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Part 1. DESIGN OF POLARIZATION ADJUSTMENT INSTRUMENTATION FOR A ROCKET PROPAGATION EXPERIMENT

by
R. C. Condon
E. A. Mechtly

Part 2. ANALYSIS OF A ROCKET EXPERIMENT TO MEASURE IONOSPHERIC ELECTRON DENSITY

by
K. S. Seino
E. A. Mechtly

December 31, 1968

Supported by
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Aeronomy Laboratory
Department of Electrical Engineering
University of Illinois
Urbana, Illinois

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A E R O N O M Y R E P O R T

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ROCKET EXPERIMENT INSTRUMENTATION

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ABSTRACT

Experiments conducted by the Aeronomy Laboratory for the investigation of the lower ionosphere by means of rockets, require circularly polarized radio waves. Until the present time, techniques of adjusting the transmitter have not produced sufficiently precise circular polarization. This paper contains a full description of the design and development of circuitry to sense the polarization and to alter the parameters of the transmitter so that its output becomes circular. The operation of this circuitry is discussed in detail.

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TABLE OF CONTENTS

	Page
Part 1. DESIGN OF POLARIZATION ADJUSTMENT INSTRUMENTATION FOR A ROCKET PROPAGATION EXPERIMENT	
ABSTRACT.	ii
ACKNOWLEDGEMENTS.	iii
LIST OF TABLES.	viii
LIST OF FIGURES	ix
LIST OF SYMBOLS, PART 2.	xiii
1. INTRODUCTION.	1
1.1 Apparatus Used in Producing Circular Polarization.	1
1.2 Preliminary Polarization Adjustments	4
1.3 Characteristics of Elliptical Polarization	8
2. RESULTS OF POLARIZATION TESTS ON ROCKET SHOTS NO. 14.360 AND 14.361 . .	17
2.1 Nature of the Testing.	17
2.2 Testing Limitations.	18
2.3 Results of the Testing	18
2.3.1 The Presence of Standing Waves.	18
2.3.2 Signal Distortion	19
3. THE POLARIZATION CORRECTION SYSTEM.	22
3.1 Qualitative Analysis	22
3.2 Quantitative Analysis.	26
3.2.1 Magnetic Aspect Signal Conditioner.	26
3.2.2 Rocket Receiver Signal Conditioner.	37
3.2.3 Logic Circuitry	53
3.2.4 Testing of the System	59
REFERENCES.	65

TABLE OF CONTENTS (continued)

Page

Part 2. ANALYSIS OF A ROCKET EXPERIMENT TO MEASURE
IONOSPHERIC ELECTRON DENSITY

ABSTRACT.	iii
1. INTRODUCTION.	1
1.1 Rocket Studies of the Lower Ionosphere	1
1.2 Radio Propagation Experiment	3
1.2.1 Ground Station.	3
1.2.2 Rocket Payload.	5
1.2.3 Data Recording.	8
1.3 Data Processing System	8
1.3.1 Block Diagram of Data Processing System	8
1.3.2 Faraday Rotation Data Processing.	13
1.3.3 Differential Absorption Data Processing	15
2. THEORETICAL ASPECTS OF THE DATA PROCESSING SYSTEM	20
2.1 Mathematical Expressions for the Rocket Receiver Output Signal and the Rocket Spin Signal.	20
2.1.1 Wave Transmitted to the Rocket.	20
2.1.2 The Rocket Receiver Output Signal	23
2.1.3 The Rocket Spin Signal.	25
2.2 Theory of Operation of the Faraday Rotation Data Processing System.	25
3. ANALYSIS OF ROCKET PRECESSION	29
3.1 Nike-Apache Precession Characteristics	29
3.2 The Precession Angle, θ_p	31
3.3 The Precession Frequency, f_p	37
3.4 A Table of θ_B , and Graphs of f_p and θ_p	37
3.5 The Effect of Precession on Faraday Rotation and Differential Absorption.	38

TABLE OF CONTENTS (continued)

	Page
3.5.1 The Effect on Faraday Rotation.	38
3.5.2 The Effect of Precession on Differential Absorption.	43
3.6 Noise Problems and a Dummy Signal Method	45
3.7 A Faraday Rotation Correction for the Rocket Distance.	46
4. CONCLUSION.	48
REFERENCES.	50

LIST OF TABLES

Part 1

Table	Page
1.1 Relation Between Elliptical Parameters and the Phase-Amplitude Values of the Transmitted Signals.	15
3.1 Potentiometer Setting vs Phase Shift	52

Part 2

1.1 IRIG Telemetry Band Allocations.	9
1.2 Magnetic Tape Format	10
3.1 Angle θ_B Between Geomagnetic Field and Precession Cone Axis for 14.270	37

LIST OF FIGURES

Part 1

Figure		Page
1.1	Top and front views of the square transmitting antenna array.	2
1.2	Generation of polarization circle (after Seino, 1968).	3
1.3	Generation of polarization ellipse (after Seino, 1968)	5
1.4	Block diagram of the apparatus used in the preliminary polarization adjustments	6
1.5	Modulation envelopes resulting from (a) elliptical polarization and (b) circular polarization.	7
1.6	Definition of the elliptical polarization parameters with respect to the YZ coordinates as determined by the transmitting antenna array (after Kelso, 1950).	11
1.7	Block diagram containing both the manual and the variable attenuators and phase shifters which control the polarization of the transmitted wave.	13
2.1	Trace of three portions of chart record from 14.361 showing the effects of standing waves. Larger amplitudes correspond to greater axial ratios.	19
2.2	Trace of three portions of chart record from 14.360 showing distortion caused by a slow AGC system. Larger amplitudes correspond to greater axial ratios	20
3.1	Sectional block diagram of entire system	23
3.2	Individual block diagram of entire system.	25
3.3	FET Schmitt trigger.	28
3.4	(a) Photograph of the sinusoidal input and square output from the FET Schmitt trigger shown in Figure 3.3, and (b) a sketch indicating the result of hysteresis.	29
3.5	702C used as an inverting integrating amplifier.	31
3.6	The input (above) and the output (below) of the 702C configuration shown in Figure 3.5.	32
3.7	710C used as a Schmitt trigger (inverting input)	33

LIST OF FIGURES (continued)

Figure	Page
3.8 (a) The sinusoidal input and square wave output from the 710C configuration shown in Figure 3.7, and (b) the transfer characteristic for the 710C.	35
3.9 Sinusoidal input and the respective four negated outputs of nor-logic establishing the quadrants labeled (a) ~ 1 , (b) ~ 2 , (c) ~ 3 , and (d) ~ 4 in Figure 3.2	36
3.10 Impedance matching network and low-pass LC filter.	38
3.11 (a) The input (below) and the resulting output (above) of the LC filter shown in Figure 3.10 at a signal frequency of 15 Hz, and (b) the same input signal and resulting output at 150 Hz	39
3.12 Bode plot of LC filter response.	40
3.13 702C used as an amplifier (inverting input).	42
3.14 Sinusoidal input and square output of the 710C configuration shown in Figure 3.7.	43
3.15 702C used as an integrating amplifier (inverting input).	45
3.16 Square input and resulting triangular output of the 702C configuration shown in Figure 3.15	46
3.17 710C used as a variable Schmitt trigger (inverting input).	47
3.18 Triangular input and resulting square output of the 710C configuration of Figure 3.17, with the potentiometer set to trigger at a level equal to (a) approximately 3/4 the peak value and (b) 1/3 the peak value of the triangular waveform.	48
3.19 Square input and spiked output of an RC differentiation circuit.	50
3.20 Sinusoidal receiver signal shown in relation to spiked output of the RC differentiation circuit.	51
3.21 Pulses formed from the spikes shown in Figure 3.20 through nor-gating. The double-pole double-throw switch is in the (a) red position and (b) white position.	54
3.22 Voltage incrementation circuit	57
3.23 Transfer characteristics of preposed (a) current controlled attenuator and (b) voltage controlled phase shifter.	58

LIST OF FIGURES (continued)

Figure	Page
3.24 Receiver signal shown undistorted (above) and after AGC distortion (below), illustrating the preservation of phase relation at the point of the negatively sloped zero crossing.	60
3.25 Trace of a section of charge record resulting from system testing, showing (top to bottom) 2X-MA, rocket receiver, OUT_p , and OUT_a signals with the maximum occurring in quadrant II . . .	61
3.26 Trace of a section of chart record resulting from system testing, showing (top to bottom) 2X-MA, rocket receiver, OUT_p , and OUT_a signals with the maximum occurring in quadrant III.	62
3.27 Circuit diagram of entire polarization correction system	63

Part 2

1.1 Block diagram of radio propagation experiment.	4
1.2 Payload instrumentation and shell.	6
1.3 Antenna and receiver unit.	7
1.4 Telemetry chart record for 14.270.	11
1.5 Block diagram of data processing system.	12
1.6 Block diagram of instrumentation for Faraday rotation data processing.	14
1.7 Block diagram of instrumentation for differential absorption data processing	17
1.8 Processed Faraday rotation data.	18
1.9 Processed differential absorption data	19
2.1 Generation of polarization circle.	21
2.2 Generation of polarization ellipse	22
2.3 Generation of rocket receiver output signal.	24
3.1 Simplified spin and precession of rocket	30
3.2 Precession effect on rocket spin signal.	30

LIST OF FIGURES (continued)

Figure	Page
3.3 Comparison of processed Faraday rotation data with rocket spin signal for 14.270.	32
3.4 Geometry of geomagnetic field and rocket precession cone axis . . .	33
3.5 Geomagnetic field components for 14.270	35
3.6 Components of rocket velocity relative to earth for 14.270.	36
3.7 Precession frequency and precession angle versus time after launch for 14.270	39
3.8 Precession frequency and precession angle versus time after launch for 14.146	40
3.9 Waveforms for explanation of phase detector	42
3.10 Look azimuth and elevation versus time after launch for 14.270.	44

LIST OF SYMBOLS

Part 2.

$A_0, a_0, A_1, A_2,$ A_3, A_4, A_6, A_7	= Constants
$\vec{B}, B, (B_x, B_y, B_z)$ (B_E, B_N, B_U)	Geomagnetic field vector, and its absolute = value, (x, y, z) components, (east, north, up) components
B_1, b_1, B_3	= Constants
c	= Velocity of light = 3×10^8 m/s
C_1, C_2	= Constants
$C_3(t)$	= Time-varying coefficient
e_{01}, e_{02}, e_{03}	= Rocket receiver output signals
$e_1, e_1^1, e_2, e_3, e_4,$ e_5, e_6, e_7 e_R, e_S, e_{S1}, e_{S2}	Signals for explanation of theory of operation of data processing system
e_{p1}, e_{p3}	= Signals with precession effect
f	= Wave frequency
f_c	= Center frequency for radio propagation experiment
f_o	= Ordinary mode frequency, $f_o = f_c - 250$ Hz
f_x	= Extraordinary mode frequency, $f_x = f_c + 250$ Hz
f_F	= Faraday rotation frequency
f_p	= Rocket precession frequency
$f_s, \Delta f_s$	= Rocket spin frequency, and its difference
G_1, G_3, G_4	= Constants
k_o, k_ϕ	= Constants
$\hat{L}_K, L_K, (L_E, L_N, L_U)$	= Unit vector along line of sight between transmitting antenna and rocket, its absolute value (=1), (east, north, up) components
M	= Peak to peak maximum value of rocket spin signal

LIST OF SYMBOLS (continued)

N	= Peak to peak minimum value of rocket spin signal
N_e	= Electron density
$\hat{P}$	= Unit vector tangent to rocket trajectory in direction from which rocket arrived at a given time on trajectory
$\hat{R}, -\hat{R}_1, -\hat{R}_2$	= Unit vector lying on rocket axis in direction of rocket nose, and two instantaneous positions of $-\hat{R}$
$\hat{S}, \hat{S}_1, \hat{S}_2$	= Unit vector along sensor direction, and its instantaneous positions
r	= Distance
t	= Time
ΔT	= Time interval between adjacent maxima and minima of rocket spin signal
$\vec{v}, v, (v_x, v_y, v_z)$ (v_E, v_N, v_U)	$\left. \begin{array}{l} \text{Rocket velocity vector relative to earth,} \\ \text{directed tangent to the rocket trajectory,} \\ \text{absolute value, (x, y, z) components, (east,} \\ \text{north, up) components} \end{array} \right\} =$
α_F	= $\omega_F t = 2\pi f_F t$
α_P	= $\omega_P t = 2\pi f_P t$
α_R	= $\omega_R t = 2\pi f_R t$
α_s	= $\omega_s t = 2\pi f_s t$
β_1, β_2	= Angles
θ_B	= Angle between $\vec{B}$ and $\hat{P}$
θ_P	= Rocket precession angle = angle between $\hat{P}$ and $-\hat{R}$
θ_{Bv}	= Angle between $\vec{B}$ and $\vec{v}$
θ_{PW}	= Angle between rocket flight path and wave propagation path
θ_{RW}	= $\theta_P + \theta_{PW}$
λ	= Wavelength

LIST OF SYMBOLS (continued)

ϕ	= Phase change of reference signal
$2\phi_F$	= Servo shaft position angle
ω	= Angular frequency
ω_P	= $2\pi f_P$
ω_R	= $2\pi f_R$, f_R = Reference signal frequency = 2 x 250 Hz
ω_S	= $2\pi f_S$

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**Part 1. DESIGN OF POLARIZATION ADJUSTMENT
INSTRUMENTATION FOR A ROCKET PROPAGATION
EXPERIMENT**

by

R. C. Condon
E. A. Mechtly

1. INTRODUCTION

Radio propagation experiments conducted by the Aeronomy Laboratory to determine electron density and collision frequency from measurements of differential absorption and Faraday rotation in the D-region of the ionosphere, make use of transmitted circularly polarized waves (Knoebel et al., 1966). There exists a need for a system which is able to determine if the polarization is indeed circular as required. If the polarization is found to be in error, then the system should be able to correct the error. The following sections outline a method of detecting any deviation from circular polarization in either the ordinary or the extraordinary mode of propagation. A system which will detect and correct the deviations is discussed in detail.

1.1 Apparatus Used in Producing Circular Polarization

The transmitted circularly polarized waves originate from a ground-based antenna array, which consists of four horizontal half-wavelength dipoles, elevated one quarter wavelength above the ground plane. These dipoles are arranged as the sides of a square, and opposite sides are fed in parallel (Knoebel et al., 1966). By means of this array (depicted in Figure 1.1), the two modes of propagation, ordinary and extraordinary, are transmitted to the rocket. These modes are circularly polarized and oppositely sensed. The frequencies of the two modes are usually in the two to four megahertz range, and differ from one another by 500 Hz.

Figure 1.2 illustrates the ordinary and the extraordinary modes rotating in opposite directions, producing a 500 Hz resultant, whose polarization axis rotates in free space at 250 rps (Seino, 1968). This is accomplished by means of the ordinary mode rotating North into West, tracing out a circle of frequency

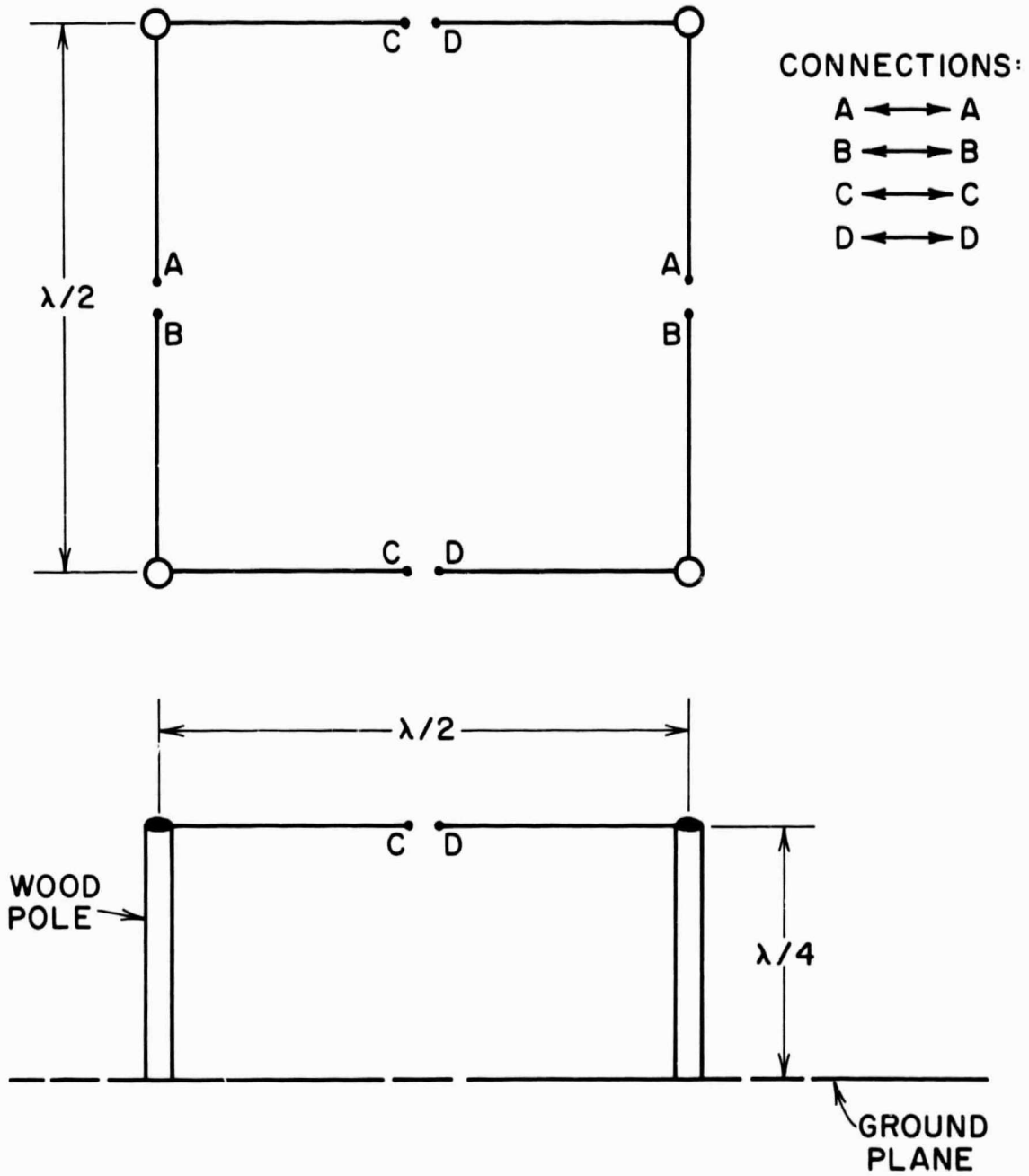


Figure 1.1 Top and front views of the square transmitting antenna array.

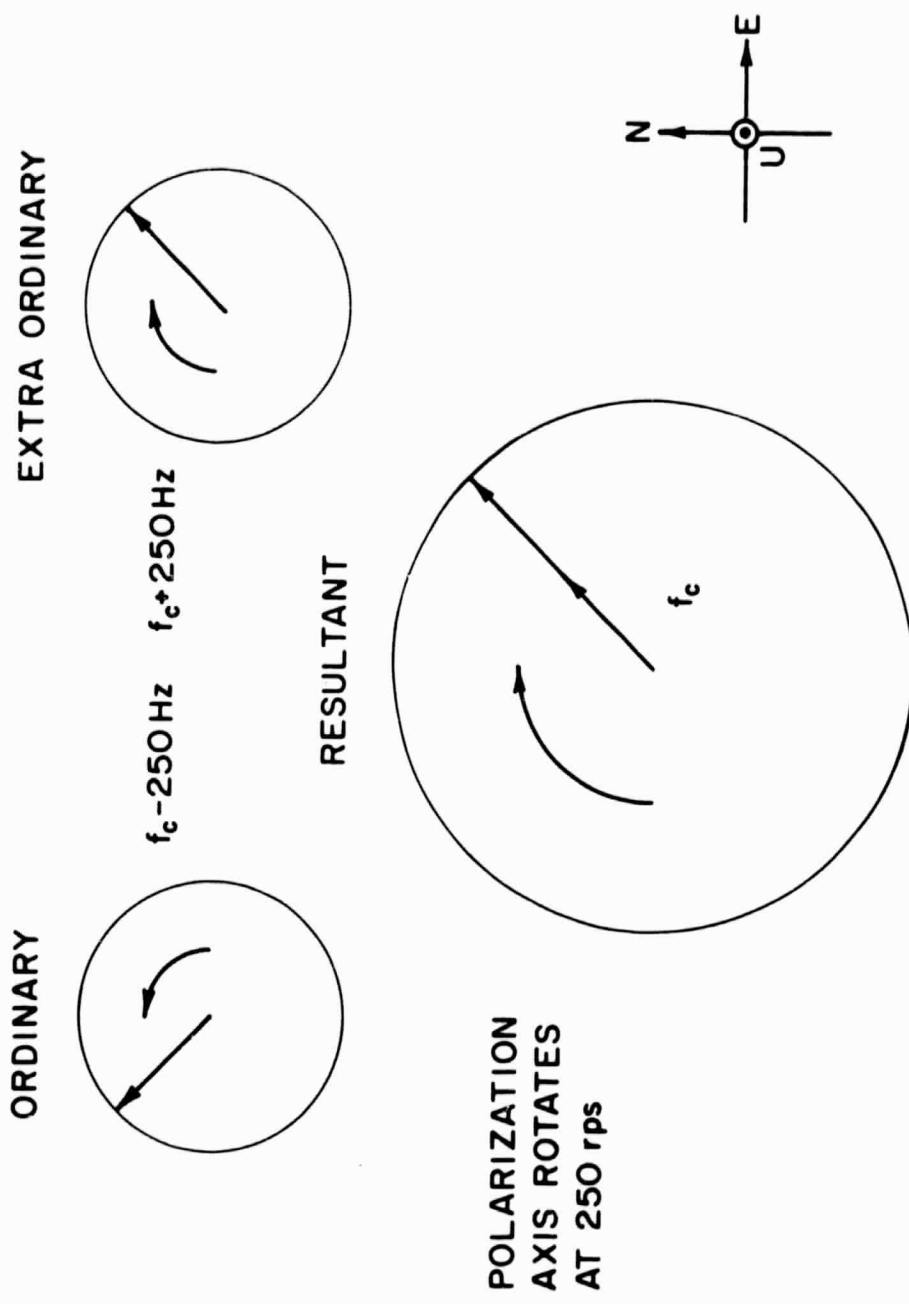


Figure 1.2 Generation of polarization circle
(after Seino, 1968).

$f_o = f_c - 250 \text{ Hz}$, where f_c is the center frequency of the transmitter. Similarly, the extraordinary mode rotates North into East, tracing a circle of frequency $f_x = f_c + 250 \text{ Hz}$ (Mechtly et al., 1967).

In Figure 1.3, the effects of a 10 dB difference in the power levels of the ordinary and extraordinary modes are shown. Normally, the ordinary has the larger power level of the two modes, and this power differential causes the overall shape of the resultant to be elliptical. However, its axis is still rotating at 250 rps, but due to the elliptical nature of the resultant, the rocket receiver now observes a total resultant which has a frequency of $2 \times 250 \text{ Hz}$ (Seino, 1968).

1.2 Preliminary Polarization Adjustments

The testing of the transmitting antenna array for circular polarization is preceeded by arranging the dipoles and feedlines of the array as symmetrically as possible (Knoebel et al., 1966). Then after tuning the transmitter, the output of the antenna array is determined by attenuating one of the transmitting modes by a factor of 50 dB, leaving the other mode to propagate alone. Next a small (approximately 20 cm in length) ferrite rod antenna, called a "whirly", is placed in the exact center of the array. The whirly rotates horizontally in a plane parallel to the ground plane (Figure 1.4). This rotation, together with the output of the transmitting array, which now consists of only one mode, is observed on the oscilloscope of Figure 1.4. This scope produces a display of amplitude versus time, so that the elliptically polarized resultant which appears, is shown as a modulated carrier (Figure 1.5a). Therefore, by means of adjusting the manual attenuator and phase shifter (which are shown later in Figure 1.7), the polarization can be altered visually, until minimum modulation of the carrier appears on the scope. Ideally, this would finally produce a carrier

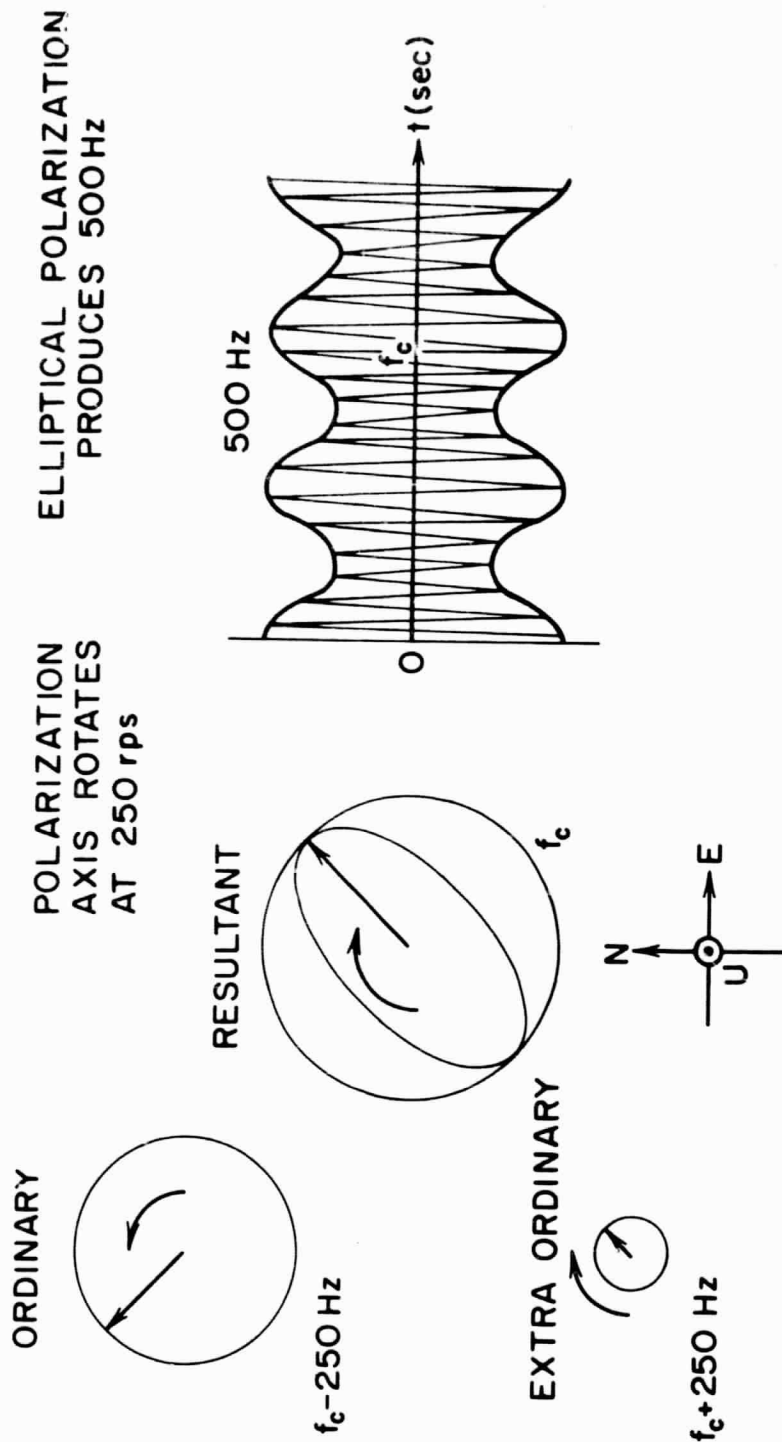


Figure 1.3 Generation of polarization ellipse
(after Seino, 1968).

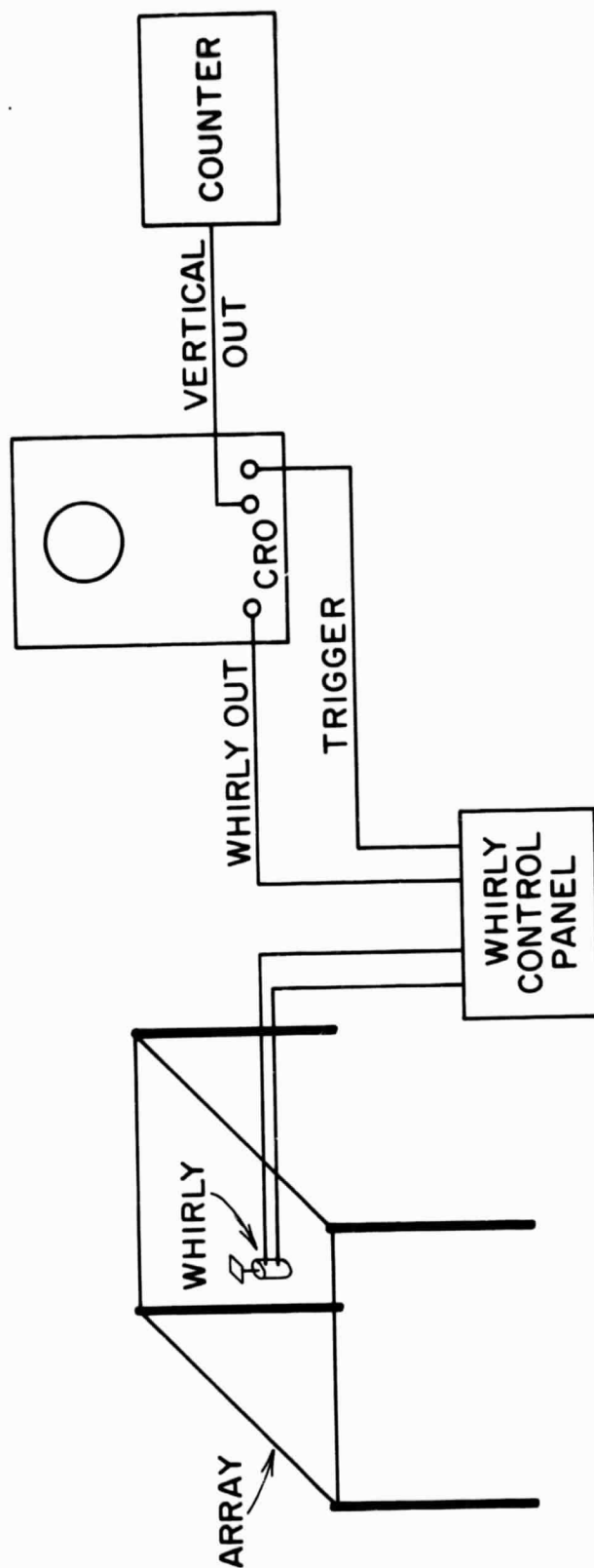


Figure 1.4 Block diagram of the apparatus used in the preliminary polarization adjustments.

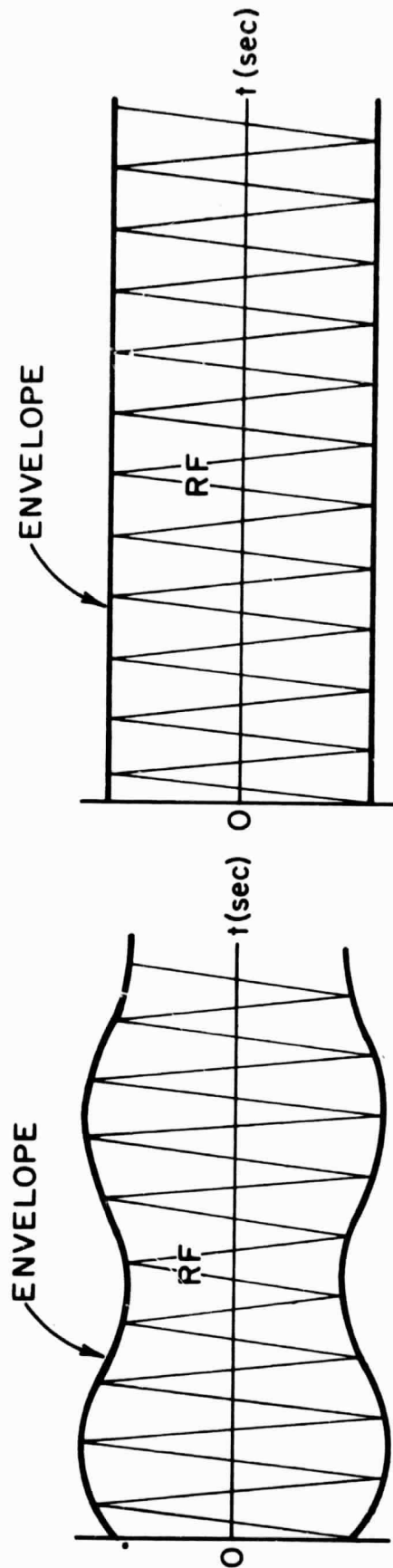


Figure 1.5 Modulation envelopes resulting from (a) elliptical polarization and (b) circular polarization.

whose envelope of modulation is precisely a straight line (Figure 1.5b), and at this point, the polarization would have become perfectly circular. After one of the modes has been circularized, the second mode is adjusted by a similar procedure.

Having attained circular polarization of both modes, we now have to determine the direction of rotation of their polarization axes. The direction can be determined by disconnecting the trigger lead in Figure 1.4 from the oscilloscope. One mode is then propagated alone with the whirly at rest and a cycle count is made, which consists of recording the frequency of the received signal. Similar cycle counts are made with the whirly rotating in both the clockwise and the counterclockwise directions, and these three results are compared. The direction of whirly rotation which is found to yield a cycle count lower than that of the mode propagating alone, is in fact the direction of rotation of that mode. As a check, the cycle count with the whirly rotating in the other direction, should be higher.

Until the present time, the above tests, and all other polarization tests which have been attempted, have not provided the desired precision in establishing and maintaining circular polarization. Such factors as undesirable near field effects, and the fact that the rocket does not proceed along the axis of the antenna beam, are two of the possible reasons for the imprecision. It must be noted however, that regardless of other inaccuracies in the testing methods, the directions of rotation, once having been found, are indeed correct and remain correct for the duration of the rocket flight.

1.3 Characteristics of Elliptical Polarization

We can represent elliptical polarization by means of two orthogonal harmonic oscillations. These oscillations can be depicted as cosine motions

of the form:

$$H_y = a_1 \cos(\omega t + \phi_1) ,$$

and (1.1)

$$H_z = a_2 \cos(\omega t + \phi_2) ,$$

assuming the positive x-direction as the direction of propagation.

Equations (1.1) can be expanded by the trigonometric identity for the cosine of the sum of two angles, and thus take the form:

$$\frac{H_y}{a_1} = \cos\omega t \cos\phi_1 - \sin\omega t \sin\phi_1 ,$$

and (1.2)

$$\frac{H_z}{a_2} = \cos\omega t \cos\phi_2 - \sin\omega t \sin\phi_2 .$$

Multiplying the first of these equations by $\sin\phi_2$, and the second by $-\sin\phi_1$, and then adding, we produce the equation

$$\frac{H_y}{a_1} \sin\phi_2 - \frac{H_z}{a_2} \sin\phi_1 = \cos\omega t \sin\phi . \quad (1.3)$$

Similarly, by multiplying the first of Equations (1.2) by $\cos\phi_2$, and the second by $-\cos\phi_1$, and again adding, we have

$$\frac{H_y}{a_1} \cos\phi_2 - \frac{H_z}{a_2} \cos\phi_1 = \sin\omega t \sin\phi \quad . \quad (1.4)$$

Squaring Equations (1.3) and (1.4) and adding the results, yields

$$\frac{H_y^2}{a_1^2} - \frac{H_z^2}{a_2^2} - \frac{2H_y H_z}{a_1 a_2} \cos\phi = \sin^2\phi \quad , \quad (1.5)$$

where $\phi = \phi_2 - \phi_1$.

Equation (1.5) is a standard form of an ellipse. Any arbitrary elliptical polarization can be fully described by three properties: (a) the ratio of major to minor axis (axial ratio), (b) the angle which the major axis makes with some reference axis (tilt angle), and (c) the sense of rotation of the vector generating the ellipse (Mayes, 1965).

Property (c), is determined by means of cycle counts, as discussed in Section 1.2. Properties (a) and (b) are illustrated in Figure 1.6, which defines the lengths a and b , and the angle ψ . We let $\tan\theta = a/b$, which is the ratio of major to minor axes, and we call ψ the tilt angle. Now by applying a series of algebraic and trigonometric operations, we express $\tan\theta$ and ψ as functions of the original variables (Kelso, 1950). The final equations are

$$\tan 2\psi = \frac{-2a_1 a_2 \cos\phi}{a_1^2 - a_2^2} \quad (1.6)$$

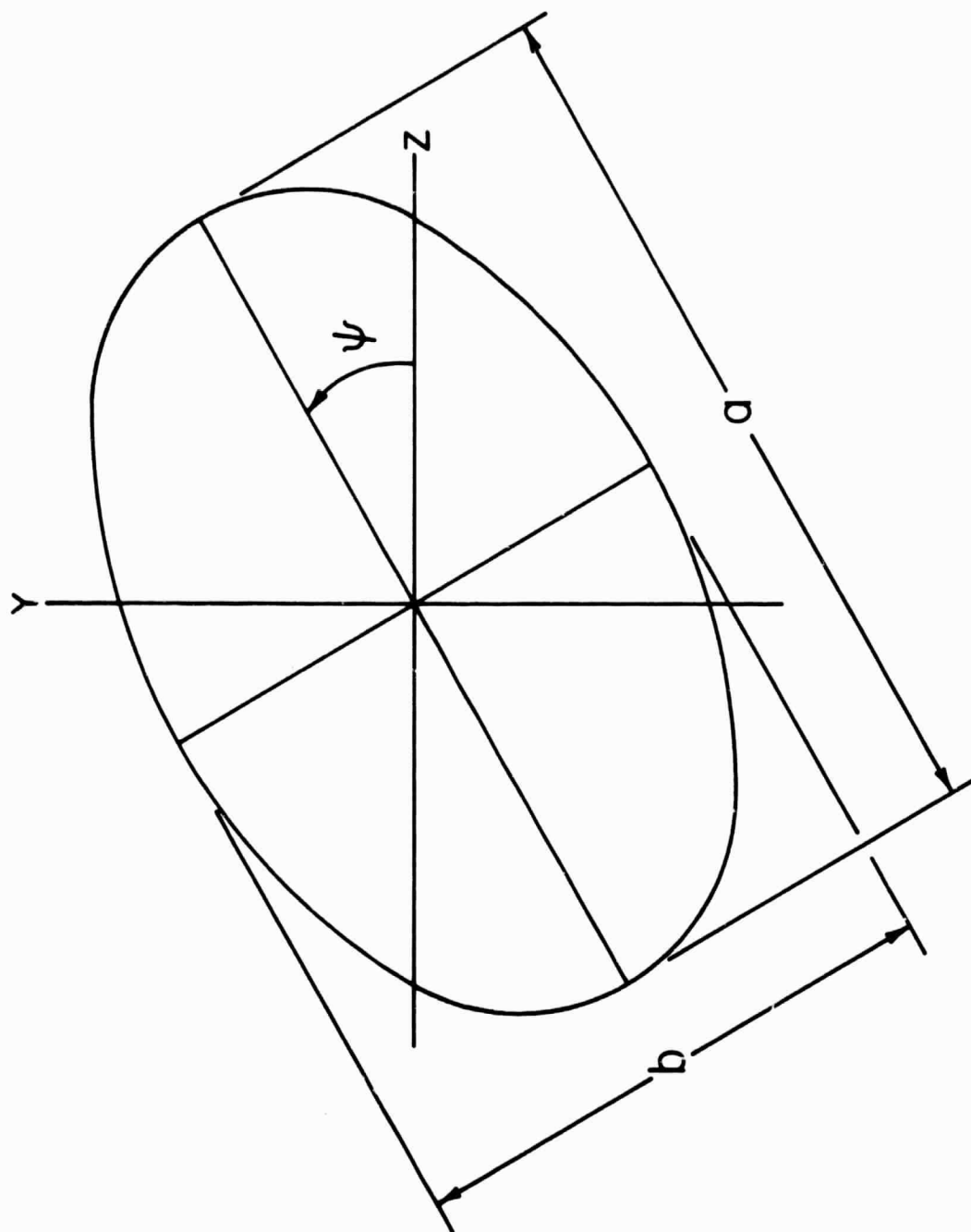


Figure 1.6 Definition of the elliptical polarization parameters with respect to the YZ coordinates as determined by the transmitting antenna array (after Kelso, 1950).

and

$$\tan \theta = \frac{a_1 \sin \phi_1 \sin \psi + a_2 \sin \phi_2 \cos \psi}{a_1 \cos \phi_1 \cos \psi - a_2 \cos \phi_2 \sin \psi} = \frac{a}{b} . \quad (1.7)$$

The above two equations, (1.6) and (1.7), involve all four of the initial variables, namely a_1 , a_2 , ϕ_1 and ϕ_2 . However, the phase shifters and attenuators shown in Figure 1.7 are designed to deal with relative quantities, as opposed to absolute quantities. The relative quantities can be obtained from the definition of the complex polarization vector, R , where

$$R = \frac{H_z}{H_y} = \frac{a_2}{a_1} e^{+j(\phi_2 - \phi_1)} = \rho e^{j\phi} . \quad (1.8)$$

This equation may be arrived at simply through transformation of the initial cosine terms of Equation (1.1) into exponentials. From Equation (1.8), we see that there now exist only two variables of interest, ρ and ϕ , where ρ is the amplitude of the polarization vector, and ϕ is the phase angle (Kelso, 1950). From here, we can see the convenience of simply selecting permanent values for two of the original variables. In other words, if we let $a_1 = 1$ and $\phi_2 = 0^\circ$ in Equations (1.6) and (1.7), we lose no generality, since only the amplitude ratio (a_2/a_1), and the phase difference ($\phi_2 - \phi_1$), are of interest. By changing the remaining two variables, a_2 and ϕ_1 , any given ellipse can still be represented.

Substituting the permanent values of a_1 and ϕ_2 , Equations (1.6) and (1.7) become

$$\tan 2\psi = \frac{-2a_2}{1-a_2^2} \cos \phi , \quad (1.9)$$

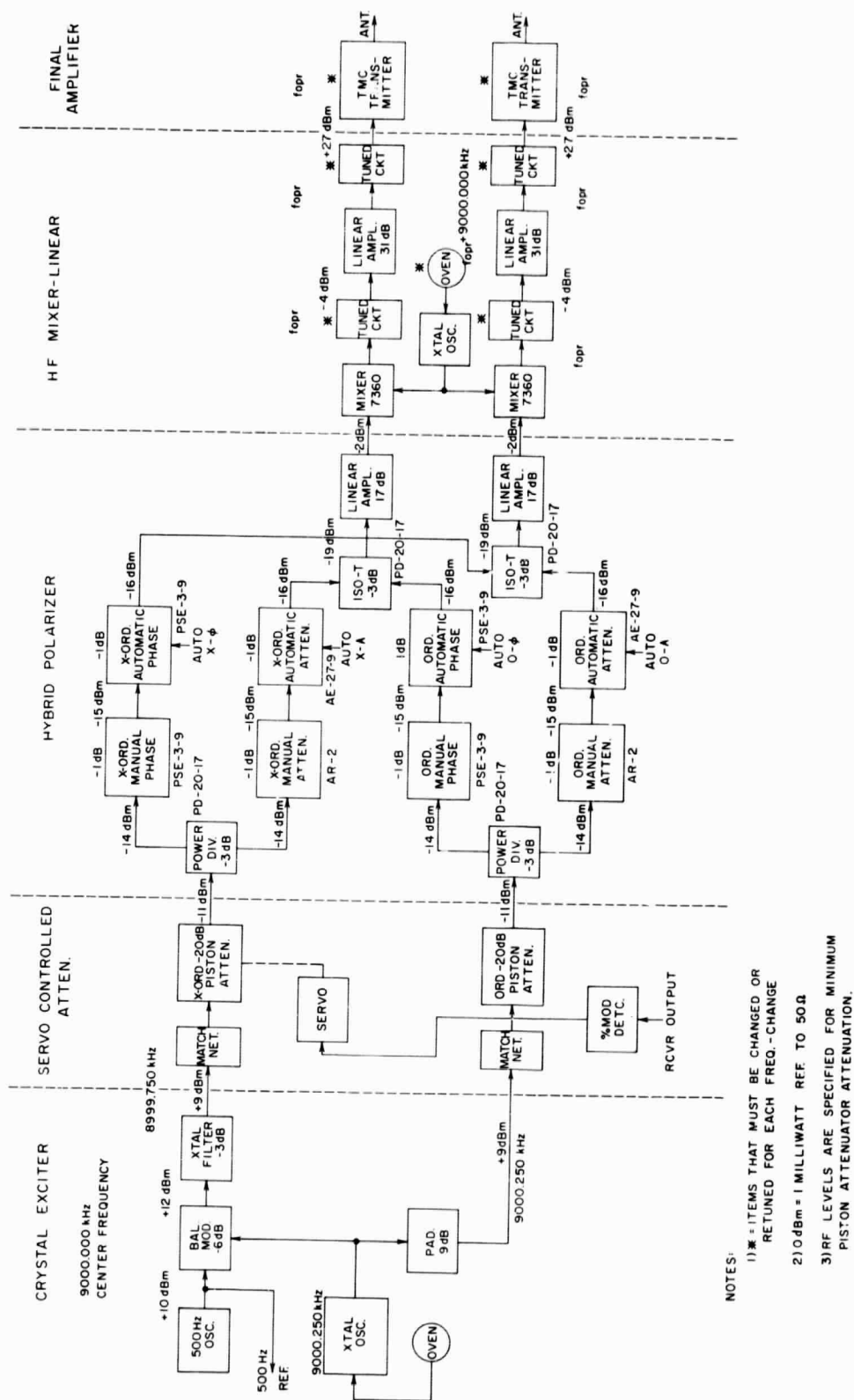


Figure 1.7 Block diagram containing both the manual and the variable attenuators and phase shifters which control the polarization of the transmitted wave.

and

$$\tan\theta = \frac{\sin\phi_1 \sin\psi}{\cos\phi_1 \cos\psi - a_2 \sin\psi} = \frac{a}{b} \quad (1.10)$$

respectively. Now, by substituting various values of a_2 and ϕ ($= -\phi_1$) into Equations (1.9) and (1.10), we can calculate the corresponding values of $\tan\theta$ and ψ . A set of values are tabulated in Table 1.1.

Examining this table, we see an ambiguity in the value of axial ratio. That is, the same value of $\tan\theta$ occurs for more than one combination of a_2 and ϕ . However, all ambiguity may be eliminated by considering both the value of $\tan\theta$ and the value of ψ together. Even if the table were much more comprehensive and depicted far more values of a_2 and ϕ , we would still see a unique one to one correspondance between (a) any given pair of quantities a_2 and ϕ , and (b) the corresponding combination of tilt angle (ψ) and axial ratio ($\tan\theta$). It is this uniqueness that permits the development of a method to achieve circular polarization.

As an example of the method, let us turn our attention to the heavily outlined square of Table 1.1 which has $\psi = 25^\circ$ and $\tan\theta = 2.0$. We immediately know that the value of a_2 is $8/12$ and the value of ϕ is 60° , since the uniqueness described above forbids any other possible values of these variables. Therefore, we at once know that we should decrease the attenuation of a_2 (thereby increasing its value toward 1.0), and increase the phase ϕ (thereby increasing its value toward 90°). By repeated incremental changes of a_2 and ϕ , we move from one square to another, getting nearer the center of the table with each movement. Finally, after a sufficient number of steps have been taken, we will have converged on the center square of the table, where we achieve an axial ratio of 1.0. At this point, of course, we have circular polarization.

Table 1.1 Relation between Elliptical Parameters and the Phase-Amplitude Values of the Transmitted Signal

	$\phi=45^\circ$	$\phi=60^\circ$	$\phi=75^\circ$	$\phi=90^\circ$	$\phi=105^\circ$	$\phi=120^\circ$	$\phi=135^\circ$
$a_2 =$ 6/12	$\tan\theta=$ 3.20 $\psi =$ 22.0°	$\tan\theta=$ 2.48 $\psi =$ 16.6°	$\tan\theta=$ 2.11 $\psi =$ 9.4°	$\tan\theta=$ 2.00 $\psi =$ 0° (180°)	$\tan\theta=$ 2.11 $\psi =$ 170.6°	$\tan\theta=$ 2.48 $\psi =$ 163.4°	$\tan\theta=$ 3.20 $\psi =$ 158.0°
$a_2 =$ 7/12	2.90 26.8°	2.20 22.2°	1.83 8.5°	1.72 0° (180°)	1.83 171.5°	2.20 157.8°	2.90 153.2°
$a_2 =$ 8/12	2.66 30.1°	2.00 25.0°	1.63 16.0°	1.50 0° (180°)	1.63 164.0°	2.00 155.0°	2.66 149.9°
$a_2 =$ 9/12	2.55 33.1°	1.87 30.5°	1.48 19.7°	1.33 0° (180°)	1.48 160.3°	1.87 149.5°	2.55 146.9°
$a_2 =$ 10/12	2.47 38.0°	1.79 35.5°	1.38 27.8°	1.20 0° (180°)	1.38 152.2°	1.79 144.5°	2.47 142.0°
$a_2 =$ 11/12	2.43 40.8°	1.75 40.1°	1.33 36.0°	1.09 0° (180°)	1.33 144.0°	1.75 139.9°	2.43 139.2°
$a_2 =$ 12/12	2.41 45.0°	1.73 45.0°	1.30 45.0°	1.00 none	1.30 135.0°	1.73 135.0°	2.41 135.0°
$a_2 =$ 14/12	2.46 50.7°	1.77 53.3°	1.36 61.0°	1.17 90.0°	1.36 119.0°	1.77 126.7°	2.46 129.3°
$a_2 =$ 16/12	2.55 56.9°	1.87 59.5°	1.48 70.3°	1.33 90.0°	1.48 109.7°	1.87 120.5°	2.55 123.1°
$a_2 =$ 18/12	2.66 59.9°	2.00 65.0°	1.63 74.0°	1.50 90.0°	1.63 106.0°	2.00 115.0°	2.66 120.1°
$a_2 =$ 20/12	2.86 63.3°	2.13 68.4°	1.79 77.2°	1.67 90.0°	1.79 102.8°	2.13 111.9°	2.86 116.7°
$a_2 =$ 22/12	3.04 66.2°	2.32 71.0°	1.95 79.2°	1.83 90.0°	1.95 100.8°	2.32 109.0°	3.04 113.8°
$a_2 =$ 24/12	3.20 68.0°	2.48 73.4°	2.11 80.6°	2.00 90.0°	2.11 99.4°	2.48 106.6°	3.20 112.0°

Note that the values of ψ all lie between the limits of 0° and 180° . This, of course, is due to the elliptical nature of the polarization (two maxima and two minima for each rotation of the rocket). Therefore to resolve the ambiguity which exists when talking of the value of ψ in a general ellipse, we restrict our consideration to the first 180° of rotation of the vector generating the elliptical polarization.

2. RESULTS OF POLARIZATION TESTS ON ROCKET SHOTS NO. 14.360 AND 14.361

Basic polarization tests were made during two of the rocket shots at Wallops Island, Virginia, on July 24, 1968. Polarization results determined from the chart records of those shots are presented in this section.

2.1 Nature of the Testing

Changes in the settings of the manual attenuators and phase shifters of Figure 1.7 were made during the flights of rockets 14.360 and 14.361. In order for these tests to be meaningful, they were not performed until after 10 seconds had elapsed, allowing for all possible transients, due to the take-off, to have diminished. Also, to be perfectly sure that the tests would not interfere with data which is taken immediately upon entry into the ionosphere, all tests were terminated after 40 seconds had elapsed. (This approximate 30-second limitation on the testing period must, for the same reasons, hold for any system developed to produce circular polarization.)

Pre-flight calibrations were made in the manner already described in Section 1.2. On rocket 14.360, after approximately 10 seconds, the extraordinary mode was attenuated and the ordinary allowed to propagate. The attenuator and phase shifter controlling the ordinary were then moved from their pre-flight settings. These changes were made to allow us to note the corresponding variations in the amplitude and phase of the receiver output, using the output from the magnetic aspect sensor on the rocket as a phase reference. At approximately 25 seconds of elapsed time, the ordinary was attenuated and the extraordinary was transmitted. The same type of changes were made on its corresponding attenuator and phase shifter until the elapsed time of approximately 40 seconds. At this time, both modes were once more restored to their pre-flight power levels, and all

pre-flight attenuator and phase-shifter settings were also restored. The same manner of testing was used on 14.361, with the exception that the order in which the modes were transmitted was reversed.

2.2 Testing Limitations

Only the manual attenuators and phase shifters, shown in Figure 1.7, were in use during the time of this testing. These devices are restricted in the sense that the phase shift and attenuation are mutually dependent. That is to say, by merely changing the setting of (for example) the attenuator alone, a change in phase shift is simultaneously introduced (the converse being also true). There is no simple relation governing this mutual dependence, and therefore no easy way of knowing beforehand, the exact change which takes place. Some elaborate method of point by point measurement would be required to predict the changes, and this would be highly tedious and impracticable. It is for this reason that the tests conducted could not be used as a means of checking the calculated variations of tilt angle and axial ratio with respect to attenuation and phase as discussed in Section 1.3

It is evident that the data from only two rocket shots can not reveal all the effects of such things as time of day, weather conditions, or variations in different rocket receivers without further testing. However, the following section describes the conclusions drawn from the two tests which were conducted.

2.3 Results of the Testing

2.3.1 The Presence of Standing Waves

Rocket shot 14.360 was conducted at 12:00 noon EST and rocket shot 14.361 at 4:36 PM EST. In the 25 to 40 second interval of 14.361, with the ordinary mode propagating, the chart records showed multiple peaks during each period of the receiver output. At no other time during the testing of either rocket,

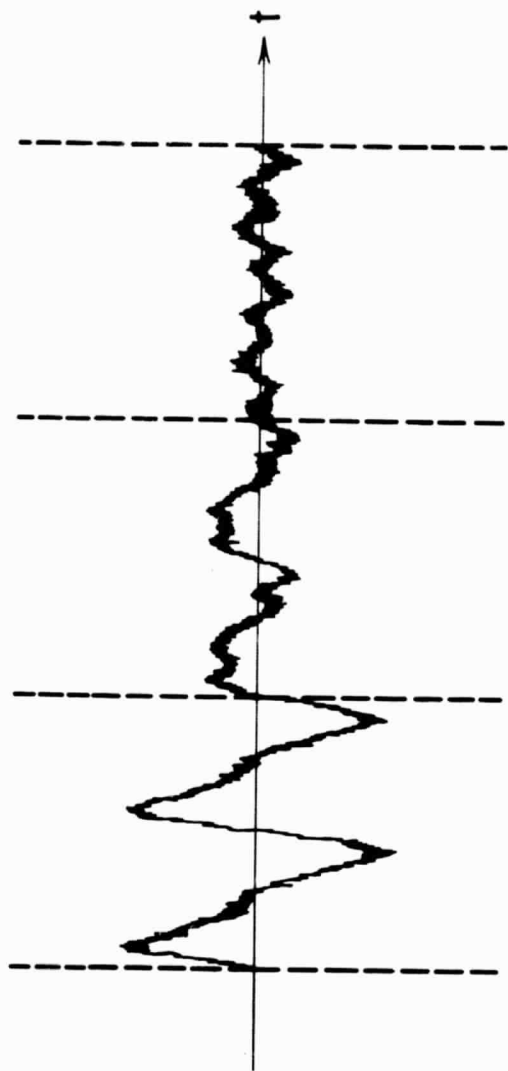


Figure 2.1 Trace of three portions of chart record from 14.361 showing the effects of standing waves. Larger amplitudes correspond to greater axial ratios.

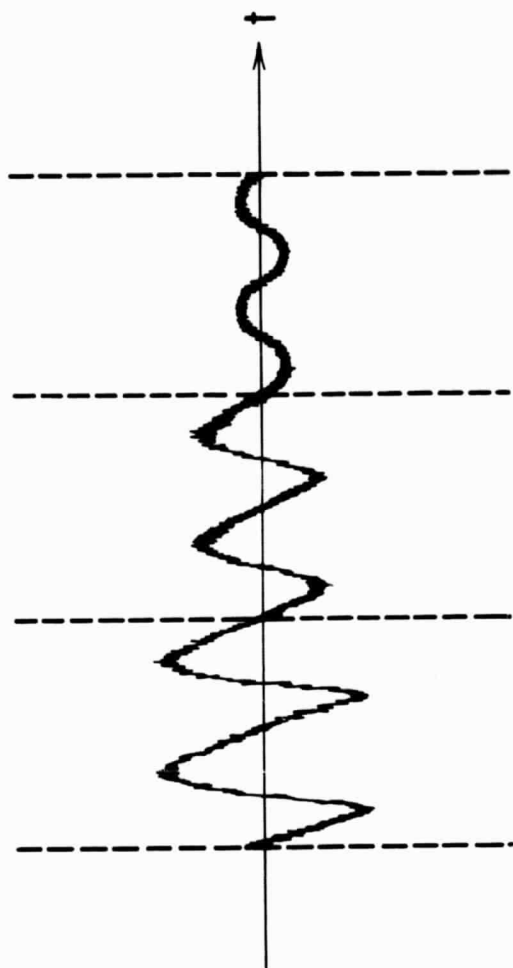


Figure 2.2 Trace of three portions of chart record from 14.360 showing distortion caused by a slow AGC system. Larger amplitudes correspond to greater axial ratios.

had this phenomenon occurred. Taking note of the respective times of day, we attribute the phenomenon to the existence of standing waves. This conclusion is based on the fact that the extra peaks did not occur regularly at any multiple of the rocket roll rate (as shown in Figure 2.1), and are therefore thought to stem from an external source.

Since D-region absorption is larger near noontime (when 14.360 was launched) than at 4 PM (when 14.361 was launched), it is reasonable to conclude that reflected signals were sufficiently strong to set up standing waves at 4 PM but not at noon. We therefore attribute the multiple peaks which occurred in the chart record of 14.361 to the existence of these standing waves.

2.3.2 Signal Distortion

It was also found, that at times (independent of the particular mode propagating) the signal from the receiver was distorted as shown in the left and center portion of Figure 2.2. We attribute this to a slow reacting AGC system in the receiver itself. This explanation is plausible since the frequencies we are dealing with are in the 5 to 10 Hz range. The figure shows that the distortion diminishes as the polarization is corrected, that is, as the amplitude of the sinusoid is decreased. Based on this fact, we deem it highly improbable that, after the pre-flight polarization adjustment of both modes, the polarization would even be bad enough to have this distortion become appreciable.

3. THE POLARIZATION CORRECTION SYSTEM

3.1 Qualitative Analysis

We have established in Section 1.3 that apparatus capable of determining the tilt angle, ψ , and the corresponding axial ratio for elliptical polarization, is a necessary part of a system able to correct elliptical polarization. This part of the system would be required to determine in which of the four quadrants of Table 1.1 the tilt angle occurs. For example, a value of ψ found to be within the range $0^\circ < \psi < 45^\circ$, must necessarily occur in the upper left quadrant of Table 1.1, and only in that quadrant. Once the quadrant is determined, the remainder of the system must be able to appropriately increase (or decrease) both the amplitude a_2 , and the value of the angle, ϕ . Such a system would be able to correct any elliptical polarization to a more circular polarization.

A system which is capable of these functions consists of the four blocks of circuitry shown in Figure 3.1. Block one conditions the signal from the magnetic aspect sensor (MA), and block two does the same for the rocket receiver signal. They are conditioned in such a manner, that when connected through the logic circuitry of block three, they form a signal which can correctly drive the incrementation circuitry of block four. The MA signal is used as a phase reference with which the phase of the signal from the rocket receiver can be compared. It should be noted, that the phase of the magnetic aspect signal (assuming that the rocket does not precess about a field line) is directly related to the fixed coordinate system defined in Figure 1.6. This coordinate system is determined by the orientation of the transmitting antenna array located on the ground and the known direction of the geomagnetic field vector. Therefore, the MA signal does indeed qualify as a valid phase reference.

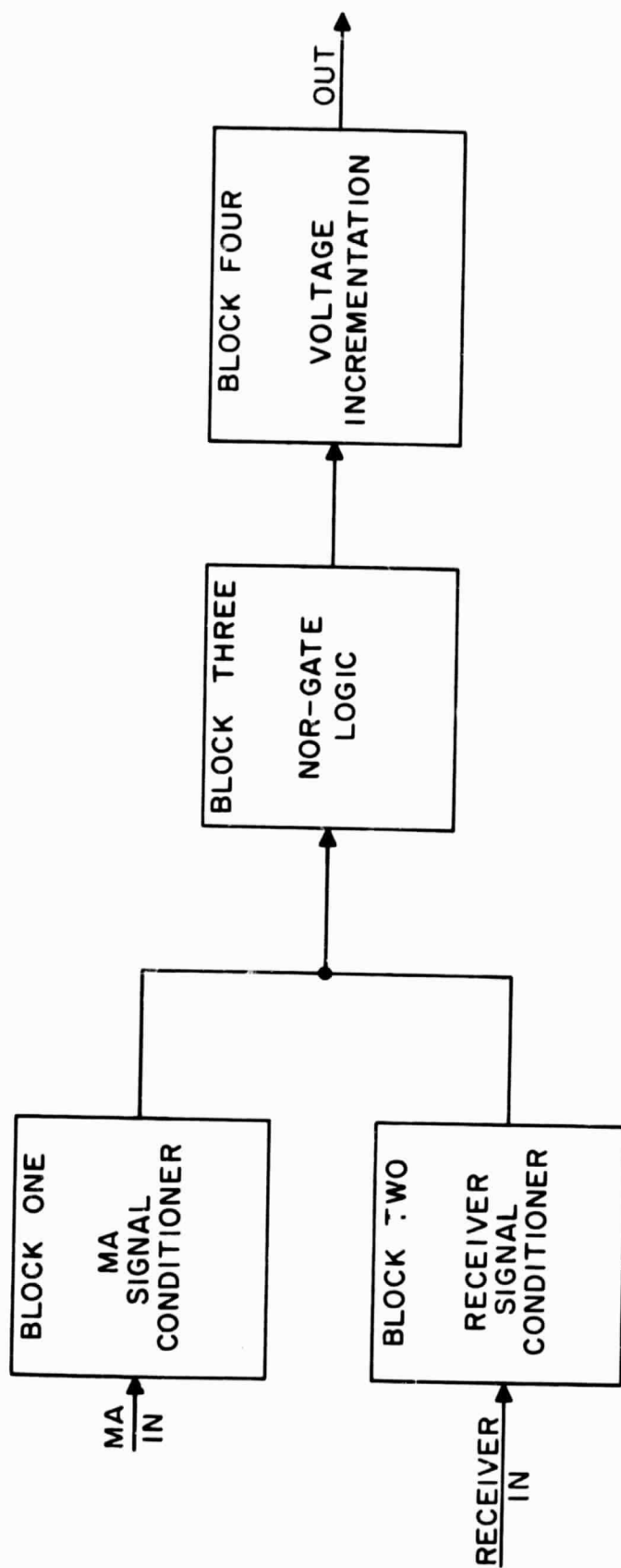


Figure 3.1 Sectional block diagram of entire system.

The procedure we now follow divides this sinusoidal MA reference signal into four distinct quadrants (designated by the numbers 1, 2, 3 and 4 in Figure 3.2) which correspond to the four quadrants which we have discussed in Section 1.3. We then work with the rocket receiver signal, each period of which we transform into a signal pulse occurring only at the point where the maximum of the signal had occurred. This pulse is designated by the letter C in Figure 3.2. Now by comparing this pulse with signals representing the four quadrants, via logic circuitry, we are able to determine the quadrant of occurrence of the pulse (and thus of the maximum). In this manner we determine the quadrant location of ψ . We are then left with four distinct outputs (one for each quadrant) which are fed in appropriate combinations into two, dual input voltage incrementation circuits. These circuits perform the function of either raising or lowering their respective output voltages by incremental amounts.

Let us clarify this point by means of a specific example. Suppose that the receiver pulse is found to occur in the upper left quadrant of Table 1.1. Subsequent logic circuitry transmits the pulse and combines it with that corresponding quadrant as determined from the MA signal. This combination is made in such a manner as to cause one incrementor circuit (labeled "attenuator" in Figure 3.2) to lower its output voltage. In a like manner, it causes the output voltage of the other incrementor circuit (labeled "phase shifter") to be raised. These voltages then, are the desired final outputs of the system, and are intended to be used as inputs to a current controlled attenuator and a voltage controlled phase shifter respectively. The attenuator, in turn, operates directly on the quantity a_2 (of Table 1.1), and the phase shifter operates on ϕ . Recalling that these two quantities are parameters of the transmitting

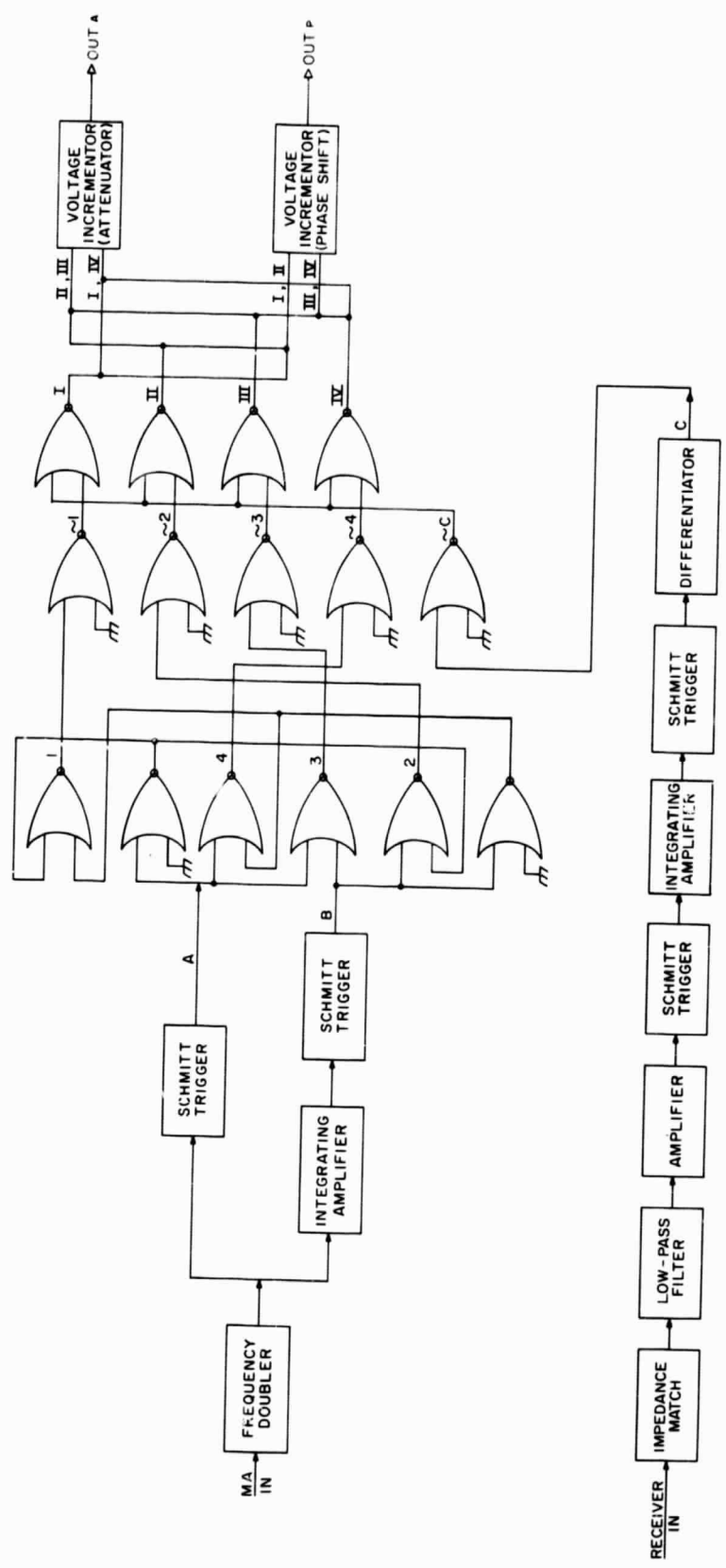


Figure 3.2 Individual block diagram of entire system.

circuitry, the incrementing circuits in effect, change the pre-set values of a_2 and ϕ (which had caused ψ to be located in the upper left quadrant in the first place). Thus the value of a_2 is increased toward 1.0 (by having its attenuation decreased), and the value of ϕ is increased toward 90° , since the attenuation and phase shift are directly proportional to the output voltages of their respective incrementor circuits. Now, of course, we are nearer to circular polarization (nearer to the center of Table 1.1). The system operates as a closed loop until the best possible polarization has been achieved. At this point, the system can be disengaged, with the two final values of a_2 and ϕ controlling the transmitted signal for the duration of the rocket flight.

3.2 Quantitative Analysis

3.2.1 Magnetic Aspect Signal Conditioner

Now that the overall operation of the system has been outlined, let us examine in detail each of the blocks of the diagram shown in Figure 3.1. We begin by considering block one, which conditions the signal of the magnetic aspect sensor.

The MA signal has a frequency equal to that of the rocket roll rate, but the signal from the rocket receiver, being elliptical in nature, has an effective frequency of two times the roll rate. Therefore, in order to make the two signals have a one to one correspondence, the frequency of the MA signal must be doubled. The doubler must introduce no variation in phase over the frequency range of the rocket roll (since the accurate relative phase relationship of the signals involved contains the required information). Also, the frequency doubler must maintain a constant output amplitude. An AGC system is included for this purpose.

Once having doubled the frequency of the MA signal and having rendered it constant in amplitude, we "quadrantize" it (i.e. divide it into four equal parts). This is done by first separating the doubled signal into two parts. One part is fed directly into the FET Schmitt trigger configuration of Figure 3.3. This trigger was designed specifically to eliminate all effects of hysteresis, and therefore trigger symmetrically and as nearly as possible to the zero crossing of the incoming sinusoidal waveform. The AGC system of the frequency doubler is a great aid in accomplishing these results. With constant input amplitude, the circuit of Figure 3.3 always triggers at exactly the same point.

The $4.7\text{ k}\Omega$ resistor in the figure determines the loop gain of the circuit and controls hysteresis. With this particular value of resistance, hysteresis is a minimum as shown by the input and output waveforms of the trigger, photographed in Figure 3.4a. In contrast, Figure 3.4b shows the input and output waveforms with $R = 6.8\text{ k}\Omega$. The undesirability of the latter output waveform will become evident later when its application is discussed. The $1\text{ }\mu\text{F}$ capacitor also shown in Figure 3.3 is used as a speed-up capacitor, enabling us to attain the fastest possible rise times in triggering.

The same doubled MA signal is simultaneously fed into an integrating amplifier which, in turn, is followed by another Schmitt trigger. However, once having integrated the signal (basically by means of a capacitor) the output amplitude of the integrating circuit will necessarily vary with frequency, thus making it very difficult to design an ordinary Schmitt trigger for symmetrical triggering. Therefore, it was decided that packaged integrated circuits would be used for triggering. The reason for this will be illustrated in Figure 3.8b which shows that switching (for the type 710C integrated circuit

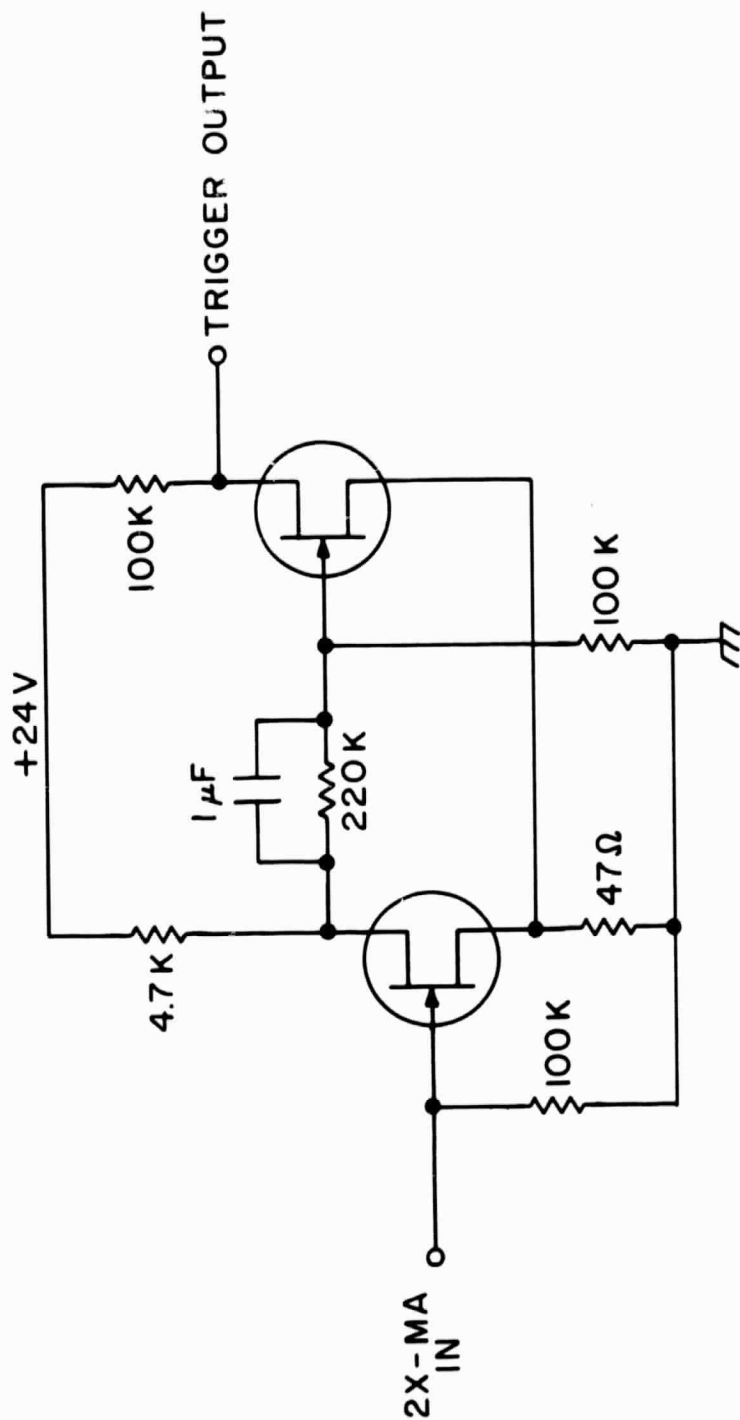
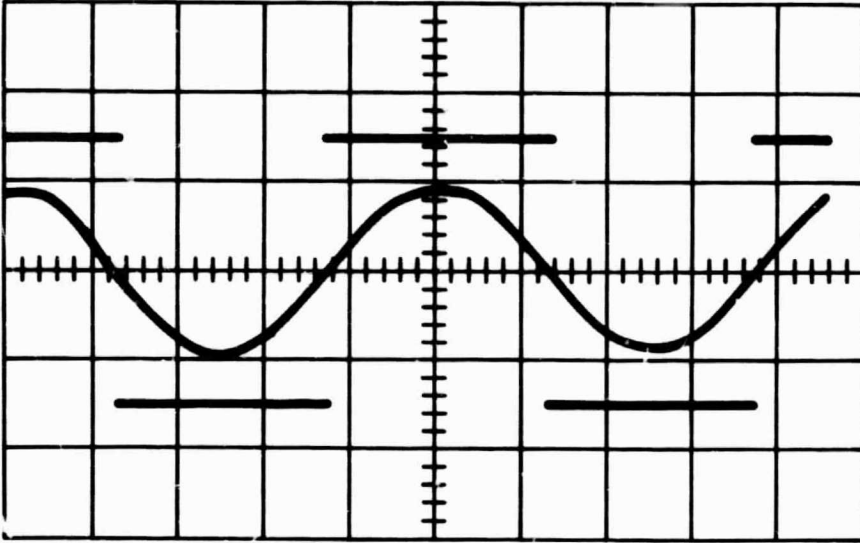
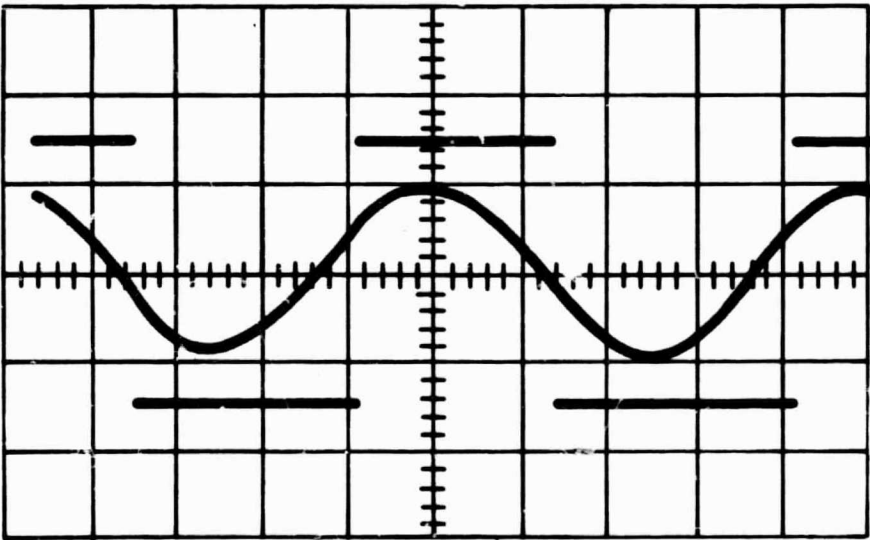


Figure 3.3 FET Schmitt trigger.



(a)



(b)

Figure 3.4 (a) Photograph of the sinusoidal input and square output from the FET Schmitt trigger shown in Figure 3.3, and (b) a sketch indicating the result of hysteresis.

which was selected) occurs within one millivolt of the zero crossing of the input signal, thus insuring symmetry regardless of the variations of input amplitude. Another IC package, the 702C (shown with its connections in Figure 3.5), was chosen for purposes of integration and amplification. It has two possible inputs (terminals 2 and 3), one of which inverts and the other does not. We select the inverting input (terminal 2) in order to achieve a positive cosine waveform from the input sine wave through the dual processes of integration and amplification (as shown in the photograph displayed in Figure 3.6). Amplification is accomplished via the 150 k Ω feedback resistor, and integration by means of the 1 μ F capacitor (Figure 3.5). These particular values make the overall gain for the 702C approximately 1/3, which is purposely low in order to insure that any subsequent IC circuitry will never be overdriven. The 0.1 μ F capacitor in terminal 6 of the device acts as a frequency compensator, with this particular value of capacitance causing the 702C to roll off at a frequency (20-30 kHz) well beyond the frequency range of the doubled rocket roll rate.

The 702C is followed by a Schmitt trigger in the form of another integrated circuit, type 710C. This 710C is listed as basically a differential voltage comparator intended for applications requiring high accuracy and fast response time--making it the ideal device for our present needs. The connections made to the device are illustrated in Figure 3.7. The package runs on the same bias voltages (+12 and -6) as the 702C of Figure 3.5, and thus, in itself, requires no extra power supplies. For this device the roles of terminals 2 and 3 are reversed with respect to the 702C, so that having our input at terminal 3, we again achieve inversion. This results in the overall input-output waveforms (for the combination of integration and triggering) photographed

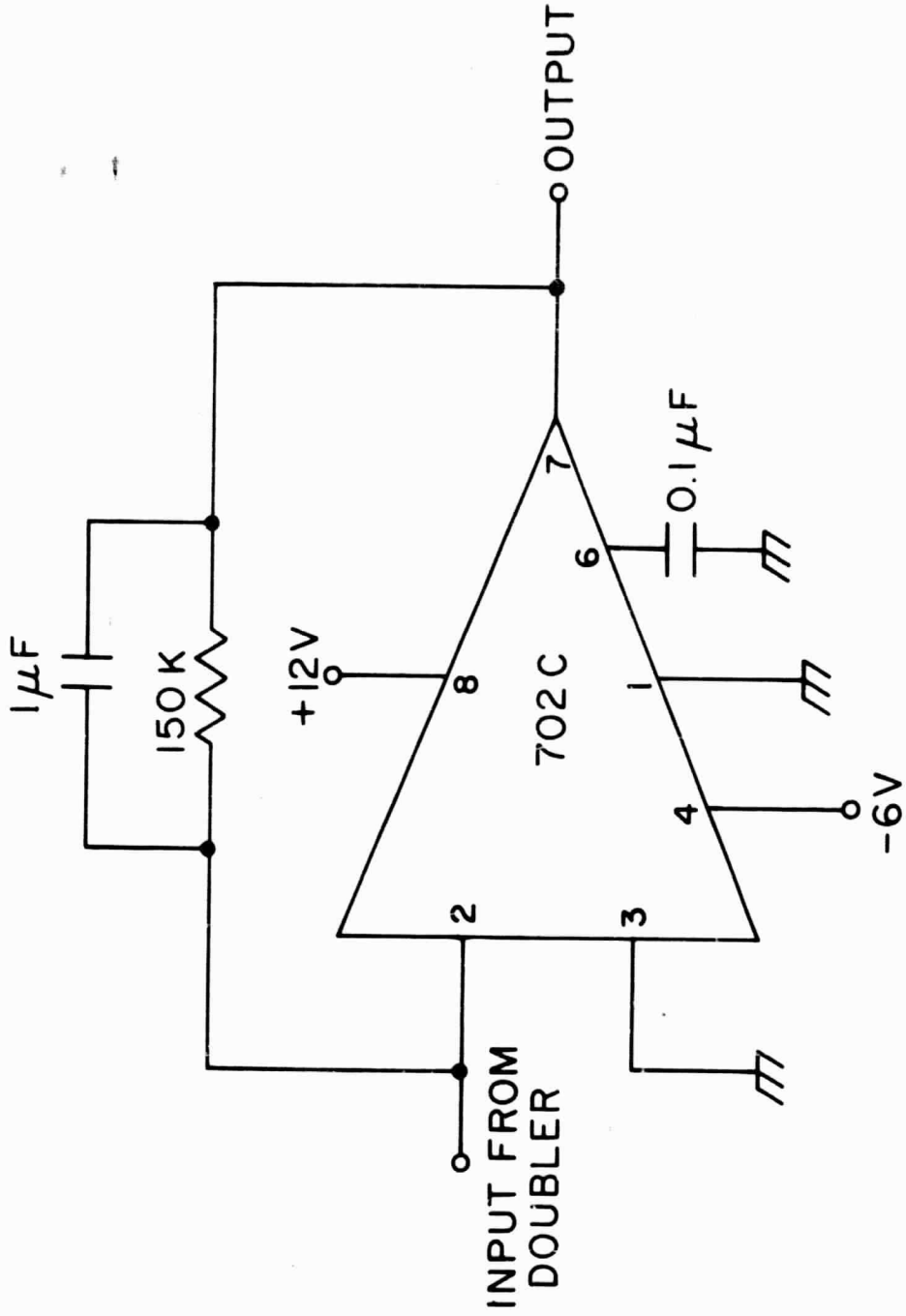


Figure 3.5 702C used as an inverting integrating amplifier.

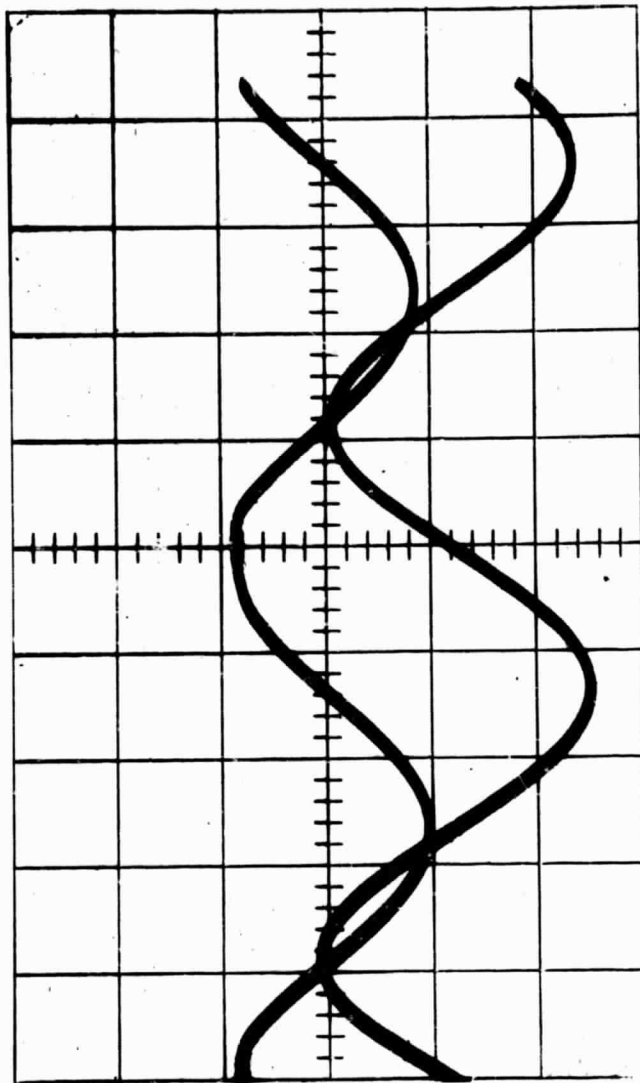


Figure 3.6 The input (above) and the output (below) of the 702C configuration shown in Figure 3.5.

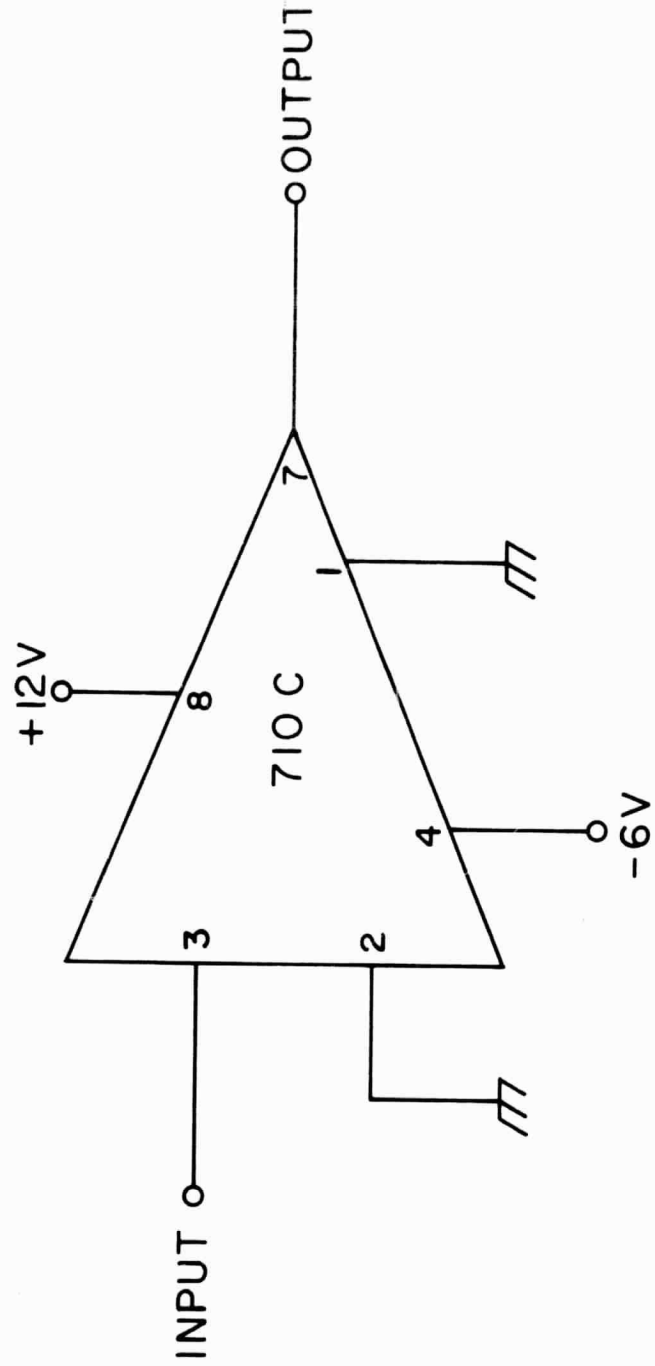
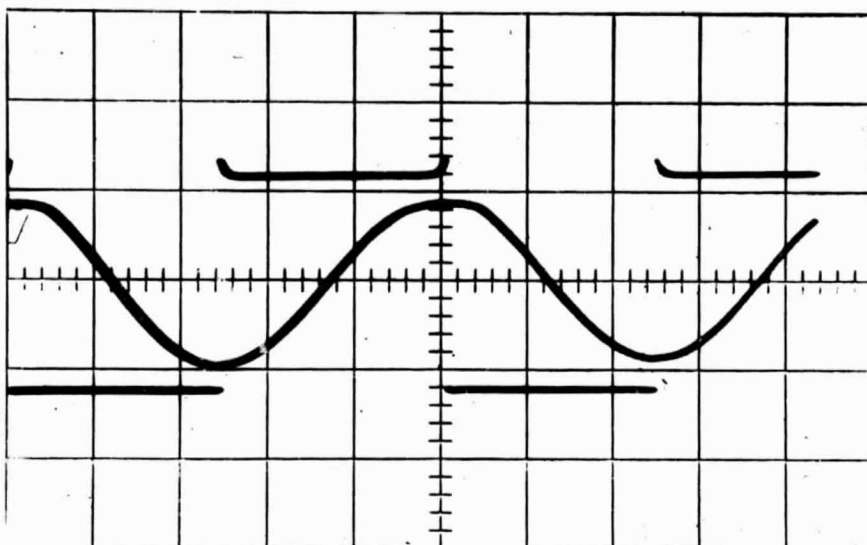


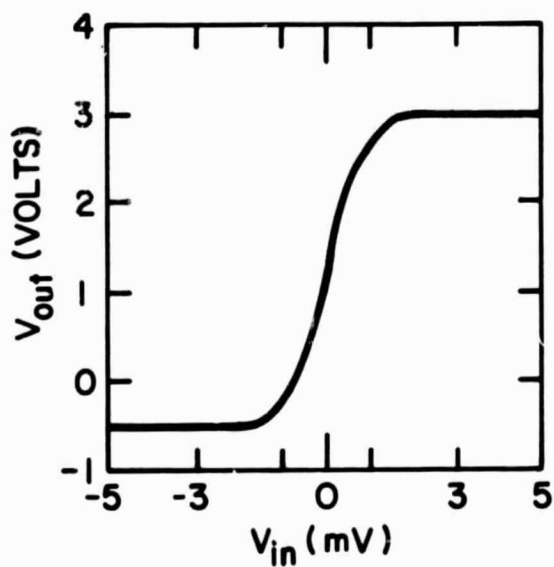
Figure 3.7 710C used as a Schmitt trigger (inverting input).

and displayed in Figure 3.8a. The input wave in this photograph is identical to the input wave in Figure 3.4a. Therefore, a visual comparison of the squared outputs of both figures can now be made, showing that the combined triggering points appear at the boundaries of the conventionally defined 90° quadrants of a sine wave.

Now we have to combine these two square wave outputs so that we can differentiate between the four quadrants. We do so by first defining the upper horizontal levels of either square wave (Figures 3.4a and 3.8a) as the one-state and the lower horizontal levels as the zero-state. Now our terminology is applicable directly to logic circuitry, which we will use to combine these waves. The logic we will use is in the form of nor-gates. The device containing these gates is the MC724P, which contains four such gates in one package. The gates are shown individually in 3.2 (the package is not shown) and require a +3.6 volt supply for biasing purposes. Now, let us designate the output of the FET trigger by the letter A, and the output of the IC circuitry by the letter B. Then we can go directly back to Figure 3.2 and observe the actual interconnection of A and B through the nor-logic. The result of these interconnections are the outputs labeled 1, 2, 3 and 4 in the Figure. These outputs are then negated and labeled ~ 1 , ~ 2 , ~ 3 and ~ 4 . Photographs of these four negated outputs of the nor-gates are displayed in Figure 3.9. All four are shown in relation to the doubled MA signal which is displayed in each picture. Therefore, by definition of the quadrant boundaries of a sine wave at its peaks and zero crossings, we see that these quadrants correspond respectively to the negated square waveforms produced by the logic. Thus, we have accomplished the separation of the doubled sinusoidal MA signal into four quadrants. The signal is now "quadrantized".



(a)



(b)

Figure 3.8 (a) The sinusoidal input and square output from the 710C configuration shown in Figure 3.7, and (b) the transfer characteristic for the 710C.

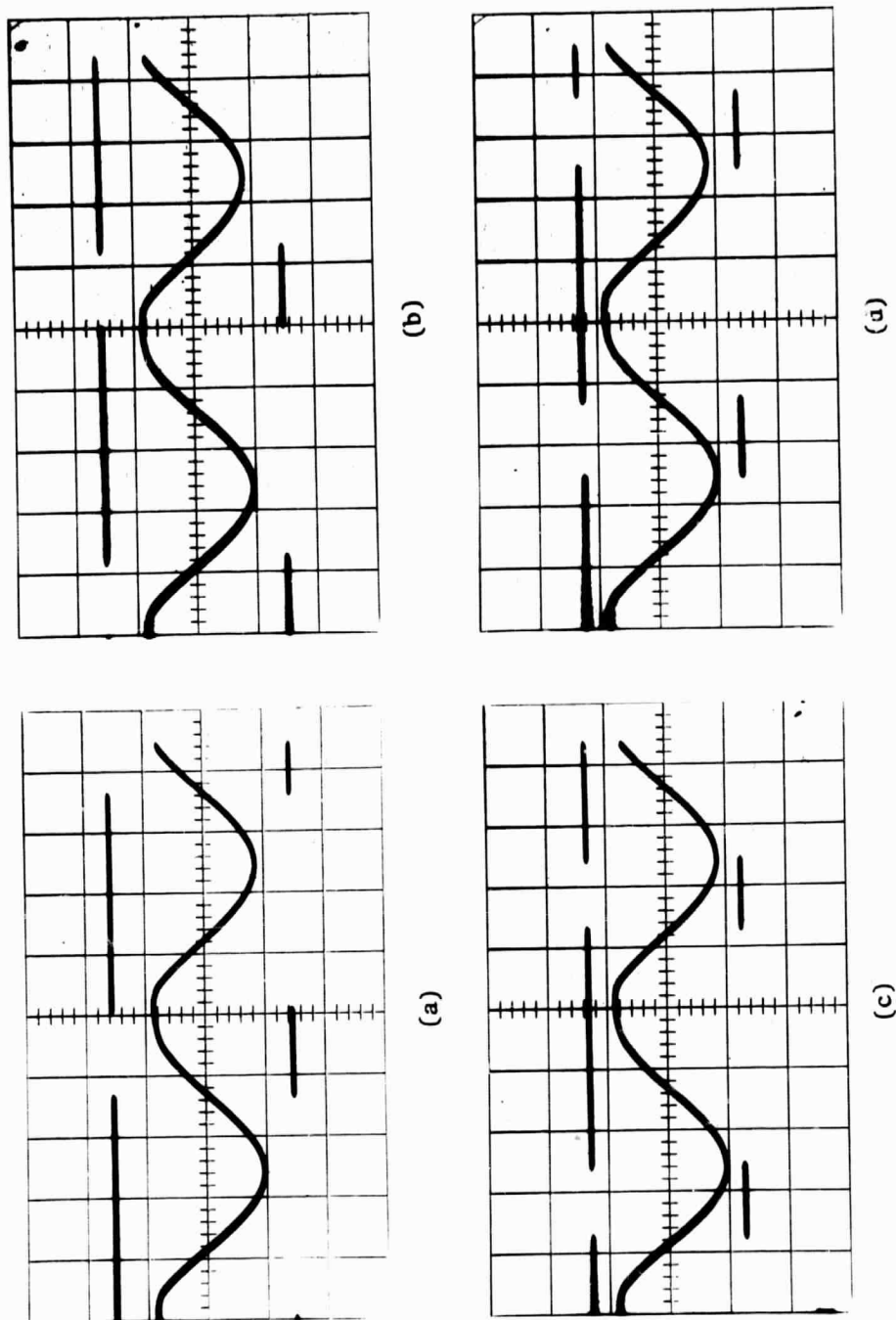


Figure 3.9 Sinusoidal input and the respective four negated outputs of nor-logic establishing the quadrants labeled (a) ~ 1 , (b) ~ 2 , (c) ~ 3 , and (d) ~ 4 in Figure 3.2.

3.2.2 Rocket Receiver Signal Conditioner

The receiver signal conditioner, block two of Figure 3.1, modifies the signal from the rocket receiver. This is the waveform of primary interest, since it contains the actual polarization information. The basic shape of this signal is sinusoidal (as discussed in Section 1.3), and it is of the same frequency as the output of the MA signal's frequency doubler. Therefore, we must find the quadrant location (using the quadrants just developed) of the maximum of this sinusoidal wave and thus, in effect, find the quadrant location of the tilt angle ψ .

Since our reference quadrants have already been defined, we must now find the maximum of the rocket receiver signal and determine its quadrant location. The actual circuitry which was developed to convert the signal of the rocket receiver into single pulses occurring only at the maxima of that signal, begins with the impedance matching circuitry shown in Figure 3.10. Again FETs are used, and the rocket receiver's high output impedance is matched to the much lower input impedance of subsequent circuitry. Figure 3.10 also shows an LC filter, a low-pass filter capable of suppressing any possible interfering signals of frequencies greater than a few hundred Hz. For this purpose the values of L and C were chosen such that the corresponding "break point" in the straight line Bode plot for the filter (Figure 3.12) occurs at 65 Hz ($\omega \approx 408\text{rps}$). Thus any frequency in the range of the doubled MA signal would be passed totally unimpeded, yet interfering signals in the few hundred Hz range, would be suppressed. For an illustration, Figure 3.11 shows two photographs each containing input and output waveforms of the filter. The input wave in each case has the same amplitude, but the amplitude of the output

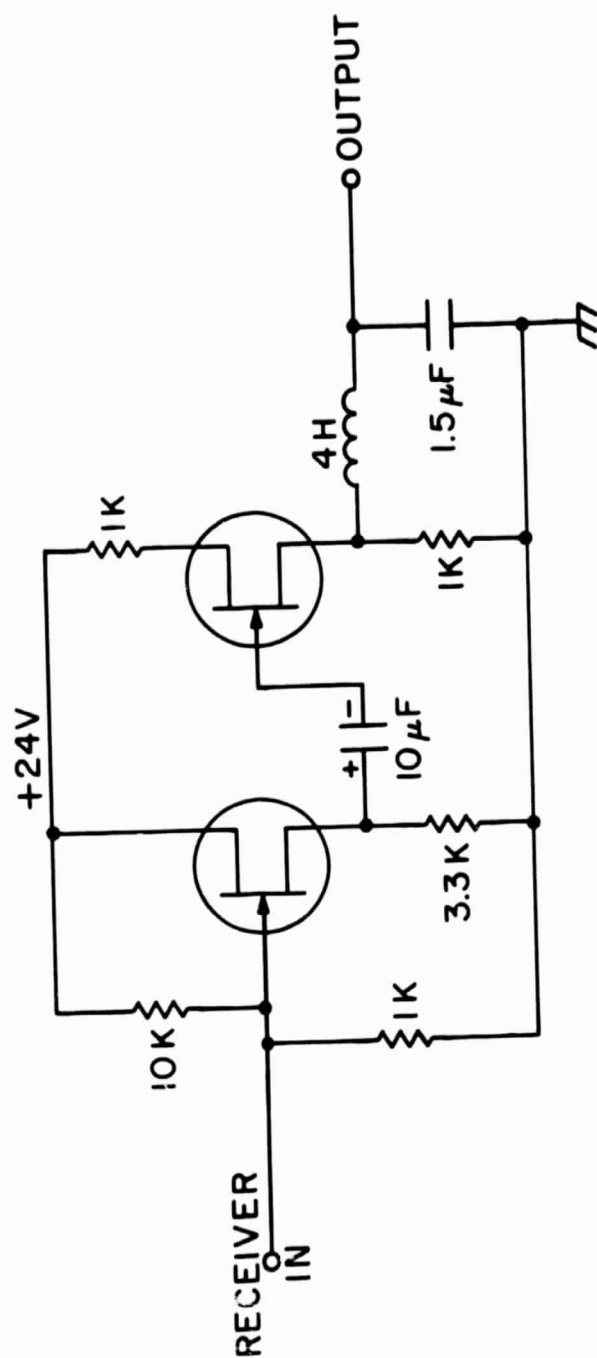
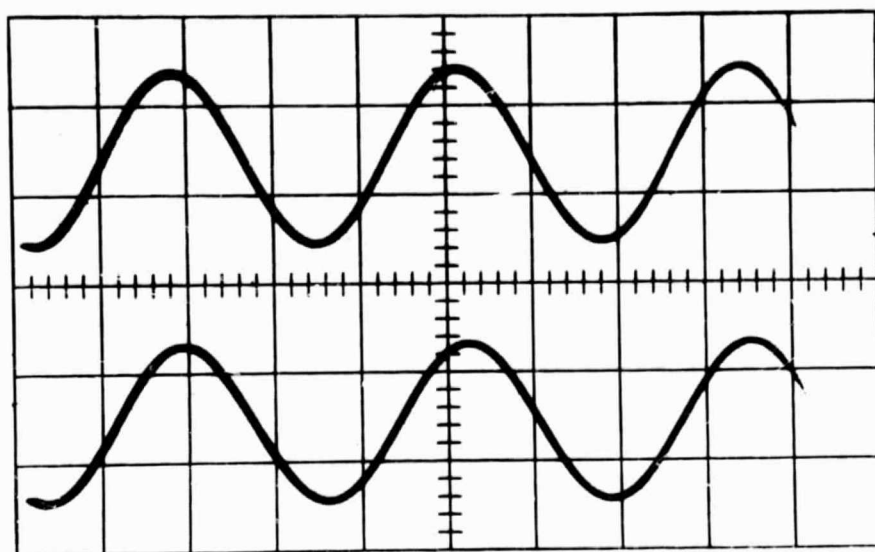
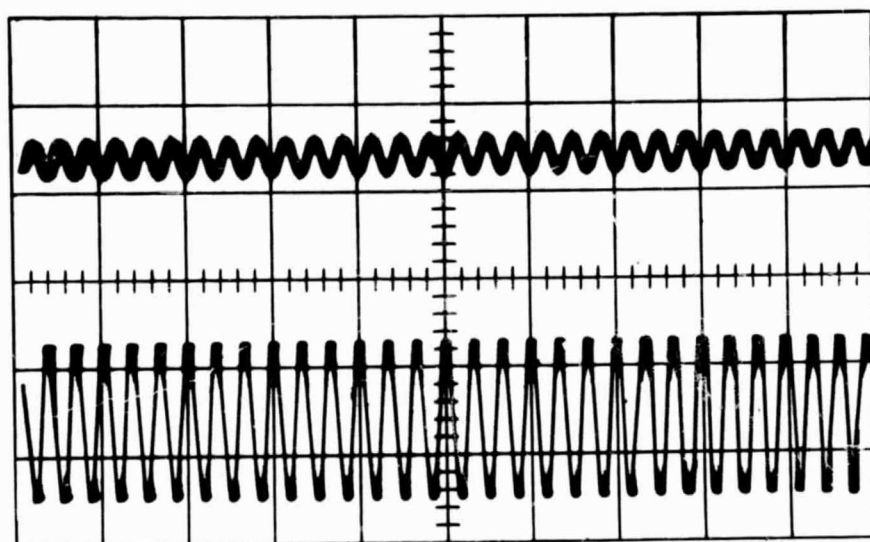


Figure 3.10 Impedance matching network and low-pass LC filter.



(a)



(b)

Figure 3.11 (a) The input (below) and the resulting output (above) of the LC filter shown in Figure 3.10 at a signal frequency of 15 Hz, and (b) the same input signal and resulting output at 150 Hz.

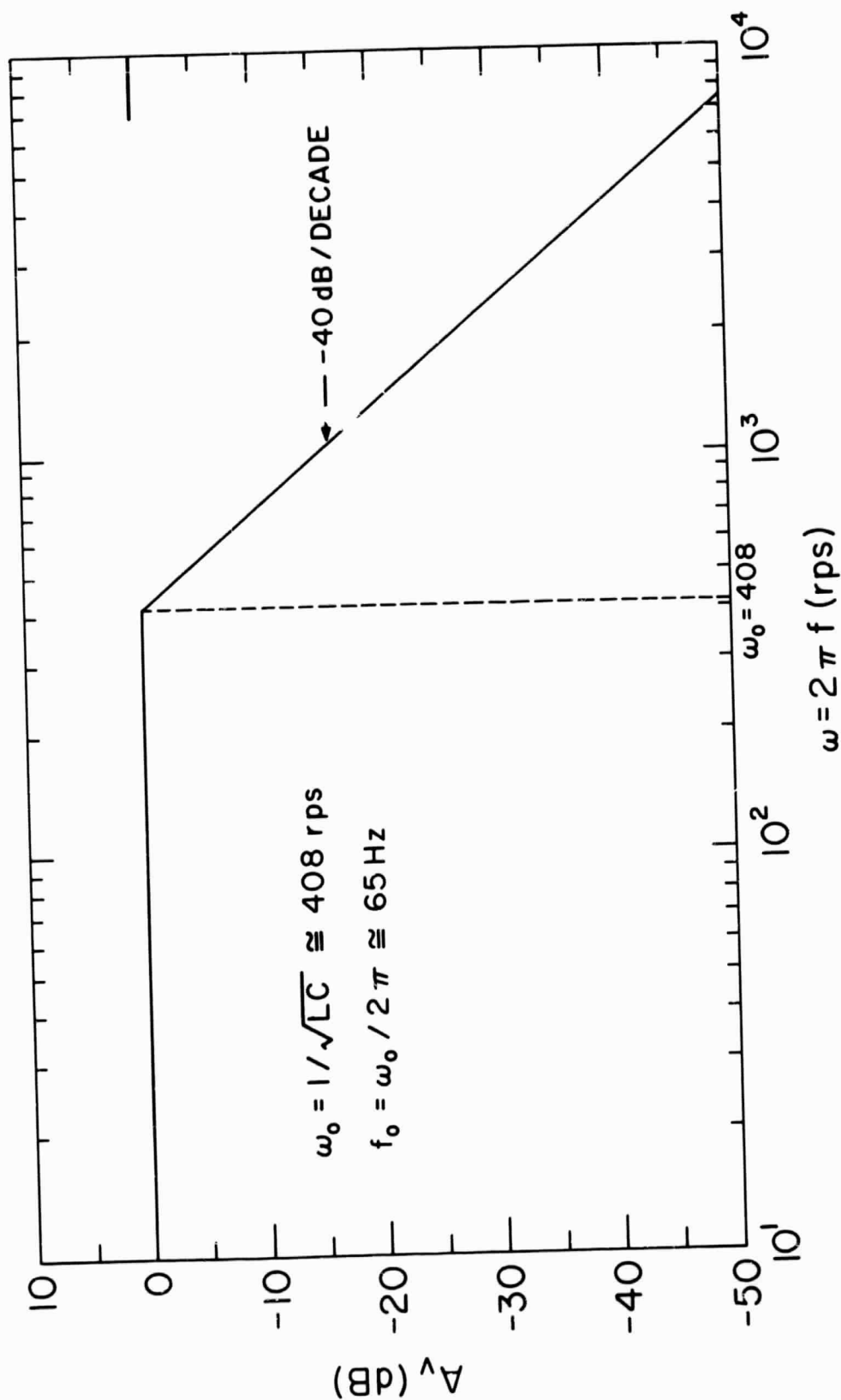


Figure 3.12 Bode plot of LC filter response.

waves (pictured on exactly the same scale) shows the effect of the filter at 15 Hz (Figure 3.11a) and 150 Hz (3.11b). Hence, at 150 Hz, the output waveform is greatly suppressed.

We should now amplify the filtered signal so that the relatively low amplitudes resulting from only partial corrections of the polarization will not fall below the sensitivity level of the system itself. For this, we use another 702C, connected as in Figure 3.13. Here we use only a resistor in the feedback line since we require only amplification and not integration as well. The 100 k Ω resistor chosen for feedback, produced an overall gain for the device of approximately 25/1. It might be noted here, that a major purpose for using this integrated circuit for amplification is impedance matching with subsequent integrated circuitry.

The next requirement is internal phase shifting within the system itself. We require an adjustable phase shift to compensate for; (a) any possible constant phase shift attributable to the frequency doubler or other previous circuitry, (b) the phase difference between the set of quadrants derived from the MA signal and that from the fixed coordinate system (Figure 1.6) determined by the ground-based antenna array and (c) any constant phase shift developed within the polarization correction system itself. Therefore, the phase shifter should be variable over the entire 360° range to ensure a capability of coping with all possible combinations of the above phase shifts. We begin by squaring the sinusoidal receiver signal (which has thus far been filtered and amplified) by means of another 710C, connected in the same fashion as the one in Figure 3.7. A photograph of the input and the resulting square output waveforms of this device is shown in Figure 3.14.

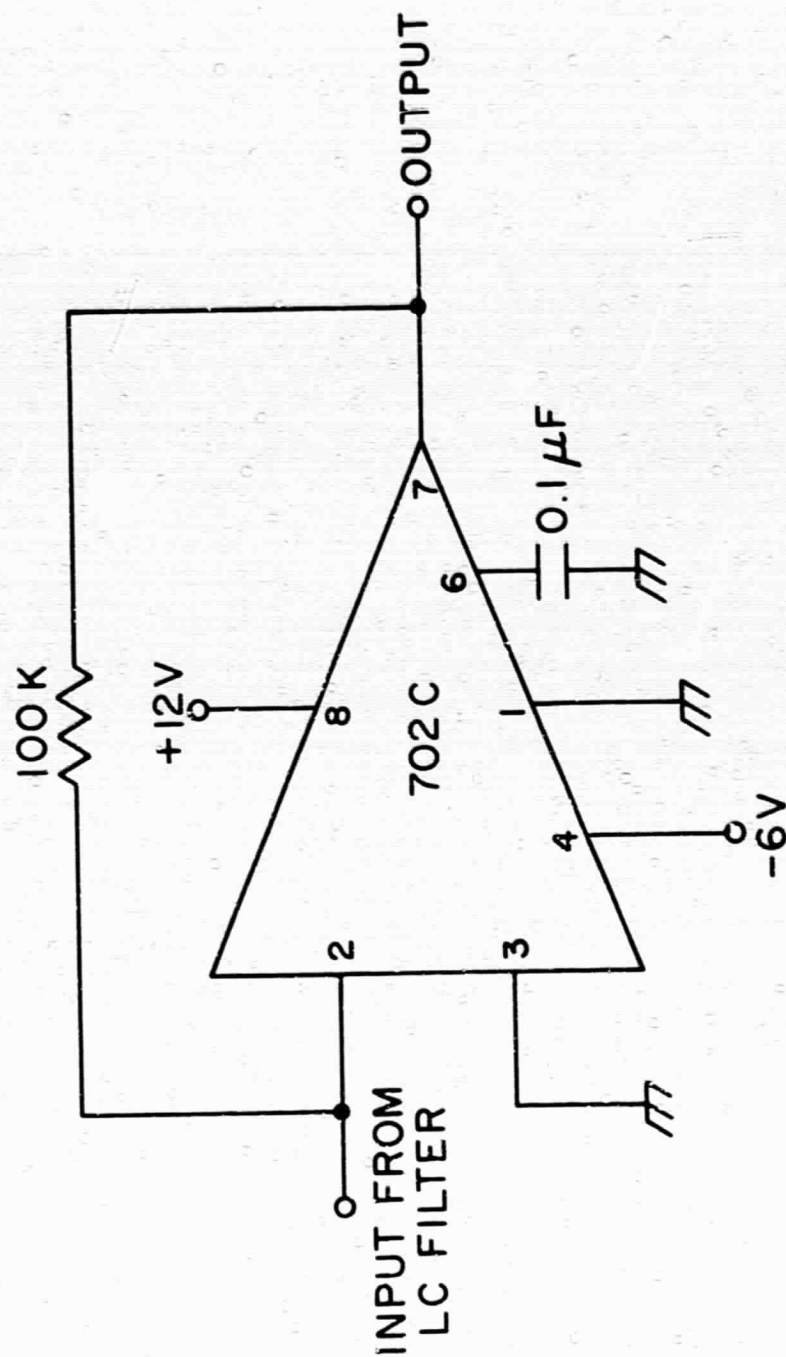


Figure 3.13 702C used as an amplifier (inverting input).

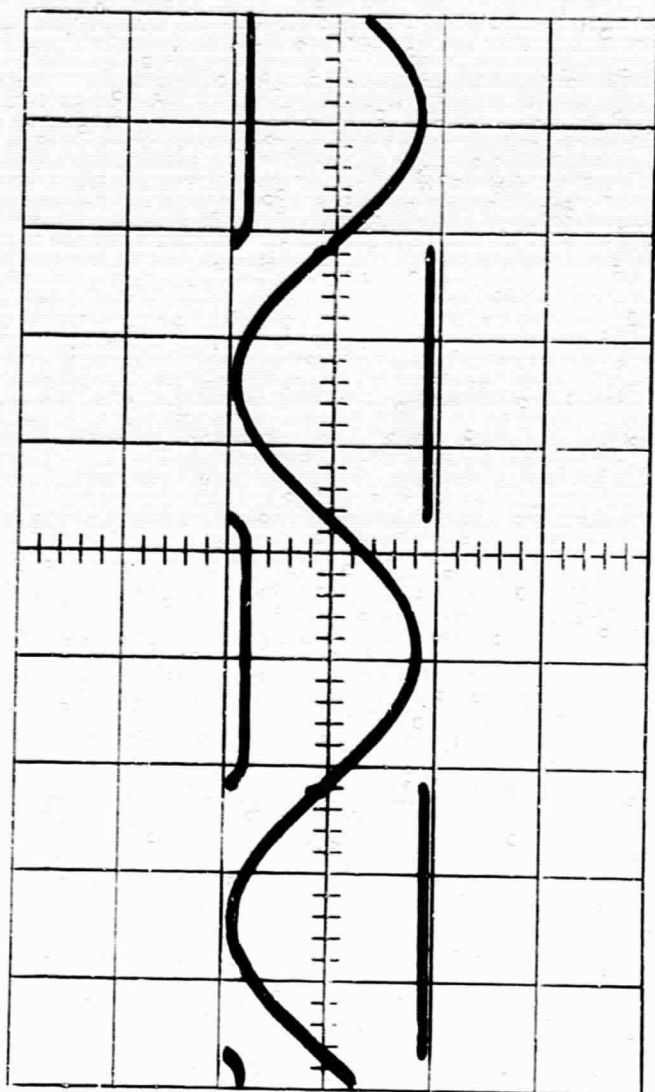


Figure 3.14 Sinusoidal input and square output of the 710C configuration shown in Figure 3.7.

Once having a square wave, we are able to integrate it so that we obtain a basically triangular waveform. For integration purposes, we again turn to another 702C (Figure 3.15). In this case, we adjust the RC feedback to obtain an output sufficiently triangular in shape, and yet of large enough magnitude to give an appreciable peak-to-peak voltage differential. The $2\text{ k}\Omega$ resistor and $20\text{ }\mu\text{F}$ capacitor in Figure 3.14 were selected for this purpose. A photograph of the input and output waveforms for the device is displayed in Figure 3.16.

We now use this triangular waveform to drive another 710C. However, this time, instead of grounding the unused input terminal (#2) as we have done previously, we connect it to a dc bias-potentiometer combination as shown in Figure 3.17. The 710C, as a device, is made to trigger solely on the difference in potential between its two input terminals. Therefore, by use of the negative 6-volt dc supply connected to one end of a $1\text{ k}\Omega$ potentiometer in Figure 3.17, we are able to vary the potential on terminal 2 from 0 volts to -6 volts. Thus, we can obtain either an upward or downward triggering at every (phase) point of the triangular wave. For example, if the 710C triggers at a 3 volt differential between inputs, and the triangular waveform ranges from 0 to -2 volts peak-to-peak, by adjusting the potentiometer so terminal 2's voltage ranges continuously from -3 to -5 volts dc, we have either a positive or a negative triggering at every possible position in the 360° period of the triangular wave. By making the peak-to-peak voltage differential of the triangular signal quite large, we obtain a facility in distinguishing between two phases relatively close to one another. Photographs of two possible levels of triggering are shown in Figure 3.18. By simply projecting the vertical lines of the square waves upward, one can see the point (level) of the triangular input signal at which the 710C is actually triggering.

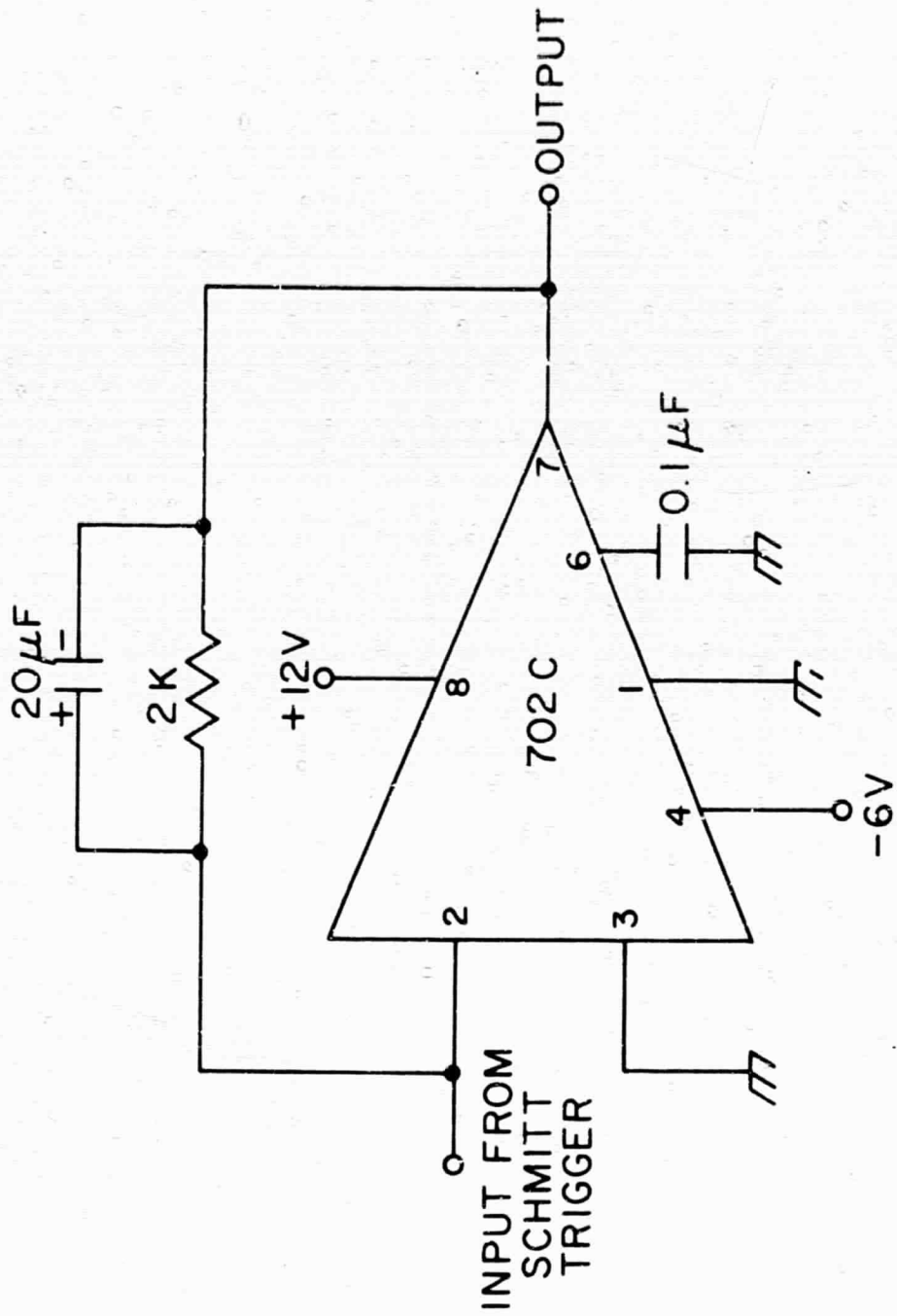


Figure 3.15 702C used as an integrating amplifier (inverting input).

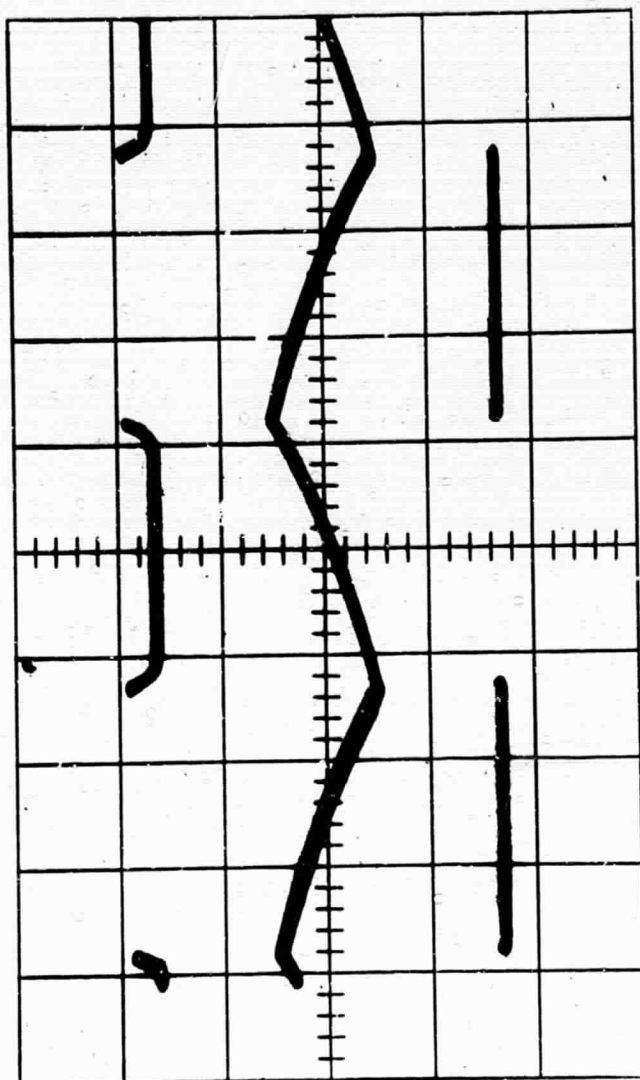


Figure 3.16 Square input and resulting triangular output of the 702C configuration shown in Figure 3.15.

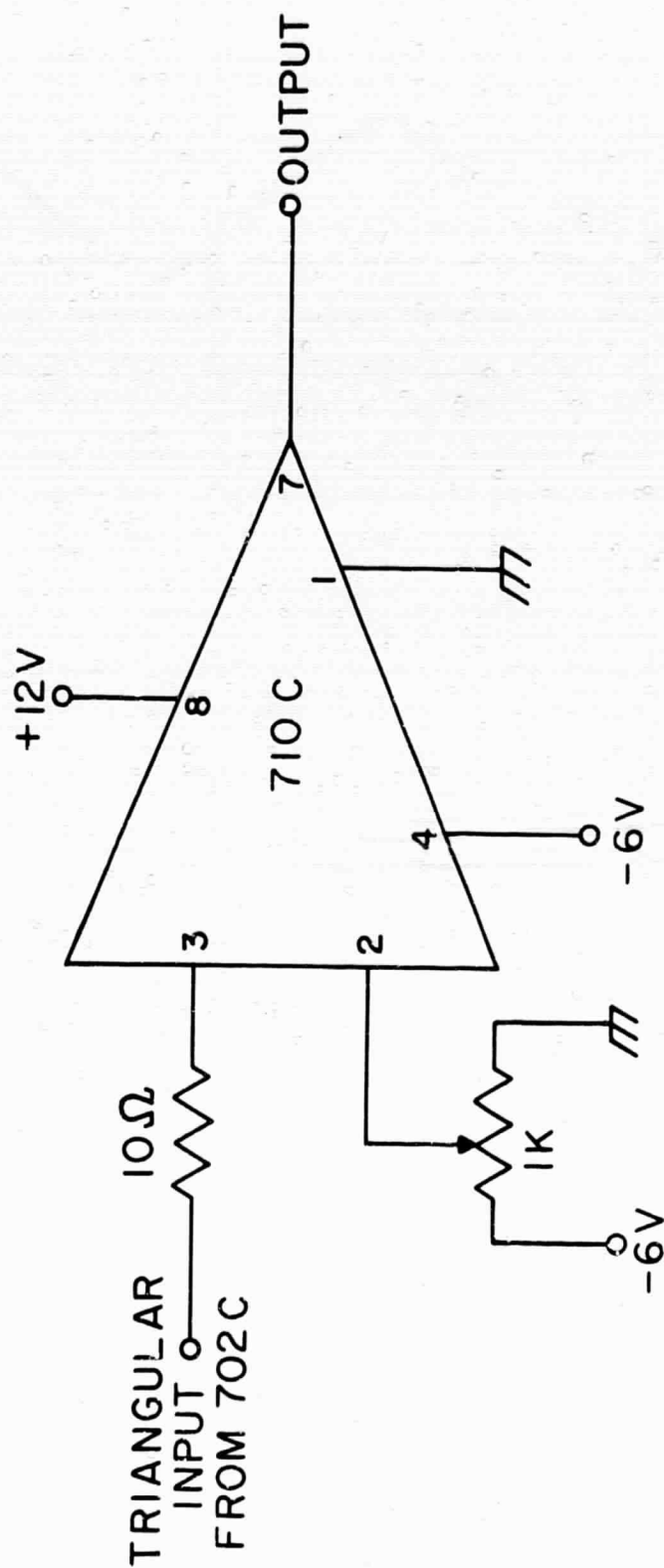
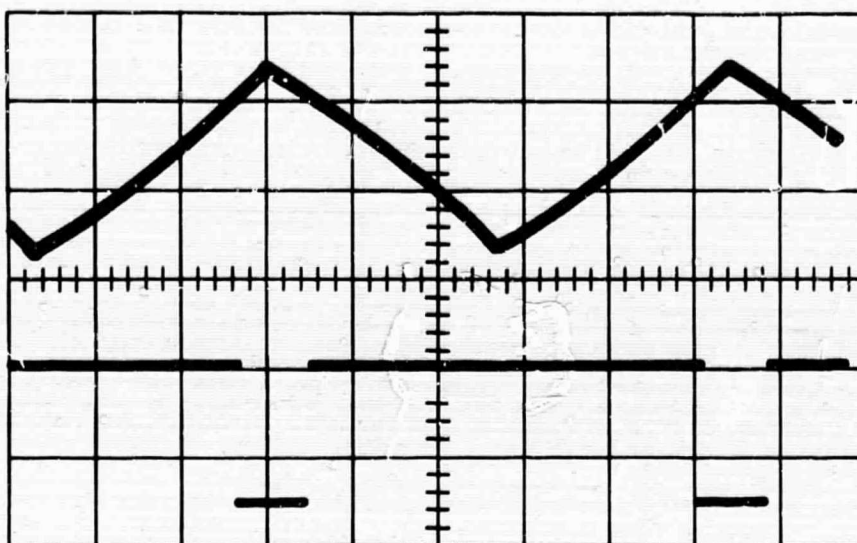
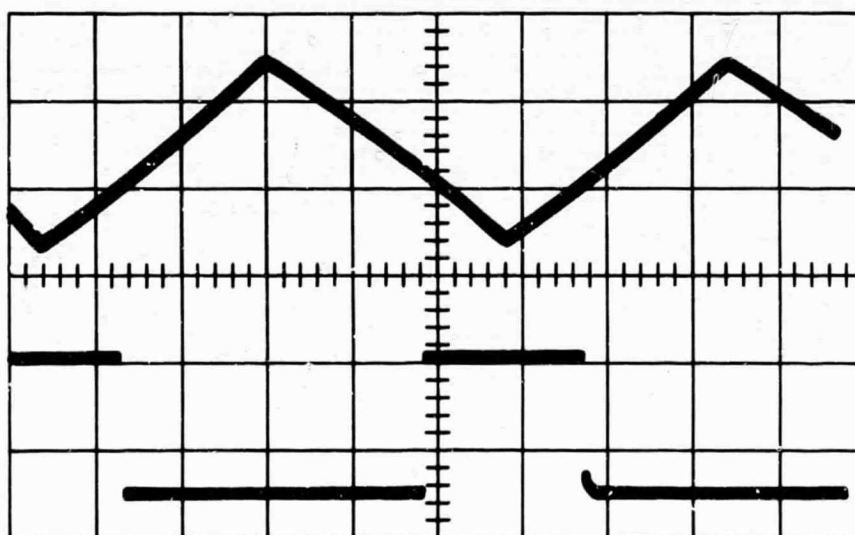


Figure 3.17 710C used as a variable Schmitt trigger (inverting input).



(a)



(b)

Figure 3.18 Triangular input and resulting square output to the 710C configuration of Figure 3.17 with the potentiometer set to trigger at a level equal to (a) approximately $3/4$ the peak value and (b) $1/3$ the peak value of the triangular waveform.

Table 3.1 illustrates the phase shifts which result from corresponding settings of the potentiometer. The letters R and W refer to the two poles of a double-pole/double-throw switch. This switch selects either the upward or the downward triggering points of the 710C (both of which are needed to cover the full 360° range). As shown in the table, there are six potentiometer settings which read "none". These occur in two groups of three, and represent the points where the upward and the downward triggering points become very close to one another and finally merge together. In these intervals, the triggering points are not clearly defined, and therefore they cannot be used for purposes of precise phase shifting. As stated, the phase shifter is used to compensate for the total constant phase shift resulting from the sources mentioned earlier. Once this total phase shift has been measured for a given antenna array, and for the given circuitry, it remains constant. Therefore, the phase shift required of the system can be predetermined once and for all, and the potentiometer set to the corresponding value for all subsequent rocket shots. However, should this value happen to be near one of the six "none" entries of Table 3.1, the 10 ohm resistor leading into terminal 3 of the 710C in Figure 3.17 can be changed, thereby changing the dc level of the entire triangular wave, and accordingly shifting the potentiometer settings such that the required value of phase shift can be obtained.

Now, the square wave output of the 710C is differentiated by means of a simple RC differentiation circuit. A photograph of the differentiated signal is shown in Figure 3.19. This sequence of positive and negative spikes is compared with the original rocket receiver signal in the photograph displayed in Figure 3.20. We transform these spikes into pulses via two separate nor-gating configurations. The first configuration consists of one nor-gate which

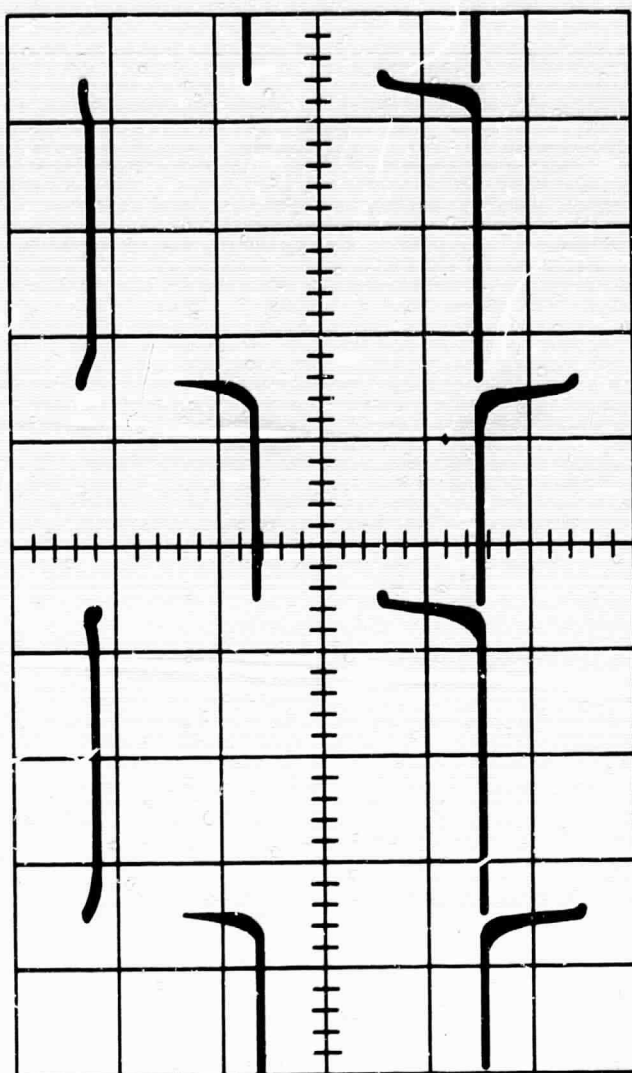


Figure 3.19 Square input and spiked output of an RC differentiation circuit.

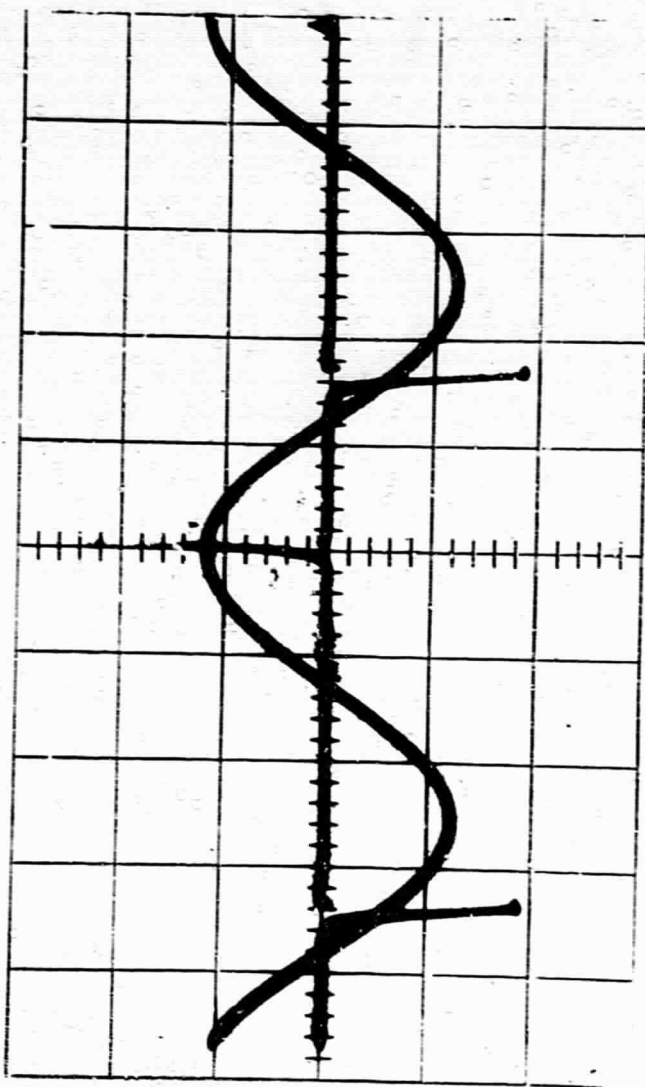
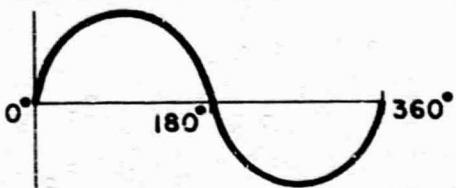


Figure 3.20 Sinusoidal receiver signal shown in relation to spiked output of the RC differentiation circuit.

Table 3.1 Potentiometer Setting vs Phase Shift

	
Potentiometer Setting	Phase Shift (deg)
none	n (360)
none	12
973 R	24
967 R	36
961 R	48
955 R	60
950 R	72
945 R	84
941 R	96
937 R	108
933 R	120
929 R	132
925 R	144
921 R	156
918 R	168
none	180
none	192
none	204
928 W	216
935 W	228
941 W	240
947 W	252
952 W	264
957 W	276
961 W	288
965 W	300
968 W	312
971 W	324
974 W	336
none	348

R = switch in red position

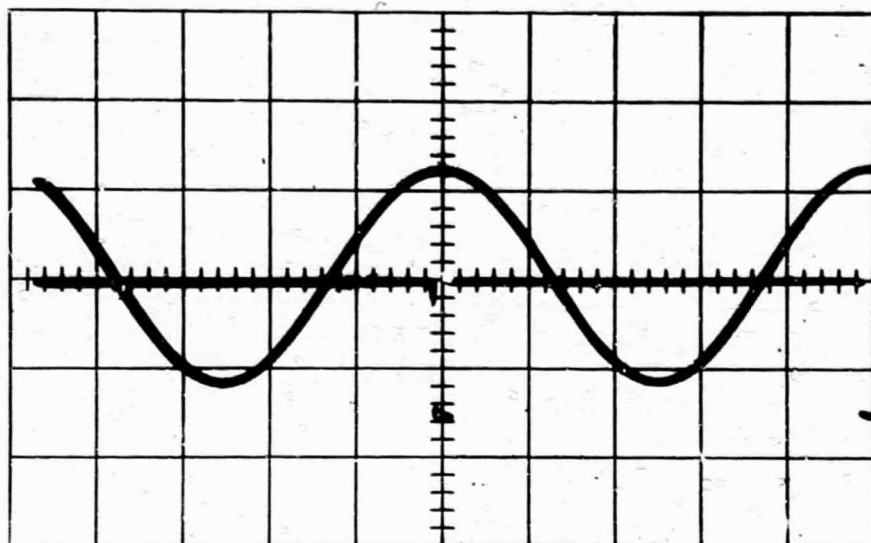
W = switch in white position

receives the spikes directly at one input terminal. Its other input terminal is grounded, yielding only negative going pulses where the positive spikes had occurred. The second configuration consists of a nor-gate which receives the spikes after they have been positively biased. This biasing transforms the negative spikes to a voltage level such that they yield a zero-state at the output, while all remaining portions of the spiked waveform generate a one-state. Thus the total output appears as positive pulses, which are then negated to yield negative pulses, occurring only where the negative spikes had occurred. We are able to choose between the positive and the negative spikes by means of the double-pole double-throw switch. Thus, whichever position of the switch we choose, we receive one negative pulse per cycle as the output of the respective gating configuration.

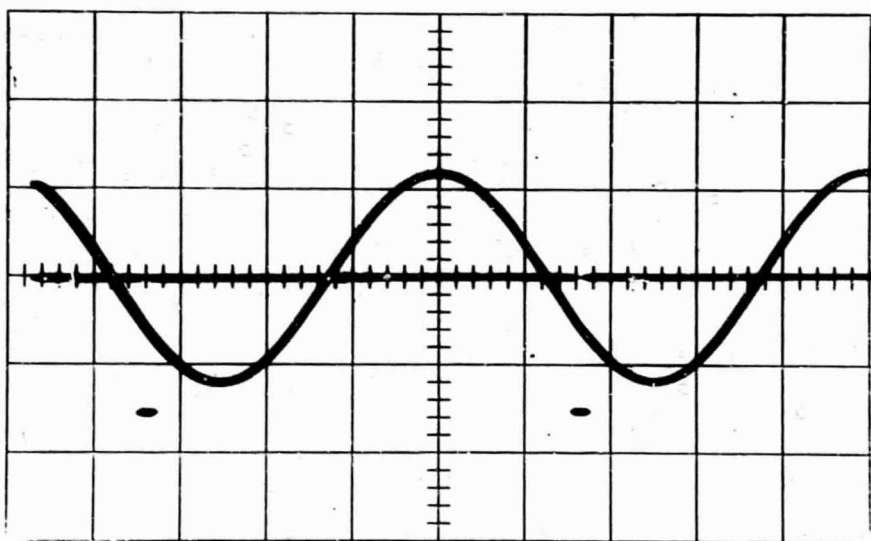
One pole of the switch is red and designated by the letter R in Table 3.1. This pole selects the configuration which yields a pulse at the location of the positive spike. The other pole is white and designated by the letter W. It is associated with the negative spike. To illustrate, Figure 3.21 shows the results of the two gating configurations when the same spikes of Figure 3.20 are used as the input to both. Figure 3.21a results when the switch is in the "R" position, and Figure 3.21b, when in the "W" position

3.2.3 Logic Circuitry

Now we have accomplished our intended purpose, namely, resolved the signal from the rock... receiver into a pulse (labeled VC in Figure 3.2) which can be made to occur at the maximum of that signal. By combining this pulse in the correct manner with the previously developed four quadrants of the MA signal, we are able to determine in which of these quadrants the pulse occurs.



(a)



(b)

Figure 3.21 Pulses formed from the spikes shown in Figure 3.20 through norgating. The double pole, double throw switch is in the (a) red position and (b) white position.

This is accomplished by the further use of nor-gates (represented by block three of Figure 3.1). The "negative" quadrants established (labeled ~ 1 , ~ 2 , ~ 3 and ~ 4 in Figure 3.2) are each one input of four different nor-gates. The other input of each gate is $\sim C$, and the respective four outputs of these gates are designated by the numerals I, II, III and IV in Figure 3.2, (the Roman numerals proceed from their corresponding Arabic numeraled quadrants). These four outputs consist of a pulse per cycle occurring only at that Roman numeraled output in whose respectively numbered quadrant the maximum of the rocket receiver signal occurred. Therefore, at any given interval of time, one of these outputs takes the form of a pulse per cycle, while the other three outputs are zero.

Thus, by connecting the four output terminals to appropriate input terminals of circuits capable of changing the attenuation and phase, we correct the polarization. The circuitry needed to do this consists of two "voltage incrementor" circuits (block four of Figure 3.1). One of these is shown in Figure 3.22, the other being an exact duplicate. It is a dual input circuit, which transforms incoming pulses into an increasing or decreasing dc voltage level. A pulse on the terminal labeled positive increment in Figure 3.22, will increase the charge on the $1.5 \mu\text{F}$ output capacitor for the duration of the pulse. A similar pulse on the negative increment terminal will do the same thing in reverse (i.e. decrease the charge on C). The RC time constants for both the increasing and the decreasing inputs have been made the same for purposes of uniform incrementation in both the positive and negative directions. The value selected is 30 ms (found by taking the product of two $10 \text{ k}\Omega$ resistors in series and the $1.5 \mu\text{F}$ capacitor). Thus it takes approximately 30 ms for the capacitor to attain a voltage equal to about $2/3$ that of the supply voltage

(in our case $2/3 \times 6$ volts = 4 volts). The period, T , of course, is inversely proportional to the frequency, and therefore variable over the frequency of rocket roll. However, the value of T affects both the size of the increments and their frequency of occurrence--the two tending to have a cancelling effect on one another. Therefore, the total time to achieve any desired voltage change is very nearly frequency independent. One more point must be made in discussing the circuit of Figure 3.22. With a $1.5 \mu\text{F}$ capacitor at its output, if we want the output voltage to remain constant for the duration of the rocket flight (approximately 500 seconds), the effective impedance which will parallel this capacitor (as determined by the load) should be sufficiently large in order to not drain the capacitor appreciably during this interval.

As stated, the outputs of these two incrementor circuits are intended for use in a current controlled attenuator and a voltage controlled phase shifter. These are the respective devices labeled "variable" in Figure 1.7, and their transfer characteristics are shown in Figure 3.23. Thus as the voltage output from the incrementor circuitry is altered, the attenuation on a_2 and the phase angle ϕ in the transmitting signal can be changed according to the curves of Figure 3.23. In summary, the rocket receives a signal from the transmitter; that signal is fed through the system and transformed into a pulse at the occurrence of the signal's maximum; the phase relation of that pulse is determined in terms of the quadrants of the MA signal; knowing the operations which have to be performed on a_2 and ϕ to make the polarization more circular, the attenuation and phase shift of the transmitted signal are changed accordingly; with this new attenuation and phase shift, a different signal with a more circular polarization is transmitted; the rocket receives the new signal from the

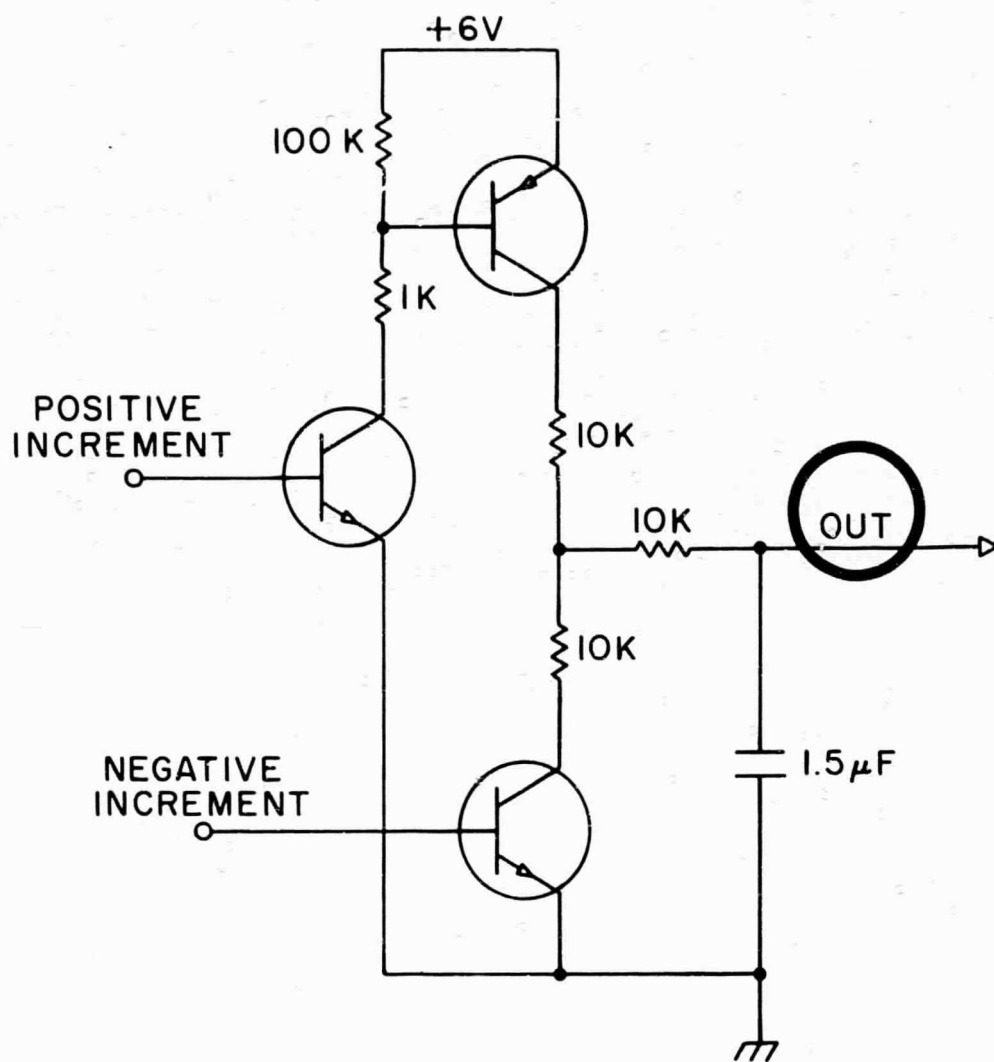


Figure 3.22 Voltage incrementation circuit.

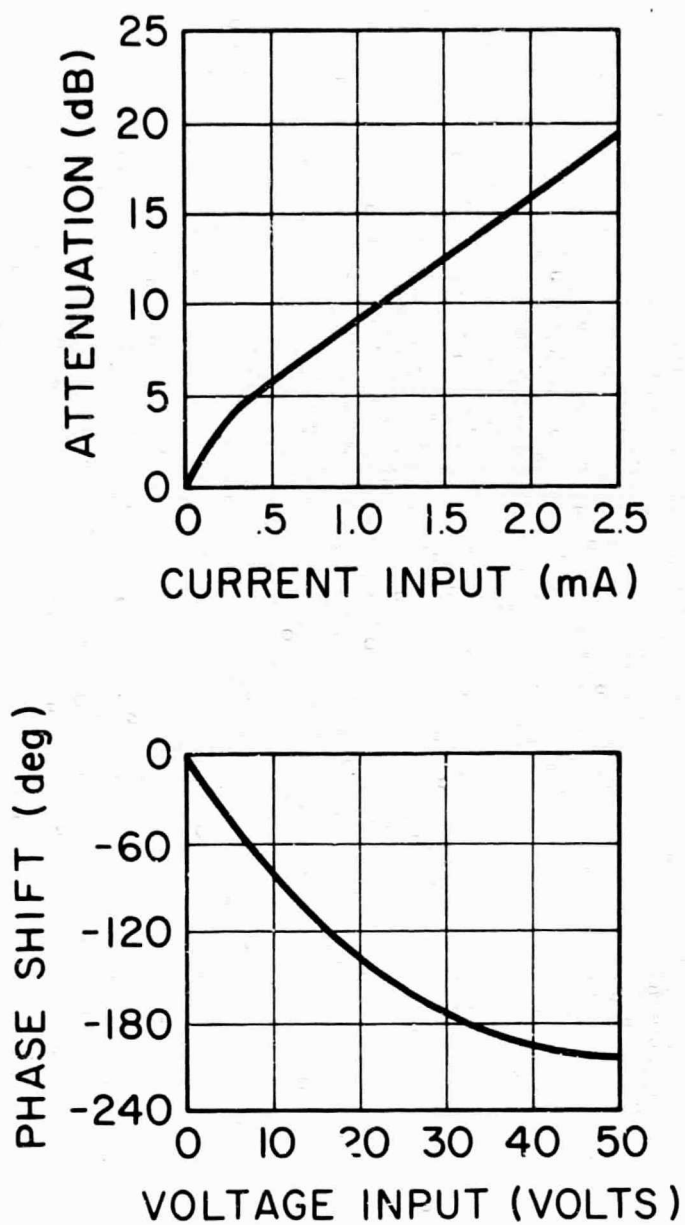


Figure 3.23 Transfer characteristics of proposed (a) current controlled attenuator and (b) voltage controlled phase shifter.

transmitter, and the process is repeated. The process continues in this closed loop fashion until the polarization is circular, as required.

3.2.4 Testing of the System

After the circuitry was completely breadboarded and functioning properly, the system was tested by means of telemetry data from rockets 14.360 and 14.361 (discussed in Section 2). By replaying the tapes from these shots, we were able to simulate the actual rocket flights. During the tests, four signals were recorded, the doubled magnetic aspect sensor signal, the receiver output and the outputs of the polarization correction system (the voltage outputs of the incrementation circuits which led to the variable phase shifter and the attenuator).

The internal phase shift of the system itself was pre-set for 90° to detect the maxima directly (i.e. no compensating phase shift was pre-set into the system). When the recorded signals were analyzed, we observed the distortion in the rocket receiver signal as a result of the slow reacting AGC system (as discussed in Section 2). Thus, in order to determine the location of the maximum within the distorted waveform, we had to find one point of the wave which was never distorted by the AGC. That point is at the occurrence of the downward sloping zero crossing, as shown in Figure 3.24. Therefore, for purposes of data analysis we located the maximum by measuring the amount $T/4$ (Figure 3.24) back from the correctly phased zero crossing. Upon comparing this point to the doubled MA signal, we visually determined the quadrant location of the maxima, and were thus able to predict how the system outputs should be responding. Checking these predictions with the actual recorded outputs, we found that they agreed in all cases throughout both rocket shots. Figures 3.25 and 3.26 show two typical segments of the recorded test results, depicting the responses of the system to the occurrence of the maximum in the second and third quadrants respectively.

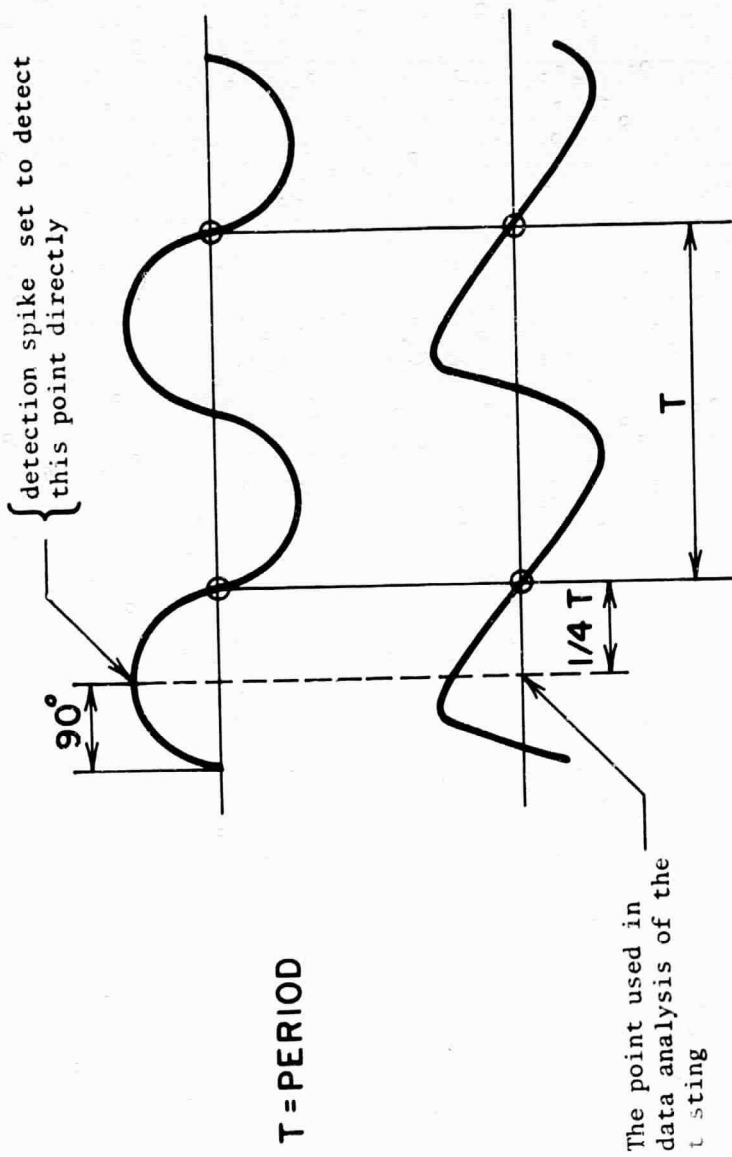


Figure 3.24 Receiver signal shown undistorted (above) and after AGC distortion (below), illustrating the preservation of phase relation at the point of the negatively sloped zero crossing.

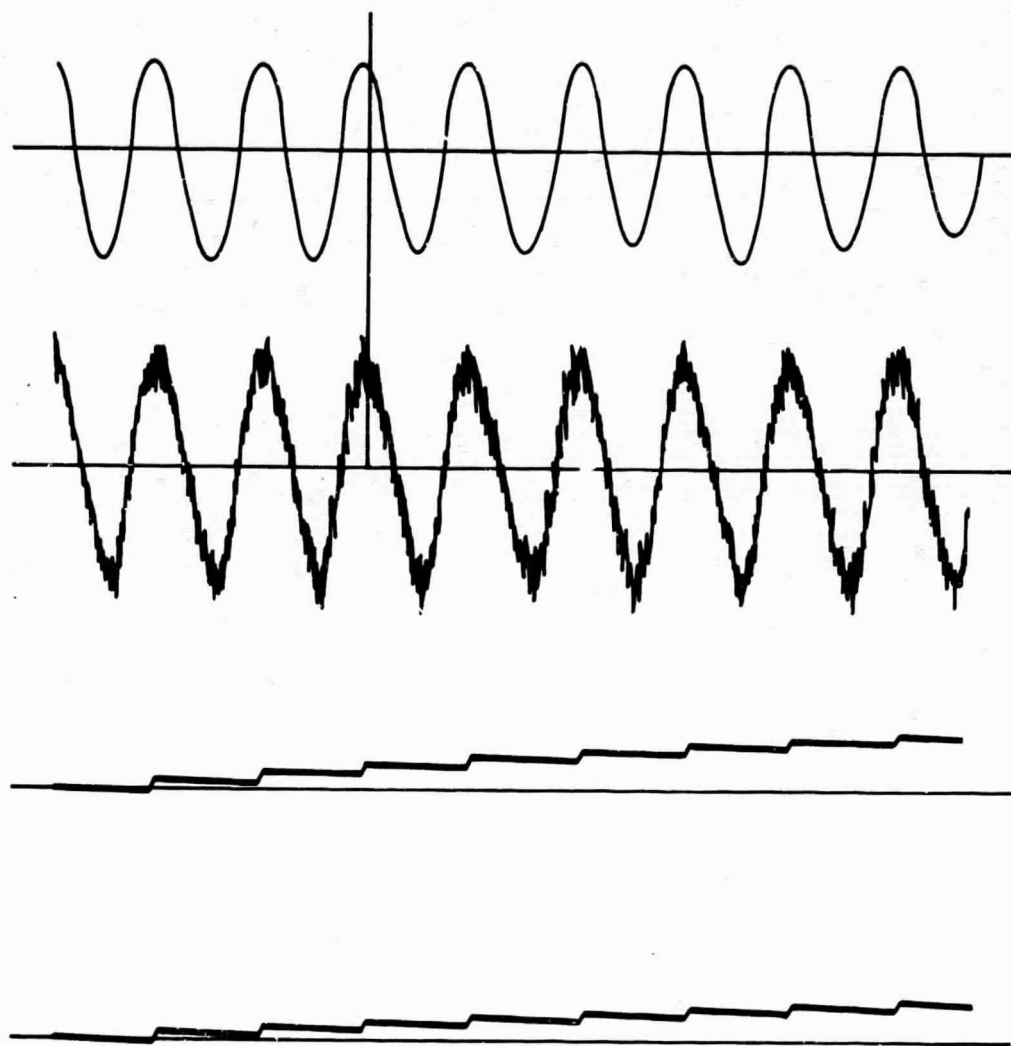


Figure 3.25 Trace of a section of chart record resulting from system testing, showing (top to bottom) 2X-MA, rocket receiver, OUT_p , and OUT_a signals with the maximum occurring in quadrant II.

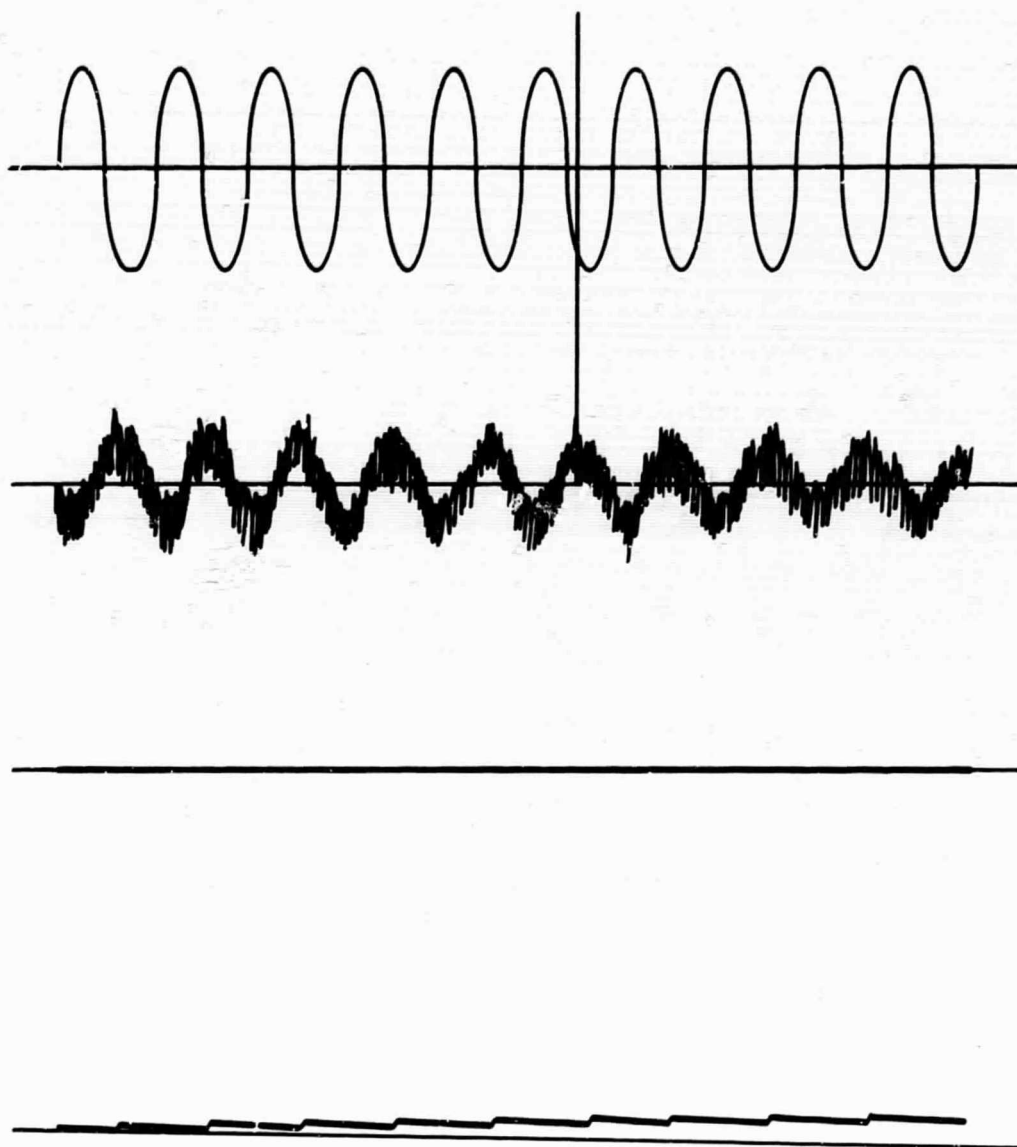


Figure 3.26 Trace of a section of chart record resulting from system testing, showing (top to bottom) 2X-MA, rocket receiver, OUT_p and OUT_a signals with the maximum occurring in quadrant III.

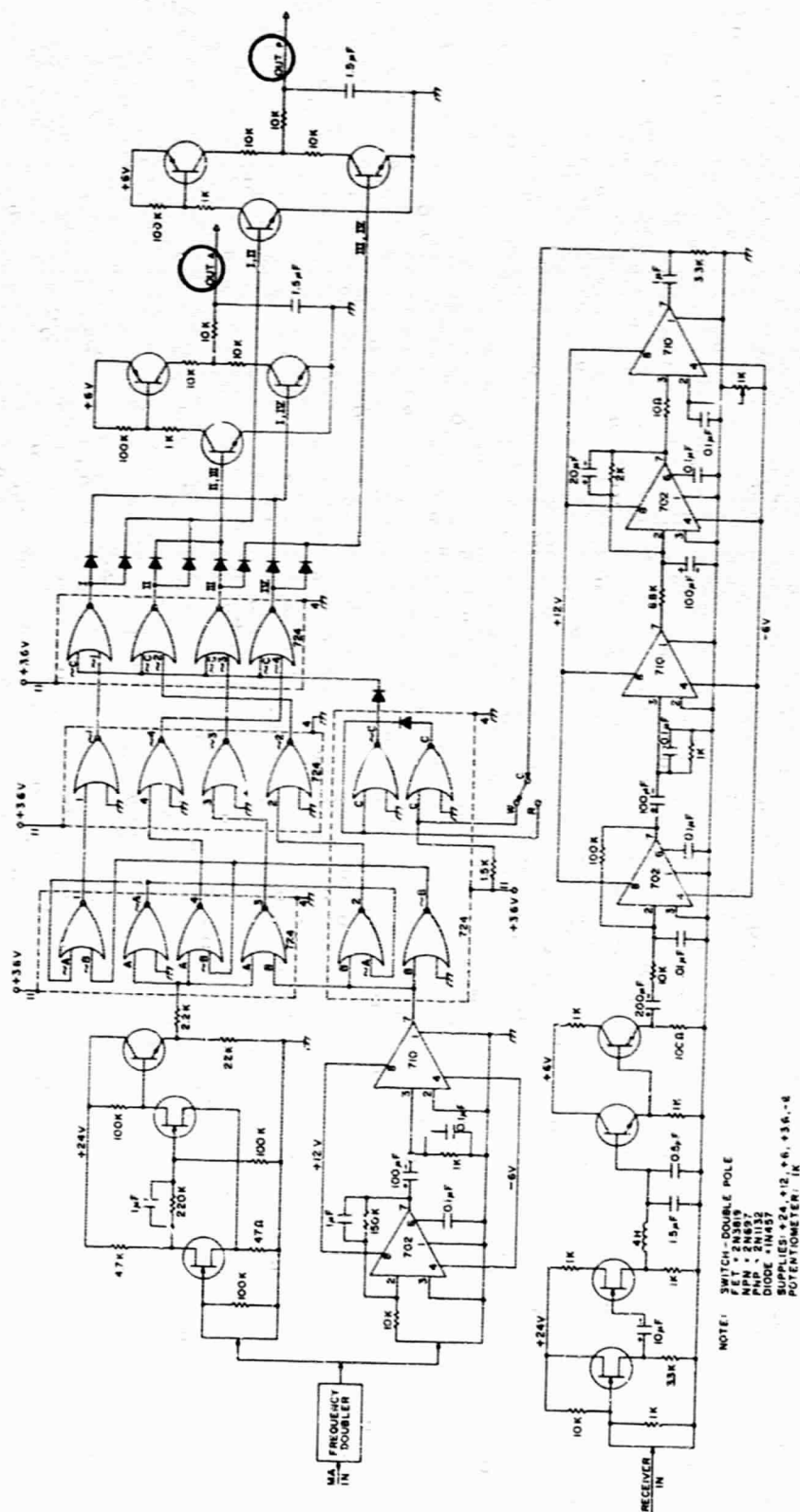


Figure 3.27 Circuit diagram of entire polarization correction system.

Finally, Figure 3.27 is the overall circuit diagram for the entire system. This diagram contains all of the discussed circuits together with their coupling circuitry. It should be noted that a total of five different power supplies are required for the system, each of which supplies an output current of less than 100 mA.

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N69-24674

**Part 2. ANALYSIS OF A ROCKET EXPERIMENT TO
MEASURE IONOSPHERIC ELECTRON DENSITY**

**by
K. Seino**

ABSTRACT

A radio propagation experiment has been developed at the University of Illinois for the measurement of lower ionosphere electron densities. The experiment is based on Faraday rotation and differential absorption measurements obtained from sounding rocket data. At altitudes less than 70 km, where the electron density is very low, the accuracy of the experiment is adversely affected by several phenomena. To find the electron density in this region, theoretical studies, careful examination of data and modification of the present techniques are needed.

The experimental technique is reviewed and analyzed. The effects of rocket spin, noise, and the phase delay of signals are studied.

1. INTRODUCTION

This section briefly describes a radio propagation experiment developed at the University of Illinois for the measurement of lower ionosphere electron densities.

The general concept of the experiment is discussed by Bowhill (1965), the engineering details by Knoebel, et al. (1965), and by Gooch, et al. (1966), and a method of data analysis by Mechtly, et al. (1967). These works are briefly reviewed in this section. Following sections analyze the experiment, the data processing system, and the method of analysis.

1.1 Rocket Studies of the Lower Ionosphere

The physical and chemical processes taking place in the ionosphere, the upper atmosphere between 50 and 1000 km altitude, have acquired the name "aeronomy" in recent years. The aeronomy of the ionosphere above 100 km is now reasonably well understood. However, the aeronomy of the lower ionosphere, 50-100 km, remains poorly understood and has recently attracted remarkable attention. Measurements in this region by balloons and satellites are difficult because balloons cannot ascend to these altitudes and satellites cannot remain in orbit because of large drag forces. However rockets are well suited for the purpose.

Below 90 km, even the daytime electron density is less than 10^6 cm^{-3} . However, even such small electron densities at a height between 70 and 90 km in the D region are very important because of their effect on broadcast communications. The region between 50 and 70 km, called the C region, is distinguished by an ionization production rate which is independent of solar zenith angle, supposedly due to galactic cosmic rays, and is also responsible for the pre-sunrise ionospheric effects on very low frequency radio propagation.

Before the IQSY, many rockets were launched for the development of new experimental techniques for making measurements in the lower ionosphere. During and after the IQSY, the Aeronomy Laboratory combined basic well-tried experiments on rocket payloads, designed to be used repeatedly under a wide variety of ionospheric conditions to answer specific questions about the behavior of the upper atmosphere for the solution of specific aeronomic problems. Each of the payloads included a radio propagation experiment. The radio experiment is a variation of the Seddon-Jackson (1958) radio propagation technique. The principle of the radio measurement of electron density is a comparison of the difference in attenuation coefficients (differential absorption) and phase velocities (Faraday rotation) of the ordinary and extraordinary magnetoionic components, at a frequency in the range of 2 to 4 MHz.

The radio propagation experiment has been used successfully by the University of Illinois more than 20 times for the measurement of electron density in the region between 50 and 100 km. However, below 70 km, since the electron density is very low, the accuracy of the experiment is adversely affected by several phenomena. To improve the accuracy of the electron density measurements in this region, theoretical studies, careful examination of data and refinement of the present techniques are desired.

The objective of this study is to develop an understanding of the effects of rocket precession, noise, phase delay, and other undesirable effects on Faraday rotation and differential absorption as a basis for improving the accuracy of the electron density measurements in the lower ionosphere.

1.2 Radio Propagation Experiment

1.2.1 Ground Station

A block diagram of the experiment is shown in Figure 1.1. The two exciters, designated O and X, are crystal-controlled oscillators, O is operated at a frequency of $f_o = f_c - 250 \text{ Hz}$, and X is at $f_x = f_c + 250 \text{ Hz}$, where f_c is the chosen frequency for a given rocket. The two attenuators, fed by the exciters, are controlled by the feedback signal from the rocket. Each attenuator output is divided into two parts. One part goes to a variable phase shifter, and the other goes to a variable attenuator for the generation of circular polarization. The outputs are added, amplified, and fed to the antenna array. The array consists of four horizontal half-wave dipoles, elevated one quarter wavelength above the ground. The phase shifters and attenuators are adjusted so that circularly polarized waves of opposite senses, are radiated from the antenna. One is the ordinary mode of circular polarization, rotating north into west in the northern hemisphere, and tracing a circle at a frequency of $f_o = f_c - 250 \text{ Hz}$. The other is the extraordinary mode rotating north into east at a frequency of $f_x = f_c + 250 \text{ Hz}$.

The ordinary mode power is held constant at 10 watts and the extraordinary mode is, initially, 1 watt. This 10 dB power ratio produces a 31.6% amplitude modulation on the signal of the receiver in the rocket. As the rocket advances into the ionosphere, the extraordinary mode is absorbed about six times more rapidly than the ordinary mode and the modulation ratio begins to decrease. However, the modulation ratio is sensed during the rocket flight and used in the servo loop, which includes the transmitter, the rocket receiver, and the

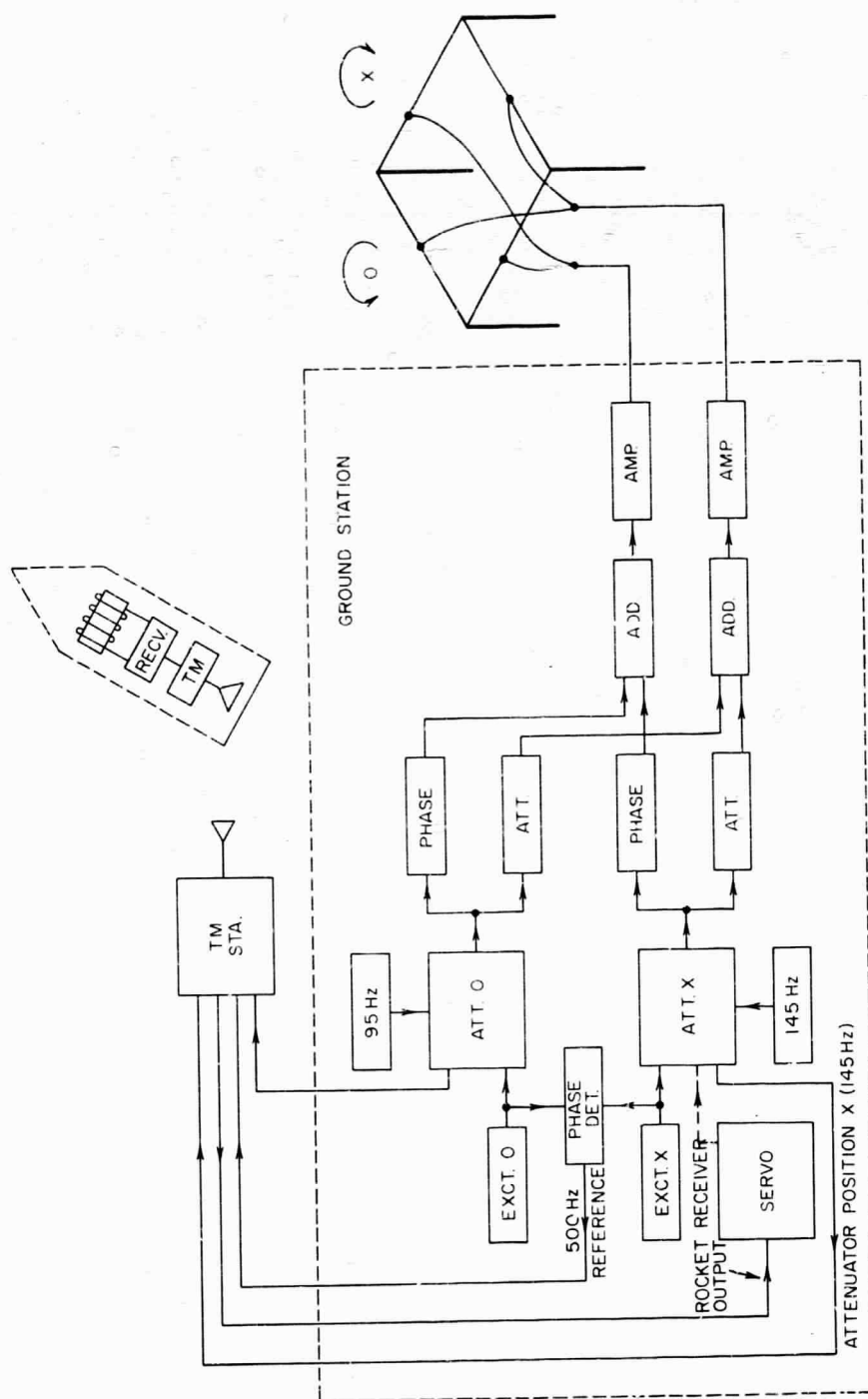


Figure 1.1 Block diagram of radio propagation experiment.

telemetry system, to restore and maintain the 31.6% modulation by increasing the extraordinary mode power. The position of the attenuator which controls the transmitted extraordinary mode power is recorded on magnetic tape as the amplitude of a 145 Hz sine wave. The amplitude is proportional to the transmitted power on a decibel scale. This recording is processed on a data processing system (described in Section 1.3) which gives digital values of extraordinary mode power in dB versus time after launch.

1.2.2 Rocket Payload

Three payload types have been developed. The basic payload type, designed for daytime experiments, and designated "Type A", consists of the radio propagation experiment, a dc probe, ultraviolet photometers at $1216\text{\AA}$ and $1450\text{\AA}$, and solar and magnetic aspect sensors. The "Type B" payload, designed for nighttime experiments, includes an rf probe, with either a negatively-biased spherical probe, or a spherical ion trap instead of the ultraviolet photometer and the solar aspect sensor. The "Type C" includes a mass spectrometer. Figure 1.2 is a photograph of the Type A payload.

The magnetic aspect sensor or aspect magnetometer, mounted transversely to the rocket spin axis, provides an angular reference for the Faraday rotation experiment. This angular reference signal will be called the rocket spin signal in the following sections. Information pertaining to the rocket precession period and precession cone angle are contained in the rocket spin data. The receiving antenna and receiver of the radio propagation experiment are designated "receiving antenna" in Figure 1.2. An enlarged view of this unit is shown in Figure 1.3. This unit includes the ferrite loop antenna, the

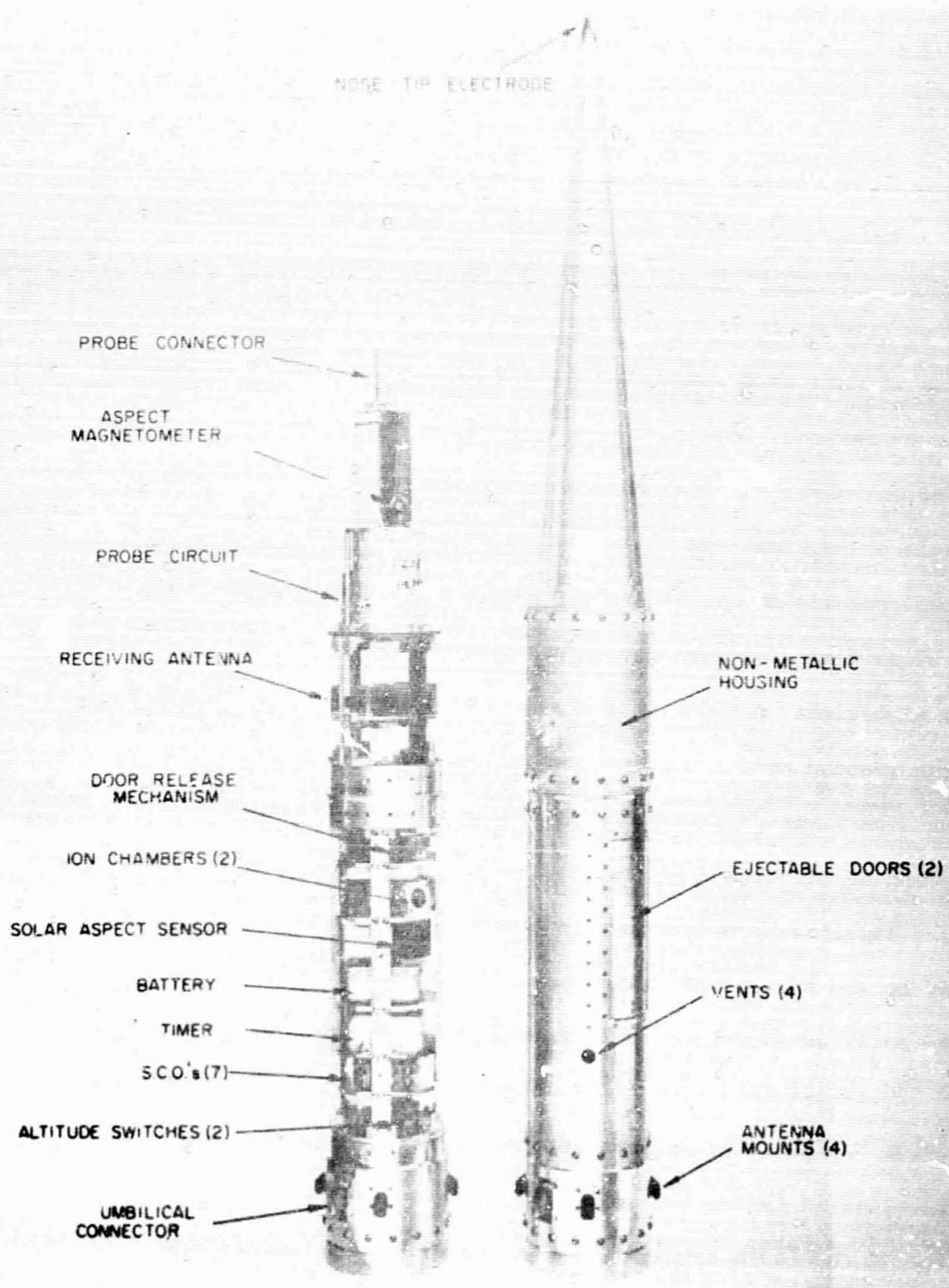


Figure 1.2 Payload instrumentation and shell.

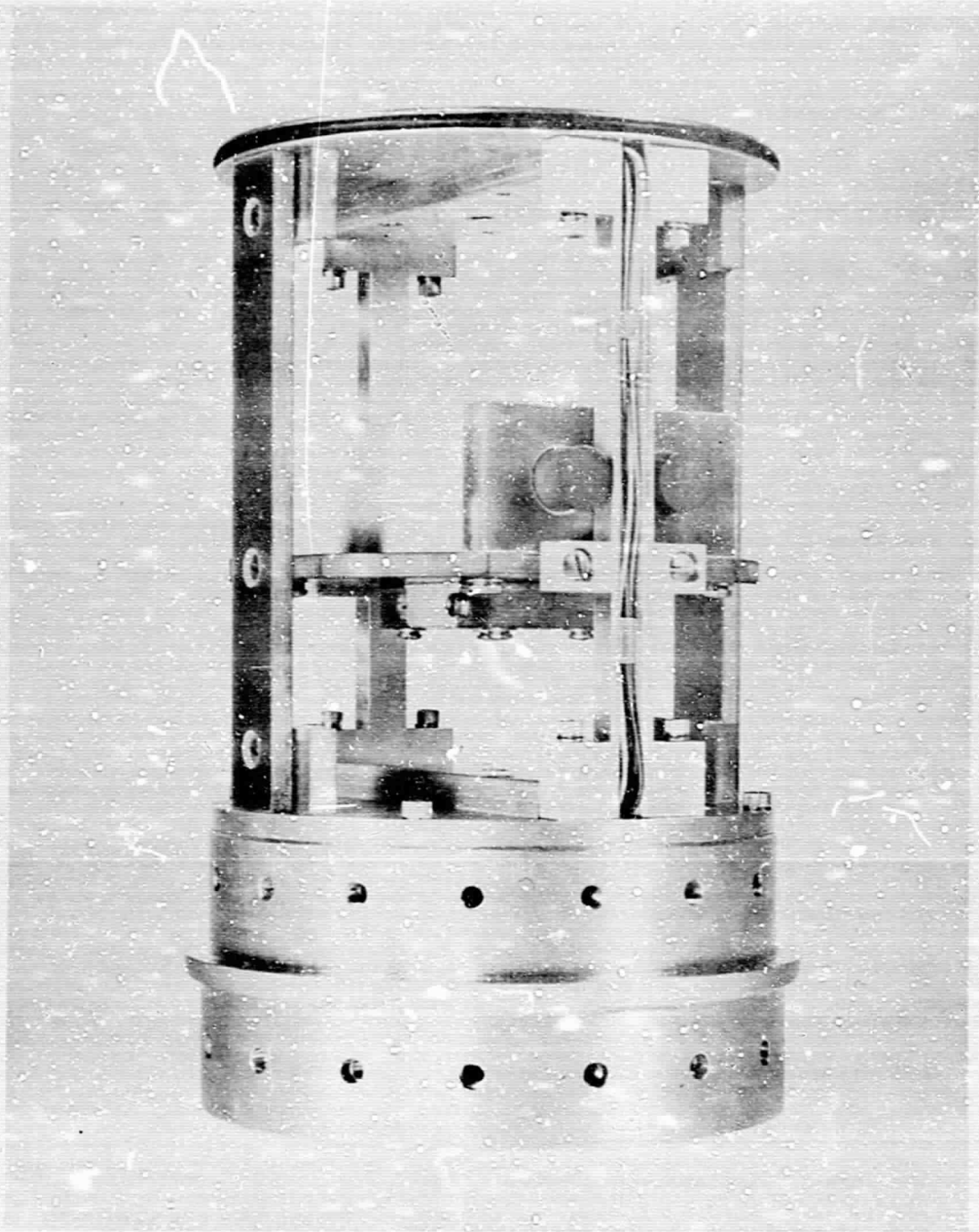


Figure 1.3 Antenna and receiver unit.

receiver (at the base) and a tuning network. This part of the payload is enclosed by a fiber glass section of the payload shell. The ferrite loop antenna is mounted perpendicular to the rocket axis. It consists of two parallel ferrite rods, wound with a number of turns of insulated wire. The output of the antenna is fed to a transistorized crystal-controlled superheterodyne receiver with a bandwidth of approximately 2 kHz, operating at 2.225 MHz or 3.385 MHz. The receiver output signal, which contains Faraday rotation and differential absorption data, is fed to the telemetry system (located in the lower part of the payload not shown in the figure), and sent back to the ground station.

The FM/FM telemetry system employs a 250 milliwatt solid-state transmitter operating at 231.4 MHz. Continuous information is obtained from all data channels by frequency division multiplexing. The IRIG telemetry band allocations of the Type A payload are shown in Table 1.1.

1.2.3 Data Recording

During the rocket flight, all necessary information is recorded on magnetic tapes at the telemetry station. The magnetic tapes usually follow the format shown in Table 1.2, and oscillograph records are in the form shown in Figure 1.4. These records are used in data processing and analysis.

1.3 Data Processing System

1.3.1 Block Diagram of Data Processing System

The block diagram is shown in Figure 1.5. In the data processing system, there are three subsystems; Tape Transcription Subsystem, Magnetic to Punch Subsystem and Computer Processing Subsystem.

TABLE 1.1
IRIG Telemetry Band Allocations

Type A Payload		
IRIG Band	Center Frequency	Description of Data
19	93 kHz	Solar Aspect
18	70	Rocket Receiver Output
17	52.5	DC Probe Linear (+ 2.5V)
16	40	DC Log (+ 2.5V)
15	30	UV High Gain
14	22	UV Low Gain
13	14.5	Magnetic Aspect
11	7.35	Rocket Receiver AGC
Type B Payload		
19	93 kHz	Ion Trap (1)
18	70	Rocket Receiver Output
17	52.5	DC Probe Linear (+ 2.5V)
16	40	DC Probe Log (+ 2.5V)
15	30	Electron Temperature
14	22	Ion Trap (2)
13	14.5	Magnetic Aspect
12	10.5	Commutator
11	7.35	Electron Temperature, AGC

TABLE 1.2
Magnetic Tape Format

Tape Track No.	Data
1	Voice
2	Telemetry Receiver Video Output, Diversity Combined
3	Telemetry Receiver Video Output, Right Hand Circular
4	Time Code, NASA 36 BIT
5	Multiplex No. 1, Data Lines (Specified below)
6	Multiplex No. 2, Receiver AGC Voltages
7	100 kHz Reference (17 kHz/60 Hz T.S.C. not recorded)

Multiplex No. 1, Data Lines

IRIC Band	Frequency (kHz)	Data
9	3.9	Phase Detector No. 1, Output
10	5.4	Phase Detector No. 2, Output
12	10.5	Expanded Extraordinary Power (30 to 20 dB)
14	22.0	Ordinary Power (0 to 50 dB)
15	30.0	Extraordinary Power (0 to 50 dB)
16	40.0	500 Hz Reference
17	52.5	Time Code, NASA 28 BIT
18	70.0	Time Code, NASA 36 BIT

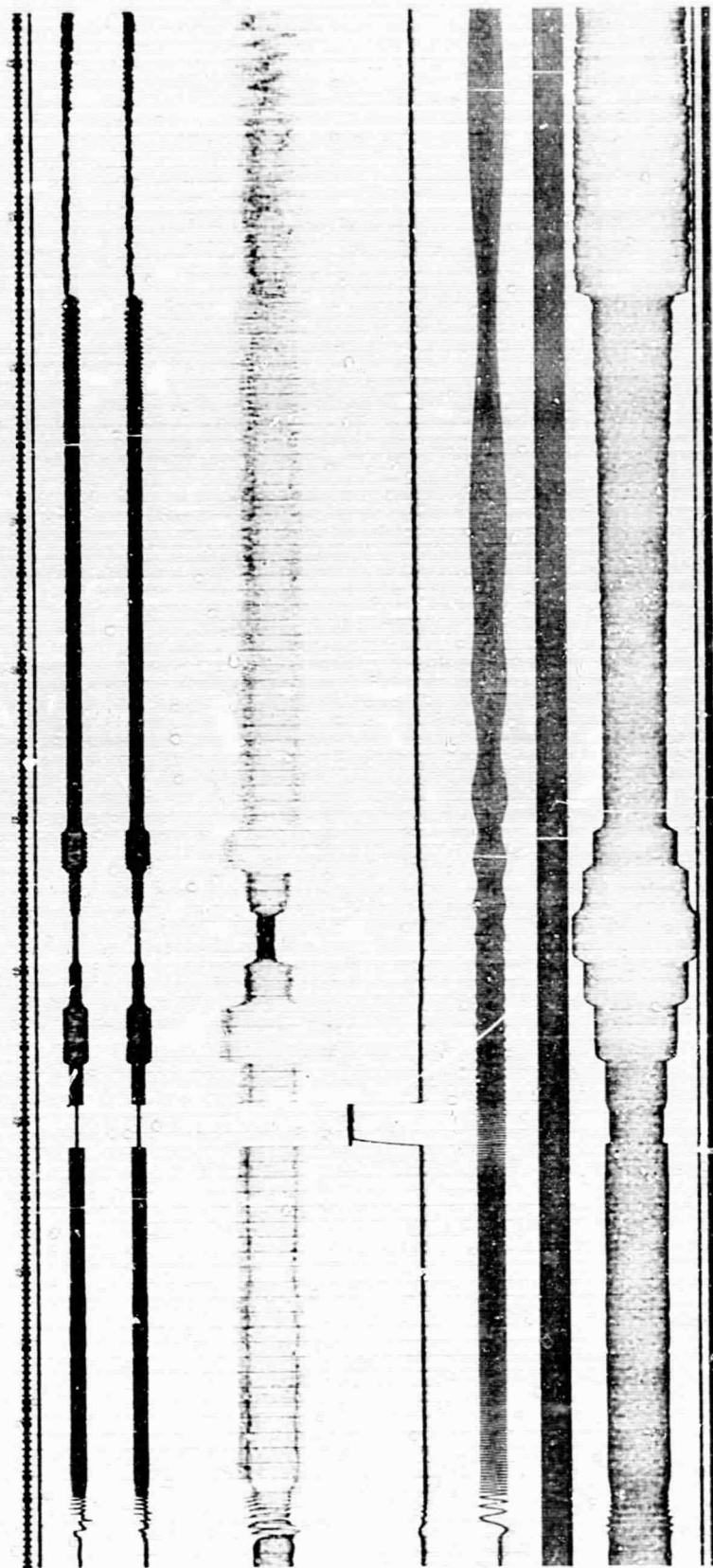


Figure 1.4 Telemetry chart record for 14,270. Reading from top to bottom, the lines represent (1) 28 Bit Time Code, (2) Base Line, (3) Phase Detector 1, (4) Phase Detector 2, (5) Rocket Receiver Output, (6) Rocket Receiver AGC, (7) Magnetic Aspect Sensor, (8) Ordinary Power, (9) Extraordinary Power, (10) Base Line, and (11) 36 Bit Time Code.

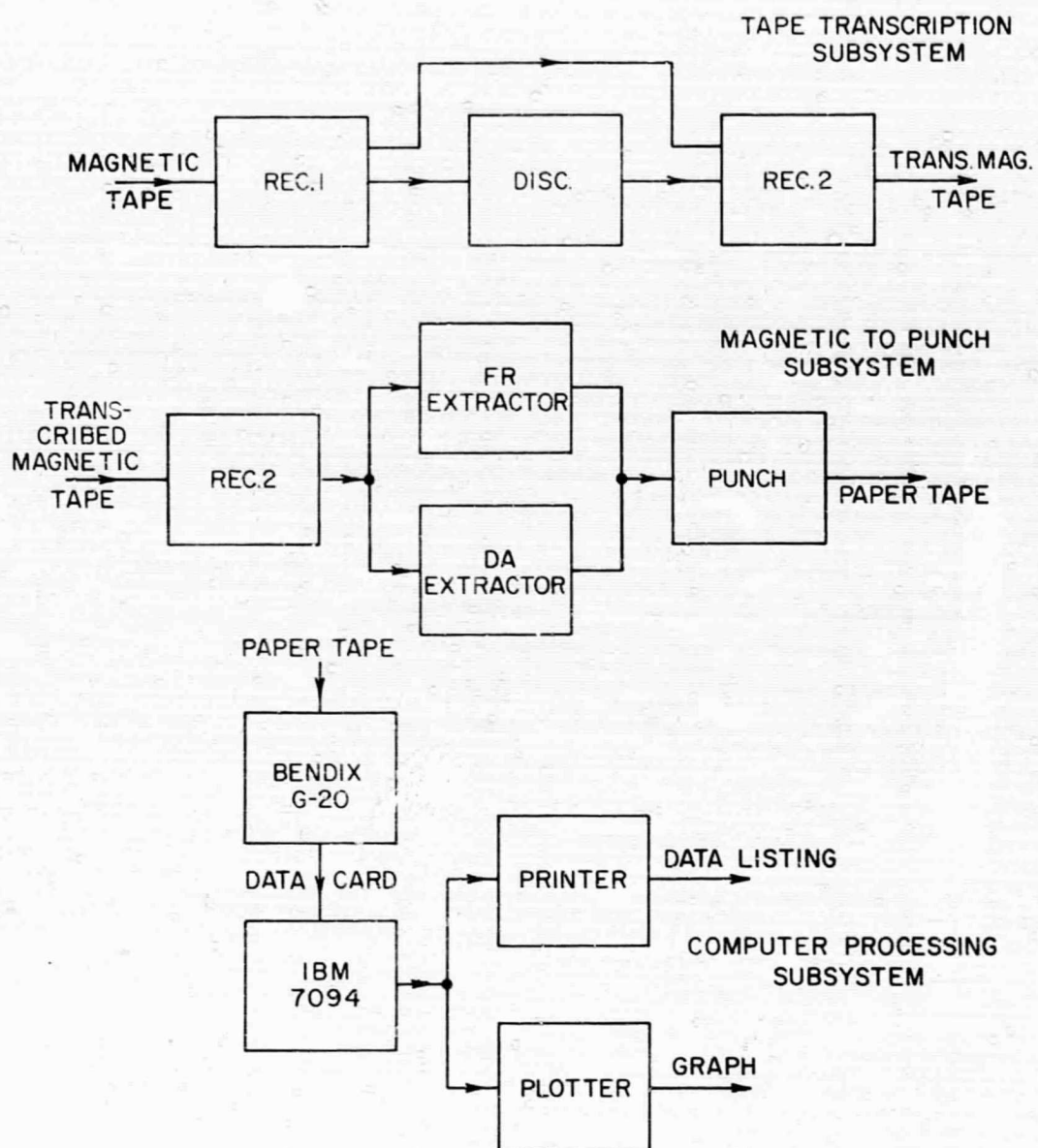


Figure 1.5 Block diagram of data processing system.

In the Tape Transcription Subsystem, information on the magnetic tape which is frequency modulated or multiplexed is demodulated and separated channel by channel by the discriminator (Disc.), and recorded on another magnetic tape by Recorder #2 (Rec. 2).

In the Magnetic to Punch Subsystem, the transcribed magnetic tape is played back to extract the Faraday rotation data or the differential absorption data. The extracted data are then punched on paper tape.

In the Computer Processing Subsystem, the data on paper tape is transferred to IBM cards by a Bendix G-20 computer. The data is listed from the card deck and graphed by an IBM 7094 Calcomp Plotter.

1.3.2 Faraday Rotation Data Processing

A block diagram of instrumentation for Faraday rotation data processing is shown in Figure 1.6. Four signals; reference (2×250 Hz), rocket spin, rocket receiver output, and time code, are obtained from Rec. 2. The rocket receiver output is a resultant signal, whose frequency components are 2×250 Hz, $2f_s$, and $2f_F$, where f_s is the rocket spin rate, and f_F is the Faraday rotation rate. Therefore, the 2×250 Hz and $2f_s$ are subtracted at this stage from the resultant of the rocket receiver output in order to find $2f_F$. The 2×250 Hz reference signal in the figure, firstly, is fed into a quadrature network (Quad. Net. in the figure), where the signal is divided into two parts with equal amplitudes, but with 90° difference in phase (S is the sine part and C is the cosine part in the figure). Then, at the mechanical shaft phase shifter (Mech. Phase Shift. in the figure), these two parts have their phases shifted by a double Faraday rotation angle and go to the mixer block to be combined with the double rocket spin signal. The rocket spin signal at the output of

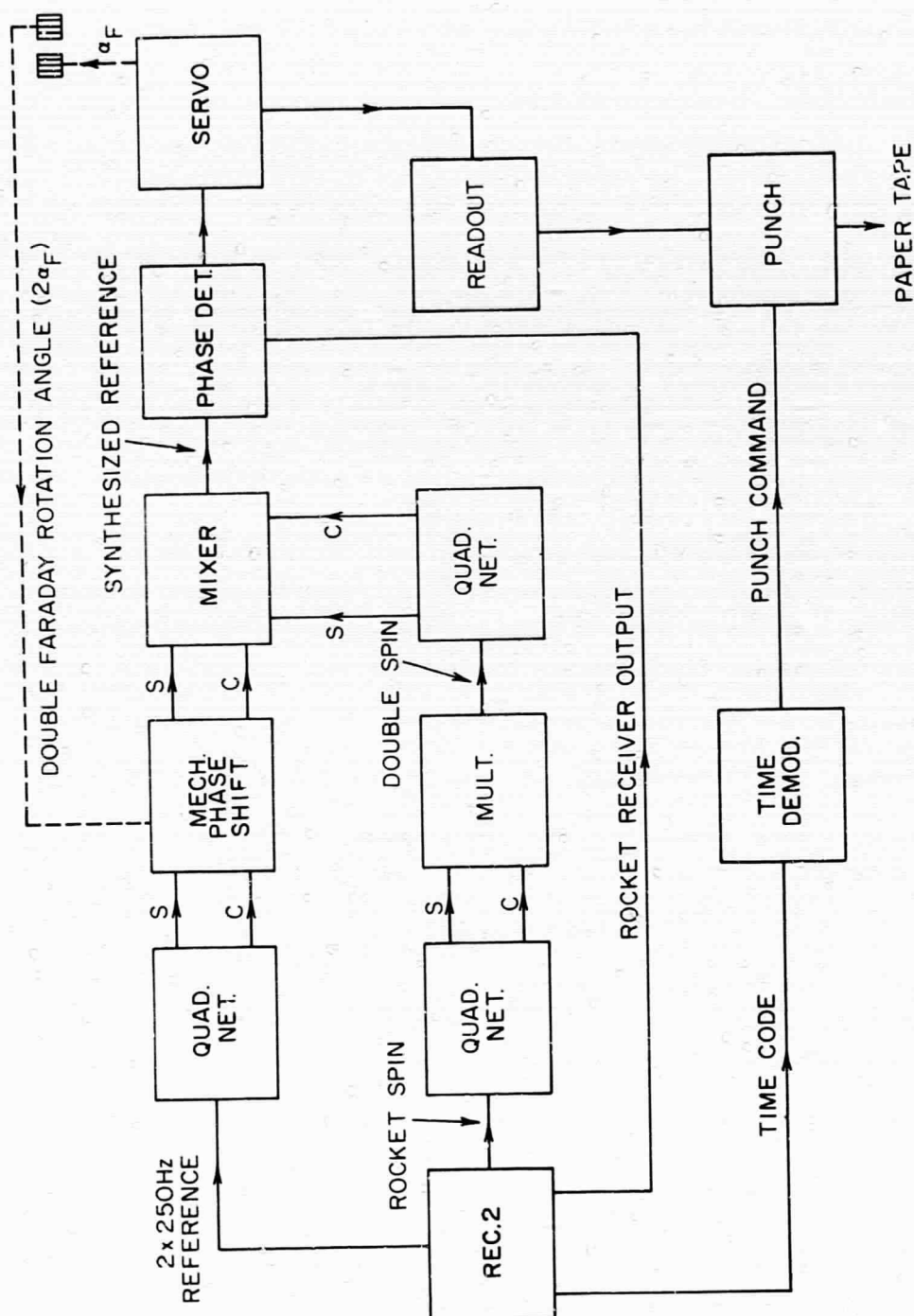


Figure 1.6 Block diagram of instrumentation for Faraday rotation data processing.

Recorder 2 goes through a quadrature network and a multiplier to be doubled in frequency, and is divided into sine and cosine parts in the following quadrature network. In a mixer, the 2×250 Hz reference and the rocket spin are combined to form a synthesized reference, which is compared with the rocket receiver output in a phase detector (Phase Det. in the figure). The servo motor is controlled by the phase detector output.

Before the rocket enters the ionosphere there is no Faraday rotation, and for a suitable initial servo position, the phase difference of the rocket receiver output and the synthesized reference differ by 90° and no output is obtained from the phase detector, and no servo driving signal is present. As the rocket enters the ionosphere Faraday rotation begins. The phase of the rocket receiver output signal changes with respect to the reference phase, and a polarized output from the phase detector is produced. This output is a servo error signal which causes the servo to rotate the mechanical phase shifter an amount necessary to restore the phase difference between the rocket receiver signal and reference signal. The rotation of the servo shaft is directly proportional to the Faraday rotation angle, and is read out by a helipot in the readout block. The output from the readout block is punched on paper tape. The time code signal consists of repetitive pulses which count elapsed time with respect to the launch time. These pulses are shaped to give punch command pulses in the time demodulator (Time Demod. in the figure).

1.3.3 Differential Absorption Data Processing

Differential absorption is represented by the excess of the extraordinary transmitted power required to maintain 31.6% amplitude

modulation ratio between the ordinary and the extraordinary modes as seen at the output of the rocket-borne receiver. A return path from the rocket to the ground, through the telemetry system provides for servo controlling the extraordinary power to a level which maintains the desired ratio during the rocket flight. The position of the attenuator, which controls the transmitted extraordinary power, is recorded, as the amplitude of a 145 Hz sine wave. The amplitude is directly proportional to the extraordinary power on a decibel scale.

The block diagram of the equipment for differential absorption data processing is shown in Figure 1.7. The extraordinary power signal (145 Hz) is fed into a full wave rectifier, where the 145 Hz signal is converted to a dc signal, which is directly proportional to the extraordinary power on a decibel scale. This dc signal is readout and punched on paper tape in the same way as in the case of Faraday rotation data processing. In Figure 1.8 and Figure 1.9, processed Faraday rotation and differential absorption data are shown, respectively.

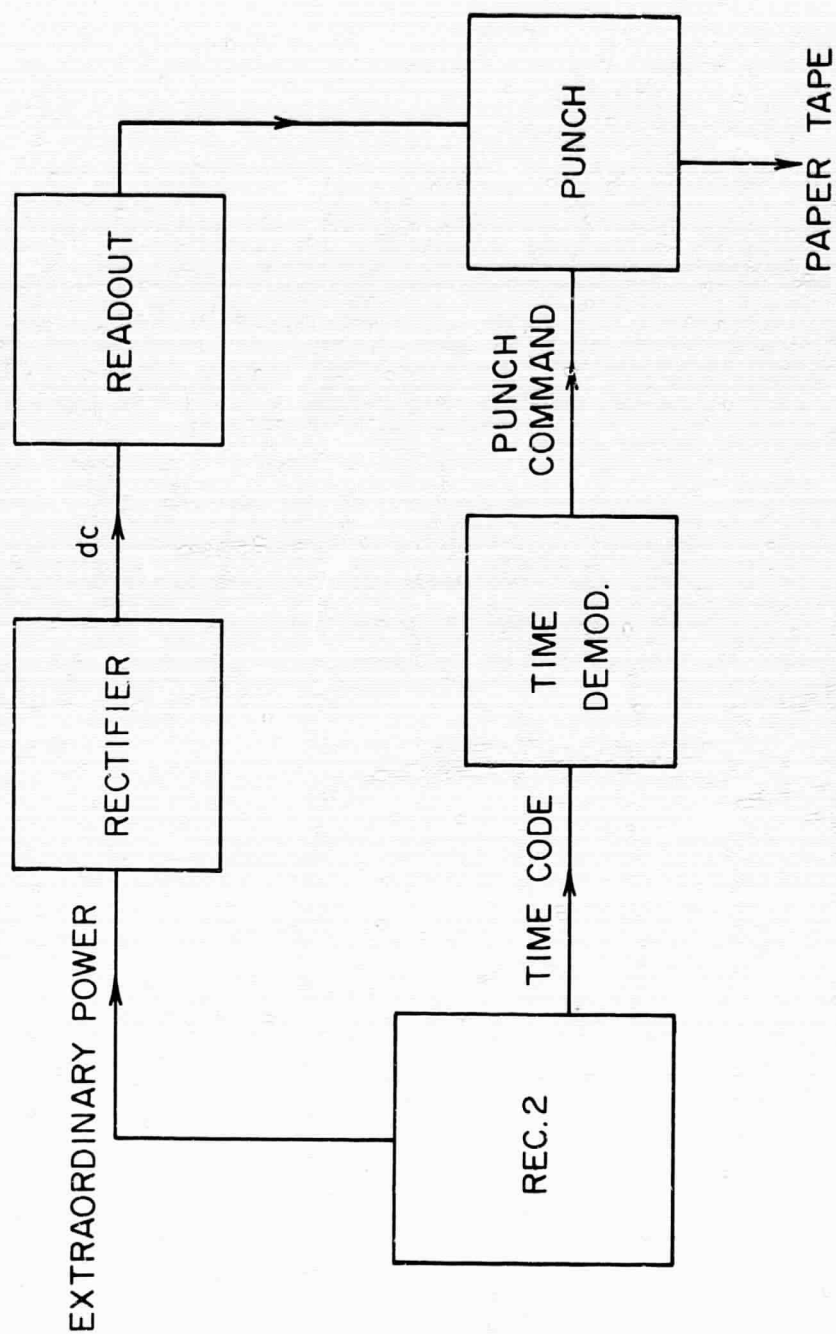


Figure 1.7 Block diagram of instrumentation for differential absorption data processing.

ROCKET NO. 14270B
 FARADAY ROTATION VS.
 TIME AFTER LAUNCH (SEC)
 COMPUTER PROCESSED DATA
 EVERY DATA POINT
 LAUNCH 164 DAY 9 HR 18 MIN 30 SEC GMT
 100 DATA POINTS/SEC

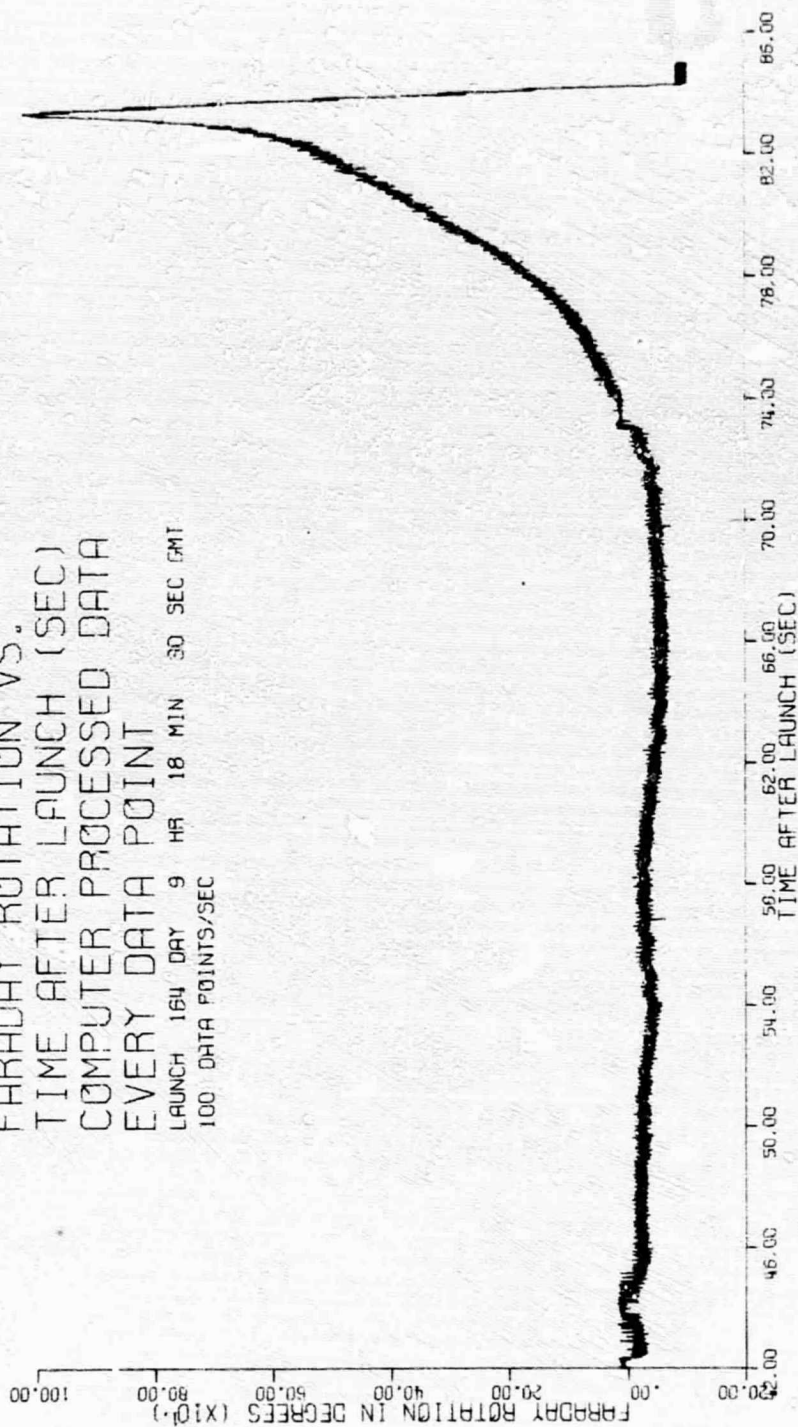


Figure 1.8 Processed Faraday rotation data.

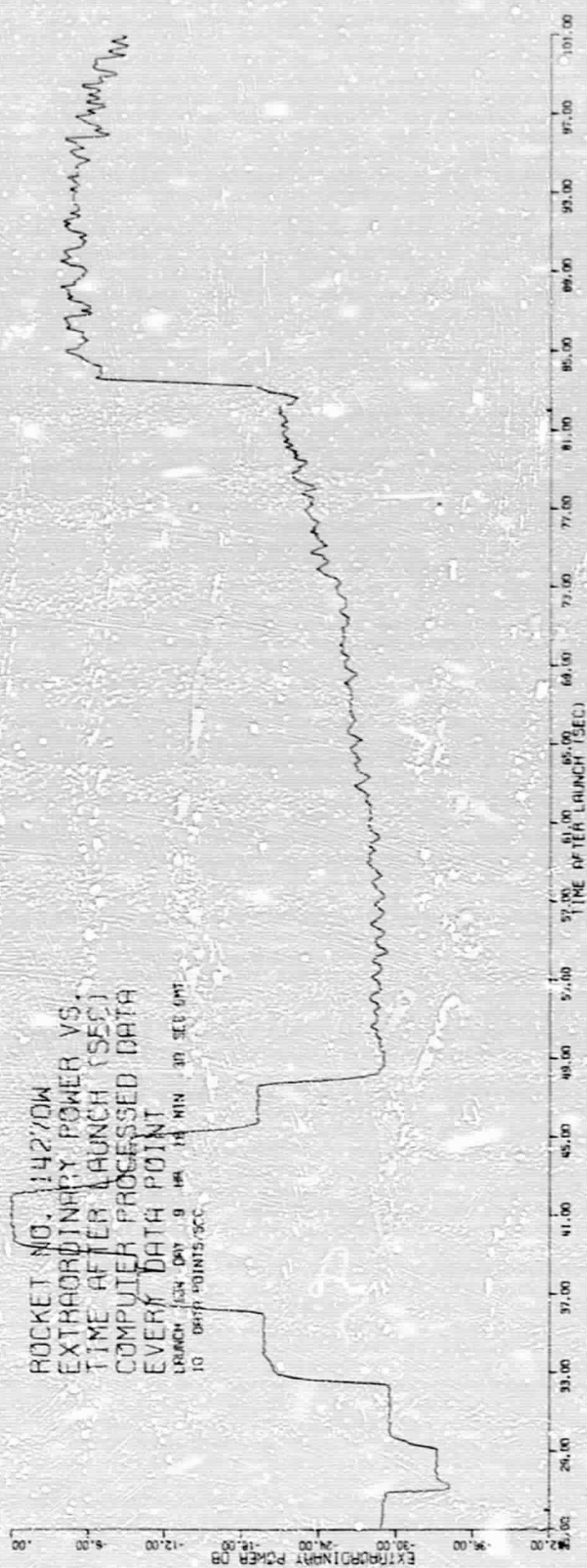


Figure 1.9 Processed differential absorption data.

2. THEORETICAL ASPECTS OF THE DATA PROCESSING SYSTEM

In this section, mathematical expressions for the rocket receiver output signal and the rocket spin signal are developed, and the theory of operation of the data processing system is discussed. As a first approximation, we consider an idealized experiment in which rocket precession effects are absent. Later in Section 3, we consider actual conditions, including the effects of precession.

2.1 Mathematical Expressions for the Rocket Receiver Output Signal and the Rocket Spin Signal

2.1.1 Wave Transmitted to the Rocket

In Figure 2.1 we see two components--the ordinary mode and the extraordinary mode. The ordinary mode of circular polarization rotates north into west tracing a circle at a frequency of $f_o = f_c - 250$ Hz where f_c is the center frequency chosen for a given rocket (see Mechtly et al., 1966). Usually, f_c is chosen as 3385 or 2225 kHz, depending on the ionospheric conditions. The extraordinary mode rotates north into east tracing a circle at a frequency of $f_x = f_c + 250$ Hz. The two modes, differing in frequency by 500 Hz, produce a resultant whose polarization axis rotates in free space at 250 revolutions per second.

Figure 2.2 shows the actual case, where the ordinary mode is greater than the extraordinary mode by 10 dB in power. This difference of the two modes in power produces a resultant elliptical polarization rather than a linear polarization. Because of the elliptical polarization, even though the axis is rotating at 250 revolutions per second, a 2×250 Hz component is observed at the antenna of the receiver on the rocket.

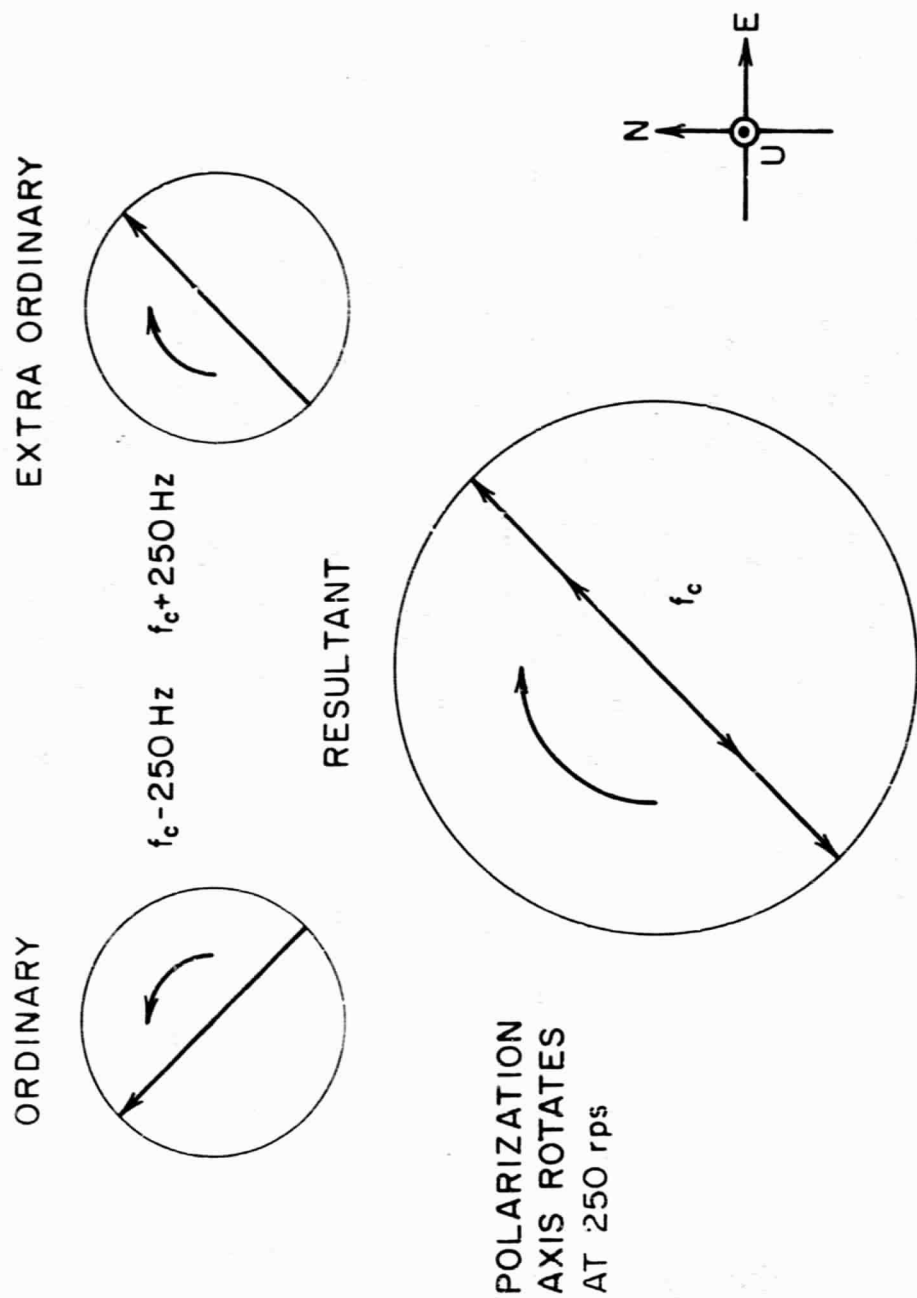


Figure 2.1 Generation of polarization circle.

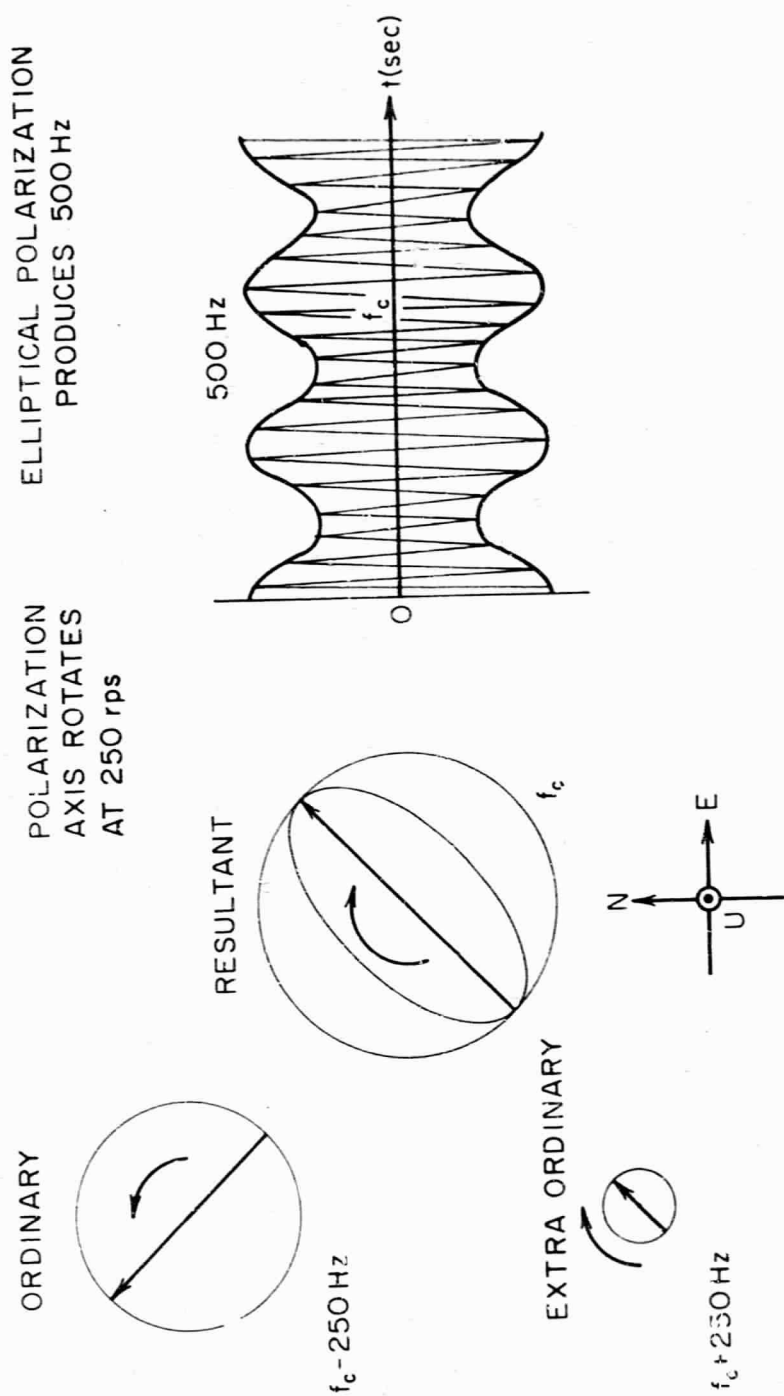


Figure 2.2 Generation of polarization ellipse.

2.1.2 The Rocket Receiver Output Signal

The wave is received by the ferrite antenna on the rocket, amplified and detected by the receiver. The detected signal is transmitted to the ground station by the telemetry system.

Equations expressing the receiver output signal are shown in Figure 2.3.

Case (a). In the simplest case, the rocket is assumed to be without spin, the antenna rod is stationary, and the rotation of the ellipse is caused only by synthesis of the two transmitted modes. In this case, the rocket receiver output signal is

$$e_{01} = E_o \cos 2 \omega_R t ,$$

where

$$\omega_R = 2\pi \times 250 \text{ rad/sec} .$$

Case (b) includes the rocket spin. The antenna rod rotates at a rate ω_s , and the polarization ellipse of the incoming wave rotates at a rate ω_R as in case (a). In this case the output signal is

$$e_{02} = E_o (1 + k_o \cos 2\omega_s t) \cos 2\omega_R t$$

where

$$\omega_s = 2\pi \times (\text{rocket spin frequency}) .$$

Case (c) shows the situation in which the transmitted wave has experienced Faraday rotation before reaching the rocket. In the figure, the Faraday rotation angle is expressed by α_F , which represents a phase difference between the wave at the rocket and the reference wave near the transmitting antenna

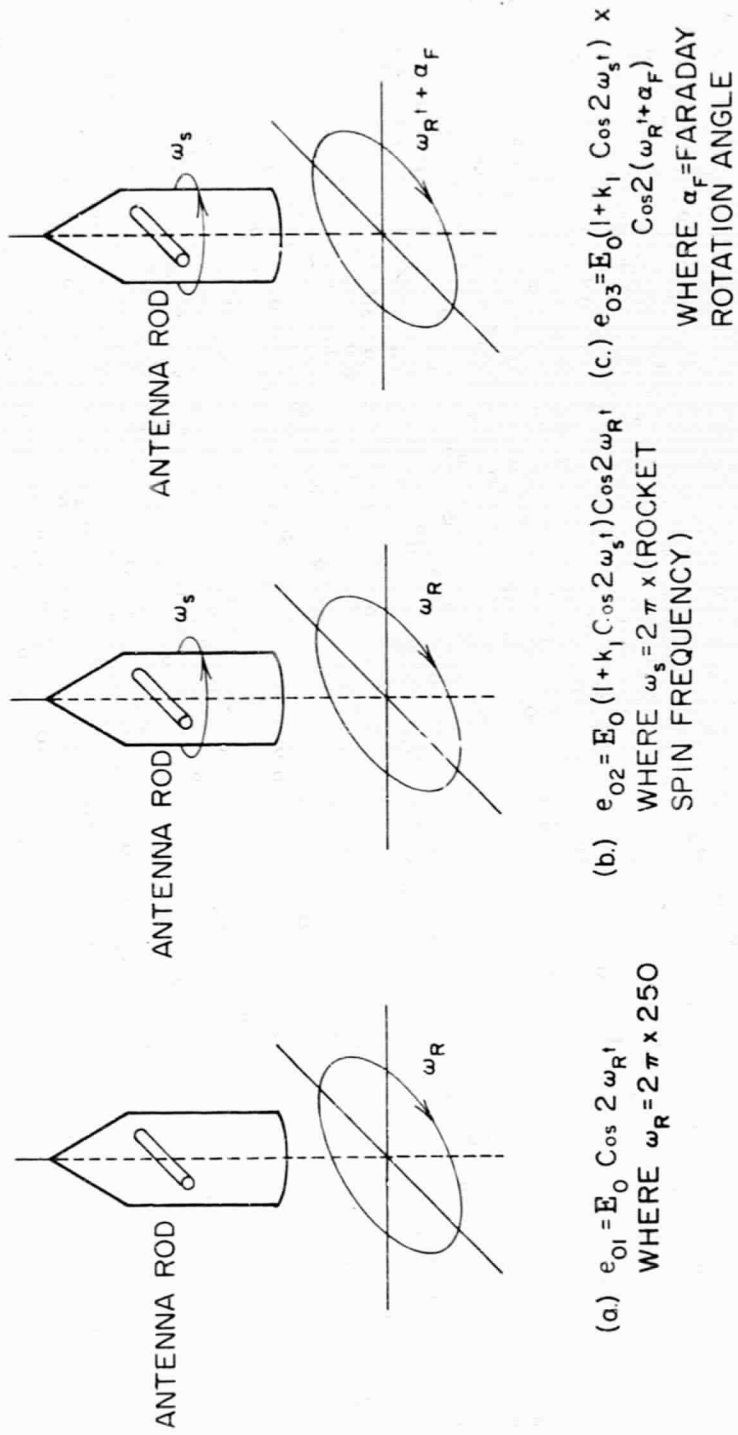


Figure 2.3 Generation of rocket receiver output signal.

on the ground. With the inclusion of the Faraday angle α_F , the output signal is

$$e_{03} = E_0 (1 + k_0 \cos 2\omega_s t) \cdot \cos 2(\omega_R t + \alpha_F)$$

where

α_F = the Faraday rotation angle. Ideally, E_0

and k_0 are constants.

2.1.3 The Rocket Spin Signal

The spin motion of the rocket is detected by a magnetic aspect sensor, which is mounted transversely to the rocket axis (Smith *et al.*, 1965). The projection of the geomagnetic field on the plane, on which the sensitive direction of the magnetic aspect sensor is rotating due to the rocket spin, determines the peak-to-peak value of the rocket spin signal, E_s . By the spin motion of the rocket, this signal varies sinusoidally. We express the rocket spin signal as:

$$e_s = E_s \cos \omega_s t$$

where

$\omega_s = 2\pi \times$ (rocket spin frequency). Ideally,

E_s is a constant.

2.2 Theory of Operation of the Faraday Rotation Data Processing System

Three signals are involved in finding the Faraday rotation angle. These signals are the rocket receiver output, the rocket spin, and the phase reference (2×250 Hz). Again we consider an ideal case first in which we exclude effects of rocket precession. The equations for the three signals are:

(1) for the rocket receiver output signal,

$$e_0 = A_0 (1 + a_0 \cos 2\alpha_s) \cos 2(\alpha_R + \alpha_F) \quad (2.1)$$

(2) for the rocket spin signal,

$$e_1 = A_1 \cos \alpha_s \quad (2.2)$$

(3) and for the phase reference signal,

$$e_2 = A_2 \cos 2\alpha_R \quad (2.3)$$

where the equations have been simplified and made symmetrical by the identities:

$$e_0 \equiv e_{03}, A_0 \equiv E_0, K_0 \equiv a_0, e_1 \equiv e_s, \text{ and } A_1 \equiv E_s.$$

There are three main steps in extracting the Faraday rotation angle from these signals.

(Step 1) Doubling the rocket spin rate.

In this step, the rocket spin signal is divided into two parts, both of which are equal in amplitude. One of them is advanced in phase by $\frac{\pi}{4}$, and the other is delayed by $\frac{\pi}{4}$. Their product gives $2\alpha_s$ as represented by Equation (2.4).

$$e_1' = G_1 \cos \left(\alpha_s + \frac{\pi}{4} \right) \cos \left(\alpha_s - \frac{\pi}{4} \right) = G_1' \cos 2\alpha_s \quad (2.4)$$

(Step 2) Synthesizing signals to form a reference signal.

In this step, the rocket spin and the phase reference signals are combined to form a synthesized reference signal. Here, we explain the operation only by mathematical equations:

$$e_3 = G_3 \left[\cos (2\alpha_R + 2\phi_F + \frac{\pi}{4}) \cos (2\alpha_s - \frac{\pi}{4}) + \cos (2\alpha_R + 2\phi_F - \frac{\pi}{4}) \cos (2\alpha_s + \frac{\pi}{4}) \right] = A_3 \cos 2(\alpha_R + \phi_F + \alpha_s) \quad (2.5)$$

where $2\phi_F$ = the servo shaft position angle, which is added to $2\alpha_R$ of the phase reference signal before the above operation.

(Step 3)

In this step, the synthesized reference signal and the rocket receiver output signal are compared in phase to find the Faraday rotation

angle α_F . Before the rocket enters the ionosphere there is no Faraday rotation, and for a suitable initial servo position, the phase difference of the rocket receiver output and the synthesized reference is 90° (neglecting the path length phase change of $1.2^\circ/\text{km}$) and no output is obtained from a phase detector, and no servo driving signal is present. As the rocket enters the ionosphere, Faraday rotation begins. The phase of the rocket receiver output signal changes with respect to the reference phase, and a polarized output from the phase detector is produced. This output is a servo error signal which causes the servo to turn a mechanical phase shifter an amount necessary to restore the phase difference between the rocket receiver signal and reference signal to 90° . The servo shaft position, which is directly proportional to the Faraday rotation angle, is read out. The following equations represent the operations described above.

The synthesized reference signal is:

$$e_3 = A_3 \cos 2(\alpha_R + \phi_F + \alpha_S) . \quad (2.5)$$

With a phase delay by 90° , we have:

$$e_4 = A_4 \sin 2(\alpha_R + \phi_F + \alpha_S) .$$

The rocket receiver output signal is:

$$e_0 = A_0 (1 + a_0 \cos 2\alpha_S) \cos 2(\alpha_R + \alpha_F)$$

which can be written as

$$e_0 = A_0 \left[\cos 2(\alpha_R + \alpha_F) + \frac{a_0}{2} \{ \cos 2(\alpha_R + \alpha_F + \alpha_S) + \cos 2(\alpha_R + \alpha_F - \alpha_S) \} \right] \quad (2.6)$$

Then the product of e_0 and e_4 is

$$\begin{aligned} e_5 &= e_0 e_4 \\ &= G_4 \sin 2(\alpha_R + \phi_F + \alpha_S) [\cos 2(\alpha_R + \alpha_F) + \frac{a_0}{2} \{ \cos 2(\alpha_R \\ &\quad + \alpha_F + \alpha_S) + \cos 2(\alpha_R + \alpha_F - \alpha_S) \}] . \end{aligned}$$

All the terms generated by this equation except one are removed by a filter network in the data processing system. The important term is

$$e_6 = A_6 \sin 2(\phi_F - \alpha_F) \quad (2.7)$$

which is one of the terms of the product

$$e_7 = A_7 \sin 2(\alpha_R + \phi_F + \alpha_S) \cos 2(\alpha_R + \alpha_F + \alpha_S).$$

If the value of e_6 of Equation (2.7) is not zero, the servo restores the value to zero by changing the servo shaft position angle ϕ_F . Then we have

$$\alpha_F = \phi_F \quad (2.8)$$

where α_F = the Faraday rotation angle.

ϕ_F = the servo shaft position angle.

Therefore the Faraday rotation angle is given by the servo shaft position angle.

3. ANALYSIS OF ROCKET PRECESSION

The objective of a study of rocket precession is an understanding of the errors which the precession causes in measurements of Faraday rotation and differential absorption, and hence in measurements of electron density.

3.1 Nike-Apache Precession Characteristics

A precessing Nike-Apache rocket is illustrated in Figure 3.1. The rocket spin rate, f_s , is usually about 5 to 7 Hz. The rocket precession rate, f_p , is usually about 0.1 to 0.4 Hz. The spin angular velocity is $\omega_s = 2\pi f_s$, and the precession angular velocity is $\omega_p = 2\pi f_p$. The precession cone angle, the angle between the axis of the precession cone and the rocket axis, θ_p , in Figure 3.1 is determined in the analysis to follow. The quantities ω_p and θ_p are found to vary slowly with time.

In Figure 3.2 (a) we visualize the unit vector of the rocket axis $\hat{R}$, the geomagnetic field vector $\vec{B}$, the unit vector of the magnetic aspect sensor $\hat{S}$ perpendicular to $\hat{R}$, and ω_s the rocket spin about $\hat{R}$. By the rotation of $\hat{S}$ about $\hat{R}$, we expect the rocket spin signal to be

$$e_{s1} \propto B \sin \omega_s t.$$

In Figure 3.2 (b), $\vec{B}_1$ and $\hat{S}$ are coplanar and we expect the result

$$e_{s2} \propto B_1 \sin \omega_s t.$$

Finally, in Figure 3.2 (c) we visualize a rocket rotating about its axis $\hat{R}$ at a rate ω_s , and $\hat{R}$ itself gradually precessing at a rate ω_p about a precession axis (vertical in the figure) which is tangent to the rocket trajectory. In this case we expect a signal as shown at the foot of Figure 3.2 (c).

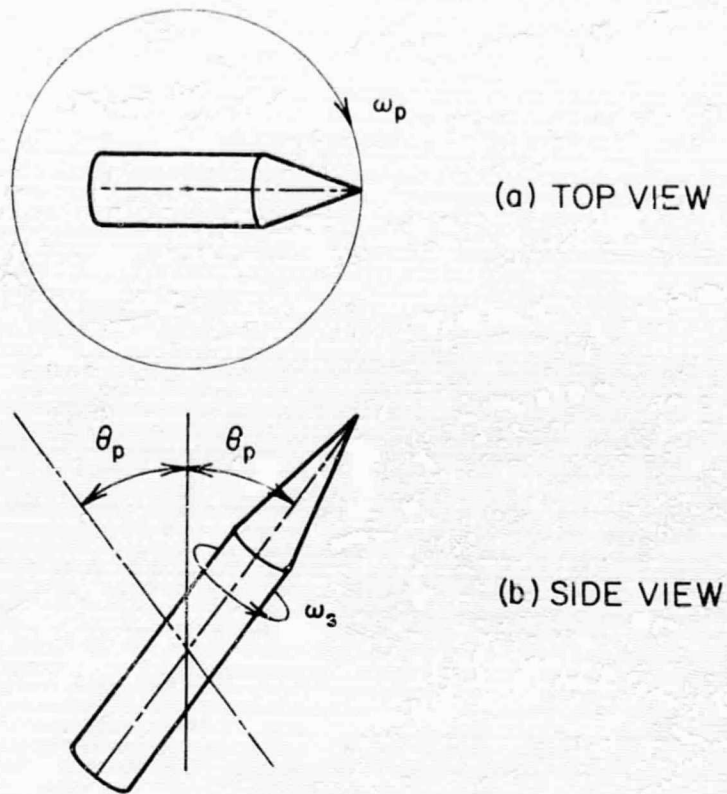


Figure 3.1 Simplified spin and precession of rocket.

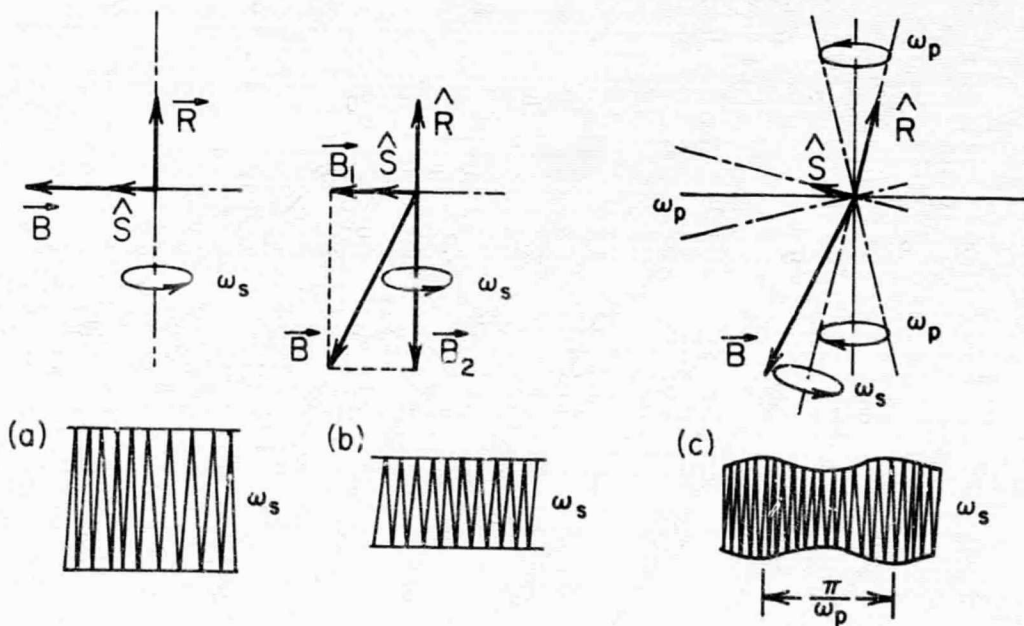


Figure 3.2 Precession effect on rocket spin signal.

So far, we have briefly considered the precession itself and its effect on the rocket spin signal. Now, let us look at Figure 3.3 for a comparison of processed Faraday rotation data with rocket spin signal for Nike-Apache 14.270. We notice a gradual variation along the Faraday rotation curve with the same changing rate as the envelop change of the rocket spin signal above in the figure. On the following pages, we will analyze the precession, and try to explain how the Faraday rotation variation has been brought about, and attempt to estimate the Faraday rotation error.

3.2 The Precession Angle, θ_p

The plane defined by the geomagnetic field vector $\vec{B}$ and a unit vector, $\hat{P}$, on the axis of the rocket precession cone is shown in Figure 3.4. The unit vector $\hat{R}$ lies on the rocket axis in the direction of the rocket nose. The rocket axis precesses about $\hat{P}$ at a precession angle θ_p , to be determined.

The $\hat{R}_1$ direction corresponds to a maximum p-p spin signal, M , and the $\hat{R}_2$ direction corresponds to a minimum p-p signal, N . Quantitatively,

$$M = k\phi B \sin(\theta_B + \theta_p), \text{ and} \quad (3.1)$$

$$N = k\phi B \sin(\theta_B - \theta_p), \quad (3.2)$$

where

θ_B = the angle between $\vec{B}$ and $\hat{P}$, and

$k\phi$ = a constant of the magnetic aspect sensor.

Dividing (3.1) by (3.2) and solving for θ_p ,

$$\theta_p = \tan^{-1} \left[\tan \theta_B \frac{M - N}{M + N} \right]. \quad (3.4)$$

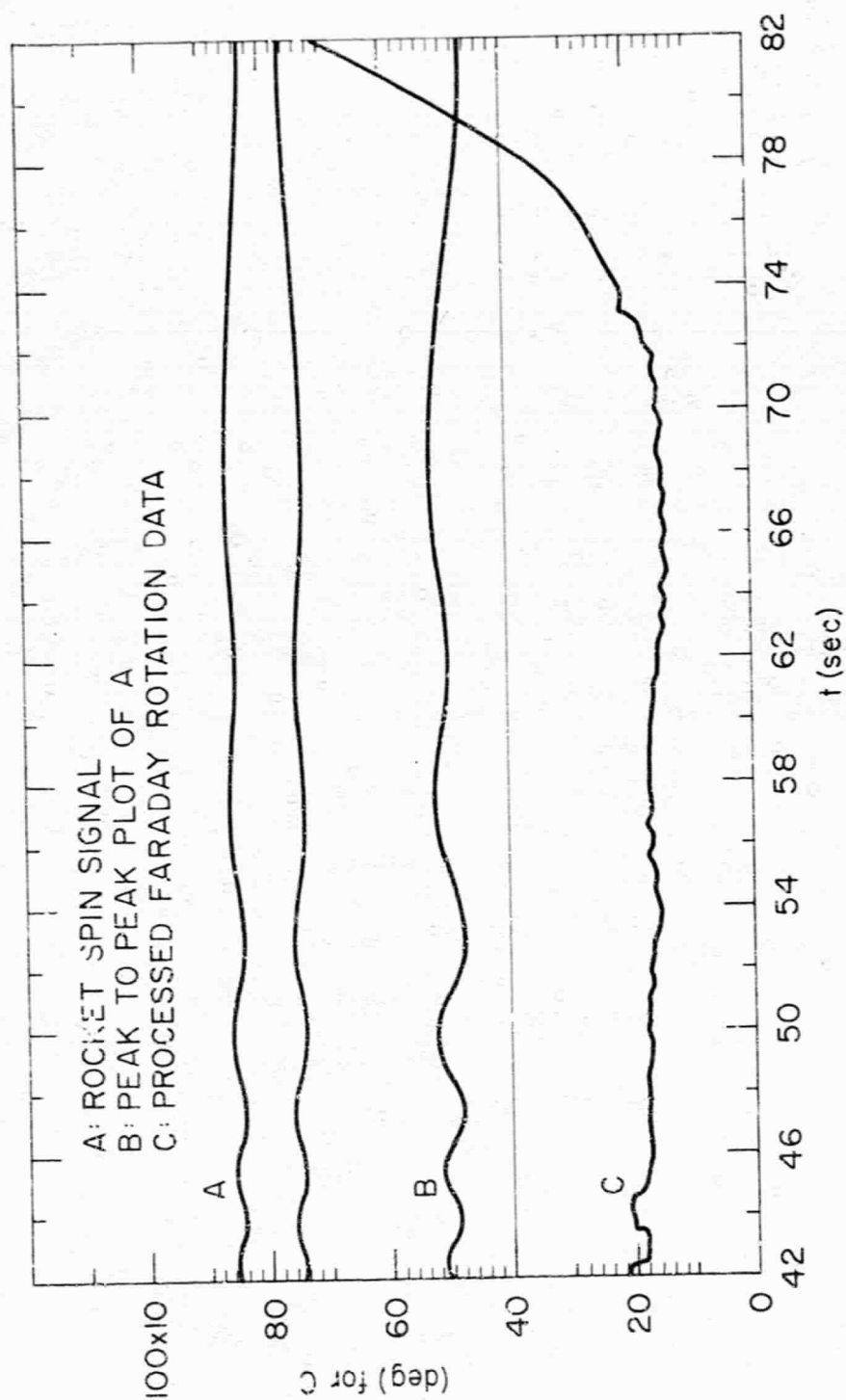


Figure 3.3 Comparison of processed Faraday rotation data with rocket spin signal for 14.270.

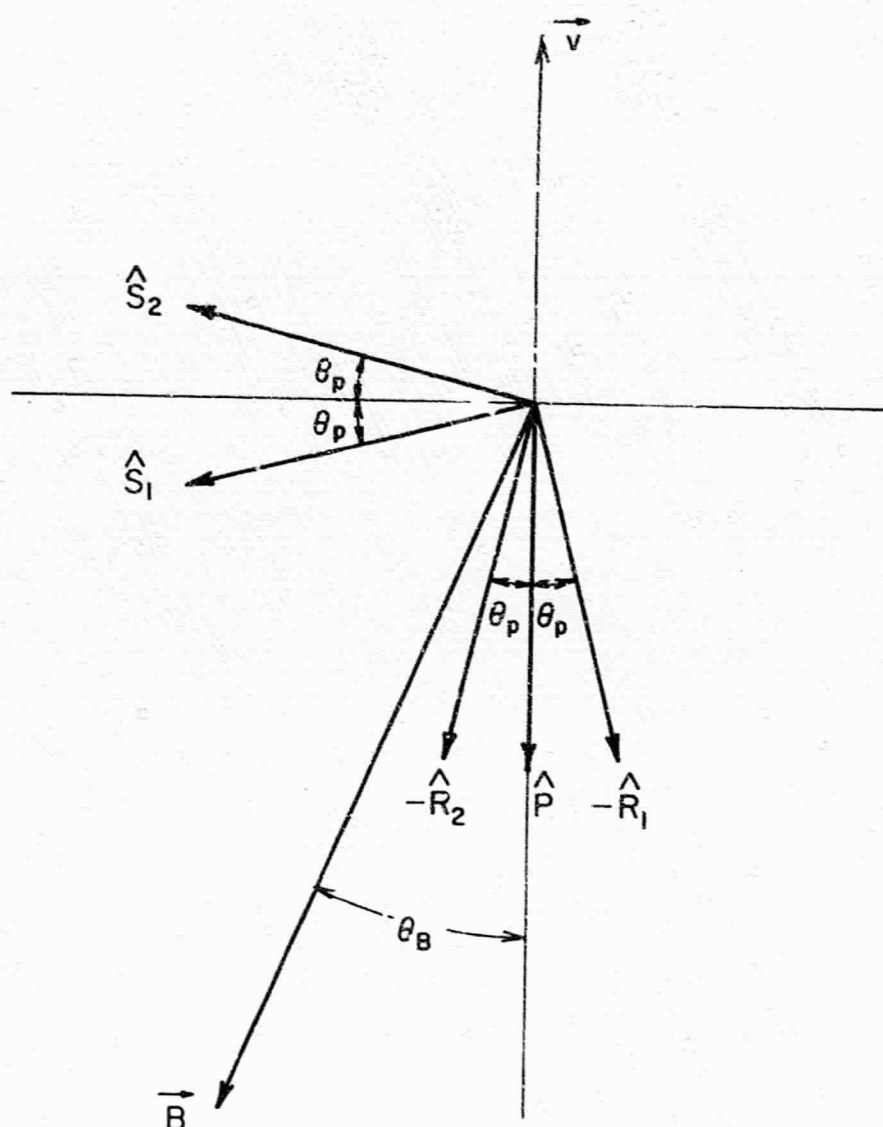


Figure 3.4 Geometry of geomagnetic field and rocket precession cone axis.

The spin signal extrema, M and N, are known from the spin signal telemetry record. If θ_B can be determined, the precession angle then follows from (3.4).

During ascent of the rocket in the lower ionosphere the unit vector $\hat{p}$ lies accurately tangent to the rocket trajectory, and θ_B can be obtained from a knowledge of the direction cosines of the rocket trajectory and a knowledge of the geomagnetic field.

The scalar product of $\vec{B}$ and the rocket velocity $\vec{v}$ is

$$\vec{B} \cdot \vec{v} = Bv \cos \theta_B = B_x v_x + B_y v_y + B_z v_z$$

Thus

$$\theta_B = \arccos [(1/Bv) (B_x v_x + B_y v_y + B_z v_z)] \quad (3.5)$$

In Figures 3.5 and 3.6 are values of the components of $\vec{B}$ and $\vec{v}$ for Nike-Apache 14.270.

In these figures the coordinates x, y, z are East, North, and Up respectively.

At $t = 60$ seconds after launch, for example,

$$B = 5.30 \quad B_E = -0.360 \quad B_N = +1.76 \quad B_U = -4.98$$

(in units of 10^{-5} Wb/m^2)

$$V = 1.52 \quad V_E = 0.384 \quad V_N = -0.075 \quad V_U = 1.48$$

(in units of 10^3 m/s)

Then, from (3.5), $\theta_B = 18.6^\circ$.

From Figure 3.3, the spin signal record of 14.270

M = 12.2 divisions at $t = 57.5$ sec after launch

N = 9.8 divisions at $t = 61.8$ sec after launch.

Substituting these into Equation (3.4), we have $\theta_p = 2.1$ (deg).

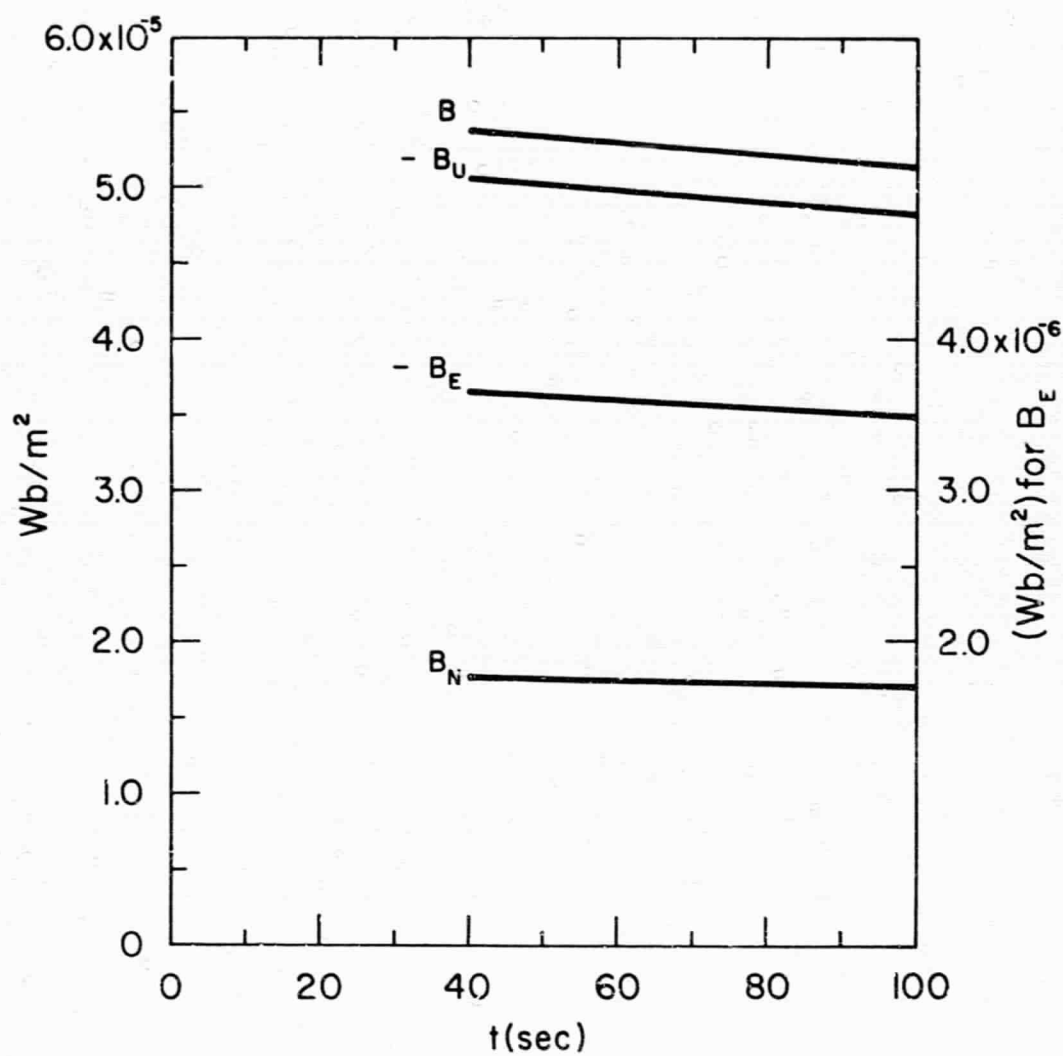


Figure 3.5 Geomagnetic field components for 14.270.

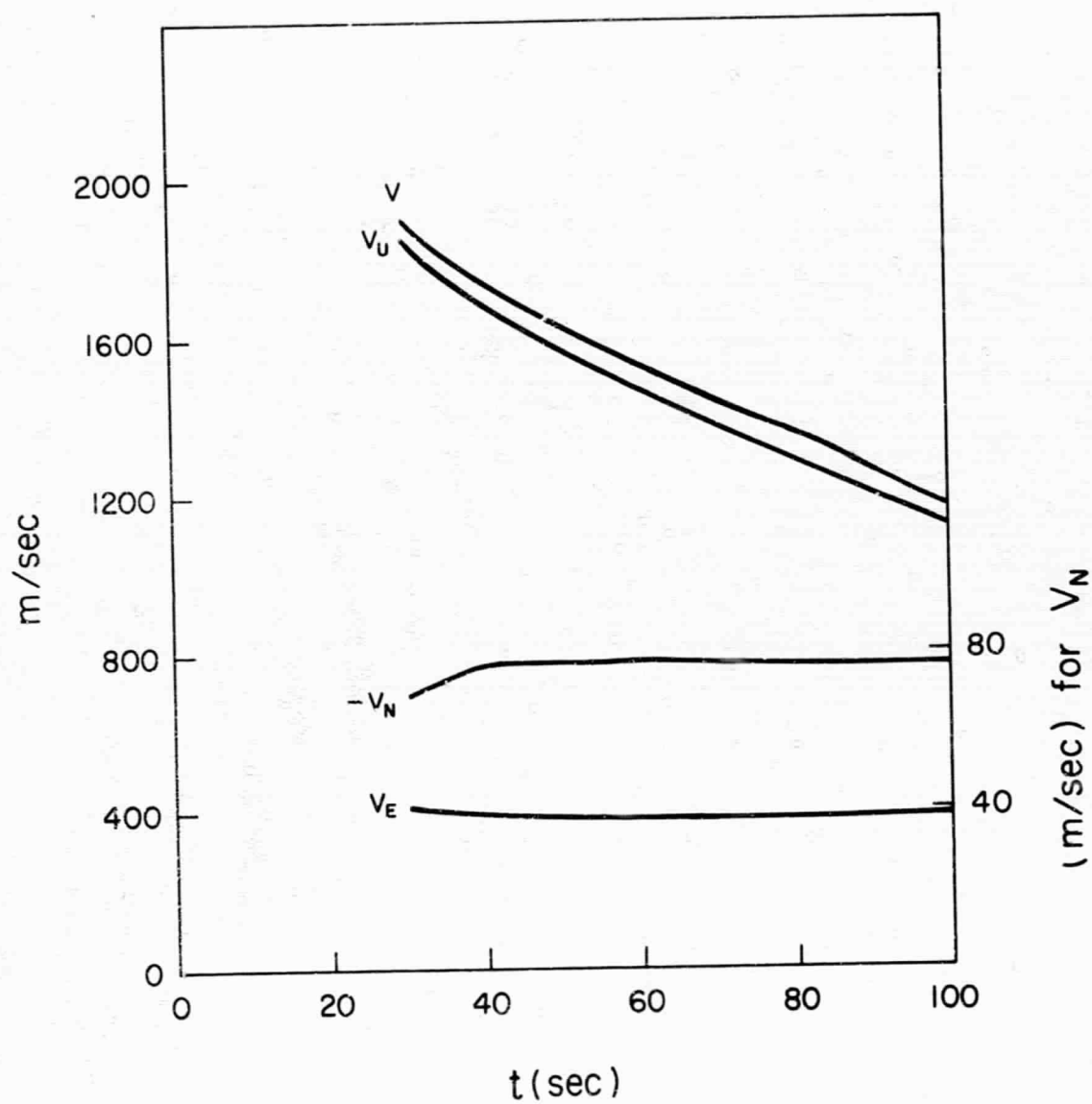


Figure 3.6 Components of rocket velocity relative to earth for 14.270.

3.3 The Precession Frequency, f_p

The precession frequency, f_p , is easily derived from the spin signal record by the equation

$$f_p = \frac{1}{2\Delta T} \text{ (Hz)} \quad (3.6)$$

where ΔT = the time interval between adjacent maxima and minima of the rocket spin signal.

At $t = 44.6$ sec, for example, we see a maximum at $t = 45.4$ seconds and a minimum at $t = 43.8$ seconds. Hence

$$t = 45.4 - 43.8 = 1.6 \text{ (sec)}.$$

Then from Equation (3.6) we have

$$f_p = \frac{1}{2\Delta T} = \frac{1}{2 \times 1.6} = 0.312 \text{ (Hz)}.$$

3.4 A Table of θ_B , and Graphs of f_p and θ_p

The following table shows calculated values of θ_B for the experiment 14.270

Table 3.1

Angle θ_B Between Geomagnetic Field and Precession
Cone Axis for 14.270

Time after launch (sec)	43.2	44.6	46.4	48.5	51.2	55.1	59.7	64.9	74.6
θ_B (deg)	18.9	18.9	19.8	19.3	18.9	19.6	18.7	18.9	19.6

The average value of θ_B is 19.25 (deg), and the range of change is 19.25 ± 0.55 (deg).

Figure 3.7 shows precession frequency, f_p , and precession angle, θ_p , versus time after launch for experiment 14.270. The precession frequency, f_p , decreases from 0.45 Hz to 0.10 Hz between 42 and 54 sec after launch, and is nearly constant at $(8 \pm 2) \times 10^{-2}$ Hz, from 54 to 82 sec.

The precession angle, θ_p , varies from 1.4 to 7.1 deg between 42 and 82 sec.

Figure 3.8 shows precession frequency, f_p , and precession angle, θ_p , versus time after launch for 14.146 (Wallops Island, July 15, 1964). In this figure, the precession frequency f_p decreases from 0.3 to 0.02 Hz between 50 and 90 sec, and is within $(2.0 \pm 0.2) \times 10^{-2}$ Hz between 90 and 300 sec. The precession angle θ_p increases from 2 to 11 deg for 50 to 90 sec, and is within 11.0 ± 0.5 deg for 90 to 300 sec.

3.5 The Effect of Precession on Faraday Rotation and Differential Absorption

3.5.1 The Effect on Faraday Rotation

The spin signal with rocket precession was illustrated qualitatively in Figure 3.2 (c). Quantitatively, this signal is

$$e_{p1} = B_1 (1 + b_1 \cos \alpha_p) \cos \alpha_s \quad (3.7)$$

This equation reduces to (2.2) in the absence of precession.

Since $\alpha_p \ll \alpha_s$, the precession component α_p is included in the electronic operations discussed in Section 2.2 and the synthesized reference signal is

$$e_{p3} = B_3 (1 + b_1 \cos \alpha_p) \cos 2(\alpha_R + \phi_F + \alpha_s), \quad (3.8)$$

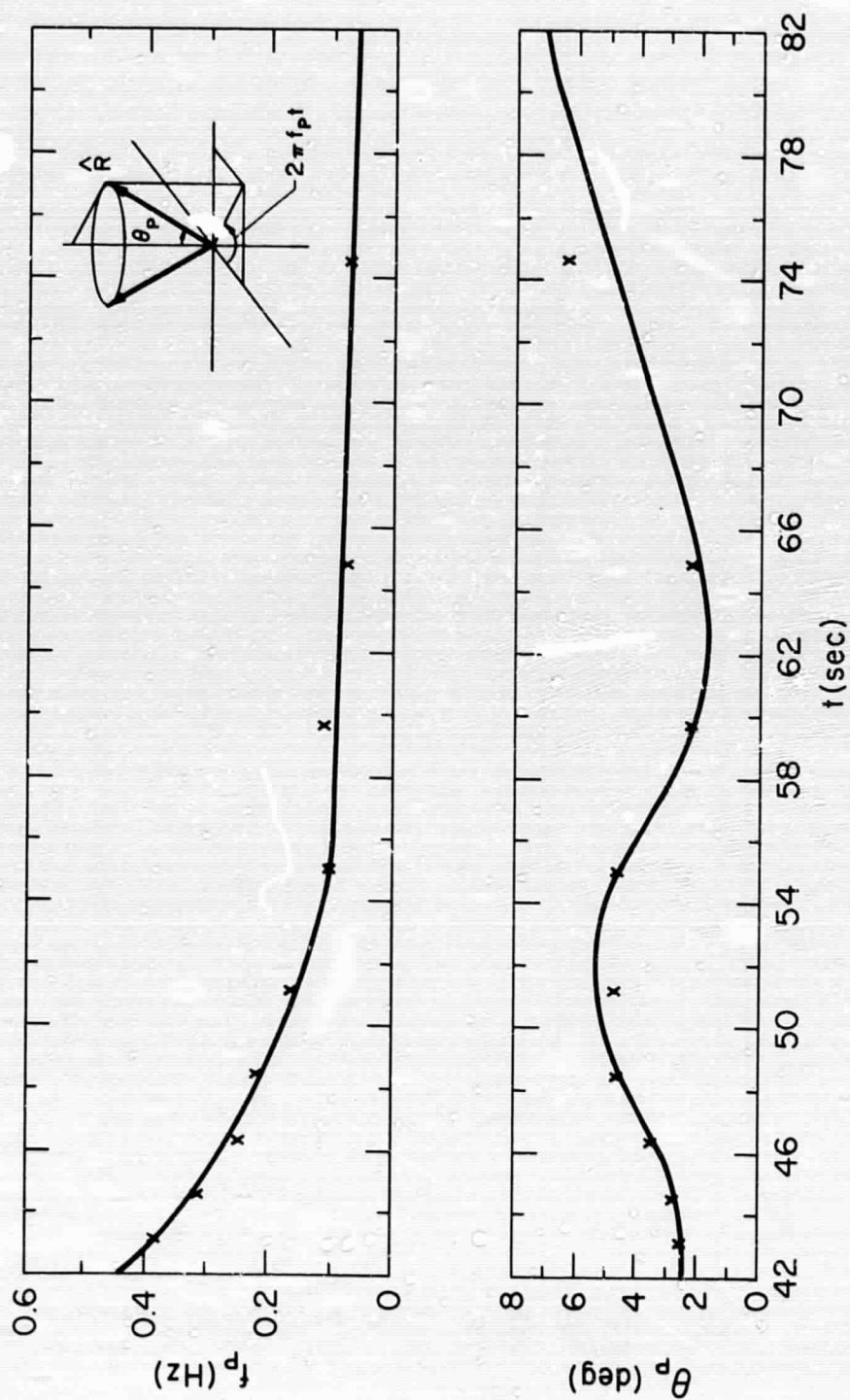


Figure 3.7 Precession frequency and precession angle versus time after launch for 14.270.

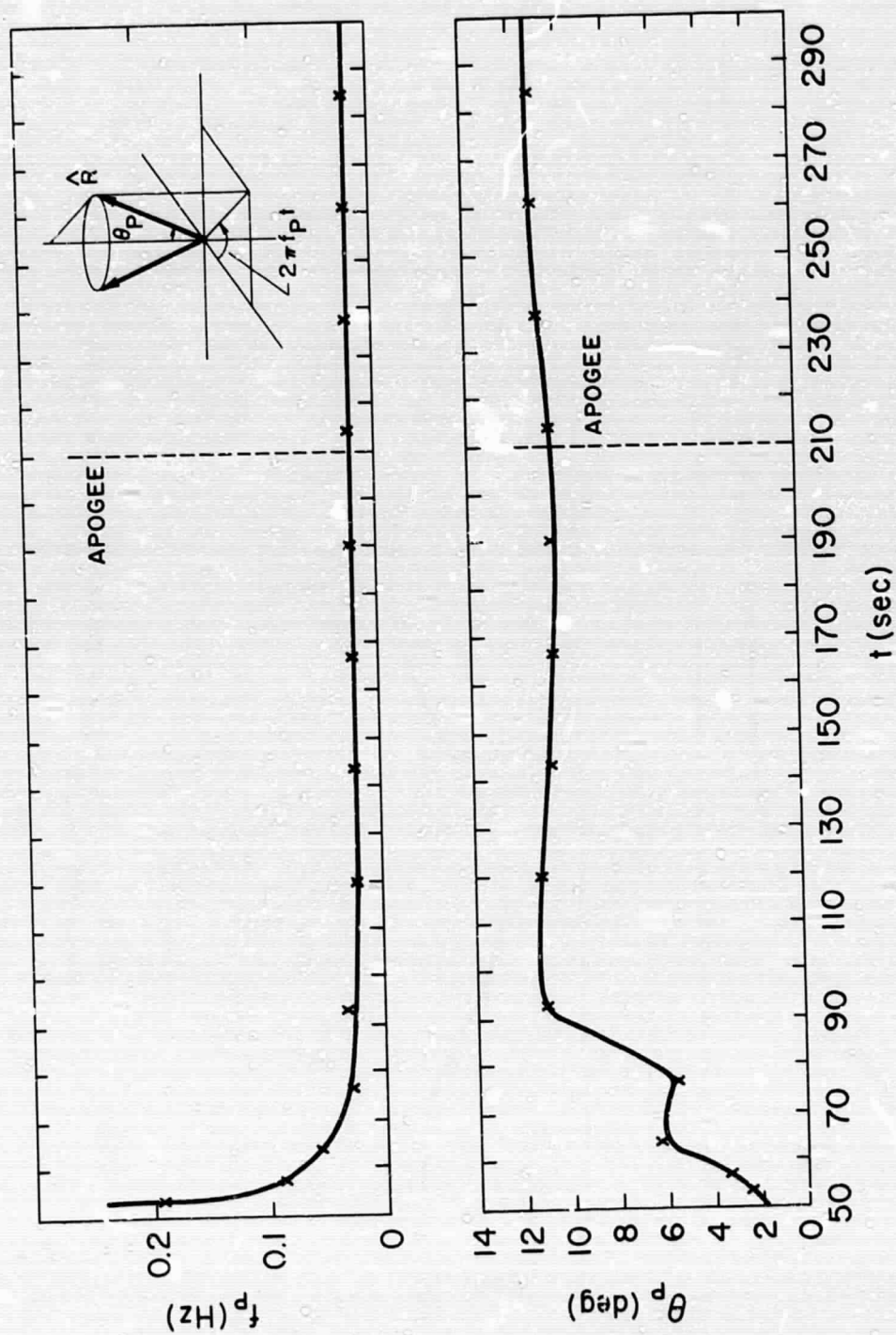


Figure 3.8 Precession frequency and precession angle versus time after launch for 14.146.

which compares with Equation (2.5) in the zero precession case

$$e_3 = A_3 \cos 2 (\alpha_R + \phi_F + \alpha_S). \quad (2.5)$$

Before evaluating the effect of the factor $(1 + b_1 \cos \alpha_p)$, we consider the fundamental properties of the phase detector. In Figure 3.9, are shown four different waveforms. If the waveform (a) and the waveform (b) are the phase detector inputs, the operation is as follows: $C_1 \cos \beta_1$ is delayed in phase to become $C_1 \sin \beta_1$, which is multiplied with $C_2 \cos \beta_1$ to give $C_1 C_2 \sin \beta_1 \cos \beta_1$, which can be rewritten as $C_1 C_2 / 2 [\sin (\beta_1 + \beta_1) + \sin (\beta_1 - \beta_1)]$, the first term of which is filtered out to give

$$\frac{C_1 C_2}{2} \sin (\beta_1 - \beta_1), \quad (3.9)$$

the argument of (3.9) is zero. Therefore, the output voltage of the detector is zero.

If the waveform (a) and the waveform (c) are inputs, the result is

$$\frac{C_1 C_3(t)}{2} \sin (\beta_1 - \beta_1), \quad (3.10)$$

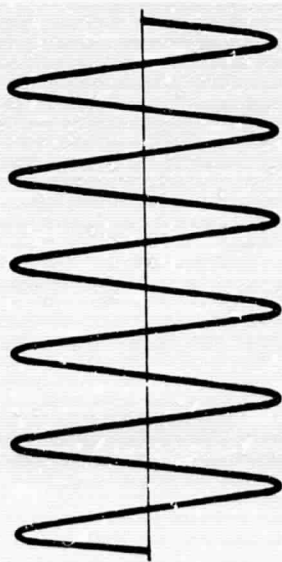
comparing Equation (3.10) with Equation (3.9), we notice that $C_3(t)$ is different from C_2 and gradually varying with respect to time. But the arguments of both of the signals are the same, β_1 , in frequency and phase. Therefore, the output voltage of the detector is again zero.

Finally, if the detector input waveforms are (a) and (d), the result is

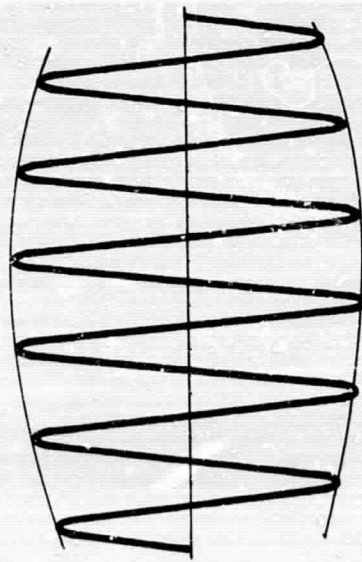
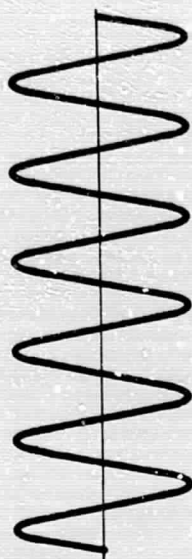
$$\frac{C_1^2}{2} \sin (\beta_1 - \beta_2). \quad (3.11)$$

Obviously, since β_1 is different from β_2 in frequency or phase, this expression cannot be zero.

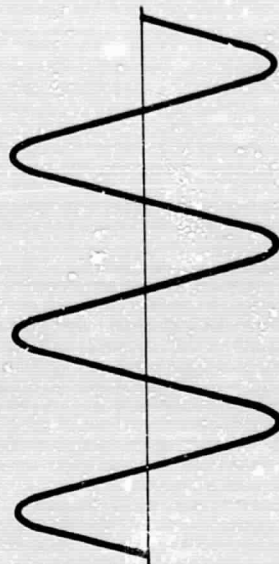
(a) $C_1 \cos \beta_1$



(b) $C_2 \cos \beta_1$



(c) $C_3(t) \cos \beta_1$



(d) $C_1 \cos \beta_2$

Figure 3.9 Waveforms for explanation of phase detector.

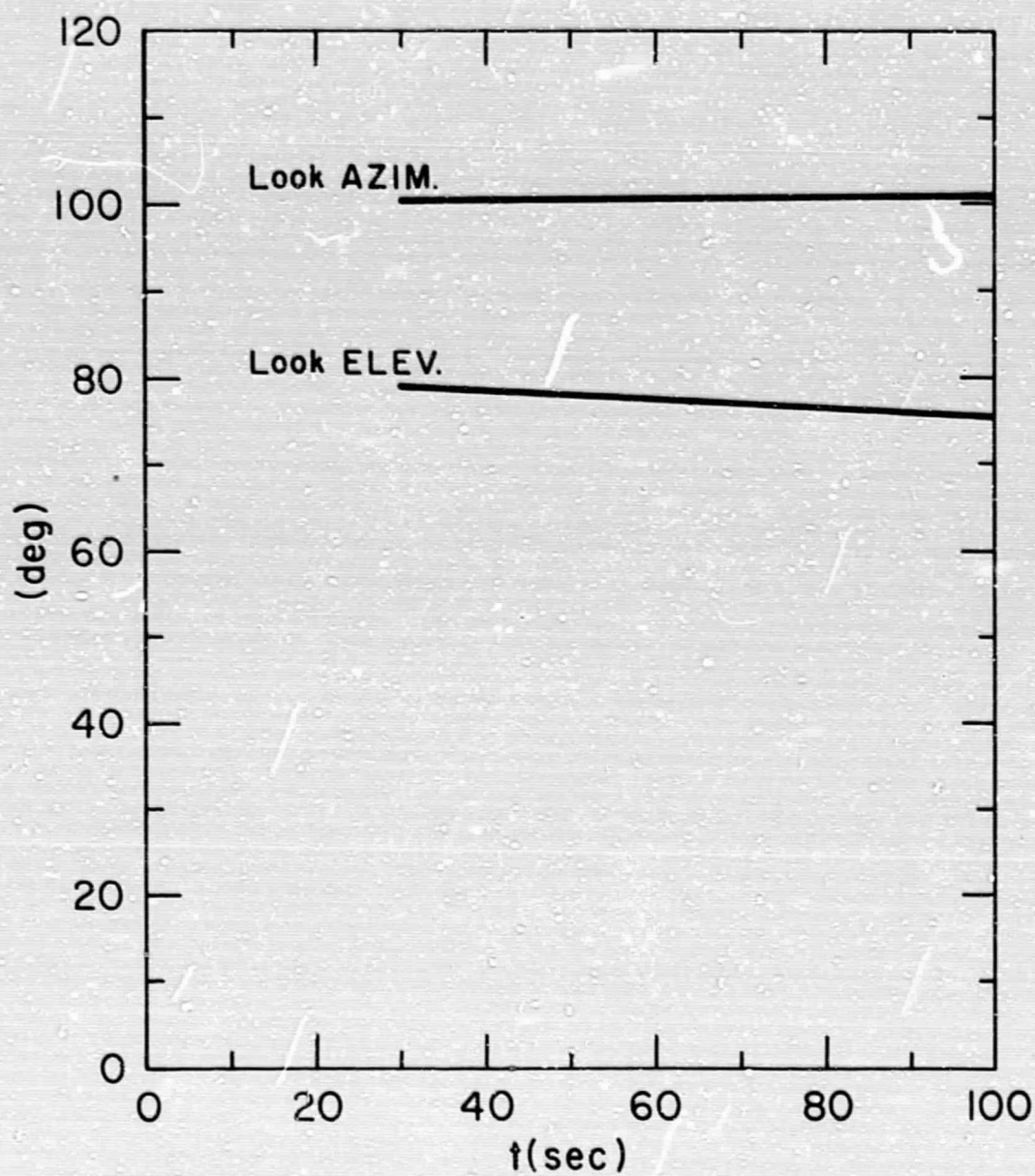


Figure 3.10 Look azimuth and elevation versus time after launch for 14.270.

From other tabulated trajectory data,

$$L = 1 \quad L_E = 0.206 \quad L_N = -3.87 \times 10^{-2} \quad L_U = 0.978$$

Hence, $\theta_{PW} = 3.6^\circ$ from Equation (3.12).

The angle θ_p , calculated in Section 3.2, added to the angle θ_{PW} , gives the maximum value of the angle θ_{RW} .

A set of maximum values of θ_{RW} for experiment 14.270 follows:

Time after launch:	40	50	60	70	80	sec
θ_{PW} :	0	3.6	0	5.1	0	deg
θ_p :	2.4	5.0	2.0	3.4	6.6	deg
$\theta_{RW} = \theta_{PW} + \theta_p$:	2.4	8.6	2.0	8.5	6.6	deg
$\cos \theta_{RW}$:	0.999	0.985	0.999	0.985	0.993	

The received powers of both the extraordinary and ordinary modes are reduced by factors equal to or less than these values of $\cos \theta_{RW}$. The reductions are consistently less than 2%. Furthermore, both modes are reduced by the same factor so that the power ratio is not changed by the small departures of the rocket axis from the wave normal direction.

Therefore no error in differential absorption measurements results from the small departures of the rocket axis from the wave normal direction.

3.6 Noise Problems and a Dummy Signal Method

The tape recording of the rocket experiment 14.304, which was one of four eclipse rockets launched on 12 November 1966 from Rio Grande, Brazil, was very noisy. The rocket spin signal was affected most.

An attempt was made to overcome this difficulty by substituting a signal from a signal generator for the rocket spin signal. However, the rocket spin frequency is 1% higher at the beginning and 1% lower at the end of the Faraday rotation range (41 through 83 seconds after launch) than the center frequency (about 6.7 Hz). A 1% change in f_s is 0.067 Hz or 24.1 deg/sec, which is an intolerably large fraction of a typical Faraday rate ranging from 2 to 500 deg/sec. Therefore the signal generator must be phase locked with the rocket spin signal, to preclude a large error in the measured Faraday rotation angle. Phase locking a signal generator to the noisy spin signal with a required accuracy of about 0.1% or less has not yet been attempted.

3.7 A Faraday Rotation Correction for the Rocket Distance

There is a phase difference between the 2 x 250 Hz reference signal and the 2 x 250 Hz component of the rocket receiver output signal as recorded on the telemetry tapes. This phase difference consists of two parts. There is a constant phase shift in the electrical networks of the instrumentation system. This shift is independent of the position of the rocket and does not introduce an error in Faraday rotation measurements. There is also a phase difference which is a function of the distance, r , between the ground station and the rocket. This shift does introduce a Faraday rotation error.

The free space transit time, t , for signals to travel the round trip, $2r$, to the rocket is $t = 2r/3 \times 10^8$ (sec). During this period the phase change of the reference signal is

$$\phi \text{ (deg)} = (2 \times 250) \times t \times 360 = 1.20 r, r \text{ in km.}$$

The time rate of phase change is

$$\frac{d\phi}{dt} \text{ (deg/sec)} = \frac{d\phi}{dr} \frac{dr}{dt} = 1.20 v$$

where $v(\text{km/s})$ is the rocket velocity.

The velocity of a Nike-Apache rocket in the lower ionosphere is of the order of 1.5 km/sec. This velocity results in a phase change rate or apparent Faraday rotation rate of 1.8 deg/sec. Over the typical range of measured Faraday rotation rate, from 2 to 500 deg/sec, a correction for the 1.8 deg/sec apparent rate is unnecessary at the greater altitudes but is important for the accurate measurements of the small electron densities at the lower altitudes.

4. CONCLUSION

The following conclusions have been reached in the course of this study.

1. On rocket precession:

- a. The angle between the precession cone axis and the geomagnetic field, θ_B , is nearly constant (19.25 ± 0.55 deg) for the time interval of 43 to 75 sec after launch, as shown in Table 3.1 for 14.270.
- b. The precession frequency, f_p , varies from 0.4 to 0.02 Hz, and the precession angle, θ_p , varies from 1.6 to 10.5 deg for time interval of 40 to 90 sec, as shown in Figures 3.7 and 3.8. For the interval of 90 to 300 sec, f_p is $(2.0 \pm 0.2) \times 10^{-2}$ Hz and θ_p is 11.0 ± 0.5 deg, as shown in Figure 3.8 for 14.146.

2. On precession effects:

- a. There is no precession effect on Faraday rotation. The essence of the analysis discussed in Section 3.5.1 is that a slow variation on the envelope of the rocket spin signal, due to precession, does not affect the Faraday rotation angle measurement.
- b. The intensity of radio waves at the rocket-borne antenna depends on the angle between the rocket axis and the direction of the wave normal. This angle varies as the rocket ascends. Therefore the received intensity of the radio waves changes due to this precession. However, both the ordinary and the extraordinary modes are affected equally, and consequently the power ratio of these modes

does not change. Therefore, there is no precession effect on differential absorption, as concluded in Section 3.5.2.

3. On important properties of the signals for Faraday rotation measurements:
 - a. Amplitude variations of the signals at a rate less than several Hz do not affect the measurement result.
 - b. A small error in frequency or phase of a simulated rocket spin signal does affect the result. As shown in Section 3.6, when the rocket spin frequency is 6.7 Hz, an error of 1% corresponds to a Faraday rotation rate of 24.1 deg/sec.
 - c. Fixed phase shifts in the electrical networks of the rocket instrumentation system do not introduce errors in Faraday rotation measurements. However, a time dependent phase shift of the 2×250 Hz component of the receiver output signal introduces an error in Faraday rotation measurements of about 2 deg/sec. This is a 100% error initially but decreases to a 0.4% when the Faraday rate increases to 500 deg/sec.

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