A spaceborne magnetometer tested under extended temperature conditions (experiment MAREMF-OS/MARS-96)

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Abstract. The Space Research Institute of the Austrian Academy of Sciences took part in the experiment MAREMF (MARian Electrons and Magnetic Field) which consists of a dual fluxgate magnetometer (MAREMF-OS and MAREMF-IS) and a 3D electron spectrometer (MAREMF-ES). MAREMF was part of the plasma payload of the Russian MARS-96 mission which unfortunately failed half an hour after launch because of a rocket problem. Digital electronics and firmware of the MAREMF-OS magnetometer were developed at the Space Research Institute, Graz, Austria. The sensor was supplied by the Institute of Geophysics and Planetary Physics (IGPP), UCLA, USA. The sensor electronics were jointly developed with the IGPP. Due to the expected temperature conditions during cruise phase and the orbit around Mars, an improved low-field temperature test facility for magnetic field sensors was constructed at the Magnetometer Laboratory of the Space Research Institute. It enabled all basic test and calibration measurements for magnetic field sensors within a temperature range of ±150 °C. Additionally, a three-layer magnetic shielding set generated a low-field environment. The same facility is now used for the development and calibration of a new generation of magnetic field sensors for the ROSETTA mission to comet P/Wirtanen.

Keywords: fluxgate, magnetometer, magnetic shielding, magnetic field, calibration

1. Introduction

Magnetic field experiments play an important role in the investigation of interplanetary space, the interaction of the solar wind with planets, moons, asteroids and comets and in the exploration of the surface and interior of bodies in the solar system.

The combined experiment MAREMF (MARian Electrons and Magnetic Field) aboard the Russian spacecraft MARS-96 consists of two fluxgate magnetometers, MAREMF-OS (Berghofer et al 1994) and MAREMF-IS (Rustenbach et al 1994), assembled in one electronics box (see figure 1), and a 3D electron spectrometer, MAREMF-ES (see figure 2). Because of a rocket failure the mission failed half an hour after launch in November 1996. Parts of the spare and qualification model will possibly be used for the upcoming European Space Agency (ESA) mission MARS-EXPRESS.

The Space Research Institute of the Austrian Academy of Sciences developed the digital electronics and the firmware of the MAREMF-OS (OS stands for outer sensor) magnetometer. The sensor was supplied by the Institute of Geophysics and Planetary Physics (IGPP), UCLA, USA. The sensor electronics were jointly developed with the IGPP.

The main scientific objective of the experiment was the investigation of the magnetic field vector in the solar wind and in the plasma environment of Mars with high accuracy, reliability and time resolution. An essential point of interest hereby, was the question of the existence of an
2. MAREMF-OS instrument description

2.1. MAREMF-OS technical data

The following list summarizes the technical characteristics of the MAREMF-OS magnetometer. Parameters such as operating temperature range, power consumption and mass are constraints on the MARS-06 spacecraft concept. All other parameters have been either defined or achieved to fulfill the scientific objectives of the mission.

- Measurement range: ±128 nT
- Resolution: 4 pT (16-bit)
- Noise density at 1 Hz: <0.5 pT Hz^-1/2
- Carrier frequency: 9 MHz, 22 Hz
- Offset (at 25 °C): <1 nT
- Offset stability: Sensor: ±30 to ±70 °C, ±1 nT

Electronics: ±20 to ±200 °C, ±0.7 nT

- Linearity error: ±10°
- Operating temperature range: Sensor: -100 to +80 °C
- Electronics box: -20 to +60 °C
- Power consumption (sensor plus digital electronics): ≤2 W
- Mass: Sensor: 434 g
- Electronics box: 720 g

2.2. Sensor and sensor electronics

The MAREMF-OS magnetometer is based on the well known three-axis fluxgate principle described by Armar (1974), Arnold et al. (1980), Gordon and co-workers (1965, 1972), Mages (1980), Pürrer (1980), Primdahl (1970, 1979) and others. The non-linear magnetization curve of a soft magnetic ring core is used for measuring the magnetic field. A single sensor consists of a soft magnetic ring core which is toroidally wrapped with several drive windings and placed in the centre of a solenoid sense coil. These single fluxgate sensors are assembled to one sensor triad for measuring the three components of the magnetic field vector. The main advantages are high resolution, flexible measuring range, small power consumption and weight, simple three-component measurement of the magnetic field vector as well as high stability against thermal and mechanical influences. This is why fluxgate magnetometers have often been used aboard scientific space missions.

In order to meet the requirements for the sensor temperature range (-100 to +80 °C), a spacequalified sensor and sensor electronics design was used for the MAREMF-OS magnetometer. The fluxgate sensor and the know-how for the sensor electronics were made available by the IGRF (Pürrer 1980). The single sensor itself was originally developed at the Naval Ordnance Laboratory (NOL) (Gordon et al. 1968). Several layers of a soft magnetic 6-813 thin-permallyloy foil are wound around a non-magnetic bobbin (of diameter one inch). The alloy was investigated through a long-term magnetometer
sensor program started in 1964. It features low noise and high stability because of low coercive force, high initial permeability, low magnetostrictive and low anisotropic values. Inconal X-759 material was used as the bobbin material because of its non-magnetic properties and its coefficient of expansion that closely matches the coefficient of expansion of the 6-81-3 material. The wrapped ring core and the solenoid sense coil are potted in a fiberglass box, which makes the single sensor resistant to any environmental influence.

A similar sensor triad was first used for the Lunar Surface Magnetometer (Dyal and Gordon 1973) and afterwards aboard numerous famous US space missions such as ISEE, Voyager and Pioneer Venus.

The sensor electronics (power consumption 1 W) are divided into drive and sense units which have been
described in more depth by Arnold et al (1990), Magnes (1994) and Pierce (1989). The drive unit symmetrically saturates the soft magnetic material in positive and negative directions with a drive frequency of 9 kHz. The frequency spectrum of the OS-X drive current is depicted in figure 3. For space missions the power consumption of the drive unit has to be as low as possible, which results in an extremely nonlinear drive current and strong odd harmonic frequencies. It is much more important to have a very small second harmonic in the drive signal, because it would be coupled to the sense coil and measured as offset.

The sense unit converts the field-proportional second harmonic signal (18 kHz) of the sense coil to a DC output voltage. The second harmonic is amplified, filtered (passive bandpass), synchronously detected and finally integrated (see figure 4). The loop is closed by feeding a DC (low frequency) current, which is proportional to the DC output, through the sense windings in order to increase the linearity of the system. The scale factor of the magnetometer only depends on the number of turns of the sense coil and the feedback resistor.

Much effort was made to achieve a small temperature drift of the sensor electronics (Magnes 1994); it is less than
1.5 nT over the required electronics temperature range (−20 to +50°C).

2.3. Digital electronics and firmware

The MAREMF-OS digital electronics consist of three functional units: an analogue-to-digital converter (ADC), digital processing unit (DPU) and telemetry. The maximum power consumption was limited to 1 W according to the spacecraft system requirements. The firmware controls all tasks of the instrument such as sampling and filtering the magnetic field vector, extracting the correct instrument mode, handling the serial links to MAREMF-ES and the search coil experiment ELSMA (see figure 2), decoding the control command words (CCW's) received from the spacecraft computer and transmitting the MAREMF-OS data frames via the telemetry system.

2.3.1. Analogue-to-digital converter (ADC). The MAREMF-OS analogue-to-digital converter (ADC) digitizes the three magnetic field output voltages of the sensor electronics and some additional housekeeping voltages (electronics and sensor temperature, supply voltages...), with 16-bit resolution (see figure 5). For redundancy, buffered MAREMF-OS sensor output voltages are also sampled by the MAREMF-ES ADC and vice versa (see figure 1).

The ADC board is based on a Crystal CS 5016 chip working at a sampling frequency of 819.2 Hz. This well known chip has a very low power consumption and the self-calibration facility of the chip maintains accuracy over time and temperature.

The board is shielded by a metal layer in order to avoid any coupling from outside. Special attention was paid to the layout with separate analogue and digital ground planes that are connected only at one point. Furthermore, all digital signals to or from the converter board are buffered and bypassing capacitors are positioned at sensitive components. The board contains separate power regulators for the ADC, a very low-drift and low-noise reference voltage (LT1019-4.5, 880 nV), a low offset and high-stable amplifier, precision anti-aliasing filters and very low impedance eight-channel CMOS analogue multiplexers. The resolution is 1.7 μV per least significant bit. The noise, when shorting the ADC inputs, is about 2 least significant bits (LSB's) peak to peak and the temperature drift over the required box temperature from −20 to +50°C is less than 10 LSB's. Effects caused by differential and integral non-linearity are negligible.

2.3.2. Data processing unit (DPU). The DPU is based on an 8059 microprocessor and its peripherals. The system has 125 kbytes RAM, 64 kbytes ROM and runs at a clock frequency of 6.144 MHz. The DPU controls data sampling, the spacecraft interface of the experiment and two inter-experiment serial links to MAREMF-ES and ELSMA (search coil magnetometer). The serial links are decoupled by opto-couplers to avoid ground loops and the propagation of noise between the experiments. The on-board data are analysed, pre-processed and compressed by the software-controlled DPU. One 8255 timer chip works as a real-time clock; a second one provides the clocks for the ADC and the sensor electronics. A watchdog circuit continuously supervises the operation of the CPU and resets it in the case of an unattended system crash.

2.3.3. Telemetry. On board the MAR-56 spacecraft a special telemetry system, called MORION (Russian acronym), was used for scientific data acquisition, data recording and supporting scientific experiments with the required information. The MAREMF-OS telemetry board provides the interface to the spacecraft computer according to the MORION telemetry system interface specification. Data frames (120 bytes long) are transmitted via an autonomously working 4096 bytes long first-in-first-output memory (DPU). The FIFO automatically handles the data transfer to the telemetry system. At the maximum vector rate of 64 Hz the telemetry output data rate in 4090 bits s⁻¹ and at a typical vector rate of 1 Hz it is 40 bits s⁻¹. The telemetry board also contains an 8-bit digital-to-analogue converter (DAC) for driving a small calibration coil inside the magnetic field sensor. A special mode with different calibration signals is available for verifying the correct operation of the analogue and digital electronics and the software.

2.3.4. MAREMF-OS firmware. The MAREMF-OS software controls the operation of the instrument depending on the CCW's received from the spacecraft computer. There are more than 100 commands available for MAREMF-OS, which can be processed immediately after reception or at a specified spacecraft time (time tagged command). The
CCWs select the desired data rate, the instrument mode and optionally a time tag at which the CCW should be executed.

The principle of MAREMF-OS data flow is depicted in figure 5. 14 digital filter stages are used for data filtering and decimation. Each filter stage is implemented as a finite impulse response (FIR) filter as well as a simple averaging filter. The FIR filter gives better results in avoiding aliasing, but if there are unforeseen problems with the FIR filter, the averaging filter can be chosen by commanding the instrument. Each filter stage reduces the data by a factor of two. Thirteen different data rates (from 1 to 4996 vectors per minute) and seven instrument modes are available. After collecting 16 magnetic field vectors, corresponding to the current data rate, a data frame is prepared. Each data frame is 120 bytes long and contains 16 filtered magnetic field vectors (14-bit integer format), time, housekeeping information, frame identification, a checksum byte and an additional data field. The additional data field holds data depending on the current instrument mode. Instrument modes for preparing wave analysis data (FFT, standard deviation), short sequences of unfiltered magnetic field data (273 Hz snap shot data) or high-resolution data requested from the ELISMA experiment are selectable.

By default, data frames are transmitted via the telemetry interface. In case of malfunction of the interface the frames can be redirected to MAREMF-ES via an inter-experiment link. MAREMF-ES is then transmitting both MAREMF-OS data frames as well as its own frames. The same redundancy mode is available for MAREMF-ES.

A special mode is implemented for the orbit around Mars, when only a few commands can be transmitted to the instrument. Eight commands can be stored in an execution queue together with time intervals between the commands. After triggering the queue, the commands are sequentially executed. The queue can be triggered automatically by the spacecraft (e.g. at the pericentre) of the orbit or manually by commanding the interface. Eight different queues can be stored into an EEPROM. The queues can be reprogrammed during flight. Furthermore, it is possible to store the current instrument set-up to EEPROM and reload it in one single command.

In case of malfunction of the command interface, MAREMF-OS commands can be received via MAREMF-ES and vice versa.

The software was developed in C language and optimized for maximum execution speed.
3. Low-field temperature test facility

The calibration of fluxgate sensors designed for small magnetic fields (measurement range less than ±1000 nT) is a sophisticated operation. Parts of the temperature test facility have to be packed into a magnetic shielding because of the huge Earth field and the superimposed disturbances especially in urban areas.

The low-field temperature test facility at the Space Research Institute was constructed for the two MAREM magnetometers (range, ±128 nT) as well as for future spaceborne magnetic field experiments. The sensor under test can be mounted by a Teflon pipe (see figures 7 and 8 later) for an accurate offset measurement during the whole temperature cycle. This is a unique advantage of the system because external influences have no effect on the offset measurement. Cooling and heating within has temperature test cycle is not possible at the moment because of the completely separate low- and high-temperature test equipment. After a low-temperature cycle the test configuration has to be taken apart in order to run a high-temperature cycle and vice versa. This slows down the temperature test, but combining the low- and high-temperature test equipment is planned in order to run a full thermal cycle without interruption.

The temperature test device consists of the following main parts: three-layer magnetic shielding set, low-temperature equipment, high-temperature equipment and a calibration coil for magnetic field stimuli.

3.1. Magnetic shielding set

A three-layer cylinder set, vertically positioned on a mobile board, is used for shielding the Earth’s magnetic field (see figure 6). The shielding set was designed at the Space Research Institute (Mocnik et al. 1994) in co-operation with the IGPP and manufactured by Williams Manufacturing Corp., San Jose, CA. It is made from highly permeable (μ> > 350000) 1.5 mm thick Hipernorm provided by Carpenter Technology. After machining and assembling, the shields are annealed in dry hydrogen. The cylinders are closed at the bottom. At the top, each cylinder can be closed with removable caps which are also made from Hipernorm. Sensor cables and mounting rods can be led
through small holes in the caps. The shielding factor was determined in the Magnetometer Lab of the Space Research Institute under total Earth field condition (about 47,300 nT), with closed caps and by using a fluxgate sensor (Mocnik et al 1994). With the fluxgate sensor placed on a wooden turntable, it was possible to position the sensor in many different places within the shielding. The shielding factor is of course dependent on the position within the cylinders.

With closed caps the shielding is best along the cylinder axis and 200 mm above the bottom of the inner cylinder (see figure 6). At this point the residual horizontal field is less than 1 nT and the residual vertical field is about 2 nT. The non-homogeneity is about 0.1 nT cm⁻¹. This area of the shielding set gives a unique rest field environment for many calibration measurements (e.g. offset, noise and noise density, transfer function, long-term stability, etc).
Figure 11. Power consumption versus sensor temperature.

3.2. Low-temperature equipment

Figure 7 shows the configuration of the low-temperature test equipment. A PC-controlled regulation unit (developed and manufactured by Vectotherm) drives the heater in the liquid nitrogen (LN$_2$) storage tank until the nominal temperature in the test area is reached. The actual temperature for the regulation is measured by a Pt100 element positioned close to the magnetic field sensor. The vaporized nitrogen is blown through the double-walled and evacuated supply pipe into the Dewar. The glass Dewar isolates the temperature environments around the magnetic field sensor for minimizing temperature losses and temperature changes of the magnetic shielding. Temperatures down to −150°C can easily be obtained, limited only by the test sensor and its thermal energy content. The nominal temperature (regulation accuracy is about ±0.5°C) as well as the cooling velocity between two temperature values (e.g. 0.01°C s$^{-1}$) can be adjusted stepwise.

The MAREMF-OS qualification model sensor was successfully tested down to −100°C (Koren et al. 1994) and the MAREMF-OS flight model sensor down to −80°C.

3.3. High-temperature equipment

The contrast to the low-temperature set-up described above, the heating device requires hot air circulation. It is realized by a fan heater system which is connected to the glass Dewar via two flexible and heat resistant tubes (see figure 8). The Vectotherm regulation unit controls the power of the heater in the same way as the heater within the liquid nitrogen tank described before. Temperatures up to 150°C can be reached. The MAREMF-OS qualification model was successfully tested up to 100°C. The flight model sensor was not tested at such high temperatures.

3.4. Calibration coil for magnetic field stimuli

A cylindrical calibration coil was placed between the glass Dewar and the inner magnetic shielding cylinder to apply test fields to the sensor during the measurement cycle. The coil is 700 mm long and has a diameter of 270 mm. At the top and the bottom of the coil the winding pitch is smaller (0.75 mm) than in the middle (1 mm) in order to smooth out the field strength variation (Mocnik et al. 1994). The coil coefficient is 1.25 nT µA$^{-1}$.

4. Results of the sensor temperature tests

To avoid measurement errors caused by a temperature gradient in the fluxgate sensor, the sensor temperature was stabilized for at least one hour at each temperature step. At the end of the stabilization period the offset, noise density, supply current, linearity and scale factor were measured.

The offset results of the high- and low-temperature tests for MAREMF-OS flight model are presented in figure 9. The offset drift over the whole temperature range from −80 to +70°C is less than 2 nT. Approximately the same offset drift was measured with the spare and qualification model.

Figure 10 shows the noise density (0 to 30 Hz) of one sensor component at three different sensor temperatures. The 1 Hz noise density is 12.7 pT Hz$^{-1/2}$ at 70°C and decreases to 8.9 pT Hz$^{-1/2}$ at −80°C. Within the expected temperature range during flight (−60 to 0°C) the noise density at 1 Hz will be less than 10.5 pT Hz$^{-1/2}$.

A calibration coil was used for measuring linearity and relative changes of the scale factor. The analogue output data of the sensor electronics were sampled by a 16-bit ADC (see figure 7) and evaluated in Matlab. No linearity...
change was measured during the temperature cycle. The scale factor drift is less than 0.1%.

The power consumption of the sensor electronics is proportional to the sensor temperature (figure 11).

5. Conclusion

Temperature tests with MAREMF-OS have confirmed that the magnetometer meets the scientific requirements in resolution and stability (see section 2.1) for accurate and successful measurements during flight. Without the temperature test facility it would not have been possible to check and calibrate the magnetometer with its low measurement range sufficiently. Even though the flight model crashed into the Southern Pacific instead of flying to planet Mars we have learned much for our current (Earth field variometer CHIMAG, participation in magnetometers aboard ROSETTA) and possibly future projects (MARS-EXPRESS, ALPSAT).

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