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Pioneer Venus Orbiter Fluxgate Magnetometer

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Abstract-The fluxgate magnetometer on the Pioneer Venus orbiter spacecraft is described. Special features include gradiometer operation, on board despinning, a floating point processor and variable Nyquist filters. Initial operations have been entirely successful.

INTRODUCTION

THE EARTH'S atmosphere is shielded from the solar wind, the rapidly expanding ionized gas of the sun's outer corona, by a moderately strong magnetic field generated by a dynamo inside the liquid core of the earth. That Venus is not thus shielded was evident from the measurements of the earliest probes to Venus [1], [2]. It was not certain that these measurements indicated that Venus had no intrinsic field. Rather, the existence of a small intrinsic field was still possible [3], and in fact expected from dynamo models [4]. A measure of the size of any Venus moment would be a check on our understanding of planetary dynamos Furthermore, the solar wind was thought to interact directly with the upper atmosphere of Venus, a situation quite unlike that probed on other planetary missions. (Mars may have a similar interaction with the solar wind, but Martian studies have concentrated on the surface and lower atmosphere rather than the upper atmosphere.) Such an interaction is only poorly understood. It is possible that the weak magnetic field of the solar wind could act to shield the upper atmosphere by inhibiting the solar wind penetration into the atmosphere. Thus it was important for both aeronomical and planetological reasons to measure the magnetic field in the near vicinity of Venus. Only from an orbiter with a controllable periapsis altitude could the requisite series of low-altitude measurements be made.

The intent of the Pioneer Venus mission was to be both comprehensive and low cost. The former requirement led to the inclusion of a large number of instruments and the need for a moderately high data rate and hence a despun antenna. The latter requirement led to a spinning spacecraft, a minimum magnetic cleanliness program and no allowance for redundancy. Even with a despun antenna the Pioneer Venus spacecraft would sometimes have to transmit data at rates as low as 8 bits/s when Venus was on the far side of the sun and the deep space net telemetry stations were being used for outer planet missions. These constraints made for some exacting design challenges both for the spacecraft design team and the magnetometer team.

SYSTEM DESIGN

Since the spacecraft designers were attempting to maximize the use of off-the-shelf hardware from programs without a need for magnetic cleanliness, the decision was made early in the program to place the sensors as far away from the center of the spacecraft as possible (~ 5 m). Since there would be moderately high thrust at orbit injection and interplanetary measurements and deployment of the magnetometer were needed before orbit injection, the boom for the magnetometer was made rigid. This rigid boom was stowed in three hinged sections on top of the spacecraft and deployed by centrifugal force shortly after launch and interplanetary insertion.

A magnetic field is a vector quantity which can be specified by a magnitude and two angles or the three orthogonal components of the vector. At any instant of time this measurement requires three orthogonal detectors. On a spinning spacecraft, if the external field remains steady and the spacecraft field and internal instrument zero levels are accurately known, a single sensor tilted with respect to the spin axis will suffice. There will be a sine wave whose amplitude and phase, relative to some direction in space such as the sun, give the two components of the field in the spin plane. The average over a spin period gives a measure of the field along the spin axis. Although conditions of sufficiently steady field are frequent in the vicinity of Venus, the interesting regions are where the field values change rapidly. Thus three sensors were deemed necessary.

The despun antenna assembly was expected to be magnetic as were several other subsystems. Furthermore, it was possible that these fields might change during the mission. Monitoring the field at two radial distances would help monitor such changes through the differences between the two readings if the sensors gains and zero levels remained constant. While this feature was desirable it was not affordable within the weight and power allowance of the magnetic fields investigation. A compromise design was to take one of the sensors from the triad on the end of the boom and install it 1/3 of the way back along the boom tilted with respect to the satellite spin axis and at right angles to the sensor in the spin plane. At low frequencies, well below the spacecraft spin frequency, this provided two measures of the field at varying distances from the spacecraft subject to the limitations discussed above. At high frequencies, at which interference was expected to be minimal, the readings could be combined to give the equivalent readings of three mutually orthogonal sensors. Not only did this approach provide a rudimentary gradiometer, but also reassuring redundancy. Only the failure of both sensors with components along the spin axis would have prevented the measurements of three components of the magnetic field. No single sensor failure or other pair of failures would have jeopardized the measurement.

Our next design challenge was the problem of the occasional very low telemetry rates. At 8 b/s, we would obtain only one vector sample of the magnetic field every 21 or 64 s depending on which telemetry format was being used. Since the spin period of the spacecraft was 12 s these low data rates were insufficient to enable the amplitude and phase of the signal from the sensors with components in the spin plane to be determined. Thus it was necessary to "despin" the measurements to an inertial frame before transmittal. The optimum despinning routine would be to multiply the data by sine and cosine waves in phase with the rotation and average over an integral number of spin periods. Again weight and power were not available for the optimum approach and we used a Walsh transform rather than a Fourier transform. The Walsh transform is basically the multiplication of the data by two square waves in quadrature at the spin period. Overlapped averages are accumulated in six averaging registers, half of which were read out one telemetry cycle and the other half the next. There are 64 samples in each average which could be spread over 1, 2, or 4 spins, resulting in overlapped samples being returned every 1/2, 1, or 2 spins or every 6,12, or 24 s. Thus at the lowest bit rate,8 b/s, when the telemetry format is returning a vector every 21 s, accurate vector measurements are obtained. As mentioned above, well below the spin frequency one can determine the two components of the field in the spin plane from one sensor with a component in the spin plane. Thus in normal operation at low bit rates (called NORMAL MODE) the instrument performs a Walsh transform on only the out-board sensor in the spin plane (called the T sensor). The in-phase average of T and quadrature average of T are stored along with the usual average of the readings from the outboard sensor parallel to the spin axis (the P sensor). This scheme provides only a measure of the field at the outboard sensor. Another operating mode (Gradiometer mode) was included to provide in-phase and quadrature transforms and a regular average of the inboard G sensor. In the Gradiometer mode all sample rates remain the same. The only difference is that the G sensor averages are stored in the second set of three averaging registers at the expense of overlapped averages. To obtain both the desired range ((128 nT) and resolution ((16 nT), a 12-bit analog-to-digital conversion was used. To optimize the utilization of the available telemetry,32 bits per vector sample, two of the 12-bit samples were converted to floating point words consisting of an eight-bit mantissa and a two-bit exponent by checking the leading bit for zeroes and shifting bits if the leading bit was zero. A maximum of three shifts was permitted. The number of shifts formed the exponent. Thus these two measurements had resolution of (1/2 nT when the reading was greater than 64(in magnitude changing to (16 nT when the reading was less than 16 nT.

It is necessary to limit the bandwidth of the magnetometer so that signals of frequency too high to be resolved by the telemetry system, do not enter the sampling circuitry. The maximum frequency that can be properly analyzed is half the sampling frequency and is called the Nyquist frequency.

If signals enter the telemetry stream at frequencies above the Nyquist frequency they appear to occur at a frequency below their true frequency. This process is called aliasing and the filters in the instrument that prevent this are called aliasing filters, although a more proper name would be nonaliasing filters. Since the telemetry rate of the spacecraft varied over an enormous range, the comer frequency of the aliasing filters too had to vary. These corner frequencies were controlled automatically according to the instrument sample rate. Depending on the telemetry format the instrument could sample once per minor frame (512 bits) or three times. These modes were called SLOW sampling and FAST sampling, respectively.

At telemetry rates of 512 b/s and below the comer frequency was kept fixed at 0.2 Hz. The resultant sample rates and 3 dB points are given in Table I. When the sample rate drops below 0.5 Hz, onboard averaging is generally used.

Since the spacecraft was to undertake a lengthy trip in space (over 6.5 months) before making its prime measurements and since a long useful lifetime of the spacecraft was anticipated, a commandable calibration signal was included. The signal is a dc current applied to an external winding surrounding each sensor so that the readings changed by approximately 40 nT.

The current is applied for a telemetry major frame which is 64 minor frames. During a minor frame the magnetometer is read out either once or three times. The reference voltage in the instrument's 12-bit analog-to-digital converter is used to power the calibrate signal. Since this voltage also is the reference for the digitization of the signal only a change in the analog circuitry will result in variations in the apparent size of the calibrate signal.

To check the invariance of the reference voltage, it is digitized by the spacecraft analog-to digital converter and telemetered to earth.

THE BASIC MAGNETOMETER

The basic magnetometer has been described by Snare and Means [5] and is similar in many respects to the ISEE-1 and 2 magnetometers [6]. Briefly it is a fluxgate magnetometer with large loop gain and feedback. The sensors are ring core types manufactured by the Naval Surface Weapons Laboratory, White Oak [7]. The drive voltage is a very clean 7.25-kHz sinewave with an amplitude of about 4-V peak-to-peak. The drive current is approximately 150 mA. The detected signal is the second harmonic of the drive frequency, detected in a double sideband suppressed carrier mode. The openloop gain is unity at 300 Hz and approaches 108 at dc. The closed-loop system response is flat with a first-order corner at 300 Hz.

CONSTRUCTION

The basic magnetometer uses integrated-circuit operational amplifiers mounted on a two-sided printed circuit board. The digital circuit are all CMOS integrated circuits mounted on stitch wired boards. The electronic assembly chassis is all magnesium. Sensor assemblies were machined from epoxy fiberglass stock. Conceptual and preliminary design was performed at UCLA with detailed design and fabrication at Westinghouse Electric Company, Baltimore, MD. The electronic unit mounted on the main body of the spacecraft measures 15 X 22 X 15 cm and weighs 1.7 kg. The inboard sensor assembly measures 6 X 7 X 6 cm and weighs 110 g. The outboard sensor assembly measures 8 X 5 X 4.5 cm and weighs 170 g. The total power required is 2.2 W at 27-V dc.

INITIAL OPERATION

The magnetometer was turned on shortly after launch and has operated continuously since that time except for brief periods at orbit injection and during the long eclipse season. The instrument has operated flawlessly. Daily checks of the instrument calibration show no change in gain in over one year's operation in space.

Despite the fact that Venus had been probed many times before, including two Soviet orbiting vehicles, much has been learned during the first year's operation. We will start in the solar wind and work inwards to the planet rather than attempt to prioritize the findings. First, the bow shock, which stands in front of the planet and deflects and heats the supersonic solar wind when it encounters the planetary obstacle, is significantly further out now than it was in 1975 when the shock was probed by the Venera 9 and 10 orbiters [8]. This suggests that there has been a change in the Venus ionosphere since then as the solar cycle progressed towards solar maximum. Second, the bow shock is much weaker than the terrestrial bow shock [9]. This phenomenon could be caused by slowing down of the solar wind before it reached the bow shock by mass addition from the Venus hydrogen geocorona, or by absorption of solar wind by the upper atmosphere of Venus. Third, the shock does not appear to be asymmetric about the solar wind flow direction as reported earlier from a more limited set of Venera bow shock crossings [10] . Fourth the ionopause, the upper limit of the ionosphere, appears to be a tangential discontinuity with approximate pressure balance maintained between the thermal pressure of the electrons and ions in the ionosphere and the magnetic field external to the ionosphere [11]. The magnetic field strength in the ionosphere is generally very low [12]. Fig. 1 shows the magnetic field strength on four successive passes through the ionosphere. Most often low field regions interspersed with narrow twisted filaments of field or flux ropes [13] are observed. Occasionally a more steady field is found as in orbit 163. Finally, we have not yet found any evidence for a planetary field. The upper limit to the Venus magnetic dipole moment is now much less than theoretical expectations [14] .

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Fig. 1. Magnetic-field strength on four successive passes through the Venus ionosphere. The solar zenith angel (SZA) and altitude at periapsis are given for each pass.

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