A MAGNETOMETER FOR THE SOLAR ORBITER MISSION

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ABSTRACT

The magnetometer is a key instrument to the Solar Orbiter mission. The magnetic field is a fundamental parameter in any plasma: a precise and accurate measurement of the field is essential for understanding almost all aspects of plasma dynamics such as shocks and stream-stream interactions. Many of Solar Orbiter's mission goals are focussed around the links between the Sun and space. A combination of in situ measurements by the magnetometer, remote measurements of solar magnetic fields and global modelling is required to determine this link and hence how the Sun affects interplanetary space. The magnetic field is typically one of the most precisely measured plasma parameters and is therefore the most commonly used measurement for studies of waves, turbulence and other small scale phenomena. It is also related to the coronal magnetic field which cannot be measured directly. Accurate knowledge of the magnetic field is essential for the calculation of fundamental plasma parameters such as the plasma beta, Alfvén speed and gyroperiod. We describe here the objectives and context of magnetic field measurements on Solar Orbiter and an instrument that fulfils those objectives as defined by the scientific requirements for the mission.

1. SCIENTIFIC OBJECTIVES

The Solar Orbiter mission will provide new science by virtue of a number of properties of the instruments that it will carry and by its unique orbit. In particular, Solar Orbiter will a) travel closer to the Sun than ever before (0.22 AU), allowing measurement of the solar wind in a state closer to its origin in the corona; b) combine in situ and remote sensing instruments, making it possible to study the connections between solar events and their impact on the heliosphere; c) approximately co-rotate above the solar surface for several intervals of a few days, viewing the evolution of surface and coronal fields, and how these affect the solar wind, from a fixed and optimal viewing angle; and d) travel to heliolatitudes over 30º, making remote measurements of the polar magnetic field and coronal holes, and passing into high speed solar wind from polar coronal holes.

The magnetic field is a fundamental property of any plasma, as it orders the motion of all charged particles, both thermal and energetic. Field-particle interactions, through waves, shocks and turbulence, have profound effects on the energy and motion of the plasma. The field is an important tracer of heliospheric structures such as the Interplanetary manifestations of Coronal Mass Ejections (ICMEs), Co-rotating Interaction Regions (CIRs) and the heliospheric current sheet (HCS). In addition, high precision magnetic field data are the best tool for studying fundamental plasma processes such as turbulence. The magnetometer has a fundamental role in contributing to all the key objectives of Solar Orbiter; some of these are discussed below.

1.1 Links between the solar surface, corona and inner heliosphere.

Solar Orbiter's rapid passes through the inner heliosphere will allow the mapping of the large scale structure of the magnetic field for the first time in both distance and latitude. Magnetometer measurements between 0.22 and 1 AU will play a key role in understanding how this field links into the interplanetary medium. Using these data, it will be possible to observe and model the dynamic interactions that produce the complex large-scale magnetic field structures such as CIRs that we observe in the heliosphere.

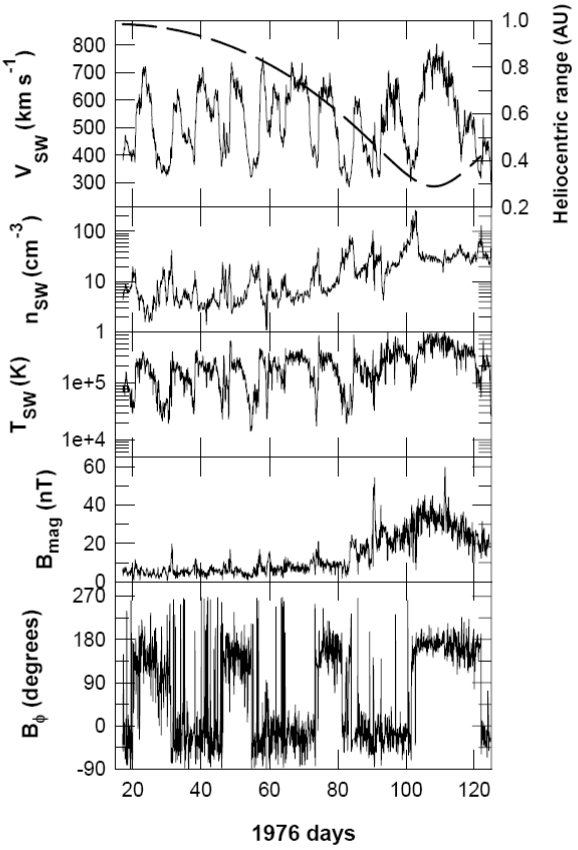

Figure 1. Helios 2 observations of the solar wind and the interplanetary magnetic field (IMF) during the first orbit from aphelion to perihelion in January to May 1976, showing the stream structure of the solar wind and the sector structure of the IMF. These observations, made in the ecliptic plane, are very characteristic of solar minimum when the sources of high speed streams are close, in both hemispheres, to the solar equatorial plane. Note in particular the multiple encounters with slow streams in the negative magnetic sectors due to the "skimming" of the Heliospheric Current Sheet by the orbit of Helios.

The Helios spacecraft showed that, at 0.3 AU, there is great variability in the solar wind on scales of hours to days: this disappears by 1 AU [1], often into pressure balanced structures where the magnetic field plays a key role. The results from the Helios probes, the only spacecraft so far to have explored the inner heliosphere, have been extensively described in [2]. Figure 1 illustrates the evolving appearance of interacting solar wind streams as Helios-2 travelled from 1 AU to its first perihelion at 0.3 AU. Fully developed CIRs were observed by Ulysses at larger distances; in this case, dynamics has masked the origin of the solar wind streams and only the ion charge composition data indicates the different origins of the solar wind streams. The Ulysses observations as a function of heliolatitude are an important guide to what Solar Orbiter will observe, but show a more evolved structure of the heliosphere [3]

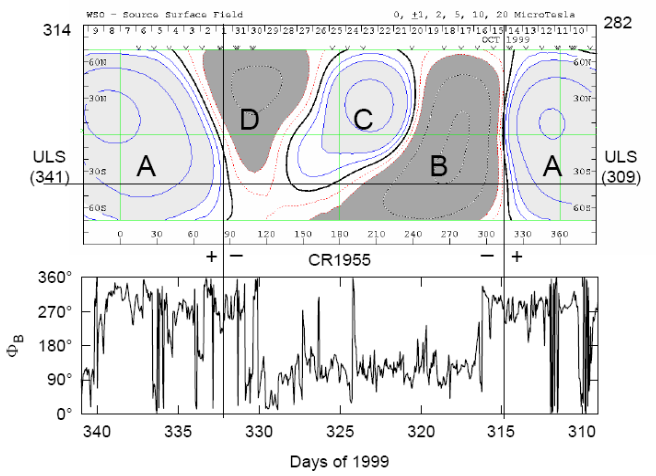

Figure 2. Matching heliospheric and solar coronal magnetic polarities. The magnetic polarity at the source surface in the solar corona and the observed heliospheric magnetic polarity at Ulysses near solar maximum. The match between the implied and observed polarities is generally good in both cases, but there are clearly differences introduced by heliospheric dynamics when interaction regions occur.

Source surface potential field models have been successful in predicting many aspects of the interplanetary magnetic field [4, 5], but discrepancies still persist which indicate that our knowledge is by no means complete, as illustrated in Figures 2 and 3. Solar Orbiter, by flying very close to the Sun and moving slowly above its surface as well as travelling out of the ecliptic, will let us test these models more precisely than has been possible before.

The magnetic field can be used to study the magnetic helicity and polarity of CMEs as they appear in the heliosphere (ICMEs) and, in combination with remote sensing instruments, determine the link between their properties and those of their source regions. Using remote observations and matching these to the magnetic field structure of the ejected material it will be possible to determine the links between the eruption and its signature in interplanetary space, before significant interaction with the solar wind has taken place.

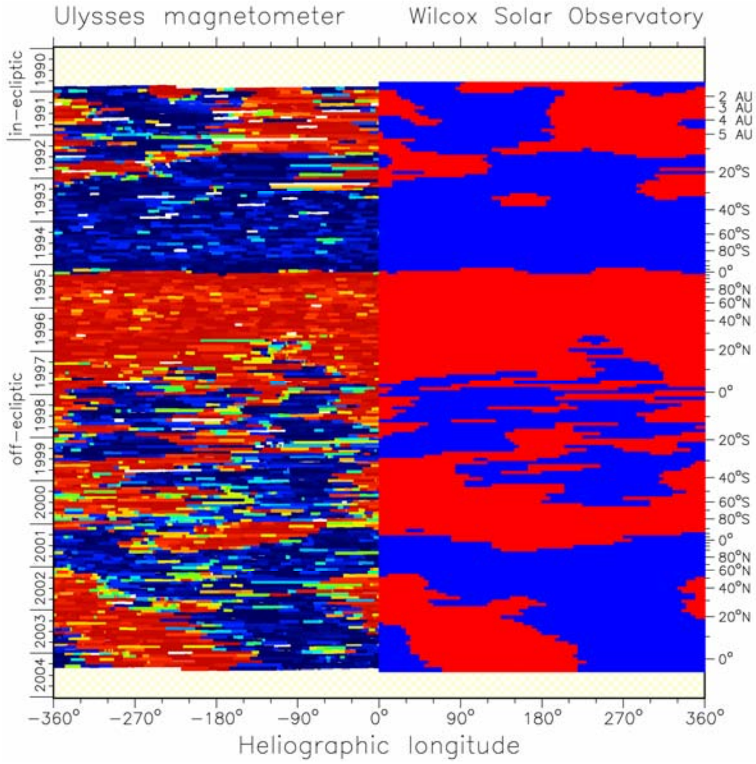

Figure 3. Matching of magnetic field polarities measured in the 3D heliosphere onboard Ulysses with those calculated by a potential field model. On the left, polarities measured by Ulysses are shown, propagated to the source surface using the measured solar wind velocity as a function of Carrington rotation (horizontal axis) vs. time (left hand axis) and heliolatitude (right hand axis). On the right, the magnetic field polarities from the potential field model are shown. The match between measured and model polarities is generally good, with small but significant differences, particularly at high heliolatitudes during solar maximum (1999 to 2001). Figure by G. Erdõs, RMKI-KFKI.

While the fast solar wind originates in coronal holes, the origin of slow wind is still not clear. As the solar wind travels away from the Sun, stream-stream interactions make it difficult to determine its origin. Directly linking coronal regions to the outflowing solar wind is needed to make progress in identifying the regions of origin of the slow solar wind. In situ magnetic field and particle data and remote-sensing data (e.g. abundances, magnetic field), along with modelling [6], can be used to tie specific slow wind streams back to active regions on the solar surface, and analyse how both slow and rapid changes in surface and coronal structures influence the wind properties.

The continuing puzzle of coronal heating will be addressed by Solar Orbiter with both remote sensing and in-situ instruments. Helios measurements showed that the open field coronal plasma – i.e. solar wind ions – is not fully thermalised by 0.3 AU: see [7] for a review. Solar Orbiter will be able to measure the particles and, using the magnetometer, their interactions with the field to reveal the signatures of nano-flares or wave-particle interactions, both thought to be significant contributors to coronal heating. These measurements will be combined with remotely sensed atmospheric dynamics to study the heating processes and their direct consequences in interplanetary space. In addition, the magnetometer will measure MHD fluctuations which originate in the corona, providing an estimate of the energy available for coronal heating from these waves. Solar Orbiter thus stands to advance our understanding of the closed corona, in which the physical details have been largely obscured to remote-sensing instruments. Ulysses measurements of variations in the high speed solar wind suggest that these may be the result of coronal variations on the supergranular scale – but could not unambiguously link them together. By flying close to the Sun, Solar Orbiter will measure magnetic field variations as well as those in the solar wind plasma and link them directly to remotely observed coronal structures. In addition, the high speed of Orbiter during perihelion passes will slow its movement in solar longitude. In this way, the timescales of longitudinal and radial structures will be decoupled, making it possible to distinguish between temporal variability and spatial structure. The magnetic polarity is fundamental in signalling connections to topologically different coronal regions. Magnetic measurements of wave activity in the solar wind are direct signatures of wave power in the corona and hence related to coronal heating.

The heliospheric current sheet (HCS) is the topological boundary between the two polarities of the Sun's magnetic field in the corona. It exhibits a complex internal structure which is related to its origin, within the highly variable slow solar wind, as well as its interactions with structures around it as it is carried outwards from the Sun ([8]). Solar Orbiter's magnetic field measurements will allow us to measure HCS internal structure close to the Sun, before stream-stream interactions have disturbed it, and hence relate it to its coronal origins.

Remote sensing measurements of variability within coronal holes, for example observations of nano-flares, can be correlated with magnetic field and plasma data to try to determine any signature of these processes in the solar wind – and hence better to understand their role in coronal heating and solar wind acceleration.

ICMEs are key triggers of energy transfer into the Earth's magnetosphere and magnetospheric storms. Solar Orbiter will study ICMEs close to the Sun, before they are affected by their interactions with the ambient solar wind, in order to elucidate how their structure and dynamics are related to phenomena at or near the solar surface.

Flares and shocks can accelerate particles to high energies; these particles then propagate through the complex, turbulent interplanetary magnetic field to the spacecraft, or the Earth. Many questions remain about the details of both their acceleration and propagation. Shocks close to the Sun appear to be much more effective accelerators of particles, than those near 1 AU. By using magnetic field, plasma and energetic particle data, the efficacy of inner heliospheric shocks as particle accelerators will be studied to determine what properties make them so effective.

Complex magnetic field structures, such as those around compression regions, are effective barriers to energetic particle propagation [9]. Using magnetic field data in combination with energetic particle data the effects of magnetic field structures on particle propagation in the inner heliosphere, before stream-stream interactions develop, can be studied.

Near perihelion, Solar Orbiter will measure the most dynamically young solar wind turbulence yet seen, allowing us to study it in a unique state. Study of wave-particle interactions, in particular, will shed light on kinetic processes which thermalise the plasma. The processes by which turbulent fluctuations on magnetohydrodynamic scales transfer energy into smaller, kinetic scales and therefore heat the plasma are not well known. Solar Orbiter's high time resolution magnetic field and plasma data will let us study the wave-particle interactions over these scales, to shed light on this fundamental process.

The evolution of turbulent fluctuations from 0.3 AU to the termination shock has been measured (see, e.g. [10] for a recent review), but not in the very inner heliosphere, where they are dynamically young and unevolved, unaffected by stream-stream interactions. Solar Orbiter will provide essential new data to extend our measurements, over a very wide range of scales and distances, to study the development of plasma turbulence – such turbulence plays a key role in transporting energy and momentum in many plasma environments throughout the Universe

1.2 The origin of solar magnetism and its evolution

The magnetic field in space is directly related to the dynamo-generated coronal field. Temporal variations in the solar field are therefore closely mirrored in interplanetary space. The magnetometer will be crucial in determining how supergranular structures and emerging flux affect the heliosphere at large scales and how the global field reversal is propagated into the solar system. The precise nature of the polar magnetic field reversal at solar maximum, and how this is reflected in the heliospheric magnetic field, is an open question. This can only be resolved by improving the link between solar and heliospheric measurements.

ICMEs gradually break their magnetic connection to the Sun as they travel into interplanetary space, sometimes carrying significant magnetic helicity with them. Does this field, carried in around 1 ICME per day during high activity, affect the evolution of the global solar magnetic field, and hence the solar cycle? Solar Orbiter will allow us to measure the helicity of the magnetic field within young ICMEs, and their connectivity to the Sun, to place an inner limit on the flux carried away from the Sun by these structures.

1.3 Magnetometer science team

The science goals described above require expertise across a wide range of solar, heliospheric and plasma physics. The magnetometer team contains experts in all these fields, including data analysis, theory and modelling, and members of either instrument teams with complementary science goals. In this way, we aim to maximise the science return from the magnetometer and the overall mission.

2. MAGNETOMETER FOR SOLAR ORBITER

The scientific goals detailed above, combined with the spacecraft orbit and hence its expected parameters lead to a set of requirements for the magnetometer. These concern accuracy in magnitude and direction together with time resolution. The magnetometer described here satisfies, or exceeds, all of these requirements. The absolute precision of the magnetometer, however, is also dependent on the level of magnetic cleanliness in the spacecraft as a whole. The baseline magnetometer instrument concept comprises two identical fluxgate sensors. This configuration will satisfy, or exceed, all of the instrument performance requirements. An alternative configuration, using a combination of one fluxgate sensor with a vector-helium sensor (as successfully used on Ulysses and Cassini) would provide certain operational advantages, and consequently remains under consideration.

2.1 Fluxgate sensor operation

The fluxgate sensors will be of conventional design. However, while many fluxgates use three cores, one for each axis, the Ultra Electronics sensor design uses two cores, each with two sets of windings, so all three axes can be sensed at a lower mass. These sensors, shown in Figure 4, have been successfully flown on the two Chinese/ESA 'Double Star' spacecraft; their excellent noise performance is shown in Figure 5. The overall performance and resources needs are shown in Table 1.

Parameter	Units	Value
Instrument noise	pT/√Hz	<7 (at 1 Hz)
Offset stability	nT	<0.5nT / 100 hours
Linearity	%	<0.05
Temperature range	ºC	-100 to +100
Normal data (16vectors/s)	bps	850
Burst data (128 vectors/s)	bps	6450
Measurement ranges	nT	±128, ±512, ±2048
Ground test range	nT	±65536
Bits per sample	N/A	16
Digital resolution	pT	4
Total mass	kg	1.88
Total power (no heaters)	W	1.5

Table 1. Performance parameters of the magnetometer for the Solar Orbiter.

2.2 Spacecraft interfaces

The magnetometer will clearly interface to the spacecraft using whichever protocol is defined by the project: at this time, a Spacewire interface is likely, using a Remote Terminal Control (RTC) ASIC. The modest computational requirements of the magnetometer mean that the RTC chip can also perform the role of the instrument DPU, using the included LEON core. The block diagram of the magnetometer is shown in Figure 6.

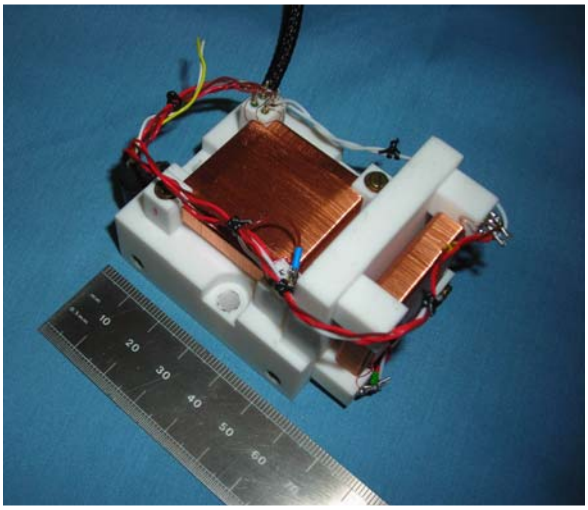

Figure 4. The prototype model of the Double Star FGM sensor which is the baseline design for Solar Orbiter.

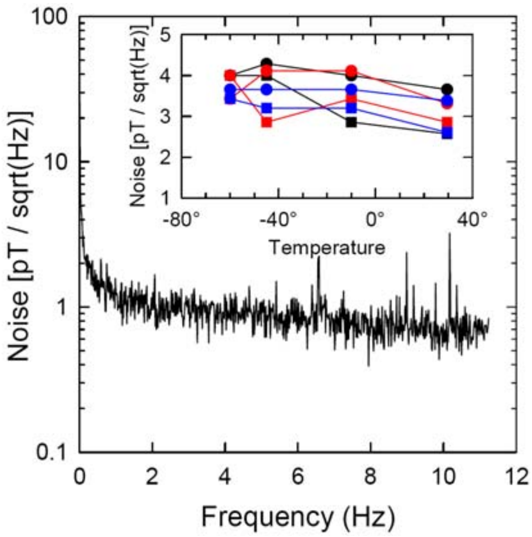

Figure 5. The power spectral distribution of a fluxgate sensor as a function of frequency (main graph). The noise level of a three-axis magnetometer at ~1 Hz (Double Star) for different measurement ranges as a function of temperature (insert).

2.3 Instrument accommodation

The two sensors will be placed on the deployable spacecraft boom. This boom must be rigid, both to prevent off-pointing for the remote sensing instruments and to ensure accurate pointing knowledge for the magnetometer. Sensor to spacecraft reference frame alignment knowledge should be 0.2 degrees or better to allow accurate recovery of the magnetic field vector.

The magnetometer consortium will provide the boom harness. The mass figure in Table 1 assumes a 4m boom with the primary sensor at the far end and the secondary inboard – ideally by around 1m. The magnetometer will require a relatively small electronics box since the 4 boards within it (primary and secondary sensor electronics, DPU board, power supply: see Figure 6) will all be small: approximately 15×14×10cm, similar to the Venus Express magnetometer box.

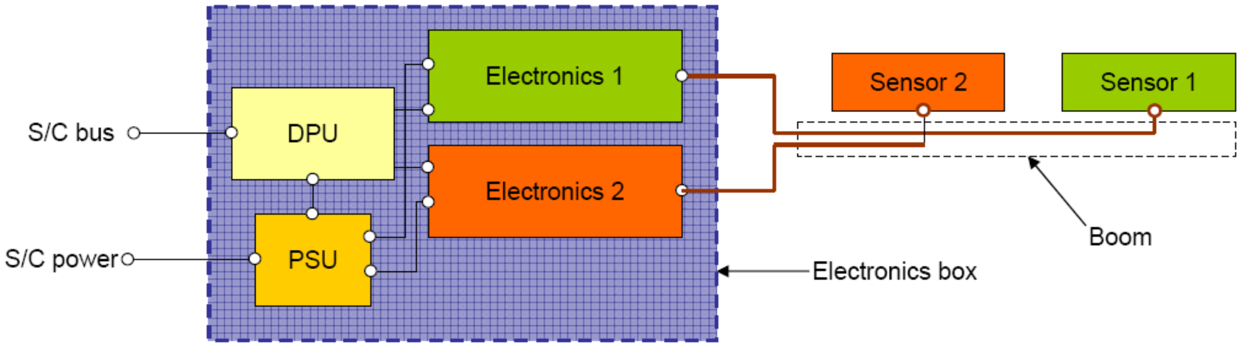

Figure 6. Overall block diagram of the magnetometer, indicating the two boom-mounted fluxgate sensors and the spacecraft-mounted electronics unit.

3. COORDINATION WITH OTHER INSTRUMENTS

In common with many spacecraft, magnetic field data will be passed in real time to the plasma and energetic particle instruments, allowing them to calculate field-aligned distribution functions. However, Solar Orbiter science can be improved by further, close coordination between instruments. Limited telemetry rates mean that burst modes will be necessary to capture the rapid variations associated with wave-particle interactions, which are vital for solar wind heating and acceleration studies. Burst mode triggering must be coordinated between the in situ instruments. Particularly close coordination is required between the RPW instrument and MAG, to ensure that sampling rates are synchronised so the combination of DC and AC magnetic and electric field measurements will be easier.

The linking of in situ measurements to remote sensing data is pivotal to Solar Orbiter science. The magnetic field is the path along which particles travel from the Sun to the spacecraft and hence will play a key role. Magnetograph and magnetometer measurements, combined with global modelling efforts, are the only way to determine these connections. The magnetometer team includes experts from all of these fields, with the aim of ensuring that we maximise the science output of the mission.

4. REFERENCES

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