Software Interface Specification
for the
Hayabusa2/MASCOT Magnetometer (MasMag) Products

Version 1.3

January 24, 2024

Prepared by

David Hercik [1], Hans-Ulrich Auster[1],

1: Institut für Geophysik und extraterrestrische Physik, Technische Universität Braunschweig

Signature Page

This SIS is approved by:

Name :
Organization: A
Date: **/***/****

Name :
Organization :
Date : **/***/****

Name :
Organization :
Date : **/***/****

Name :
Organization :
Date : **/***/****

Name :
Organization :
Date : **/***/****

Name :
Organization :
Date : **/***/****

Name :
Organization :
Date : **/***/****

Name :
Organization :
Date: **/***/****

Name :
Organization :
Date: **/***/****

Name :
Organization :
Date: **/***/****

Table of Contents

Change Log

DATE	*CHANGE*	*AFFECTED SECTIONS*
2017/12/07	Initial Draft	All
2020/05/02	Update of data product description	
2020/06/23	Data structure updated	5
2020/07/23	HK conversion algorithm, data calibration	new section 6 added
2020/07/24	correction of typos	all
2020/03/18	description of the calibration procedure	6
2024/01/24	calibration procedure updated	6

Acronyms and Abbreviations

Acronym/Abbreviation	*Definition*
MasMag	MASCOT magnetometer
NAIF	Navigation and Ancillary Information Facility
PDS	Planetary Data System
SCLK	Spacecraft Clock
SIS	Softwares Interface Specification
SPICE	Space, Planet, Instruments, C-Matrix, Event
UTC	Coordinated Universal Time
HK	Housekeeping data products
HY2	Hayabysa2 mission of JAXA
SCI	Science data products
IPDA	International Planetary Data Alliance
JAXA	Japan Aerospace Exploration Agency
DLR	Deutsches Zentrum für Luft- und Raum fahrt
IAS	Institute of Planetary Research, Institut d'Astrophysique Spatiale, Université Paris-Sud
IGeP, TU-BS	Institute for Gephysics and Extraterrestrial Physics, Technical University of Braunschweig
MLI	multi-layered insulation
ADC	Analog to digital converter
MUSC	Microgravity User Support Center (MUSC) in Cologne, DLR
CNES	Centre national d’études spatiales
UINT	unsigned integer
HEX	hexadecimal format
INT	signed integer
GNC	guidance, navigation and control MASCOT system
CAM	MASCOT camera
MARA	MASCOT radiometer unit

1 Purpose and Scope of Document

The purpose of this Data Product Software Interface Specification (SIS) is to provide users of the raw, calibrated and derived data products from the MASCOT magnetometer (MasMag) with a detailed description of the products. The document also contains a description of how the products were generated, including sources and destinations. The products defined in this document are raw, draft calibrated, and final calibrated scientific data and instrument housekeeping (HK). The scientific data are three components of magnetic field vector during separation, descent, and on-asteroid (162173 - Ryugu) MASCOT mission phase.

The SIS is intended to provide enough information to enable users to read and understand the MasMag data products as stored in PDS.

1.1 Applicable Documents

This SIS is consistent with the following Planetary Data System Documents as adopted by the International Planetary Data Alliance (IPDA):

1. Planetary Data System Standards Reference, Version 1.14.0.0, May 22, 2020.
2. PDS4 Data Dictionary – Abridged – Version 1.14.0.0, Mar 23, 2020.
3. PDS4 Information Model, V.1.14.0.0, Mar 23, 2020.

This SIS is responsive to the following Hayabusa2 mission documents:

4. Science Policy for Hayabusa2 Project, Version 3.0 May 14, 2018
5. MASCOT magnetometer EIDB, Iss. 2, Rev. 3, August 8, 2015
6. Fluxgate magnetometer calibration for MASCOT (MASCOT-MAG-TR-0008), Iss. 1, Rev. 1, January 16, 2014
7. Magnetic signature test report (MASCOT-MAG-TR15-MST-000), Iss. 0, Rev. 1, July 14. 2014
8. Magnetic signature 2 test report (MASCOT-MAG-TR16-MST2-000), Iss. 0, Rev. 0, July 25. 2014
9. Magnetic signature 3 test report (MASCOT-MAG-TR17-MST3-000), Iss. 0, Rev. 0, May 26. 2015

2 Introduction

2.1 Mission

The Mobile Asteroid Surface Scout (MASCOT) is a small lander on the Hayabusa2 mission of the Japan Aerospace Exploration Agency (JAXA) bound for the near-Earth asteroid 162173 Ryugu (provisional designation 1999 JU_3). and will then return samples to Earth. The MASCOT was developed under DLR/CNES/IAS/TU-BS colaboration. The MASCOT lander will provide in situ observations of the surface morphology, surface temperature, and magnetic field. The MASCOT payload comprises a camera (CAM), a radiometer (MARA) an infrared spectrometer (MicrOmega), and a magnetometer (MasMag).

2.2 Instrument

The data products described within this SIS are generated by the MASCOT magnetometer (MasMag). The data are processed by the PI institute: Institute for Geophysics and extraterrestrial Physics, Technical University Braunschweig, Germany.

2.3 Contact Names and Addresses

Karl-Heinz Glassmeier, IGeP, TU-Braunschweig
PI of the instrument
kh.glassmeier@tu-bs.de

Hans Ulrich Auster, IGeP, TU-Braunschweig
Technical manager, Co-I
uli.auster@tu-bs.de

David Hercik, IGeP, TU-Braunschweig
Project manager, Co-I
d.hercik@tu-bs.de

3 Relationships with Other Interfaces

Changes to the data products described in this SIS affect the following software, products or document:

Name of Interface	*Type*	*Owner*
MasMag Database Schema	Product	MasMag Team
MasMag Raw Science Data	Product	MasMag Team
MasMag Raw Housekeeping Data	Product	MasMag Team
MasMag Calibrated 1 Science Data	Product	MasMag Team
MasMag Ground Data Processing	Software	MasMag Team
MasMag Archive Software	Software	MasMag Team

4 Data Product Characteristics and Environment

4.1 Scientific objectives

Measurements of remanent magnetization of primitive bodies like asteroids and comets may provide records of the solar nebula magnetic field and of small-body dynamos. MasMag measurements of asteroid Ryugu offer the possibility of inferring the intensity of the nebular field at a distinct location and time in the early solar system not represented by the other bodies analyzed in detail so far (i.e., the S-type asteroid 433 Eros, comet 67P, and the LL, CV, and CM chondrite parent bodies). MASCOT provides a suitable platform for such observations. MasMag is placed inside the MASCOT lander body and the accommodation provides a convenient measurement situation as the sensor is very close to the surface. Single-point measurements are difficult to generalize. MASCOT has the ability to relocate itself on the surface of the asteroid thanks to a built-in mobility mechanism consisting of a movable arm with an eccentric mass. The relocation will provide a unique opportunity to measure magnetic fields at several locations, enabling higher confidence levels for the measurements as well as magnetic field gradient information. Investigation of the magnetic field during the descent and hopping will provide information on the spatial decay of the field from which useful information about a global field or local sources might be obtained.

Another objective of the magnetometer is the determination of the electrical conductivity of Ryugu. The method used for the analysis is based on the electromagnetic induction in the conductive body. As the inducing signal serves the interplanetary magnetic field. The surface magnetic field is then superposition of the inducing and induced signal. If the conductivity is sufficiently large, the contribution of the induced signal might be detectable. The ratio of induced to the inducing field strength is called Rikitake factor and is dependent on the conductivity of the body and frequency of the signal. As there is no magnetometer on the orbiter to provide space truth for the surface measurements, the reference signal shall be based on standard solar wind conditions supported by simulations. Case study shows that rather large conductivity (~100S/m) is needed to detect change in the solar wind turbulence slope, which is an indication of the induction.

4.2 Instrument Overview

The MASCOT magnetometer instrument is a vector-compensated three-axis fluxgate magnetometer consisting of a sensor head and digital electronics. The instrument has a long heritage from various space missions such as THEMIS (Auster et al. 2008), Venus Express (Zhang et al. 2007), ROSETTA (Auster et al. 2007) or BepiColombo (Glassmeier et al.2010). The sensor itself has been built at the Institut für Geophysik und extraterrestrische Physik (IGeP), Technische Universität Braunschweig in cooperation with Magson GmbH (Berlin) providing the electronics.

The MasMag electronics board (PCB) is placed inside MASCOT's common electronics box, while the sensor itself is mounted near a corner of the lander's body frame (Fig. 1). Above the magnetometer sensor, the camera instrument (CAM) is mounted. The payload compartment is furthermore occupied by the radiometer (MARA) and the spectrometer (MicrOmega). The four instruments are designed for a detailed characterization of the asteroid surface. The magnetometer will measure three components of a magnetic field with a 10 Hz sampling rate. The performance parameters are summarized in Table 2.

Parameter	*Value*
Sensor mass [g]	89
Electronics mass [g]	180
Power consumption [W]	0.5
Sensor dimensions [mm3]	55 × 55 × 50
Electronics dimensions [mm3]	109 × 94 × 20
Dynamic range [nT]	±12000
Sensor noise @1 Hz [pT/√Hz]	<15
Resolution [pT]	2
Sampling rate [Hz]	10
Nominal data volume [bit/s]	1010

Table 1: MasMag parameters and performance.

The magnetometer sensor (Figure 1) resides in the payload compartment of the lander as depicted in Figure 2. The sensor is mounted on the bottom plate of the MASCOT structure. The sensor head is attached via bolts to a ring-shaped stand-off made of PEEK and connected to the electronics card located in the MASCOT E-BOX via a pigtail harness.

Figure 1: MasMag sensor wrapped with MLI.

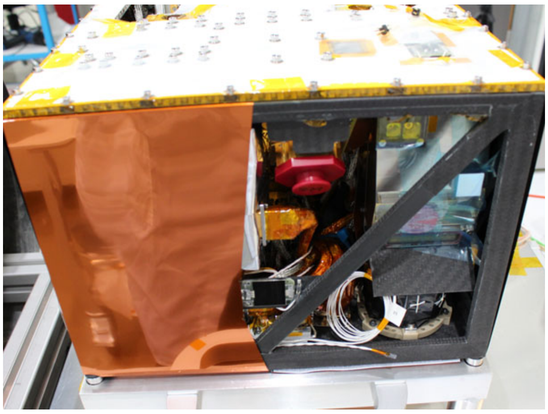


Figure 2: MasMag as integrated in the MASCOT lander. MasMag sensor is accommodated in the right bottom corner.

The principle of operation of a fluxgate-type magnetometer is based on periodic positive and negative saturation of a highly permeable material. An excitation current driven with a specific excitation frequency through a coil wound around the core material produces an alternating signal in the core that is picked up by a secondary coil. According to the fluxgate principle, an external magnetic field distorts the symmetry of the magnetic flux inside the core and generates a signal in even harmonics of the excitation frequency proportional to the external field. A sense coil picks up the external field component in the direction of the coil axis. By proper design of a system of three perpendicular secondary coils, complete information about the direction and magnitude of the external field can be extracted.

The MasMag sensor design consists of two ring core elements of high permeability material (mu-metal) that serves as the external magnetic field concentrator. The excitation coils are wound tightly around the ring cores. A second set of coils—the three axes sensing coil system—picks up the induced signal. Additionally, a complete Helmholtz coil system is mounted within the sensor to provide feedback and to maintain the center of the sensor in a near-zero field. This feature keeps the sensor in a linear regime and avoids the need of range switching. Information about the ambient magnetic field is then extracted using both the sensed signal and the feedback current values. The sensor coil system is encapsulated in a cylindrical aluminum shell and connected to the electronics via a ∼ 10 cm long pigtail harness. The payload compartment of the lander is thermally uncontrolled. Therefore, the sensor is covered by multi-layered insulation (MLI) to achieve maximum thermal stability. The thermal control of the sensor is completely passive. The temperature of the sensor is monitored by the magnetometer electronics.

Additional details about the instrument design and ground calibrations of the MasMag instrument can be found in Hercik et al., 2017 and in Hercik et al. 2020.

4.3 Data Product Overview

The MasMag data products are raw (RAW), draft calibrated (CAL1) and final calibrated (CAL2) magnetic field data. All the data products are stored in ASCII format.

The MasMag data products are:

1. **MasMag Raw Data**:
   Magnetic field vectors (3 components) that have been reassemble from downlinked telemetry as ADC values.
   Science : MOBT, UTC, BX, BY, BZ
2. **MasMag Draft Calibrated Data**:
   Data in physical units (nT), calibration based on ground calibration parameters, i.e., offset and misalignment correction.
   Science_A (in MasMag Coordinates) : MOBT, UTC, BX, BY, BZ, SW, QF
3. **MasMag Final Calibrated Data:**
   Data in physical units (nT), cleaned from offset and spacecraft/lander disturbances.
   Science_B (in MasMag Coordinates) : MOBT, UTC, BX, BY, BZ, SW, QF
4. **MasMag HK Raw Data:**
   Housekeeping data as extracted from the telemetry in raw ADC values.
   HK : MOBT, UTC, +5 V line Voltage, +5 V line Current, -5 V line Voltage, -5 V line Current, +3.3 V line Voltage, +3.3 V line Current, Sensor Temperature, PCB Temperature
5. **MasMag HK Calibrated Data:**
   Housekeeping data converted to physical units (currents: mA, voltages: V, temperatures: degC).
   HK: MOBT, UTC, +5 V line Voltage, +5 V line Current, -5 V line Voltage, -5 V line Current, +3.3 V line Voltage, +3.3 V line Current, Sensor Temperature, PCB Temperature
6. **MasMag Calibration File:**
   Calibration file including the removed interferences.
   Interference field (in MasMag Coordinates) : MOBT, UTC, BX, BY, BZ, SW, QF

<table>
<tr><th>Value</th><th>Description</th></tr>
<tr><td>MOBT</td><td>MASCOT on-board time.</td></tr>
<tr><td>UTC</td><td>Coordinated universal time, computed from MOBT, using the time conversion information from Hayabusa2 and MASCOT timestamp pairs.</td></tr>
<tr><td>SW</td><td>Status word. The status word indicates, which of the MASCOT other instruments and units, usually causing magnetic interference is on or off, or indicates measurement phase or MASCOT state. The status word is 1 Byte integer with following meaning:
<table>
<tr><td>bit</td><td>1</td><td>0</td></tr>
<tr><td>7 (MSb)</td><td>Camera ON</td><td>Camera OFF</td></tr>
<tr><td>6</td><td>Mobility ON</td><td>Mobility OFF</td></tr>
<tr><td>5</td><td>MicrOmega ON</td><td>MicrOmega OFF</td></tr>
<tr><td>4</td><td>GNC ON</td><td>GNC OFF</td></tr>
<tr><td>3</td><td>MASCOT moving</td><td>MASCOT at rest</td></tr>
<tr><td>2</td><td>MASCOT separated form HY2</td><td>MASCOT inside HY2</td></tr>
<tr><td>1</td><td>Ryugu’s day</td><td>Ryugu’s night</td></tr>
<tr><td>0 (LSb)</td><td>Antenna switch over (red<->main)</td><td>Antenna stable at one unit</td></tr>
</table></td></tr>
<tr><td>QF</td><td>Quality flag indicates if the data are disturbed by interferences that cannot be cleaned and are therefore not usable (QF = 0). If the QF is set</td></tr>
</table>

	to 1, data are good enough for scientific analysis, even if some additional cleaning might be needed.
BX,BY,BZ	Components of the magnetic field vector in [nT].

4.4 Data Processing

This section of the SIS provides general information about data product content, format, size, and production rate.

4.4.1 Data Processing Level

MasMag will deliver raw, draft calibrated, and final calibrated data to PDS. Table 2 describes the processing level of each product in the PDS4 terms.

MasMag Product	*PDS4 Processing Level*	*Product Description*
Raw	Raw	Timestamped magnetic field data that have been extracted from downlinked telemetry. Data are provided in ADC raw values.
Draft Calibrated	Partially Processed (Reduced)	Timestamped magnetic field vectors (3 components: Bx, By, Bz) converted to physical units (nT) and draft calibrated for offset and misalignment based on ground calibration parameters.
Final Calibrated	Calibrated	Timestamped magnetic field vectors (3 components: Bx, By, Bz) in physical units (nT) and calibrated for offset from in-flight offset determination and cleaned from spacecraft (MASCOT) interferences.
HK Raw	Raw	Timestamped HK parameters that have been extracted from downlinked telemetry. Data are provided in ADC raw values.
HK Calibrated	Calibrated	Timestamped HK parameters converted to physical units. For currents: [mA], voltages: [V], temperatures: [degC].

Table 2: MasMag data products.

4.4.2 Data Product Generation

4.4.2.1 Raw Data

Raw data is downlinked from the spacecraft and transferred to MUSC and CNES data servers. The magnetic field data and the HK raw data are extracted to physical units by IGeP Ground Data Processing software.

4.4.2.2 Draft Calibrated Data

The draft calibrated data are converted from the raw data using the calibration parameters determined during the on-ground calibration campaign. The on-ground calibration is described in Applicable Document 6 (MASCOT-MAG-TR-0008). We apply reduced transfer matrix to correct for misalignment and sensitivity. Temperature dependency is not corrected as the model shows negligible dependence and MAG temperatures during the mission are within a very low range.

4.4.2.3 *Final Calibrated Data*

The final calibration and cleaning is done manually by the MasMag team based on the in-flight data for offset calibration and on-ground magnetic cleanliness tests performed At DLR and JAXA with the whole MASCOT in order to characterize magnetic signature of the MASCOT units. The cleaning of the data requires experience with this kind of data calibration. The final calibrated data contain only limited phases during the mission as not all data can be easily cleaned from disturbances.

4.4.2.4 *Calibration files*

There are two types of calibration files included in the bundle: a) calibration data and b) calibration log. The calibration file has the same structure as the science data file, it contains however aggregated magnetic field signature of all identified interference signals, that was removed during the final calibrated data processing from the draft data. The log file then shows times (in MOBT) and interference type, when the specific single signature occurred.

4.4.3 Data Flow

MasMag data products are build by the Ground Data Processing software at IGeP. The raw data are acquired from the MUSC/DLR data server maintaining the MASCOT telemetry. The final products are then sent to CNES to be archived in a MASCOT database.

Main part from switch-on of the magnetometer (2018-10-02 T 22:50:54) during HY2 descent prior to MASCOT separation till 2018-10-03 T 11:16:53, when the instrument was intentionally switched off to save power. Additionally, there were two short interval, when the magnetometer was switch on for testing purposes mainly. The measuring intervals are therefore:

Interval	*Start (UTC)*	*End (UTC)*	*Duration*
main measurement	2018-10-02 T 22:50:54	2018-10-03 T 11:16:53	12h 25 min 59 sec
switch on before relocation 2	2018-10-03 T 18:01:43	2018-10-03 T 18:03:55	2 min 12 sec
switch on prior to the End-Of-Life	2018-10-03 T 18:40:31	2018-10-03 T 19:03:49	23 min 18 sec

The MasMag data products within the archive cover the MASCOT mission phase from the MASCOT separation till the end of mission ~13 hours after the separation.

Type	*Parameter*	*Value*
Science	telemetry rate	10 Hz
	duration	~13 hours
	total data volume (final calibrated)	235 kB
	total data volume (partial calibrated)	80.3 MB
HK	telemetry rate	0.125 Hz
	duration	~13 hours
	total data volume per product	1.25 MB

The science product time span in UTC is 2018-10-02 T 22:50:54 to 2018-10-03 T 19:03:49. Engineering products start slightly before and end slightly after these times.

4.4.4 Labeling and Identification

All MasMag data products are labeled with PDS4 compliant detached XML labels. These labels describe the content and format of the associated data product. Labels and products are associated by file name with the label having the same name as the data product except that the label file has an .xml extension.

MasMag data products are identified with file names in the format of:

hyb2_msc_mag_yyyymmdd_hhmmss_ddddd_xyz.{tab, xml}

where:

- yymmdd - begin of observation period date in UTC
  - yyyy = year
  - mm = month
  - dd = day
- hhmmss - begin of observation period time in UTC
  - hh = hour
  - mm = minute
  - ss = second
- ddddd - duration of the observational period in seconds
- xyz - datatype
  - x = **g** for ground, **f** for flight (full record), **pn** for phase, where **n** is phase number (0-6)
  - y = **s** for science data, **h** for housekeeping data
  - z = data processing level:
    - **2** for raw data (HK, SCI)
    - **3** for calibrated data (HK)
    - **a** for draft calibrated science data in MasMag coordinates
    - **c** for final calibrated science data in MasMag coordinates
    - **k** for calibration files used to produced final calibrated data from partially calibrated (includes interference signatures removed)
- tab - ASCII data file
- xml - associated xml label file

Data is save in full record and also split into phases 0-6, where:

0 - MASCOT within HY2
1 - MASCOT descending towards Ryugu
2 - MASCOT at rest at measurement site 1
3 - MASCOT first relocation
4 - MASCOT site 2 measurement up to MAG switch OFF
5 - MASCOT second relocation until voltage drop-off
6 - EOL phase

phase	*start (UTC)*	*stop (UTC)*	*duration [sec]*	*description*
0	2018-10-02T22:50:54	2018-10-03T01:57:19	11184	Pre-Separation phase 0
1	2018-10-03T01:57:19	2018-10-03T02:34:29	2230	Descent, from separation till the AT REST flag.
2	2018-10-03T02:34:29	2018-10-03T07:50:11	18942	Site 1 measurement, from AT REST untill relocation 1 start
3	2018-10-03T07:50:11	2018-10-03T08:28:03	2271	Relocation 1, from GNC start until end of the AT REST flag (GNC stoped monitoring).
4	2018-10-03T08:28:03	2018-10-03T11:16:53	10129	Site 2 measurement up to MAG switch off.
5	2018-10-03T18:01:43	2018-10-03T18:03:55	132	Relocation 2, MAG switchedd shortly before, power crashdown during mobility mechanism activation.
6	2018-10-03T18:40:31	2018-10-03T19:03:49	1398	End of Life phase

4.5 Standards Used in Generating Data Products

4.5.1 PDS Standards

All data products described in this SIS conform to PDS4 standards as described in the PDS Standards document noted in the Applicable Documents section of this SIS.

In consultation with the PDS, the Hayabusa2 Mission shall use the 1.14.0.0 version of the PDS4 information model. All Hayabusa2 products will conform to this standard, however products may have various versions of specific Discipline Dictionaries.

4.5.2 Time Standards

All Hayabusa2 data products contain a UTC time that has been derived from the Hayabusa2 spacecraft clock and MASCOT on board time. The transformation from the spacecraft clock to UTC is performed by the MASCOT and MasMag team and assigned to each data product.

4.5.3 Coordinate Systems

The coordinate systems used in the data products are MasMag internal coordinate system and MASCOT lander system. Defined as follows.

The MasMag coordinate system is defined as shown in Figure 3, the +X axis is pointing towards the pigtail harness, +Z is pointing from the sensor head towards the stand-off (towards the asteroid surface), and +Y is completing the right-handed coordinate system. The center of origin is the center of the cylindrical sensor head.

MASCOT coordinates are defined as shown in Figure 4, it shows also the default position for steady measurement phase on the asteroid, where the bottom plane number 4 is on the asteroid surface and plane 2 is facing deep space. The origin of MASCOT coordinate system is located in the center of the plane 4. The +Z' axis of MASCOT points towards plane 2. Axis +Y points from the MASCOT center towards the plane 1, enclosing a payload compartment, where the instruments are accommodated. The +X' completes the right-handed coordinate system.

The transformation matrix from MasMag coordinate system to the MASCOT one and back is following:

$$A = A^{-1} = \begin{pmatrix} 0 & -1 & 0 \\ -1 & 0 & 0 \\ 0 & 0 & -1 \end{pmatrix}$$

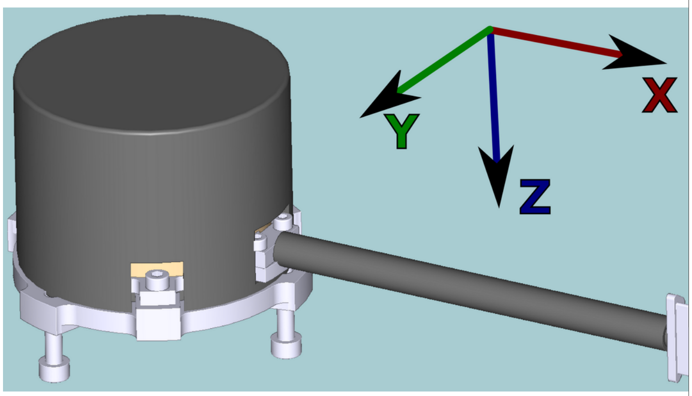


Figure 3: MasMag coordinate system.

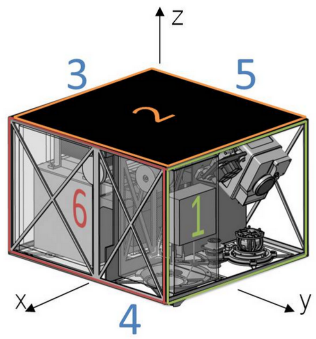


Figure 4: MASCOT coordinate system.

4.5.4 Data Storage Conventions

All MasMag data producs are stored as ASCII files.

4.6 Data Validation

The MasMag products are processed by a ground data processing software package. The software has been validated on th in-flight calibration data for correct data processing. Final data cleaning and calibration will be done manually by the MasMag team. The data set will be checked independently by different team members. PDS conformity will be validated by available PDS validation tools.

5 Detailed Data Product Specifications

The following sections provide detailed data product specifications for MasMag data product. These specifications will provide sufficient detail, so that data product users can read and interpret the products.

5.1 Data Product Structure and Organization

The Hyabusa2/MASCOT data archive is organized as bundles by instrument. The MasMag bundle of the archive is organized by processing level and product type. The general bundle structure is shown in Figure 5. The data are in the 'data' collection, that is divided by data type ('sci' for science data and 'hk' for housekeeping) and data level (raw, partial, calibrated).

```
hyb2_mascot_mag
    ├── bundle.xml
    |---- calibration
    |   |----collection_calibration.xml
    |   |----collection_calibration.csv
    |   |----hyb2_msc_mag_calibration.log
    |   |----hyb2_msc_mag_calibration.xml
    |   |----hyb2_msc_mag_20181002_225054_72774_fsk.xml
    |   |----hyb2_msc_mag_20181002_225054_72774_fsk.tab
    ├── data
    |   |---- collection_data.csv
    |   |---- collection_data.xml
    |   | ---- data_hk_calibrated
    |   | ---- data_hk_raw
    |   | ---- data_sci_calibrated
    |   | ---- data_sci_partial
    |   | ---- data_sci_raw
    └── document
        ├── collection_document.csv
        ├── collection_document.xml
        ├── dpsis_MasMag_20240124.pdf
        ├── dpsis_MasMag_20240124f.xml
        ├── MASCOT-MAG-EID-B-0014.pdf
        ├── MASCOT-MAG-EID-B-0014.xml
        ├── MASCOT-MAG-TR-0008_CALIBRATION_REPORT_IGEP.pdf
        └── MASCOT-MAG-TR-0008_CALIBRATION_REPORT_IGEP.xml
```

Figure 5: Basic instrument bundle structure and organization.

All products are stored as ASCII files a detached PDS label. The detached PDS labels are PDS4 compliant XML labels that describe the contents of the file and contain all necessary metadata to interpret the product.

1. Raw SCI Data – raw uint/int values from the telemetry.
2. Draft Calibrated (Partial) Data – data converted to physical units (nT) with basic calibration using the on-ground (pre-flight) calibration parameters.
3. Final Calibrated Data - flight offset calibrated and cleaned of spacecraft interference.

For the UTC time format following notation is used: YYYY - year, mm - month, dd - day, HH - hour, MM - minute, SS - second, ffffff - microseconds.

5.2 Data Format Descriptions

Format '%0.3f' means floating point number with 3 decimal places.

5.2.1 Scientific Raw Data

ASCII file with tab separated 5 columns:

Column	*Content*	*Format*	*Description*
1	MOBT time	YYYYmmddTHHMMSS.ffffff	MASCOT on-board time stamp
2	UTC time	YYYYmmddTHH:MM:SS.ffffff	UTC time stamp
3	Bx	24-bit UINT in HEX format	magnetic field x-component
4	By	24-bit UINT in HEX format	magnetic field y-component
5	Bz	24-bit UINT in HEX format	magnetic field z-component

5.2.2 Scientific Draft Calibrated Data

ASCII file with tab separated 7 columns:

Column	*Content*	*Format*	*Description*
1	MOBT time	YYYYmmddTHHMMSS.ffffff	MASCOT on-board time stamp
2	UTC time	YYYYmmddTHH:MM:SS.ffffff	time stamp
3	Bx	%0.3f	magnetic field x-component in nT
4	By	%0.3f	magnetic field y-component in nT
5	Bz	%0.3f	magnetic field z-component in nT
6	Status Word	UINT	status word indicating, which other sub-system on MASCOT is ON (see section 4.3 for description).
7	Quality Flag	0/1	indicating data quality in terms of level and removability of interference (see section 4.3 for description).

5.2.3 Scientific Final Calibrated

Same format as Draft Calibrated data in Section 5.2.2.

5.2.4 Housekeeping Raw Data

ASCII file with tab separated 10 columns:

Column	*Content*	*Format*	*Description*
1	MOBT time	YYYYmmddTHHMMSS.ffffff	time stamp
2	UTC time	YYYYmmddTHH:MM:SS.ffffff	time stamp
3	+5 V voltage	16-bit INT in HEX format	+5 V line voltage
4	+5 V Current	16-bit UINT in HEX format	+5 V line current
5	-5 V Voltage	16-bit INT in HEX format	-5 V line voltage
6	-5 V Current	16-bit UINT in HEX format	-5 V line current
7	+3.3 V Voltage	16-bit INT in HEX format	+3.3 V line voltage
8	+3.3 V Current	16-bit UINT in HEX format	+3.3 V line current
9	Sensor Temperature	16-bit UINT in HEX format	temperature of the MasMag sensor head
10	PCB Temperature	16-bit UINT in HEX format	temperature of the MasMag electronics board

5.2.5 Housekeeping Calibrated Data

ASCII file with tab separated 10 columns:

Column	*Content*	*Format*	*Description*
1	MOBT time	YYYYmmddTHHMMSS.ffffff	
2	UTC time	YYYYmmddTHH:MM:SS.ffffff	time stamp

3	+5 V voltage	%0.3f	+5 V line voltage
4	+5 V Current	%0.3f	+5 V line current
5	-5 V Voltage	%0.3f	-5 V line voltage
6	-5 V Current	%0.3f	-5 V line current
7	+3.3 V Voltage	%0.3f	+3.3 V line voltage
8	+3.3 V Current	%0.3f	+3.3 V line current
9	Sensor Temperature	%0.3f	temperature of the MasMag sensor head
10	PCB Temperature	%0.3f	temperature of the MasMag electronics board

5.3 Label and Header Descriptions

All MasMag data products contain date and time information that can be used to sort and correlate data products.

6 Calibration

6.1 HK

In order to process the raw HK data into calibrate, following general equation:

$$HK = a R^2 + bR + c \quad ,$$

where HK is the calibrated value in physical units, R is the RAW value interpreted either as signed integer (INT) or unsigned integer (UINT), and a,b,c are coefficients determined during the on-ground calibration:

parameter	*a*	*b*	*c*	*R type*
+5V voltage [V]	0	0.00018305439	0	UINT
+5V current [mA]	0	0.0110	7.2340	INT
-5V voltage [V]	0	0.0003012888	-7.7	UINT
-5V current [mA]	0	-0.001945	0.125	INT
+3.3V voltage [V]	0	0.000091527197	0.0	UINT
+3.3V current [mA]	0	0.004208	0.0308	INT
sensor temperature	0.00000110490	-0.013802731	-125.2511	UINT
PCB temperature	0.00000110490	-0.01380013	-125.2548	UINT

The magnetic field data in the HK dataset are calibrated into physical units in the same way as the science data, see following section.

6.2 Science data

6.2.1 Partial calibrated data

The magnetic field raw data (B_r) are in 24 bits two's complement representation. The raw data are converted into physical units in the following way:

$B_m^i[nT]=(B_r^i-2^{24})C$, for B_r^i >>23 = 1 (the most significant bit equals to 1, signifying negative number)

$B_m^i[nT]=(B_r^i)C$, for B_r^i >>23 = 0 (the most significant bit equals to 0),

where B_r^i is the raw (UINT) magnetic field value of component *i*, B_m^i is the measured magnetic field in physical units (nT), $i\in(x,y,z)$, and C = 0.0014305 [nT/LSB] is the resolution coefficient.

The converted data are further calibrated using the on-ground determined transfer matrix T:

$\vec{B}_c=T\vec{B}_m$, where $T=\begin{pmatrix}0.998451 & 0.0 & 0.0\\ -0.005475 & 0.999126 & 0.0\\ -0.005108 & +0.002181 & +0.998839\end{pmatrix}$ includes the misalignment and the sensitivity corrections. $\vec{B}_c$ is the calibrated magnetic field vector in nT. The details are provided in the bundle documentation (applicable document 6).

6.2.2 Final calibrated data

The final calibrated data included in the bundle do not cover the whole measurement period as such processing was not possible in all the data due to various interference and time demands. The period included in the final calibrated products covers few minutes of measurement before the first contact with the surface. These data are of high importance for estimating the magnetization of the surface material. The cleaning of data follows complex procedure of removing interference and perturbations from the data. The detailed description of the process is given in Hercik et al., 2020 (doi.org/10.1029/2019JE006035). The processing chain is also described in the following chapter: Data calibration procedure.

6. 3 Data calibration procedure

The following procedure specifies the steps performed on the partially calibrated data in order to derive the calibrated data in the bundle. The calibrated data contain only segment of the full data series, representing data acquired from the release of MASCOT prior to first touchdown. The process is iterative with two main phases:

1. Manual interference removal
2. Automatic disturbance removal

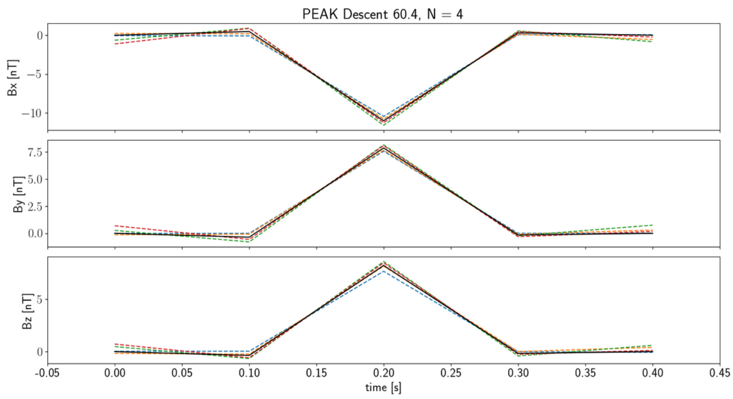
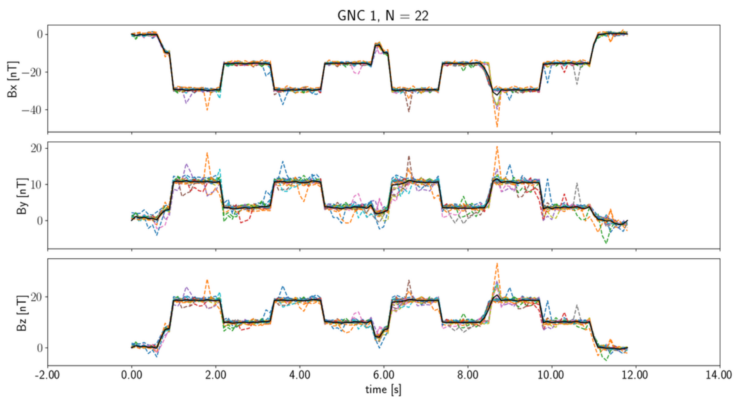
The phase 1. is based on the extensive ground calibration testing campaigns to characterize specific units and their magnetic field profile produced by their operation. The detection of the interference is manual.

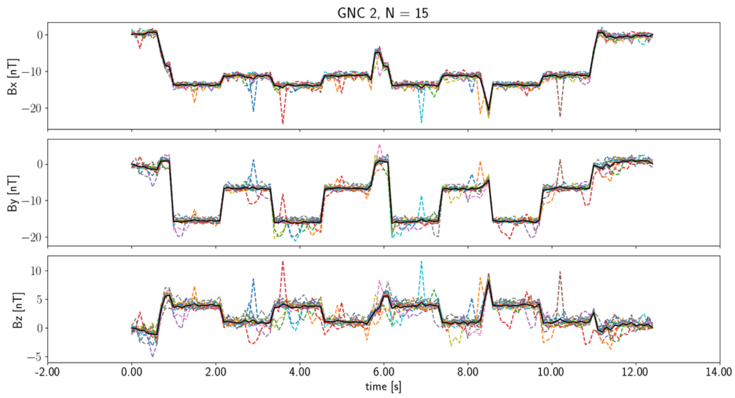
The second phase follows a procedure based on the assumption, that the main interference is directional and can be therefore separated by minimum variance method into single axis. This component is then cleaned by using a simple running average. Further more, the data from the descent need to be corrected (despun) for rotation of the spacecraft due to its tumbling. If the user wishes, original data from the MASCOT as measured, a despun procedure can be omitted in the process. The calibrated data within the bundle are provided in the instrument (MasMag) coordinate system as oriented at the approximate time of release from Hayabusa-2 : 2018-10-03T01:58:49.808763. This approach provides easier analysis and, transformation into other coordinate systems.

The two calibration phases are described below.

6.3.1 Manual interference removal

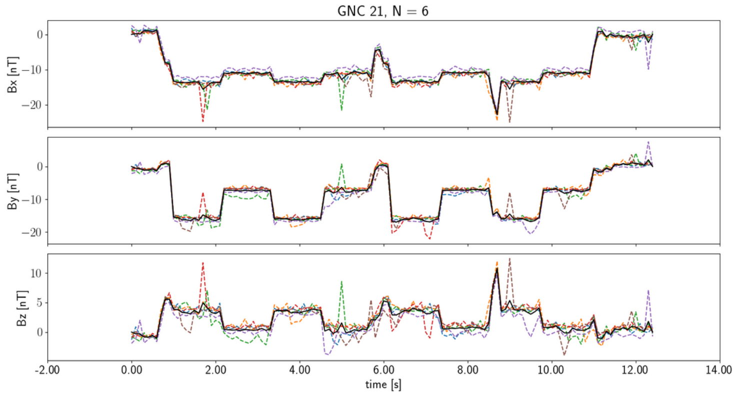
The data contain know interference signatures. These signatures were investigate during magnetic cleanliness campaigns pre-flight as well as during in-flight commissioning. The main investigation of the signatures is reported in the referenced documents MASCOT-MAG-TR15-MST, MASCOT-MAG-TR16-MST2, and MASCOT-MAG-TR17-MST3. The removed interference profiles are listed in Table 3, the profiles are computed using a superposed epoch analysis.

OBC 10 sec. period pulse	
	The observed periodic signal with single peak profile and period of 10 seconds was identified already during the testing as related to onboard data processing.
GNC 1	
	GNC (guidance, navigation, and control) responsible for monitoring the orientation has several modes of operations with different profiles. This interference is a signature of a GNC 1 mode.
GNC 2	



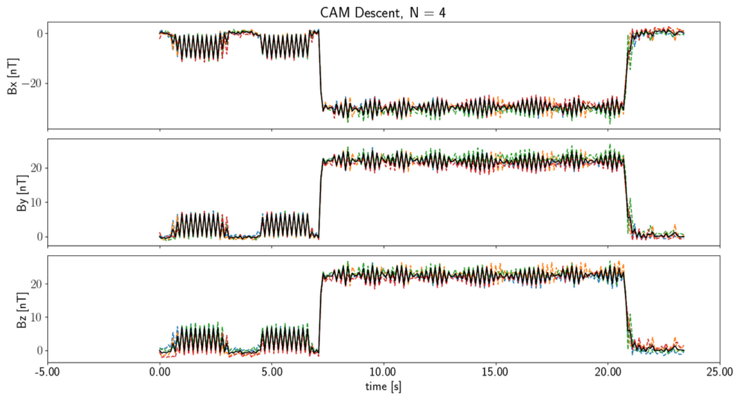
GNC 2 mode signature.

GNC 21



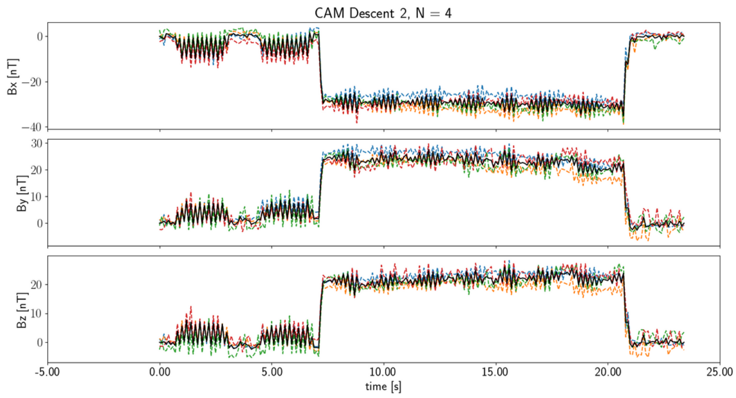
Second sequence of GNC mode 2 type.

CAM Descent

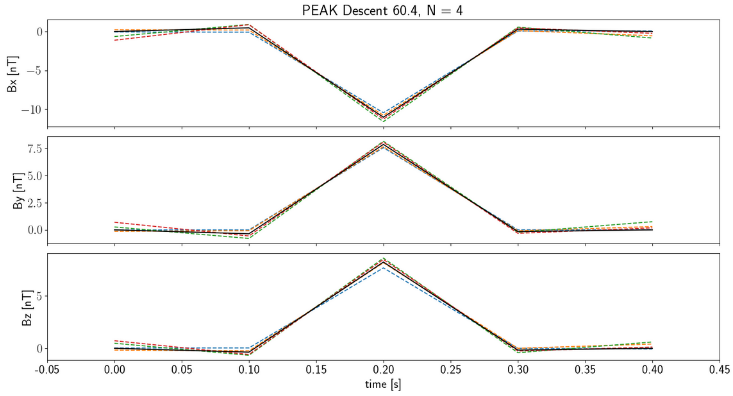
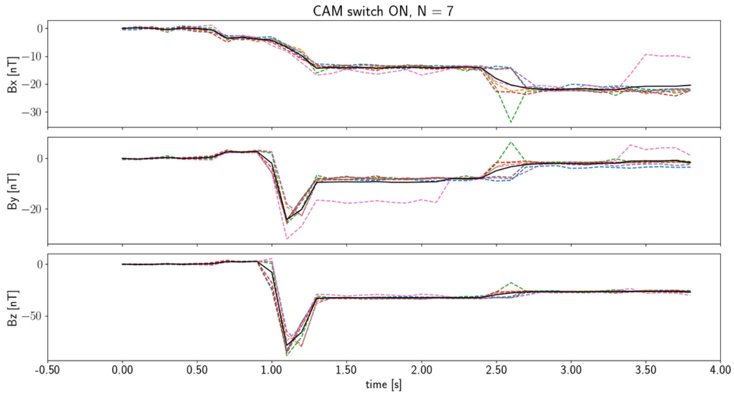


Camera signature during the descent of MASCOT towards the surface.

CAM Descent 2



Second sequence of descent signatures of the CAM instrument with slightly worse background conditions.

PEAK Descent 60.4	
	Periodic peak interference with period of 60.4 seconds.
CAM switch ON	
	Profile of the camera instrument, when switched on.

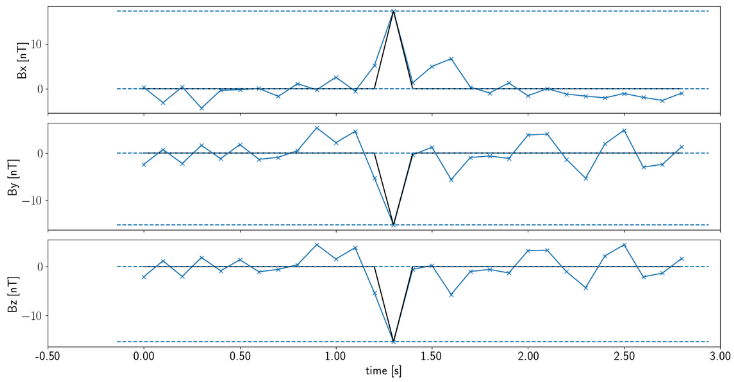
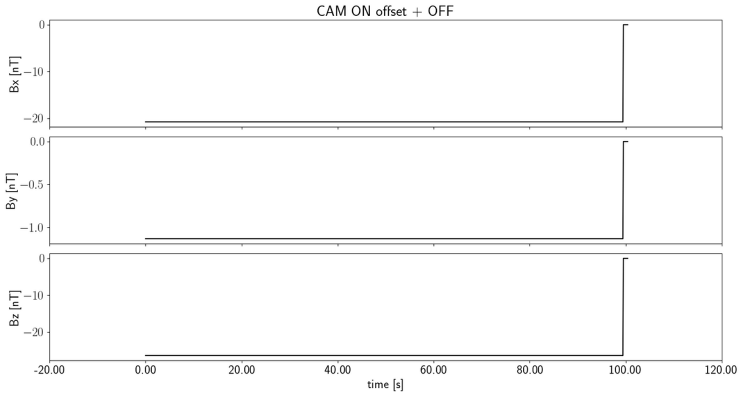
<table>
<tr><th colspan="2">peak</th></tr>
<tr><td>
</td><td>At several places, artificial non-periodic peaks were identified in the data. The relate to the operation of CAM instrument and were removed manually by computing average of the data excluding the peak and then removing the height of the peak value above this average. The black curve in the example on the left shows the removed signature.</td></tr>
<tr><th colspan="2">CAM offset</th></tr>
<tr><td>
</td><td>During the CAM operation (when the instrument is switched ON), there is a constant offset in the magnetic field visible. The figure on the left shows an example of the detected offset, that is removed from the data for the whole duration of the CAM operation.</td></tr>
</table>

Table 3: Removed interference profiles, the names of the signatures shown in the table correspond to the names indicated in the calibration log file.

The bundle includes:

1. Log file (hyb2_msc_mag_calibration.log) with pairs of timestamp (in MOBT) and interference name (as per Table 3), indicating, when the relevant interference type was removed from the data.
2. Data calibration file with all the interference removed from the data summed up. An intermediate product from partial to calibrated, respective to the phase 1 of the calibration can be obtained by subtracting the data calibration file (hyb2_msc_mag_20181002_225054_72774_fsk.dat) from the partially calibrated data.

In order to reproduce the calibrated data file from the bundle, a second phase of the procedure, described in detail in the following chapter needs to be performed. The user might however prefer to use other method and start from the partial data, using the first phase interference removal and proceed with other process, tailored to specific needs.

6.3.2 Automatic disturbance removal

There are still lots of smaller disturbances remaining in the data after the first pass of cleaning. These kinds of interference have no clear signature in the time series. However, it appears, that the disturbances have a predominant direction, as they are probably generated by the electrical current changes flowing in the common electronic box. The following analysis is, however, conducted only on a specific data period prior the first touchdown as this is the primary focus from the scientific point of view. The period is starts from 2018-10-03T01:58:49 with a duration of 263 seconds. The resulting data are in a file: hyb2_msc_mag_20181003_015849_00263_fsc.dat.

1) First, we filtered the data with a high pass filter to separate the disturbances from the low frequency oscillations. The high-pass filtering was implemented by first smoothing the original data with a running average window of 10 data points (1 sec), see Figure 6. The average (low-pass filtered) signal was then subtracted from the original data, leaving higher frequency part of the data, for the interference extraction Figure 7.

2) The high frequency part of the data was then used to find the coordinate system, where the interference is mainly in one axis. The maximum variance analysis is being used to compute eigenvalues and eigenvectors. The eigenvectors than define the “noise” maximum variance (NMV) coordinate system. Original data were rotated into the NMV system (Figure 8).

3) The rotated data were then cleaned in the single axis with maximum variance by running average with 10 points (1 sec), as shown in Figure 9 by the red curve.

4) The cleaned data were rotated back from the NMV into the MasMag coordinates (Figure 10).

5) Another maximum variance analysis was performed in order to get the maximum variation caused by the rotation (spinning) of the MASCOT lander. Data were transformed into the “rotational” maximum variance system (RMV) as shown in Figure 11.

6) A least-square method fit was performed on the data to find the spinning period and axis. The fit result (in red curve) is shown in Figure 12.

7) Fitted parameters:

- rotational axis in MasMag coordinates: (-0.71,-0.60,0.35)
- rotational period: 138.9 sec.
- offset in MasMag coordinates: (-243.01,370.11,-134.49) nT

were used to despun the data to the RMV system (Figure 13) and finally into the MasMag coordinates system (Figure 14), which is the data, stored within the bundle as the calibrated data.

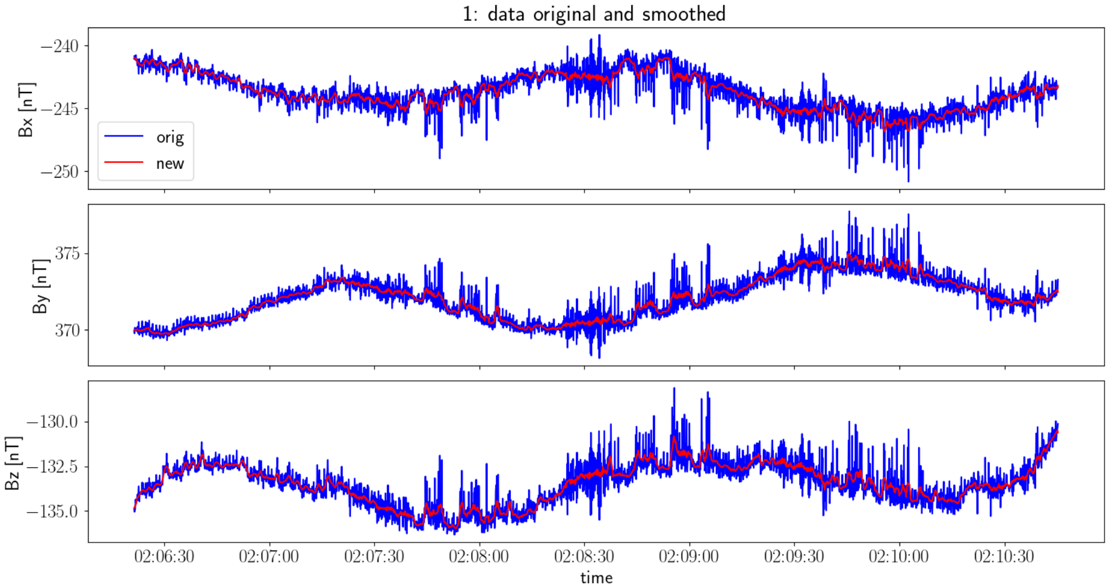


Figure 6: Draft calibrated MAG data (blue) and smoothed data with running average.

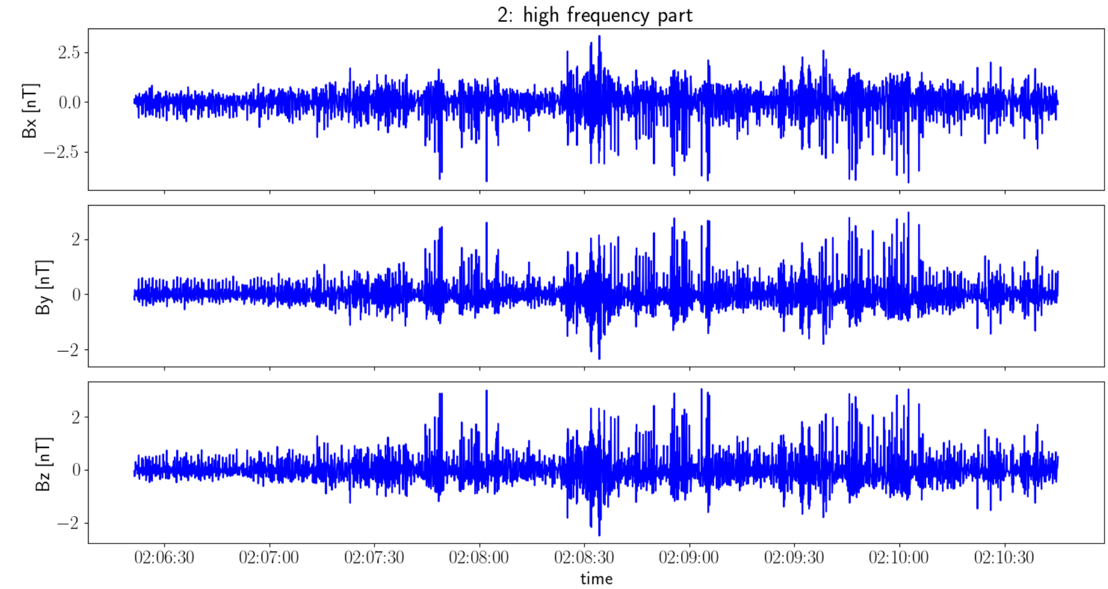


Figure 7: High frequency part remainder after removing the running average.

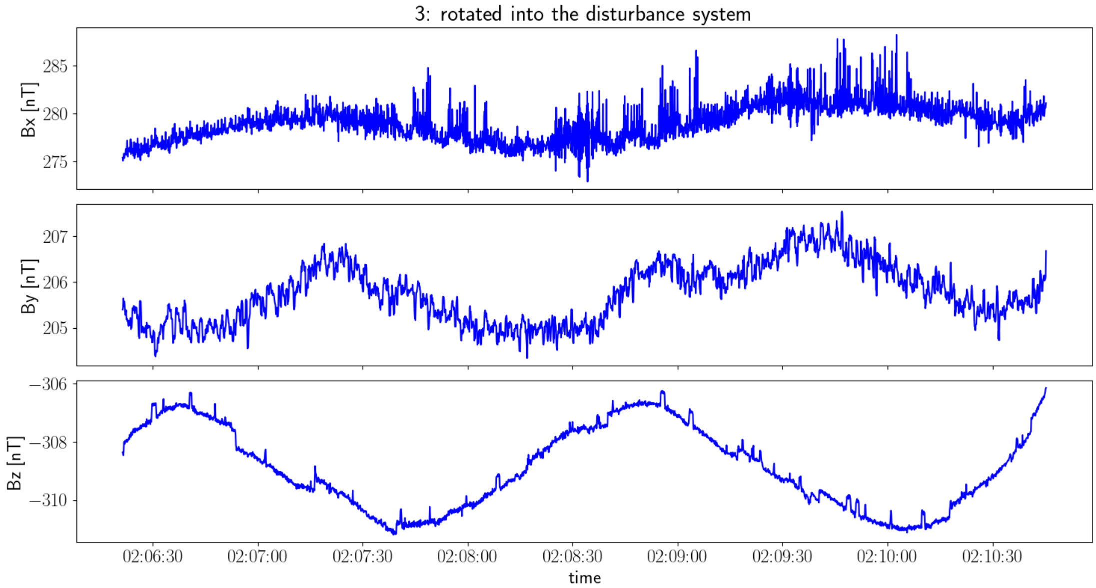


Figure 8: Original data rotated into the maximum variance system (NMV).

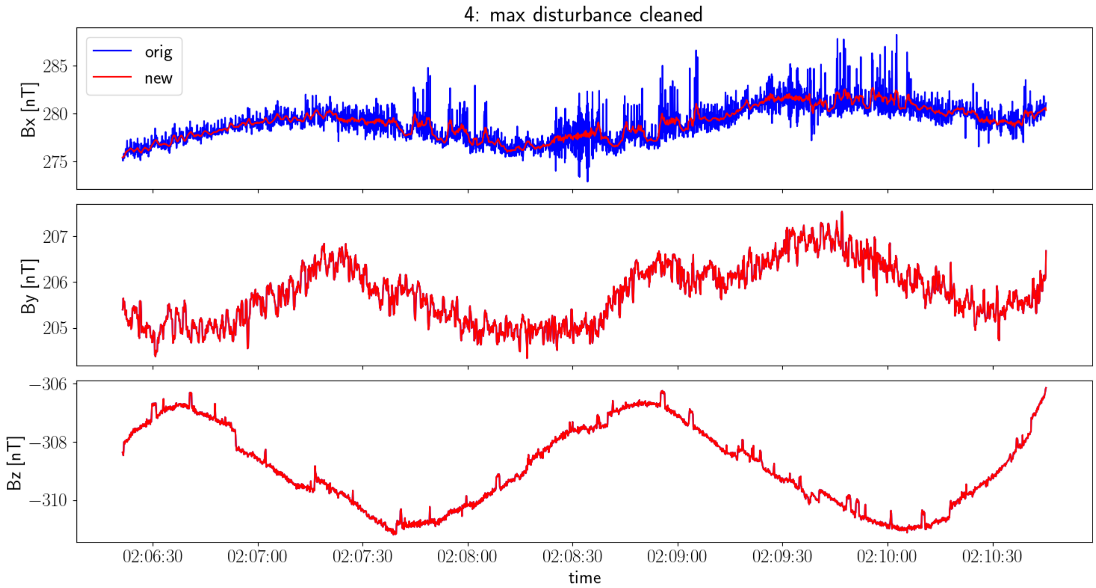


Figure 9: Red curve shows the data cleaned from the high frequency noise (in one axis).

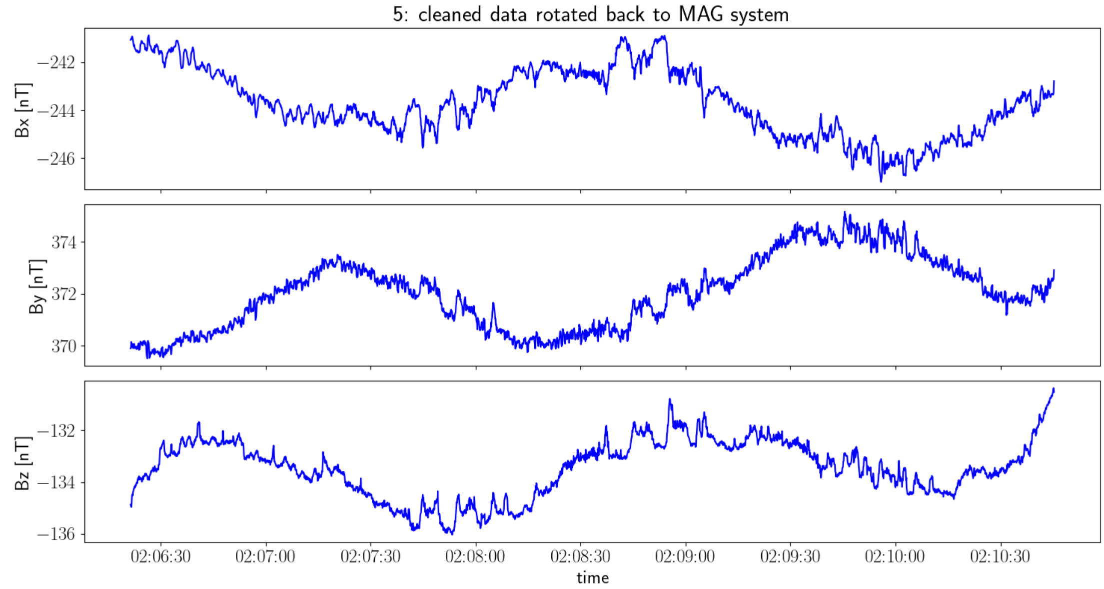


Figure 10: Cleaned data rotated back to the MasMag coordinate system.

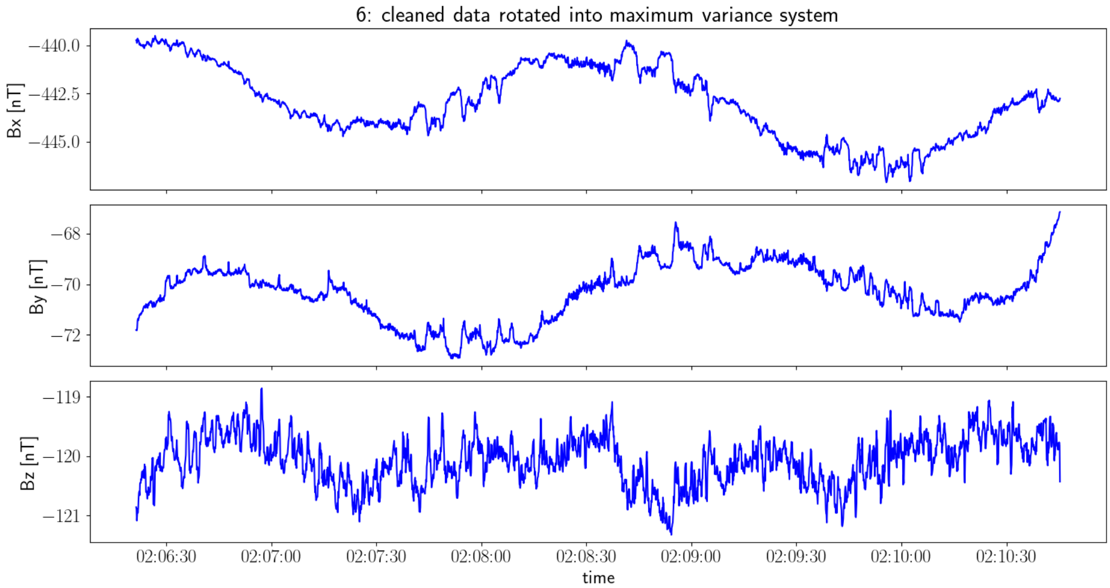


Figure 11: Cleaned data rotated into the maximum variance system (RMV).

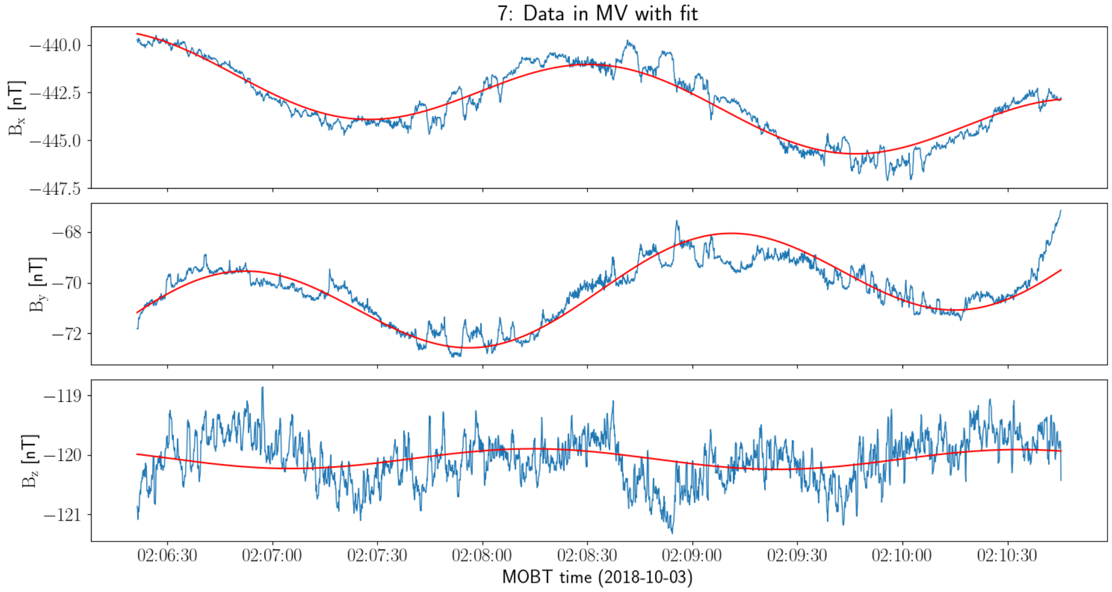


Figure 12: Data in the maximum variance system (blue) with rotational fit (red).

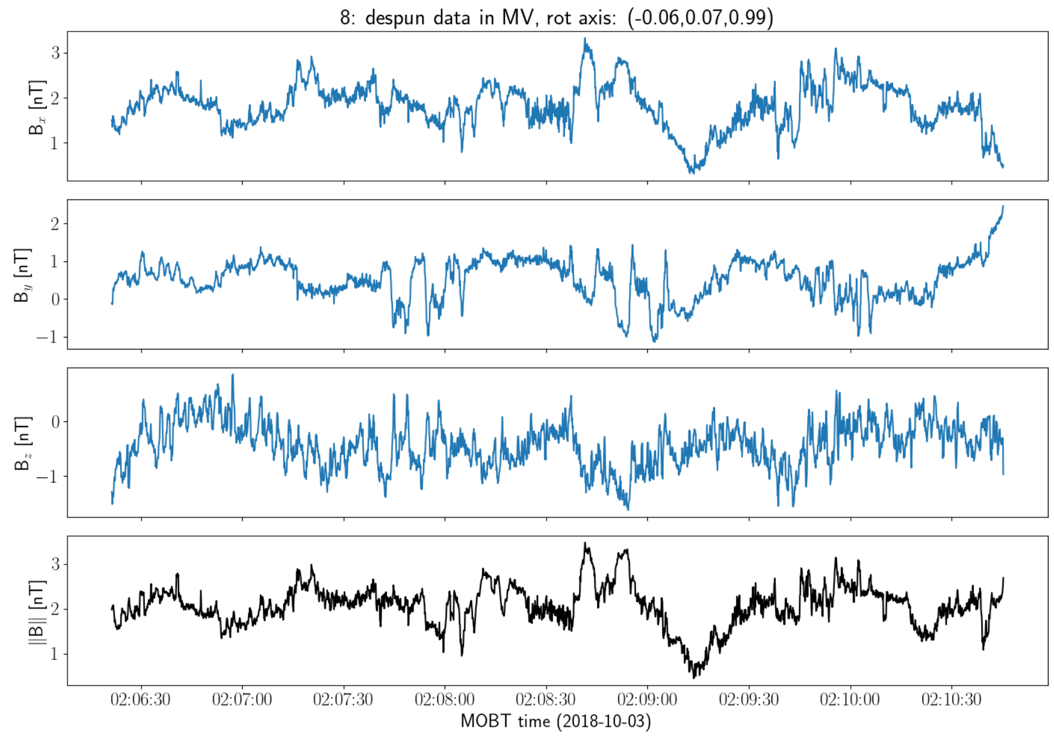


Figure 13: Cleaned data despun in the minimum variance system.

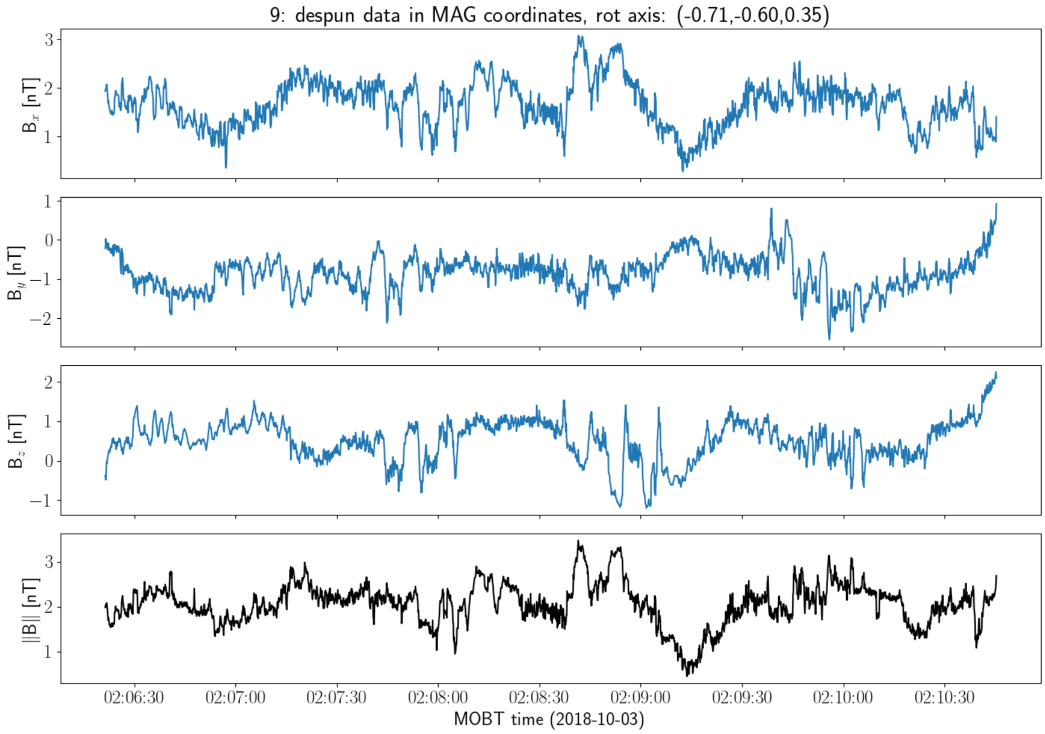


Figure 14: Cleaned data despun in the MasMag coordinate system.

7 Applicable Software

7.1 Utility Programs

At the current time, the Hayabusa2 project has no plans to release any mission specific utility programs.

7.2 Applicable PDS Software Tools

Data products found in the Hayabusa2 archive can be viewed with any PDS4 compatible software utility.

7.3 Software Distribution and Update Procedures

As no Hayabusa2 specific software will be released to the public, this section is not applicable.

8 Appendices

8.1 References

1. Herčík, D. et al. (2017), The MASCOT Magnetometer, Space Sci. Rev., 208(1), 433–449, doi:10.1007/s11214-016-0236-5.
2. Herčík, D. et al. (2020), Magnetic properties of asteroid (162173) Ryugu. Journal of Geophysical Research: Planets, 125, doi.org/10.1029/2019JE006035
3. Auster, H.-U. et al. (2007), ROMAP: Rosetta magnetometer and plasma monitor. Space Sci. Rev. 128(1–4), 221–240. doi:10.1007/s11214-006-9033-x
4. Auster, H.-U. et al. (2008), The THEMIS fluxgate magnetometer. Space Sci. Rev. 141(1–4), 235–264. doi:10.1007/s11214-008-9365-9
5. Glassmeier, K.H. et al. (2010), The fluxgate magnetometer of the BepiColombo Mercury Planetary Orbiter. Planet. Space Sci. 58(1–2), 287–299 . doi:10.1016/j.pss.2008.06.018
6. Zhang T.L. et al. (2007), MAG: the fluxgate magnetometer of venus express. ESA SP 1295, 1–10

8.2 Definitions of Data Processing Levels

PDS4 Data Processing Levels (From PDS Policy on Data Processing Levels (2013-03-11)):

Telemetry: An encoded byte stream used to transfer data from one or more instruments to temporary storage where the raw instrument data will be extracted.

Raw: Original data from an instrument. If compression, reformatting, packetization, or other translation has been applied to facilitate data transmission or storage, those processes will be reversed so that the archived data are in a PDS approved archive format.

Partially Processed: Data that have been processed beyond the raw stage but which have not yet reached calibrated status.

Calibrated: Data converted to physical units, which makes values independent of the instrument.

Derived: Results that have been distilled from one or more calibrated data products (for example, maps, gravity or magnetic fields, or ring particle size distributions). Supplementary data, such as calibration tables or tables of viewing geometry, used to interpret observational data should also be classified as ‘derived’ data if not easily matched to one of the other three categories.

MasMag Product	*PDS Data Processing Level*
Raw	Raw
Draft Calibrated	Partially Processed
Final Calibrated	Calibrated