

THE MAGSAT PRECISION VECTOR MAGNETOMETER

The Magsat precision vector magnetometer was a state-of-the-art instrument that covered the range of $\pm 64,000$ nanoteslas (nT) using a ± 2000 nT basic magnetometer and digitally controlled current sources to increase its dynamic range. Ultraprecision components and extremely efficient designs minimized power consumption.

INTRODUCTION

The instrumentation aboard the Magsat spacecraft consisted of an alkali-vapor scalar magnetometer and a precision vector magnetometer. In addition, information concerning the absolute orientation of the spacecraft in inertial space was provided by two star cameras, a precision sun sensor, and a system to determine the orientation of the sensor platform, located at the tip of a 6 m boom, with respect to a reference coordinate system on the spacecraft.

The two types of instruments flown aboard the spacecraft provided complementary information about the measured field. The scalar magnetometer measured the magnitude of the field independent of its orientation with respect to the sensor, with an absolute accuracy that is determined by atomic constants and thus is not subject to change as a function of time. On the other hand, the precision vector magnetometer measured the projections of the ambient field in three orthogonal directions with an absolute accuracy determined by calibrations with respect to a standard; thus they were subject to error and drift. Accuracy goals for the mission required a vector magnetometer capable of measuring the ambient field with a maximum error of ± 1 part in 64,000 in magnitude and 5 arc-s in orientation ($1 \text{ arc-s} = 0.00028^\circ$). The development of such an instrument within the constraints imposed by the spacecraft represents a major technological achievement that would have been impossible without parallel developments in the areas of ultraprecise linear integrated circuits and miniature resistors. The design implemented for Magsat represented an optimum compromise among many conflicting requirements and limitations imposed by available resources, reliability considerations, and state-of-the-art electronics. This paper presents a brief description of this unique instrument.

INSTRUMENT DESCRIPTION

Figure 1 is a block diagram of the vector magnetometer. The heart of the instrument is a highly

stable and linear triaxial fluxgate magnetometer with a dynamic range of ± 2000 nT ($1 \text{ nT} = 10^{-9}$ weber per square meter). The principles of operation of fluxgate magnetometers are well known and will not be repeated here. The reader is directed to Refs. 1, 2, and 3 for further information concerning the detailed design of these instruments.

To extend the range of the basic magnetometer to the 64,000 nT required for Magsat, three digitally controlled current sources with 7 bit resolution and 17 bit accuracy were used to add or subtract automatically up to 128 bias steps of 1000 nT each. The X, Y, and Z outputs of the magnetometer were digitized by a 12 bit analog-to-digital converter that, in conjunction with the 7 bits associated with the digital current sources, yielded an overall instrument resolution of ± 0.5 nT.

The ambient magnetic field was sampled 16 times per second along each of the three orthogonal directions, and the digital current sources were updated at the same rate. The digital data corresponding to the "fine" (12 bit) and "coarse" (7 bit) information were fed directly to the spacecraft through a serial interface. The fine data were sampled at 16 samples per second; the coarse data were sampled at only 4 samples per second. This sampling scheme took advantage of the fact that the ambient magnetic field changed slowly over the Magsat orbit; hence, coarse updates were not needed as frequently as fine updates. The response of the instrument to increasing and decreasing ambient fields is shown in Fig. 2. The current steps, which are added or subtracted depending on the magnitude and direction of the external field, maintained the effective magnetic field seen by the fluxgate sensor within its operating range of 2000 nT. The stepping threshold was actually 1000 nT to allow the magnetometer to follow rapid changes in the field between two adjacent updates of the bias steps without loss of data.

As can be seen from Fig. 1, the magnetometer electronics, analog-to-digital converters, and digitally controlled current sources were implemented with redundant designs. This was also true for the

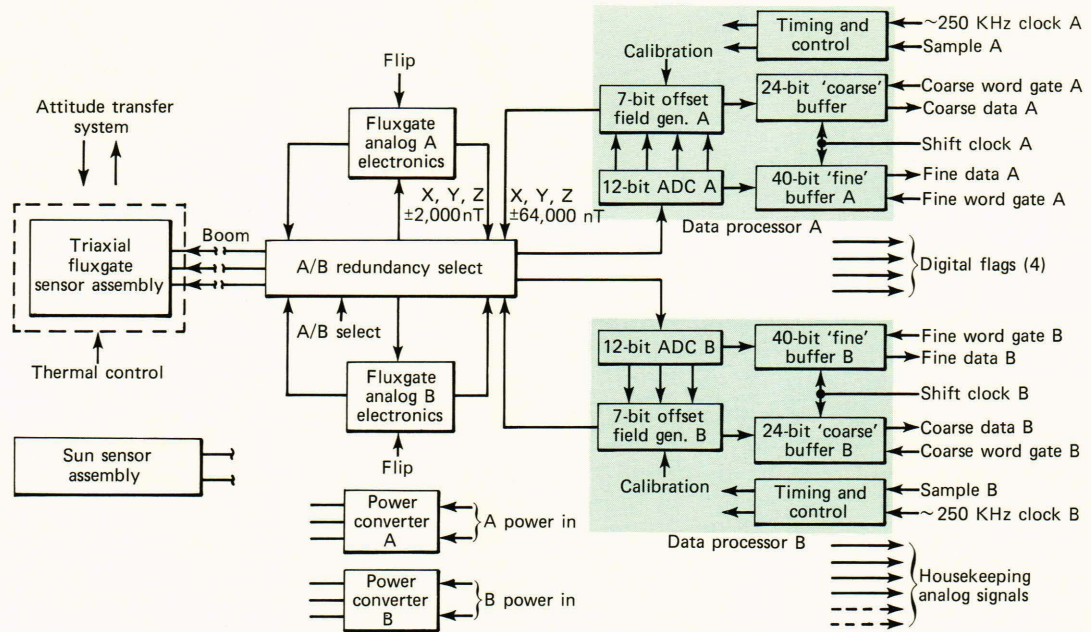


Fig. 1—Block diagram of the precision vector magnetometer. All subsystems are implemented with redundant designs to avoid loss of data in case of failures.

digital processors and power converters. The block-redundancy approach provided a fundamental measure of reliability to this important instrument and eliminated from consideration single-point failures in the electronics. Selection of the particular system used (A or B in Fig. 1) for both the analog and digital portions of the instrument was executed by ground command.

TRIAxIAL FLUXGATE SENSOR

The fluxgate sensor used in the Magsat vector magnetometer was a unique design that took advantage of the ring core geometry. This particular geometry exhibits superior performance characteristics in terms of noise and zero-level stability. In ad-

dition, its uniform expansion characteristics were essential for achieving the angular stability required. Figure 3 is a schematic diagram that shows the construction of each sensor. Crucial elements in the Magsat fluxgate sensor design were the feedback coil that nulls the external field, and the sensor core itself; they constitute the most important sources of error in terms of alignment stability as well as variation of scale factor with temperature. Any distortion or motion of the sensor core within the feedback coil represents an effective alignment shift. Structural deformations larger than 50 μm were sufficient to exceed the alignment stability tolerance.

The fundamental strategy followed for the Magsat vector magnetometer was to match the expan-

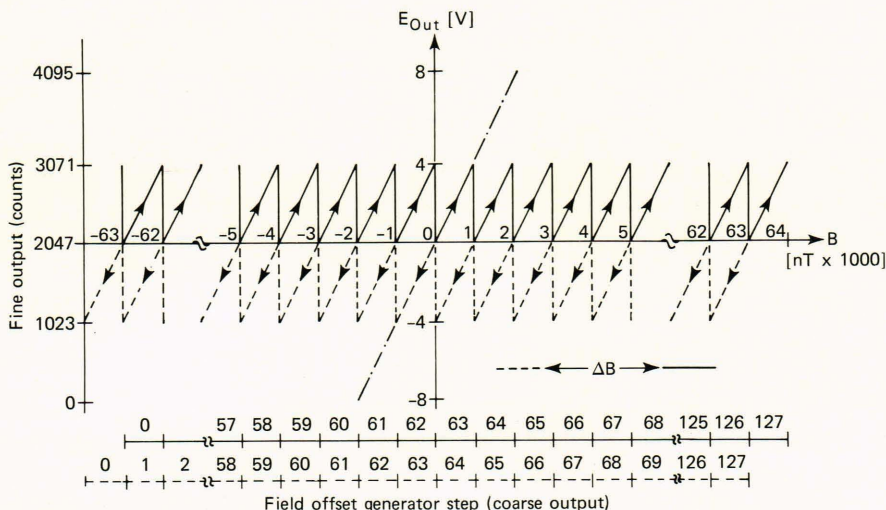


Fig. 2—Instrument response for increasing (solid curve) and decreasing (dashed curve) ambient field. Note the large safety margin in the switching threshold (half scale).

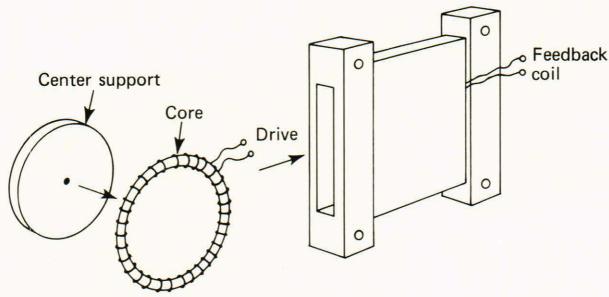


Fig. 3—Individual fluxgate magnetometer sensor construction. All parts have identical expansion coefficients.

sion coefficients of all the materials used in the construction of the sensor assembly (core, feedback coil, and support structure) so that differential stresses induced by temperature variations were minimized. Since the sensor core expansion coefficient is approximately $10 \text{ ppm}/^\circ\text{C}$, platinum wire was used to wind the feedback coil, and the support structures were machined from solid blocks of Macor, a machinable glass-ceramic. The triaxial sensor assembly was mounted on a temperature-stabilized baseplate whose temperature was actively maintained at $25 \pm 1^\circ\text{C}$. The attitude transfer system mirrors were mounted under this baseplate. Their expansion coefficient was nearly zero; hence, active thermal control of this crucial interface was needed.

Since the overall expansion coefficient of the sensor feedback coil was nonzero, the magnitude of the feedback field was a strong function of temperature. To minimize this effect, the magnetometer electronics incorporated a correction circuit that sensed the coil temperature by changes in its resistance and adjusted the feedback current to make the generated field independent of temperature.

The external magnetic field generated by the triaxial fluxgate sensor assembly was less than $\pm 1 \text{ nT}$ at the location of the scalar magnetometer. This low field value minimized the interference with the accuracy of the measurements obtained by the scalar instrument.

To determine the absolute orientation of the sensors with respect to a reference coordinate system, two optical cubes were bonded to the sensor mount. They allowed the sensor assembly to be rotated exactly 90° during calibrations to establish the absolute direction of the magnetic axes and later to reference the scalar instrument measurements to the principal spacecraft coordinate system.

MAGNETOMETER ELECTRONICS

The electronics design for the vector magnetometer incorporated a number of advanced developments derived from the Voyager 1 and 2 magnetic field experiments^{1,2} that were directly applicable to this instrument. However, the extreme accuracy re-

quired of the analog signal processing circuits dictated the use of ultraprecise components, some of which had to be specifically developed for Magsat. The maximum allowable error voltage for the digitally controlled current sources was only $125 \mu\text{V}$ so considerable attention had to be paid to the problem of thermally generated electromotive forces that are produced across dissimilar metal junctions. Circuit layouts with a minimal number of solder joints, the proximity of essential conductors in order to minimize thermal gradients, and the use of cadmium-tin alloys for soldering and assembly reduced the instrument errors to an absolute minimum. The resistors used in the digital current sources as well as the magnetometer feedback circuit were ultraprecise, hermetically sealed units with an absolute temperature coefficient of less than $0.5 \text{ ppm}/^\circ\text{C}$ and a long term stability of 20 ppm/year . The calibration of the analog circuits required special test instrumentation with accuracies established by the National Bureau of Standards and resolution of about 1 ppm (a type of design usually restricted to laboratory-grade instruments). Extensive reliability and performance trade-off analyses were carried out to ensure mission success.

The digital processors were implemented with CMOS digital integrated circuits to reduce power consumption to a minimum. Only one processor was powered at any given time by its respective power converter; the same was true for the analog electronics subsystem. As is illustrated in Fig. 1, there were then four possible arrangements for these subsystems, depending on how they were interconnected. To simplify testing, the "A-A" and "B-A" combinations were calibrated by an indirect analysis of the "A-A" and "B-B" configurations test data. A summary of performance parameters and technical characteristics of the magnetometer and the electronics system is given in Table 1.

CALIBRATION AND ALIGNMENT

The problem of determining the orientation of a given magnetic field vector traditionally has been solved by assuming that the field orientation can be established accurately by the geometry of a calibration coil. This method is generally sufficient to determine sensor orientation within a few arc-minutes from its true direction, but it is certainly not accurate enough for the Magsat case where accuracies of the order of 2 arc-s were required. The method to determine the sensor alignment assumed that the deviations from orthogonality of the sensor assembly and triaxial test coil system were small. In this case, a very accurate alignment of the sensor and test coil system can be obtained simultaneously by rotating the sensor twice through exactly 90° in two planes. This method has been described in Refs. 4 and 5. An accurate optical reference coordinate system was first established at the Goddard Space Flight Center (GSFC) Magnetics

Table 1

SUMMARY OF TECHNICAL CHARACTERISTICS OF THE
MAGSAT PRECISION VECTOR MAGNETOMETER*Basic Fluxgate Magnetometer*

Dynamic range: ± 2000 nT
 Resolution: 12 bit A/D converter (± 0.5 nT)
 Noise: 0.008 nT rms (8 Hz bandwidth)
 Zero level stability:
 Sensor (-60 to $+60^\circ\text{C}$): ± 0.2 nT
 Electronics (-20 to $+50^\circ\text{C}$): ± 0.2 nT
 Drive frequency: 12.5 kHz
 Linearity error (compensated): less than 1 part in 10^5
 Angular stability better than ± 3 arc-s over a temperature range of 10 to 40°C

Offset Digitally Controlled Current Sources

Dynamic range: $\pm 64,000$ nT
 Quantization step: 1000 nT
 Temperature coefficient: less than 0.5 ppm/ $^\circ\text{C}$
 Long-term stability: within 2 parts in 10^5 per year

Sensor Assembly

Mass: 0.6 kg
 Dimensions: $11.4 \times 5.72 \times 5.8$ cm

Electronics (redundant)

Mass: 2.6 kg
 Dimensions (approximate): $22.23 \times 17.8 \times 11.4$ cm
 Total power consumption:
 1.8 W at 25°C
 2.0 W at 0°C

Test Facility by means of a pair of first-order theodolites referenced to a 400 meter baseline. Numerous magnetic contamination problems associated with the optical system had to be solved to realize the intrinsic accuracy obtainable by this method. The short- and long-term mechanical stability of the triaxial coil system presented very difficult problems at times in terms of the consistency of test results. Nevertheless, after many hours of dedicated testing to determine the true performance

of the magnetometer and coil system, excellent results were obtained, as is evident by the outstanding in-orbit performance of the vector magnetometer.

The individual axis scale factors were calibrated using a proton precession magnetometer as a reference standard for fields greater than 20,000 nT. For small fields, the calibration constants were synthesized from selected incremental measurements above 20,000 nT to determine the exact "weights" of each of the 7 bits in the digitally controlled current sources. Final overall calibration included coordinated tests with the scalar magnetometer to determine mutual interference and relative accuracy. Significant problems were encountered in this respect with the relatively large RF power required for operation of the scalar magnetometer. Prior to the installation of RF shielding on the spacecraft, this interference was rather serious, and considerable effort was dedicated to its elimination.

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ACKNOWLEDGMENTS — The author would like to acknowledge the dedication and support provided during the development, test, and integration of this instrument by J. Seek, C. Seearce, J. Scheifele, and E. Worley of GSFC; C. Fewell of Northrop Services; R. Lundsten, and J. Scarzello of NSWC; and F. Mobley, J. Roberts, E. Marshall, and J. Smola of APL. The outstanding optical support provided by S. Hinkal was essential to the success of the calibration activity. The GSFC Magnetism Test Facility personnel, C. Harris, R. Bender, and R. Ricucci, spent many hours waiting for us to understand our spacecraft; their contribution is deeply appreciated.