PROJECTILE HIGH-G TELEMETRY FOR LONG RANGE DYNAMICS MEASUREMENTS

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Summary Devices to measure the pitching, yawing, and rolling motion of a projectile from on board and telemeter the measurements to ground receiving stations have been developed. Two of these devices, a solar aspect sensor and an accelerometer, are described in detail. The complete telemetry system with g-hardening to survive gun-launch accelerations is described and techniques for high-g are discussed. The results of several recent flight tests of these yawsondes are presented and show the unique usefulness of the instruments for measuring dynamical behavior of projectiles over their entire flight paths. Hitherto such information has not been available to the shell designer or the aerodynamicist.

Introduction The dynamical pitching, yawing, and rolling motion of a projectile is usually measured and observed in aeroballistic ranges using conventional spark shadowgraph instruments (1). Such measurements are restricted to the first several hundred calibers of trajectory and quite often cannot predict the future motion of the projectile during its mid-course and terminal flight. On-board sensing devices such as sunsensor and accelerometer yawsondes as well as high-g telemetry circuits have been developed to measure the motion of a shell over its entire flight path and transmit .-he results to ground receiving stations.

High-g telemetry systems have been developed over the past decade (2-5) and have become moderately reliable in transmitting flight data. Such systems operate at very-high-frequencies (VHF) or ultra-high-frequencies (UHF) and include bopnisticated subassemblies such as voltage-controlled oscillators (VCO), commutators, voltage regulators, amplifiers, and similar electronic circuits. Although the electronic subassemblies have been well developed, each particular application poses additional problems to be evolved. Projectiles with high spin rate may produce failures in payloads which had previously survived high accelerations in slowly spinning shell. In fact, minor changes in electronic components and assemblies always require additional preflight g-testing to establish confidence in performance and to weed out potential failures.

Two methods of measuring dynamical motion have been developed and are discussed in this paper. The one method uses solar aspect sensors to give periodic data on the angle between the axis of the projectile and the sun. This sensor requires clear, sunny days and can be used only at certain hours of the day. It produces two-dimensional data (spin rate and solar aspect angle) on the motion of the shell which in reality executes three dimensional motion (spin, pitch, and yaw). Sophisticated data reduction techniques are needed to extract the three dimensional motion of the projectile from the two-dimensional data. The second method of dynamical sensing uses accelerometers mounted normal to the axis of the shell at some distance from the center of gravity. This method produces data on the forces and moments acting on the projectile. The aerodynamic behavior is a direct result of measurement. Accelerometers can be used independent of weather conditions or time of day.

In both methods the data are taken electronically, amplified, transmitted, received, recorded, and played back for analysis. Additional supporting instrumentation must be provided on each test firing so that the telemetered data can be properly interpreted. Such supporting measurements as meteorological conditions, elapsed time, and radar track of the trajectory must be obtained and recorded.

In this paper the solar aspect sensing instrument and the accelerometer instrument will be discussed. The VHF telemetry systems with calibration methods will be described and some results of recent flight tests will be shown.

Solar Aspect Sensing Telemeter The theory of operation of a solar aspect sensing system has been described in detail elsewhere (6) but will be reviewed here in brief for a fuller understanding of the electronic system. Information about the attitude of a projectile in flight can be obtained by a simple aspect sensing system using a pair of silicon solar cells mounted behind slits which define narrow, tilted fields of view. These slits are positioned on the surface of a projectile so that the sun can enter the slits as the shell rotates in flight. The system in its present design can only be used with spinning projectiles and indeed where the spin rate is an order of magnitude greater than the expected pitching or yawing rates.

The fields of view of the two slits form a V in space as shown in Figure 1. As the projectile rotates about its axis in flight, each field of view in turn intercepts the sun. When the solar cell associated with the illuminated slit is irradiated by the sun it produces a voltage output. Since the slit sweeps past the sun, the voltage output of a solar cell is a pulse whose duration depends on the spin rate of the projectile. The time between successive solar intercepts by the two cells depends on the angle between the missile axis and a vector drawn from the missile to the sun (called the solar vector). As the missile nose tilts towards the sun (in the geometry of Figure 1) the time between intercepts increases. As the nose tilts away from the sun the time between intercepts decreases. If the roll rate is constant, a simple relation between intercept time interval and solar aspect angle can be derived (6). The data from the sensing system, then, consist of pulses from the silicon cells. The phase relationships between the pulses are direct functions of the aspect angle of the projectile. The frequency of occurrence of alternate pulses (pulses from the same cell) is simply the roll rate or spin of the missile.

If the pulses can be identified or labelled in some way, it becomes possible to determine the roll direction of the missile. The roll orientation of a spin-stabilized projectile is known because of the direction of rifling in the gun tube. For fin-stabilized shell, however, it may become important to know in which direction the projectile is rolling. A complete revolution in roll of the projectile is needed in order to make a single aspect measurement. If the roll rate and the pitch-yaw frequencies are in the same order of magnitude, then the projectile is changing its aspect substantially during a single revolution and the resulting data are indeterminate.

a) <u>Data transmission</u> is accomplished through an FM/FM telemetry link. A block diagram of the telemeter, which consists of amplifier, VCO, and radio-frequency oscillator (RFO), is shown in Figure 2. Since the sunsensor slits are narrow, the useable area of the silicon photovoltaic cells is small and the output is typically in the order of tens of millivolts. The cell output, then, requires amplification. In the amplifier the polarity of one of the cells is inverted for identification purposes. The amplifier circuit diagram is shown in Figure 3a. The amplifier itself is an integrated circuit with appropriate external resistors and capacitors added to provide a nominal gain of 200. With normally incident sunlight, the pulses will be clipped. This is done so that at extreme angles of solar incidence a reasonable pulse height will be produced to modulate the VCO. The amplifier operates with a capacitor on each input to eliminate d.c. offset. No phase errors are introduced into the pulse data using this particular ic. amplifier.

The voltage-controlled oscillator (Figure 3b) is a multivibrator with a wave shaper on the output. The center frequency was chosen to be 70 KHZ to insure reasonable frequency response for the pulse information, Some solar sensor system designs have the data pulses modulate the RF carrier directly in hopes of higher frequency response. Such a method allows unwanted noise and RF interference as well as amplitude modulation during transmission. The data from a single flight consist of thousands of pulse ensembles which require automatic data handling and reduction. Spurious noise or amplitude changes complicate the data processing and occasionally make automatic reduction impossible. Although the FM/FM system has a reduced response, as long as the leading edges of the pulses are altered consistently and the phase relationships are not changed, error should not be introduced by using a VCO.

The radio-frequency oscillator, Figure 3c, is a simple tuned-base, tuned-emitter circuit which develops up to 0.2 watt into 50 ohms at 250 MHz. Even though not crystal controlled, the RFO is stable and does not shift more than 0.5 MHz at gun-launch accelerations up to 60,000 g. The RFO is coupled into the antenna using a capacitor to match impedances. The antenna is the projectile itself split into two parts to form an asymmetric dipole. The characteristic impedance of the antenna is several times greater than 50 ohms and will change due to high-g launch. This simple design of RFO is insensitive to pulling and the center frequency does not shift more than 0.5 MHz provided the VSWR in the antenna circuit is less than 10:1. The electrical characteristics of the telemeter are summarized in Table I.

TABLE I

VHF TELEMETRY SYSTEM PARAMETERS

Transmitter Power, nominal	200 mw
Transmitter Frequency, nominal	250 Mz
Transmitter Freq4 Peak Deviation	±200 KHz
Transmitting Antenna Gain	- 10 db
Subcarrier Center Frequency, nominal	70 KHz
Subcarrier Deviation, ± 2.5 V input	± 15%
Type of Data Transmission	FM/FM
Amplifier Gain, nominal	200
Solar Cell Output (with slit), nominal	100 mv

b) The transmitting antenna is simply the body of the projectile itself. Two parts of the body of the shell are insulated from each other using a threaded fiberglas joint as shown in Figure 4. The joint is located as far forward on the body as possible to eliminate possibility of mechanical failure. The nose of the missile is torqued to the main body through the fiberglas joint to provide a prestress of 10,000 psi. Pre-stressing provides an added safety margin to keep the projectile intact during launch.

The result of this design is an asymmetric dipole antenna which must be matched to the transmitter using a small capacitor in parallel with the radiation gap. The antenna pattern is shown in Figure 5. The existence of several very wide lobes insures that the RF signal will be received despite large changes in curvature of the trajectory.

c) Potting of all electronic and mechanical assemblies is required to survive the high launch accelerations. Potting is done with epoxy resins such as Epon 815 with flexibilizer Thiokol LP-3, or with Stycast 1090SI. The transmitter section is usually potted with the Stycast resin because of its low loss factor and reduced capacitance in comparison with Epon 815.

d) Electrical power for the telemeter is derived from commercially available Nickel-Cadmium rechargeable cells. The NiCad cells are small, come in stacks, and are available in 50-, 100-, and 250-mah capacities. These batteries have routinely survived accelerations as high as 60,000 g. They require an external turn-on device such as an inertia switch.

e) Calibration of the solar aspect sensing yawsondes is done with a light source, a precision table, and various readout instruments as shown in Figure 6. Parallel light is formed by collimating the output of a zirconium arc lamp and is passed through a chopper to produce pulses of light. The beam of light pulses is allowed to fall incident on the projectile in the region of the solar sensors. The projectile is located on a precision turntable so that it can be rotated about its longitudinal axis as well as about an axis perpendicular to the longitudinal axis.

The light beam is aligned to fall on the missile exactly perpendicular to the longitudinal axis using a reflective system of mirrors (8). The alignment accuracy is better than 0.001 degree. Readings are then taken of the current setting of the rotary precision table and further calibration readings will be referenced to the normal alignment reading. Normally incident light is considered to be zero degrees of yaw. The projectile is now rotated about its longitudinal axis until each sensor in turn sees the light beam. This, of course, produces a change in the VCO which is observed on an oscilloscope. The roll orientation of the missile is recorded when each sensor gives an output. The difference in roll orientation versus yaw is the calibration of the solar aspect sensing system.

The output of the VCO must be monitored rather than using the transmitter to relay the pulses to a receiver. If the transmitter is turned on, calibration personnel affect the transmitter frequency by handling the projectile or simply moving about in the same room and a calibration is most difficult to obtain. The precision rotary table is accurate to 5.0 minutes of arc while the rotary head reads to 15.0 seconds of arc. The calibration, then, is accurate to better than 0.05 degree and has been repeatable to within 0.1 degree.

Acceleration Sensing Telemeter During the past several years, accelerometers which can survive high accelerations became commercially available and have been fired from guns to provide direct in-flight measurements of the moments acting on a projectile.

a) The accelerometer chosen for projectile use is a Columbia Research Corporation Model 1105-1 and is a special modification of their standard accelerometer to accomodate high cross-axis accelerations. The accelerometer has two perpendicular sensitive axes and is used with these axes mounted perpendicular to the longitudinal axis of the projectile. The sensing elements are piezoelectric crystals which are coupled to field effect transistors (FET) for low output impedance. The sensitivity of each axis is 10 mv per g at low frequencies. The response of the accelerometer is flat from 0.5 Hz to 40

Hz aid can be calibrated to as low as 0.1 Hz. voltage limiting circuit is built into the accelerometer to keep the high accelerations experienced in the gun from producing excessively high voltages at the FETs. Preliminary tests of the accelerometer have shown it capable of surviving 45,000 g cross-axis accelerations while in the gun and subsequently measuring 0.5 g along the sensitive axes.

b) Data transmission for the a ccelerometer telemeter is almost the same as for the solar aspect sensor. An additional VCO is needed for the extra data channel. Two integrated circuit amplifiers are used to boost the millivolt data signals to the volt levels needed for the VCO's. Since amplitude accuracy is important for acceleration data, an in-flight calibrator is built into the accelerometer telemeter. The calibrator derives reference pulses from a zener diode source and imposes the reference pulses on each channel of accelerometer output. The data transmission chain is shown schematically in Figure 7. A sample data output from one channel with reference pulses is shown in Figure 8. Of course, while the in-flight calibrator is ON, data from the accelerometer is interrupted. The calibrator produces about one reference pulse per minute.

c) Potting, power, and antenna details are the same as for the solar aspect sensor.

d) Calibration of the accelerometer is done with a shake table at frequencies from 10 to 50 Hz. Below 10 Hz the accelerometer is slowly spun in the earth's gravitational field. The calibration setup is shown schematically in Figure 9. The entire telemeter is calibrated since the gain of the amplifier is usually not set precisely, nor is the deviation of the VCO set precisely.

During calibration the VCO output is discriminated and the accelerometer signal recorded on an oscillograph. The frequency and amplitude of the shake table vibrations are monitored using a reference accelerometer accurate to 0.1%. The signal recorded on the oscillograph is compared to the in-flight calibrator pulse amplitude and the results are plotted. The frequency sensitivity at 0.4 g is shown in Figure 10 while the acceleration sensitivity is shown in Figure 11.

e) An in-flight yaw inducer has been made a part of the accelerometer experimental system. This device imparts a side moment to the projectile at a predetermined point in space so that the shell will start pitching and yawing and its subsequent motion can be measured by the accelerometer. The yaw inducer consists of an explosive chamber in the rear of the missile as far from the center of gravity as possible. The chamber is filled with black powder and is connected to an electronic delay fuse (9). The side wall of the chamber is drilled out to hold a brass slug but the hole is not quite drilled through to the chamber leaving a thin diaphragm.

The mechanical details of the yaw inducer are shown in Figure 12. At the preset fuse time the detonator is set off. The black powder is ignited and explosive pressures develop until the diaphragm wall ruptures. The brass slug receives a “shot start” leaving the projectile at velocities up to 300 meters/sec. The shell reacts with an overturning moment and pitches and yaws along its trajectory. This motion is observed by the accelerometer and transmitted to ground stations. Below 15 kilometers, yaw angles UP to 3 degrees can be produced while even higher angular motion results at higher altitudes.

Yawsonde Flight Tests and Results The solar aspect sensing yawsonde has been used successfully on both fin- and spin-stabilized projectiles. Angular motion of the HARP 5-1 vehicle (10) has been measured during its reentry into the earth’s atmosphere. These results have been reported (6). Spin-stabilized developmental artillery shell such as the 155mm, XM483 have been instrumented with solar sensors and have shown interesting behavior over their entire flights.

Accelerometer payloads have been used strictly on fin-stabilized missiles in conjunction with the in-flight yaw inducer. Some difficulties have come up in the use of accelerometers and limited data have been produced in test firings.

a) <u>Solar aspect sensors</u> used with spin-stabilized shell usually do not suffer from the problem of roll-yaw interaction (the yawing frequency comparable to the roll rate). The roll rate is usually more than an order of magnitude greater than the pitch frequency. The resulting data from solar sensors is a digitized yawing motion.

Figure 13 shows a small segment of raw pulse data from test No. El-5127 done at Wallops Island, Virginia, in October 1970. This test used a 155mm, XM483 projectile with solar aspect sensors located 180 degrees apart on the circumference of the projectile near the note. The inclination angle of each sensor was 45 degrees with respect to the axis of the projectile. Thus, the yawsonde was capable of seeing yawing motion of ± 45 degree amplitude. The projectile with one of the sensors visible is shown in Figure 14.

Round El-5127 was launched with a muzzle velocity of approximately 245 meters/sec at an elevation of 45 degrees. The total flight time was 26 seconds. The spin rate of the shell was about 72 rps so that about 1,900 data points relating to aspect angle were produced on the entire flight. The raw data pulses were played back through a hybrid computer which measures the time interval between pulses in the Analog section and applies the calibration in the digital section. At this point the data have the form of normal solar aspect angle versus time (the normal angle is the solar angle with respect to a perpendicular to the projectile). If radar data on the trajectory of the shell are available, the velocity history can be computed and the solar aspect angle can then be expressed as a function: of distance down the trajectory.

For test E1-5127, the data have the appearance shown in Figure 15. A first look at these data show several striking features. Two frequencies are obviously present and can be related to the familiar precessional and mutational motion of a gyroscopically stabilized shell. Indeed, these two frequencies can be measured directly from the data of Figure 15 and the overturning moment of the shell computed. Such a computation agrees well with ballistic range derived values. Another striking feature of the data is that the amplitudes of the two frequencies do not change appreciably over the entire flight. This observation leads one to suspect that the projectile is executing limit cycle motion. Such motion has long been suspected as a characteristic of the XM483 shell but has not been verified until this particular flight with yawsondes.

The data of Figure 15 represent the solar aspect angle while the desired result for aerodynamic purposes is the angle of attack of the projectile (the angle between the projectile axis and the trajectory). For small amplitude angular motion, the solar aspect angle relative to an average curve drawn through the fluctuations can indeed be treated as the angle of attack with small loss in accuracy. For geometrically large angles, however, say greater than 10 degrees, this approximation breaks down. In order to relate the axis of the projectile to the trajectory, several complicated mathematical expressions can be derived. These relationships do not a priori give -unique results but can be used in fitting processes in an attempt to extract further aerodynamic information from the test data.

A number of fitting processes have been developed over the past several years including epicyclic fitting, WOBBIE, analog simulation, and the method of Chapman and Kirk (11-14). Such methods have been applied to the data from test El-5127 and preliminary values of the aerodynamic coefficients have been derived. For example, the static moment coefficient (11) derived from the yawsonde data has a value of 4.5 at the data Mach number which agrees well with the ballistic range derived value of 4.3 for the same Mach number and angle of attack.

b.) <u>Accelerometer</u> data have been obtained from a number of flights of the HARP 5-1 projectile. In all cases, only one channel of the biaxial accelerometer functioned during the early portion of the flight. Yaw inducers were included on all flights. Both channels of accelerometer output were present during the reentry portions of the flights. The cause of initial data blackout on one channel has not yet been determined.

Typical data received from the accelerometer after the yaw inducer has functioned is shown in Figure 16. The timing channel and the data channel are shown in the Figure. The yaw inducer was set to function 5 seconds after launch and did function at 5.5 seconds. The expanded portion of the data shows that the signal amplitude did not exceed the calibration pulse amplitude. The accelerations, thus) were less than 1 g. This level of acceleration corresponds to a yaw amplitude less than 4 degrees. The accelerometer signal dies out in about 0.8 second and has superposed on the slowly changing signal a higher frequency component of about 25 Hz. The HARP 5-1 projectile is fin-stabilized with slightly beveled fins to ,produce a slow roll of about 5 - 10 rps. On the other hand, the natural pitching frequency of the projectile is about 20 Hz at 6 kilometers altitude. This is approximately where the yaw inducer functioned. From these considerations, we can identify the 25 Hz ripple signal as the mutational motion while the slowly changing dominant signal is the precessional motion.

Several flights of the HARP 5-1 vehicle have produced similar results on a single axis of the accelerometer. These data are being reduced and analyzed while mathematical models to interpret the data are being developed. From a first look at the raw data, the results seem consistent with what is known about the 5-1 projectile.

Discussion and Conclusions The solar aspect sensing yawsonde is now almost a routine instrument for observing the dynamical behavior of projectiles over their entire trajectories. It suffers from the inconvenience of requiring that every projectile be modified to accept the antenna system as well as the solar sensors themselves. A simpler yawsonde, which is not quite as versatile but which can be applied to a large variety of artillery shell without modifying the shell, has been developed by the Harry Diamond Laboratories (6,15) and used on a large number of firings with success. The Harry Diamond sonde, modeled after an original British design, uses a pinhole camera principle to admit light onto a photosensitive surface masked in the form of a V. The amplified pulses are of the same polarity and directly modulate the RF carrier. This design is being modified by Picatinny Arsenal and the Ballistic Research Laboratories to include a VCO for FM/FM data transmission. Some modifications to the internal geometry of the device are being considered.

The capability of the solar sonde to produce information over an entire flight and the current capability to extract aerodynamic coefficients from the flight data have made this sonde a valuable tool for aerodynamic research. With the incorporation of the Harry Diamond sonde into our test programs, our in-flight measurement capability will be extended to developmental work and perhaps also to commanders of artillery units in the field. The reliability of the sondes to produce data is reasonably high. Only two out of twenty versions of the Ballistic Research Labs solar sonde have failed in flight and only one of thirty of the Harry Diamond sondes has failed.

The accelerometer yawsonde is still in the developmental stage. More work is needed to determine the cause of single channel failure early on in the flight. The most serious drawback of the present circuitry for accelerometer measurements is the location of the in-flight calibrator which is situated after the amplifier and before the VCO. If the amplifier gain changes during launch, the amplitude of the accelerometer data would be in error. The frequency characteristics of the data would still, however, be correct. A solution to the problem would be to install the calibrator ahead of the amplifier and methods for fabricating a low level calibrator are currently being explored.

Since the accelerometer instrument uses piezoelectric crystals with FET's coupled to the crystals, it cannot reproduce constant accelerations. If a projectile is rolling at a constant rate, the rolling motion of the shell will not be observed by the accelerometer instrument. To obtain roll data, current plans call for a combined solar sensing-accelerometer payload for future projectile tests.

The work reported in this paper represents the results of the first attempts to measure the motion of projectiles over long flight paths using g-hardened, on-board instruments. The ability of the electronic payloads to survive accelerations in the neighborhood of 60,000 g, to transmit useful data to ground stations, and the ability to use the data to provide meaningful measurements of the dynamics and aerodynamics of the shell have been demonstrated.

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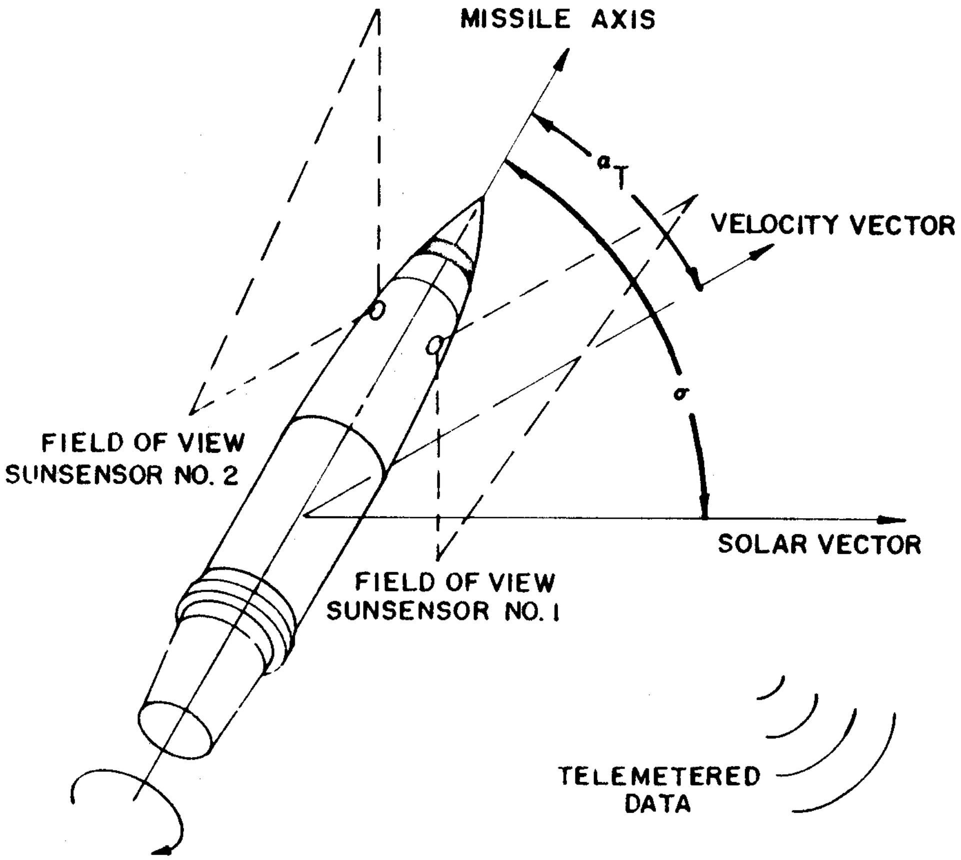


Fig. 1 - Geometry of the Solar Aspect System in Flight.

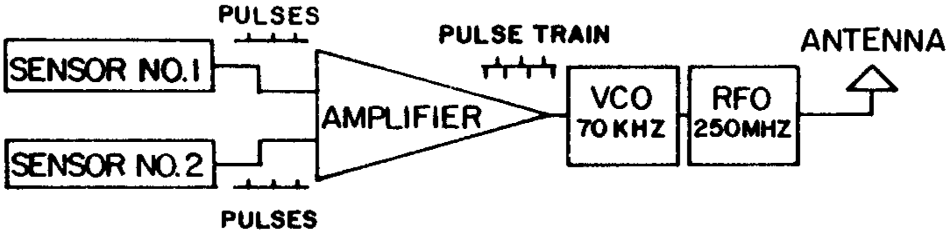
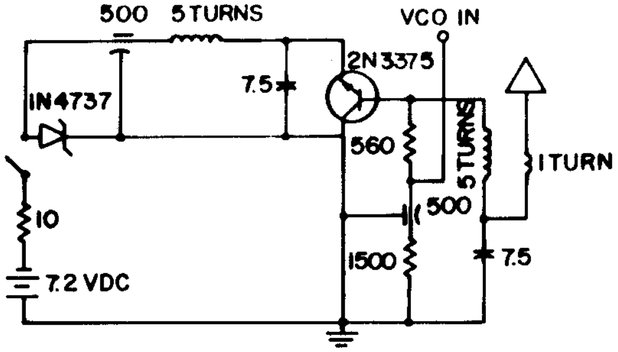
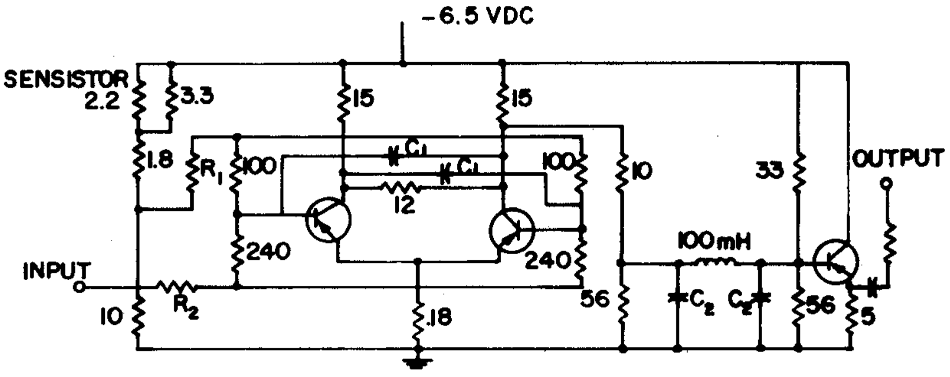


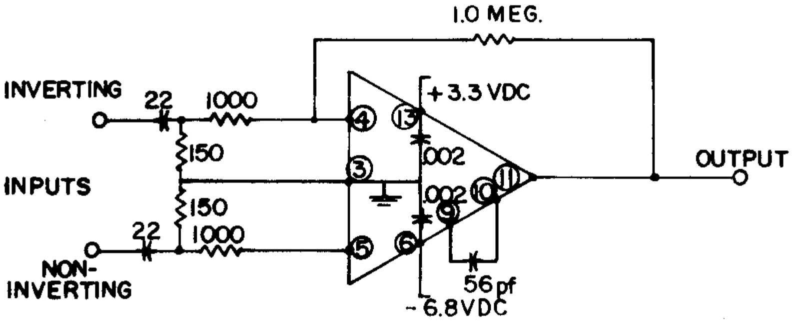
Fig. 2 - Flaw Diagram of the Solar Aspect Sensing Telemeter.



C) RESISTORS IN OHMS
CAPACITORS IN PICOFARADS



B) ALL TRANSISTORS 2N3702
ALL RESISTORS IN K OHMS
R_1, R_2, C_1, C_2 ADJUSTABLE FOR CENTER FREQ.
AND BAND PASS



A) RESISTORS IN OHMS, CAPACITORS IN
MICROFARADS, EXCEPT AS NOTED

Fig. 3 - a) Integrated Circuit Amplifier; b) Voltage-Controlled Oscillator; c) Radio-Frequency Oscillator.

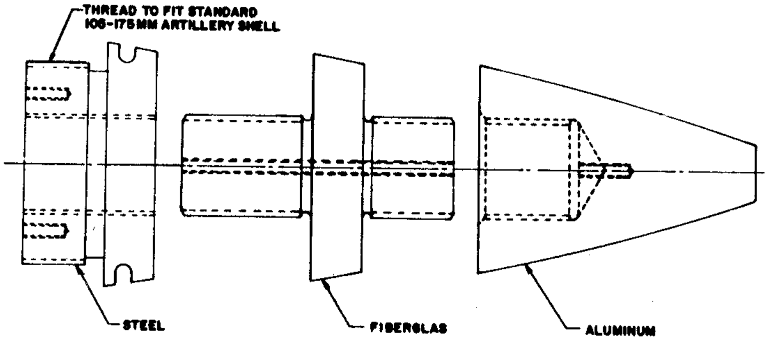


Fig. 4 - Mechanical Details of the Projectile Nose-Antenna System.

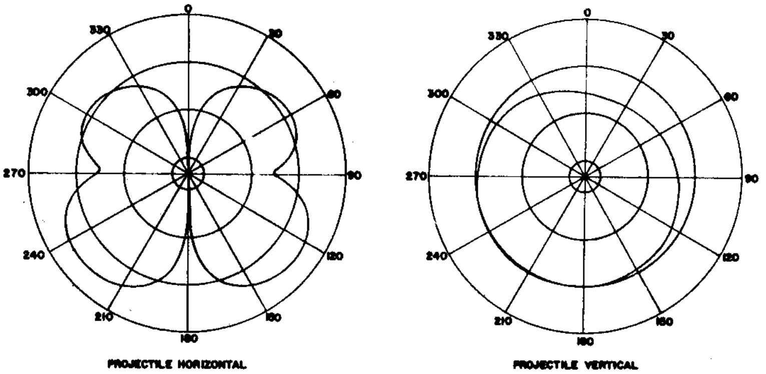


Fig. 5 - Horizontal and Vertical Radiation Pattern for Projectile Nose-Atenna.

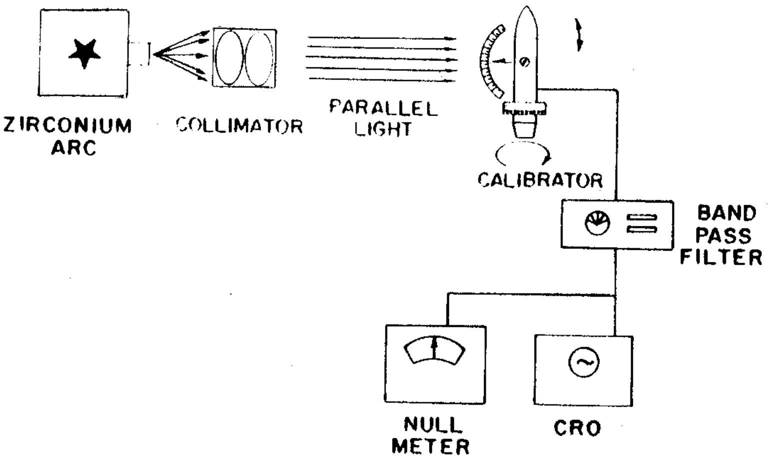


Fig. 6 - Calibration Setup for Solar Sensor Yawsondes.

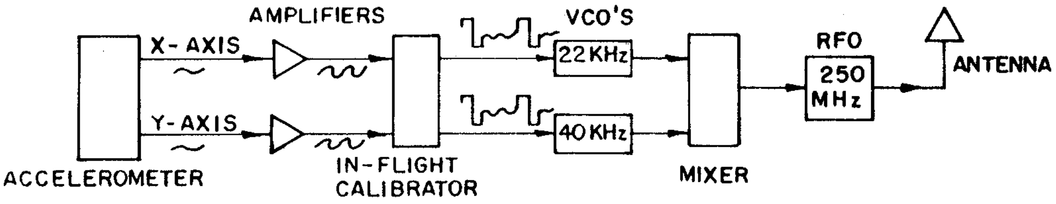


Fig. 7 - Flow Diagram of the Accelerometer Sensing Yawsonde.

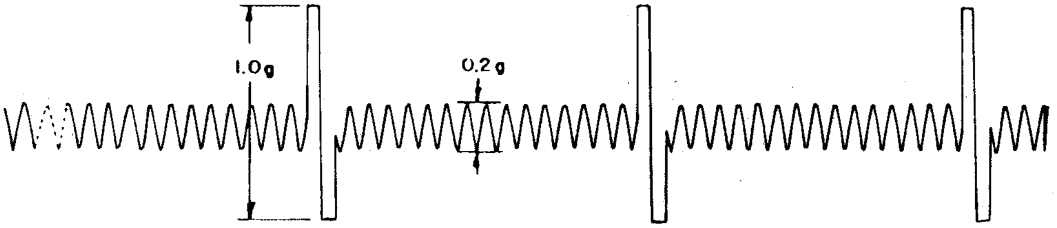


Fig. 8 - A Sample of Calibration Data From One Accelerometer Channel Showing the In-Flight Calibrator Reference Pulses.

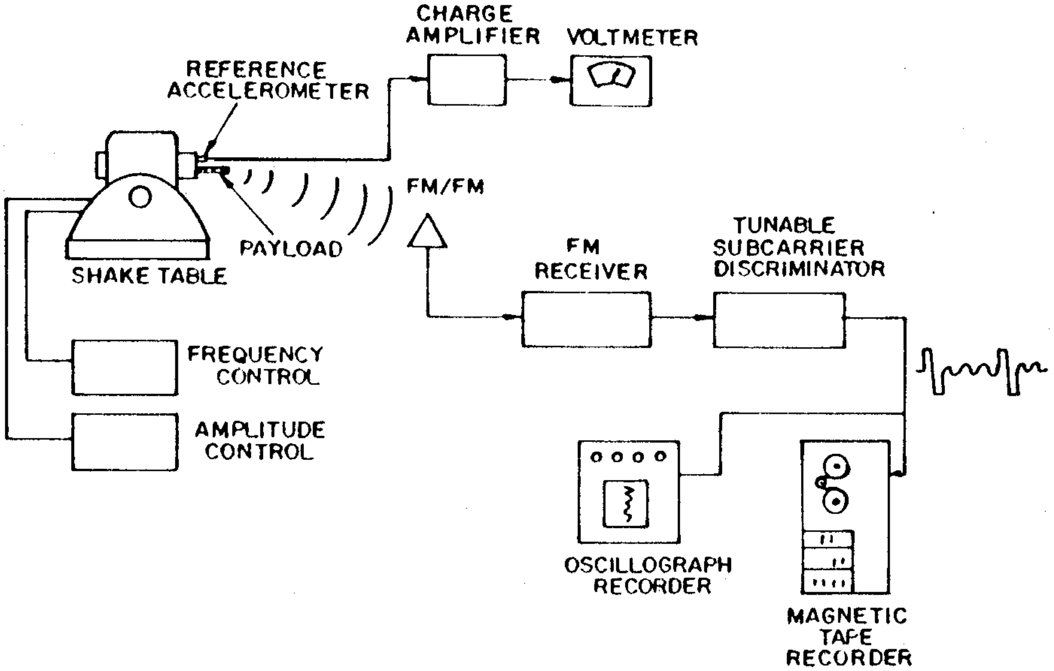


Fig. 9 - Calibration Setup for Accelerometer Yawsondes.

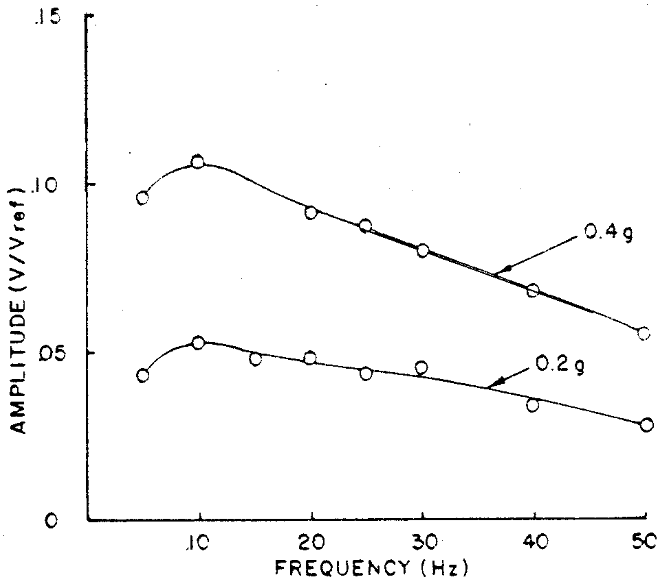


Fig. 10 - Frequency Response of a Typical Accelerometer at Two Levels of Acceleration.

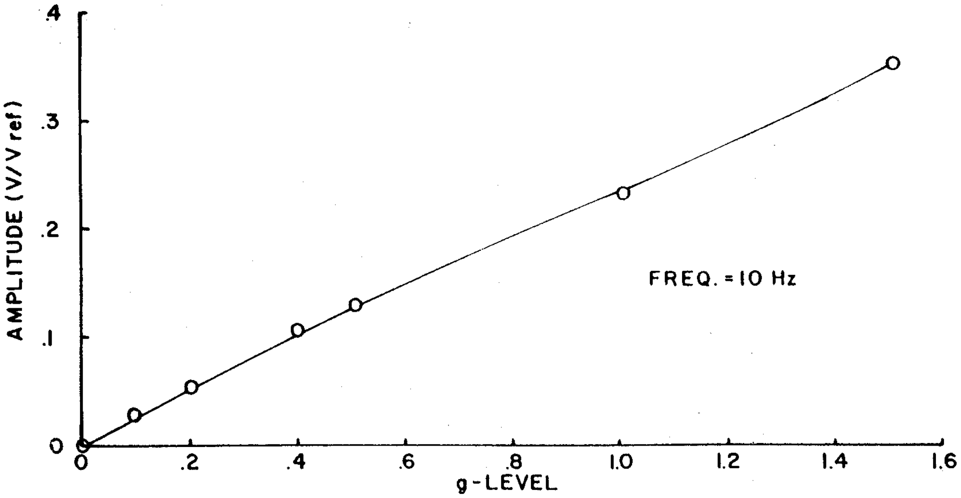


Fig. 11 - Amplitude Response of a Typical Accelerometer at a Fixed Frequency.

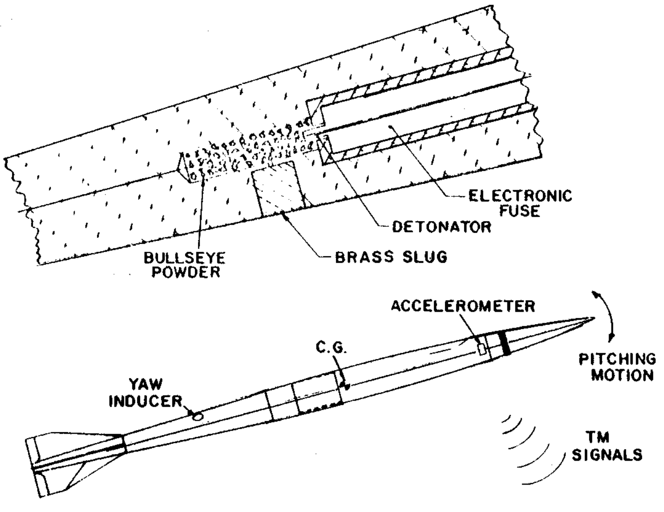


Fig. 12 - The In-flight Yaw Inducer on Board the Projectile with Exploded View.

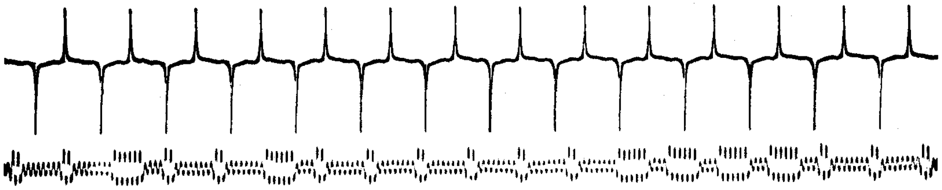


Fig. 13 - Sun Sensor Pulse Train from Test E1-5127- Only Several Pulses Out of 3800 Are Shown. Reference Timing Signal Is Also Shown.

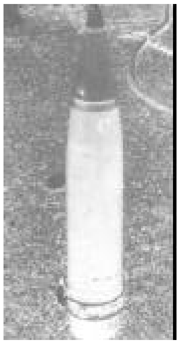


Fig. 14 - Photograph of the 155MM Projectile Showing One of the Two Solar Aspect Sensors.

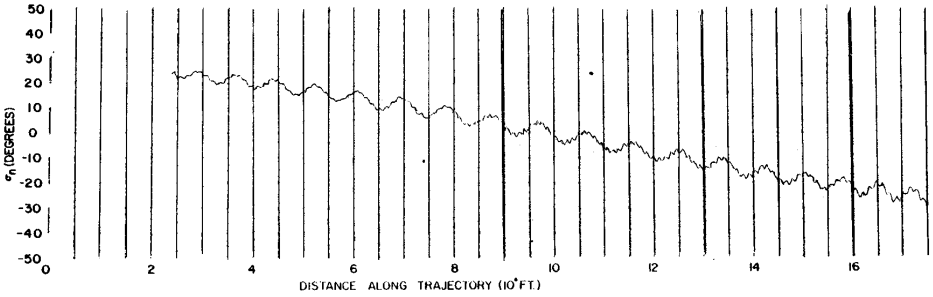


Fig. 15 - Data from the Entire Flight of Test E1-5127. The Normal Solar Aspect Angle is Plotted Versus Distance Along the Trajectory.

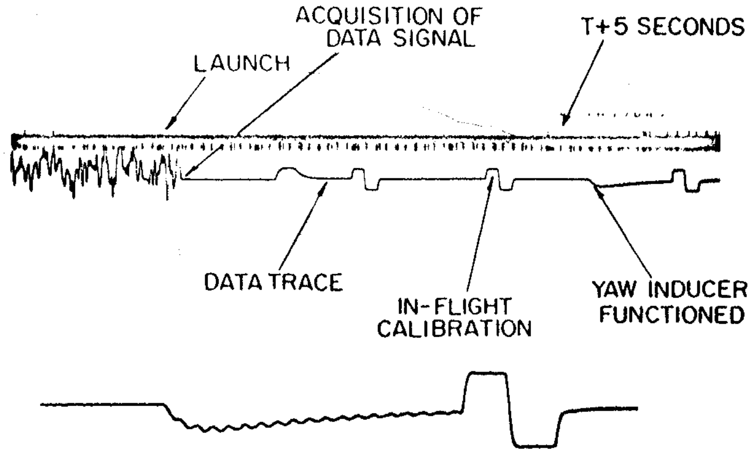


Fig. 16 - Accelerometer Data Received from the Firing of a HARP 5-1 Projectile The Exploded View Shows Only the Accelerometer Signal During Yaw Response.