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Multisensor Pinhole Yawsonde

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The yawsonde is a device used at the U.S. Army Research Laboratory (ARL) to investigate the in-flight behavior of spinning projectiles. The standard yawsonde consists of a pair of solar cells and slits that respond to solar rays. The sun is used as an inertial reference to measure the pitching and yawing motions of the projectile. An FM telemetry package transmits the sensor data to a ground receiving station for analysis. The standard yawsonde package is housed in an M577-type artillery fuse body. The spinning motion of the projectile serves as the sampling rate for the measurements. When the spin rate is not significantly higher than the yaw rate, multiple sets of sensors must be used to effectively increase the sampling rate. The multiple-sensor pinhole yawsonde was developed for projectiles that require multiple sets of sensors in a very limited space. This pinhole yawsonde consists of a number of sensors located behind pinholes placed around the projectile's circumference. Since each pinhole makes a yaw measurement, many measurements, or samples, are taken with each projectile spin revolution. More pinhole sensors may be added to increase the measurement sampling rate. One application of this yawsonde is to aid in evaluating the performance of tactical devices and inertial systems onboard projectiles with limited space for instrumentation.

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PREFACE

On 30 September 1992, the U.S. Army Ballistic Research Laboratory (BRL) was deactivated and subsequently became part of the U.S. Army Research Laboratory (ARL) on 1 October 1992.

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ACKNOWLEDGMENTS

The authors are indebted to Mr. Fred Brandon, Mr. Raymond Von Walde, Mr. Malcolm A. Steele, and Mr. Vural Oskay of the Weapons Technology Directorate (WTD), U.S. Army Research Laboratory (ARL), for offering insight during the development of this sensor. The authors are also indebted to Mr. Lawrence Burke, Mr. David Vasquez, Mr. Eric Irwin, Mr. Charles Mitchell, Mr. Jonah Faust, and Mr. James Bowen, all of WTD, ARL, for their collective effort in providing electronic design, fabrication, and packaging of the signal conditioning and telemeter circuits used to gun qualify this sensor.

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1. INTRODUCTION

The yawsonde is a device that was used at the U.S. Army Ballistic Research Laboratory (BRL) for many years, and is now used at the U.S. Army Research Laboratory (ARL), to investigate the flight dynamics of instrumented projectiles. The yawsonde is an electro-optical device that uses the sun as a reference point to measure the in-flight yaw, pitch, and rolling motion of finned and spin-stabilized projectiles. The components of a yawsonde include a number of silicon photo-sensitive cells (solar cells), a fixture to hold the cells and to provide a suitable optical field of view, and a mounting arrangement on the projectile or shell that provides a geometry such that the yawsonde output is sensitive to projectile yaw and spinning motion. Associated with yawsondes are signal conditioning circuits and a radio frequency telemeter that transmits voltage signal outputs from the yawsonde to ground receiving stations for processing.

This report will very briefly discuss yawsondes that have been used at BRL, including what became the BRL standard yawsonde and early pinhole yawsondes. The remainder of the report will describe a multisensor, pinhole yawsonde design that is being developed at the ARL for applications in which the standard BRL yawsonde is not suitable. Details of the signal conditioning electronics and the telemetry link will not be presented here.

2. GENERAL DISCUSSION ON YAWSONDES

A yawsonde is designed to measure the angle between a projectile's roll axis and a vector originating at the center of gravity of the projectile and ending at the sun (the solar vector). This angle is called the *solar aspect angle* (σ). The solar aspect angle will change during the flight of the projectile. It changes because of trajectory effects and because of the motion of the projectile's roll axis about its velocity vector. Figure 1 illustrates the solar aspect angle and the effects of projectile trajectory on the solar aspect angle.

Generally, a yawsonde requires at least two sensors and a fixture that defines an optical field of view for each sensor. A sensor generates a voltage pulse every time it sees the sun. The signals from both sensors are conditioned, combined, and transmitted to a ground receiving station by a telemeter on the projectile. Figure 2 illustrates this process with a simple block diagram. The resultant output of the yawsonde is a train of pulses, usually bipolar pulses (also illustrated in Figure 2). The geometry in which

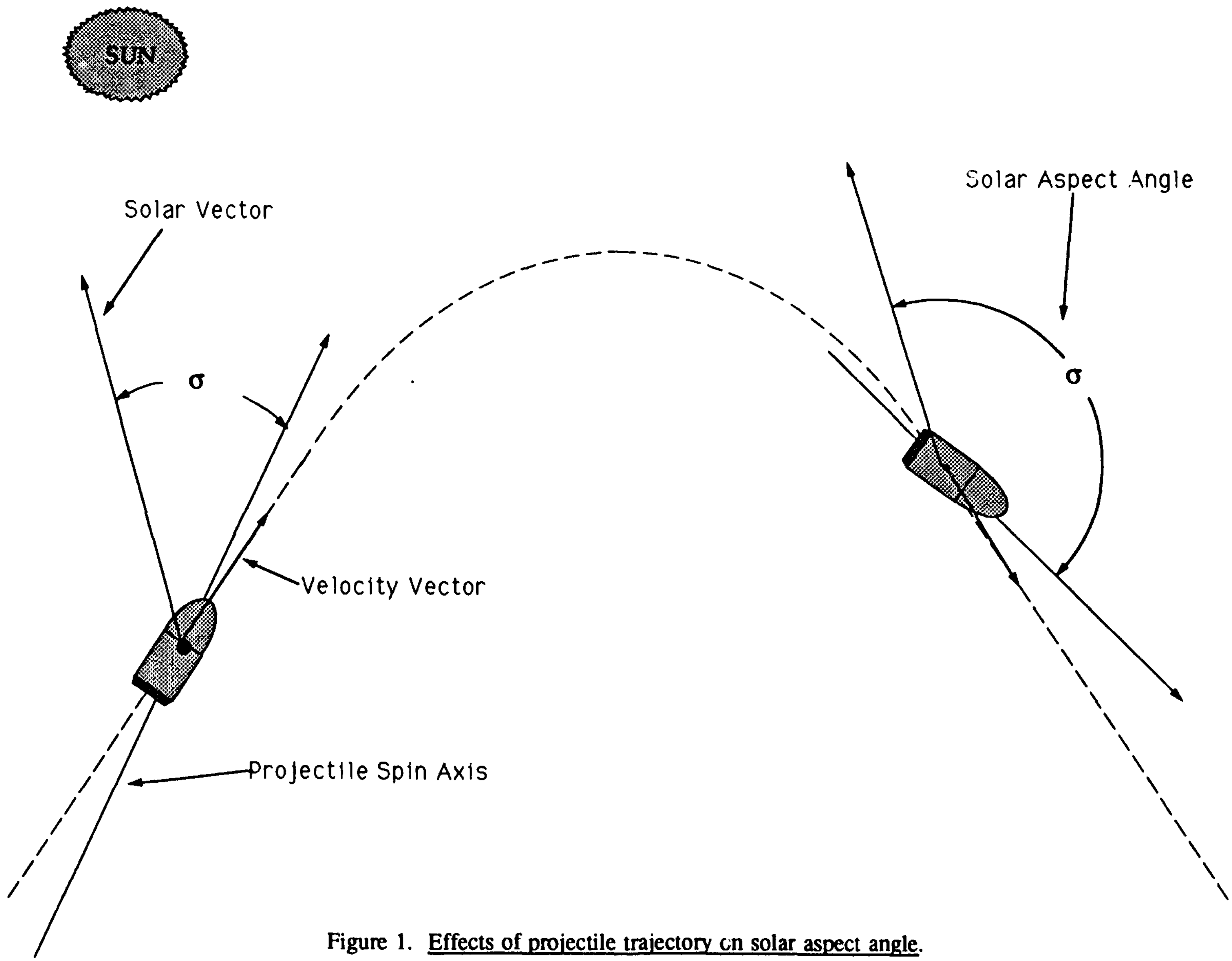

Figure 1. Effects of projectile trajectory cn solar aspect angle.

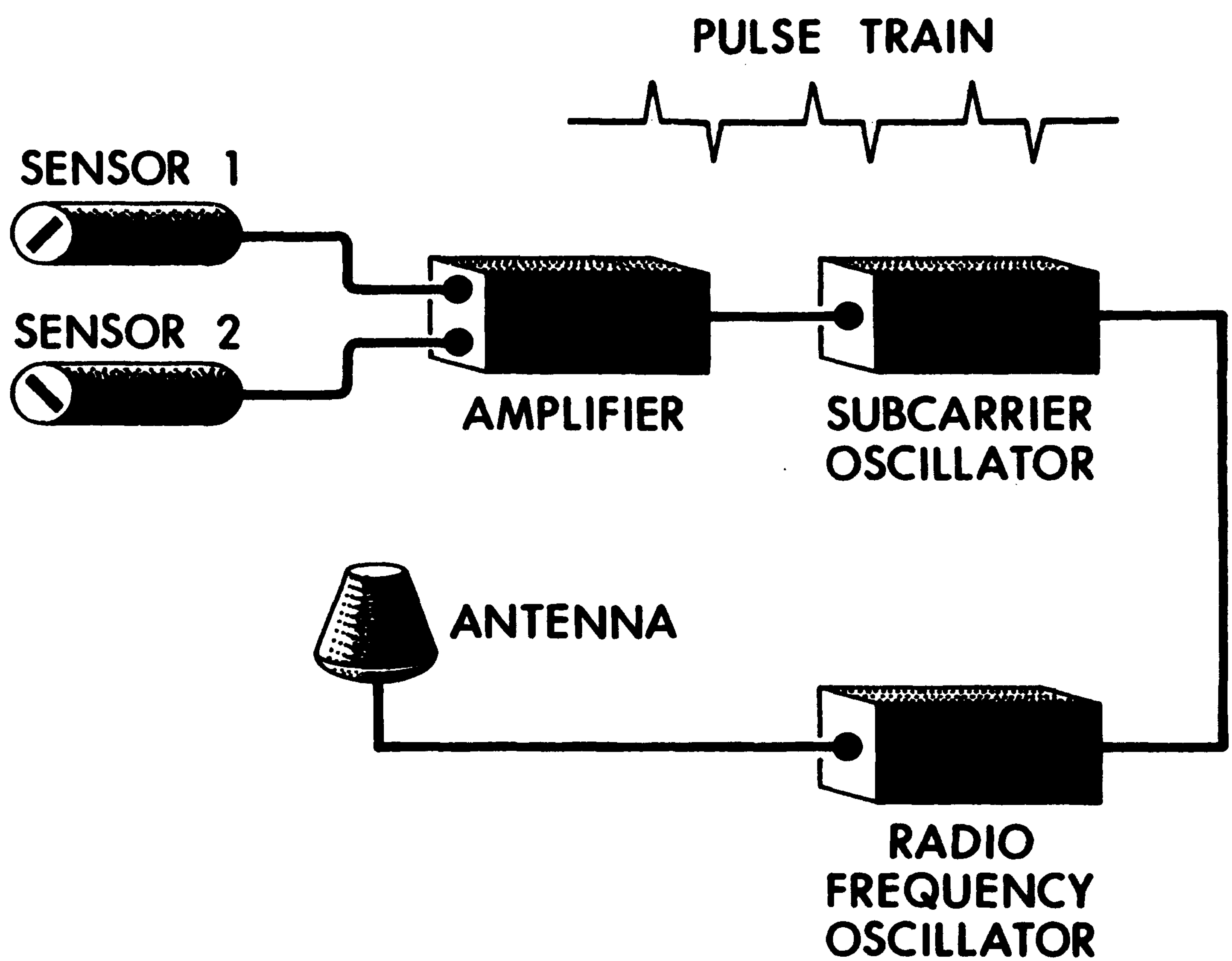

Figure 2. Sensor data transmitting process.

the sensors are mounted makes the duty cycle of this pulse train sensitive to the solar aspect angle. The yawsonde requires that the projectile be spinning in order to measure the solar aspect angle. Since the yawsonde uses the sun and the spin rate of the projectile as a sampling mechanism, the spin rate should be at least 10 times the maximum yaw frequency in order to resolve yaw amplitudes.

In the early 1970s, BRL used both pinhole yawsondes developed by the Harry Diamond Laboratory (HDL) and a yawsonde developed at BRL itself. The BRL yawsonde was more adaptable to the wide variety of applications and became the standard for BRL in basic yawsonde technology. Figure 3a is a photograph of a standard BRL nose-fuse yawsonde, and Figure 3b is a photograph of the HDL pinhole yawsonde. These two types of yawsonde differ mainly with the geometry and technique of making the sensor outputs sensitive to changes in solar aspect angle, although they both require the volume of a standard fuse for an artillery projectile.

Detailed descriptions of BRL yawsondes are given in Mermagen (1971), Mermagen and Clay (1974), and the details of the HDL pinhole yawsonde are given in Elmore (1971) and Clay (1973). Simply put, the basic BRL yawsonde uses two separate sensors, with planar fields of view mounted with their optic axis, making an angle of 80–90° with respect to the roll axis (this angle can be varied) and with an angular spacing of usually 180° between the two optic axes (this angle is variable as well). The sensitivity to yaw arises out of the inclination of the slits that define the field of view for each sensor, with respect to the roll axis. The pinhole concept utilizes a pinhole in the surface of the projectile or projectile fuse and a sensor or sensors mounted directly below the pinhole. The surface of the sensor(s) is masked so that only a small area in the shape of a "V" is sensitive to light. As the projectile spins, an image of the pinhole traverses the two legs of the "V," generating a voltage pulse each time. A train of pulses whose duty cycle is proportional to solar aspect angle is produced.

The end result of both the HDL pinhole yawsonde and the BRL yawsonde is the same. Only the mechanism of achieving it is different. Figure 4 is a plot of typical yawsonde data that could be produced by these systems. Note that the vertical axis is labeled "Sigma-N." Sigma-N (σ_n) is the complement of σ (i.e., $\sigma_n = 90^\circ - \sigma$). Plotting σ_n produces a graphical zero, which represents the middle of the yawsonde's field of view. The bias in the plot is produced by trajectory curvature, and the sinusoidal waveform represents projectile yawing motion.

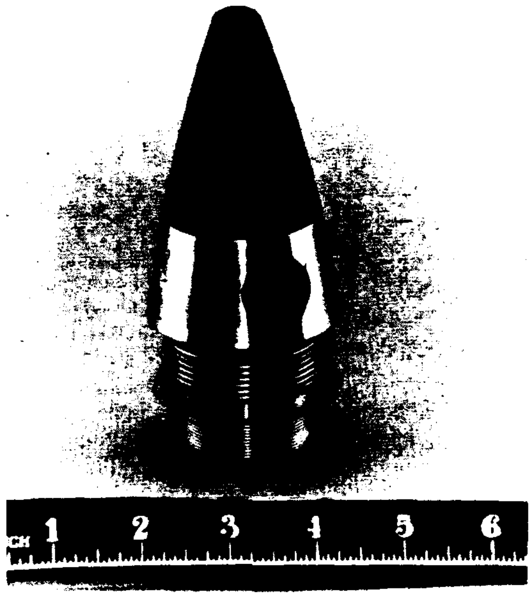

Figure 3a. Standard BRL yawsonde.

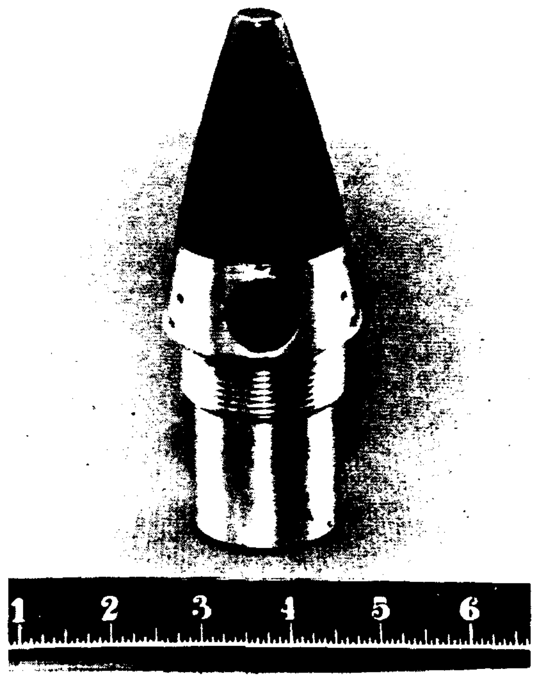

Figure 3b. HDL pinhole yawsonde.

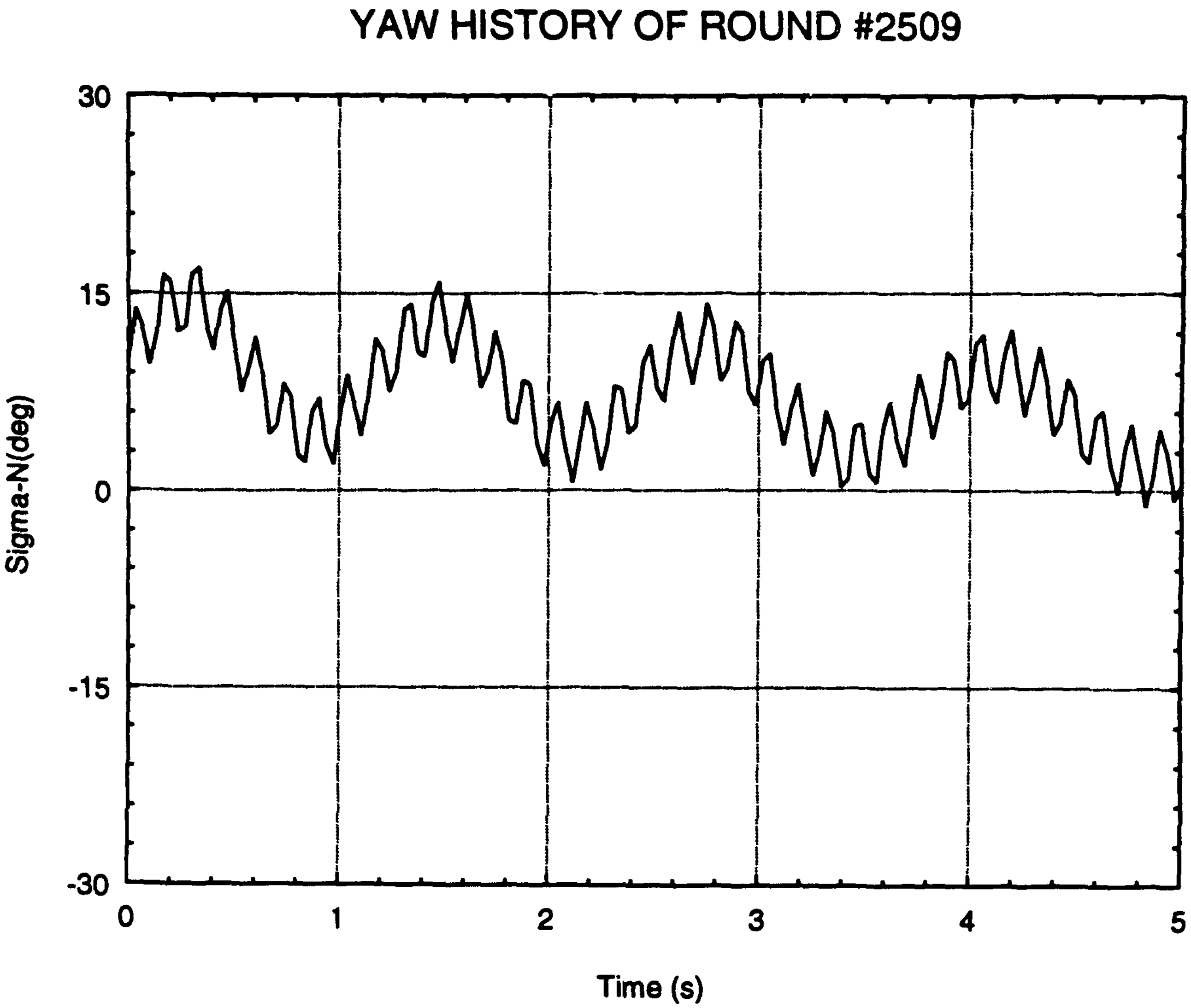

Figure 4. Plot of typical yawsonde data.

3. MULTISENSOR PINHOLE YAWSONDE

There are advanced munitions being developed that could benefit from a yawsonde measurement system onboard to aid in testing during their development cycle. These include HEAT rounds and kinetic energy projectiles. Kinetic energy projectiles are usually long, slender, solid rounds with very little space available for instrumentation. The BRL and the HDL yawsondes (Mermagen 1971; Mermagen and Clay 1974; Elmore 1971; Clay 1973) mentioned above are physically too large to use in some of the advanced munitions. In some cases, the spin to yaw rate ratio (steady state) of the projectile is less than 10, so in order to sample the yaw properly, multiple yawsondes must be installed. This compounds the lack of space problem. For this reason, the basic pinhole yawsonde concept was investigated and modified to develop a miniature multiple-sensor pinhole yawsonde that can be used to investigate the yawing and spinning motion of a variety of advanced munition projectiles. This report further describes the multisensor pinhole yawsonde.

The BRL pinhole sun sensor is comprised of four major components: the pinhole plug, the mask, the solar cells, and the body. The actual shape and dimensions of the body vary with the projectile dimensions and the number of sun sensors that are desired. This sun sensor may, therefore, be configured in several different ways.

The four-sensor configuration contains four sun sensors which provide the resolution needed for measuring the yaw motion of projectiles with spin to yaw rate ratios of 2.5 or more. Figure 5 shows the components of this sun sensor. The pinhole plug is the first component shown. It helps to define the yawsonde's field of view and furnishes the pinhole through which a small beam of light may pass. There is a conical void within the pinhole plug. This void defines the bounds in which the light that passes through the pinhole may travel. The pinhole plug is threaded and screws into the body of the test projectile. Two spanner wrench holes are provided to allow the plug to be screwed into place.

The mask is a thin, nonelectrically conductive, opaque material with three areas cut out of it. The two longest cutouts form a shape similar to the letter "V." The width of each of these two cutouts is the diameter of the pinhole. The third cutout area is used to align the mask over the solar cells. The "V" shape in the mask is what permits the measurement of projectile yawing motion. An explanation of this mechanism will appear later in this report. The angle between the "V" legs was determined by choosing the angle that would use the most solar cell surface and, therefore, provide the widest yaw angle measuring range.

The solar cells produce a voltage whenever they are exposed to light. Two solar cells are required for each pinhole sensor, one for each "V" leg of the mask. The solar cells are also wired with opposite polarity. This causes them to output voltages of opposite sense, that is, one cell will produce positive voltages and the other will produce negative voltages. This bipolar output facilitates spin direction monitoring. There is a brass plate on the back of each solar cell that helps to keep them from fracturing under the shock of a gun launch.

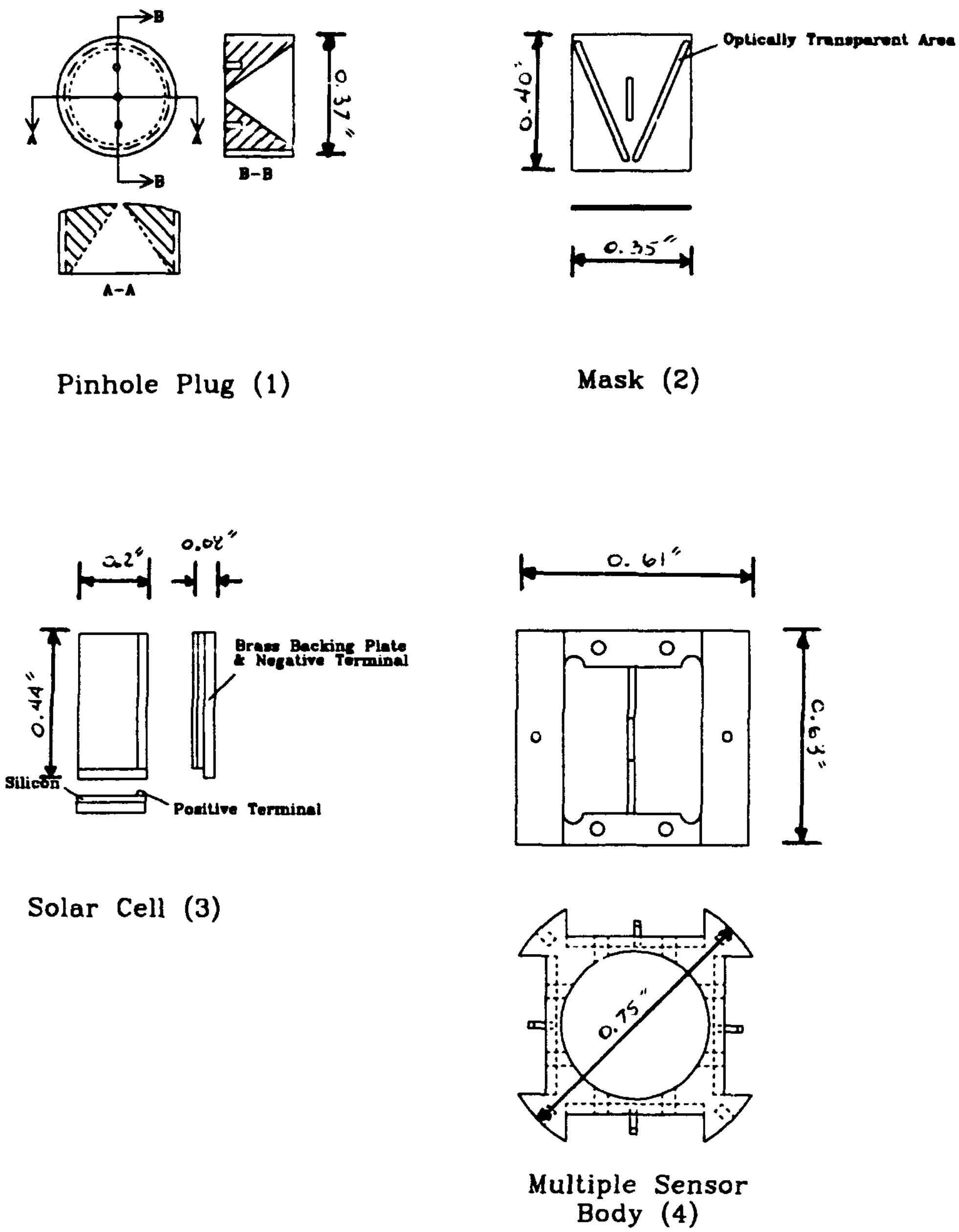

Figure 5. <u>Principle components of the multisensor pinhole yawsonde</u>.

The multiple-sensor body holds the solar cells and the masks and further defines the field of view of each sensor. It has holes in it so that indexing screws may be used to secure and align the body in the test projectile. The body is hollow in the middle to allow wires to pass through. Although the body shown in Figure 5 is for a four-sensor pinhole yawsonde, the configuration may be modified to accommodate any number of sensors. These modifications, however, are dependent upon space availability within the test projectile and will affect the yawsonde's measurement characteristics. The configuration shown was designed to fit into a projectile with an inner diameter of 0.75 inches.

Figure 6 shows all of the four-sensor pinhole yawsonde parts assembled in a projectile. This configuration provides each sensor with a 56° field of view and allows measurement of σ_n ($90^\circ - \sigma$) values in the range of $\pm 24^\circ$. The height of the sensor body is 0.7 inches.

The pinhole yawsonde relies on the projectile spin motion to make the yaw measurements. Since the projectile is spinning, whenever the solar vector enters the sensors' field of view, a beam of light sweeps across the masked solar cells. Figure 7 illustrates how the beam of light sweeps across the mask as the projectile spins. This beam of light cuts across the "V" legs at different places, depending upon the projectile yaw angle, or solar aspect angle. Figure 8a shows two extreme yaw angles for a projectile. Figure 8b shows two extreme paths that may be taken by the beam of light as it crosses the "V" legs. A voltage pulse is produced by one of the solar cells each time the light beam crosses a "V" leg. When the beam crosses one leg, a positive pulse is produced, and when the beam crosses the other leg, a negative pulse is produced. An ideal set of pulses for extreme yaw angles is shown in Figure 8c.

Figure 9 shows the basic geometry of one of the pinhole yawsonde sensors. From this geometry, it can be shown that the distance between the "V" legs is defined by the equation:

$$y(\sigma) = 2\alpha \, (L\tan(\sigma) + X),$$

where $y(\sigma)$ is the "V" leg separation as a function of σ,

σ is the projectile yaw angle, or the solar aspect angle,

α is the half angle of the "V" at its vertex,

L is the distance from the pinhole to the "V" mask, and

X is the distance from the projection of the pinhole onto the "V" mask to the vertex of the "V".

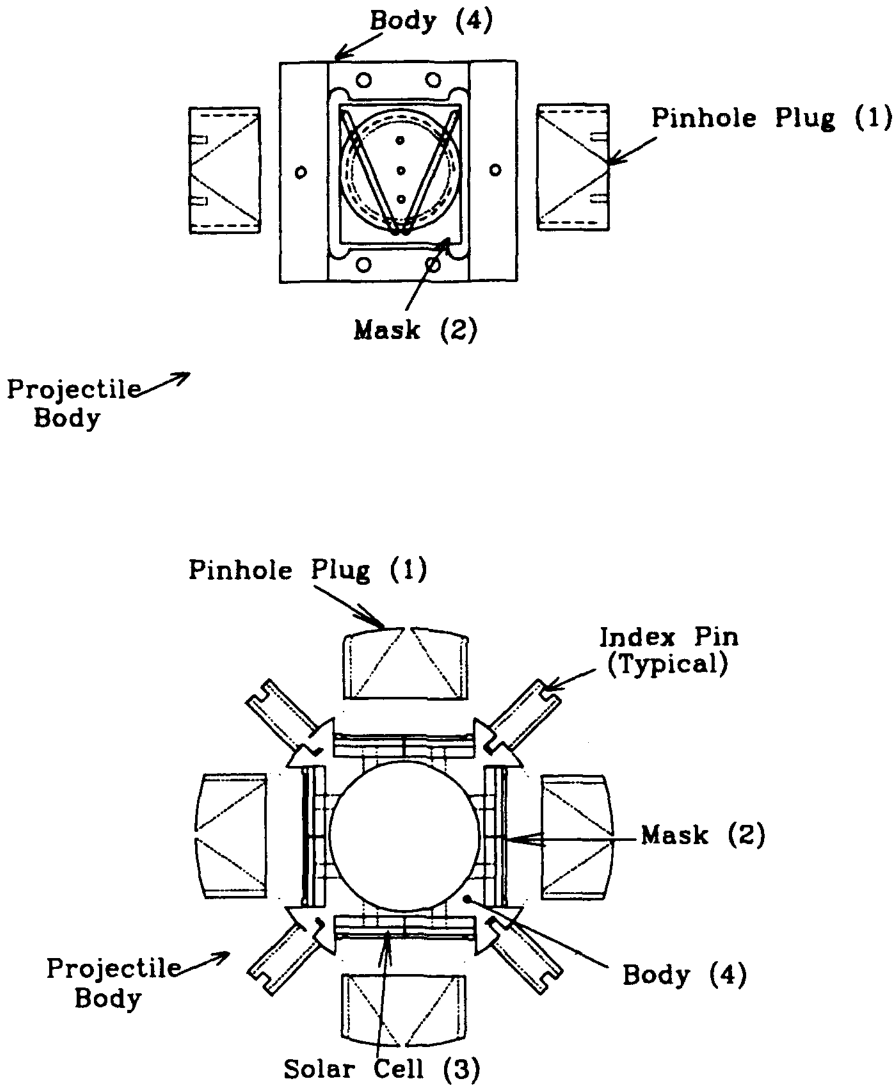

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Figure 6. Assembled four-sensor configuration.

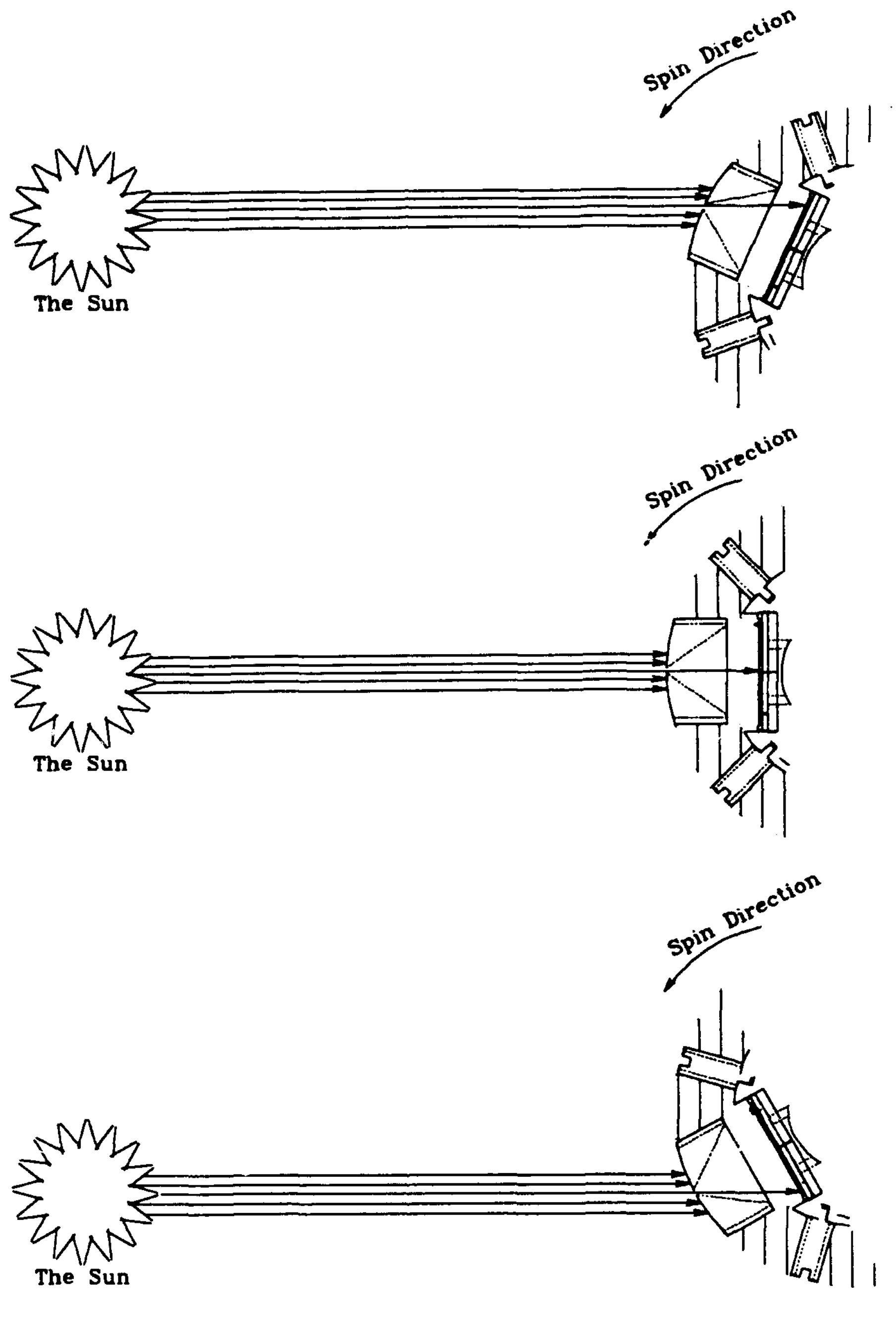


Figure 7. Light beam sweeping across the mask as the projectile spins.

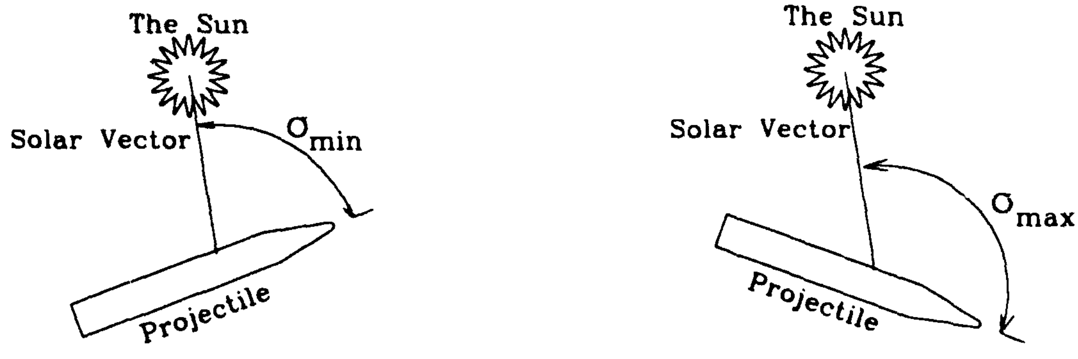


Figure 8a. Projectile at two extreme yaw angles.

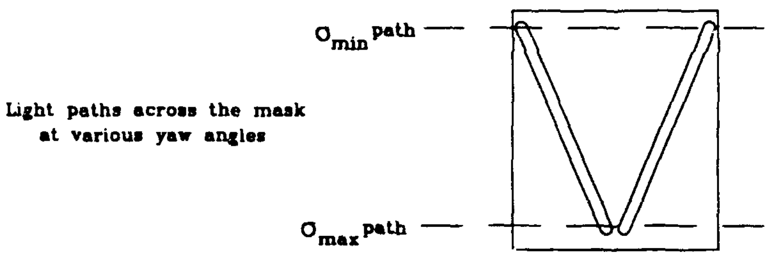


Figure 8b. Two extreme paths which may be taken by the beam of light.

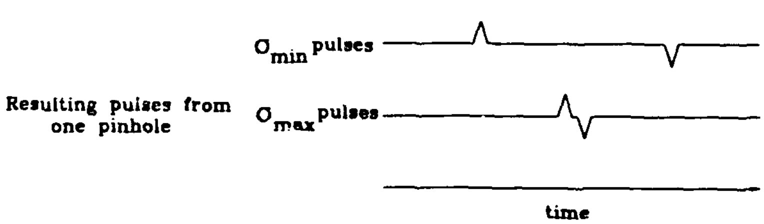


Figure 8c. Resulting pulses generated by the extreme yaw angles.

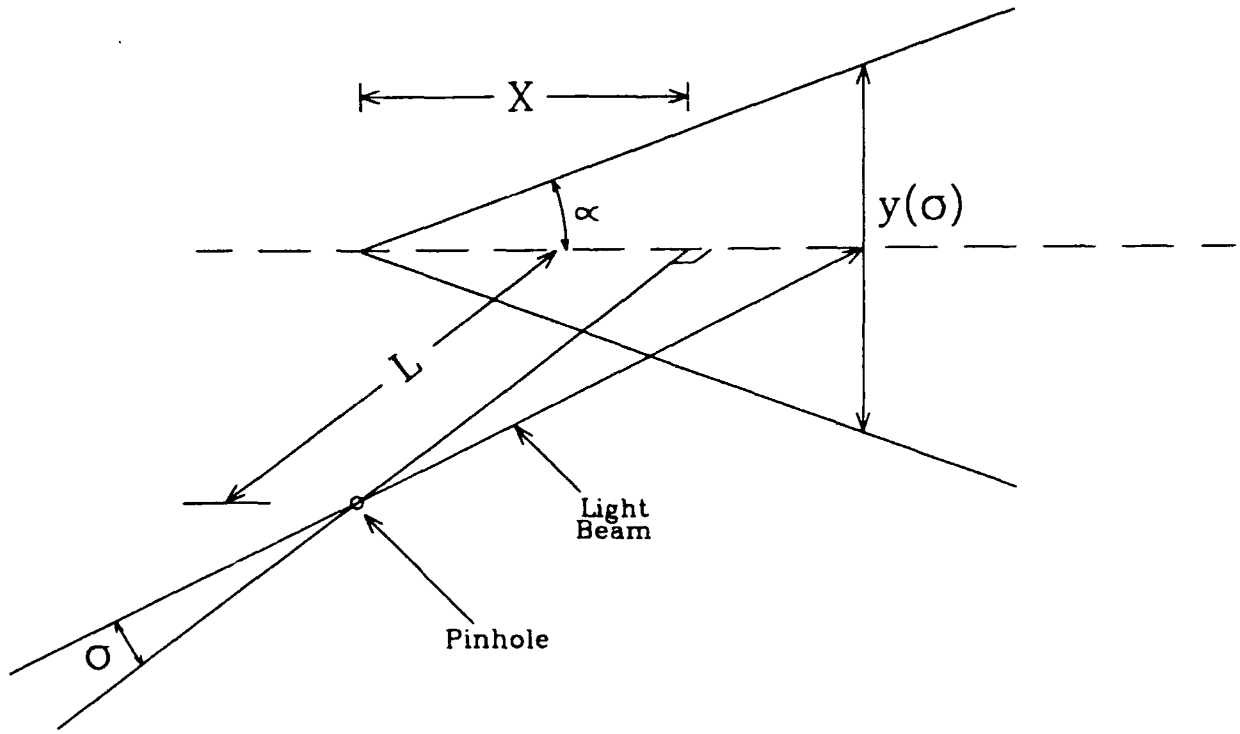


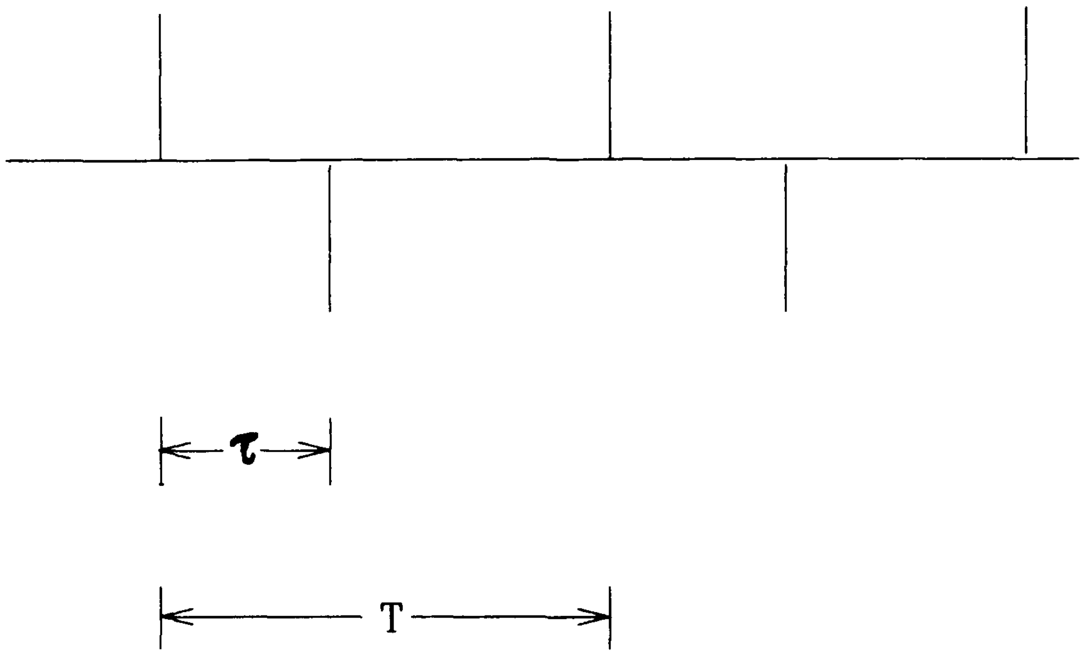
Figure 9. Basic geometry of the pinhole yawsonde sensors.

At a constant projectile spin rate, the time between pulses will be proportional to the separation between the two legs of the "V," and σ can be easily determined. When most projectiles are fired, however, the spin rate will vary with time. This causes the absolute pulse spacing to change. To determine σ in this case, it is assumed that the projectile spin rate does not change rapidly as the sun goes from one pinhole to the next. Using this assumption, we can measure the ratio of τ to T, where τ is the time from a positive pulse to the next negative pulse, and T is the time from a positive pulse to the next positive pulse (Figure 10). Using this ratio allows σ to be determined regardless of the spin rate since τ/T is constant for all spin rates. The solar aspect angle, σ, may be determined with more sophisticated algorithms when the spin rate changes rapidly by first determining the spin rate and acceleration.

4. TESTING

The four-sensor pinhole yawsonde was successfully tested on a cantilevered roll drive assembly positioned in the path of sunlight. Figures 11a and 11b show pulse trains that were generated by this yawsonde when it was positioned at two different solar aspect angles.

Idealized Pulse Train



The ratio τ/T does not vary with spin rate, but does vary with Solar Aspect Angle σ.

Figure 10. Measurements taken to yield a spin-independent value which varies with σ.

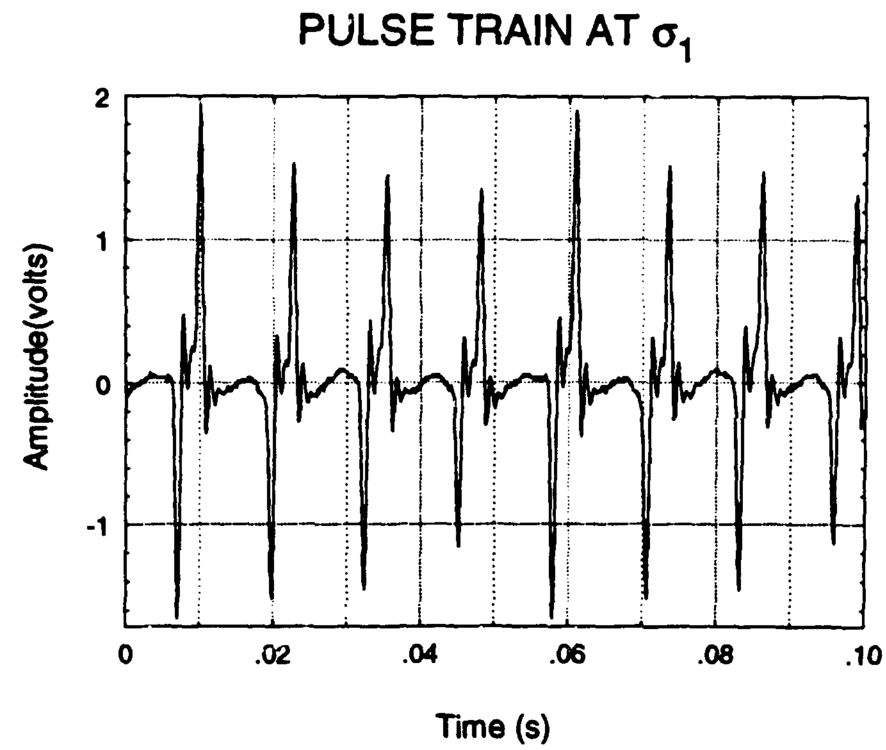


Figure 11a. Resulting pulse train from position σ_1.

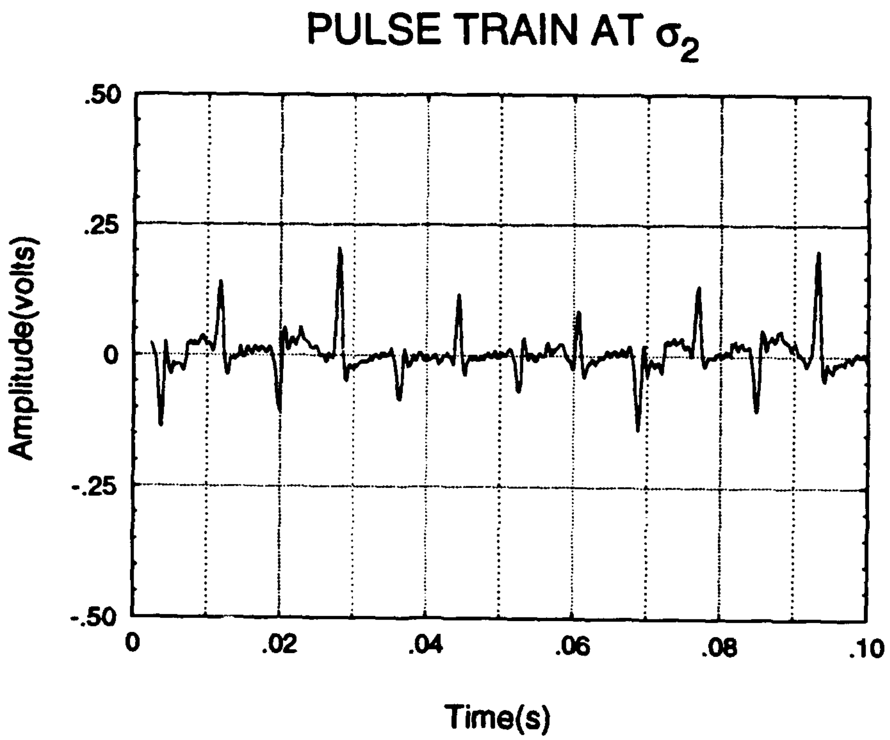


Figure 11b. Resulting pulse train from position σ_2.

The four-sensor pinhole yawsonde was gun tested on 10 July 1992. The yawsonde was mounted in the spike of a modified DM-18 round. The spike was used to simulate the geometry of a kinetic energy round. The electronics required to transmit the yawsonde data were miniaturized, with the use of surface mount technology, to a size that could fit this restrictive geometry as well. Figure 12 shows how the yawsonde and its associated electronics were arranged in the DM-18 spike.

Both the multiple-sensor pinhole yawsonde and its associated electronics survived a 10,000-g launch. The data received from the yawsonde were typical and indicated that the DM-18 round flew as predicted.

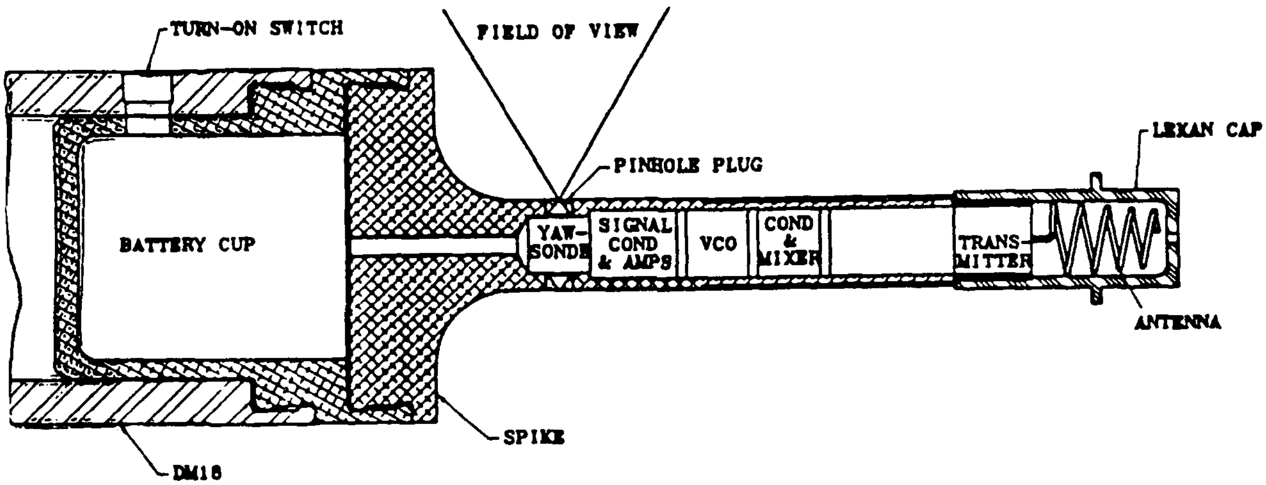


Figure 12. Arrangement of the yawsonde module and associated electronics in the spike of a modified DM-18 round.

5. SUMMARY

A multiple-sensor pinhole yawsonde has been designed for measuring projectile yaw motion of projectiles with limited space and low spin to yaw rate ratios. The multiple-sensor pinhole yawsonde discussed in this report focused on the four-sensor configuration, but it can be configured to meet as many sensor requirements as space permits.

In addition to early shock testing, spin testing, and several computer simulations, the four-sensor pinhole yawsonde was gun launched in a modified DM-18 round. The yawsonde and its associated electronics, many of which relied on surface mount technology to conserve space, survived a 10,000-g launch. The data received from the yawsonde were typical and indicated that the DM-18 had performed as predicted.

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