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by Michael Spafford, Richard Wiack, and Ronald Woodman

Goddard Space Flight Center
Greenbelt, Md.

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SUMMARY

A Rocket Interferometer Tracking (RIT) system is described. It uses a modified 108 Mc Minitrack receiver converted for 73.6 Mc operation and a newly developed phase measuring system. The output of the system is real time direction cosine data for two channels, East-West and North-South, in analog and digital form. The analog data are recorded on an x-y recorder and on a strip chart recorder; and the digital data are automatically recorded on punched tape. The RIT system has been integrated with the ranging portion of the Radio Doppler Interferometer Tracking system (RADINT) at the Wallops Island Launch facility, and records the range data on the same punched tape.

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INTRODUCTION

The interferometer method is a simple and accurate technique for radio tracking of rockets and satellites. Several systems based on this technique have been developed and are in actual use; among others, the Radio Doppler Interferometer Tracking System (RADINT)† for sounding rockets and the Minitrack tracking system for satellites. There has been one drawback with the interferometer technique as compared to other tracking systems using radar or automatic tracking antennas: because of an inherent ambiguity problem, there is no real time information. Manual or computer processing is necessary, with consequent delay in availability of the tracking data.

The Rocket Interferometer Tracking (RIT) system, by using a different phase measuring technique, circumvents this limitation. It is a real time system; real time direction cosine data are obtained, recorded, and displayed. Ambiguity of the interferometer data is resolved by "tracking" the rocket from its known launching position. After the rocket is launched the RIT system automatically keeps track of the correct interferometer lobe. The phase measuring technique used permits a relatively narrow post-detection bandwidth, thereby avoiding the need for computer data smoothing.

The RIT system, as do other interferometer systems, obtains the angular position of a radio signal source by measuring the phase difference of signals arriving at two pairs of antennas, one in the North-South and the other in the East-West direction. The antennas in each pair are spaced 16 wavelengths apart. These phase differences are related to the directional cosine of the source by the following relations:

$$\phi_{E-W} = 16 \cos \alpha \, , \tag{1}$$

$$\phi_{N-S} = 16 \cos \beta \, , \tag{2}$$

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†The RADINT system was formerly known as the Single-Station Doppler (SSD) tracking system.

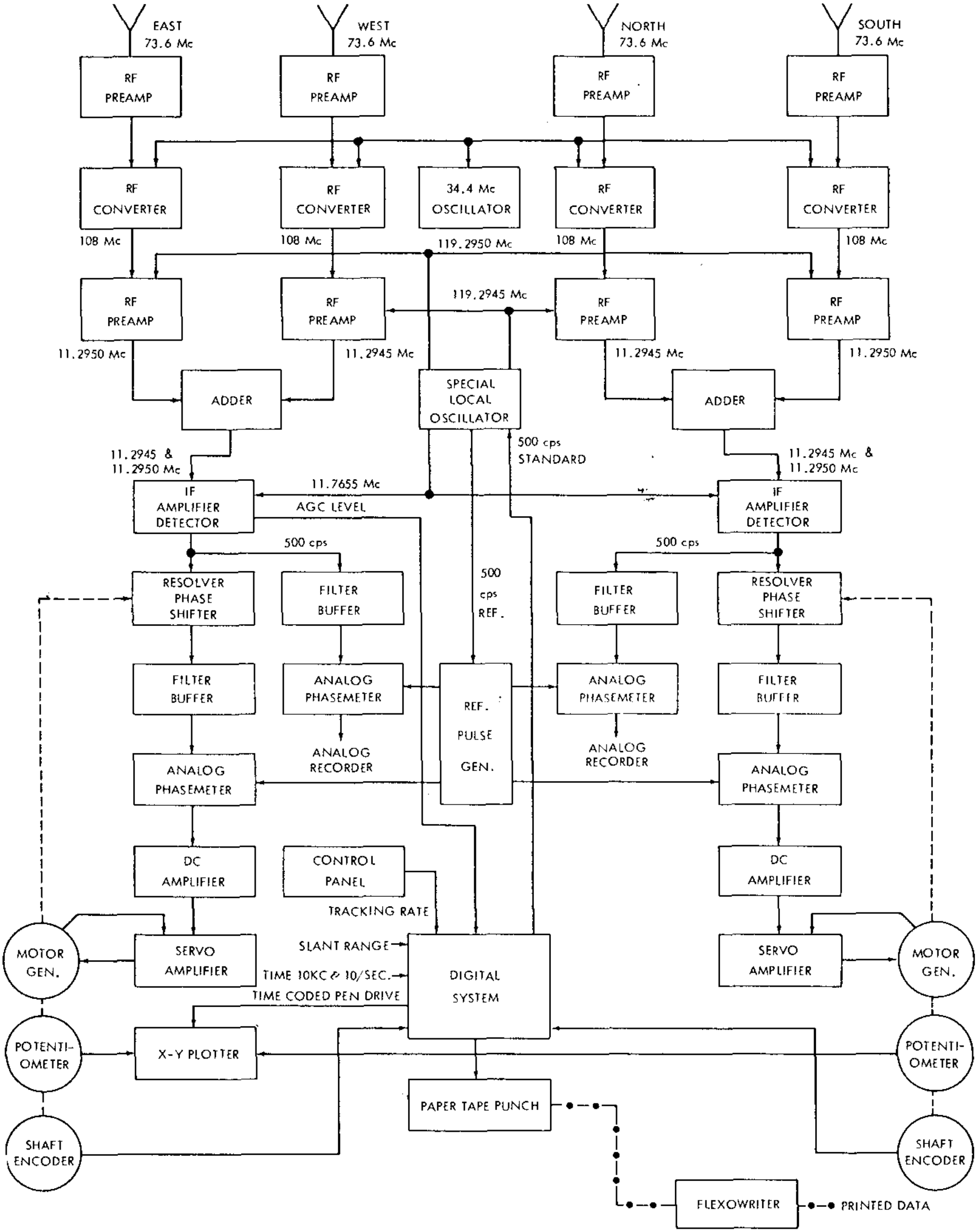


Figure 1—The Rocket Interferometer Tracking (RIT) system.

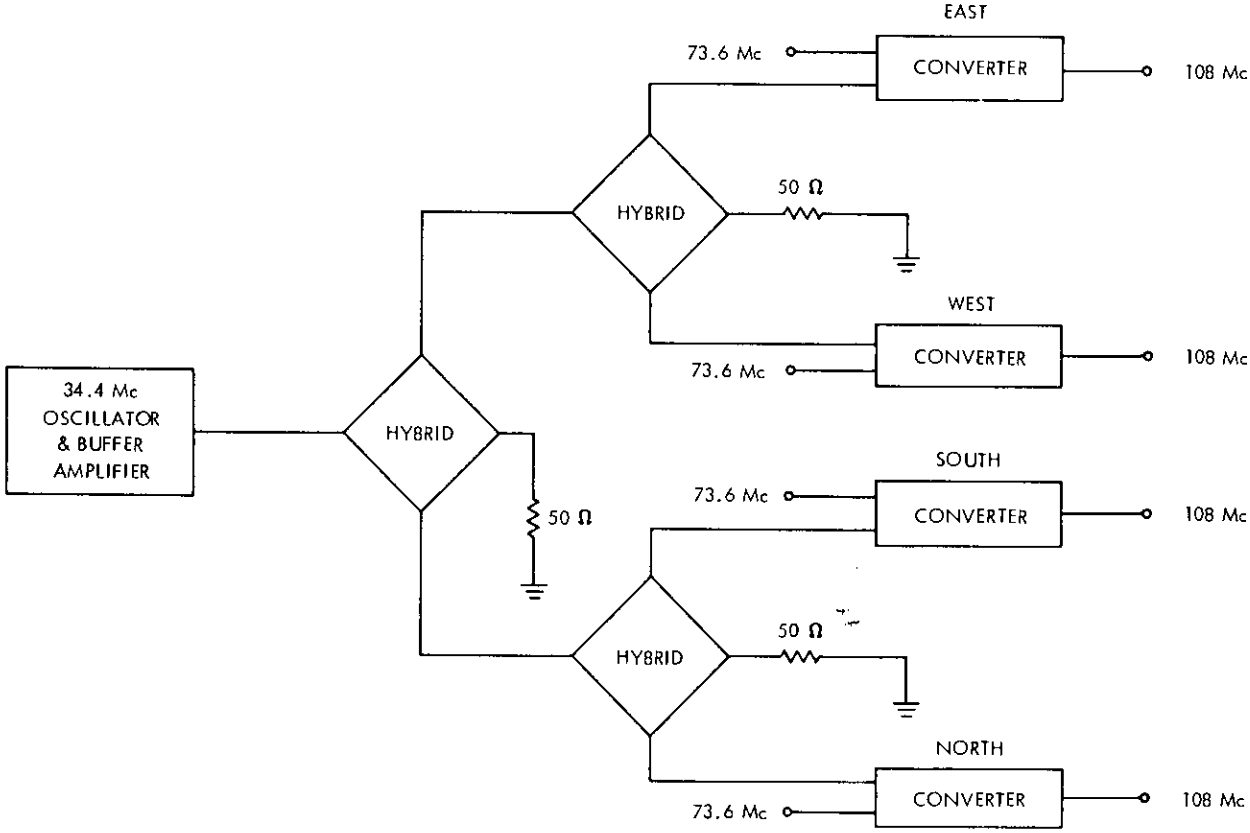


Figure 3—RF up-converter, 73.6 to 108 Mc.

phase characteristics of the IF amplifier itself affects both signals identically, thereby reducing their relative phase shift to a minimum. There is a second conversion in the IF amplifier to 470.0 kc and 470.5 kc, and most of the receiver amplification is done at these frequencies. The pre-detection bandwidth is 12 kc. The two-frequency output (470 kc and 470.5 kc) is fed to a detector which detects the beat between these two frequencies, i.e., a 500 cps signal with a phase relative to a 500 cps reference signal which is identical to the phase difference between the two interferometer antennas.

Servo Phasemeter

The function of the servo phasemeter is to measure the phase of the 500 cps signal from the receiver detector as compared to the phase of the 500 cps reference, and to calculate the direction cosine (see Equations 1, 2).

Most conventional phasemeters, including the original Minitrack phasemeter, convert phase into voltage or into a digital number in such a way that this voltage or digital number repeats itself periodically every 2π radians. The functional relationship between phase and time is therefore a discontinuous one. The disadvantage of this approach is that linear filtering of voltage is generated by the analog phasemeter, amplified by the dc operational amplifier, converted to ac by means of a modulator, and fed to the servo amplifier of a speed controlled motor-generator. The motor, through proper speed reduction, then drives the shaft of the resolver phase-shifter rotor, and shifts the phase of the input signal until the error is reduced to zero.

The phase at the output of the resolver phase shifter, ϕ_0, is

$$\phi_0 = \phi_s - \theta \tag{3}$$

where

ϕ_s = phase of the 500 cps input signal, and

θ = angular rotation of the resolver phase-shifter shaft.

Under steady-state conditions (the dynamic behaviour will be seen later), the error of the loop is zero, i.e.,

$$\phi_0 - \phi_r = 0$$

or

$$\phi_0 = \phi_r \ , \tag{4}$$

where ϕ_r is the phase of the 500 cps reference. And if we take the phase of the 500 cps reference signal as the arbitrary zero, we have

$$\phi_s - \theta = \phi_0 = \phi_r = 0 \ .$$

or

$$\theta = \phi_s \ .$$

That is, the rotor shaft position, θ, of the resolver phase shifter equals the phase of the 500 cps signal, ϕ_s, which in turn equals the phase difference between the interferometer antennas. This phase difference is related to the direction cosine by Equation 1 or 2:

$$\theta = 16 \cos \alpha \ .$$

Thus, for θ in revolutions,

$$\cos \alpha = \frac{\theta}{16} \ .$$

The range of the direction cosine data is from -1 to +1, corresponding to -16 to +16 turns, a total range of 32 turns for θ. The analog direction cosine is obtained from a potentiometer,

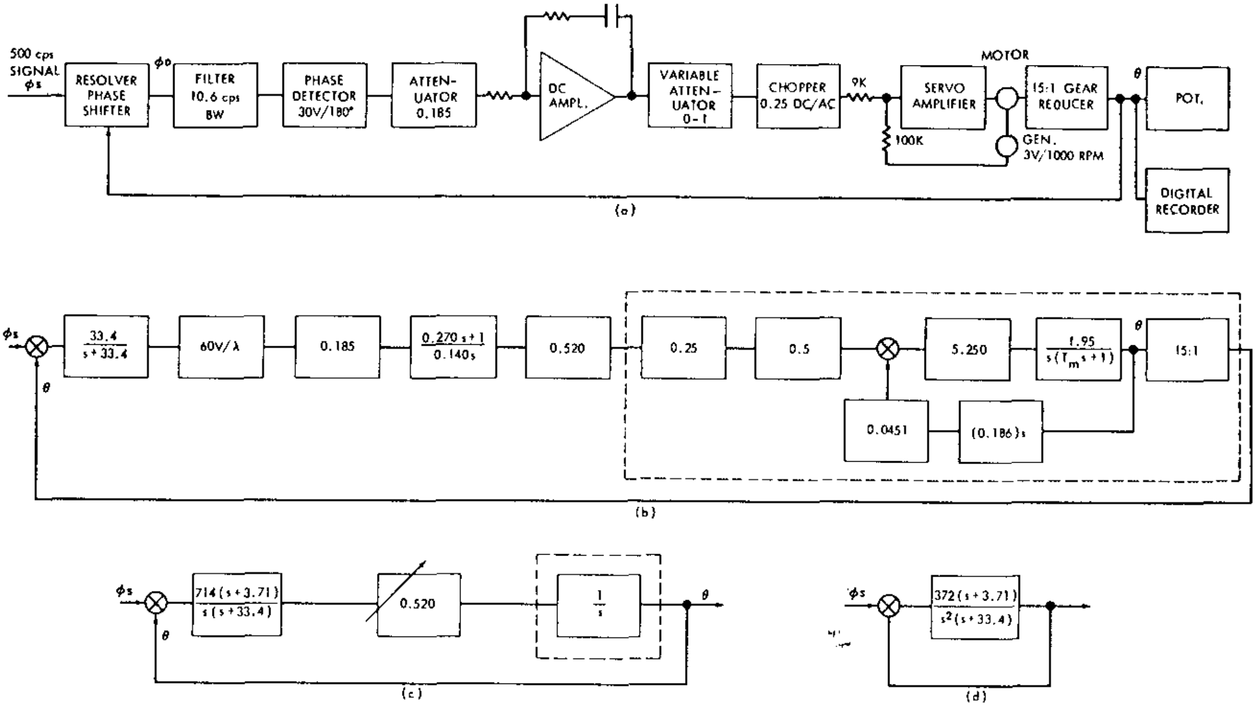


Figure 5—Diagrams of the transfer function for the 3 cps bandwidth servo phasemeter: (a) functional diagram; (b) dynamic diagram showing transfer function of each block; (c) same as (b) but simplified; (d) further simplified.

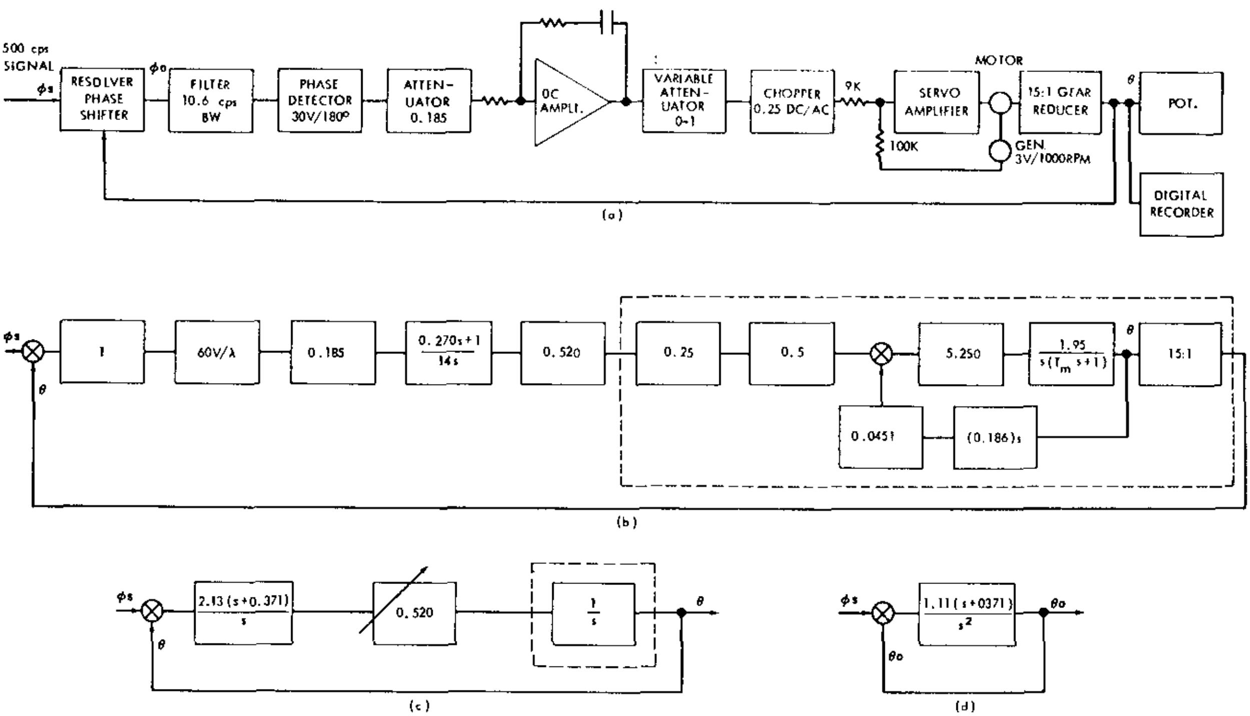


Figure 6—Diagrams of the transfer function for the 0.3 cps bandwidth servo phasemeter: (a) functional diagram; (b) dynamic diagram showing transfer function of each block; (c) same as (b) but simplified; (d) further simplified.

errors can be permitted provided they are less than half a phase cycle or lobe so that the system does not lose lock. We can observe from the ramp input response (Figure 9) that if the phase rate were to change from zero to 5 cycles per second instantaneously (an infinite acceleration impulse), then the maximum error would be 0.3 of a phase cycle. The actual case is less severe since the phase rate is acquired very gradually. The limiting factor on the system's ability to maintain phase-lock is the maximum phase rate it can track; and this in turn is limited by the maximum speed of the servo motor. The present rate is 4.5 phase cycles per second, a rate that adequately meets the present requirements as used at Wallops Island. It should be noted that as the distance from the launch pad to the antenna system is increased, the maximum phase rate decreases; however, problems associated with obtaining range data increase.

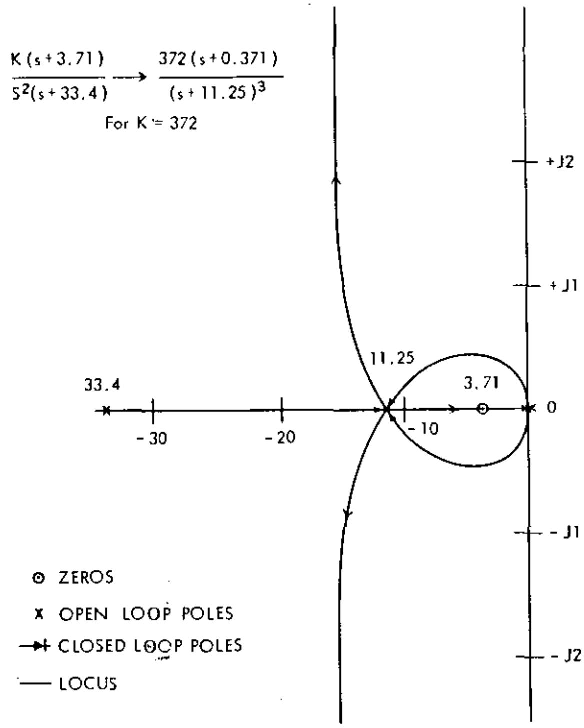


Figure 7—Root locus plot for the 3 cps bandwidth.

The dynamics of the 0.3 cps bandwidth mode is similar to that of the 3 cps bandwidth mode but scaled 10 times slower. The open loop transfer function is similar to that of the 3 cps bandwidth with the stabilizing zero at 1/10 of the 3 cps bandwidth value and with no pole due to the 500 cps bandpass filter. The 500 cps filter is still in the circuit with the same bandwidth and for the same purpose as before but its effects on the system dynamics are at frequencies much higher than the critical ones and can be neglected. The open loop transfer function for the 0.3 cps bandwidth is

$$G(s) = \frac{1.11(s + 0.371)}{s^2} .$$

Figure 10 shows the corresponding root locus plot and the pole and zero configuration of the closed loop for this mode of operation. The corresponding closed loop transfer function is

$$\frac{\theta(s)}{\phi_s(s)} = \frac{1.11(s + 0.371)}{s^2 + 1.11s + 0.412} .$$

The frequency response is shown in Figure 11. The open loop transfer function is realized by simply changing the value of two resistors to lower the frequency of the stabilizing zero and to change the gain of the servo loop by a factor of 10. Since only resistors need be switched to change

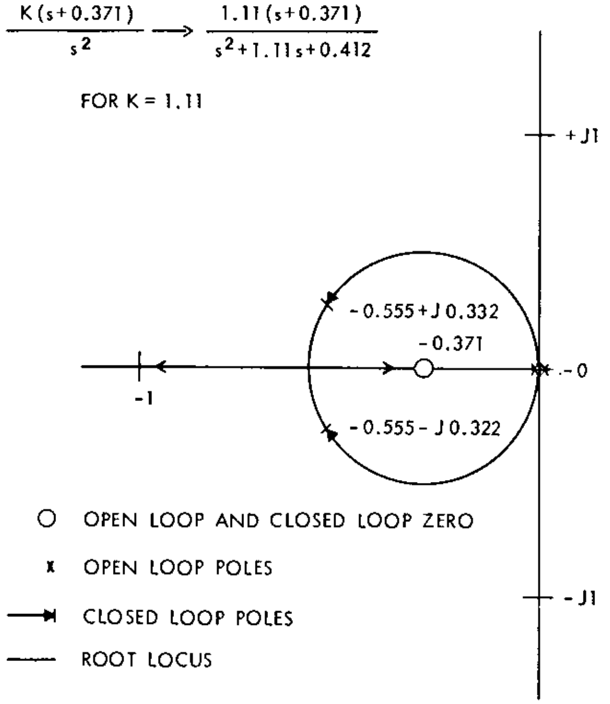


Figure 10—Root locus plot for the 0.3 cps bandwidth.

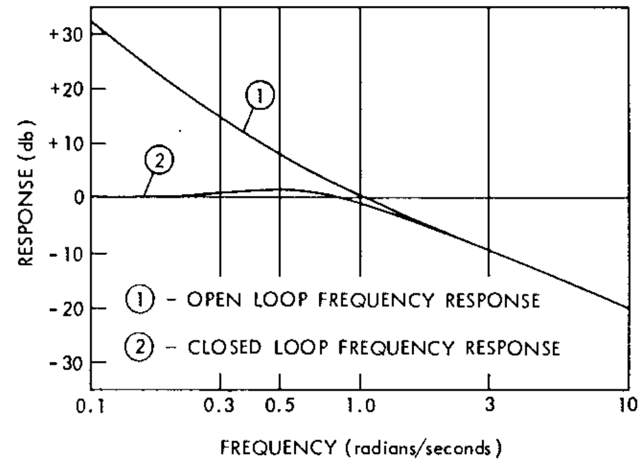


Figure 11—Frequency response for the 0.3 cps bandwidth.

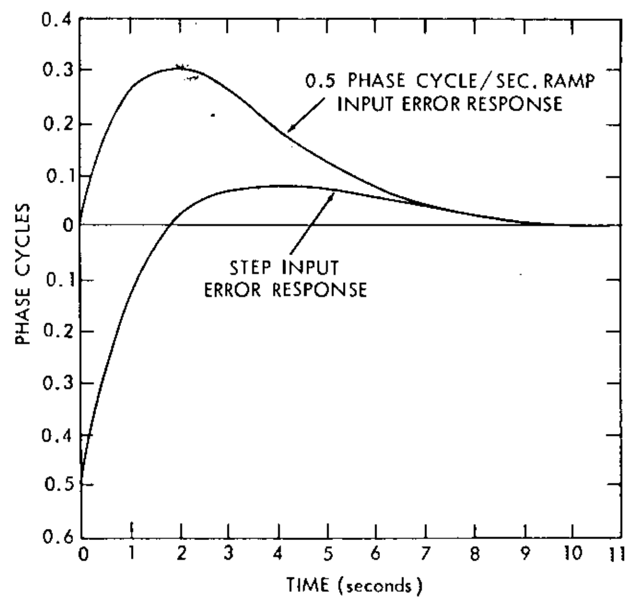


Figure 12—Time response for the 0.3 cps bandwidth.

and the error due to a constant acceleration a is given by

$$\phi_s(t) - \theta(t) = \frac{2a}{K_a} .$$

For an acceleration in the order of 1×10^{-3} phase cycles/sec^2, the error would be in the order of 5×10^{-3} phase cycle which is about the order of magnitude of accuracy in the overall system. The 0.3 cps bandwidth is therefore limited to the portions of the flight where the phase accelerations are lower than those values. This bandwidth cannot be used during the launch phase since the servo loop would be unable to lock-on or during the first 20 seconds of flight, when the acceleration would be too large; but the 0.3 cps bandwidth could be (and has been) used during the greater portion of the coasting flight with a corresponding improvement in signal to noise ratio and data smoothing.

X-Y Plotter

The X-Y plotter is an ink recorder whose pen rides in the vertical or Y axis on an arm, and the arm travels in the horizontal or X axis. The recorder in the RIT system uses a 10" × 15"

Time information can be recorded by lifting the pen at periodic intervals; the decision to record time information is made from the control panel.

Because it is possible to obtain slant range data from a potentiometer in the RADINT system, two very useful real time computations could be plotted. In one case it is possible to compute the sub-rocket position; this would be of use for range safety purposes. Another interesting application would be to compute the real time altitude. This has been done by means of a simple analog computer which essentially performs the following computation:

$$h = R \sqrt{1 - \left(\cos^2 EW + \cos^2 NS\right)}$$

where h is the altitude and R the slant range. The $\cos^2$ functions are readily obtained from the RIT servo system by using a two-gang potentiometer as a servo multiplier.

A plot of real-time altitude is shown in Figure 14. Real time altitude could be useful to program experiments on board the rocket from the ground. This computer is accurate to ±3%; higher accuracies are possible but at increased cost.

Control Panel

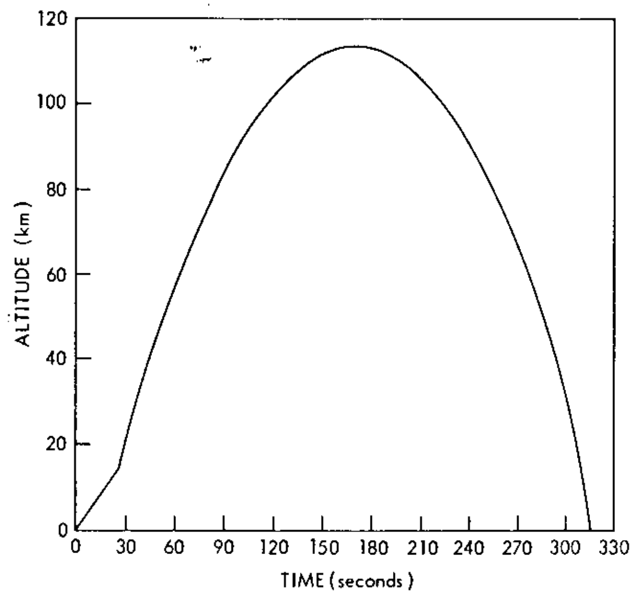


Figure 14—RIT real time altitude plot from Nike Cajun flight, February 3, 1964.

The operation of the RIT system is centered at the control panel (see Figures 15, 16). The operator can see the setting of the gear train by either reading the dials on the gear train or by looking at the digital display unit directly above the servo chasis; these both agree. The operator operates the servo gear train from the control panel until each channel is set for the approximate value of the direction cosine from the station to the launcher during the pre-launch operation and this should be within a 1/2 wavelength. The operator can also look at the X-Y recorder and see if the azimuth heading agrees with the known launch azimuth location. The servo unit is placed in a standby mode once the above settings are reached. Both channels are automatically turned on after rocket lift-off. A training delay feature, adjustable from zero launch time to a maximum of 1 second after launch is presently built into the system for those cases where the signal jitters prior to liftoff. The delay could be increased if necessary. Present records at Wallops Island indicate a maximum delay of 1 second is sufficient. If the delay is too great, there is a risk that the servo unit will not lock onto the signal because the phase rate increases rapidly shortly after launch. A delay override switch is provided as a backup

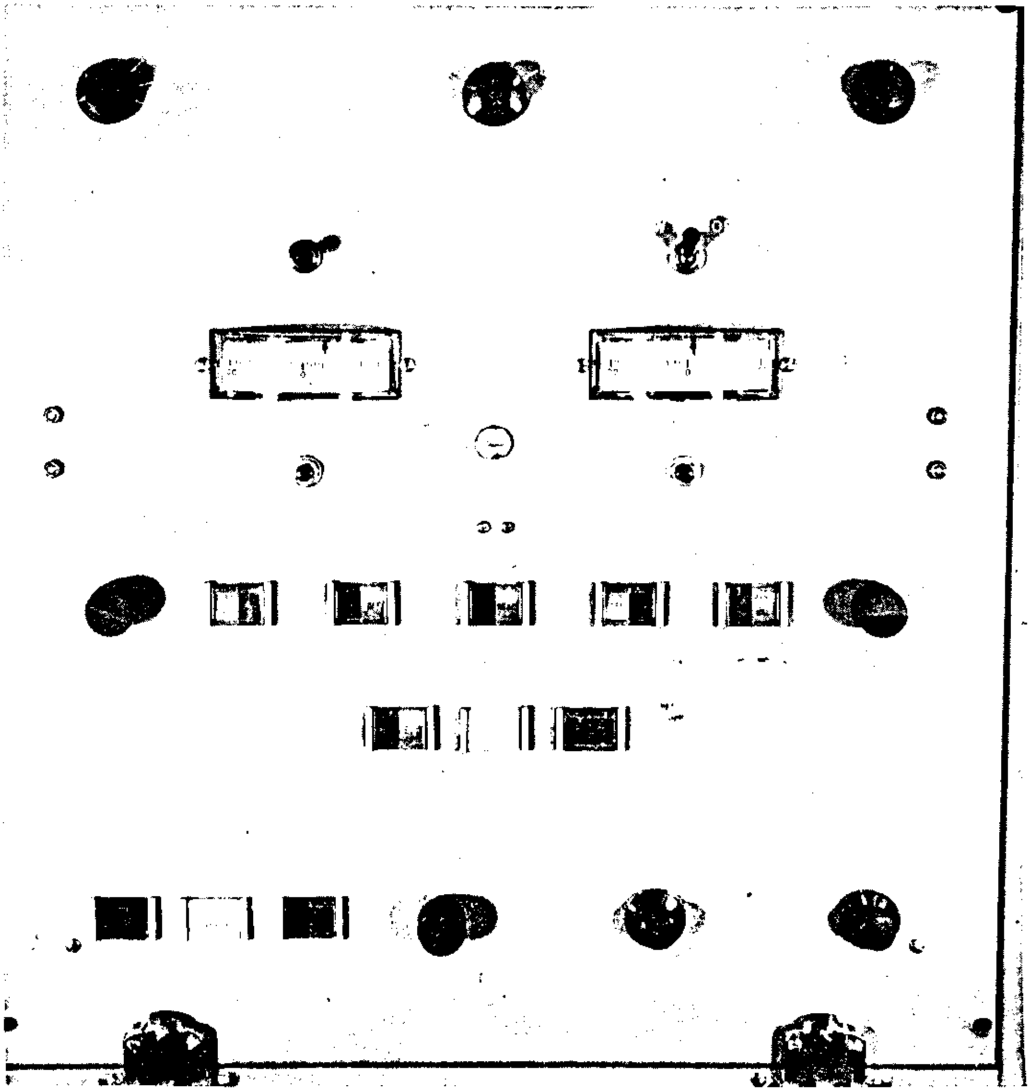


Figure 16—System control panel.

a resolution of .0001 where the direction cosine from horizon to zenith to horizon varies from minus 1 to 0 to plus 1; true rocket slant range whether the rocket is moving toward or away from the station; elapsed time from the moment of rocket launch; receiver AGC level from 1 to 9; and the Tracking Rate Switch position (servo bandwidth selection). After the launch the punched paper tape is fed into a Flexowriter to obtain printed data in tabulated form. The digital system also provides: a Time Light that indicates the moment of rocket launch; a time-coded X-Y pen mode that allows time correlation with the X-Y recorder plot; a signal that automatically starts the Servo System at rocket launch; a 500 cps standard frequency for the RIT Special Local Oscillator; an Error Light that indicates shaft-angle encoder malfunction; and the necessary controls to operate the digital system.

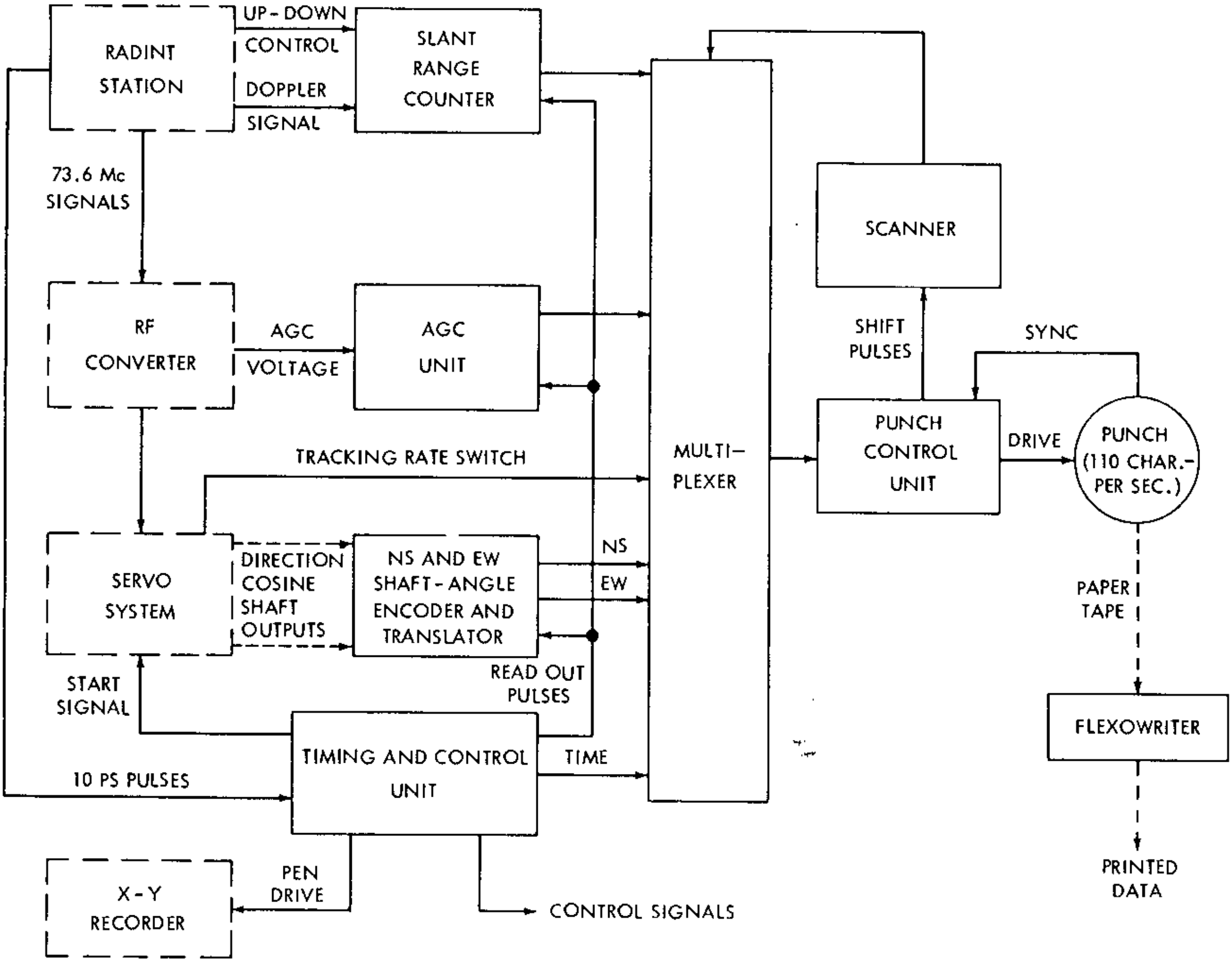


Figure 17—RIT digital system.

arbitrary time, or even simultaneously, the synchronizing circuit for the counter allows a doppler signal to be counted, the up-down control to change, and a counter reading to be dumped into a storage register. The input to the Slant Range Counter has an input impedance of 1 megohm so it will not load down the source.

The receiver AGC voltage is digitized by means of a standard Analog-to-Digital conversion technique. A control gate allows 10 kc pulses to be counted by an 8421 BCD counter, and a Digital-to-Analog card then converts the counter outputs into a staircase analog voltage. A Comparator card closes the control gate when the staircase voltage just exceeds the AGC voltage. The 8421 BCD number left in the counter after the control gate closes is proportional to the AGC voltage level. A weak receiver signal is digitized as a 1 and a strong receiver signal is digitized as a 9. The digitized AGC is visually displayed on the Digital Display Unit. The input to the AGC Unit has an impedance of 1 megohm so the source will not be loaded down.

The Timing and Control Unit performs a number of timing and control functions. One such function is the generation of read-out pulses, which cause the North/South and East/West Direction ignores all even parity codes and this produces an irregularity in the printed format which is easily noticed. The error can later be corrected.

The RIT Digital Unit has a test panel that allows several diagnostic tests to be made without requiring external test equipment. The punch can be tested by itself, the Scanner and the punch can be tested as a unit, or the Scanner can be manually stepped so that the multiplexed information can be punched out character by character. An error light indicates when the encoders make an error or when the test switches are not in the normal operating position.

Special attention has been given to the digital drawings. An effort has been made to make the drawings clear and concise (Figures 18 and 19). Good drawings greatly facilitate system understanding and maintenance. Logic symbols are used that are consistent with the digital card manufacturer's instruction manual.

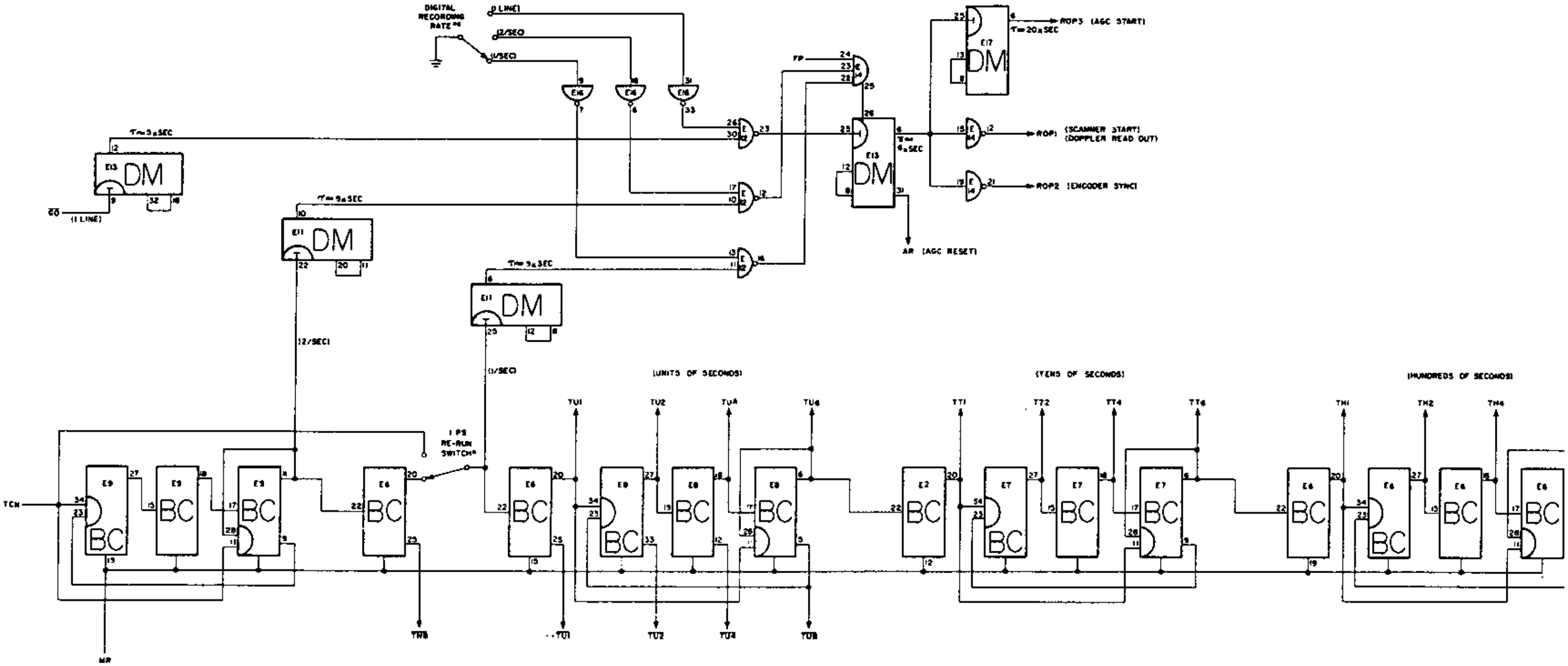
TEST RESULTS

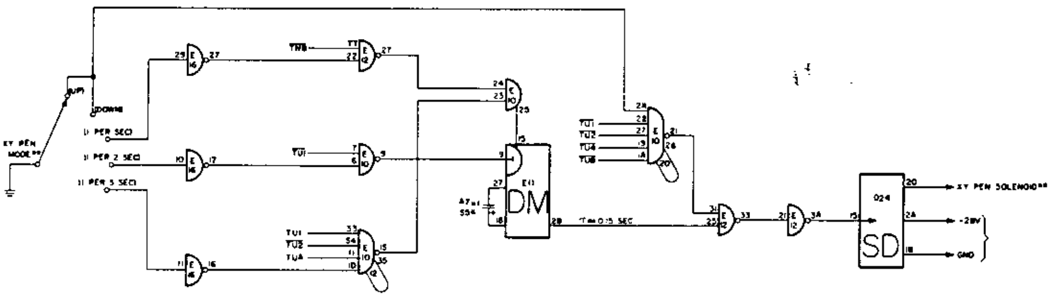
In actual operation between May and December, 1963, the RIT system was able to lock-on and unambiguously track sounding rockets four times, for a 100% record; also the doppler data were very accurate because of the use of a beacon transponder technique. The data from the last two tracks were compared with data from an FPS-16 radar; the deviation in the altitude averaged 9.6 meters at altitudes up to 80 km. Further data were not available as the radar was used to track a balloon ejected from the rocket at 80 km. The slant range was approximately 87 km. Graphical smoothing of the RIT data had very little effect in reducing the average difference between the radar data and the RIT data.

A sample of the digital data recorded on December 7, 1963, for a Nike-Cajun sounding rocket is shown in Figure 20. The first three digits on the left indicate time in seconds from lift-off; the next four digits N/S direction cosine, the next four digits E/W direction cosine (for negative angles and a space for positive angles, where North and East are considered positive directions); next digit is a measure of AGC or signal strength, the number 1 indicating a weak signal and the number 9 a strong signal (the station performs an actual calibration against a known signal strength source); the next digit in this group of two indicates the tracking bandwidth, 0 for the 0.3 cps bandwidth and 1 for the 3 cps bandwidth; the remaining seven digits record slant range data in units dependent on the radio wavelengths, in this case a multiplying factor of 1.0183 converts the data to meters.

The RIT system represents an improvement in resolution by a factor of 3 in measuring phase as compared to the RADINT system. This improvement is not only due to the high resolution of the digital system but also represents the capability of the servo phasemeter.

At present the only problem associated with obtaining unambiguous direction cosine data occurs in tracking the rocket from liftoff. There have been occasions when the signal at liftoff had a large amount of phase jitter in which the servo system locked onto the incorrect lobe. This means that the





CARD POSITION	CARD TYPE
D24	SD - 30
E4	BC - 20
E7	BC - 20
E8	BC - 20
E6	BC - 20
E10	DN - 20
E11	DN - 20
E12	DI - 20
E13	DM - 20
E14	CH - 20
E16	DI - 20
E17	DM - 20

*SWITCH IS LOCATED ON TEST PANEL—SEE DWG 110-3
**EXTERNAL TO DIGITAL SYSTEM—SEE DWG 110-1

Figure 19—Timing logic digital system.