PINHOLE YAWSONDE SENSOR

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ABSTRACT

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 pinhole yawsonde sensor 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.

KEY WORDS

Pinhole Yawsonde, Projectile Flight Dynamics, Sensor.

INTRODUCTION

The yawsonde is a device that is 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. The pinhole yawsonde sensor was designed for applications that demand low volume and high data resolution. Such applications are typical of the advanced munitions being developed for modern battle tanks.

YAWSONDE THEORY OF OPERATION

Yawsondes are 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 solar aspect angle.

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 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 on the order of 10 times the maximum yaw frequency in order to resolve yaw amplitudes. Detailed descriptions of yawsondes used by the U.S. Army are given in references 1 and 2.

Figure 3 is a plot of typical processed yawsonde data. Note that the vertical axis is labeled "Sigma-N." Sigma-N (σ_n) is the complement of σ (i.e., $\sigma_n = 90^o - \sigma$). Plotting σ_n produces a graphical zero that 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.

PINHOLE YAWSONDE SENSOR PARTS

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

The four-sensor configuration contains four pinhole 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 4 shows the components of this 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 these cutouts is the diameter of the pinhole. The third cutout area is used to align the mask over the solar cells. The "V" shape of the mask is what permits the measurement of projectile yawing motion. An explanation of this mechanism appears later in this paper. 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.

The multisensor 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 4 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 5 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° - σ) values in the range of $\pm 24^{\circ}$. The height of the multisensor body is 0.63 inches.

PINHOLE YAWSONDE SENSOR THEORY OF OPERATION

The pinhole yawsonde sensor, like all of ARL's yawsonde sensors, 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 6 illustrates how the beam 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 7a shows two extreme yaw angles for a projectile. Figure 7b 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 7c.

Figure 8 shows the basic geometry of a pinhole yawsonde sensor. From this geometry, it can be shown that the distance between the "V" legs is defined by the equation:

$$y(\sigma) = 2 \tan\sigma (L \tan\sigma + X) \qquad (1\text{-}1)$$

where $y(\sigma)$ = "V" leg separation as a function of σ
- σ = projectile yaw angle or solar aspect angle
- α = half angle of the "V" at its vertex
- L = distance from pinhole to the "V" mask
- X = distance from the projection of the pinhole onto the "V" mask to the vertex of the "V."

At a constant projectile spin rate, the time between pulses will be proportional to the separation between the two legs of the "V," and s 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 s 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 between positive and negative pulses and T is the time between positive pulses (Figure 9). Using this ratio allows σ to be determined regardless of the spin rate since τ / T for a particular σ 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 iteratively determining the effect of the varying spin rate.

SUMMARY

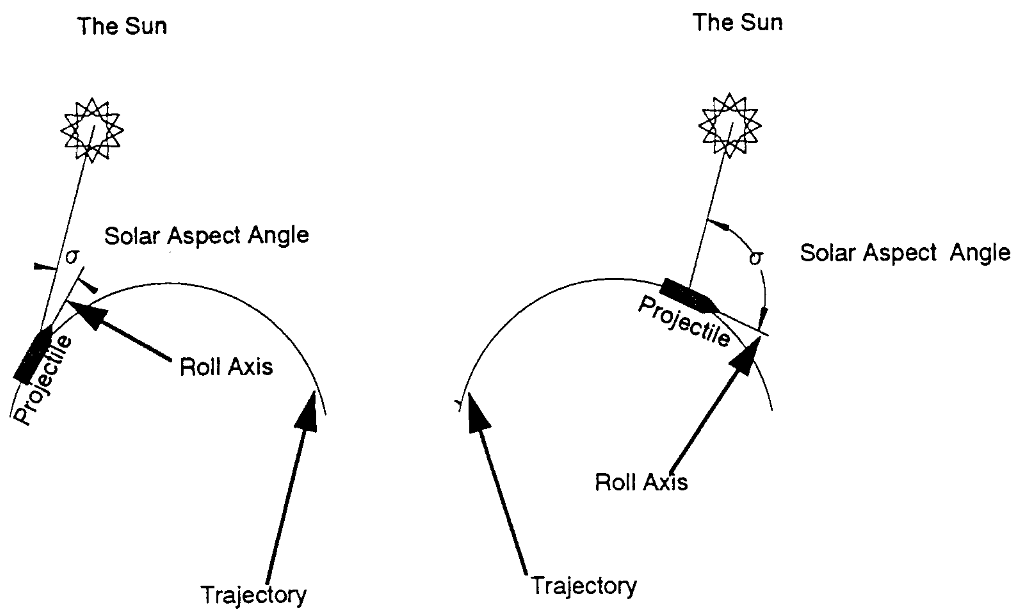
A pinhole yawsonde sensor has been designed for measuring projectile yaw motion of projectiles with limited space and low spin-to-yaw rate ratios. The sensor discussed in this paper focuses on the four-sensor configuration, but it can be configured to meet as many sensor requirements as space permits.

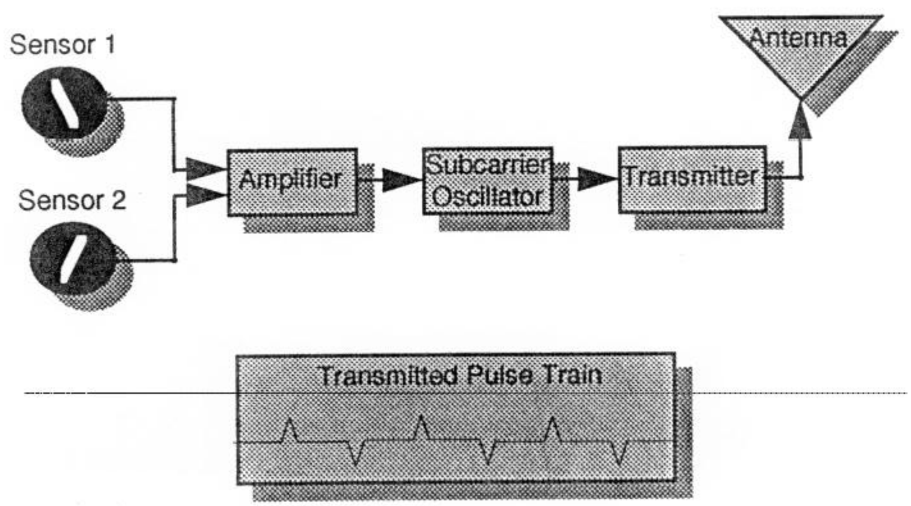
This sensor has been used in testing sponsored by the Army Research Development and Engineering Center (ARDEC) X-Rod program.

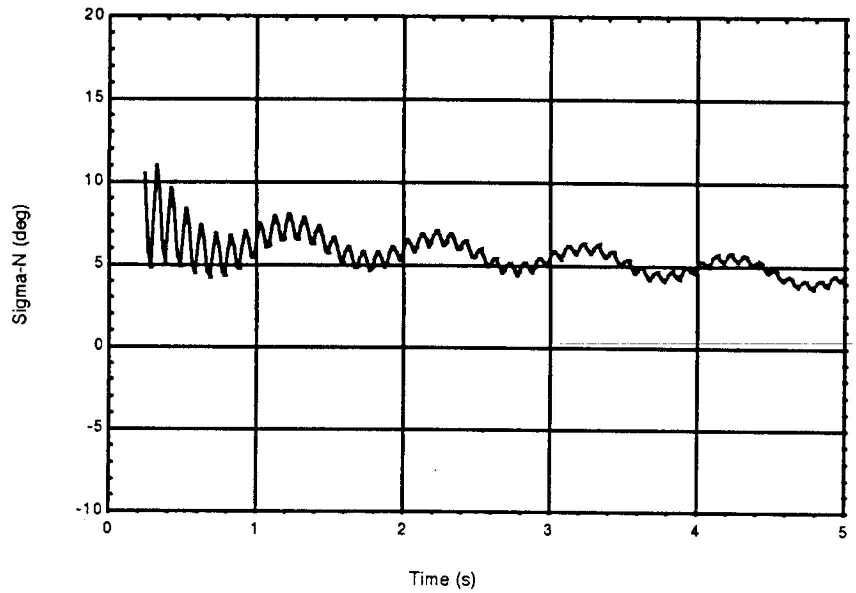
REFERENCES

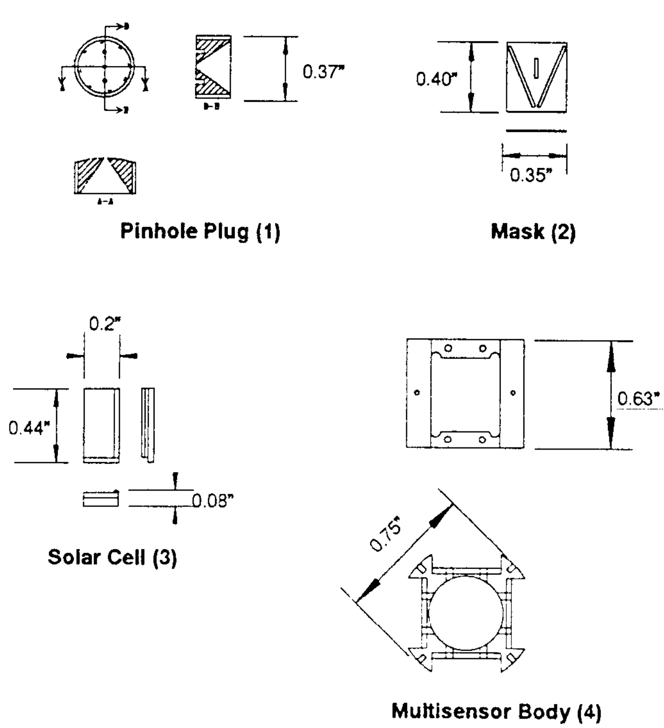
1. Mermagen, W. H. “Measurements of the Dynamical Behavior of Projectiles Over Long Flight Paths,” Journal of Spacecraft and Rockets, Vol. 8, No. 4, pp. 380-385, April 1971.

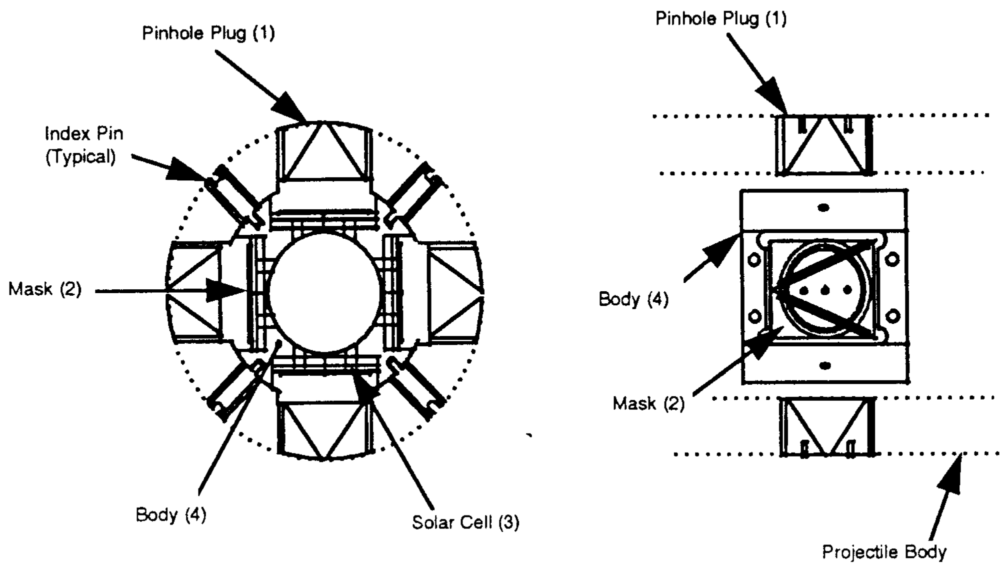
2. Mermagen, W. H., and Clay, W. H. “The Design of a Second Generation Yawsonde,” BRL-MR- 2368, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, April 1974.


The Sun
Solar Aspect Angle
σ
Projectile
Roll Axis
Trajectory
The Sun
σ
Solar Aspect Angle
Projectile
Roll Axis
Trajectory

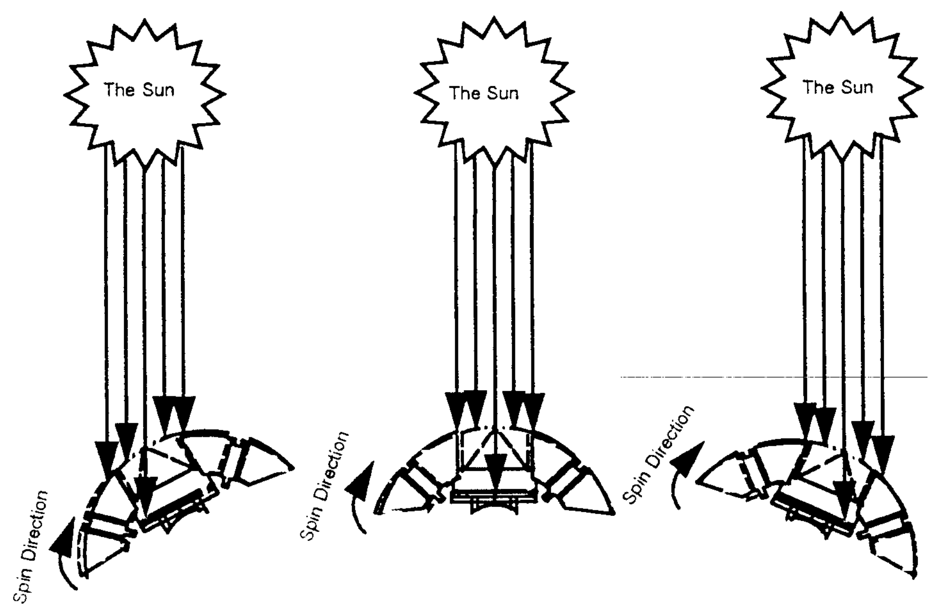

Sensor 1
Sensor 2
Amplifier
Subcarrier Oscillator
Transmitter
Antenna
Transmitted Pulse Train


20
15
10
5
0
-5
-10
0
1
2
3
4
5
Sigma-N (deg)
Time (s)

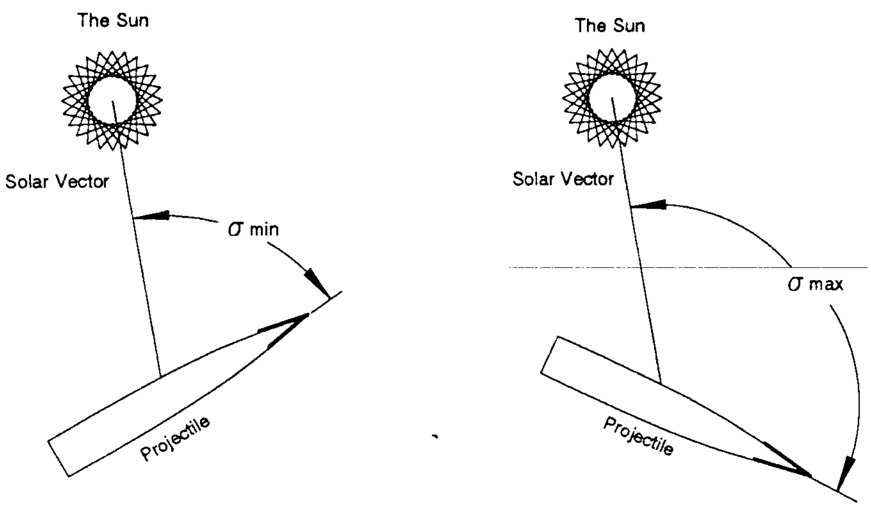

0.37"
0.40"
0.35"
Pinhole Plug (1)
Mask (2)
0.2"
0.44"
0.08"
0.63"
0.75"
Solar Cell (3)
Multisensor Body (4)

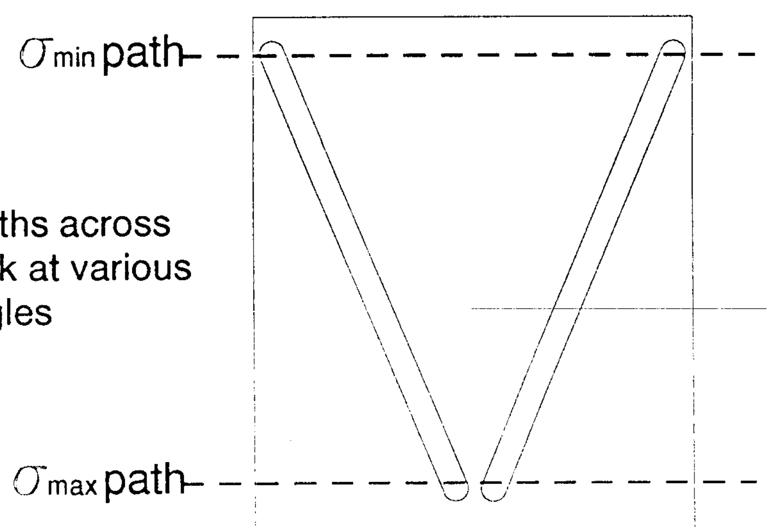


Pinhole Plug (1)
Index Pin
(Typical)
Mask (2)
Body (4)
Solar Cell (3)
Pinhole Plug (1)
Body (4)
Mask (2)
Projectile Body

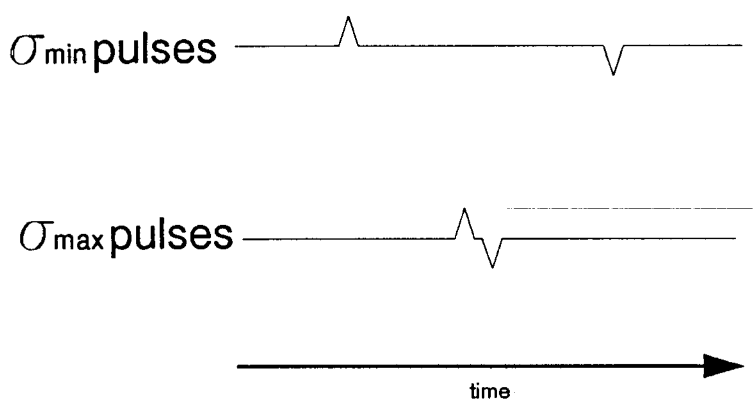


The Sun
Spin Direction
The Sun
Spin Direction
The Sun
Spin Direction

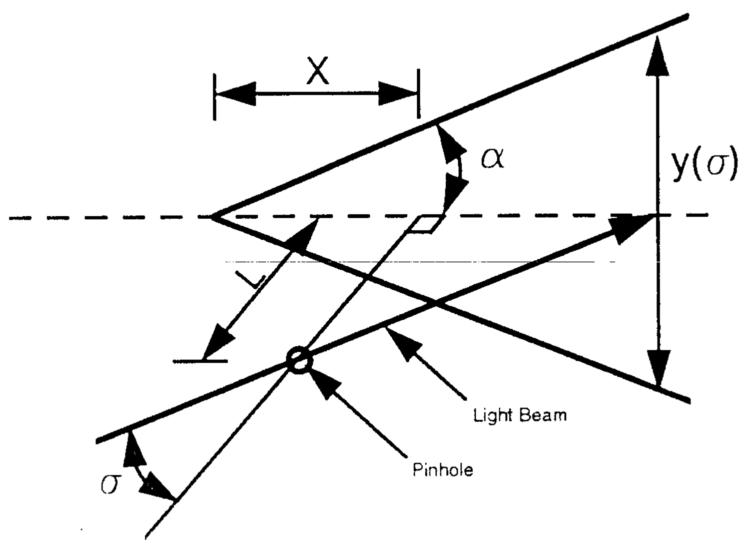




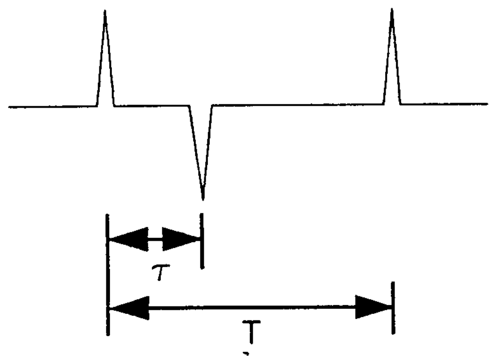
Light paths across the mask at various yaw angles



Resulting pulses from one pinhole



Segment of the Pulse Train



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