wave orientation, θ_0, is a linear function of the RF phase difference, $\Delta\phi$, between the left-hand phase, β_{LH}, and the right-hand phase, β_{RH}. The factor E_2/E_1 is the ellipticity ratio (minor-to-major axis voltage ratio) for circular polarization. Ideally, $E_2/E_1 = 1$ for perfect circular polarization.

The phase difference versus time between the two circularly polarized signal components is graphically shown in Figure 2 for values of the orientation angle, $\theta_0 = 0°, 45°, 90°$ and $180°$.

It is also apparent from Figure 2 that $\theta_0 = \Delta\phi/2$ for $E_2/E_1 = 1$. An interesting point is that $\Delta\phi = 0°$ for both $\theta_0 = 0°$ and $\theta_0 = 180°$ which are the ambiguous

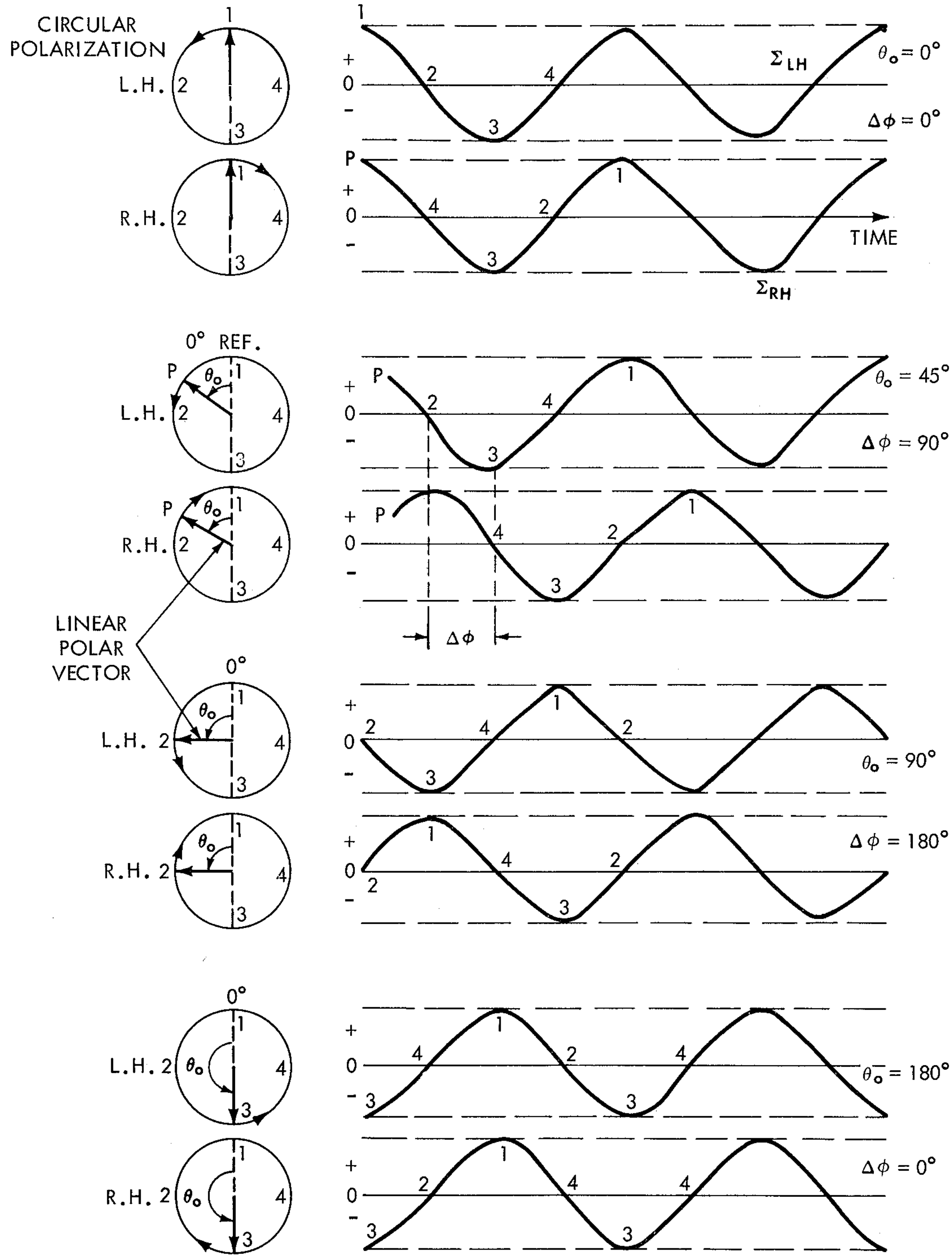


Figure 2. Antenna Signal Phase Characteristics.

points. However, this ambiguity need not be resolved since only the location of a plane is required. A calibration boresight antenna would be utilized to establish the $\Delta\phi = 0°$ reference plane (see Figure 2).

It is now apparent that a suitable technique is desired to accurately measure the RF phase difference, $\Delta\phi$. The use of a direct-reading phase measuring system such as a minitrack-type interferometer, or a dual-channel phase-lock system, could be used to accomplish this function. However, a simpler scheme is to use a null-indicating device to measure $\Delta\phi$. An amplitude sum-and-difference ratio can be generated to indicate $\Delta\phi$ and hence θ_0.

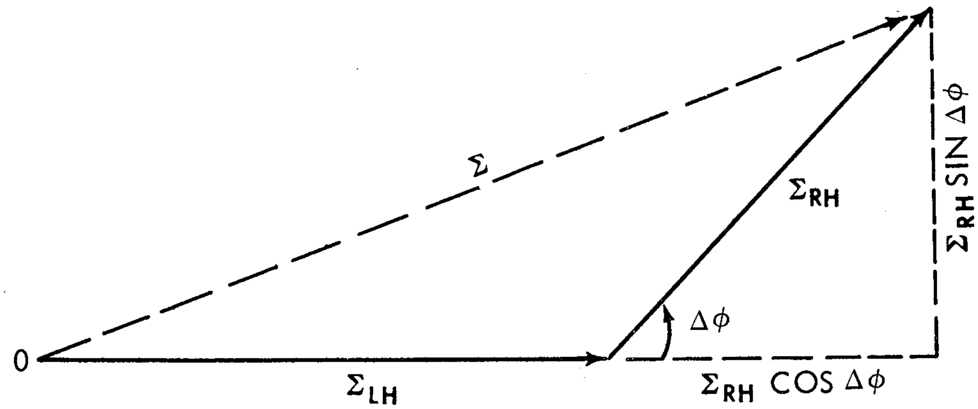
Such a system employs a continuously adjustable phase shifter that automatically corrects for the phase difference, $\Delta\phi$, to maintain an in-phase relationship at the two inputs to an RF hybrid (see Figure 1). The resulting Σ and Δ channels are amplified in low-noise preamplifiers and frequency converted from 2 GHz down to 136 MHz. A conventional autotrack receiver produces the sum-and-difference ratio utilized to drive the servo.

The two circular polarization output transmission lines are critical, in terms of differential phase and amplitude variations, from the antenna to the two input arms of the sum-and-difference RF hybrid in that these parameters directly affect θ_0. However, these parameters are readily controlled since these lines are short. The sum-and-difference RF hybrid generates sum-and-difference signals that are relatively insensitive to differential phase and amplitude changes in the output lines. For example, the normal gain and phase changes between preamplifiers (i.e., 1 db and 5°), and remotely located (up to 1500 ft. away) polarization tracking receiver channels (i.e., 2 db and 10°), no longer affect the accuracy of the orientation angle measurement.

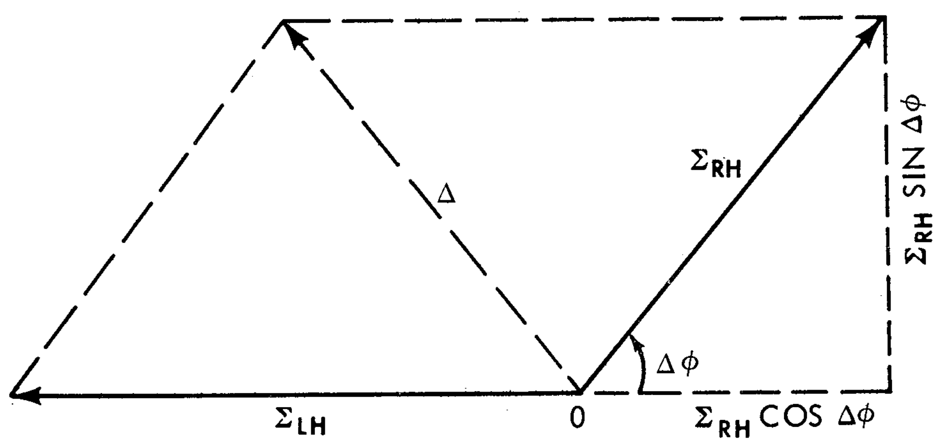
A motor-driven adjustable phase shifter is suggested since the phase rates are not large. A digital optical encoder, such as a Wayne-George type 12-bit encoder, would provide a convenient remote readout of θ_0 with a precision better than 0.1°. An alternate method would be to monitor θ_0, directly, as an indicator output from the servo electronics.

An electronic phase-shifter, such as a ferrite device, could be incorporated instead of the mechanical phase shifter. However, the problems associated with high insertion loss and maintaining good phase linearity off-set advantages of a ferrite phase shifter. In any event, a motor-driven phase shifter is vastly superior to a motor-driven antenna feed.

The sum-and-difference ratio, $|\Delta| / |\Sigma|$, from the polarization tracking receiver is derived as follows. The Σ component (see Figure 3a) from the RF



(a) VECTOR SUM COMPONENTS



(b) VECTOR DIFFERENCE COMPONENTS

Figure 3. Phase Diagram of Σ and Δ Signals.

hybrid can be expressed as

$$\text{Sum, } \Sigma = \left(\Sigma_{LH} + \Sigma_{RH} \cos \Delta\phi\right) + j\, \Sigma_{RH} \sin \Delta\phi \tag{13}$$

Reducing to

$$|\Sigma|^2 = \left(\Sigma_{LH} + \Sigma_{RH} \cos \Delta\phi\right)^2 + \left(\Sigma_{RH} \sin \Delta\phi\right)^2 \qquad (14)$$

Similarly, the Δ component (see Figure 3b) is

$$\text{Difference, } \Delta = \left(\Sigma_{LH} - \Sigma_{RH} \cos \Delta\phi\right) + j\, \Sigma_{RH} \sin \Delta\phi \qquad (15)$$

$$|\Delta|^2 = \left(\Sigma_{LH} - \Sigma_{RH} \cos \Delta\phi\right)^2 + \left(\Sigma_{RH} \sin \Delta\phi\right)^2 \qquad (16)$$

From (14) and (16),

$$\frac{|\Delta|}{|\Sigma|} = \pm \left[\frac{\Sigma_{LH}^2 - 2\,\Sigma_{LH}\Sigma_{RH} \cos \Delta\phi + \Sigma_{RH}^2}{\Sigma_{LH}^2 + 2\,\Sigma_{LH}\Sigma_{RH} \cos \Delta\phi + \Sigma_{RH}^2}\right]^{1/2} \qquad (17)$$

For equal amplitudes, $\Sigma_{LH} = \Sigma_{RH}$ and (17) reduces to

$$\frac{|\Delta|}{|\Sigma|} = \pm \left[\frac{1 - \cos \Delta\phi}{1 + \cos \Delta\phi}\right]^{1/2} \qquad (18)$$

Equation (18) further reduces to,

$$\frac{|\Delta|}{|\Sigma|} = \tan\left(\frac{\Delta\phi}{2}\right) \qquad (19)$$

From (12)

$$\Delta\phi = 2\theta_0 \left(\frac{E_1}{E_2}\right) \qquad (20)$$

Substituting (20) in (19)

$$\frac{|\Delta|}{|\Sigma|} = \left[\tan\ \theta_0\left(\frac{E_1}{E_2}\right)\right] \tag{21}$$

Equation (21) is the servo error function obtained from the tracking receiver product detector. A plot of (21) is shown in Figure 4 for a ratio of $E_1/E_2 = 1.03$ corresponding to an antenna circular polarization ellipticity ratio of 0.3 db.

The servo system will always make $|\Delta|/|\Sigma| = 0$, for values of $\theta_0 < \pm\ \pi/2$, where θ_0 is measured from the 0° reference plane. The automatic phase-shifter, therefore, continuously adjusts for $\Delta\phi$ to maintain an in-phase relationship between the two input ports of the Σ and Δ hybrid. The shaft rotation of the automatic phase-shifter gives a direct indication of θ_0.

Error Analysis

Table 1 is a tabulation of the polarization orientation variations for various values of $\Delta\phi$ and θ_0 for an antenna ellipticity ratio of 0.3 db. Table 1 indicates that this system comes close to achieving the design goal of 1°, or better. However, a 0.3 db antenna ellipticity ratio means that the antenna must be practically perfect. The variation in θ_0, due to the ellipticity ratio, can be reduced using a rotating calibration boresight source. It should be possible to maintain $\Delta\theta_0 < 1°$ through appropriate preflight calibration which would relax the ellipticity ratio to about 0.5 db. θ_0 ideal is obtained for perfect circular polarization where $E_1/E_2 = 1$.

Table 1

Angular Error in $\Delta\phi_0$, versus $\Delta\phi$

ELLIPTICITY RATIO	$\Delta\phi$	θ_0 INDICATED	θ_0 IDEAL	$\Delta\theta_0$
0.3 db	45°	21.8°	22.5°	0.7°
0.3 db	90°	43.7°	45.0°	1.3°
0.3 db	135°	65.5°	67.5°	2.0°

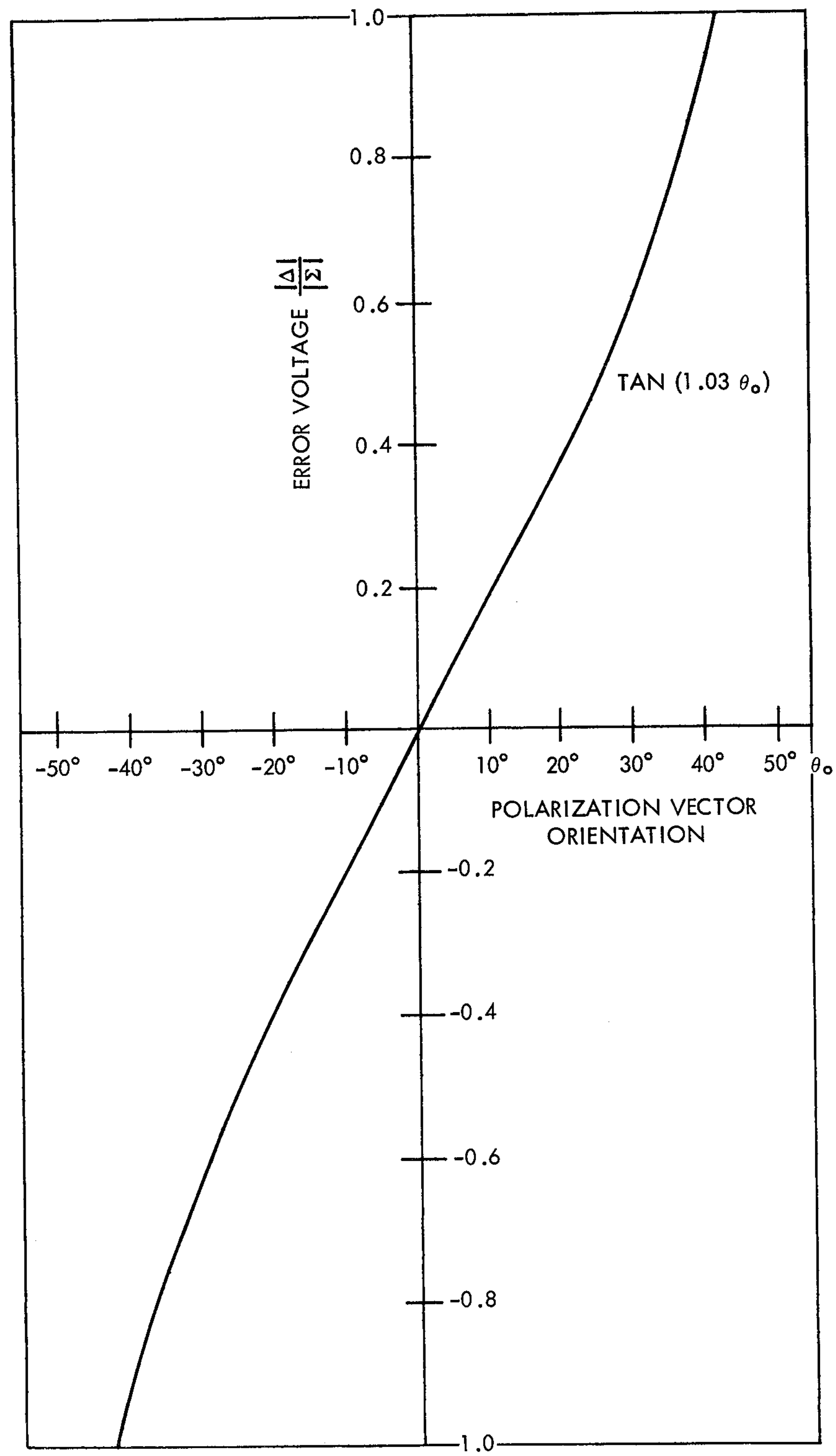


Figure 4. Polarization Error Function.

Another factor which limits the accuracy of $\Delta\phi$ is the polarization tracking signal-to-noise ratio (SNR). This thermal noise error is expressed as,

$$\sigma_{\Delta\phi} = 57.3 \left(\frac{N}{S}\right)^{1/2} \text{ degrees rms} . \tag{22}$$

The corresponding polarization orientation error is $\Delta\theta_0 = \sigma_{\Delta\phi}/2$ for an antenna ellipticity ratio, $E_2/E_1 = 1$.

Table 2

Angular Error in θ_0 Due to Thermal Noise

S/N (POWER RATIO)	$\sigma_{\Delta\phi}$	$\Delta\theta_0$
+ 40 db	0.57° rms	0.29° rms
+ 50 db	0.18° rms	0.09° rms
+ 60 db	0.057° rms	0.029° rms

It is apparent from Table 2 that a SNR $\geq$ + 40 db should be maintained to keep the polarization orientation error, due to thermal noise, less than 0.3° rms to achieve a peak error of 1°, or less. An input SNR of +40 db is fairly high but is not difficult to achieve. Calculations show that a nominal SNR $\geq$ +40 db can be maintained for the S-band down-link carrier signal for the polarization angle measurement. This SNR can be obtained in a 1 Hz loop tracking bandwidth for a 1-watt 2 GHz signal transmitted at synchronous altitude. It is assumed a 30-ft. dish and 2 db noise figure preamplifier will be used.

Feed Characteristics

The recommended design characteristics for the polarization tracking ground antenna feed elements are as follows:

(1) Elements must be located at the focal point, or as close as possible, to obtain identical far-field radiation patterns that coincide to insure a suitable ellipticity ratio.

(2) Circularly polarized feed elements with opposite sense must be provided (i.e., one element RHC- right-hand circular and the other LHC - left-hand circular).

(3) Ellipticity ratio of 0.5 db, or less, is desired.

(4) VSWR (voltage standing wave ratio) of 1.15:1, or less, is desired.

(5) Isolation to be at least 45 db between RHC and LHC output ports.

(6) Amplitude balance within 0.3 db between Σ and Δ hybrid input ports assuming an ideal ellipticity ratio of 0 db.

NETWORK APPLICATIONS

ATS-F&G Satellites

The automatic electronic polarization tracking technique described herein is applicable to the ATS-F&G proposed ground equipment using a 30 ft. diameter paraboloidal dish antenna with a cassegrainian type feed. The following ATS-F&G operational requirements can be met with this system, namely,

Frequency: 2200 - 2300 MHz

Antenna Polarization: Linear (incoming wave)

Accuracy of Polarization Angle Measurement: $\pm 1°$

Polarization Orientation Angular Rate: 1° per second, maximum.

It is planned that the Goddard Range and Range Rate (RARR) stations at Rosman, N. C.; Madgar (Tananarive, Malagasy Republic); Carnarvon, Australia; Santiago, Chile; and Alaska sites be converted to the new frequency allocations of 1750-1850 MHz, earth to space, and 2200-2300 MHz, space to earth. Also, the RARR dual, 14 foot diameter, paraboloidal S-band antenna, one receive and one transmit, will be replaced with a single 30-foot diameter dish with a cassegrainian feed that will include a polarization tracking capability.

An additional operational requirement is to provide simultaneous telemetry and command functions in the 30 foot dish at the same time as the polarization angle measurement is made.

Apollo SATCOM (Satellite Communication)

The automatic electronic polarization tracking technique, described herein, is also under consideration for the Apollo Instrumentation Ship (AIS) SATCOM ground terminal stations using a cassagrainian 30 foot dish antenna with a 6 GHz up-link and a 4 GHz down-link. A polarization tracking accuracy of ± 1°, at 4 GHz, is required for this application. The attitude of the polarization vector will vary at a rate much less than 1° per second since the SATCOM satellite will be in a synchronous orbit.

CONCLUSIONS

An electronic polarization tracking concept has been developed that provides automatic polarization tracking of an incoming linearly polarized wave to an accuracy better than ± 1°. This technique is applicable to the ATS-F&G satellite (2 GHz down-link) and Apollo SATCOM satellite (4 GHz).

This technique is a simplified approach in that it eliminates the requirement for a mechanical rotating antenna feed. It also simplifies the microwave transmission line plumbing problem in similar systems using half-wave plates, mechanical rotating joints, etc.

ACKNOWLEDGMENT

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APPENDIX I

MOTOR-DRIVEN POLARIZATION TRACKING SYSTEM

A motor-driven polarization tracking system for ATS-B, at 4 GHz, exists in the Rosman No. 2 85 foot dish, the Mojave, California 40 foot dish, and the 40 foot dishes at the Japanese and Australian sites for tracking of ATS-B polarization at frequencies between 4100-4200 MHz.

A block diagram of this system[5] is shown in Figure 5. The antenna feed has a port that excites a mode orthogonal to the principal receiving polarization vector. This creates the effect of a null channel when the reference and error channel outputs are compared in a phase-sensitive detector that produces a voltage proportional to the error in polarization tracking and drives the feed back to the null point.

The accuracy of the polarization orientation angle, θ_0, is affected by both differential phase shift and differential amplitude unbalance between the two channels.

For a servo error voltage equal to zero and for a polarization tracking error less than 2 degrees, the polarization orientation angular error, $\Delta\theta$, is

$$\Delta\theta = -\frac{E_q}{E_c} \tan\phi \tag{23}$$

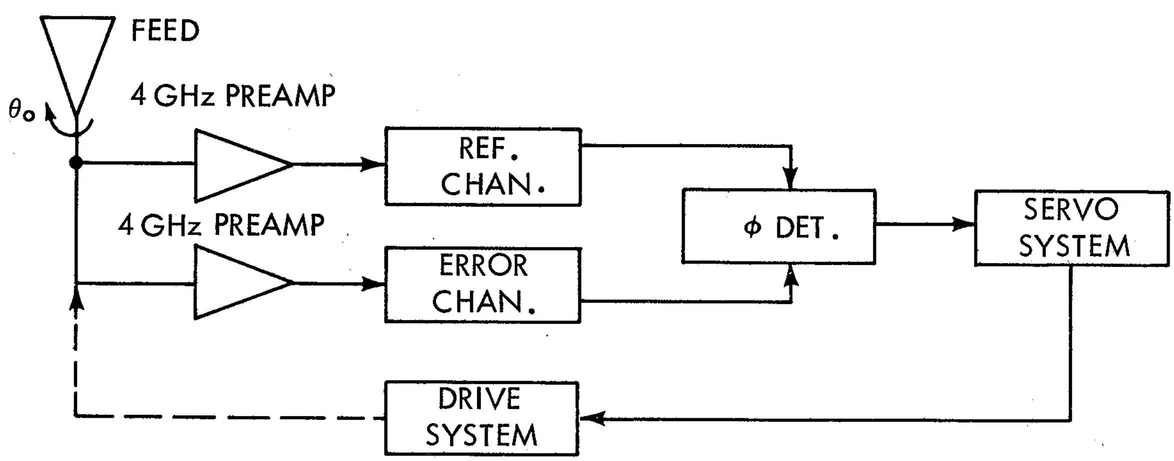

Figure 5. Motor Driven Feed Type Polarization Tracking System for ATS-B (Rosman 2).

ϕ = Differential phase shift between reference and error channel, degrees.

E_q = Amplitude of quadrature voltage in error channel.

E_c = Amplitude of co-phasal voltage in error channel.

The ratio of E_q/E_c in (23) can be determined from,

$$\frac{E_q}{E_c} = \frac{R_1 \pm R_2}{R_1 R_2 \pm 1} \tag{24}$$

R_1 and R_2 are the axial voltage ratios of the incident wave and receiving antenna, respectively, for two elliptically polarized antennas.

A typical value of $E_q/E_c = 0.2$ which corresponds to $R_1 = 20$ db and $R_2 = 20$ db. The Rosman 4 GHz parametric preamplifier has a low phase drift of about 1°, however, the total differential phase shift including the polarization tracking receiver is probably not maintained to better than $\phi = 5°$. This corresponds to an angular error, $\Delta\theta = 1°$.

The major difficulty with any polarization angle measurement scheme is the accurate calibrating and establishing of reference positions. From the measurement of the ATS-B orbit, after apogee motor firing, it was possible to determine the error in the attitude measurement. This error is a combination of sun sensor data and polarization angle measurement. It was found that the measured attitude was incorrect by 0.9 degree. From this history of polarization tracking and the similar problem calibrating for any scheme, it is not anticipated that polarization angle measurement errors may be reduced significantly below one-degree.