The Fluxgate Magnetometer for the AMPTE UK Subsatellite

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Abstract—The fluxgate magnetometer flown on the Active Magnetospheric Particle Tracer Explorers United Kingdom Subsatellite (AMPTE UKS) spacecraft and its operation are described. The instrument is a modified flightspare from the ISEE 1/2 mission and shares many features with the ISEE instruments. During routine operations data are returned to the United Kingdom Control Centre and displayed in real time in a geophysical coordinate system. Instrument and data system are all operating successfully.

I. Introduction

The MAGNETIC-field measurements made with the fluxgate magnetometer on the United Kingdom subsatellite (UKS) will form a core data set in the Active Magnetospheric Particle Tracer Explorers (AMPTE) mission both during periods of passive magnetospheric observation and at times of ion releases. The AMPTE mission in which agencies in three nations, the United States, Germany, and the United Kingdom, are providing spacecraft, has unique requirements for accurate monitoring of the ambient magnetic field in the plasma environment of the Earth. Magnetic measurements prior to Li^+ ion releases in the solar wind upstream from Earth or in the magnetotail are a vital diagnostic for release decisions and prediction of subsequent ion behavior. During the Ba^+ magnetosheath release, when an artificial comet should be created, the field should be depressed dramatically below ambient values (5–10 nT) in the initial phases of formation of the ion cloud. Later the field is expected to penetrate the cloud and control the transfer of momentum from the solar wind, and the ultimate cloud dispersal. The UKS magnetometer measurements from the interior will allow direct testing of these ideas.

In the last decade it has become clear that the magnetic field is an important agent for the transfer of energy and momentum into the terrestrial magnetosphere from the surrounding solar wind plasma streaming away from the sun. A high scientific priority of the nonrelease-phase science of the UKS program will be to make high-resolution magnetic-field and plasma measurements in the boundary layer between terrestrial and solar plasma regimes. Studies of the bow shock, near-Earth tail, magnetosheath, and hydromagnetic waves are also a priority; many require field measurements accurate to less than 1 nT. The UKS spacecraft can only operate in the full scientific mode for 4–6 h/orbit, but the spacecraft will be in view of the United Kingdom ground station for about 12 h/orbit. The magnetometer can operate in a spacecraft engineering mode, and the data received in real time (R/T) at the Chilton, United Kingdom, control center can be used to make decisions concerning the initiation of science activities and mode setting for other spacecraft instruments (electron, ion, particle correlator, and wave experiments). Magnetometer data in nearly all instances provide the simplest instantaneous guide to spacecraft position and ambient conditions in the highly variable terrestrial plasma environment.

The UKS magnetometer data will be used near perigee where the field direction is known for confirmation of spacecraft attitude.

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II. Administration

The UKS program was faced with two basic requirements in instrument provision: to obtain it at low cost and rapidly. For provision of the magnetometer it was decided to make use of an existing flight-proven instrument. NASA permitted the use of a modified flight spare built for the ISEE 1/2 mission, provided by UCLA. Responsibility for integration, modification, and testing of the instrument fell to UCLA under contract to Imperial College, London, who are providing the principal investigator and take ultimate responsibility for delivery, data reduction, and analysis. The groups involved had already collaborated closely on the ISEE mission in addition to other scientific projects.

The ISEE 1/2 magnetometers were described in detail by Russell [1]. Many details of the UKS instrument are the same, but are repeated here for completeness and ease of reference.

III. The Magnetometer

The magnetometer itself is a three-axis orthogonal fluxgate instrument. It uses ring core sensors built by the U.S. Naval Ordnance (Surface Weapons) Laboratory and is located on a boom ~1 m from the spacecraft body. The configuration of the boom, sensors, and spacecraft axes are complicated because the boom is kinked for ease of stowage prior to deployment and canted 15° with respect to the spacecraft (X, Y) plane. There is one sensor axis nominally aligned with the spacecraft Z (spin) axis. The others are nominally at right angles in the spin plane, but not aligned with X, Y axes (see later). Fig. 1 shows the nominal orientation of sensor axes with respect to the spacecraft axes in the two orientation states used by the instrument. Switching between orientations is achieved by operating a flipper mechanism. As the figure indicates, sensors

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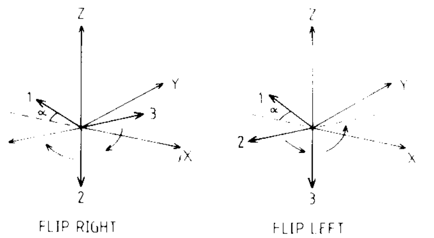

Fig. 1. Illustration of the "flip-right" and "flip-left" sensor configuration with respect to spacecraft (X, Y, Z) axes. The curved arrows illustrate sensor motion during flip. The flipper mechanism enables either sensor 2 or 3 to be moved from spin axis (Z) alignment to the spin plane or vice versa. The angle α is about 45°. Detailed pointing information is given in Table II.

TABLE I
INSTRUMENTATION CHARACTERISTICS

Weight	Sensor assembly	0.53 kg
	Electronics	2.16 kg
Power	Normal operations	3.9 watts
	During flip operations	7.8 watts
Dimensions	Electronics	21 x 12 x 15 cm
	Sensors	11 x 9 cm (dia)

2 or 3 may be placed along the spin axis. As we outline later, the purpose of the flipper is to allow in-orbit calibration.

As described in [1], a flip takes about 4 min at room temperature in vacuum. Should the flipper mechanism, which works by heating a bimetallic strip to rotate sensors from one stable spring held position to another, not operate within a fixed time (dependent on bit rate), the power to the flipper is shut down. This feature has at times required that a second flip command be sent. In practice, this has not caused problems.

Mass, power, and instrument dimensions are listed in Table I. The figures differ from the ISEE instrument [1] only in the mass figure; additional tantalum shielding has been added to the electronics box to enhance radiation shielding.

The instrument has, as has the ISEE instrument, two commandable ranges nominally ±8192 nT in low gain state and ±256 nT in high gain. The instrument is accurate to one part in 2^{13} (i.e., to approximately ±1 nT at low sensitivity and ±0.03 nT at high sensitivity). Digital aliasing filters are used to remove signals at the Nyquist frequency and its harmonics. The magnetometer gain is flat below about one tenth of the Nyquist frequency.

IV. Command and Data Handling

Readings from the sensors are digitized by a 12-bit analog to digital converter at a rate of 512 samples per second per axis. Samples are averaged in overlapping groups of 32, 64, 128, or 256 to provide an instrument output of 32, 16, 8, or 4 samples/s. As explained in [1], the inherent time variation in each sensor due to the spacecraft spin allows a 16-bit sample to be transmitted to ground, the averaging over many digital windows providing a more accurate estimate than a single sample. Digital noise is negligible [1]. The field vector sample rate provided to ground is proportional to spacecraft bit rate. In the spacecraft science mode at 8 kbit/s, 8 vectors are provided per second. In the engineering mode, 1 kbit/s provides 4 vectors/s. In operation 4, 8, 16 samples/s have been regularly used.

The instrument output, the data records, are handled in blocks of 64 (minor frame) vectors starting with the major frame pulse. Commands (e.g., range changing) are stored for execution at a major frame pulse. There is no automatic range changing facility, but there is no difficulty in specifying range (high or low gain) from the ground given reasonable orbit knowledge.

V. Data Reduction

The operation of UKS is unusual. The spacecraft is commanded from the ground and data taken only when in view of the United Kingdom Operations and Control Centre (UKOCC) at Chilton. The only exception is during release phases when the NASA Deep Space Network (DSN) is used. Furthermore, the spacecraft is able to operate in the full science mode only for ~5 h on any pass. The latter constraint places considerable importance on effective real-time reduction of the magnetometer data. In general, the magnetometer can be operated both in the engineering and science modes, and decisions on switching the spacecraft to the science mode can be made on the basis of magnetometer data.

There are three basic levels of data reduction for all UKS instruments. The crudest is the real-time data. The second level is post-pass analysis data, averages of which will form our initial contribution to the summary data set (SDS). Finally, there is the fully reduced data with full time resolution and merged justified orbit and attitude information, which will constitute the finally processed data set.

All R/T data will be produced at the UKOCC using two dedicated PDP 11/34A computers. During R/T contact with UKS, one computer (A) is dedicated to commanding and control of the spacecraft and the other (B) to processing and display of experimental data. The R/T magnetic data processing is done on A, the command and control machine.

In deciding on a strategy for developing the R/T magnetometer data reduction, one had to balance conflicting needs to maximize the data rate with the need to minimize core use on the control computer and to time share. The data rate constraint was a very serious consideration for it is necessary that the R/T magnetic data be adequate for the determination of the plasma regime in which the spacecraft is at any stage. It was decided that sampling somewhere near the spin rate (~5 s) or major frame acquisition rate (8 s at 8 kbit/s in the science mode) would be adequate for the level of identification required, but any substantially slower rate could cause difficulties.

For the magnetometer data to be readily assimilable by the control team members, some form of spin demodulation must be done. Initially we investigated the notion of stripping out one sample per spin synchronized with the sun pulse, a procedure which has the virtue of eliminating the need for data rotation in the spin plane. At the lowest data rates (4 samples/s) in the engineering mode such a procedure could result in the displayed field direction on any particular measurement being up to 18° off the true direction. In addition, any slow beat between the sampling rate and the spin frequency could produce a spurious ultralow-frequency signal in the field direction. The idea was rejected, but in consequence some quality check can be done on the stripped out sample. In line with the notion of sampling at near the spin rate the R/T program searches the most recent major frame for a reliable sample and after consulting the attitude file, rotates the measurement to a fixed nonrotating spacecraft reference frame. A further rotation takes the vector into a geophysical system (GSE). The new data point is then added to the R/T display. The program can be run repetitively at any multiple of the major frame period; the rate being determined by balancing demands on the A machine for spacecraft control, attitude processing, etc., and for knowledge of the spacecraft magnetic environment.

The magnetometer data stream contains no flag or direct information on flipper status. A record of flipper power use is kept, but normally in R/T processing a brief initial run is done using full sampling at highest bit rate to confirm flip status directly by testing rms deviation in each component over a spin. (Under all but the most exceptional conditions the spin plane components have a large rms signal at the spin frequency; the component antiparallel to the spacecraft spin axis will not.)

The R/T data are not archived. The next stage of processing uses the raw data together with nominal orbit and attitude information to create 1-min and 5-s average magnetic vectors for the summary data set.

Initial summary data set plots are widely distributed. Magnetometer team plans are to use SDS plots as a basic "road" map to aid choice of segments of data meriting further study. Post-pass analysis is done at UKOCC.

Full data reduction of the entire magnetometer data set is done at Imperial College using the Space Physics Group PDP 11/40 computer once final attitude and orbit information are available. A by-product of the production of the full set of magnetic vector readings are updated 1-min average field values and 5-s resolution field values which will be returned to UKOCC to replace the preliminary SDS data set. This justified data set will form the master data record (MDR).

SDS data created in the post-pass analysis are being widely circulated, but should be treated with some caution for detailed scientific use. The full processing at Imperial College involves checks of the instrument gain and offset. The latter may be a sensor effect or due to residual spacecraft fields. The latter are a significant consideration for a magnetometer located relatively close to the spacecraft body. The flipper mentioned earlier is a simple device for testing offset. The flipper allows the switching of the sensor along the spin axis into the spin plane and one of the spin plane sensors to an orientation parallel to the spin axis. Fig. 1 illustrates the actual configurations (flip states right and left). With a spinning spacecraft one can correct for spacecraft fields or sensor offsets in the spin plane. The presence of the flipper leaves only one real unknown in flight, the axial spacecraft field. In magnetic tests the soft magnetic component induced in a 5×10^4-nT field was of order 0.5 nT. Further in-orbit calibration will require comparison with the IRM magnetometer data in quiet regions of the solar wind. We anticipate flip operation about once a week (once every 3–4 orbits) during the mission.

TABLE II

Flip Right			
	X	Y	Z
Sensor 1	- 0.731	0.681	0.028
Sensor 2	- 0.005	0.025	- 1.000
Sensor 3	- 0.664	0.748	- 0.009

Flip Left			
	X	Y	Z
Sensor 1	- 0.751	0.660	- 0.009
Sensor 2	- 0.652	- 0.758	- 0.030
Sensor 3	- 0.016	- 0.029	- 0.999

VI. Commandable Features

The UKS spacecraft ground system allows real-time commanding of instrumentation. There is no intention in the magnetometer team to make great use of this opportunity. Flip operations are used sparingly. It is possible to trade precision for bit rate [1], but priority is for the best possible resolution of the field. Range changes (high or low gain) are commanded from ground, but more than one change in a pass is not anticipated. All commands are executed at a major frame pulse.

VII. Instrument Pointing

Nominally, two sensor axes are aligned in the spin plane and the third is antiparallel to the nominal spacecraft spin axis (Z axis). More precise pointing has been determined using the magnetic test facilities of the Royal Aircraft Establishment, Farnborough. Table II presents the direction cosines of the three sensors relative to spacecraft axes (X, Y, Z) for flip-left and flip-right instrumental states. Beam sag due to gravity was eliminated by making the measurements with the spacecraft Z axis pointing both vertically up and downward. The matrices given are those expected in operation in space. Note that, unlike the ISEE configuration [1], the AMPTE 1, 2, 3 sensor directions form a left-handed set.

VIII. The First Month of Operation

This paper was completed some three weeks after the three AMPTE spacecraft were launched from the Kennedy Space Center. The magnetometer was switched on shortly after the final separation between the UKS and the German IRM spacecraft. The instrument is working well and the flipper mechanism has been used on three occasions. The preferred mode of operation is in the "flip-right" state, and the flipper has always been used to flip left and then to return to right after about 1 h.

Initially, the R/T reduction of data was hampered by a larger than expected spacecraft field, and initial R/T displays were contaminated by spin tones introduced by the demodulation program operating on a field which is stationary with respect to the spacecraft. The R/T program now recalibrates automatically to take account of small residual variable spacecraft fields. Time and machine capacity preclude any sophisticated treatment of spin tone signals in real time; the compromise adopted is to recalibrate on a single spin cycle, but only to implement recalibration if the two spin plane sensors agree on the spin plane field magnitude. A large offset on sensor 3 has led us to prefer to leave the instrument in the flip-right state for routine operation although there is no evidence of sensor drift.

Flipper use combined with cross comparison with the IRM data kindly supplied by H. Lühr (Braunschweig) has enabled us to calibrate the measurements in the spin-axis direction fairly confidently. The configuration whereby the IRM spin axis (in ecliptic) and the UKS spin axis (normal to ecliptic) are at right angles is invaluable in this respect. Relative gains on all three sensors compare with nominal values obtained in ground calibration.

At low bit rates in the engineering mode the R/T sampling rate has been increased to 4 samples/major frame. Equally well at 16 kbit/s in the science mode (1 major frame/4 s), the program has been modified to produce a vector every second major frame thus maintaining generally 8- or 16-s resolution in real-time plots.

The R/T program is satisfactorily robust. It has no difficulty identifying flip state except during very poor telemetry. During periods where telemetry has been of poor quality the program has shown itself capable of selecting good vectors and producing a vector per major frame where there are only a few good vectors (3-4) in the 64 of the major frame. The program can also wait for extended periods during data gaps and pick up once the data stream returns.

An example of the standard R/T display is shown in Fig. 2.

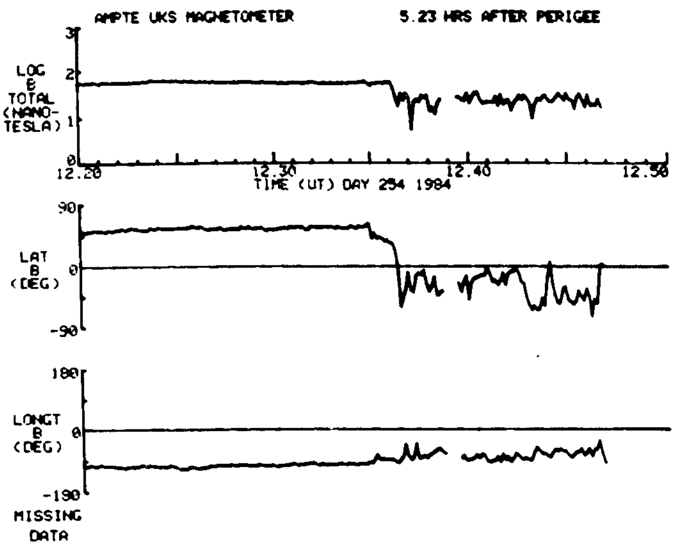

Fig. 2. Example of real-time magnetometer display from U.K.O.C.C. The logarithmic range is set by instrument sensitivity. The data show a magnetopause crossing on day 254, 1984 (September 10) obtained as the spacecraft is outbound near local noon.

The display is updated every 10 min. The field is given in polar geocentric solar ecliptic (GSE) coordinates. The example shown is taken from the hard-copy device attached to the R/T display at UKOCC.

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REFERENCE

[1] C. T. Russell, "The ISEE 1 and 2 fluxgate magnetometers," *IEEE Trans. Geosci. Electron.*, vol. GE-16, p. 239, 1978.