USE OF A MAGNETIC AZIMUTH-INDICATOR SYSTEM DEVELOPED FOR BALLOON PAYLOADS OF THE PLANETARY ENTRY PARACHUTE SYSTEM

By Wayne L. Darnell

NASA Langley Research Center

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ABSTRACT

An azimuth-sensing system was used for continuous, ground monitoring of the azimuth orientation of the balloon-borne Planetary Entry Parachute Program (PEPP) spacecraft. The system utilized two magnetic field sensors located in the spacecraft so as to produce a unique set of voltage outputs for any azimuth. Electronics onboard the spacecraft encoded the magnetometer outputs and fed the encoded signal to a C-band modulator which imposed the intelligence onto the radar tracking beacon pulses. A conviently located ground radar received the modulated pulses and the magnetometer outputs were reproduced after demodulation. For fast, direct readout, an X-Y plotter was calibrated to cross plot the reproduced signal of the two magnetometers on a combination rectangular-polar graph indicating the correct true azimuth in real time. The method was used successfully on three of the PEPP balloon-borne spacecraft to determine when the spacecraft was pointed in the most advantageous direction for release from the balloon, at 130,000 feet altitude. The use of such a system of azimuth monitoring is suitable to balloon payloads which are virtually stable with respect to the horizontal but may be rotating about the vertical axis. Angular accuracies within $\pm 10^\circ$ could generally be expected.

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The Planetary Entry Parachute Program, conducted by NASA's Langley Research Center, required the flight testing of several types of parachutes which were considered candidates for Mars entry decelerators. The program also required that the initial deployment of these chutes take place in the wake produced behind a large blunt body simulating a typical Mars entry spacecraft. The method selected to place this large spacecraft at the necessary altitude for testing was to carry it aloft under a large balloon system.

The task of providing a balloon system that could place the PEPP spacecraft at the desired test point was given to AFCRL. Figure 1 shows a sketch of the typical flight configuration used. The spacecraft, a 15 ft diameter conical body, was rigidly mounted on the balloon system load bar. The load bar-spacecraft was suspended in flight under an open safety chute which was attached to the base of the main balloon. In flight the spacecraft-load bar was free to rotate about its line of suspension in the manner of a torsional pendulum. In order to perform the parachute testing the spacecraft was attached under the load bar at an angle of 60° upward and also equipped with rocket motors. When the balloon system attained the desired altitude the spacecraft was released by remote command. Figure 2 shows the spacecraft under the main balloon just after its release at 130,000 ft altitude. Following the release, the rocket motors propelled the spacecraft several miles further upward and approximately 10 miles to the side in the direction it was pointed at release. To assure that the azimuthal direction which the spacecraft would take would not violate flight safety requirements or produce unfavorable impact locations of the flight items a spacecraft azimuth monitoring system was required. This system needed to either be able to control the azimuth of the rotating spacecraft at its release point or else be able to provide real time flight azimuth data on the spacecraft to a ground control station so that the release of the spacecraft could be made to occur only when the spacecraft had rotated itself into the most favorable direction. Due to its simplicity this second possibility was pursued. This paper will present information on a magnetic-azimuth sensing system developed for this need and the flight results obtained with it. Application of this azimuth sensing method to other balloon payloads will be discussed.

The components of the azimuth indicator system are shown in the block diagram of figure 3. Two magnetometers provided signal voltage combinations which varied with the azimuth of the spacecraft. Next the two signal voltages were sequentially pulse position modulated by the encoder. This signal was then transmitted to the ground by a C-band telesponder. The telesponder was keyed to reply only to the interrogations of a specially equipped ground radar. On the ground the selected C-band radar received the modulated telesponder output. At the radar station demodulation of incoming pulses took place and the stripped off signal was available for decoding. The two reproduced magnetometer voltages were fed into digital volt meters and an x-y plotting machine for visual display. A digital to analog converter fed the voltage to a strip chart recorder or magnetic tape recorder.

The heart of the azimuth sensing system was the magnetometers themselves and involved the concept of how they could be adapted to produce a useful voltage-azimuth relation. The magnetometers used for the PEPP flights are shown in figure 4. Each magnetometer consists of an electronic unit and a magnetic field sensor. The magnetometers used had a sensitivity of 4 millivolts per milligauss and a magnetic field sensing range of ± 600 milligauss. The signal output from the electronic unit is biased about 2.4 volts so that the output signal centers about 2.4 volts at 0 milligauss and will reach 0 and 5 volts at the extremes of +600 and -600 milligauss.

It was anticipated that the balloon system would be very stable after reaching high altitudes and that only a slow turning of the spacecraft would take place. With this premise, the two probes were mounted rigidly on the frame of the spacecraft, situated so that they would both lie in a common horizontal plane when the spacecraft was suspended in its normal flight attitude under the balloon. The north pole of probe 1 was pointed in the direction of the spacecraft nose while probe 2 was rotated 90° clockwise. In this installation, both probes were expected to sense only the horizontal component of the earth's magnetic field.

When the probes were rotated through 360° in the horizontal plane their variation of voltage output with pointing azimuth was the simple cosine curve shown in figure 5. It should be noted that the azimuth indicating sensitivity varied over the curve, being greatest on the straight line portions of the curve. Also it can be seen that the curve is double-valued requiring a selection of the proper azimuth for each voltage produced. The proper azimuth can be found by looking at the azimuth values resulting from the two probes simultaneously (fig. 6). When the two probes are positioned 90° apart as in the spacecraft, their two voltages will represent four spacecraft azimuth values, two of which will match to within the accuracy of the system. This matching set of two azimuths indicate the azimuth of the spacecraft which is 70° in the example shown in figure 6. The remaining two azimuth values can be discarded. This method of azimuth matching was used on the first flight to determine spacecraft azimuth. However, it proved to be too slow to provide the advance predictions required. Post flight analysis revealed that the flight 1 spacecraft rotated much more rapidly than had been anticipated. A faster azimuth readout procedure was required. Further study revealed that by properly cross-plotting the voltages from each probe on a combination polar-rectangular graph, the azimuth of the spacecraft could be given directly. Figure 7 shows a typical layout of the graph. The voltages of probe no. 1 were plotted on the vertical scale and those of probe no. 2 on the horizontal. Combinations of any two voltage values resulting from the probe arrangement in this spacecraft will produce points on the graph that lie on the polar circle. Their location on the circle indicates the azimuth of the spacecraft. Use of this graphical azimuth indicating method offered two important advantages: (1) The maximum sensitivity portions of the cosine curves of both probes are used to maximum advantage in determining the spacecraft azimuth, (2) Because, in actual usage, the points indicating spacecraft azimuth do not always fall exactly on the polar circle, the distance of their displacement from the circle provides an indication of the relative validity of the points as they are plotted. To take advantage of this plotting method an x-y plotter was ranged and phased to automatically plot the spacecraft's azimuth in real time during the flight. This left only the need for reading off azimuthal bearings at selected time intervals to provide a time-azimuth relationship from which advance spacecraft azimuths could be predicted during the period leading up to its release from the balloon.

Before each launch a magnetometer calibration was performed. For this operation, the spacecraft was supported on a ground fixture in the same position it would have while under the balloon during flight. With the magnetometers installed and the spacecraft telesponder operating as in flight, the spacecraft and fixture were rotated through 360° over a compass rose. Ground receiving electronics matching those of the radar site were used to reproduce the two probe voltages providing a voltage to spacecraft azimuth relationship. These calibration data were used to scale the x and y coordinates on the x-y plotter graph for flight use and to make post-flight conversions of the voltages recorded during flight.

Four PEPP balloon flights were made during the summers of 1966 and 1967. The balloon launchings were made at Walker Air Force Base, New Mexico and prevailing winds allowed the spacecraft release to occur over a target drop above White Sands Missile Range approximately 100 miles away. The transit time to the drop point required 3 - 3 1/2 hours. At approximately 40 minutes before the anticipated release point, all remaining ballast was dumped allowing the balloon to stabilize at 130,000 ft. At 30 minutes before anticipated release monitoring of the spacecraft azimuth began. Personnel located at the x-y recorder at the ground receiving radar made azimuth readings off the polar graph each 15 seconds. These values were plotted simultaneously on a large time graph in the balloon control room showing the pointing azimuth of the spacecraft as it approached the target drop area. The trend of the spacecraft's azimuth was extrapolated to the release point and corrected as necessary. When only a few minutes remained before anticipated release, holds were called as required to produce a spacecraft azimuth at release as favorable as possible.

The flight results on the spacecraft's azimuth as taken from the x-y plotter are shown in figure 8.

Independent azimuth data available from onboard camera film beginning just after release showed agreement between the magnetic sensor and the camera data to within 1°, 2°, and 6° for the three flights on which camera data were available.

Errors which may be produced by this magnetic azimuth sensing system may result from three areas. These are outlined as follows:

A. Ground calibration operation

B. Flight environment changes

   1. Altitude effects

   2. Temperature effects

   3. Magnetic field changes

C. Spacecraft pitching during flight

Calibration errors involve the inaccuracies of the instruments and probes but result mainly from how well the probe voltages can be ranged and centered on the x-y plotter's graph to represent the actual calibration curve. Slight magnetic field anomalies were present in the area of calibration. These tended to require a calibration circle for the x-y plotter which was slightly distorted or had bumps. Since it was not possible to duplicate this with the x-y plotter some amount of azimuth error would result. For the PEPP flights the resulting azimuth errors were as great as 6° for a severe distortion although the error for normal portions of the circle was 0°-2°.

The environment which the spacecraft sees at 130,000 ft is quite different from that during ground calibration. Because the magnetic field strength of the earth decreases with altitude it was found that a 2% loss of field strength was effected at 130,000 ft. In addition, wide variations in temperature were felt by the spacecraft during its flight. At some locations on the spacecraft temperatures were higher than on the ground while at others they were much lower. To overcome such difficulties the more temperature sensitive electronics on the spacecraft were located in temperature controlled boxes. Also to be considered is the variation of magnetic field strength and declination at different points over the surface of the earth. This effect was found to be capable of producing a maximum of 1° of error for the distance traversed from launch to the drop point. The effects from all three of these environmental factors were small enough to be considered negligible for the accuracy requirement needed for the PEPP flights.

Pitching motions of the spacecraft during azimuth monitoring offered the possibility for the greatest error. The probes in the spacecraft were expected to measure only the component of total magnetic field in the plane in which they lay, which was the horizontal component of the field for zero pitch of the spacecraft. In the case of a slightly pitched condition, the probes would sum the pitch angle components of the horizontal and vertical magnetic field. This generally resulted in a milligauss value greater than that for an unpitched condition since the vertical component of the magnetic field is much stronger than the horizontal. Consequently, an erroneous azimuth will be indicated. The amount of error due to the pitching will depend on the spacecraft's azimuth, the angle of pitch, and the azimuth of the pitch axis. The most severe error results from the condition where the azimuth of the pitch axis is at right angles to the direction of magnetic north or south. Figure 9 presents a plot of the spacecraft azimuth error produced for several values of pitch angle for the case where the azimuth of the pitch axis is at right angles to the direction of magnetic north or south. Because the spacecraft's azimuth values are essentially determined from magnetometer probe orientations falling between 45° and 90° (due to the application of fig. 7) the peak errors seen in figure 9 would not be expected to occur. For the PEPP flights, even after dumping ballast, the pitch oscillation appeared to be less than ±2° during the measuring period.

Certainly a prerequisite for the use of such a system would be that the pitching motion be maintained below 2°. Although additional complexities arise a third magnetometer on the vertical axis could be considered for definition of pitching motions or for swinging payloads which exceed 2° pitch.

The system as presented was a passive system only but could be adapted to seek a magnetic bearing in order to provide orientation for balloon payloads. For long distance balloon flights which involve a large change in the earth's magnetic field some type of sliding relationship between the magnetic field sensed and the payload azimuth indicated may be necessary.

The advantages of the system presented are its simplicity, light weight, and compactness.

In conclusion, this magnetic azimuth system has been used successfully on three balloon payloads. It provided azimuth data accurate to within 10° including possible errors caused by pitching of the payload. The system offers simplicity, lightness, compactness, and operates independently of reference bodies such as sun, stars. These advantages need to be traded off against possible problems of significant magnetic field changes for long distant balloon flights.

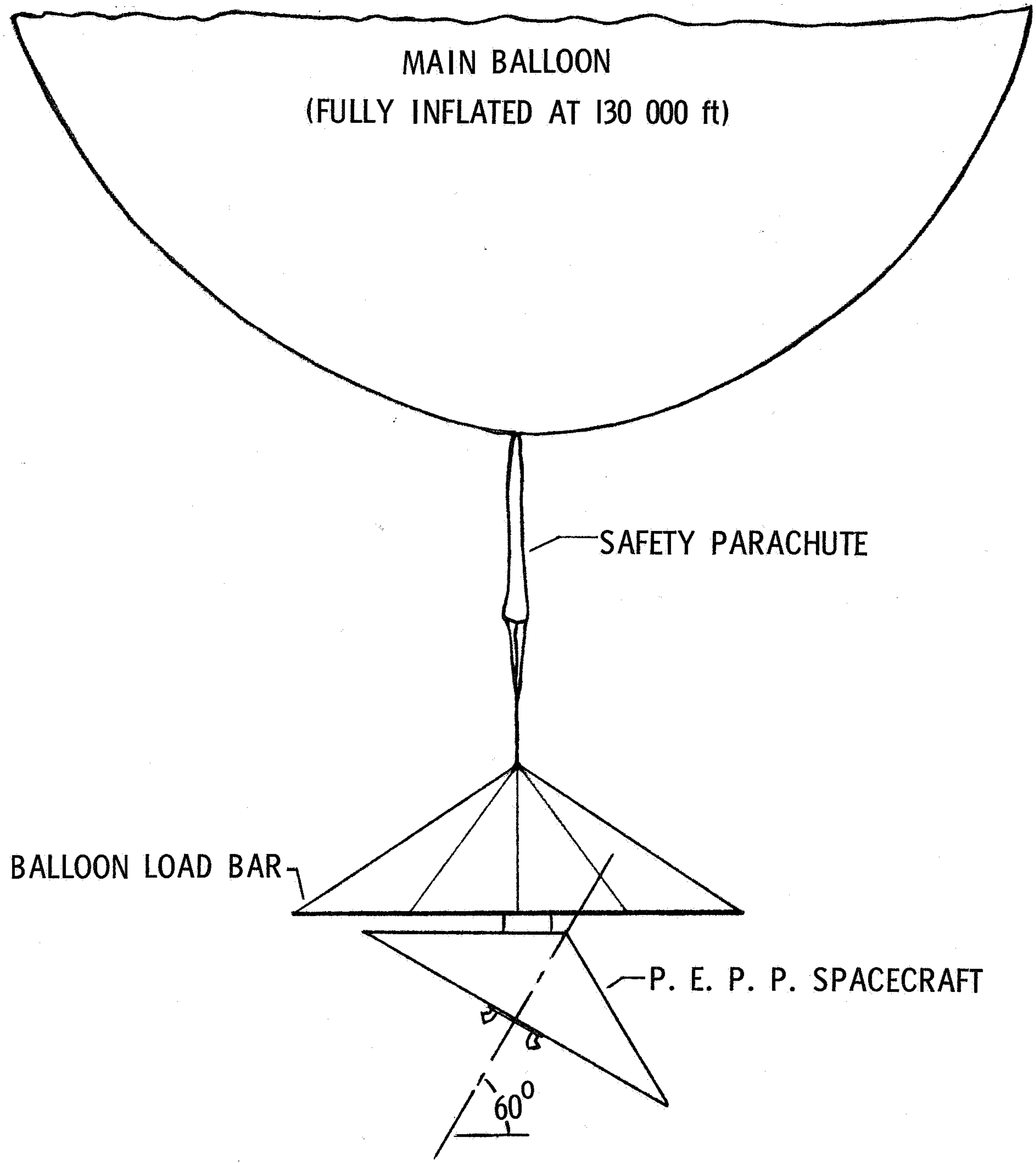

Figure 1.- PEPP balloon launching configuration.

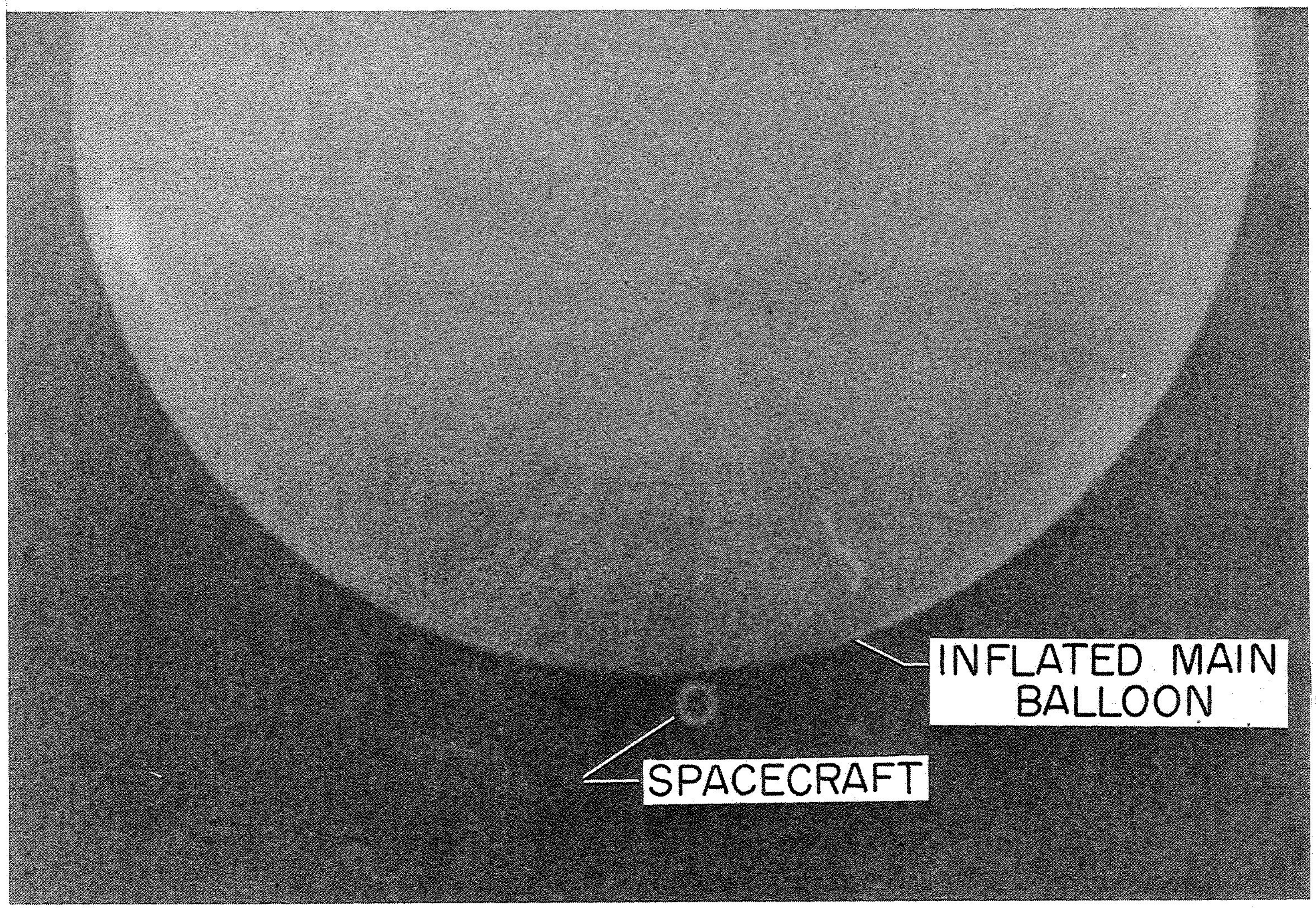

Figure 2.- Inflated main balloon and spacecraft just after spacecraft release at 130,000 ft.

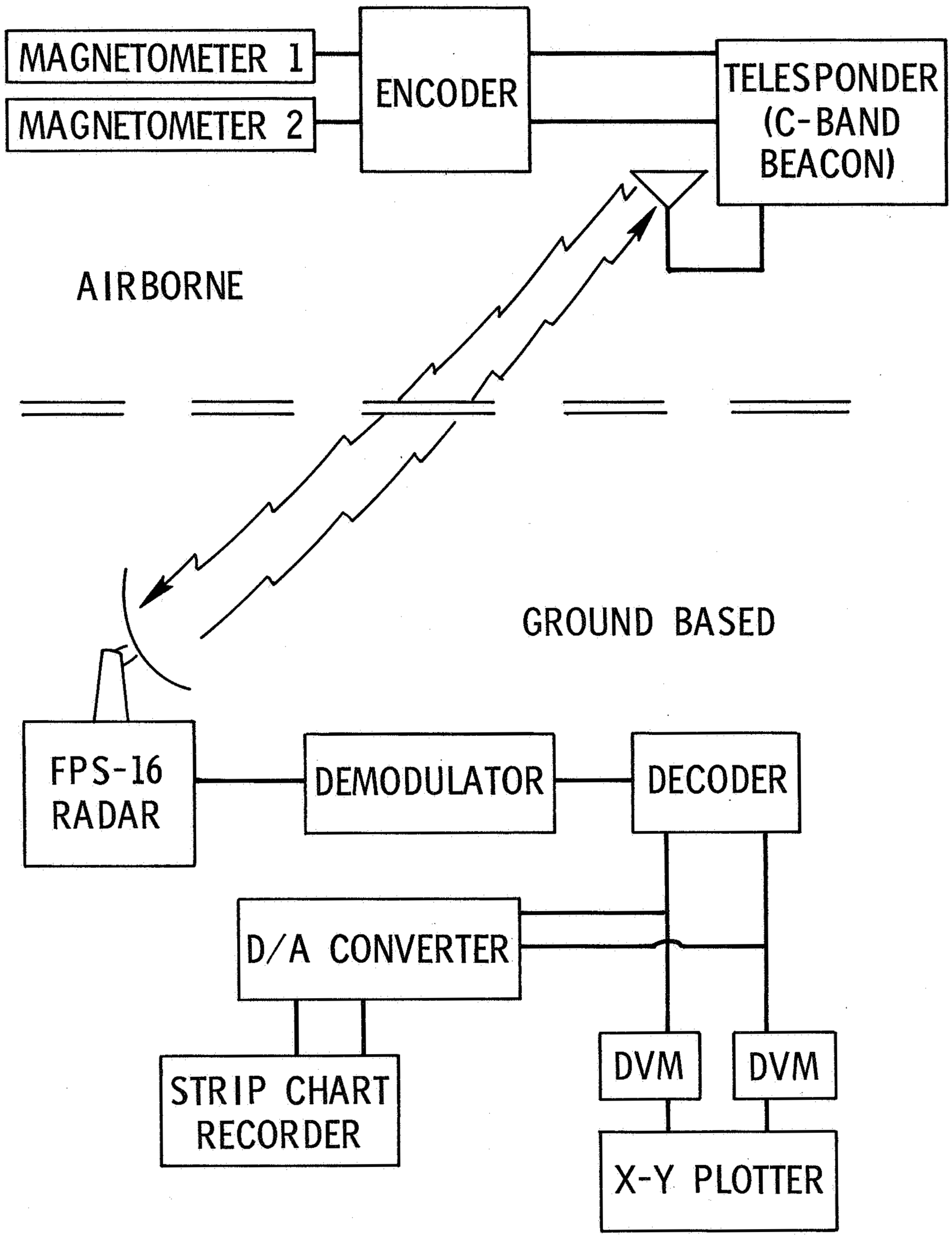

Figure 3.- Components of the magnetic-azimuth indicator system.

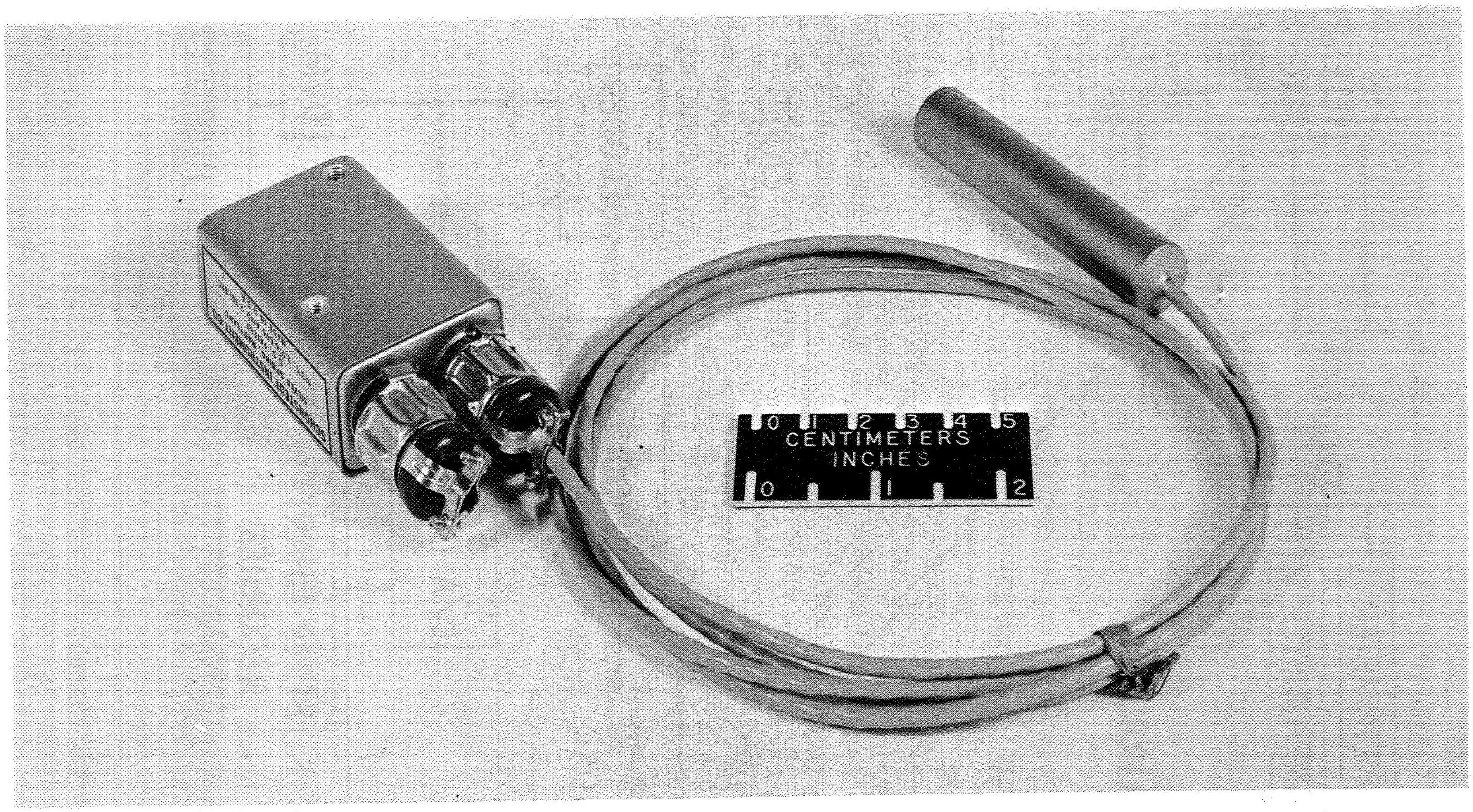

Figure 4.- Flight Magnetometer.

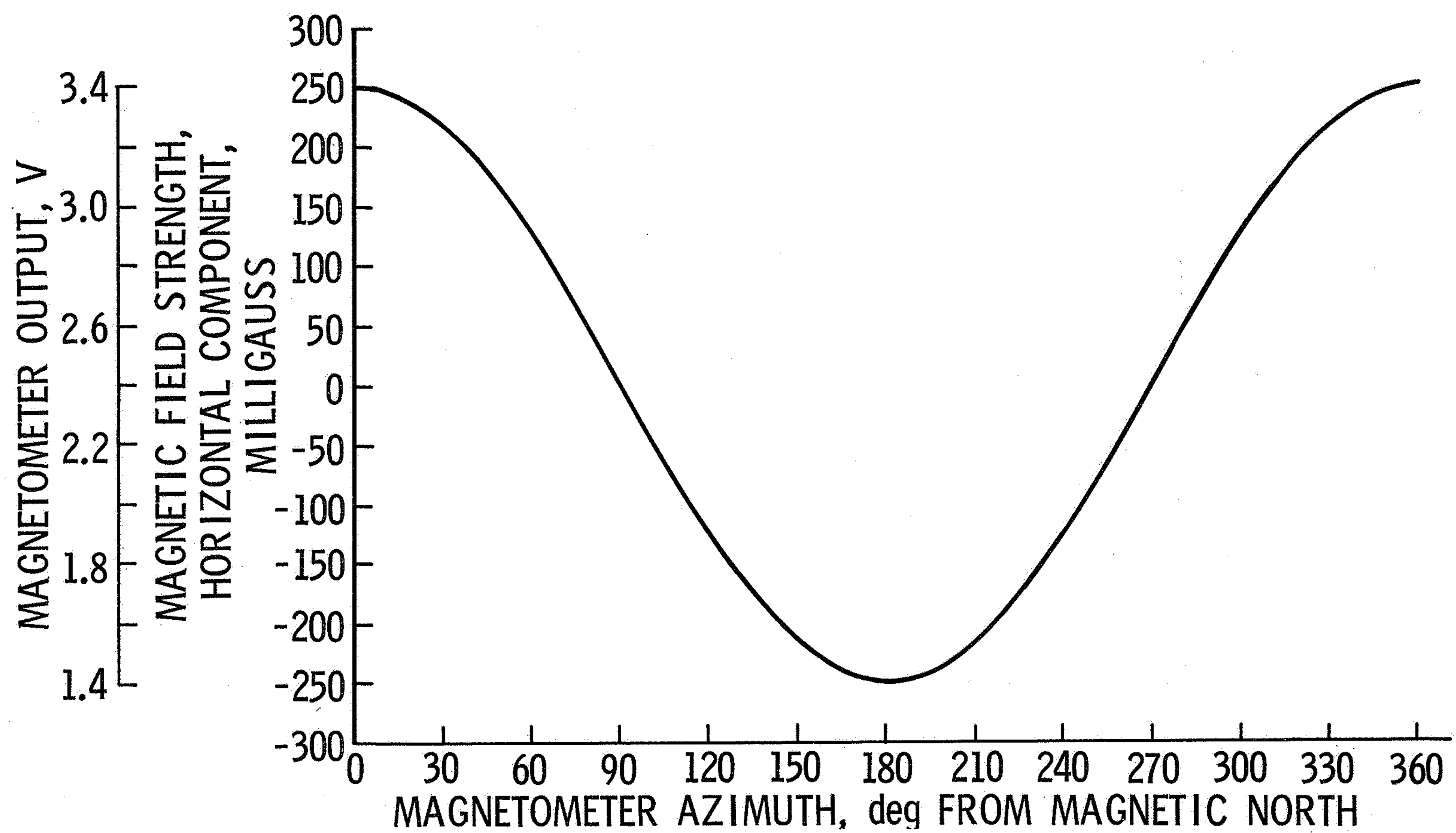

Figure 5.- Typical variation of magnetometer voltage with azimuth.

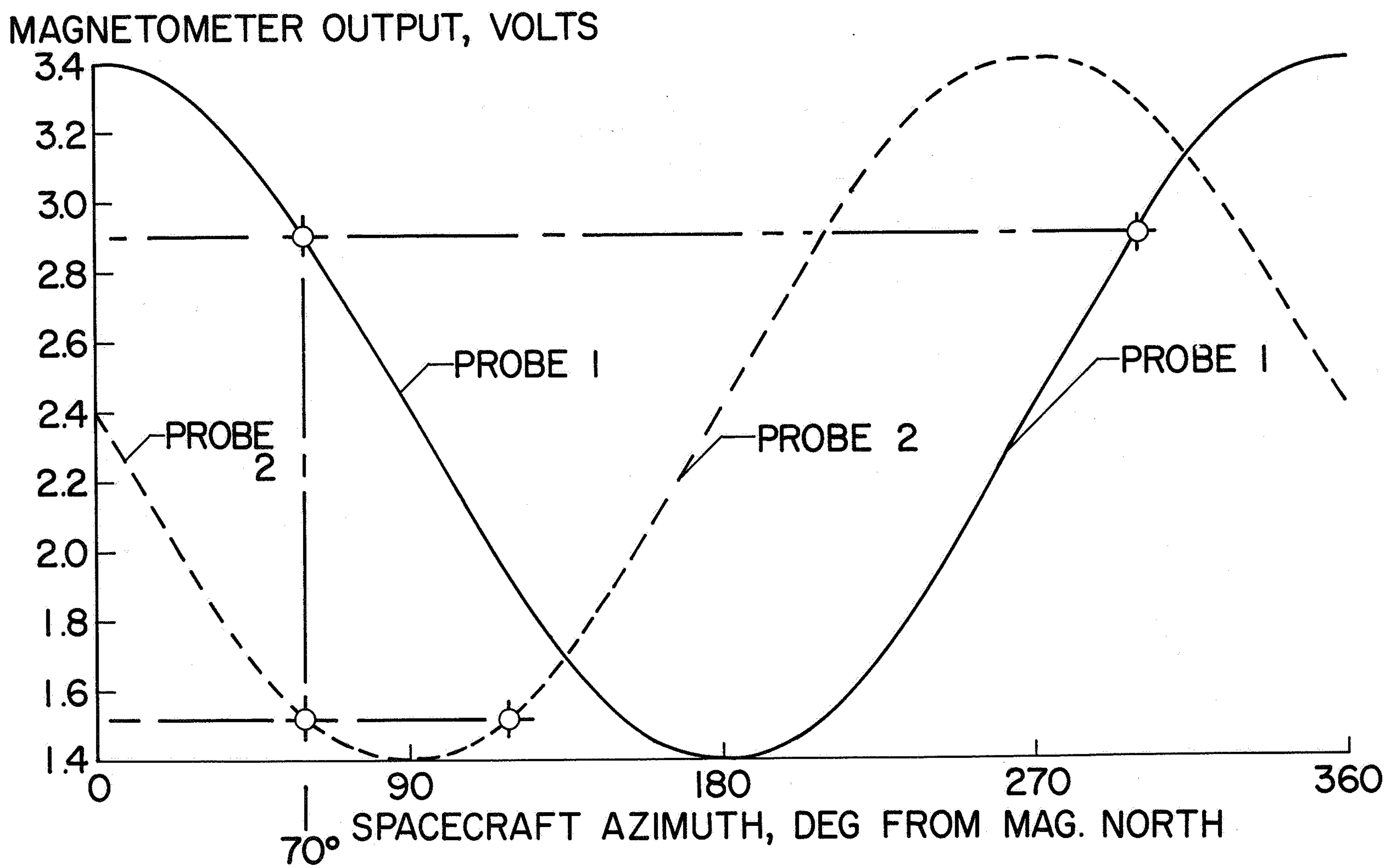

Figure 6.- Spacecraft azimuth determination using two probes.

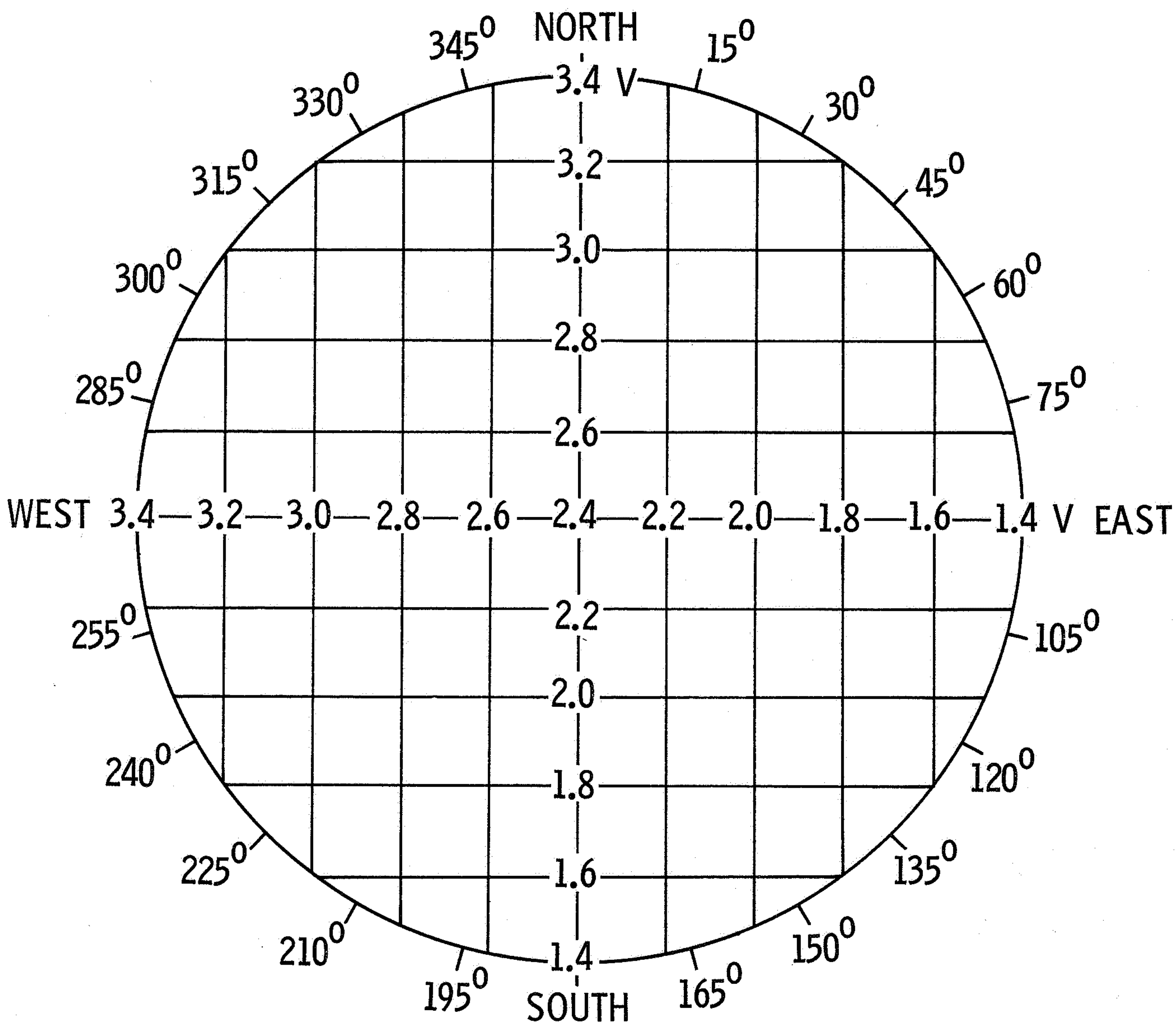

Figure 7.- Typical layout for direct spacecraft azimuth determination.

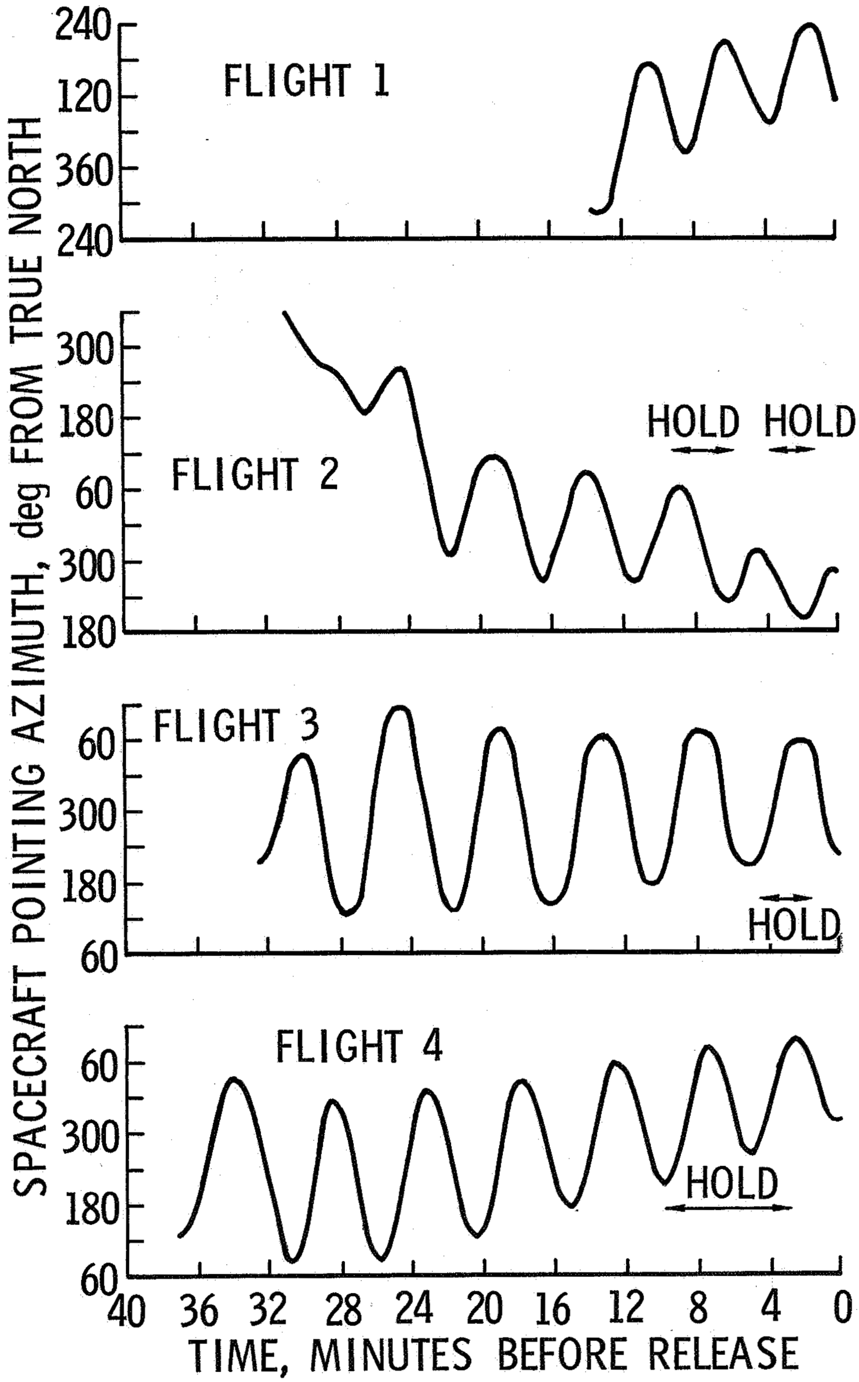

Figure 8.- Pointing azimuth of the PEPP spacecraft.

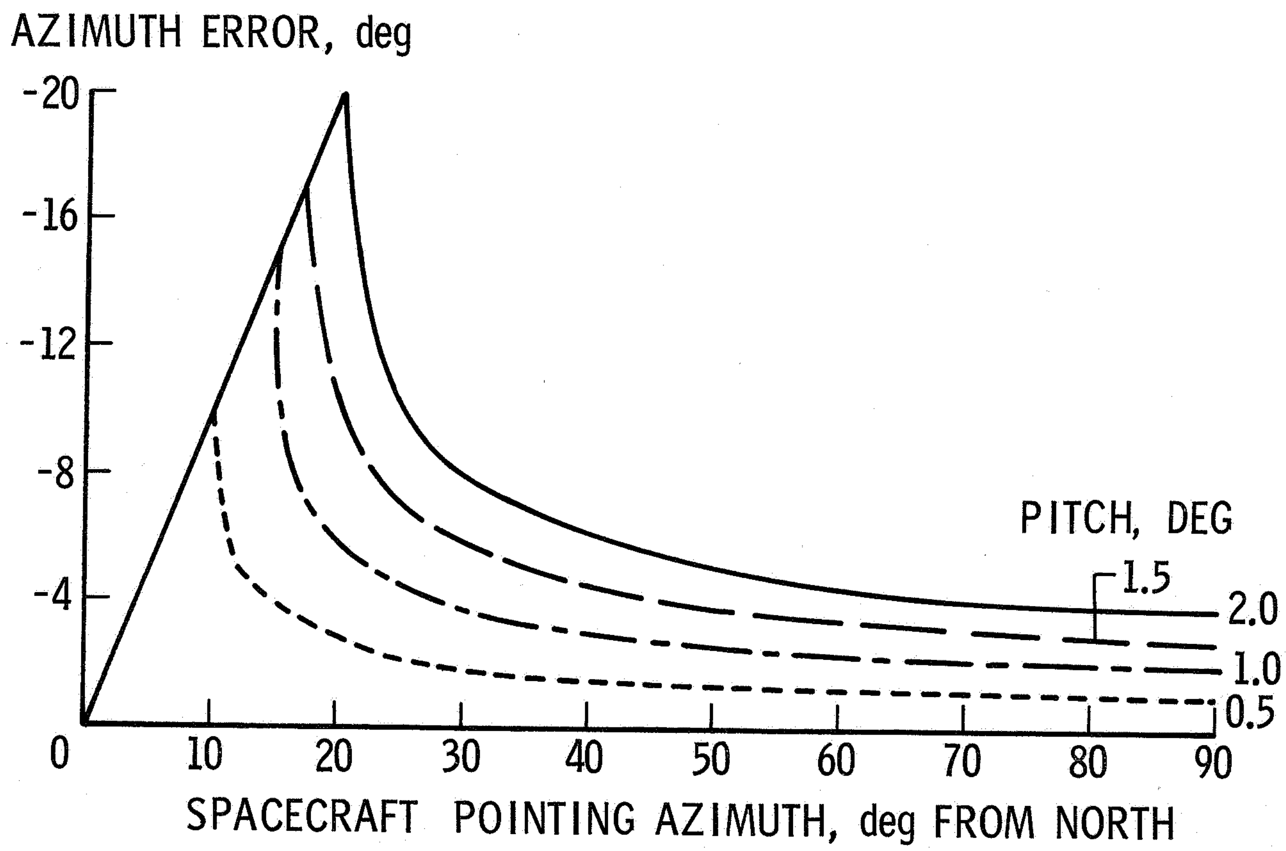

Figure 9.- PEPP spacecraft pitching effects.

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