# Solar Orbiter magnetometer user guide

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## Purpose of this document

This document describes the publicly released data from the magnetometer experiment (MAG) on the Solar Orbiter spacecraft. In general, the MAG data are of very high quality and are immediately useable for science. There are, however, some issues, some of which are very hard to identify from the processed data, which you should be aware of. This document therefore provides a quick overview of MAG RTN coordinate data and describes outstanding issues which are of relevance for people who want to do science with the data: if you are one of those people, we strongly recommend that you read this document first. If you want more detail than is contained here, please refer to the MAG Data Product Definition Document (DPDD).

This document will be updated with each significant public data release.

## Introduction to the magnetometer

The Solar Orbiter magnetometer experiment is described in detail by Horbury et al (2020). It has two fluxgate sensors, both mounted on the spacecraft boom, on the anti-Sun side, in shadow.

While the MAG team is distributing several data products, the one most useful for scientific analysis is provided in RTN coordinates and based largely on data from the outboard sensor (OBS); data from the inboard sensor (IBS) is used to characterise and remove various artificial signals.

### Ranges

The instrument telemeters a fixed number of bits for each field component, so in order to maximise precision each sensor has four ranges (0,1,2,3) and autonomously changes between them based on the ambient field magnitude: see Table 1. Range 3 is the most precise range and OBS has spent almost all of its time in this range; IBS has spent time in ranges 2 and 3. Small field errors can occur around range changes and we have replaced a small number of data points with NaNs around these times. The range is recorded in the `VECTOR_RANGE` variable in the CDF files.

| Range code | Nominal Range in nT | Nominal Digital Resolution |
|---|---|---|
| 3 | +/-128nT | 4pT |
| 2 | +/-512nT | 16pT |
| 1 | +/-2048nT | 64pT |
| 0 | +/- 60000 nT | 1.8nT |

*Table 1. MAG instrument ranges*

### Reference frames

Each sensor measures the three components of the magnetic field. The precise non-orthogonality of each sensor is measured on ground and is not expected to vary in flight. Gains – the conversion of the digitised signal from counts into nT – is also based on ground measurements and is a function of range.

Raw data is converted into the Unit Reference Frame (URF) which is orthogonalized and fixed with respect to the sensor structure.

URF data is converted into the spacecraft reference frame (SRF) using transformations provided by the prime contractor, based on the pre-flight modelled boom deployment orientation. We expect these to be accurate to around 1 degree and this is the largest element in the error budget for the overall field vector orientation knowledge.

The URF to SRF transformation is the same for the OBS and IBS sensors since they are expected to be co-aligned. More detail about the transformations used can be found in the DPDD and the matrices are contained in the calibration files accompanying each data release.

## Time

Instrument time is synchronised to the spacecraft clock using the SpaceWire data link. Spacecraft time is converted to UT on the ground using project-supplied SPICE kernels.

A preliminary comparison of time-stamping between the MAG and RPW sensors has been undertaken and shows generally good agreement to within a tenth of a second; a more detailed assessment will be made in future.

## Operations concept

The MAG operational concept is always to keep the instrument in science mode. Normal mode data is generated continuously whenever the instrument is in science mode; this is typically 8 vectors/s from the outboard sensor during the cruise phase but at times can be 16 vectors/s or 1 vector/s.

Burst mode data, at either 64 or 128 vectors/s, is produced when telemetry allows. Sometimes we have 24 hours/day of burst mode for many days; at other times, just a few short intervals per day. Burst mode files therefore vary significantly in size from day to day and care also needs to be taken since the cadence of the data can also vary. To date, all burst mode operation has been scheduled by telecommand; in future, burst data will also be taken in response to a shock detection trigger generated by the RPW instrument.

The instantaneous time resolution of the normal and burst mode data is reported in the `VECTOR_TIME_RESOLUTION` variable in the Level 2 CDF files.

Early in the instrument development, it was decided to prioritise the return of a continuous normal mode stream over burst mode; since the project does not guarantee to return all the burst mode data, the decision was therefore made to continue to return normal mode data even when burst mode was operating and as a result the daily normal mode files have continuous coverage when the instrument is in science mode.

A list of possible instrument operating modes is shown in Table 2.

| Mode type | Name | Primary vectors/s | Secondary vectors/s |
|---|---|---|---|
| **Normal** | N | 16 | 1 |
| **Normal** | Equal8 | 8 | 8 |
| **Normal** | Low | 1 | 1 |
| **Burst** | B | Not used | Not used |
| **Burst** | B64 | 64 | 8 |
| **Burst** | E128 | 128 | 128 |

*Table 2. MAG science modes. For all operations to date, the primary sensor has been OBS and secondary IBS.*

All data is low pass filtered onboard to remove high frequency interference. The filters are optimised for each selected cadence (and hence burst and normal mode are filtered independently even when recorded at the same time); the filters are described in detail in Horbury et al. (2020) and their effect can be seen in Figure 1.

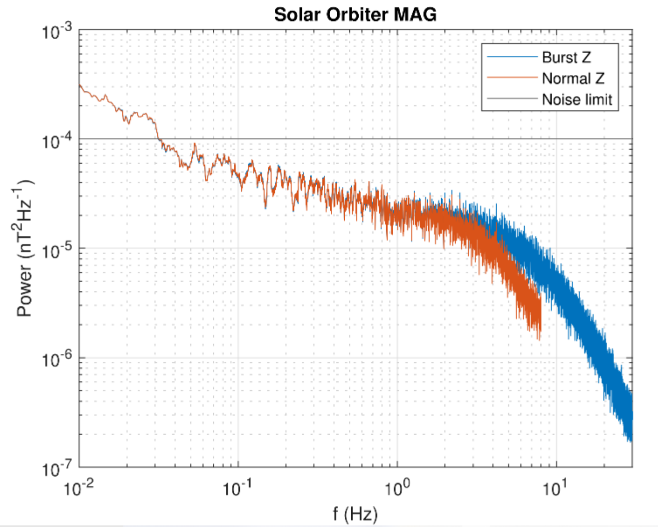


*Figure 1. Ground-measured power spectra for normal mode (red) and burst mode (blue) data. Low pass filters are optimised for the selected data rate. Figure from Horbury et al. 2020.*

The MAG team has also produced a 1 minute cadence sub-sampled and filtered data set for easier browsing of large periods of data. This is generated on ground from the normal mode stream.

## Instrument operations in practice

While the MAG team's goal has always been to operate the instrument continuously, unfortunately a range of spacecraft issues have meant that MAG has been turned off on several occasions. These include spacecraft failures and an update to the spacecraft operating system. Recorded data has also been lost on occasion due to downlink issues. The MAG team has also on occasion rebooted the instrument which results in short periods of lost science data.

We will be releasing monthly operations reports which describe these issues in more detail and we suggest that you look at these reports if you are unsure why data are missing for a particular period.

## Instrument performance

Overall performance of the sensors in flight has been excellent, with high stability and low noise floor that makes it possible, on occasion, to detect whistler waves at tens of Hz; see Figure 2. The general quality of the data is very high. Data from the instrument itself, therefore, are not of concern; it is the artificial signals in the data that need to be considered with care.

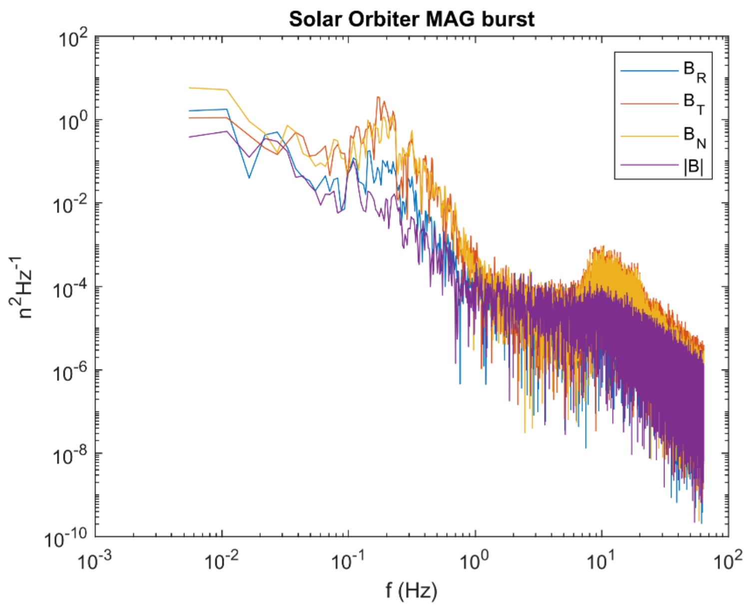


*Figure 2. Example power spectrum of MAG burst mode data, showing ion cyclotron waves at ~0.2Hz and whistler waves at ~10Hz. Note that the spectrum between ~1 and ~10Hz is the noise floor of the instrument.*

## Released data

Public MAG data releases contain Level 0, 1 and 2 data in CDF format. The level 2 science data files are likely to be of most interest. These are the MAG team's best estimate of the true magnetic field and are provided in RTN and SRF coordinates. They are largely based on OBS data but use IBS data on occasion to remove some spacecraft fields. They have a range of artificial signals removed, as described below. They also contain a range of flags which indicate the quality of the data at various times.

## Quality flags

We have provided several flags in the Level 2 CDF files which provide information on the artificial signals that have been removed from the data and when you should be careful with the data. These are not perfect but are a good guide and we strongly encourage you to look at them, and in particular check them if you find a surprising signal in the data.

The `QUALITY_FLAG` variable provides overall information on the useability of the data, point by point, and is largely based on the status of the various other more detailed flags. The quality flag can take the values shown in Table 3, with the definitions given in the table.

| Flag | Definition |
|---|---|
| 0 | Bad data |
| 1 | Known problems use at your own risk |
| 2 | Survey data, possibly not publication quality |
| 3 | Good for publication, subject to PI approval |
| 4 | Excellent data which has received special treatment |

*Table 3. Quality flag values and meaning.*

At this time, the highest quality value in the data files is 3. *Note that following the ESA-defined meaning of a quality flag of 3, PI approval is required for publication of all MAG data released to date.*

The variable `QUALITY_BITMASK` contains a series of individual flag bits, held as a bitmask, that identify times when various signals were identified or removed, as shown in Table 4, which also describes how these various bits are used to change the `QUALITY_FLAG` variable.

| Bit | Binary | Name in Skeleton | Type of Flag | Definition | Impact on Quality Flag | Data source |
|---|---|---|---|---|---|---|
| 1 | 1 | INBOARDPRIMARY | Warning | Raise if data is from Inboard sensor. | Set quality flag to 1 | MAG HK: Primary sensor is IB. |
| 2 | 2 | SCETUNSYNC | Warning | Raise if onboard time is not synchronised. | Set quality flag to 1 | MAG HK: Time is unsynchronised. |
| 3 | 4 | MAGHEATERON | Warning | Raise if MAG heater operational. While the influence of the heater on MAG data has been removed from the time series, periodic signals which correlate to this bitmask flag should be raised with the MAG team. | None | SC HK: MAG Heater status. |
| 4 | 8 | TONEREMOVED | Cleaning has occurred | Raise if interference tones were detected and removed. | None | Tone removal code sets flag. |
| 5 | 16 | THRUSTER REMOVED | Cleaning has occurred | Raise for thruster firing, for duration of cleaning algorithm correction time series. | Set quality flag to 2 | Thruster removal code sets flag, based on profile generated from analysis of data around thruster firing. Thruster firing detected from SC HK. OBS and IBS at same cadence required. |
| 6 | 32 | SCINTERFERENCE | Warning | Raise if SC generated interference detected through a large signal in IBS-OBS cleaned data. Covers timescales from around 1 second to 1 minute (algorithm based), time scales >1 hour via human analysis of time series. | Set quality flag to 2 | IBS-OBS > threshold. Requires analysis of cleaned IBS-OBS time series. |
| 7 | 64 | SAMOVEMENT | Warning | Raise at times of solar array movement. Solar array movements cause changes in spacecraft generated offset at the MAG sensors both due to position and due to thermal impact on SC. Impact on offsets is taken into account generating the MAG data, but influence is not yet completely understood, and can last several hours (up to 17 hours following movement).<br><br>Note this flag is also used to cover solar array lubrications, which usually consist of a 15 degree rotation one way and then back again. These do not have an impact on the data beyond the time when the arrays are moving, so the flag is raised for a shorter period. | Set quality flag to 2 | SC HK: SA angle, plus assessment of impact on offset reviewing IBS-OBS data. |
| 8 | 128 | INSTRUMENTREMOVED | Cleaning has occurred | Raise if an interference field signal from instrument operation has been detected and removed. Note that not all signals are detected or removed. | None | Instrument current related removal code. |

*Table 4. Quality bitmask codes and meanings.*

The remainder of this document describes the various artificial signals which we have identified, how we remove those that we can, and how they are identified in the data files which we have released.

# Spacecraft and instrument-generated magnetic fields

The Solar Orbiter spacecraft is magnetically noisy. In principle, the artificial field will be different, at each sensor, at every single measurement. We have done what we can to identify, quantify and remove these signals but we emphasise that this process is not perfect so some signals remain. In general, these are small enough not to be visible and should not affect the science that can be done with the data.

## Offsets

The spacecraft magnetic field changes on a broad range of timescales, including over periods of days to weeks. The origin of these changing fields in not clear but evidence suggests that thermoelectric currents on the boom are significant. The MAG team assesses the average artificial field at the sensor locations using a procedure similar to that of Leinweber et al. (2008) and then produces a simplified time series of the estimated offset which his removed from the data.

While the original goal for absolute accuracy of the field estimation, which is driven by the offset, was 0.1nT, it has become clear in flight that spacecraft fields are far too variable for us to achieve this objective at this time. We currently estimate our absolute field accuracy to be around 0.2 nT.

## MAG heaters

The two MAG sensors are in shadow on a very cold boom and therefore have heaters to keep them within their operational range. The heaters operate together on both sensors and are powerful, raising the temperature rapidly. The spacecraft operates these heaters based on the temperature of a thermistor within the OBS sensor housing, with a lower set point of -90C. In practice, the heaters operate for one minute every approximately 15 minutes.

These heaters produce a significant signal in the MAG data, which lasts beyond their time of operation; this is likely to be due to thermoelectric currents. This signal slowly varies on timescales of days, perhaps due to variations in the boom temperature.

The heater signal is averaged over the many operations in each day and this signal is removed from the data. This is largely successful but on occasion a residual signal can be seen, particularly in very quiet periods. The `MAGHEATERON` flag is set during heater operation which makes it possible to identify these events.

## Thrusters

Spacecraft thruster operation produces a very large magnetic field, up to ~100 pT at OBS, which can last a few minutes. There is also an additional signature which can last up to 45 minutes after the thruster firing. The MAG team does not know what causes this signal.

Thruster signals have been removed from the data by calculating the difference between the IBS and OBS field during these times and subtracting a fraction of the field from the OBS time series. This process is generally successful but residual fields might be present. The duration over which signals are removed is captured by setting the `THRUSTERREMOVED` flag.

## Spacecraft-operated heaters

The spacecraft has over 100 hundred thermostatic heaters. The spacecraft heater control philosophy is to turn these on or off on minute boundaries (in practice, these are currently around 15s after the minute boundary in UT) based on thermistor readings. The MAG team is provided with one minute cadence information on the status of these heaters.

We have used this information to perform a superposed epoch analysis of the field during the switch on and off of each heater that operates. In practice, many heaters do not produce a detectable signal but we have identified 64 heaters which do. Some of these operate often so in practice at almost every minute boundary, there is a change in the magnetic field at the MAG sensors due to the spacecraft. Some of these fields can be large: the maximum field that we have estimated due to a single heater is around 0.14nT at the OBS sensor. The total field due to spacecraft heaters at OBS can exceed 0.5 nT.

Using the spacecraft heater operation data, we routinely subtract the signal that we estimate from the heater operation. This process is imperfect but produces a dataset which seems cleaner that the original.

Note that different heaters turn on and off at slightly different times at the minute boundary, separated by tens of milliseconds. We have not yet managed to correct for this effect. In addition, we have evidence for field spikes at minute boundaries when spacecraft telemetry indicates that no heater switched on or off and we have no explanation for this effect.

## Additional spacecraft tones

The spacecraft contains a data bus which operates at 8 Hz and which can produce a noticeable signal at 8Hz and harmonics in the MAG data. At other times this signal is not present; the MAG team does not know why this variation occurs. Various other tones above 1 Hz also sometimes appear.

We have implemented a simple algorithm to detect narrowband tones in the data and remove them. This can remove the most obvious examples but is not always entirely successful so some tones are still present in the data, particularly in burst mode.

Times when a significant signal has been removed from the data are denoted by the `TONEREMOVED` flag.

## Reaction wheels

Following an extensive magnetic shielding programme by the spacecraft prime, we have so far detected no signals from the reaction wheels. They are known to operate over a range of frequencies from a few Hz up to tens of Hz; multiple harmonics of these frequencies would also be present if the signal were large enough for MAG to detect.

## Instrument signals

It is clear that the operation of some instruments generates significant magnetic signals. The complexity of instrument operations, particularly of the telescopes, means that we have not managed to isolate signals from all instruments. One approach is to look for signals that correlate with the current consumption of instruments. Using this approach, we have so far identified three such signals (see Table 5) and these are removed from the data using spacecraft housekeeping information on the instruments' current consumption. Note that this is only a crude removal process at this time and since the current data has only 1 minute cadence, it cannot entirely remove these signals.

| Instrument | LCL TM | Proportionality OBS (nT/A x, y, z, URF) | Proportionality IBS (nT/A x, y, z, URF) |
|---|---|---|---|

| | | | |
|---|---|---|---|
| **METIS** | B_LCL1_14 METIS-A1 TM | (-0.0675 0 -0.0850) | (-0.3375 0 -0.4250) |
| **SoloHI** | B_LCL4_09 SoloHI-ADpl TM | (0 0.4400 0.3250) | (0 2.2000 1.6250) |
| **EUI** | B_LCL5_17 EUI-A TM | (-0.0625 0.1000 0) | (-0.3125 0.5000 0) |

*Table 5. Instrument-generated signals that have been removed from the data for this release.*

Whenever a signal has been removed in this way, `INSTRUMENTREMOVED` flag is raised.

We aspire to improve this removal process for future data releases.

### Solar array movements

Solar array movements can produce spurious magnetic fields; these are rare but periods when these occur are identified by the `SAMOVEMENT` flag.

### Additional, unidentified noise

Using differences between the IBS and OBS time series, we have identified times when there are major sources of interferences which can affect the OBS data. ESA has not been able to tell us the source of these signals and we therefore cannot predict them and their characterisation is very difficult since they are quite variable, but they can last for hours, cover a broad range of frequencies and vary in amplitude over time.

We have written an algorithm which attempts to identify times when these signals occur, but this is by necessity an imperfect process. The `SCINTERFERENCE` flag is raised when we detect these signals, but we do not remove them because we cannot adequately characterise them at this time.

## Finally…

The MAG engineering team have worked enormously hard, both before and after launch, to generate the data that we have released. Please take a moment to reflect on the effort that this has required and please enjoy using the data.

## List of abbreviations

BM – burst mode
IBS – inboard sensor
DPDD - Data Product Definition Document
MAG – magnetometer
NM – normal mode
nT - nanoTesla
OBS – outboard sensor
RTN – radial, tangential, normal heliocentric coordinate system
SRF – spacecraft reference frame
URF – unit reference frame (that of each sensor)

## References


MAG Data Product Description Document, H. O'Brien et al., Issue 2 Release 0, September 2020

The Solar Orbiter magnetometer, T. S. Horbury et al., Astron. And Astrophys., 2020, https://doi.org/10.1051/0004-6361/201937257

An advanced approach to finding magnetometer zero levels in the interplanetary magnetic field, H. K. Leinweber et al., Meas. Sci. and Tech., 2008, https://doi.org/10.1088/0957-0233/19/5/055104