The fluxgate magnetometer for the Venus Express Mission

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The MAG (Magnetometer) instrument aboard the Venus Express spacecraft is designed to investigate the Venus plasma environment. Although Venus has no intrinsic magnetic moment, the magnetic field plays an important role in the solar wind interaction with the planet. The Space Research Institute (Institut für Weltraumforschung, IWF) in Graz, in collaboration with IGEP of TU Braunschweig and Imperial College London, is responsible for the development and manufacturing of the magnetometer. The hardware benefits from the heritage of the Rosetta Lander magnetometer ROMAP. It consists of two sensors, one electronics box (including sensor electronics, data process unit and power supply unit), and a one-meter long carbon fiber boom. One sensor is located at the tip of the boom and the other one is mounted on the surface of the satellite. This configuration with two sensors enables us to separate magnetic effects of the spacecraft origin from the ambient space magnetic field, which is of scientific interests.

1. Scientific Objectives

Venus, like other planets in the solar system, is under the influence of a continuous flow of charged particles from the Sun, the solar wind (cf., Russell and Vaisberg, 1983; Luhmann, 1986; Phillips and McComas, 1991). However, its lack of an intrinsic magnetic field makes Venus a unique object to study the interaction between solar wind and the planetary body. Venus has a dense atmosphere, but no magnetic field, and thus the solar wind interacts directly with the upper atmosphere. The highly electrically conducting ionosphere deflects the oncoming supersonic solar wind around the planet so that a bow shock is formed. The interaction of post-shock solar wind flow with the ionosphere results in a distinct boundary, the so-called ionopause. This ionopause separates the thermal plasma of the ionosphere from the hot magnetized plasma of the magnetosheath which is defined as the region between the ionopause and bow shock.

The absence of a planetary magnetic field leads to important differences between Venus' and Earth's atmospheric escape and energy deposition processes. The upper atmosphere of Venus is not protected by the magnetic field from the direct interaction with the solar wind. As a result, a large portion of the exosphere resides in the shocked solar wind flow; photo ionisation, charge exchange and electron impact ionisation lead to the removal of ionised exospheric components by the action of plasma flow. Another type of atmospheric loss is due to the tailward convection of the plasma mantle, situated between the shocked solar wind flow and the ionosphere. Ions gyrating around the magnetic field lines embedded in the plasma may re-enter the atmosphere, causing extensive sputtering. Finally, erosion of the Venusian ionosphere under varying solar wind conditions provides an additional mechanism for loss of atmospheric constituents. The solar wind interacts with the top of the ionosphere to form a complex array of plasma clouds, tail rays, filaments and ionospheric holes on the night side through which a substantial amount of material leaves the planet. Figure 1 illustrates the associated electrodynamics processes and plasma domains of the Venus upper ionosphere, as derived from Pioneer Venus Orbiter (PVO) observations during solar maximum.

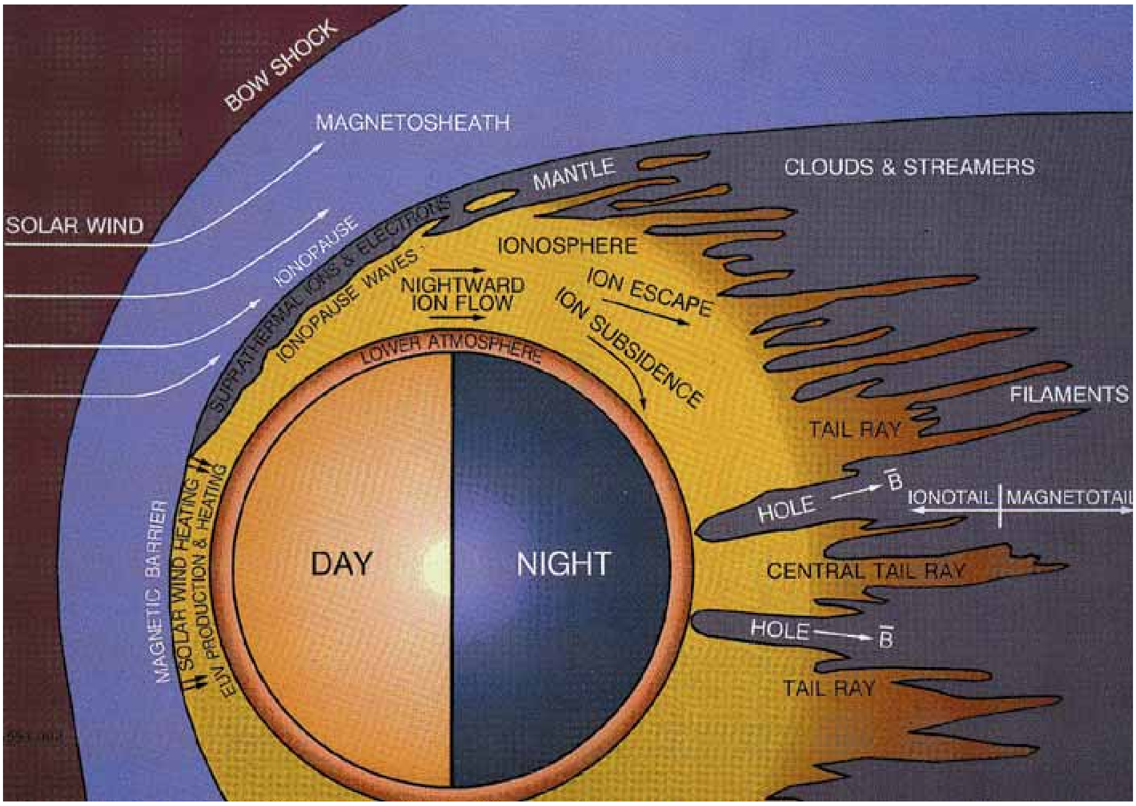

Figure 1. Venus plasma environment during solar maximum as observed by PVO (After Brace et al., 1983). Since the Venus Express will be inserted into orbit during solar minimum, Venus Express will see a different plasma environment than in this picture. We expect to re-draw this picture based on the upcoming Venus Express observations.

From the earlier Venera and Pioneer Venus Orbiter missions, it was found that the current induced by the solar wind electric field forms a magnetic barrier, which deflects most of the solar wind flow around the planet and leads to the formation of a bow shock (Zhang et al, 1991). The ionosphere is terminated on the dayside, developing rapid anti-sunward convection and tail rays. However, the short lifetime of the Venera-9 and 10 orbiters, and insufficient temporal resolution of the Pioneer plasma instrument did not allow a study of the mass exchange between the solar wind and the upper atmosphere of Venus and energy deposition in the upper atmosphere in sufficient detail.

The MAG instrument aboard Venus Express will enable the following studies:

- Determine how the solar wind interacts the Venus atmosphere at solar minimum.
- Map with high time-resolution the magnetic properties in the magnetosheath, magnetic barrier, the ionosphere, and the magnetotail.
- Characterize the plasma boundaries between the various plasma regions.

- Determine the strength and occurrence of electromagnetic waves associated with any atmospheric electrical discharge.
- Provide supporting magnetic field data for particle observations of planetary ion pickup and similar processes.

2. The Instrument

2.1 Overview

The Venus Express magnetometer MAG measures the magnetic field vector with a cadence of 128 Hz. It consists of two triaxial fluxgate sensors. The dual sensor configuration will enable a separation of stray field effects generated by the spacecraft from the ambient space magnetic field, which is the real scientific interest. The electronics box comprises two sensor electronics boards, the DPU board and the DC/DC converter. In addition to the nominal magnetometer, a one meter boom is provided by the MAG team as part of the magnetometer hardware. The outboard sensor is mounted to the tip of this one meter deployable boom whereas the inboard sensor is directly attached to the spacecraft with a separation of 10 cm from the +Z panel of the spacecraft. The hardware benefits from the heritage of the Rosetta Lander magnetometer ROMAP which has successfully been commissioned in spring 2004 (Auster et al, 2005). The block diagram of the instrument is shown in Figure 2; the completed flight model (FM) including boom and outboard sensor, inboard sensor and electronics box in Figure 3. The key elements of the instrument characteristics are provided in Table 1.

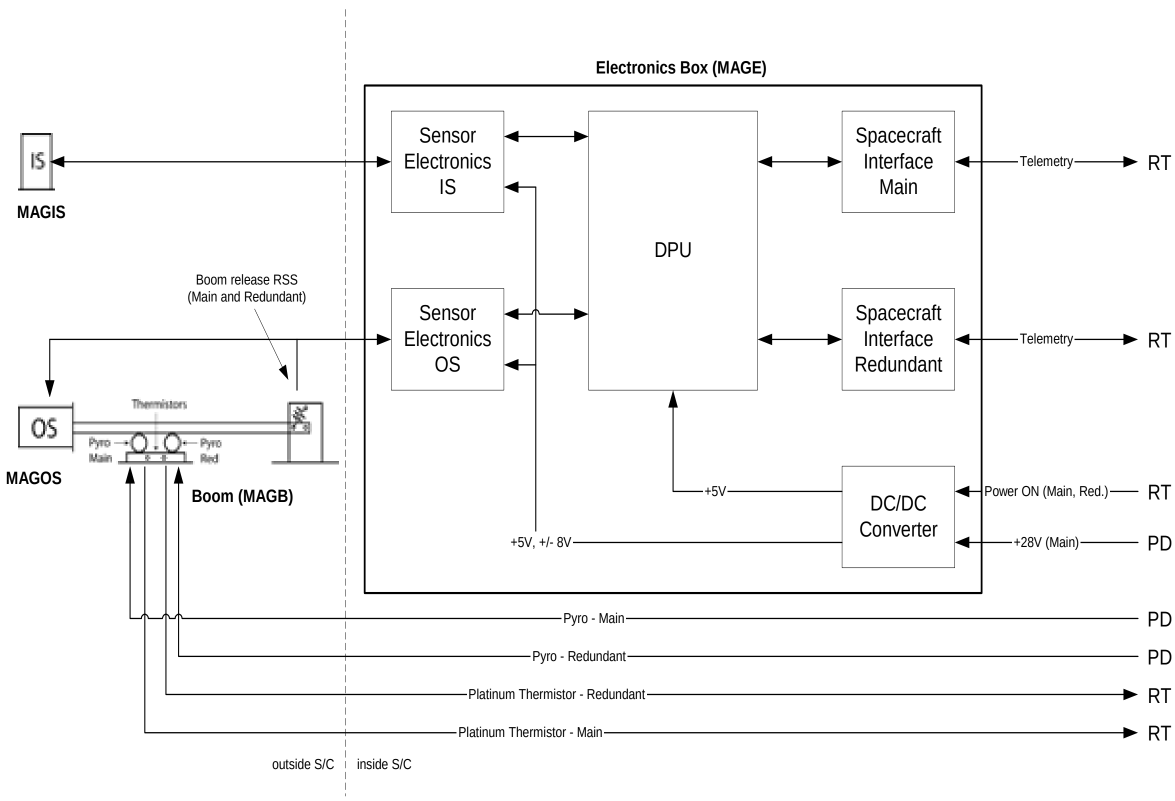

Figure 2. Block diagram of the magnetometer onboard Venus Express

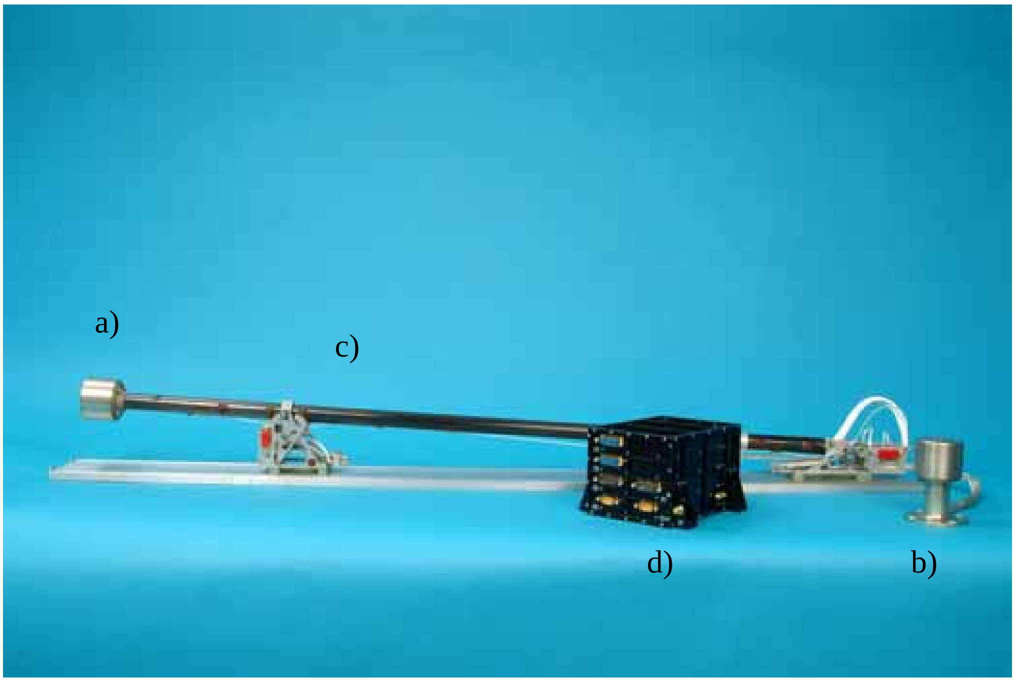

Figure 3. MAG FM: a) outboard sensor, b) inboard sensor, c) boom with launch lock and hinge and d) electronics box

Range	+/-262 nT (default OB sensor) +/- 524 nT (default IB sensor)
Resolution	8 pT (default OB sensor) 16 pT (default IB sensor)
DC compensation	+/-10,000 nT
Data rate	2*128Hz, 2*32 Hz, 2*1 Hz (OB and IB)
Telemetry	3328 bit/sec or 104 bit/sec
Power consumption	Max. 4.25 W
Mass total (incl. boom, harness and MLI):	2308 g
Electronics box	992 g
Sensors	75 g (OB sensor) + 120 g (IB Sensor)
Boom + hinge + launch lock	496 g
MLI and harness	625 g
Dimensions of electronics box	155 x 142 x 98.6 mm^3
Dimensions of one sensor	approx. 67 x 67 x 42 mm^3

Table 1. MAG instrument main characteristics

2.2 Fluxgate Sensors

Both fluxgate sensors (Figure 4), featuring low mass and power consumption, consist of two single ring-core sensors measuring the magnetic field in X- and Y-direction. The magnetic field in Z-direction is measured by a coil surrounding both single sensors. The sensor is identical to the ones of Rosetta Lander and MIR instrument package and similar to the ones flown on Equator-S (same soft-magnetic ringcores made of an ultra-stable 6-81 Mo perm-alloy band: 2 mm × 20 µm). The ringcores have been tested under extreme environmental conditions aboard numerous space missions as well as in applied geophysics. The excellent low noise and stability behaviour of the sensor material has especially been proven aboard Equator-S. The wide operating temperature range of the fluxgate sensor from –160 °C up to +120 °C, allows mounting the sensor outside of the temperature controlled S/C, requiring only a passive multi-layer insulation blanket cover; no active heating or cooling is needed for the sensors.

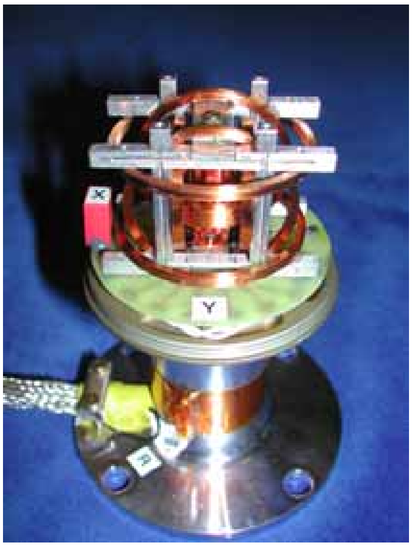

Figure 4. Photo of the magnetometer sensor

2.3 Electronics

The sensor electronics (see block diagram in Figure 5) generates an excitation AC current (fundamental frequency of approx. 9.6 kHz), which drives the soft magnetic core material deep into positive and negative saturation. According to the principle of fluxgate magnetometer operation the external magnetic field distorts the symmetry of the magnetic flux and generates field proportional even harmonics of the drive frequency in the sense coils. The induced voltage in the sense coil is digitised immediately after the preamplifier at four times the excitation frequency. The 'front end' signal processing (synchronous detection and integration and calculation of the feedback signals) is done by logic blocks within an Actel FPGA (54SX32). A feedback field increases the overall linearity and stability of the magnetometer. It is supplied to all sensor elements via 12-bit DACs (feedback DACs) and a separate pair of feedback coils (Helmholtz coils see Fig. 4) per sensor axis. Sense and feedback signals are continuously transmitted to the controller (128 Hz) which calculates the magnetic field values (24 bits) by scaling and adding up the received data (k1*ADC+k2*DAC). The appropriate dynamic range is defined by selecting and transmitting just16 bits of the calculated 24 bits mentioned above (also a kind of data compression). Therefore, the range can be modified by T/C between ±32.8nT and ±8,388.6nT with a corresponding digital resolution between 1pT and 128pT. The default range for the outboard sensor is set to ±262nT with a resolution of 8pT. The default range for the inboard sensor is ±524nT. During the operational phase, an artificial magnetic field of ±10,000nT can independently be applied to each sensor via additional 12-bit DACs for compensation of any disturbing DC stray field.

The digital magnetometer concept of MAG requires analog-to-digital conversion at a higher data rate but it shows a number of advantages over the more traditional analog fluxgate magnetometer: Early digitisation makes the sensed signal robust to changes of the environmental temperature and the supply voltages as well as insensitive to EMC (Auster et al, 1995). Furthermore, no range switching is needed for getting the full range at full resolution, which reduces design complexity and facilitates data analysis.

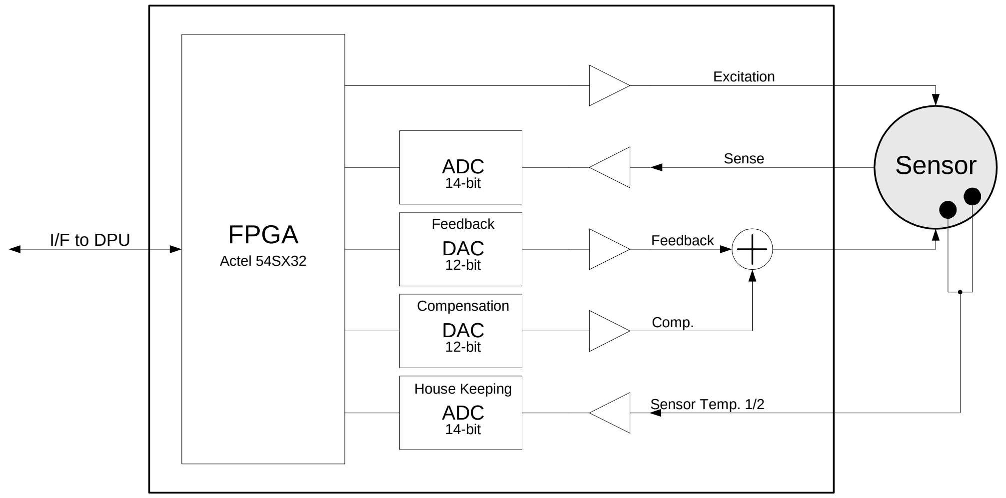

Figure 5. Block diagram of sensor electronics

2.4 Data Processing Unit

The data processing unit (DPU) designated for the instrument controls the two sensors and the spacecraft interface of the experiment and performs internal data handling (sampling, data pre-processing, compression, data frame generation). The DPU is based on an Intersil HS-RTX2010RH rad-hard microcontroller, which was especially developed for space systems embedded control. The controlling logic for the DPU, the sensor interfaces, the address decoder, the clock generator, the reset logic and the instrument spacecraft interface (standard ESA OBDH interface) are implemented in an Actel 1020RH FPGA. A watch-dog circuit, which is also implemented in the FPGA, supervises continuously the operation of the DPU and can release a cold start in case of a system crash. The DPU integrates 128 kbytes of static RAM, 64 kbytes of program memory (PROM) and 64 kbytes of EEPROM. After power-on, the onboard software is copied to RAM. After this the PROM is switched off and the instrument software is executed in RAM. This procedure helps to decrease the power consumption of the DPU. Software patches and various parameters can be uploaded to the instrument and stored in the EEPROM.

2.5 Power Supply Unit (DC/DC Converter)

The DC/DC Converter bears design heritage from the units developed by Imperial College for Cassini and Rosetta. For the Venus Express MAG instrument, a single (non-redundant) converter is provided. The +28V main and redundant primary power inputs are therefore connected together after the on/off relays. The converter provides 4 secondary supplies to the MAG instrument: +8V and ±8V to the analogue electronics, and a separate +5V digital supply. Over-current protection is implemented on the primary input side; in the event of an over-current the supply will automatically shut down. On the secondary side, the MAG electronics is protected by an over-voltage circuit, which will shut off the secondary side of the converter. The converter is stabilised with respect to changes in the load and changes in the input voltage, and is capable of maintaining the secondary voltages within the tight tolerances required by the MAG electronics.

2.6 Deployable Boom

The MAG boom bears the heritage of the Rosetta Lander magnetometer boom and is developed and fabricated by IGEP of TU Braunschweig. It consists of a 900 mm long carbon fibre (CFC) tube, a boom hinge and a launch lock. The MAG outboard sensor is mounted to the boom tip (see Figure 4). The boom release is initiated by cable cutters (main and redundant) and the deployment is spring driven. The launch lock will be opened by a string to be cut by pyros. In the deployed position the boom will be locked by a lever arm.

3. Measurements

3.1 Commands, Modes and Flight Operation

The MAG instrument is based on the dual magnetometer method to enable separation of spacecraft originated stray field effects from the ambient space field (Ness et al, 1971, Delva et al, 2004). Both sensors take measurements simultaneously. The MAG instrument operates during each entire orbit of the spacecraft around Venus and is intended to operate mostly in an autonomous mode, requiring little or no commanding (see Table 2 for description of the nominal modes).

Instrument Mode	Sensors	Data Rate
Solar wind mode	OS and IS	1 Hz
Pericenter mode	OS and IS	32 Hz
Burst mode	OS and IS	128 Hz

Table 2. MAG science modes

After switching on, the MAG instrument automatically operates in a standard mode, i.e., solar wind mode with both sensors at 1 Hz data rate. During a typical science orbit, MAG is switched to pericenter mode one hour before reaching pericenter and switched to solar wind mode one hour after the pericenter. The instrument is commanded to the high resolution burst mode one minute before pericenter for two minutes in order to detect Venus lightning (Russell, 1991).

The MAG is the first instrument to be commissioned 10 days after launch and the boom is deployed. Afterwards, the instrument remains ON during the commissioning of all other instruments, to enable registration and characterization of the magnetic disturbances generated during the payload operation.

3.2 Instrument Calibration and Performance

On-ground calibration of the MAG instrument has been carried out at IWF Graz and IGEP Braunschweig. The following calibration parameters of EQM and FM have been determined on ground:

- scale factor, linearity and frequency response;

- noise of sensor and electronics;
- time stability of the sensor offset;
- temperature stability of sensor offset, instrument noise, linearity and scale factor;
- orthogonality of the triaxial sensor;
- crosstalk.

The instrument has performed very well during ground calibration. At one Hertz the noise density is less than 10 pT/√Hz for a sensor temperature range from 0 °C to +90°C (which is the expected temperature range in orbit around Venus) and the offset stability is better than 2nT over the sensor temperature range from -75° up to 90°C (see Figure 6).

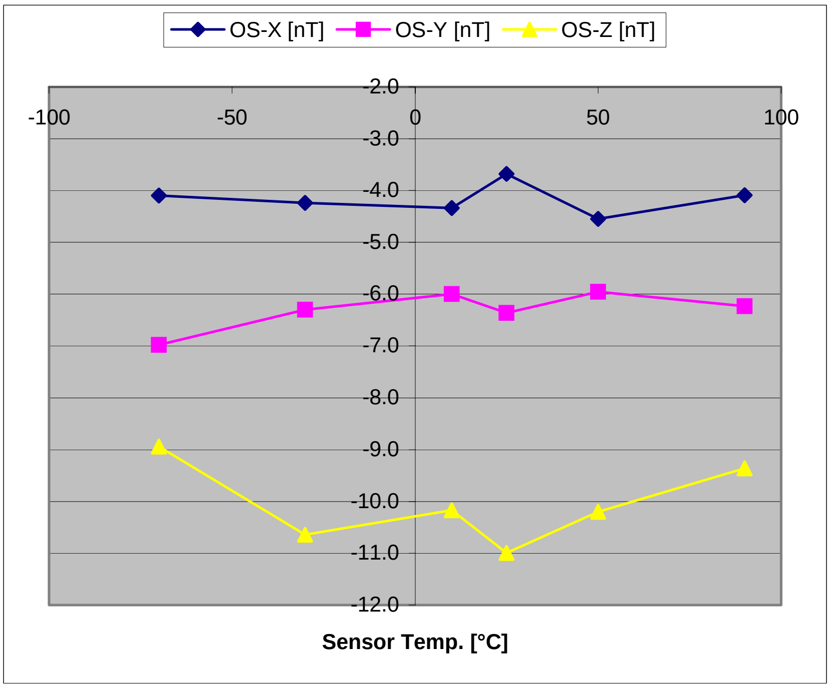

Figure 6. Offset as function of sensor temperature for MAG outboard sensor

3.3 Magnetic Examination Programme of the Spacecraft

Since the Venus Express mission is dedicated mainly to atmospheric studies, no large efforts were possible to investigate the magnetic cleanliness of the spacecraft and the instruments. Therefore, a problem to be solved for the magnetic field investigation is the determination of the magnetic stray fields (both DC and AC) due to the spacecraft and the payload . It is well known that these stray fields are primarily generated by a small number of potentially strong sources, such as thrusters, reaction wheels, solar panels etc. The magnetometer investigator team, mainly IWF Graz and IGEP Braunschweig having long experience in magnetic cleanliness issues, has undertaken a magnetic examination program to predict and determine the spacecraft stray fields at the sensors in two different approaches

In a first approach at spacecraft development level, a preliminary magnetic model of the spacecraft was constructed, based on (a) the design of the Venus Express spacecraft and its payload accommodation and (b) taking a representative set of known magnetic moments from equivalent spacecraft subsystems and payload units on the Rosetta and Mars Express spacecraft. This spacecraft model indicates a “worst case” DC magnetic background estimation of ~ 40 nT at the outboard sensor location and ~ 400 nT at the inboard sensor location, based on the known information.

In a second step, magnetic measurements with a multiple gradiometer equipment have been performed during different test phases of the Mars and Venus Express assembled spacecraft, where subsystems and parts of the payload are in operation. . Analysis of these on-ground measurements allows a description of the stray fields by means of model dipoles located on the spacecraft, indicating that the AC stray fields to be expected at the boom tip sensor are mainly in a range of 20 to 40 nT.

3.4 Data Correction for Spacecraft Stray Field Effects

The measurements during flight are the sum of the ambient space field and stray fields originated by the spacecraft, where the ambient space field is the same at both sensors. When the magnetometers are calibrated well, i.e., both sensors have the same performance, then any difference between the measurements at the out- and inboard sensor can be attributed to be of spacecraft origin. The contribution of the spacecraft (including instrument offset and spacecraft DC field) at both sensors has to be determined and corrected for to yield the ambient space field.

In case of identification of one single source at known position on the spacecraft, a model dipole field can be determined from the dual magnetometer measurement and subtracted to obtain the ambient space field. From this initial state, any change of the spacecraft effects is indicated by a change in the difference between the measurements at both sensors. In principle, identification of the disturbing source (and its temporal changes) from the in-flight telemetry data would enable a correction of the data for the stray field effects; in the optimal case the corresponding model dipoles known from the on-ground magnetic examination can be used.

However, the Venus Express spacecraft stray field effects are much more complicated and of multi-dipole nature and a combination of different methods will be used. In the solar wind well-known statistical methods, using time series of solar wind measurements, can be used to determine an initial ambient space field level from the measurements at both sensors, with a data-difference only due to some initial state of the spacecraft effects. Temporal variations from this initial state have to be detected and if possible, allocated to one single source on the spacecraft to allow correction.The method has been successfully adopted in the Double Star Project to remove routinely the solar panel disturbance in the magnetometer instrument data (Carr et al, 2005). In that case, the disturbances were clearly from the same source and had the same characteristics and pattern; they have been visually identified and removed.

For Venus Express, routine manual identification of stray field patterns and their source (as known from the previous magnetic examination campaign) and subsequent correction will be beyond the resources of the MAG team and the question is raised, if a more automated approach to the correction procedure would be possible.

Since 2003, a new method of combining the dual magnetometry and high performance computation possibilities using neural networks has been envisaged. A task group has been formed, now including K. Kudela, G. Andrejkova and L. Hvizdos from Kosice, Slovakia, and T.L. Zhang, Z. Vörös, and M. Delva from IWF Graz. A neural network pattern recognition has been developed to identify stray field effect patterns in the difference of the magnetic field measurements at the sensors. A test algorithm has been applied to simulated measurement data (ambient field and disturbance from up to seven simultaneous model dipoles) with a satisfactory result. The algorithm was also successfully tested on real magnetic field measurements of the Double Star magnetometer. Further tests will be performed, especially using the MAG data from the commissioning phase of the other instruments and the cruise phase data as "learning sequence" for the neural network algorithm.

We expect that for the in-flight data, a combination of the automated neural network method and in the worst case a correction by human resources will be applied.

4. The Team

The Venus Express magnetic field investigation has been implemented by an international team, led by the Space Research Institute of the Austrian Academy of Sciences in Graz. Other participants are the Technische Universität Braunschweig, Imperial College, London, the University of Sheffield, the Institute of Experimental Physics, Kosice, UCLA, and IRF-Kiruna. Table 3 below lists the investigator team and the responsibilities of the institutes involved in the collaboration

Investigators and team members	**Responsibilities**
Space Research Institute, Austrian Academy of Sciences, Graz	
Tielong Zhang (Principal Investigator) Gerhard Berghofer (Experiment Manager) CoI: W. Baumjohann, H. Biernat, M. Delva, H. Lichtenegger, W. Magnes, R. Nakamura, K. Schwingenschuh Team member: Ö. Aydogar, H.U. Eichelberger, I. Jernej, K. Mocnik, W. Zambelli, Z. Vörös	DPU, Sensor electronics, On-board software, EGSE, Integration, Ground and in-flight calibration, Boom qualification, Environmental tests, Magnetic Examination Programme, Data processing and analysis
Institut für Geophysik und extraterrestrische Physik, TU Braunschweig	
CoI: K.-H. Glaßmeier, H.-U. Auster, K.-H. Fornacon, I. Richter Team member: K. Okrafka, B. Stoll	Sensor, Sensor electronics, Boom, Boom qualification, Ground and in-flight calibration, Data processing and analysis, Magnetic Examination Programme
Imperial College, London	
CoI: A. Balogh, C.M. Carr Team member: T. Beek	Power Supply Unit, Electronics box enclosure, Data processing and analysis
Institute of Experimental Physics, Kosice	
CoI: K. Kudela Team member: G. Andrejkova, L. Hvizdos	Data processing and analysis
Institutet för Rymdfysik , Kiruna	
CoI: S. Barabash	Data analysis
University of Sheffield	
CoI: M. Balikhin	Data processing and analysis
University of California, Los Angeles	
CoI: C.T. Russell	Data processing and analysis
Institut für Theoretische Physik, TU Braunschweig	
CoI: U. Motschmann	Theoretical modeling and data analysis
RSSD-ESTEC, Noordwijk	
CoI: J.-P. Lebreton	Data analysis

Table 3. The Venus Express Magnetometer Team

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