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PRELIMINARY REPORT ON THE SINGLE STATION DOPPLER-INTERFEROMETER ROCKET TRACKING TECHNIQUE

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SUMMARY

A portable trailer-housed system is described that provides range timing, range safety, telemetry and rocket tracking services where normal rocket range facilities may not be available. Various methods of operating the station and preliminary results are presented with approximate cost estimates. This report discusses the general theory involved and the procedures used at the present time. Further development is in progress and will be described in a later report. Upon completion of the development, a detailed report will include electronic computer programming and a machine method of data-reading instead of the slower desk-computer technique described here to illustrate the data reduction theory.

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INTRODUCTION

During the International Geophysical Year, the very large volume of rocket firings frequently resulted in long delays in obtaining rocket trajectory information. This difficulty prevailed to such an extent that the scientific data obtained in the rocket firings often had to be shelved until the trajectory data were made available. Frequent troubles with the radar beacon or the radar itself sometimes caused the final trajectory to be incomplete. In addition, the highly accurate DOVAP* method required so much time consuming labor that these trajectories were completed only to an altitude of 100 km; this forced the experimental scientists to make a free-fall computation to determine the remainder of the trajectory. In addition, some experiments, such as the Seddon two-frequency ionosphere propagation experiment (Reference 1), require the radial velocity of the rocket which must be calculated from the position data. In order to eliminate much of the computational labor and to speed up the determination of the rocket's trajectory, a Single Station Doppler (SSD) technique was devised. Crude tests made on this system at Churchill, Canada indicated that a reasonably accurate trajectory could be determined in a relatively short time. Since the equipment required cost a very small fraction of the cost of a radar system, and since it readily could be made portable, it was decided to develop the system further to determine its capabilities, especially for synoptic rocket soundings where normal rocket range facilities might not be available.

Synoptic rocket firings at various places on the earth's surface can provide a wealth of information concerning the upper atmosphere. Often, geophysical considerations require that the firing take place in remote areas where rocket range facilities are non-existent. From the safety standpoint, it is very desirable that there be no densely populated areas in the vicinity. The SSD system provides a reasonably economical and transportable means for supplying the needed services for such operations, i.e., range timing, rocket

*DOppler Velocity And Position

tracking, range safety, and telemetry. For tracking with moderate accuracy, the equipment can be housed in one trailer. If electrical power is not available, another trailer with a motor-generator may be required. For tracking with the highest-accuracy, an additional trailer is required for a high powered transmitter. The system can be simplified somewhat, but usually at the sacrifice of other features, such as real-time read-out or increased effort in the reduction of the data obtained.

The SSD system uses the Doppler effect to obtain the radial velocity of the rocket with respect to the ground station and measures the direction cosines of the radius vector by means of a two-axis radio interferometer. Integration of the radial velocity provides the radial distance. With these data it is possible to compute the position of the rocket with respect to the ground station. For a moderately-accurate trajectory (about 1/2 percent in altitude on ascent), a very stable frequency of 73.6 Mc is radiated from the rocket to the ground station. For experimenters requiring higher accuracy, a 2 kw transmitter on the ground (in the vicinity of the SSD station) radiates half this frequency to the rocket which carries a transponder that doubles the frequency and transmits the result back to the ground station. The antennas and transponder used are the same as those employed in the usual DOVAP system.

This preliminary report describes the theory involved and the SSD station set up at Wallops Island, Virginia. Advantages and disadvantages of various ways of operating the station are pointed out, and cost figures are also given.

CONTINUOUS PHASE INTERFEROMETER

Most of the SSD experiments conducted thus far have made use of a continuous phase interferometer (CPI). A system such as that utilized by the Minitrack network (Reference 2) was rejected for a number of reasons: (1) the receivers required are not receivers in the usual sense because of the rather complicated circuitry required in the "front end", which makes the receiver unsuitable for both Doppler and telemetry reception; (2) it is very difficult to utilize such a technique and at the same time have a range safety system; and (3) a very large number of antennas are required. Other CPI systems were rejected because of the labor involved in reducing the data and the large number of recording channels required. Figure 1 is a block diagram of the system currently employed.

The circularly-polarized antennas employed in the SSD system are manufactured to be as nearly identical as possible. The four interferometer antennas located on a circle of 8λ radius, are carefully surveyed so that they lie on a true North-South or true East-West line. The radio frequency cables from these antennas are brought into a trailer located at the center of this circle (Figure 2). The cables, laid in wooden troughs to prevent damage, are carefully cut to equal lengths which are an integral multiple (electrically) of a half wavelength. These cables are connected to line stretchers having the same

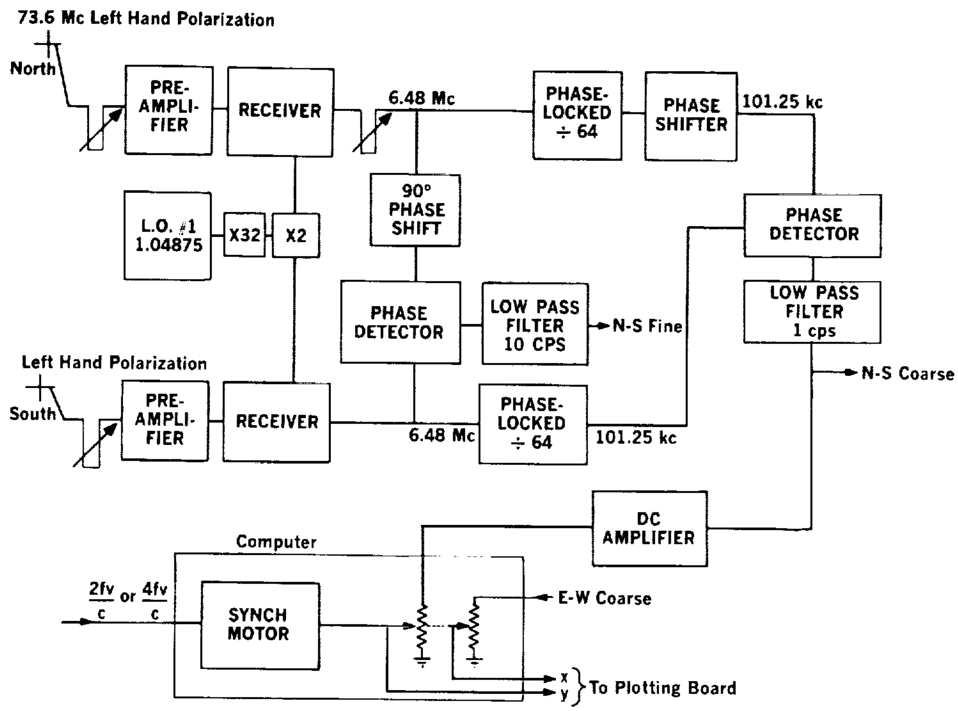


Figure 1 – Continuous phase interferometer and flight safety system

characteristic impedance so that the electrical lengths of the cables can be adjusted. A crossed-dipole turnstile antenna on the roof of the trailer is used for measuring the Doppler effect.

Since the interferometer receivers have a common local oscillator, their 6.48-Mc IF outputs have the same phase relationships as do their input signals, provided that the two receivers have identical phase characteristics. A 90-degree phase shifter shifts the phase of one receiver output so that it may be applied to a phase detector. Under these circumstances, equal phase conditions at the antennas will provide a zero voltage from the detector. A difference in phase between the signals will provide a voltage

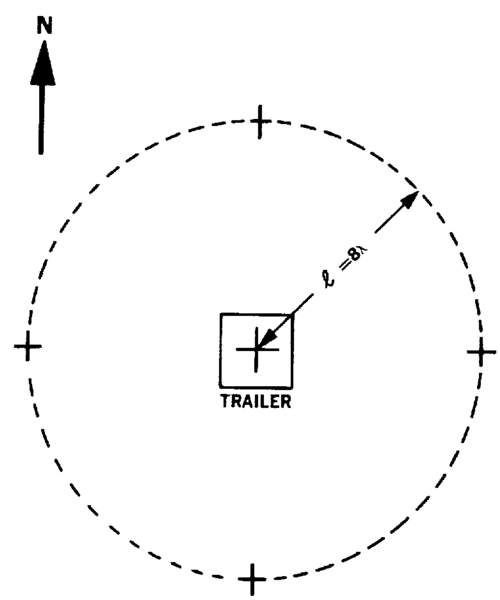


Figure 2 – Station layout

output either positive or negative, at the detector. The sense of the phase shift may be determined by adding a very short cable in series with one of the line stretchers. The phase detector output, almost linear with phase, is put through a low pass filter and is recorded on a Sanborn recorder. The antennas on each axis are separated by 16 wavelengths, and the phase detector output maximizes at ±90 degrees; thus there are 64 different interpretations for any reading of the phase difference between the input signals. It is necessary to remove this ambiguity.

The IF outputs to the receivers are fed to phase-locked dividers wherein the frequency is divided by 64. After a 90-degree phase shift on one channel, these 101.25 kc signals are applied to a phase detector. After filtering, the output of this phase detector is also recorded on a Sanborn recorder. The difference in phase of the signals arriving at the antennas from the launcher can be computed, because the direction of the launcher from the SSD station is known. This result is divided by 64 to provide the phase difference at 101.25 kc. Calibration of the phase detector therefore determines, except for sign, what voltage the phase detector should have. The sign is readily determined from the geometry.

A signal is radiated from the rocket on the launch pad to the ground station and the phase detector is set to the proper voltage by repeatedly pressing a microswitch on the phase-locked dividers until this voltage is obtained as closely as possible. The switch-pushing merely causes the dividers to slip 360 degrees at the 6.48 Mc frequency. Owing to the fact that the transmission is close to the ground where some re-radiation effects can occur, the voltage cannot be set exactly, but this is not harmful, since the dividers are locked on the proper cycle. This procedure has been called lobe-setting. Tests conducted thus far indicate that the ground, launcher, and neighboring buildings do not affect the phase difference at the 73.6 Mc frequency by more than about 90 degrees. Therefore, the coarse phase detector can be set to within about 1-1/2 degrees. This error will disappear as soon as the rocket is away from the ground. The approximate direction cosine for this axis is obtained from the relation

$$\cos \theta = \frac{64\lambda\delta_n}{360L} = 0.0111\delta_n \quad , \tag{1}$$

where L is the distance between the antennas and δ_n the phase difference, in electrical degrees, indicated by the calibration of the phase detector. The direction cosine for the other axis is determined in a similar manner.

COMPUTER FOR RANGE SAFETY

To provide a plot of the sub-rocket point on a horizontal plane through the SSD station, a simple computer is used. The outputs of the two coarse phase detectors are applied to ten-turn ganged helipots. The variable contacts of these helipots are driven by a synchronous motor which in turn is driven by the Doppler voltage obtained from the antenna on the roof of the trailer as will be explained shortly. Therefore this motor integrates the rocket's radial distance, and since the coarse phase detector outputs are proportional to the direction cosines, the computer outputs are a product of these factors. This output may be applied to an X-Y recorder, which will plot out the sub-rocket position. In the geometrical representation (Figure 3) the rocket is at D and the SSD station at 0; the radial distance is indicated by R and the angles with respect to the axes are θ and ϕ; C is the position of the sub-rocket point. Before flight, the synchronous motor is rotated by an audio oscillator until a counter geared to the motor reads the correct radial distance in meters from the SSD station to the launcher.

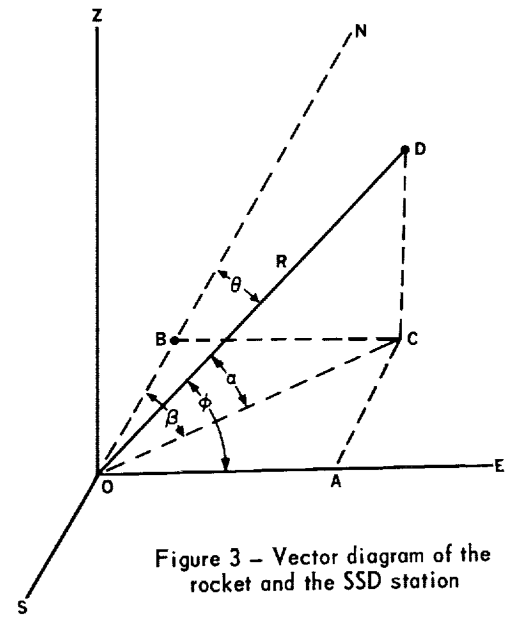


Figure 3 – Vector diagram of the rocket and the SSD station

DOPPLER MEASUREMENT

The One-Frequency Method

In the one-frequency method of Doppler measurement, the signal received by the crossed dipoles on the trailer's roof is separated into left and right hand components by means of a $\lambda/4$ delay line in one antenna cable and a cable-type magic-T (Figure 4). These two components were selected to permit the elimination of the effects of the rocket's roll, and also to double the sensitivity of the system.

The left hand polarization (lhp) signal is fed into a receiver which employs the same local oscillator as is used for the interferometer receivers. The receiver used for the rhp signal, however, has an oscillator that results in an IF frequency 15 kc higher than that of the lhp signal. This frequency difference is used to double-sideband-modulate a 6.48 Mc standard reference oscillator with the carrier suppressed. The filter is used to select the higher frequency for mixing with the IF of one receiver, whereas the reference oscillator signal is mixed with the IF of the other receiver. The outputs of these mixers have frequencies, respectively, of 15 kc plus the Doppler plus the rocket roll rate, and 15 kc minus the Doppler plus the rocket roll rate. Phase-locked tracking filters provide an improvement in the signal to noise ratio; and after mixing, a Doppler frequency of $2vf/c$ is obtained. The magnetic tape recorder preserves the data in case the tracking filter should lose lock, and also makes possible an improvement in the accuracy of the final results (see page 15). As there are only two channels on the magnetic recorder, timing is added to one of the Doppler channels by an adder circuit.

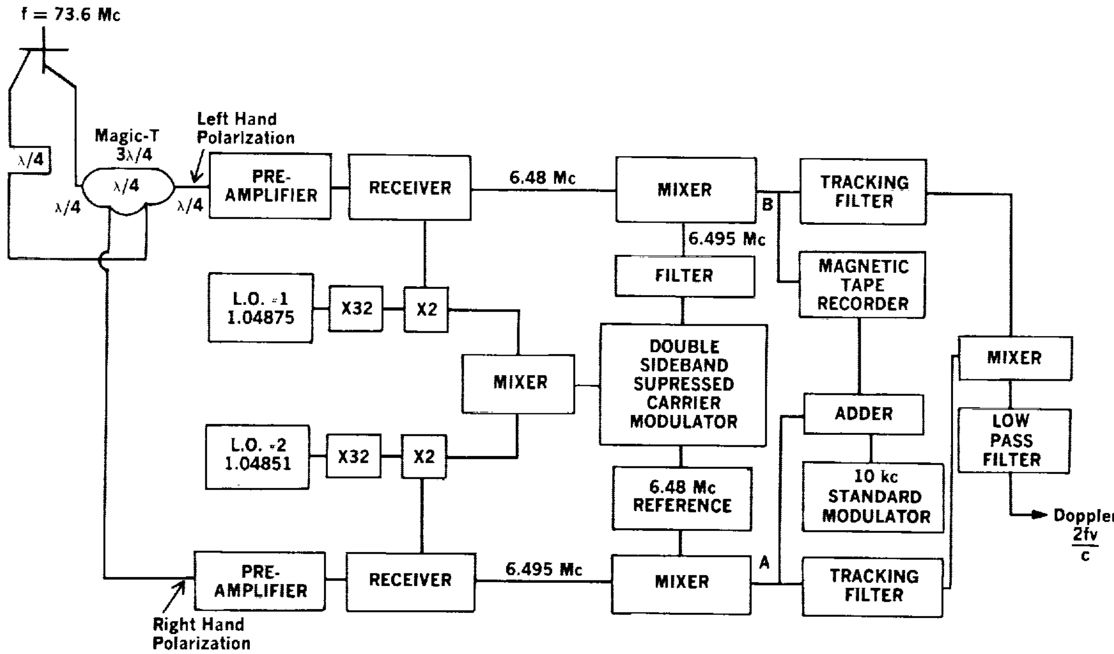


Figure 4 – The one-frequency method of radial velocity measurement

The Two-Frequency Method

Because the rocket's rough treatment of the transmitter may change its frequency slightly and thereby introduce some error into the measurements, the two-frequency method of Doppler measurement is more accurate, although it introduces additional technical problems. A 36.8 Mc signal is radiated at a power level of 2 kw from a right-hand circularly-polarized antenna near the SSD station. By means of a short wire aerial, the SSD station will receive enough of this signal for use as a comparison frequency, injecting it into the mixer as shown in Figure 5. This frequency is quite constant; but even if it did change slightly, it would have very little effect on the final results. The transponder in the rocket receives this signal shifted by the Doppler effect, doubles it in frequency, and transmits the resulting signal which is again shifted by the Doppler effect. Owing to the high signal level at 36.8 Mc, a double-stub trap is placed in the antenna cables ahead of the receivers.

Since the rocket roll rate changes the received signal frequency, and since this is doubled in the transponder, and since the transmitted frequency is also affected by roll, the frequency of the signals received on the ground are shifted by 3 times the roll rate (3ρ) for one polarization and 1 times the roll rate (ρ) for the other polarization. In other words, the upward transmission of the 36.8 Mc signal is polarized right-handed; therefore the received lhp signal contains a 1ρ term, and the rhp signal contains a 3ρ

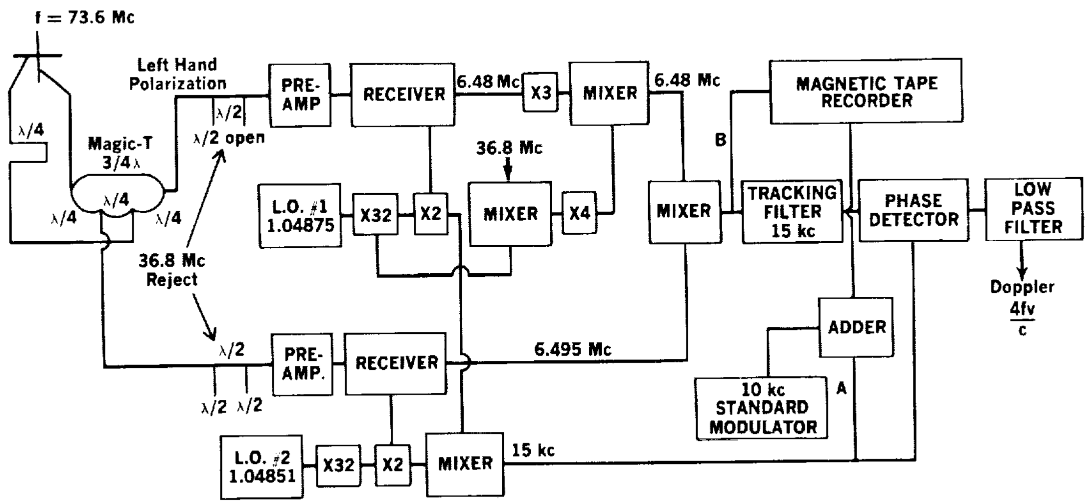


Figure 5 – The two-frequency method of radial velocity measurement

term. To eliminate the roll, the lhp signal is frequency-multiplied by 3 in a tripler stage. The transmitted 36.8 Mc frequency is mixed with half the local oscillator frequency, and the result is frequency multiplied by 4 before mixing with the output of the tripler. The result is a 6.48 Mc signal with Doppler and a 3ρ term, the latter having the same sign as that obtained from the rhp signal. These frequencies are combined in a mixer which provides a frequency of 15 kc with a Doppler shift of $4fv/c$. This frequency is applied to the tracking filter, and then to a phase detector along with the 15 kc difference frequency between the local oscillators. The result is a roll-free Doppler frequency of $4fv/c$. Thus the sensitivity of this system is twice as great as for the single frequency system; but this advantage is partially offset by the slight ionospheric effect at the lower frequency, which introduces some error.

REAL-TIME READ-OUT, RECORDING AND RANGE TIMING

The block diagram of the real-time read-out, recording and range timing is shown in Figure 6. The Doppler frequency, applied to a frequency meter, gives a continuous reading of the rocket's radial velocity during the flight. For the two-frequency system, $4f/c$ is very close to unity if c is in km/sec. Therefore a frequency meter set on the "kilocycles" scale will read directly the radial velocity in km/sec. For the one-frequency system, the reading must be doubled. To obtain total radial distance, the integration of this Doppler frequency is performed in the following manner:

The distance from the SSD station to the launcher is determined in km and the hp 521C industrial counter is set for the integral number of km. The remaining fractional km is converted into Doppler cycles and the resulting number is set on the dual preset

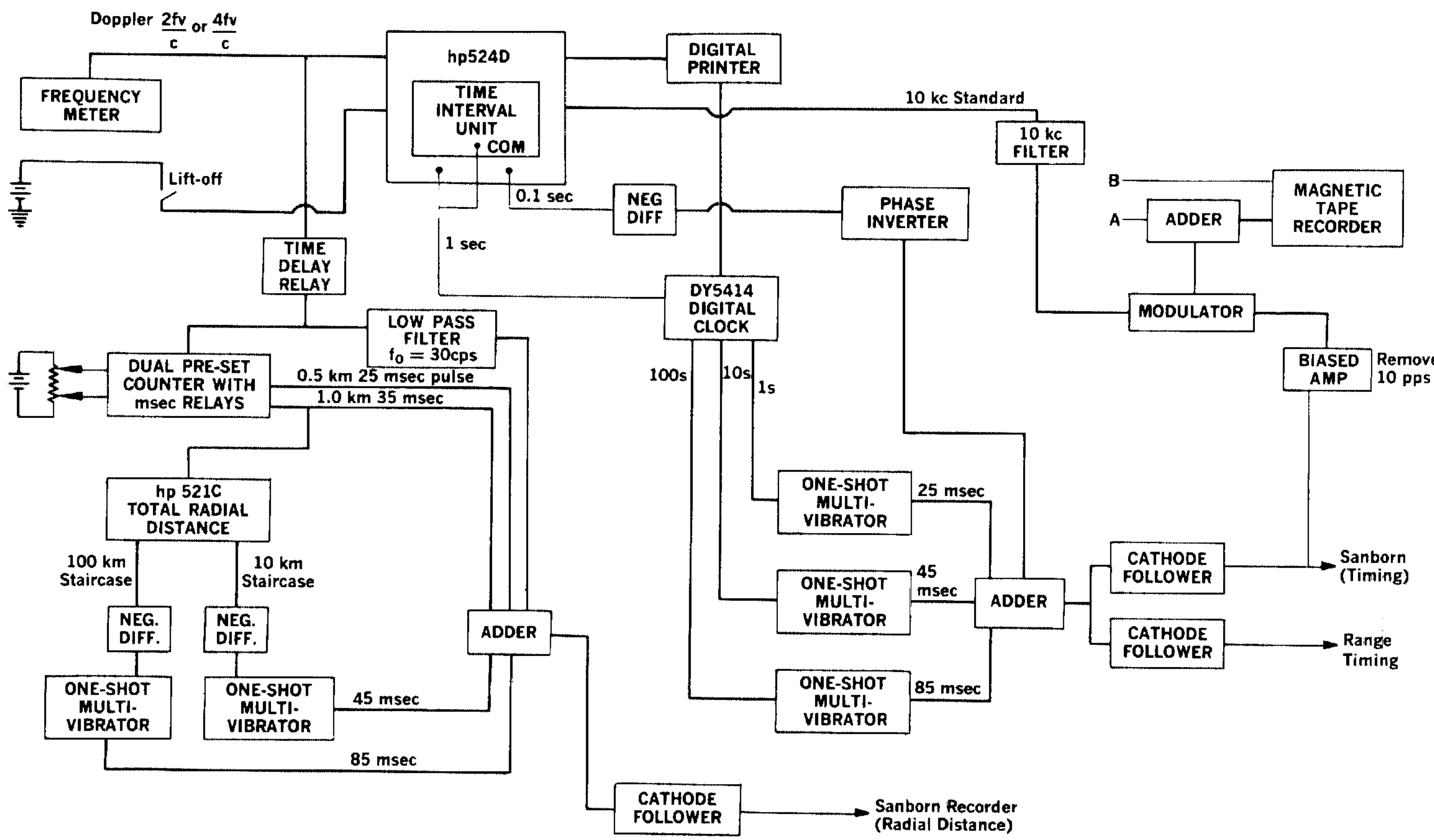


Figure 6 – Real-time read-out, recording and range timing

counter (see Appendix A). The time delay relay is open so that these settings remain fixed. The lift-off switch is held open by the weight of the rocket on the launching stand. As soon as the rocket lifts off the switch, this contact is closed and the battery voltage is transmitted by land-line to the SSD station, where it activates the time delay relay. The purpose of this relay, usually set for an interval between 0.5 and 1.5 seconds depending on the circumstances, is to prevent erroneous results due to takeoff noise. In general, the change in radial distance during this short time is small enough to be neglected, but it may be computed, if desired, from predicted rocket performance data (Appendix A).

By the closure of the time delay relay, the Doppler frequency is applied to the dual preset counter with millisecond relays. The two potentiometers provide the relays with slightly different voltages; the smaller is applied to relay A. For the one-frequency system, relay A is preset at 245 and relay B at 246, so that 1-kilometer marks occur every 491 cycles. For the 2-frequency system, relay A is set at 491 and relay B at 491. Thus relay B provides a pulse every 1.0 km and relay A a pulse halfway between. The application of the 1 km pulses to the hp 521C counter provides a real-time read-out of the total radial distance in kilometers.

For recording, the 10 km and 100 km staircase voltages are each brought out to a differentiation circuit and to a one-shot multivibrator with 45 and 85 millisecond widths, respectively. The 1/2, 1, 10, and 100 km pulses are applied to an adder which drives a Sanborn recorder. The resultant pulse shapes (Figure 7) illustrate how the differing amplitudes and shapes of the resulting pulses provide identification. In addition, the adder is supplied with the voltage obtained from a low pass filter with a 30 cps cutoff. Thus, a sinusoidal voltage is superimposed whenever the Doppler frequency is less than 30 cps; this is necessary for an accurate determination of the maximum slant range. Just before

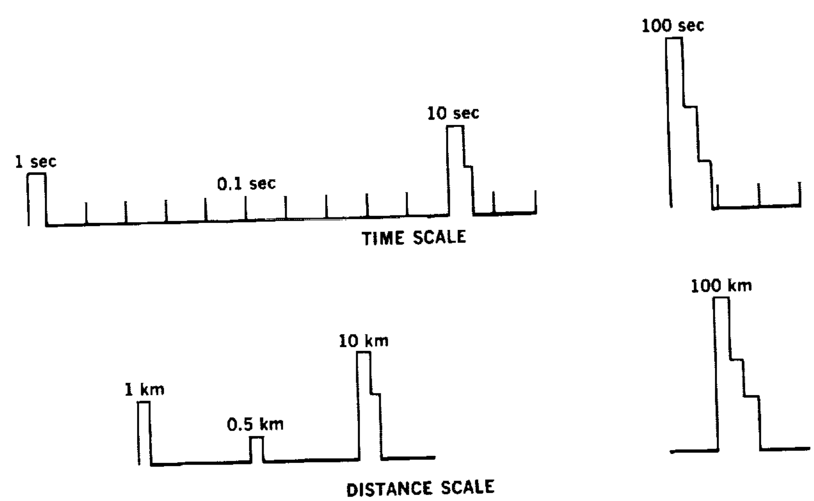


Figure 7 – Pulse shapes recorded by the Sanborn recorder

the maximum slant range occurs, a 1/2 or a 1 km pulse will appear "riding" on top of the sinusoidal voltage. The number of cycles from the latter pulse are counted until the frequency becomes zero, at which time the phase of the sinusoidal voltage reverses; at this time the slant range is maximum. To obtain the slant range during rocket descent, this maximum range must be subtracted from the indicated distances.

The timing and a digital print-out of the radial velocity are obtained in the following manner: Before launch, the phantastrons in the counter are disabled by means of a relay in the plate circuit, with the gate circuit open. In this state, the counter will continuously add up any noise coming from the Doppler circuitry. By means of an internal connection, the one-per-second gating pulses are connected to a digital clock and to the "common" connection of the time interval unit. There will be no pulses at this time because the phantastrons are inoperative.

When the rocket is launched, the lift-off switch energizes a relay (not shown) which closes the phantastron circuit, thereby providing a 1-second pulse to operate the time interval unit and the digital clock. The clock has been preset at its highest reading (239999) so that the first pulse from the counter causes it to read all zeros. This first pulse occurs 15 milliseconds after closure of the lift-off switch. Succeeding pulses alternately open and close the counter gate so that the digital printer prints the number of cycles occurring in the intervals 0 to 1, 2 to 3, 4 to 5 seconds, etc. The time recorded (in even seconds) by the digital clock is printed on the first five units of the digital printer. Thus, a print-out of 100 cycles at a printed time of two seconds indicates that 100 cycles were recorded during the interval 2 to 3 seconds and that the average velocity was 100 cycles/sec at 2.5 seconds.

Short, sharp pulses are obtainable from the digital clock at the rate of 1 each second, one every 10 seconds, and one every 100 seconds. These pulses are applied to an adder circuit along with very narrow sharp pulses having a frequency of 10/sec, which are obtained by differentiation of a staircase voltage in the electronic counter. The output wave forms are like those of Figure 7. This timing is recorded with the interferometer and radial distance channels on a Sanborn recorder. Additional cathode followers are also supplied so that the timing may be transmitted over land-lines to the launcher or to other trailers containing the equipment used by the research groups. An additional sinusoidal frequency of 100 cps (not shown in Figure 6) is also available for any research groups requiring such a frequency synchronized to the timing signals. A 10 kc standard frequency can also be made available. If extreme accuracy of the standard frequency is required, the electronic counter can be operated from a one-Mc standard frequency source.

The timing signal, in addition to being recorded on the Sanborn recorder, is also recorded on a magnetic tape recorder but with the low-amplitude 10 cps spikes removed by a biased amplifier. This same amplifier drives a modulator which modulates the 10 kc standard voltage upward, and the result is added to one of the 15 kc channels recorded.

A four-channel head for the magnetic tape recorder would obviate this undesirable mixing, and this head is presently being developed. The plans are to record separately the two 15 kc channels with Doppler and roll; the 15 kc difference between the local oscillators; and the modulated 10 kc frequency. These modifications will simplify the playback circuitry.

STATION CALIBRATION

One hour before scheduled launch time, the interferometer antenna cables are disconnected and their electrical lengths checked by means of an R-X bridge. The line stretcher is used to adjust each cable to an exact multiple of a half-wavelength. Then the antennas are reconnected and their impedances checked; and the four interferometer receiver input impedances are adjusted to the characteristic impedance of the cable. Next, a signal generator connected to a tee applies equal phase signals simultaneously to the North and South receivers at the point where the antenna cables are normally connected.

The gain on the Sanborn amplifiers is checked by substituting a separate local oscillator for one of the receivers. This oscillator's frequency differs from that of the other by about 1 cps. The gain should be such that the amplitude of the 1-cps voltage nearly fills the channel. This signal is recorded on the Sanborn recorder and provides the necessary calibrations, since the phase variation is proportional to the chart speed. The amplitude of the coarse detector output is also checked and recorded in this fashion with the local oscillator frequency differing by about 64 cps. Then the original local oscillator is reconnected, and the line stretcher in the IF circuit is adjusted to make the output of the fine phase detector bring the Sanborn pen exactly to the middle of the chart paper. Next, the switch on the phase-locked divider is pressed repeatedly until the coarse channel is 16 steps from maximum channel deflection. A final adjustment to exact center is made by the phase shifter. The East-West receivers are similarly adjusted. If it is desired to make corrections to the phase because of possible low signal level, an AGC calibration of phase is also made. This is done at 0 degrees in 10 db steps, after which the one-cycle calibrations are made at these same levels.

The Doppler circuitry is then checked for proper amplitude by throwing a switch on local oscillator No. 1, thus changing its frequency and thereby simulating a Doppler signal. If the two-frequency system is being used, the high-powered transmitter must be turned on for this test. The operation of the counters and printer are checked. The oscillator is then returned to its original frequency; and the 15 kc difference frequency between the two oscillators is checked. A slight adjustment of local oscillator No. 2, which does not affect the Doppler frequency, may be necessary. The magnetic tape recorder is checked by a test recording played back on an oscilloscope to insure that the amplitudes are appropriate, especially the modulated 10 kc standard. The timing is then recorded on the Sanborn recorder to insure that this is operating properly. The lift-off circuitry and the time delay relay are also checked.

The X-Y plotter is adjusted in the following manner. With equal-amplitude equal-phase signals into the E-W receivers, the switch on the divider is pressed repeatedly until the X reading is 8 steps from either maximum or center. At this 8th lobe, $\phi = 60$ degrees and $\cos \phi = 0.5$. The gain of the X amplifier is adjusted to provide the deflection desired for one-half the distance reading on the counter connected to the synchronous motor. The Y scale is adjusted similarly, using the N-S receivers. The zero lobes (16 steps from maximum) for both axes are made coincident at the point representing the SSD station on the graph. Next, a protractor and ruler are used to mark the location of the launcher (the direction and distance are known).

By means of a simulated low frequency Doppler signal, the hp 521C is set at the proper value, usually either 0 or 1 km. The dual preset counter is also set at the proper number of cycles to account for the number of cycles in the remaining fractional km distance from the SSD station to the launcher. The "Operate" switch is turned off when the setting is correct, and remains in this position until shortly before rocket launch. The relay in the phantastron circuit of the electronic counter is then opened, at a time when the gate is open, and will not close again until the lift-off switch operates at the launcher. The digital clock is set at 239999.

By this time, the launch should be imminent. If a long "hold" occurs, the calibration should be repeated. If no long hold occurs, the transponder (or the transmitter) in the rocket is energized about five minutes before launch. The switches on the dividers are pushed a sufficient number of times to set the pen of the X-Y plotter as nearly as possible on the position of the launcher on the chart.

In the one-frequency system, a very low Doppler frequency will be present; this is adjusted to zero frequency by very slightly varying the frequency of either the reference oscillator or local oscillator No. 1 with the radial distance channel on the Sanborn recorder under observation. The time delay relay switch is opened and the preset counter switch set to "Operate". The tracking filters are then locked on the signal. The station is in readiness for launch.

Thirty seconds before launch, the recording equipments are turned on. One man's position is at the X-Y plotter, and the other two in front of the tracking filters. The latter employ earphones to permit manual lock-on of the tracking filters should they lose lock. Additional circuitry has been incorporated into the standard tracking filters so that a panel meter indicates the amount and direction of the pulling voltage applied to the variable controlled oscillator (VCO) in the tracking filter. At takeoff, this meter reading changes from zero to some value dependent upon the acceleration of the rocket. The operator manually adjusts the VCO voltage for a meter reading of approximately zero, but slightly in the direction in which it is forced by the rocket's acceleration. This assists the tracking filter in maintaining lock, especially with high-acceleration rockets.

Shortly after last stage burnout, the acceleration is only -1 g due to gravity; thus the tracking filters will require only occasional attention. When the Doppler frequency becomes so low that it appears on the Sanborn record, it is monitored until the frequency becomes zero and reverses phase. At this time the reading of the digital clock is noted and also the reading of the industrial counter (which is reading the maximum slant range in km). This information is telephoned to the blockhouse for it provides a fair indication of whether the rocket is performing as predicted. On descent, it is sometimes necessary to watch the tracking filters very closely, because the rocket's rotation may cause signal nulls with attendant rapid phase variations severe enough to unlock the tracking filters. On signal cessation at impact, the equipment is turned off and a recalibration of the station is made.

DATA REDUCTION

Manual reduction of the data will be discussed, although a more refined and rapid technique suitable for data readers and electronic computers has been developed. Part of the latter technique is discussed in a recent unpublished report (Reference 3).

The theory involved is illustrated by describing the method that was used originally with a desk calculator. The pre-flight and post-flight calibrations of the phase detectors are examined to insure that no changes occurred during the flight. From the 1-cps calibrations, two scales can be prepared showing the amplitude at about 5 or 10 degree intervals over a 360-degree range. These scales are made for both fine channels and over a ± 90 degree range for the coarse channels. An approximate value for the direction cosine can be obtained by using this scale to determine the phase reading of the coarse channel in degrees and multiplying this by the factor 0.0111 (see Equation 1).

If the lobe number vertically overhead is assumed to be 0, the lobe number n (an integer) may be determined by means of the relation

$$n = \frac{64\delta_c}{360} = 0.1778\delta_c \quad , \tag{2}$$

where the decimal portion is neglected. The fine interferometer channel is read for the same time and if this reading is called δ_f, then the total number of electrical degrees δ of phase difference between the 73.6 Mc signals at the two antennas is

$$\delta = 360n + \delta_f \quad . \tag{3}$$

This number of degrees, multiplied by the factor $\lambda/360L = 0.00017349$, provides the direction cosine with high accuracy. The other direction cosine may be determined in the same fashion at the same time. The slant range R is read from the record, and the altitude may be computed by the relation (see Figure 3):

$$h = R \sqrt{1-(\cos^2\theta + \cos^2\phi)} \quad . \tag{4}$$

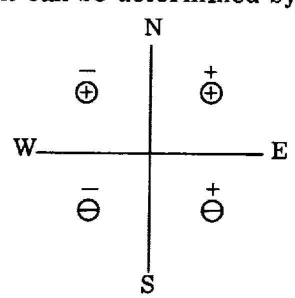
The horizontal range d from the SSD station is given by

$$d = R \sqrt{\cos^2\theta + \cos^2\phi)} \quad . \tag{5}$$

The coordinates of the sub-rocket point in the horizontal plane through the launcher are obtained from $R \cos\theta$ and $R \cos\phi$; and the angle β is given by

$$\beta = \tan^{-1} \frac{\cos\phi}{\cos\theta} \quad . \tag{6}$$

To compute the azimuth it is necessary merely to know in which quadrant the rocket is flying. For example, if the outputs of the coarse phase detectors are positive, they are represented by a + for an easterly direction, ⊕ for a north direction and similarly for negative values, then the quadrant can be determined by the following chart:



The foregoing discussion has assumed that all of the data were properly taken. In the event that the tracking filter lost lock, or if a more exact value for R is desired than that read from the Sanborn record, the data from the magnetic tape must be played back (as described on page 15). If the dividers should lose lock, as sometimes occurs when the transmitter momentarily malfunctions, or if the radio propagation conditions are badly disturbed—such as by the explosion of a grenade in the vicinity of the rocket—the direction cosines must be computed, in the following manner, from the fine interferometer data.

From a previous calculation, the lobe number of the launcher for a given axis is n_1, and the lobe numbers are decreased at rocket takeoff by one unit for every 360 degree change on the fine interferometer record. However, if a phase reversal occurs on the record, then the next lobe number is taken to be the same as the last one and succeeding lobe numbers are one larger. This procedure is quite satisfactory except in rare instances when the phase reversal may occur within 3 or 4 degrees of ± 90 degrees, in which case it may be difficult to ascertain that the phase did reverse. If the phase reversal is not noted, answers are obtained which are obviously ridiculous and the point of phase reversal must be found. This process is described later.

DATA PLAYBACK

Figure 8 is a block diagram of a method for obtaining digital values of the radial velocity at one-second intervals by playback of the magnetic tape record. The digital clock is set at 239999 and, if it is desired to obtain the same data as was obtained during the flight, the electronic counter gate should be open. Usually it is desirable to obtain the data during the odd-numbered seconds which were not obtained during the flight, so the gate is closed initially. The magnetic tape recorder is started, and at the time corresponding to lift-off the 10 kc standard frequency appears, moving the digital clock to zero. The tracking filters are manned in the usual fashion until the end of the record. By summing the odd-second and even-second tapes and adding in the number of cycles equal to the distance from the SSD station to the launcher, the radial distance R is obtained as a function of time.

If the summation of the one-second intervals is regarded as too tedious, a longer time interval can be summed by means of a slight change in the circuitry. For example, the one-shot multivibrator may be utilized to start the time interval unit, and the ten-second signal from the digital clock may be used to stop it. Thus, this digital tape will give a nine second count and the additional first second count may be added from the one-second tape. This process can be extended to 99 seconds if desired.

A method for determining the accurate time of occurrence of each integral km of radial distance is given in Figure 9. The counter gate is closed and the digital printer is set at 239999. The dual preset counter scales for the two-frequency system are set at 1 and 981 (1;981) and for the one frequency system is set at 1;490. The counter is started by the one-second pulses and is stopped at the end of 1 km, at which time the printer prints. For example, if the printer reads 00028009172, then the time for that integral km is 28.9172 seconds. The fifth digit from the right must be ignored. This system will not function during any interval of time when the radial velocity exceeds 1 km/sec. In this case, however, the times of the integral km are printed correctly for the portion of time when the radial velocity is less than 1 km/sec. A few exceptions may be found, in which the time may be in error by exactly 1 second or the print-out may be blurred. The 1 second error usually can be spotted easily, but the blurred reading cannot be remedied. The portion of the record in which the rocket velocity exceeds 1 km/sec may be re-run, using 2 km intervals with the preset counter changed to 1;1963 for the two-frequency system or 1;981 for the one-frequency system.

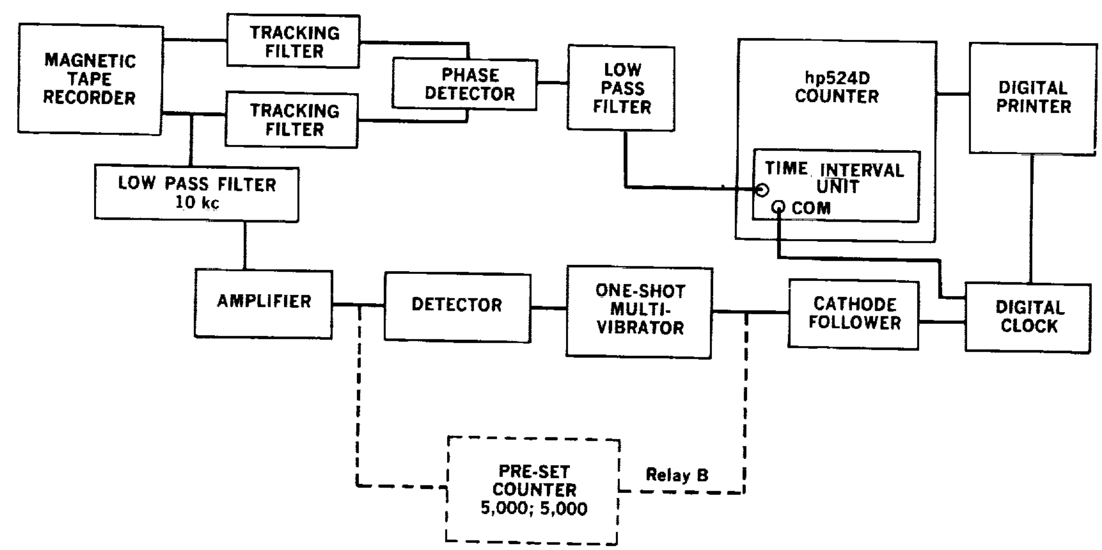


Figure 8 – Data playback (1 second intervals). Dashed lines indicate alternative method

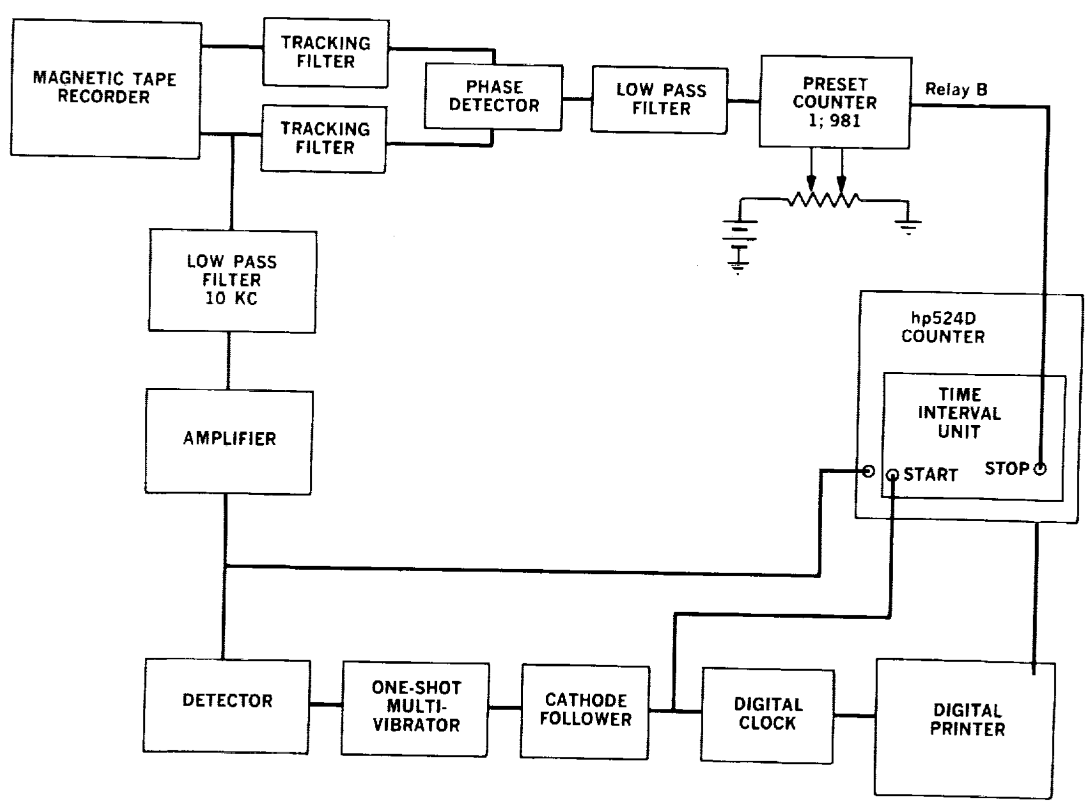


Figure 9 – Method of obtaining accurate time of occurrence of each integral km of radial distance

Except near times of ignition or burnout of a rocket stage, when the radial velocity does not vary approximately linearly with time, a more accurate value of the radial velocity can be obtained by means of equations such as the following:

$$\overline{V}_{m+\frac{1}{2}} = \frac{V_{m-1} + V_m + V_{m+1}}{3} ,$$

or

$$\overline{V}_{m+\frac{1}{2}} = \frac{V_{m-2} + V_{m-1} + V_m + V_{m+1} + V_{m+2}}{5} , \tag{7}$$

where m is the printed time. This improvement in accuracy results from the ± 1 cycle possible error in one individual counter reading.

UNUSUAL PROBLEMS

It has been found that, on a few occasions, the tracking filters obviously did not remain locked during a small portion of the first 3 to 5 seconds of flight. Investigation indicated that, in the case of very high acceleration rockets, very rough burning of the propellant may result in a 10g drag due to air resistance immediately followed by a very high acceleration of 25g or more. Under such circumstances the tracking filter sometimes fails to remain locked. In some cases a playback of the record will provide the required data, but in a few instances even this has failed. Thus far, the only solution found is to play back the tape, recording the Doppler frequency on an oscillograph and hand-counting the first few seconds.

The SSD station should be located on a flat area with no high towers or buildings in the vicinity, since re-radiation from such structures can introduce some difficulties, in particular, second-harmonic interference from the high-powered transmitter. This is apparently due to slight rectification and re-radiation from the metal structures. Also, considerable work was necessary on the transmitter itself in order to avoid second harmonic interference. However, a special filter in the transmitter and careful shielding have solved this problem. The trailer housing the transmitter and its antenna are now being operated approximately 300 feet from the SSD trailer.

Before this second harmonic problem was solved, a temporary solution was found by removing the transmitting antenna to a more distant location—about 2 km away. However, this introduced the problem of receiving a sufficient 36.8 Mc signal, free of fading effects, at the trailer; and also greatly increased the computational difficulties for obtaining the correct trajectory. Also, under such conditions, the first 10 seconds or so of data obtained by the X-Y plotter may be in error by several degrees with regard to the azimuth from the launcher. The azimuth from the SSD station will still be correct, however. It is better, of course, to have the transmitter close to the station; and in this case the fixed distance from the launcher to the station for the two-frequency system is taken to be the distance from the launcher to the mid-point between the transmitting antenna and the Doppler antenna at the SSD site.

Owing to momentary transponder failure or to the effects of an exploding grenade, there have been instances where the determination of the radial velocity has been impossible during a given second of time. This problem can be surmounted if the particular interval does not include the ignition or burnout of a rocket stage. In the latter case, a graphical plot of the velocity data can give an approximate value; but, in general, this is not necessary and the data can be handled as follows:

If v_L is the number of cycles in the distance from the SSD station to the launcher, the radial distance in cycles can be found by the summation

$$v_L + v_1 + v_2 + v_3 + v_4 + v_5, \quad \text{etc.}$$

Now for example, if v_3 is obviously incorrect, the summation may be made in the following manner:

$$v_L + v_1 + 1.5\ v_2 + 1.5\ v_4 + v_5, \text{ etc.}$$

In other words, the preceding coefficient and the following coefficient are increased by one-half. The subscripts are the times as read by the printer, and the distance obtained is to the end of the final second. In the example given above, where v_5 is the last term, the total distance obtained is the distance at 6.0 seconds.

RECEIVER ADJUSTMENTS

The 73.6 Mc receivers, as delivered, do not contain a necessary special crystal filter circuit (Reference 4). These crystal circuits must be installed in shield cans with octal plugs to fit the sockets provided in six of the receivers. The crystal filters can be dispensed with only if (1) no telemetry signals are to be used on the carrier; (2) there is no radio interference in a range of about ± 100 kc; and (3) the improved signal to noise ratio is not considered necessary.

The north, east, and two Doppler receivers are supplied with these crystal circuits and aligned to give the proper center frequency with a bandwidth of about 4 to 5 kc, an essentially flat response over a range of 3 kc, and a 60-to-6 db bandwidth ratio of 5. The south and west receivers are then matched with the north and east receivers, respectively, so that the phase versus frequency variation over approximately a 3 kc band is less than ± 1 degree. This procedure involves an unpublished technique similar to an impedance bridge balancing technique and will be described in a later report.

The differential phase variation between the north and south receivers with equal input signals varying from 0.1 microvolt to 500 microvolts, is measured. If this differential phase variation is not satisfactory, the values of small degenerative resistors in the cathode circuits of the IF amplifiers must be changed to minimize this undesirable effect. The present SSD receivers have very little phase variation with input signal from 500 down to about 50 microvolts; but at lower signal levels it has been difficult to obtain completely satisfactory results. For signals larger than about 1 microvolt, however, the total phase change is approximately 4 degrees. In general, this phase variation can be neglected in data reduction except for very low signal levels, to which a correction can be applied. The calibration must be done before or immediately after the flight by recording the one-cycle fine interferometer output as a function of various weak signals.

The present receivers will provide direction cosine information down to -105 dbm. By using a calibration chart, this may be extended to as low as -117 dbm. The Doppler receivers utilizing the tracking filters can stay locked to the signal down to -135 dbm.

TOTAL POWER INTERFEROMETER

The continuous phase interferometer described above has the very desirable feature of providing continuous data. However, great care must be exercised by the SSD crew to avoid the introduction of phase errors. For example, the air must be circulating at almost constant temperature through the racks containing the interferometer receivers. Thermostatic control of the trailer air temperature is absolutely necessary; therefore air-conditioning and controllable heat are required. Heat shields are required around the receivers which must be checked frequently to insure that their differential phase characteristics with respect to signal input amplitude have not changed. The total power interferometer (TPI) eliminates these differential phase problems, but is subject to other disadvantages; mainly: (1) the X-Y plotter for range safety purposes cannot be used; and (2) the data reduction is more laborious. The block diagram is shown in Figure 10. This circuitry has been constructed and 30 db nulls are quite easy to obtain; moreover, this value can probably be improved. The nulls in one receiver occur exactly at an integral lobe number and if the other receiver is used, these nulls occur halfway in between the lobes. It is planned to test this system on a rocket flight in the near future.

With the CPI, the input impedances of the receivers are adjusted to insure that the antennas see exactly equal impedances. However, with a magic-T the impedances cannot be made exactly equal and a matching network is required. The cable lengths are made

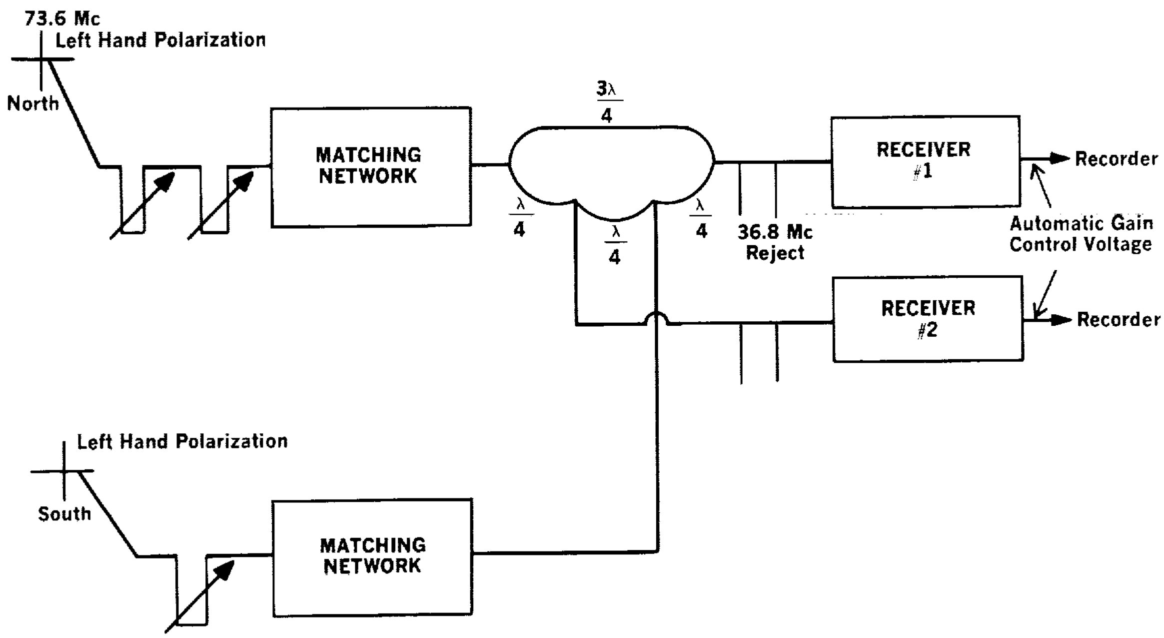


Figure 10 – Total power interferometer

equal and the line stretcher is adjusted in the same manner as for the CPI, except that the second line stretcher is adjusted to obtain a minimum AGC voltage on receiver no. 1.

The nulls will occur very frequently as the rocket takes off and if it behaves in its predicted fashion, the lobe numbers can be computed, although it is a rather tedious process. If the rocket does not follow the expected trajectory, however, the lobe numbers must be determined in a different fashion. Near motor burnout, and for a very large portion of the rocket's ascent, very few nulls will be observed. Also, a null may appear if the rocket antenna points at the ground station as a result of yaw and roll. The latter case can usually be detected by the lack of sharpness of the null if the roll rate is not high, and also by its simultaneous occurrence on both the E-W and N-S channels. In order that the data be reducible, the nulls must be recorded during the rocket's free-fall period, i.e., while it is above about 55 km. Thus the interferometer must be capable of tracking the rocket well beyond peak altitude. This is not a requirement for the CPI.

The method suggested for reducing the data is first to determine the lobe numbers for each of the nulls and then to compute X and Y as analytical functions of time. Since the lobe number at launch is known and these lobe numbers usually decrease for a time thereafter, the approximate lobe numbers during the early portion of the flight are known. These lobe numbers are tentatively assigned to the various nulls. A graph of $R \cos \theta$ as a function of time is then prepared. The first value selected is the first null which occurs for R greater than about 60 km. The value of R at this particular time is determined and, on the assumption of the known value of the lobe number, $\cos\theta$ is determined from the relation

$$\cos\theta = 0.0625n \quad . \tag{8}$$

The product $R\cos\theta$ is computed and plotted on the graph at this time. It is also advisable to calculate $R\cos\theta$ for lobes $n+1$ and $n-1$. If two receivers are in use, the half-lobe numbers may also be plotted. A plot determined from a theoretical trajectory is shown in Figure 11 where the use of only one receiver was assumed so that all lobe numbers would be integers. As $R\cos\theta$ represents the coordinate of the sub-rocket point plotted on a horizontal plane through the SSD station, this function must be very close to a straight line, since Coriolis effects are very small. It is found that only one straight line can be drawn through the various points obtained when the lobe numbers vary in sequence. The straight line in Figure 11 is therefore the proper solution; it can be seen that the lobe numbers changed their direction between 60 and 260 seconds. (The curve would have been easier to draw if the half-lobe points had also been used.) This straight line can then be expressed as an analytical function of time:

$$Y = Y_1 + \dot{Y}(t-t_1) \quad . \tag{9}$$

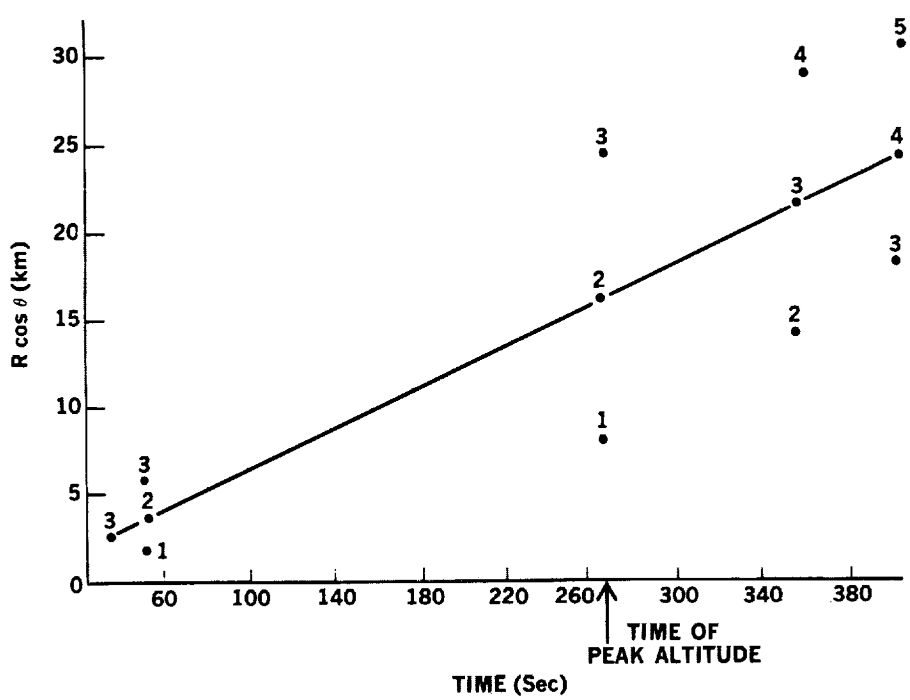


Figure 11 – Method of determining lobe numbers

A similar procedure is also performed for $X = R\cos\phi$. However, if there is a large east or west component, the Coriolis effect may be sufficient to cause the straight line to become slightly curved. The curvature is not usually enough to cause confusion in selecting the lobe numbers, but the X function is not quite linear with time. It may be determined as an analytical function of time in the following manner.

A point on the graph of X is selected so that R is greater than about 60 km, thereby insuring that the rocket is in free fall. The earliest value meeting this requirement is read from the graph at the time a null occurred on either receiver—this value is X_1. Another point is selected at a later time, the later the better, but before the rocket's peak altitude is attained, this is X_2. The approximate average E-W velocity is calculated from

$$\bar{X}_2 = \frac{X_2 - X_1}{t_2 - t_1} \quad . \tag{10}$$

Y_2 is calculated for $t = t_2$ (Equation 11) and the altitude is:

$$h_2 = \sqrt{R_2^2 - X_2^2 - Y_2^2} \quad . \tag{11}$$

The elevation angle α is computed from

$$\alpha = \tan^{-1}\sqrt{\frac{1-(\cos^2\theta + \cos^2\phi)}{\cos^2\theta + \cos^2\phi}} \quad . \tag{12}$$

Next, the radial velocity near time t_2 is determined from the printer tape and Equation 7 to determine $\dot{R}_2$ at time t_2 as accurately as possible:

$$\dot{R}_2 = V_2 \sin\alpha + \sqrt{\dot{X}_2^2 + \dot{Y}^2}\cos\alpha \quad , \tag{13}$$

from which the vertical component of velocity V_2 may be computed. The Coriolis effect on the vertical acceleration is given by

$$\Delta g = 2\omega\,\bar{X}_2 \cos\gamma \quad , \tag{14}$$

where Δg is positive if X_2 is toward the west, ω is the earth's angular velocity and γ is the latitude. The gravitational acceleration at an altitude h_2 can be determined by

$$g_2 = g_0 \frac{R_e^2}{(R_e + h_2)^2} \quad , \tag{15}$$

where R_e is the radius of the earth and g_0 is the acceleration of gravity at the surface of the earth.* The actual acceleration is $g_2 + \Delta g$ at the altitude h_2 with E-W velocity $\dot{X}_2$. To calculate the approximate peak altitude, let

*Includes the centrifugal acceleration $(\omega^2 \cos^2\gamma)\, R_e$.

$$h_p = h_2 + \frac{V_2^2 \ (R_e + h_2)}{2 \ R_e \ \bar{a} - V_2^2} , \tag{16}$$

where

$$\bar{a} = \sqrt{g_2 + \Delta g} \ \sqrt{g_0 + \Delta g}$$

Let g_p be the value of gravity at the peak altitude at time t_p ; then

$$t_p = \frac{\mu \sqrt{h_p - h_2}}{\sqrt{g_p + \Delta g}} , \tag{17}$$

where $\mu = \sqrt{2} \ (1 - 0.167 \ k - 0.030 \ k^2)$

and

$$k = \frac{h_p - h_2}{R_e + h_p} . \tag{18}$$

The term in parentheses in Equation 17 provides an approximate correction for the variation of gravity with altitude. Therefore, the E-W velocity $\dot{X}_1$ at time t_1 can be computed with much better accuracy from the relation:

$$X_2 = X_1 + \dot{X}_1 \ (t_2 - t_1) - 2\omega \cos\gamma \left[(h_p - h_1) \ (t_2 - t_1) - \frac{1}{6}\bar{g} \ (t_2 - t_p)^3 - \frac{1}{6}\bar{g} \ (t_p - t_1)^3\right] \tag{19}$$

where $\bar{g}$ is an average acceleration between h_1 and h_p:

$$\bar{g} = \left[1 + \frac{1}{6}\left(\frac{g_1 + \Delta g}{g_p + \Delta g} - 1\right)\right] g_p \tag{20}$$

The expression for X as a function of t becomes

$$X = X_1 + \dot{X}_1 \ (t - t_1) - 2\omega \cos\gamma \ \left[(h_p - h_1) \ (t - t_1) - \frac{1}{6}g \ (t_p - t_1)^3 - \frac{1}{6}\bar{g}(t - t_p)^3\right] \tag{21}$$

Other values of X obtained with the interferometer may be checked with this equation, which is valid beyond the peak until the rocket descends into the air drag region at approximately 55 km.

The altitude for any other time may be computed from Equation 11 with the subscripts changed to the new times used. The peak altitude previously obtained from Equation 16 can be checked but a modest error does not greatly affect Equation 21. This technique was satisfactorily tested on one Nike-Cajun flight by using only the integral lobe numbers obtained from the CPI, i.e., when the fine interferometer read 0 degrees; this is equivalent to using only one receiver in a TPI.

COST REDUCTION

The TPI System

The CPI listed in Appendix B can be reduced by one 6.4 Mc phase detector, two frequency dividers, one X-Y plotter, two receivers and the range safety equipment. This reduces the cost by $32,900.00, bringing the cost of the TPI system to $100,100.00. If the items marked with an asterisk are omitted, the cost reduces to $79,415.00.

Airborne Equipment

The present cost of the rocket antennas is $300.00 per frequency. Both the two-frequency transponder and the one-frequency transmitter cost $1,500.00 each. The transponder weighs 5 pounds, is 5-1/2 inches in diameter and 5-3/4 inches high telemetry included. The transmitter weighs 6 pounds, is 5-1/2 inches in diameter and 7 inches high. The transmitter does not contain telemetry, but room has been left on the panel for a small plug so that an external telemetry modulator can be connected. The telemetry modulator would be easy to design but this has not yet been done.

ADDITIONAL SYSTEM ADVANTAGES

The spare receiver in the station is very useful in the event of any receiver failure, although its use has not yet been necessary. By the simple expedient of removing the four crystal plug-in units from this receiver, the bandwidth is increased to about 60 kc without appreciable change in gain or AGC characteristics. The final tube in the receiver is removed and a plug-in unit built on a miniature tube socket plug changes its limiter to an amplitude-modulated detector with a considerably larger voltage output. This output is applied to the FM discriminator to provide the telemetry signal. The cost estimates (Appendix B) include these items but do not include a suitable recorder for the telemetry.

By connecting an additional 6.48 Mc phase detector to both IF outputs of the Doppler receivers and connecting the output to another 15 kc phase detector with the fixed 15 kc frequency, a frequency is obtained that is exactly twice the roll frequency of the rocket; this can be recorded on a separate Sanborn recorder if desired.

The frequency meter employed in the Doppler circuitry contains a discriminator which provides a voltage proportional to the Doppler frequency. This voltage can be recorded during the flight, or by playback after the flight, to obtain an analog plot of the radial velocity as a function of time. Thus information is immediately provided that normally takes an appreciable time to acquire, such as the time of ignition and burnout of various stages of the rocket, and the approximate acceleration obtained from the various stages. More accurate values of the acceleration can be obtained by analysis of the digital tape record.

ACCURACY

The two frequency SSD system has been the one most used thus far; but the results have been analyzed completely for only a few early flights made when many of the sources of phase variation had not yet been located and eliminated. Data from a few more recent flights have been partially reduced by means of a new program written for an electronic computer. These flights were performed with the low frequency high-powered transmitter at a distance of 2 km from the SSD station, and that circumstance complicated the data analysis. The second harmonic problem having been eliminated, the transmitter is again close to the SSD station for the next flights.

Preliminary results on these more recent flights indicate agreement with the FPS-16 radar data within approximately 50 meters, except at the very highest altitudes where the small rocket was giving too small a return to the radar receiver. The radar has sometimes been unable to track the rocket all the way to peak altitude, whereas the SSD station has tracked each rocket all the way to re-entry. The descent data, however, have not as yet been reduced.

The angular accuracy of the interferometer is of the order of ± 3 degrees, corresponding to roughly ± 2 minutes of arc, although this was attained only recently after considerable effort had been expended on the equipment. Examination of the FPS-16 radar data indicates angular tracking errors up to 6 minutes in elevation and distance errors up to about 30 meters (Reference 5).

Previously, one single-frequency trajectory was reduced at Churchill with less refined equipment, but no radar data were available for comparison. The individual altitudes computed were all within 70 meters of a calculated free-fall trajectory curve where 70 meters was the smallest difference that could be observed.

No attempts have as yet been made to correct for the ionospheric effect, since not all of the two-frequency rockets tracked have reached sufficient altitude to introduce an appreciable error from this effect. One rocket penetrated the ionosphere to very high altitudes using the one-frequency system in which this error (about 1/2 km) was small enough to be neglected. Corrections could be made by rough methods involving an ionospheric sounder located nearby if the additional accuracy were considered worth the effort. Under the worst conditions, such as midday near a sunspot maximum, the error at an altitude of about 300 km is about 1-1/4 km for the two frequency system. For the single frequency method, the error would be about 1/4 km.

The X-Y plotter presently used has a 3 X 3 foot chart. The results obtained show that if the dividers remain locked, the plotted azimuth from the launcher is accurate to ± 1/2 degree. Trouble has been experienced, however, at rocket takeoff when the phase-locked dividers would sometimes slip one cycle. This difficulty is thought to be greatly aggravated by the unavoidable shadowing of two of the interferometer antennas by the huge enclosed Aerobee launching tower. Signal levels at the various antennas differ markedly until about 1 second after launch. The error in azimuth introduced by one cycle slippage is about 6 degrees with respect to the SSD station; and much larger with respect to the launcher, in some cases as much as 20 degrees. A different circuit is now being tested which seems to hold lock more securely. This new circuit will be tried on the next flights in the hope that the lobe-slipping problem will be solved.

ACKNOWLEDGMENTS

The SSD system was conceived by the author while employed at the U.S. Naval Research Laboratory, Washington, D.C., which initiated the development of an SSD station under contract with the New Mexico State University. This contract was transferred to and renewed by the Goddard Space Flight Center. The system checks have been conducted at the NASA Wallops Island Station, Virginia.

The special equipment was designed and assembled under the supervision of Messrs. Wesley L. Joosten and Robert J. Sabin, NMSU project engineers. Flight testing at Wallops Island has been under the direction of Mr. Billy Gammill, also of NMSU. All three have made helpful contributions to the instrumentation.

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Appendix A

SSD Initial Condition Computation Routine

SINGLE PATH		Missile Name & No. _____
DOUBLE PATH		Firing Range _____
		Date _____

		N-S	E-W
0.	Transmitter Coordinates feet	_____	_____
1.	Launcher Coordinates feet	_____	_____
2.	SSD Coordinates feet	_____	_____
3.	Line 1 - Line 2 N-S	_____ ft.	
4.	Line 1 - Line 2 E-W		_____ ft.
5.	$R_0 = \sqrt{(\text{Line } 3)^2 + (\text{Line } 4)^2}$	_____ ft.	
6.	h = Missile Altitude (Feet) at Lift Off Delay Relay Closure	_____ ft. at	_____ sec.
7.	$R_0^1 = R_0 + \dfrac{\frac{1}{2} h^2}{R_0}$	_____ ft.	

PLOTTING BOARD

8. $R_0 = \dfrac{\text{Line 5}}{3.281} =$ _____ Mtrs

9. N-S Lobe Number $= \dfrac{16 \text{ Line 3} - 0.5 \text{ Line 4}}{\text{Line 5}}$, δ N-S = _____ + North, - South

10. E-W Lobe Number $= \dfrac{16 \text{ Line 4} + 0.5 \text{ Line 3}}{\text{Line 5}}$, δ E-W = _____ + East, - West

PRESET AND Km COUNTER

11. N_0^1 = Initial Cycles $= \dfrac{\text{Line 7}}{6.68} =$ _____ cycles
12. If $N_0^1 \leqq 245$, Preset Counter A With N_0^1 _____
13. If $245 < N_0^1 \leqq 491$, Preset Counter B With N_0^1 -245. _____
14. If $491 < N_0^1 \leqq 736$, Preset Counter A With N_0^1 -491, _____
Km Counter With 1, etc.

NOTES:

Line 6 must be determined from past or theoretical performance.

Line 9 and 10 contain an approximate correction due to Wallops Island grid coordinates being different from true coordinates.

For a remotely located transmitter the plotting board data at Wallops Island will be elongated from 0 to 300 feet along a line connecting SSD and the missile sub point.

Appendix B

Station Costs

The cost of establishing the SSD system, exclusive of land, electrical power and surveying cost is summarized below. An asterisk preceding an item indicates that the item is not commercially available and must be constructed from schematic diagrams. A cost figure followed by an asterisk indicates that it may be possible to omit the item or to substitute another piece of equipment that might be available in the laboratory, although the substitution or deletion requires additional labor.

Installation

Trailer (with air conditioning)	$21,500.00
Power Cables	200.00
Racks	1,900.00
Chassis Slides	500.00
Power Cabinet	75.00
Power Plugs (R and X)	100.00
Tools	400.00
Filing Cabinet	40.00
Work Benches	600.00
Desk and Chair	190.00
Water Cooler	400.00*
Installation Labor	8,000.00
	$33,905.00
Timing-Frequency Standard	3,400.00*
*Timing Mixer Chassis	900.00
Dymec Clock 5414	1,200.00
	$5,500.00

Doppler Equipment

Electronic Counter hp 524D	2,300.00
Printer hp 560A	1,400.00
Industrial Counter hp 521C	650.00
Time Interval Unit for 524D, hp 526B	175.00
Counter, dual pre-set	825.00
Tracking Filter, Interstate Mod. IV (2)	13,500.00
Tape Recorder, modified	1,000.00
Pre-amplifiers, Ceco or equivalent (2)	600.00
Local Oscillators (2)	3,000.00

Receivers (2)	5,000.00
Reference Oscillator (6.48 Mc)	600.00
*Crossed dipole, with magic-T	150.00
Phase Detector, 15 kc	200.00
Phase Detector, 6.48 Mc to 15 kc	300.00
*Frequency Synthesizer Chassis	500.00
Pre-amplifier, 36.8 Mc	300.00
	$30,500.00

Interferometer

Sanborn 6 Channel Recorder	4,700.00
Constant Z line stretchers (7)	600.00
Antenna Cables, Connectors	150.00
Local Oscillators	1,500.00
Receivers (4)	10,000.00
*Phase Detectors, 6.48 Mc (2)	600.00
*Phase Detectors, 101.25 kc (2)	600.00
Antennas, Ground Planes (4)	1,200.00
Pre-amps Ceco or equivalent (4)	1,200.00
*Phase-locked Frequency Dividers (2)	2,000.00
Crystals	200.00
	$22,750.00

Telemetry and/or Spares

Receiver	2,500.00*
Pre-amp (Ceco or equivalent)	300.00*
*Discriminator	500.00*
*Antenna, Ground Plane	300.00*
	$3,600.00

Range Safety

*Delay Line Chassis (AD-YU 521C)	500.00
*Computer Chassis	800.00
*Computer Control	500.00
*Frequency Divider (2)	1,500.00
	$3,300.00

High Power 36.8 Mc Gates Transmitter

Transmitter		12,000.00*

Plotting Board

Prices Vary	Approximately	20,000.00

Test and Peripheral Equipment

AC Line Regulator		700.00
Oscilloscope (Tektronix) 541		1,200.00
Oscilloscope Plug-In Unit CA		250.00
Receiver, Collins 51J4 (Range Communications, WWV)		1,000.00*
Signal Generator hp 608D		1,100.00
Frequency Meter		285.00
hp 525A Mixer Plug-In Unit		250.00
R-X Meter 250-A		1,600.00
Audio Generator		300.00
hp Attenuators 355A and B (2)		250.00
Sierra Power Meter (for adjusting rocket antennas)		375.00
Vacuum Tube Voltmeter hp 410B		245.00
Sweep Generators, for rec. alignment		500.00
		8,055.00
	Overall total	$139,610.00
	Total of items with*	$ 20,685.00

It has been shown that the above cost can be reduced appreciably at the expense of convenience without losing the necessary features.