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BEPICOLOMBO

MERCURY PLANETARY ORBITER (MPO)

MORE Experiment-to-Archive ICD (EAICD)

Prepared by	**MORE Team**
Reference	**BC-MRE-ICD-001**
Issue/Revision	**D.3**
Date of Issue	**13/06/2017**
Status	**Draft**
Document type	**ICD**

European Space Agency
Agence spatiale européenne

APPROVAL

Title MORE Experiment-to-Archive ICD (EAICD)	
Issue Number D	**Revision Number** 3
Author MORE Team	**Date** 19/03/2026
Approved By	**Date of Approval**
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CHANGE LOG

Reason for change	**Issue Nr.**	**Revision Number**	**Date**
Reformat of the table of contents.	D	3	19/03/2026

CHANGE RECORD

Issue Number D	**Revision Number 3**		
Reason for change	**Date**	**Pages**	**Paragraph(s)**
First draft of the document produced for the SGS Launch Implementation Review (LaS-IR)	13/06/2017	All	All
Update of calibration pipeline, added description for data formats in use	14/06/2022	All	All
Update to Data User Guide template. Update of Derived Data description	24/11/2025	All	All
Reformat of table of contents. Moved different sections in Annex A and B. Added further informations about data types	19/03/2026	All	All

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1 INTRODUCTION

This document describes the format and the content of the Radio Science experiment (MORE) for the BepiColombo MPO spacecraft data as archived in the ESA Planetary Science Archive (PSA). It includes detailed descriptions of the data products and associated metadata, including a description of the data generation, calibration, validation and analysis processes.

This EAICD is intended to provide enough information to enable users to understand the MORE data and their organisation. The users for whom this is intended are the scientists who will process and analyse the MORE data.

The specifications described in this document apply to all MORE products submitted to the archive, for all phases of the BepiColombo mission (i.e. near-earth commissioning, cruise, Mercury commissioning and science phases). This document is expected to evolve throughout the mission lifetime.

The scope of the document expected by the SGS Launch Readiness Review (March-May 2018) and for the first science peer-review (pre-Launch: ~May-June 2018) is:

1. Data Organisation and Data Products that will be generated and/or used during NECP and Cruise
   - Types of products (raw and calibrated data products, calibration inputs, browse products, documents), with brief description of the content of each type of product.
   - Data organisation (directory structure).
   - File naming convention.
   - Format of the data products (a reference to the Excel / XML templates in Git is sufficient).
2. Instrument Description.
3. Calibration steps (any user should be able to replicate the calibration steps applied to the products with the information provided in this document).
4. Description of the On-ground calibration (as applicable; with references to the calibration inputs; the calibration inputs should be available).

1.1 Related documentation

1.1.1 Applicable documents

The following documents, of the exact issue shown, form part of this document to the extent specified herein. They are referenced in this document in the form [AD.XX]:

[AD.01] BC-SGS-PL-014, BepiColombo Science Data Generation, Validation and Archiving Plan
[AD.02] BC-SGS-TN-026, BepiColombo Archiving Guide
[AD.03] PDS4 Standards Reference (SR)
[AD.04] PDS4 Data Dictionary (DDDB)
[AD.05] PDS4 Information Model Specification (IM)

1.1.2 Reference documents

[RD.01] BC-SGS-LI-014, SGS Glossary
[RD.02] BC-SGS-TN-042, BepiColombo Data Handling and Archiving Concept
[RD.03] BC-SGS-ICD-018, MORE Pipeline Description Document
[RD.04] 503x0b2c1 (TDM- Blue Book)
[RD.05] 505x0b2 (XML specification for navigation data message – Blue Book)
[RD.06] TTCP-ICD-SOFT-RM, TTCP Software Interface Control Document (ICD) for RM datasets
[RD.07] JPL DSMS 820-013 trk_2_24
[RD.08] JPL DSN 820-013 TRK-2-23, Revision C. Media Calibration Interface

[RD.09] 506x1b1 (Delta-DOR Raw Data Exchange Format)
[RD.10] T TCP-SUM-01, TTCP Software User Manual (SUM)
[RD.11] Software interface specification - Spherical Harmonics ASCII Data Record (SHADR)

1.1.3 Abbreviations and Acronyms

See BepiColombo Acronyms and Definitions, [RD.01].

1.2 Citation and license information

TBD

1.3 Data availability

All data can be found in the ESA Planetary Science Archive.

2 MORE SCIENCE OBJECTIVES

The Mercury Orbiter Radio-science Experiment (MORE) is a system level experiment, involving both flight and ground-station hardware, as well as a dedicated orbit determination software. The on-board Ka-band transponder (KaT) is the key instrument of the radio science experiment. The estimation of physical quantities of interest (spherical harmonics coefficients, Post Newtonian Parameters (PPN) of general relativity, etc.) will be based almost entirely upon range and range-rate observables obtained by exploiting a suitable radio link between the spacecraft and the Earth station.

Achieving the scientific goals of MORE at the expected levels of accuracy and reliability of the results requires data from other onboard instruments and spacecraft subsystems. Vice versa, other instruments and mission navigation will benefit from the accurate orbit determination provided by MORE.

The main scientific goals span in the fields of geodesy, geophysics and fundamental physics, including the determination of the planetary gravity field and topography, the surface properties, but also the internal structure of the planet and its rotational state. In principle the combined information from the rotation state and the long wavelength gravity field can constrain the internal structure of the planet, in particular the size and physical state of the core. The medium wavelength gravity field could constrain the structure of the mantle and the mantle-core interface, in particular revealing “mascons” (mass concentrations) similar to the ones known on the Moon in connection with impact basins; the combination of gravity field and altimetry data could constrain the structure of the crust and the crust-mantle interface.

In addition, the adoption of a multi-frequency link allows the uplink and downlink dispersive delay contribution to be determined separately. The combination of frequent solar conjunctions and the multi-frequency radio system, makes MORE the most complete and accurate radio science experiment for probing solar corona physics. Moreover the application of the KaT, along with the TT&C transponder of Bepi-Colombo, will equip the mission with the most accurate and complete radio system ever flown in space. Finally, the orbit determined by MORE could be useful also for operational purposes, although the delivery of quick look orbit data is currently not planned: processing will be in batches, over time scales of several weeks.

The MORE investigation will address several goals in the field of geodesy, geophysics and fundamental physics, in combination with the onboard accelerometer, high resolution camera and laser altimeter:

- Spherical harmonic coefficients of the gravity field of the planet up to degree and order 25
- Love number k2
- Obliquity of the planet and amplitude of 88 days librations in longitude and amplitude of libration induced by Jupiter
- Cm/C (ratio between mantle and planet moment of inertia)
- C/MR2 (condensation coefficient)
- PPN parameters β and η
- J2 of the Sun and the parameters of Nordtvedt equation α_1 and α_2
- Spacecraft position in a Mercurycentric frame
- Position of Mercury in the SSB frame

The accuracies of the quantities specified above and the scientific outcome of the experiment continuously evolve throughout the mission and are documented in the publications of the team (Cicalò et al., 2016; De Marchi et al., 2016; Schettino et al., 2016).

3 DATA DESCRIPTION

The complete set of MORE data is archived in one single bundle. A description of the bundle is provided in the table below. A more detailed description of its contents and format is provided in the following sub-sections.

Bundle Title	***Bundle Logical Identifier (LID)***	***Description***
MORE instrument bundle	urn:esa:psa:bc_mpo_more	This bundle contains the data collected by the Radio Science (MORE) experiment for the BepiColombo Mercury Planetary Orbiter (MPO) spacecraft, along with the documents and other information necessary for the interpretation of the data.

Table 1 MORE instrument bundle

3.1 Bundle Content and Structure

The following files are contained in the root directory of the bundle:

- bundle_bc_mpo_more.xml (*this is an inventory file for the bundle)*
- readme_bc_mpo_ more.txt *(this is a README file for the bundle; it contains a table of contents)*

Inside the bundle, the data are organised into collections, which have a corresponding directory structure as follows:

Directory Name	***Collection Logical Identifier (LID)***	***Description***
data_raw	urn:esa:psa:bc_mpo_more:data_raw	MORE raw science products, as received from the ground-stations. See section 3.2.
data_calibrated	urn:esa:psa:bc_mpo_more:data_calibrated	MORE calibrated science products (TDM data). See section 3.3.
data_derived	urn:esa:psa:bc_mpo_more:data_derived	MORE derived science products. See section 3.4.
browse_calibrated	urn:esa:psa:bc_mpo_more:browse_calibrated	Science overview and quick-look analysis plots of the data products. See section 3.6.
calibration_raw	urn:esa:psa:bc_mpo_more:calibration_raw	Tropospheric and ionospheric information from GNSS and TDCS. See section 3.5.
document	urn:esa:psa:bc_mpo_more:document	Documents related to the bundle; necessary for the use and interpretation of the data. On ground testing campaign data. See section 3.7.
spice_kernels	urn:esa:psa:bc_mpo_more:spice_kernels	SPK files containing the trajectory reconstructed by MORE. The file comes as an output of the orbit determination process and follows the standard SPICE kernels' structure.
xml_schema	urn:esa:psa:bc_mpo_more:xml_schema	XML Schemas used in the bundle.

Table 2 MORE collections

3.2 Raw data collection (data_raw)

The raw data directory contains different data types, such as:

- Doppler:
  - Open loop doppler data in RDEF format (ESTRACK)
  - Closed loop doppler data in TTCP format (ESTRACK)
  - Open loop doppler data in RDEF format (**DSN**)
  - Closed loop doppler data in TDM format (**DSN**)
- Ranging:
  - Closed loop ranging data in TTCP format (ESTRACK)
  - Closed loop ranging data in TDM format (**DSN**)
- Gain:
  - AGC Gain data in TTCP format (ESTRACK)
- Meteo:
  - Meteo data (humidity, pressure, temperature) in TTCP format (ESTRACK)
- Delay doppler:
  - Closed loop delay doppler data in TTCP format (ESTRACK)
- Delay ranging:
  - Closed loop delay ranging data in TTCP format (ESTRACK)
- Uplink frequency:
  - In TTCP format (both uplink carrier phase and frequency) (ESTRACK)
- Uplink tone:
  - In TTCP format (ESTRACK)

All data in this collection are received from the ground-station and archived with as little modification as possible. They may be analysed by experts familiar with the underlying data formats, or opened with any PDS4 compatible tools. In this case the user may still need to refer to the format description documents to understand their contents.

The principal raw data types and their characteristics are presented in the following table.

Description	***Data type***	***Data format***	***Product identifier***
Open loop doppler data (ESTRACK)	doppler	RDEF	mre_raw_sc_bepinNNNtTsSSSSrRRcCC-YYDOYHHMMSS_B
Open loop doppler data (DSN)	doppler	RDEF	mre_raw_sc_SSSS_bepi_doppler_BB_FREQ_YY-DOY-HHMM
Closed loop doppler data (ESTRACK)	doppler	TTCP	mre_raw_sc_SSSS_bepi_YYYY_DOY_DT_DP_HHMMSS_NNNN_B
Closed loop doppler data (DSN)	doppler	TDM	mre_raw_sc_YYYY_DOY_SSSS_BB_dpl

Closed loop ranging (ESTRACK)	ranging	TTCP	mre_raw_sc_SSSS_bepi_YYYY_DOY_DT_**R1**_HHMMSS_NNNN_B
Closed loop ranging (DSN)	ranging	TDM	mre_raw_sc_YYYY_DOY_SSSS_BB_rng
Gain (ESTRACK)	gain	TTCP	Open loop: mre_raw_sc_SSSS_bepi_YYYY_DOY_**op_g1**_HHMMSS_NNNN_B Closed loop: mre_raw_sc_SSSS_bepi_YYYY_DOY_**cl_g1**_HHMMSS_NNNN_B
Meteo	meteo	TTCP	Open loop: mre_raw_sc_SSSS_bepi_YYYY_DOY_**op_me**_HHMMSS_NNNN_B Closed loop: mre_raw_sc_SSSS_bepi_YYYY_DOY_**cl_me**_HHMMSS_NNNN_B
Delay doppler	doppler	TTCP	mre_raw_sc_SSSS_bepi_YYYY_DOY_**cl_dl**_HHMMSS_NNNN_B
Delay ranging	ranging	TTCP	mre_raw_sc_SSSS_bepi_YYYY_DOY_**cl_r1**_HHMMSS_NNNN_B
Uplink phase	uplink_carrier_phase	TTCP	mre_raw_sc_SSSS_bepi_YYYY_DOY_**op_u1**_HHMMSS_NNNN_B mre_raw_sc_SSSS_bepi_YYYY_DOY_**cl_u1**_HHMMSS_NNNN_B
Uplink frequency	uplink_carrier_frequency	TTCP	mre_raw_sc_SSSS_bepi_YYYY_DOY_**op_t1**_HHMMSS_NNNN_B mre_raw_sc_SSSS_bepi_YYYY_DOY_**cl_t1**_HHMMSS_NNNN_B
Uplink tone	uplink_tone	TTCP	mre_raw_sc_SSSS_bepi_YYYY_DOY_cl_**p1**_HHMMSS_NNNN_B

Table 3 MORE raw data summary

Meta-data in the products allow data products to be selected or filtered by the underlying data format and the frequency band. In the Mission_Area of the product, the Data_Content class (part of the MORE dictionary) has the following two attributes:

- bc_mpo_mre:data_type
    - possible values:
        - doppler
        - ranging
        - meteo

      - gain
      - uplink_carrier_frequency
      - uplink_carrier_phase
      - uplink_tone
      - ionosphere
      - troposphere
      - other
- bc_mpo_mre:data_format
  - possible values:
    - TTCP
    - CSP
    - RDEF
    - TDM
- bc_mpo_mre:frequency_band
  - possible values:
    - x
    - k
    - x-x
    - x-k
    - k-k
    - other

Where possible, data in these files are directly labelled so that they can be read with standard PDS4 software. Since some structures (typically headers) are not compatible, those data are re-packaged and included in a separate file which also forms part of the corresponding product.

Here follows a brief description of the files depicted above, including the relevant meta-data, details of how the files are archived, and references to their complete format description.

3.2.1 ESTRACK Doppler data, Open Loop

These are full spectrum open loop receiver data, and they are recorded in binary RDEF format. The file naming convention is the following:

- The PDS label: `mre_raw_sc_${ID}.lblx`
- The original binary file: `mre_raw_sc_${ID}.prd`
- [OPTIONAL] The original side file (.obs), if present: `mre_raw_sc_${ID}.aux`

The ID placeholder follows the structure (typical of RDEF files, with the frequency band added as a suffix, when applicable):

`ID= bepin`**`NNN`**`t`**`T`**`s`**`SSSS`**`r`**`RR`**`c`**`CC-YYDOYHHMMSS_B`**

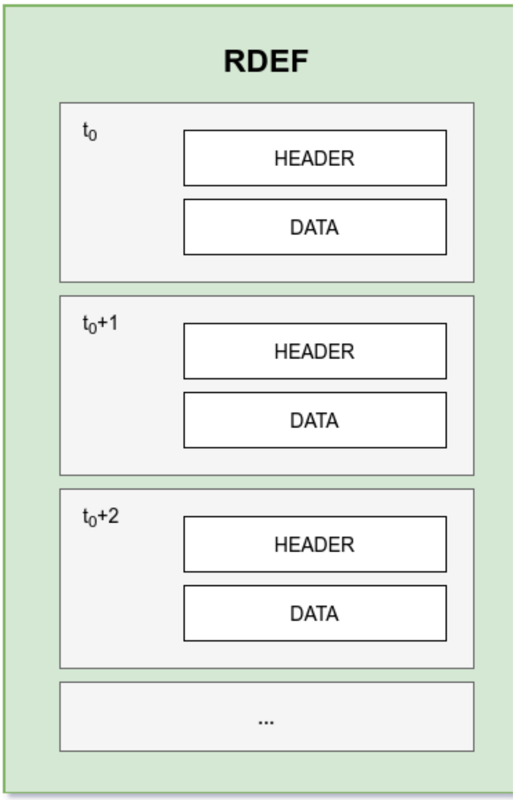
Where:

- `NNN`: recording number
- `T`: recording type (s: spacecraft)
- `SSSS`: station (MG11: malargue+receiver11)
- `RR`: receiver id (R1)
- `CC`: channel number (01)
- `YY`: last two digits of year (18, for 2018)
- `DOY`: Day of Year (343)
- `HHMMSS`: Hour minutes seconds (0-24 format)
- **`B`: band (x, k, x-x, x-k, k-k)**

Example: `mre_raw_sc_bepin001tssmg11rr1c01-18343115405_x.lblx`

The files' format and content corresponds to the standard for raw data exchange format products. A complete description of these files is given in [RD.09], which can be found in the document collection of the MORE archive as **mre_doc_eaicd_rd_10.pdf**.

In brief, the Raw Data Exchange Format (RDEF) data are recorded at both ESTRACK and DSN stations; these files are in binary format, and their structure is divided into multiple data records (as it is shown in a simplified way in **Error! Reference source not found.**). Each of these data records is composed by a binary header and a binary data part, comprising one second of recording.
The header of each data records is always composed by the same number of bytes; instead, the size of the data part may change depending on the sampling frequency and sample size applied at recording time.



This is stored in the MORE bundle as a binary table (Table_Binary) with name "TTCP OL doppler data (RDEF)". For each record the header values are directly recorded as fields in this table, whilst the data (In-phase (I) and quadrature-phase (Q) samples) are stored as a Group_Field_Binary using an unsigned byte.

Further details about the downconversion of the data are available in [RD.10]

3.2.2 *ESTRACK Doppler data, Closed Loop*

These are recorded in ASCII TTCP format. The file naming convention is the following:

- The PDS label: `mre_raw_sc_${ID}.lblx`
- The original ASCII file: `mre_raw_sc_${ID}.dat`
- Support side file required by the PDS label: `mre_raw_sc_${ID}.aux`

The ID placeholder follows the structure (typical of TTCP files, with the frequency band added as a suffix, when applicable):

`ID=`**`SSSS`**`_bepi_`**`YYYY_DOY_DT_DP_HHMMSS_NNNN_B`**

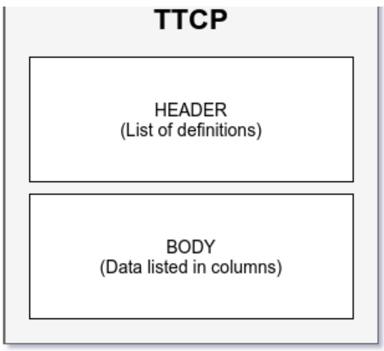
Where:

- `SSSS`: station id (MG11: Malargue, receiver id 11)
- `YYYY`: year (2018)
- `DOY`: Day of Year (343)
- `DT`: data type, in this case it is "op" (Possible values are op: operational, cl: calibration)
- `DP`: identifier of type/DAP type, in this case it is "d?" with "?" as placeholder for an integer corresponding to the channel number (Possible values are d?:doppler, r?:ranging, me:meteo, g?:gain, and the uplink carrier phase, frequency and tone as u?, t?, p?)
- `HHMMSS`: Hour minutes seconds (0-24 format)
- `NNNN`: Incremental number of the same recording sessions, starts at 0000
- **`B`: band (x-x, x-k, k-k)**

Example: `mre_raw_sc_mg11_bepi_2019_122_op_`**`d1`**`_041531_0000_x-x.lblx`

Briefly, the files' format and content corresponds to the standard for raw data exchange format products. A complete description of these files is given in [RD.06], which can be found in the document collection of the MORE archive as **mre_doc_eaicd_rd_06.pdf**.

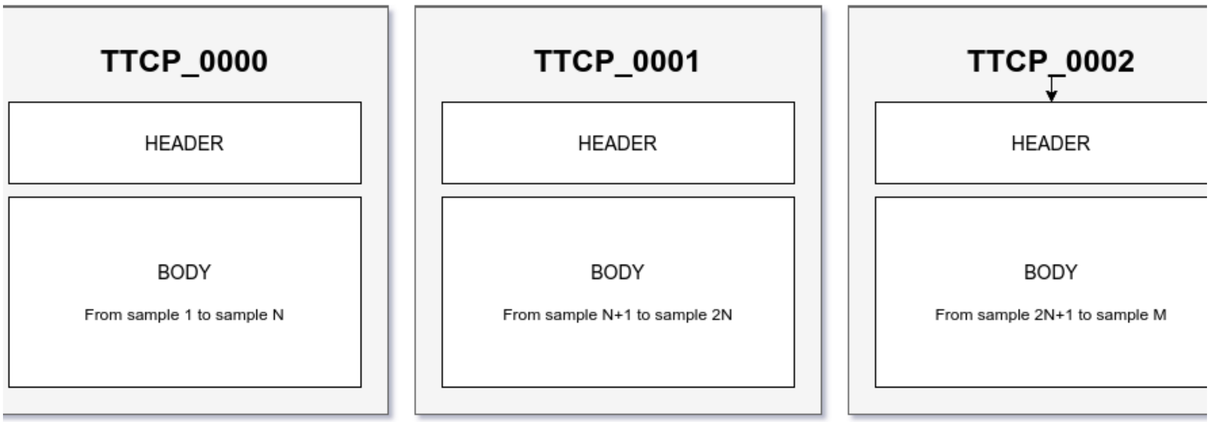
This data format comprises information collected by the TTCP receiver located at the ESA ground stations. It is an ASCII text-based document, comprising a header, where variable definitions are stored, and a body part, where data is stored in table format.



In the header, all the side information regarding the recording is depicted. If the data content is too large, these data files are split into multiple files (**Error! Reference source not found.**), where the suffix incremental number in the filename keeps track of how these files need to be ordered for their proper reading. However, an incremental sample number and a timetag string present in the data fields ensures that data can be extracted unambiguously even when considering an extracted limited subset of files.

A generic TTCP file may contain different kind of information. The TTCP types are divided in Operational (OP) and Calibration (CL), and by their main type, which is comprised in the following list:

- Doppler;
- Ranging;
- Gain;
- Meteo;
- Uplink carrier frequency;
- Uplink carrier phase;
- Uplink tone.



Meta-data in the PDS4 product will identify which content the product has and allows specific products to be identified and located.

3.2.3 DSN Doppler data, Open Loop

These are recorded in binary RDEF format. The file naming convention is different with respect to 3.2.1:

- The PDS label: `mre_raw_sc_${ID}.lblx`
- The original binary file: `mre_raw_sc_${ID}.rdef`

The ID placeholder follows the structure:

ID= **SSSS**_bepi_doppler_**BB_FREQ_YY-DOY-HHMM**

Where:

- `SSSS`: station (ds25: DSN 25)
- `BB`: band (xx, xk, kk)
- `FREQ`: sampling frequency (1khz)
- `YY`: last two digits of year (18, for 2018)
- `DOY`: Day of Year (343)
- `HHMM`: Hour minutes (0-24 format)

Example: `mre_raw_sc_ds25_bepi_doppler_xx_1khz_21-073-1455.rdef`

The files' format and content corresponds to the standard for raw data exchange format products. A complete description of these files is given in [RD.09], which can be found in the document collection of the MORE archive as **mre_doc_eaicd_rd_10.pdf**.

The same extraction procedure of the ESTRACK open loop Doppler data also holds for these files.

3.2.4 DSN Doppler data, Closed Loop

These are recorded in ASCII TDM format. The file naming convention is the following:

- The PDS label: `mre_raw_sc_${ID}.lblx`
- The original ASCII file: `mre_raw_sc_${ID}.tdm`
- Support side file required by the PDS label: `mre_raw_sc_${ID}.aux`

The placeholder follows the structure:

ID=**YYYY_DOY_SSSS_BB**_dpl

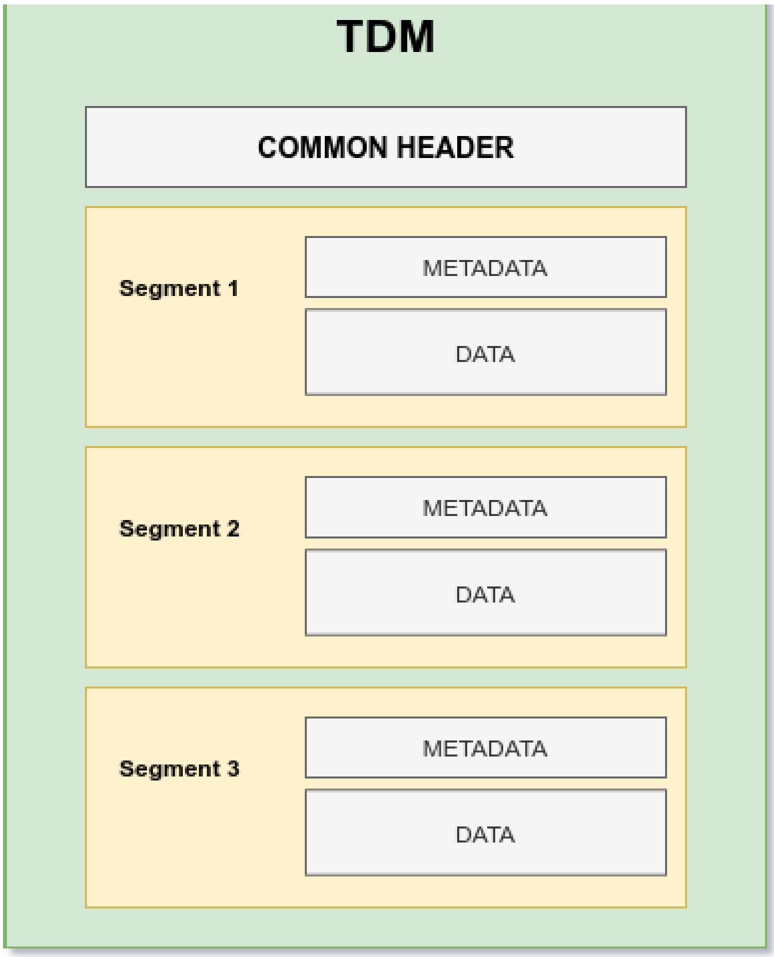
Where:

- `YYYY`: year (2018)
- `DOY`: Day of Year (343)
- `SSSS`: Identifiers of DSN stations involved (described in detail inside the tdm file)
- **BB: band (xx, xk, kk)**

Example: `mre_raw_sc_2019_122_8425_kk_dpl.tdm`

The files' format and content corresponds to the standard for raw data exchange format products. A complete description of these files is given in [RD.04][RD.06], which can be found in the document collection of the MORE archive as **mre_doc_eaicd_rd_04.pdf**.

The TDM data files are composed of a common header, which collects information valid for all the data stored inside the file, and one or many different segments, containing a metadata field and a following data field, which the metadata is referring to. The content of each segment is independent on each other segment, so that it is possible to have different data at different epochs stored in the same file. Comment lines are allowed, but they have to follow the structure defined in the TDM specification document.



Data are recorded as ASCII_Integer and can be directly extracted from the data file.

3.2.5 ESTRACK Ranging data, Closed Loop

These are recorded in ASCII TTCP format. The structure is the same as for all the TTCP files (see section **Error! Reference source not found.**), where only the DAP type is changed:

Example: `mre_raw_sc_mg11_bepi_2019_122_op_`**`R1`**`_041531_0000_x-x.lblx`

The files' format and content corresponds to the standard for raw data exchange format products. A complete description of these files is given in [RD.06], which can be found in the document collection of the MORE archive as **mre_doc_eaicd_rd_06.pdf**.

3.2.6 DSN Ranging data, Closed Loop

These are recorded in ASCII TDM format. The structure is the same as in section 3.2.4, apart for the suffix just before the file extension:

Example: `mre_raw_sc_2019_122_8425_kk_`**`rng`**`.tdm`

The files' format and content corresponds to the standard for raw data exchange format products. A complete description of these files is given in [RD.04], which can be found in the document collection of the MORE archive as **mre_doc_eaicd_rd_04.pdf**.

3.2.7 ESTRACK Gain data

These are recorded in ASCII TTCP format. The structure is the same as for all the TTCP files (see section **Error! Reference source not found.**), where only the DAP type is changed. The data type "DT" can be either "op" or "cl":

Example: `mre_raw_sc_mg11_bepi_2019_122_op_`**`G1`**`_041531_0000_x-x.lblx`

Example: `mre_raw_sc_mg11_bepi_2019_122_`**`cl_G1`**`_041531_0000_x-x.lblx`

The files' format and content corresponds to the standard for raw data exchange format products. A complete description of these files is given in [RD.06], which can be found in the document collection of the MORE archive as **mre_doc_eaicd_rd_06.pdf**.

3.2.8 ESTRACK Meteo data

These are recorded in ASCII TTCP format. The structure is the same as for all the TTCP files (see section **Error! Reference source not found.**), where the DAP type is changed and the added suffix containing the band is not present. The data type "DT" can be either "op" or "cl":

Example: `mre_raw_sc_mg11_bepi_2019_122_op_`**`ME`**`_041531_0000.lblx`

Example: `mre_raw_sc_mg11_bepi_2019_122_`**`cl_ME`**`_041531_0000.lblx`

The files' format and content corresponds to the standard for raw data exchange format products. A complete description of these files is given in [RD.06], which can be found in the document collection of the MORE archive as **mre_doc_eaicd_rd_06.pdf**.

3.2.9 ESTRACK Delay doppler data, Closed Loop

Same structure as 3.2.2, but with `DT="cl"`.

Example: `mre_raw_sc_mg11_bepi_2019_122_`**`cl_d1`**`_041531_0000_x-x.lblx`

The files' format and content corresponds to the standard for raw data exchange format products. A complete description of these files is given in [RD.06], which can be found in the document collection of the MORE archive as **mre_doc_eaicd_rd_06.pdf**.

3.2.10 ESTRACK Delay ranging data, Closed Loop

Same structure as 3.2.2, but with `DT="cl"`.

Example: `mre_raw_sc_mg11_bepi_2019_122_`**`cl_R1`**`_041531_0000_x-x.lblx`

The files' format and content corresponds to the standard for raw data exchange format products. A complete description of these files is given in [RD.06], which can be found in the document collection of the MORE archive as **mre_doc_eaicd_rd_06.pdf**.

3.2.11 ESTRACK Uplink frequency

Same structure as 3.2.2, but with any DAP type ("op" or "cl"), with `DP` among "u" (uplink carrier phase) or "t" (uplink carrier frequency) and with band limited to a single element.

Example: `mre_raw_sc_mg11_bepi_2019_122_op_`**`u1`**`_041531_0000_`**`k`**`.lblx`

Example: `mre_raw_sc_mg11_bepi_2019_122_cl_`**`t1`**`_041531_0000_`**`x`**`.lblx`

The files' format and content corresponds to the standard for raw data exchange format products. A complete description of these files is given in [RD.06], which can be found in the document collection of the MORE archive as **mre_doc_eaicd_rd_06.pdf**.

3.2.12 ESTRACK Uplink tone

Same structure as 3.2.2, but with any DAP type ("op" or "cl"), and with `DP` = "p" (uplink tone) and with band limited to a single element.

Example: `mre_raw_sc_mg11_bepi_2019_122_cl_`**`p1`**`_041531_0000_`**`x`**`.lblx`

These are recorded in ASCII TTCP format. The structure is the same as for all the TTCP files (see section 3.2.2), where only the DAP type is changed. The data type "DT" can be either "op" or "cl".

The files' format and content corresponds to the standard for raw data exchange format products. A complete description of these files is given in [RD.06], which can be found in the document collection of the MORE archive as **mre_doc_eaicd_rd_06.pdf**.

3.2.13 Final folder structure

The structure of the raw data collection is as follows:

data_raw/
- collection_mpo_more_data_raw.lblx
- collection_mpo_more_data_raw.tab
- necp
  - testing…
- cruise/
  - dsn/
    - open loop/
      - doppler/
        - 202103/
          - mre_raw_sc_${ID}.lblx

            - mre_raw_sc_${ID}.rdef
    - closed loop/
        - doppler/
            - 202204/
                - mre_raw_sc_${ID}.lblx
                - mre_raw_sc_${ID}.tdm
                - mre_raw_sc_${ID}.aux
        - ranging/
            - 202204/
                - mre_raw_sc_${ID}.lblx
                - mre_raw_sc_${ID}.tdm
                - mre_raw_sc_${ID}.aux

- estrack/
    - open loop/
        - doppler/
            - 201905/
                - mre_raw_sc_${ID}.lblx
                - mre_raw_sc_${ID}.prd
                - [optional] mre_raw_sc_${ID}.aux
    - closed loop/
        - doppler/
            - 202102/
                - mre_raw_sc_${ID}.lblx #related to DAP "d", "op"
                - mre_raw_sc_${ID}.aux
                - mre_raw_sc_${ID}.dat
        - ranging/
            - 202102/
                - mre_raw_sc_${ID}.lblx #related to DAP "r", "op"
                - mre_raw_sc_${ID}.aux
                - mre_raw_sc_${ID}.dat
        - gain/
            - 202102/
                - mre_raw_sc_${ID}.lblx #related to DAP "g", "op/cl"
                - mre_raw_sc_${ID}.aux
                - mre_raw_sc_${ID}.dat
        - meteo/
            - 202102/
                - mre_raw_sc_${ID}.lblx #related to DAP "me", "op/cl"
                - mre_raw_sc_${ID}.aux
                - mre_raw_sc_${ID}.dat
- delay_doppler/
    - 202102/
        - mre_raw_sc_${ID}.lblx #related to DAP "d", "cl"
        - mre_raw_sc_${ID}.aux
        - mre_raw_sc_${ID}.dat
- delay_ranging/
    - 202102/
        - mre_raw_sc_${ID}.lblx #related to DAP "r", "cl"
        - mre_raw_sc_${ID}.aux
        - mre_raw_sc_${ID}.dat
- uplink_frequency/
    - 202102/

- mre_raw_sc_${ID}.lblx #related to DAP "u", "op/cl"
- mre_raw_sc_${ID}.aux
- mre_raw_sc_${ID}.dat
- mre_raw_sc_${ID}.lblx #related to DAP "t", "op/cl"
- mre_raw_sc_${ID}.aux
- mre_raw_sc_${ID}.dat
- uplink_tone/
  - 202102/
    - mre_raw_sc_${ID}.lblx #related to DAP "p", "op/cl"
    - mre_raw_sc_${ID}.aux
    - mre_raw_sc_${ID}.dat

- science_phase/
  - ...

These sub-directories contain the following types of data products:

Main folders	***Subfoldes***

cruise, scienc_ephase, ...	dsn
	- open_loop/
	  o doppler/YYYYMM
	- closed_loop/
	  o doppler/YYYYMM
	  o ranging/YYYYMM
	estrack
	- open_loop/
	  o doppler/YYYYMM
	- closed_loop/
	  o doppler/YYYYMM
	  o ranging/YYYYMM
	  o gain/YYYYMM
	  o meteo/YYYYMM
	delay_doppler
	- YYYYMM
	delay_ranging
	- YYYYMM
	uplink_frequency
	- YYYYMM
	uplink_tone
	- YYYYMM

Table 4 MORE summary of the folder structure for raw data

3.3 Calibrated Data directory (data_calibrated)

The data_calibrated directory contains the raw data, which were calibrated for ground station delays, transponders delays, troposphere, ionosphere and plasma delays.

The main parameter to be extracted from the file are the RECEIVE_FREQ_1 and RANGE values, identifying respectively calibrated Doppler and range values. These data can be easily accessed from the data file and no additional processing is required.

Calibrated products can be selected or filtered by the underlying calibration procedure and the sampling/integration time. The description of the different selection possibilities is given in the next section.

3.3.1 Calibrated data:

These are recorded in ASCII TDM format, containing the ranging and doppler observables calibrated in a single day of interest, and they have links to the corresponding data raw used. The file naming convention is the following:

- The PDS label: `mre_cal_sc_${ID}.lblx`
- The original ASCII file: `mre_cal_sc_${ID}.kvn`
- Support side file required by the PDS label: `mre_cal_sc_${ID}.aux`

The placeholder follows the following structures:

`ID=`**`YYYYMMDD`**`_ ttcp_delay_schulte{_full2}_TTs`

Where:

- `YYYYMMDD`: year month day
- `{_full2}`: If it is missing, only calibration related to transponder, ground station electronics delays and Schulte vector are applied. If this is present, the ranging and doppler content of the file is also media calibrated (plasma and troposphere corrections are applied).
- `TT`: integration/sampling time (01 or 60 seconds)

Example: `mre_cal_sc_20210228_ttcp_delay_schulte_full2_01s.kvn`

The files' format and content corresponds to the standard for raw data exchange format products. A complete description of these files is given in [RD.04], which can be found in the document collection of the MORE archive as **mre_doc_eaicd_rd_04.pdf**.

3.3.2 Final folder structure

The structure of the calibrated data collection is as follows:

data_calibrated/
- collection_mpo_more_data_cal.lblx
- collection_mpo_more_data_cal.tab
- cruise/
  - 201905/
    - mre_cal_sc_${ID}.lblx
    - mre_cal_sc_${ID}.aux
    - mre_cal_sc_${ID}.kvn
- science_phase/
  - 202103/
    - …

3.4 Derived Data directory (data_derived)

These folders contain information which is the output of the estimation process performed on the calibrated data.

3.4.1 Spherical Harmonic coefficients file:

These are Spherical Harmonic ASCII (SHA) coefficient files. The file naming convention is the following

- The PDS label: `mre_der_${ID}_sha.lblx`
- The original ASCII file: `mre_der_${ID}_sha.tab`
- Support side file required by the PDS label: `mre_der_${ID}_sha.aux`

The placeholder follows the following structure (a simplified version of similar SHA files):

`ID=D_NNNN_VV`

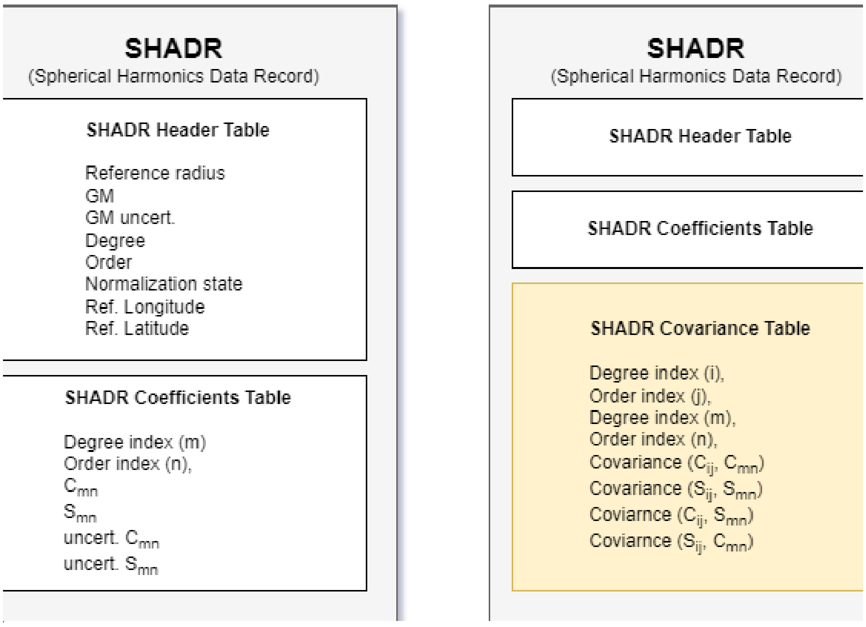
Where:

- `D`: data type (`G`: gravity field, `T`: topography, `M`: magnetic field)
- `NNNN`: is the gravity field solution (ex. Degree and order)
- `VV`: is the version

Example: `mre_der_g_0110_01_sha.tab`

Spherical Harmonics coefficients files are described in details in [RD.11].

This data format contains information in the planetocentric fixed body coordinate system, and its overall size depends on the (... is always composed by a header and ... as it is depicted in



igure 5 Spherical Harmonics Data Record, without and with Covariance t

Error! Referer

The header table is a single line, composed by 8 columns with general information about the file content. The coeffiecnts and covariance tables are composed by multiple lines, each of them with the values related to degree and order of the current line.

3.4.2 Relativistic parameters file:

This is a comma separated value (ASCII) file, containing all the outputs of the relativity experiment. The file naming convention is the following:

- The PDS label: `mre_der_estimated_data_VV.lblx`
- The original ASCII file: `mre_der_estimated_data_VV.csv`

Where:

- `VV`: is the version

Example: `mre_der_estimated_data_005.csv`

These are standard comma separated values data files. Eventual commas inside a particular field are escaped using quotation marks around the entire field. The data content depends on the data product considered.

3.4.3 Final folder structure

The structure of the calibrated data collection is as follows:

data_derived/
- collection_mpo_more_data_der.lblx
- collection_mpo_more_data_der.tab
- sha/
  - mre_der_${ID}_sha.lblx
  - mre_der_${ID}_sha.tab
  - mre_der_${ID}_sha.aux
- relativity/
  - mre_der_estimated_data_${VV}.lblx
  - mre_der_estimated_data_${VV}.csv

These sub-directories contain the following types of data products:

Directory Name	***File Naming Convention***	***Description***
sha	**mre_der_D_NNNN_VV_sha.tab** D: 'G'= gravity field NNNN: gravity field solution VV: version	Spherical Harmonic coefficient and rotational state.
relativity	**mre_der_estimated_data_VV.csv** VV: version	Contains one or more of the data derived from the relativity experiment. Each line is in a "keyword,value" shape. - Parameterized Post-Newtonian parameters (PPN parameters β and η and covariances). - Sun J2 and parameters of the Nordtvedt equation α_1 and α_2

Directory Name	*File Naming Convention*	*Description*
		- Condensation coefficient C/MR2 - Ratio mantle/planet moment of inertia Cm/C - Love number k2 Mercury obliquity and amplitude of 88 days librations in longitude and amplitude of libration induced by Jupiter

Table 5 MORE derived data products

3.5 Calibration directory (calibration)

In this directory all the data related to the calibration of the data raw files are present.

3.5.1 GNSS Iono data:

These are ionospheric data from GNSS in CSP format.

- The PDS label: `mre_raw_sc_${ID}.lblx`
- The original ASCII file: `mre_raw_sc_${ID}.csp`
- Support side file required by the PDS label: `mre_raw_sc_${ID}.aux`

The ID placeholder follows the structure:

ID= `iomedcal_iono_sc`**`SSS_YY.DOY.TTTTT-YY.DOY.TTTTT`**

Where:

- `SSS`: spacecraft id number
- `YY`: last two digits of year (20, for 2020)
- `DOY`: Day of Year (257)
- `TTTTT`: A time placeholder

Example: `mre_raw_sc_iomedcal_iono_sc`**`121_20.257.00000-20.258.00000`**`.lblx`

3.5.2 GNSS Tropo data:

These are tropospheric data from GNSS in CSP format.

- The PDS label: `mre_raw_sc_${ID}.lblx`
- The original ASCII file: `mre_raw_sc_${ID}.csp`
- Support side file required by the PDS label: `mre_raw_sc_${ID}.aux`

The ID placeholder follows the structure:

ID= `trmedcal_trop_`**`YY.DOY.TTTTT-YY.DOY.TTTTT`**

Where:

- `YY`: last two digits of year (20, for 2020)
- `DOY`: Day of Year (257)
- `TTTTT`: A time placeholder

Example: `mre_raw_sc_trmedcal_trop_`**`20.257.00000-20.258.00000`**`.lblx`

3.5.3 TDCS Tropo data:

These are tropospheric data from the Tropospheric Delay Calibration System (TDCS) in CSP format.

- The PDS label: `mre_raw_sc_${ID}.lblx`
- The original ASCII file: `mre_raw_sc_${ID}.csp`
- Support side file required by the PDS label: `mre_raw_sc_${ID}.aux`

The ID placeholder follows the structure:

ID= **`YYYY_DOY_TT`**`s`

Where:

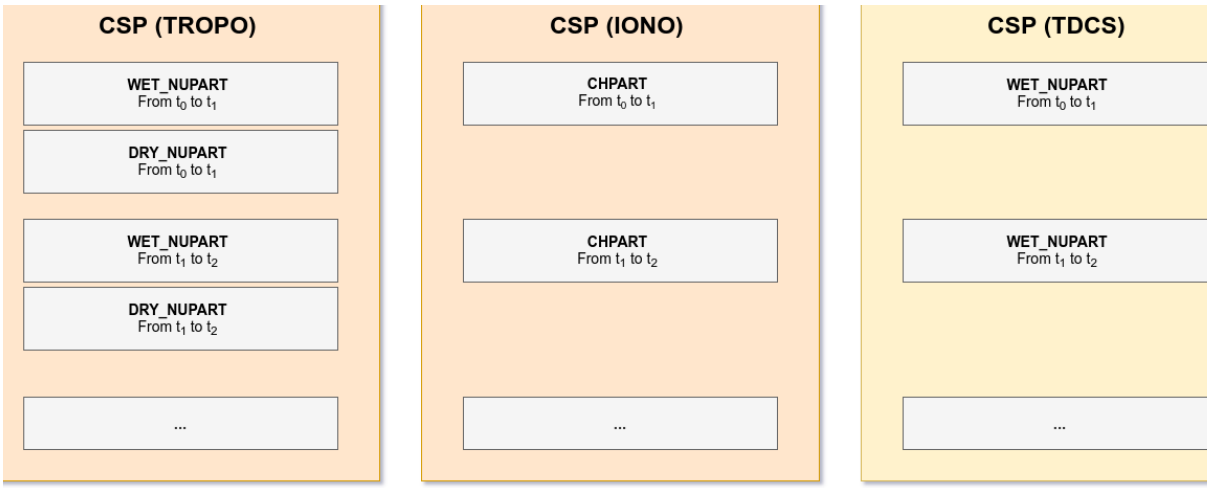
- `YYYY`: year (2020)
- `DOY`: Day of Year (257)

- `TT`: time expressed in seconds

Example: `mre_raw_sc_trmedcal_trop_`**`20.257.00000-20.258.00000`**`.lblx`

The media calibration data regarding troposphere and ionosphere are stored in the CSP format. This is an ASCII file composed by one or multiple rows, each of them addressing media correction information related to a specific time interval. The information content is in the form a normalized polynomial correction, and it may be related to:

- ionospheric charged particles (if the string MODEL(CHPART) in present in the file)
- tropospheric wet delay (MODEL(WET NUPART))
- tropospheric dry delay (MODEL(DRY NUPART)).



3.5.4 Final folder structure

The structure of the calibration collection is as follows:

calibration_raw/

- collection_mpo_more_calibration.lblx
- collection_mpo_more_calibration.tab
- cruise/
    - iono/
        - YYYYMM
            - mre_raw_sc_${ID}.lblx
            - mre_raw_sc_${ID}.csp
            - mre_raw_sc_${ID}.aux
    - tropo/
        - YYYYMM
            - mre_raw_sc_${ID}.lblx
            - mre_raw_sc_${ID}.csp
            - mre_raw_sc_${ID}.aux

3.6 Browse directory (browse)

In this directory we can find all the preview files for the corresponding data archived.

3.6.1 *Calibrated browse data:*

These are preview data from the data_calibrated directory. They consist of timeline representation of the data content of the corresponding calibrated files.

- The PDS label: `mre_cal_sc_browse_${ID}.lblx`
- The original ASCII file: `mre_cal_sc_browse_${ID}.png`

The ID placeholder corresponds to the original calibrated filename.

Example: `mre_cal_sc_browse_ ttcp_d1d2d4_r1r2r4.lblx`

3.6.2 *Final folder structure*

The structure of the browse collection maps the structure of the data collections (raw and calibrated):

browse/

- collection_mpo_more_browse.lblx
- collection_mpo_more_browse.tab
- cruise/
    - 201905/
        - mre_raw_sc_browse_${ID}.lblx
        - mre_raw_sc_browse_${ID}.png

browse_calibrated/

- collection_mpo_more_browse.lblx
- collection_mpo_more_browse.tab
- cruise/
    - 201905/
        - mre_cal_sc_browse_${ID}.lblx
        - mre_cal_sc_browse_${ID}.png

3.7 Document directory (document)

The structure of the document collection is as follows:

document/
- collection_mpo_more_document.lblx
- collection_mpo_more_document.tab
- mre_doc_${ID}.lblx
- mre_doc_${ID}.pdf

In this folder we have also documents related to the on ground calibration / testing campaign.

Document	*Description*
mre_doc_eaicd_bc_ mre-icd-xxxxx_more_eaicd.pdf/.lblx	This document
mre_doc_bc-est-rs-02524_more_eid-b.pdf	Experiment Interface Document Part-B
mre_doc_bc-sgs-sp-018_mre_pipeline_description_document.pdf	MORE Pipeline Description Document
mre_doc_eaicd_rd_02.pdf	MORE EAICD RD.02
mre_doc_eaicd_rd_03.pdf	MORE EAICD RD.03
mre_doc_eaicd_rd_04.pdf	MORE EAICD RD.04
mre_doc_eaicd_rd_05.pdf	MORE EAICD RD.05
mre_doc_eaicd_rd_06.pdf	MORE EAICD RD.06
mre_doc_eaicd_rd_07.pdf	MORE EAICD RD.07
mre_doc_eaicd_rd_08.pdf	MORE EAICD RD.08
mre_doc_eaicd_rd_09.pdf	MORE EAICD RD.09
mre_doc_eaicd_rd_10.pdf	MORE EAICD RD.10
mre_doc_*.pdf	Generic document.

Table 6 MORE documents

3.8 Data product formats

This section provides a summary of the formats used for each of the products included in the MORE science data.
Templates are maintained under version control in the MORE PDS4 repository:
- gitolite@scigit02.esac.esa.int:bepi.pds4.mre.git / mre_templates.xlsx

As described before, a single data format may be used for different processing levels (for example the TDM is used for both data_raw from DSN and for calibrated data), or vice versa (all the data_raw are split into multiple data formats).

Main format	*File extensions*	*Data interested*	*Content*	*Reference*
ttcp	.dat	data_raw	Custom ASCII	[RD.06], [RD.10]

Main format	*File extensions*	*Data interested*	*Content*	*Reference*
rdef	.rdef, .prd	data_raw	Custom Binary	[RD.09]
csp	.csp	calibration_raw	Custom ASCII	[RD.08]
tdm	.tdm, .kvn	data_raw, data_calibrated	Custom ASCII	[RD.04]
sha	.tab	data_derived	Custom ASCII	[RD.11]
csv	.csv	data_derived	CSV	Standard
pdf	.pdf	data_document	PDF	Standard

Table 7 Data formats summary

4 SCIENCE USER GUIDE

4.1 How to approach the dataset

The complete dataset produced by MORE is described in Chapter 4. Each file within the dataset serves a different analytical purpose, allowing users to tailor their investigations to specific research goals. When grouped by data type, the main ways to work with the dataset can be summarized as follows:

- **Raw data**: Open Loop and Closed Loop raw data represent the most fundamental data types in the dataset. To perform OD analyses, these data must first be calibrated, resulting in the so-called *calibrated data*. However, an external user can also work directly with the raw data to extract information about the solar plasma by applying the triple-link calibration scheme described in Chapter 3.
- **Calibrated data**: these files represent the processed version of the raw data. They are ready to be used, properly combined with the relative calibration files (such as tropospheric effects calibration CSPs), to perform Orbit Determination analysis.
- **Derived data**: when the main interest of the user are the scientific outputs of the OD process rather than the OD itself, derived data can be interrogated to extract informations about the estimated gravity field and relativistic parameters.

MORE conducts various observations during both the cruise and orbital phases, making this distinction the first criterion to consider when searching for the relevant data. After that, the other relevant reference are the time span in which the KaT was turned on to perform the scientific investigations.

To further extend the analysis, MORE data can be complemented with data from other instruments. For example, during the orbital phase ISA should support the radio-science investigations with measurements of the non-gravitational affecting the spacecraft. However, the usage of ISA data presents some critical aspects, which will be described in section 5.4. Other relevant data that can be used to complement the MORE dataset are images taken by the High Resolution Imaging Channel (HRIC) of the SIMBIO-SYS payload, support from the laser altimeter (BELA) and data from AOCS for attitude reconstruction.

4.2 Working with the data

The main core behind the radio-science investigations conducted by MORE is the Orbit Determination analysis, hence an OD software is crucial for this purpose. In the next section a description of the data analysis performed by the MORE team that can be used as a reference for an external user.

4.2.1 MORE data analysis

MORE is a system level experiment, involving both in-flight and ground-station hardware, as well as a dedicated orbit determination (OD) software to process the plasma-calibrated radio tracking data. To this end, two independent OD software packages will be used: the JPL/MONTE software, suitably adjusted for the experiment purposes, and the ORBIT14 software, specifically developed for MORE by the UniPisa Team.
The goal of the OD process is to estimate the value of a number of parameters of general interest concerning both Mercury geophysics (e.g. the planet gravity field and rotational state) and fundamental physics (e.g. some post-Newtonian parameters, whose values will be constrained in order to test metric theories of gravity as General Relativity).

Both OD software packages perform the estimation of a set of parameters by means of a non-linear least squares (LS) fit adopting the standard differential corrections method. The iterative procedure consists of minimizing a suitable target function, which is a quadratic form of the residuals, defined as the difference between the observed observables (e.g. tracking data) and the predicted observables, computed adopting

suitable mathematical models and assumptions. For in-orbit determination, the estimation approach consists of a combined solution called pure multi-arc strategy, which is the approach adopted in the JPL/MONTE software. According to this method, every single arc of observations has its own set of initial conditions, as it belongs to a different object. In this way, due to a lack of knowledge in the dynamical models, the actual errors in the orbit propagation can be reduced by an over-parameterization of the initial conditions. A different choice has been made in ORBIT14, implementing the so called constrained multi-arc strategy. The method is based on the idea that each observed arc belongs to the same object (the spacecraft). All the details can be found in Alessi et al., MNRAS 423, 2270 (2012). Adopting in general a multi-arc approach, the estimated parameters can be classified as *global* parameters that are common for each arc, e.g. the gravity field of Mercury, its rotational state and the PPN parameters, and the estimation of the *local* parameters, e.g. the initial position and velocity of MPO in each arc.
The OD receives as input the TDM and an auxiliary file containing the weights that will be used in the quadratic cost function. This auxiliary file is generated during the pre-processing phase, where all calibrations have been applied to the radio science data in order to correct for the plasma noise, ionospheric and tropospheric effects. Figure 9 gives a schematic representation of the data analysis procedure.

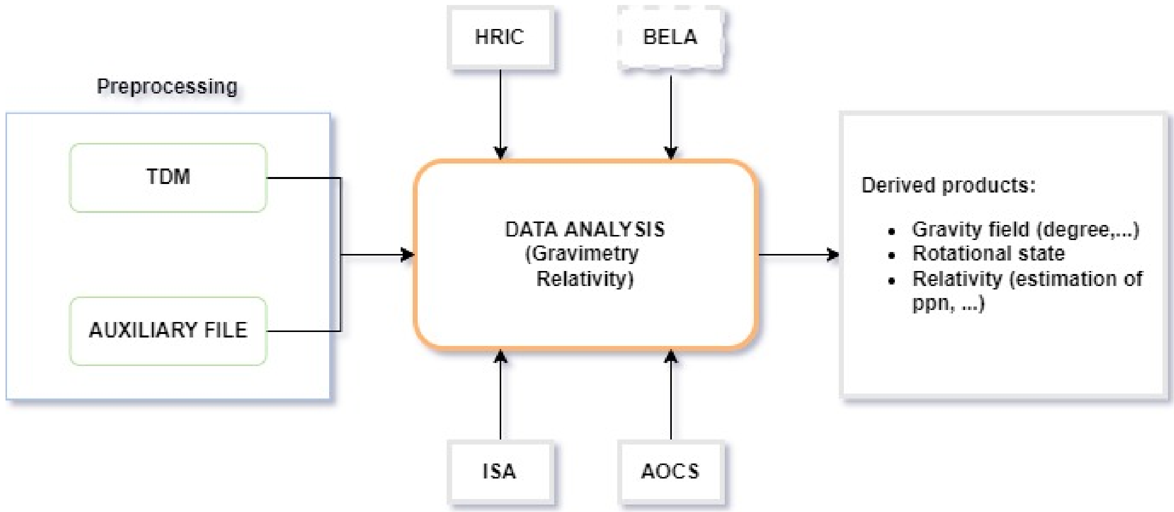


Figure 7: MORE data analysis concept

4.3 Key data and meta-data

As discussed through-out the document, the different MORE products can be mainly distinguished according to the processing level. Other relevant meta-data to be looking for are the beginning and end times of the observations conducted by the instrument.

4.4 Known issues and caveats

4.4.1 ISA calibration

A realistic model to describe the MPO Mercury-centric dynamics needs to include both gravitational and non-gravitational perturbations, due to the proximity of the Sun. Because of the general difficulty of modelling the non-gravitational effects at the level required for the purposes of MORE, the non-gravitational perturbations on the spacecraft are replaced by the ISA measurements in the trajectory integration.

There are two critical issues which affect the use of the ISA measurements for the radio science experiment. The first one concerns the fact that ISA 3-axes measurements will be affected by systematic and random errors. In particular, the systematic terms could lead to a biased estimation of some key parameters for

MORE, mainly the one concerned with the gravity and the rotation state of Mercury. This issue can be solved by means of a digital calibration of the accelerometer measurements during the LS fit. To this aim, some calibration parameters are additionally estimated during the OD process together with the spacecraft trajectory and the other parameters of interest. Different digital calibrations have been tested up to now. The estimated parameters for ISA calibration can be local or global depending on the chosen calibration strategy. The second issue concerns the fact that the mathematical model to compute the MPO dynamics is generally referred to the spacecraft centre of mass (CoM). Since ISA is not located in the CoM, the OD will not estimate the MPO CoM trajectory but the trajectory of the ISA reference point, i.e. the point where the accelerations are measured. To this point, the measurements of the azimuth and elevation angles of the on-board High Gain Antenna (HGA) become of critical importance for an accurate OD, since they will be used to compute the so-called Schulte's vector, that is the position vector from ISA to antenna phase centre in the spacecraft-fixed frame.

4.4.2 Range calibration

In general, one of the main critical issues of MORE is to properly handle the systematic effects introduced by the instrumentation. In fact, if not correctly evaluated and handled with a suitable calibration strategy during the OD process, they may lead to a significant degradation of the solution. While systematic errors introduced by the accelerometer readings could downgrade the solution for the gravity field and the rotation state of Mercury, possible residual systematic errors introduced by the ranging chain could significantly affect the General Relativity tests. In particular, the determination of the PN Eddington parameter, beta, and of the Nordtvedt parameter, eta, is extremely sensitive to even small systematics in range. To constrain this issue, it is possible to introduce a digital calibration during the differential correction process to absorb the systematic effects in the range observables. In such a way, it has been tested that the goal accuracy in the relativity parameters determination can still be achieved.

4.4.3 Desaturation maneuver ΔV estimation

The asymmetric shape of the spacecraft, due to presence of only one solar panel results in high torques balanced by the reaction wheels. Desaturation manoeuvres will yield an uncompensated Δn of 17 mm/s, 0.2 mm/s, and 42 mm/s respectively along the radial, transversal and normal components in the orbital reference frame. The manoeuvres are scheduled twice per day, one in the tracking pass in X-band and the second after approximately 12 hours, between two tracking periods. The uncompensated Δu is generally estimated in the OD process because can yield an error in the parameters estimations. In the MONTE software the ΔV of the manoeuvre in the tracking pass is estimated as a local parameter of each arc, while in ORBIT14 both the manoeuvres, one during tracking and one in the subsequent period without tracking, are estimated as local and local-external parameters.

ANNEX A INSTRUMENT DESCRIPTION

A.1 Instrument design

The Ka-band transponder (KaT) is the specific payload of the Mercury Orbiter Radioscience Experiment (MORE). However, more than any other onboard instrument, the KaT is part of a system-level experiment, which involves not only flight hardware but also ground equipment, as well as the contribution of other onboard instruments and subsystem. MORE makes use of the following hardware:

- Ka-band Transponder (KaT) to provide the specific radioscience Ka/Ka link for precise Doppler and ranging measurements.
- TT&C subsystem including the high gain antenna (HGA), the RF network, the X/X/Ka deep space transponder (DST) to provide X/X and X/Ka links for Doppler and ranging measurement.
- Tri-axial accelerometer (ISA) for the precise measurement of non-gravitational acceleration.
- Support from on board high resolution camera (SIMBIO-SYS) for the determination of Mercury's rotational state (libration experiment).
- Support from the on board laser altimeter (BELA) for the geodesy experiment.
- Support from the ACS subsystem for attitude reconstruction.
- Ground station equipment for simultaneous tracking of the spacecraft by the X/X X/Ka and Ka/Ka frequency links.
- Ground station ancillary equipment for calibration of the tropospheric effects. This includes a water vapour radiometer (WVR) for the calibration of wet path delay.

The estimation of physical quantities of interest (spherical harmonics coefficients, PN parameters of general relativity, etc.) will be based almost entirely upon range and range-rate observables obtained by exploiting the microwave link between the spacecraft and the Earth. The final accuracy in the estimated physical parameters is essentially proportional to the accuracy of range and range rate measurements determined by the end-to-end performance of the radio link. All measurements are carried out in a coherent two-way mode, in which the frequency reference is generated at the ground station and all onboard transponders (KaT and DST) are commanded in a coherent mode.

The key aspect is the implementation of a multi-frequency link, which will allow for an almost complete cancellation of the plasma noise, the dominant noise source in microwave Doppler and range measurements. In this configuration, two uplink and three downlink carriers are simultaneously used:

- A X-band downlink (X, at 8.4 GHz) coherent with an X-band uplink (at 7.2 GHz)
- A Ka-band downlink (Ka1, at about 32 GHz) coherent with the same X-band uplink
- A Ka-band downlink (Ka2, at about 32 GHz) coherent with a Ka-band uplink (at about 34 GHz)

The Ka2 link will be the primary link for the radio science experiment. The DST (part of the spacecraft TT&C subsystem) receives the uplink X-band signal and generates the coherent X and Ka1 downlink carriers. All DST carriers will be phase modulated by a Pseudo Noise (PN) ranging code at 3 Mcps (TBC). In addition, the primary radio science link (Ka2) will support a high precision ranging channel, also referred as the wide band ranging system (WBRS), used for precision measurements (crucial for all fundamental physics tests). The WBRS will be implemented by a regenerative PN ranging scheme, with a clock component at 12 MHz modulated by a 24 Mcps PN code for highly accurate measurements (16 MHz clock – 32 Mcps code is desirable). Note also that there is no need for the WBRS in the X/X and X/Ka links, as indicated in [Iess et al., 2003]. The high precision ranging procedure is carried out by the ground station as follows:

1) The standard range observable (using PN sequences at 3Mcps) is generated for the DST links (X, Ka1); ambiguity is resolved in each channel and pseudorange is measured within 1-2 m (TBC);
2) Ka2 pseudorange observables are generated for the Ka2 link;
3) The standard X and Ka1 pseudorange are finally linearly combined with the WBRS range to get the high accuracy, non-dispersive range observable.

The WBRS PN regenerative channel is the baseline configuration that will be implemented in the KaT. However, in order to carry out the experiment even in case of any accidental malfunctioning of the PN ranging system (one should remember that PN ranging is not currently supported by any existing ground station, and there is no heritage of this configuration in deep space missions), a back-up solution based on standard ranging is also foreseen and its implementation is currently under discussion (TBD).

The multi-frequency configuration, successfully used by the Cassini spacecraft, ensures a nearly complete cancellation of the plasma noise both in range and range rate measurements. Being highly immune to plasma noise thanks to the higher carrier frequency, Ka2 will be the primary link for the MORE investigation. The X and Ka1 link, used for telecommands and telemetry and provided by the RF spacecraft subsystem, are also needed for the elimination of the plasma noise. Plasma-free range and range rate are generated from a suitable linear combination of the X, Ka1 and Ka2 observables.

A.2 Instrument performance

As described in the previous section, the availability of the complete multifrequency link is crucial for the achievement of the scientific goals. The MORE equipment was designed to ensure, in full triple link, an end-to-end accuracy of 20 cm (at a few seconds of integration time) for range measurements and 0.004 mm/s at 1000 seconds of integration time for range-rate. In-flight data, however, showed an accuracy at the centimeter level for range measurements at a count-time of 4.2 seconds, exceeding the expected performance. Range-rate showed performances closer to the expectation, with an accuracy of 0.017 mm/s at 60 seconds of integration time (Cappuccio et al. 2020).

The described instrument performance can be affected and reduced by different factors such as particularly high solar activity during superior solar conjunctions or bad weather conditions at the ground station.

A.3 Instrument operations

A.3.1 Planning strategy

A.3.1.1 Cruise phase

During cruise phase, the Ka-transponder was turned on to conduct different solar conjunction experiments (SCE). Superior solar conjunctions are the ideal testbed to perform tests of general relativity. Among the different opportunities encountered during the cruise phase, a total of six conjunctions, the ones without propulsion arcs in their time window, were exploited to perform such investigations. The detailed timeline is as follows:

- Solar Conjunction Experiment #1: conducted between March 10th and March 24th 2021.
- Solar Conjunction Experiment #2: conducted between January 29th and February 12th 2022.
- Solar Conjunction Experiment #3: conducted in July 2022.
- Solar Conjunction Experiment #4: conducted between January 29th and February 12th 2023.
- Solar Conjunction Experiment #5: conducted between June 26th and July 6th 2023.
- Solar Conjunction Experiment #6: conducted between December 8th and December 22nd 2023.

Due to technical difficulties, data from SCE #3 could not be included in the scientific analysis and the overall dataset.

A.3.1.2 Hermean phase

During the orbital phase, different tracking sessions with the full multifrequency link available will be performed to conduct gravity, geodesy and fundamental physics investigations. The observation windows will be restricted due to power consumption management.

A.3.2 Operating modes

The KaT operation modes are:

- Off: the Unit is switched off;
- Warm-up: the Unit is switched on and the internal oscillator (i.e. the Oven Controlled Crystal Oscillator, OCXO) is warming-up to achieve its steady-state condition;
- Calibration: the Unit is configured in loopback mode in order to carry out the on-board group delay estimation;
- Nominal: the Unit is operative and ready to support the radio-science experiment.

The following flowchart shows the KaT mode transition diagram:

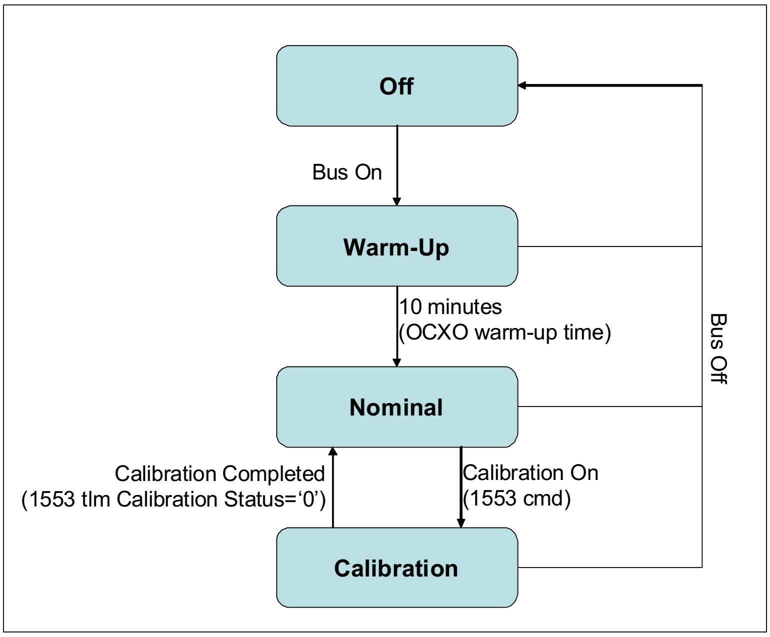
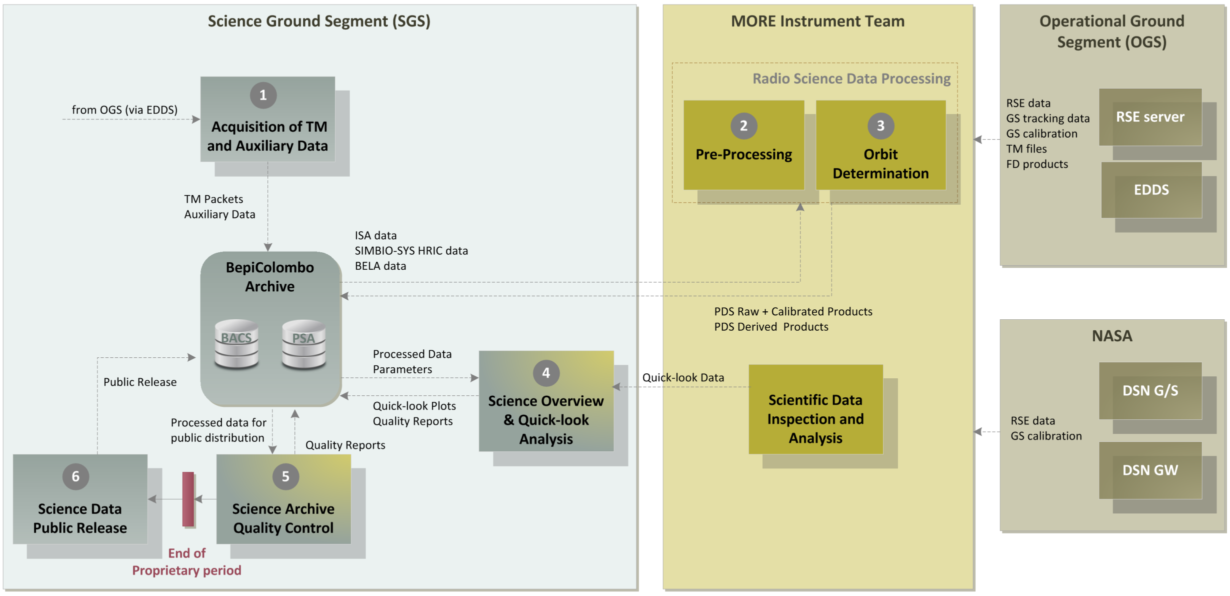


Figure 8: KaT Mode Transition diagram

A.4 Data handling

A.4.1 Overview of the Science Data Flow

This section provides an overview of the data flow for the MORE data, from on-board acquisition by the MORE instrument through to ingestion into the ESA's Planetary Science Archive (PSA).



EDDS: EGOS Data Dissemination System
BACS: BepiColombo Archive Core System
PSA: Planetary Science Archive

Figure 9: Science Data Flow

A.4.2 Data generation

Radio science data is collected by different parties and consist of:

- Tracking Data Message (TDM) closed loop doppler and ranging data from JPL
- Raw Data Exchange Format (RDEF) open loop doppler data from both JPL and ESA
- Telemetry and Telecommand Processor (TTCP) closed loop doppler and ranging, gain and meteorological data from ESA
- Control Statement Processor (CSP) language tropospheric data from the Tropospheric Delay Calibration System (TDCS) instrument
- Control Statement Processor (CSP) language tropospheric and ionospheric data from the Global Navigation Satellite System (GNSS) receivers.

The Tracking Data Message standard of the CCSDS has been selected as the standard data exchange format. Choosing this internationally approved TDM format implies that the task of the pre-processing software is to compute and apply calibrations for all dispersive and non-dispersive noise sources and to output a tracking data file in TDM format.

The University of Bologna team will pre-process the open and closed loop data, the ancillary data and generate a TDM that will be used for the orbit determination process (**Error! Reference source not found.**).

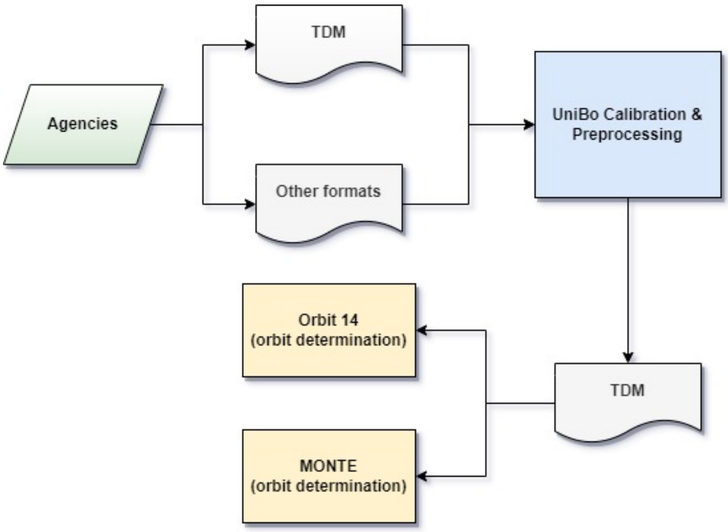


Figure 10: Top-Level Pre-Processing S/W Block Diagram

The Agencies data flow is currently divided as follows:

- JPL/RDEF and ESA/RDEF open loop data
- JPL/TDM and ESA/TTCP closed loop tracking data
- ESA/TTCP Meteo and Gain data
- ESA/CSP Media data
- ESA/CSV Wind data
- ESA/BMP Cloud images
- JPL/CSP Meteo/Media data

The closed loop tracking data can also be generated from open loop data with a Ranging & DPLL algorithm by the University of Rome team. Other ancillary information are exchanged with a JPL proprietary format.

The TDM specifies a standard ASCII-based message format for the exchange of spacecraft tracking data, in order to facilitate interagency cross-support. The TDM header and data content shall be represented in the “keyword = value” structure, also assessed as KVN (see [RD.04]).

ANNEX B CALIBRATION

B.1 Calibration strategy

The block diagram in **Error! Reference source not found.** shows the pipeline structure for the data calibration. The full calibration process is composed by three main steps:

1. Calibration of antenna geometry and hardware electronics
2. Media calibration
3. Boa to TDM conversion

As inputs, we have doppler and ranging data acquired at the ground stations (ESTRACK and DSN).

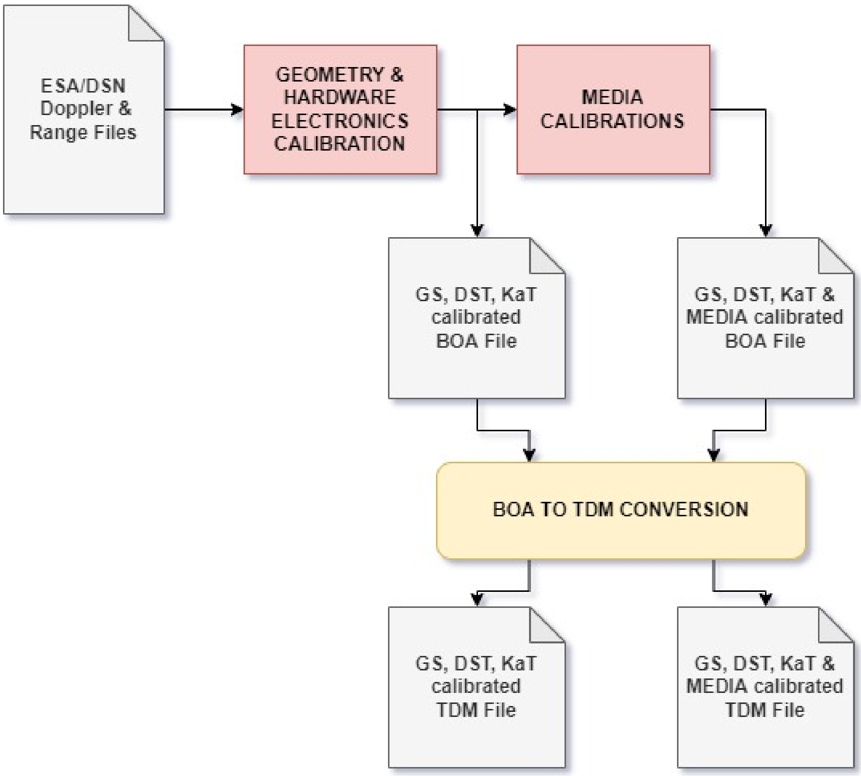


Figure 11: Data calibration pipeline

B.1.1 Antenna geometry & hardware electronics calibration

The first calibration process takes into account the delays introduced into the observables by the electronics of the different systems that operate along the uplink and downlink paths, namely the Ground Stations (GS), the Deep Space Transponder (DST) and the Ka Transponder (KaT).

The first step of the process involves, as inputs, the raw TTCP data coming from ESA. In particular, in this phase, the files of our interests are those containing the operational data (OP files) and the ones containing the calibration data (CL files), in which information about the delay introduced by the GS are stored. These two kinds of files are elaborated together in order to produce, as output, a file in which the Range and Doppler observables contained in the operational TTCPs are corrected with respect to the ground station delay. This output file is in BOA format. In the case DSN data are available, a similar procedure is performed in parallel for these files. DSN data are generally distributed in TDM format, however, in our case they only store information about Range and Doppler observables. To perform the first calibration step on the DSN observables, since a calibration TDM file is not available, the information relative to DSN ground station delay are in general obtained from technical documents. The output of this process is another BOA file which is then merged with the ESA BOA generating a unique file containing all the available observables.

The second calibration step involves, as an input, the final BOA file coming from the ground station calibration process. In this phase, the observables are calibrated taking into account the delays introduced by the 2 on-board transponders: DST and KaT. Information about KaT's group delay are obtained thanks to a self-calibration system, installed into the KaT itself, which, recursively, computes the delay introduced by the transponder. The data collected by the self-calibrator are stored in the spacecraft telemetry. Together with the telemetry, other information about KaT's delay are also included in some Test Reports which describe the results of the on-ground calibration campaign performed before the launch. Concerning DST, telemetry does not include any "online" calibration data since this transponder is not equipped with a self-calibration system, so the only reference available are the values collected during the on-ground calibration campaign. Further details about the on-ground calibration campaign are reported in section 3.2.

Taking into account all the information about transponders' delays, the observables contained into the BOA file are then corrected for these delays. The output file is then reprocessed in order to adjust the geometry through the Schulte reference point implementation. Thanks to this operation we can modify the point of the Schulte vector chain that we want to use as a reference point. The final output of the first calibration phase is a BOA file which contains the observables calibrated for the delays introduced by the systems operating in the Earth-Probe link.

All the files generated up to now contain the observables sampled at 1 second. The final file is then compressed to generate a 60 seconds-sample file.

Below, the block diagram in **Error! Reference source not found.** illustrates the pipeline for the first calibration phase.

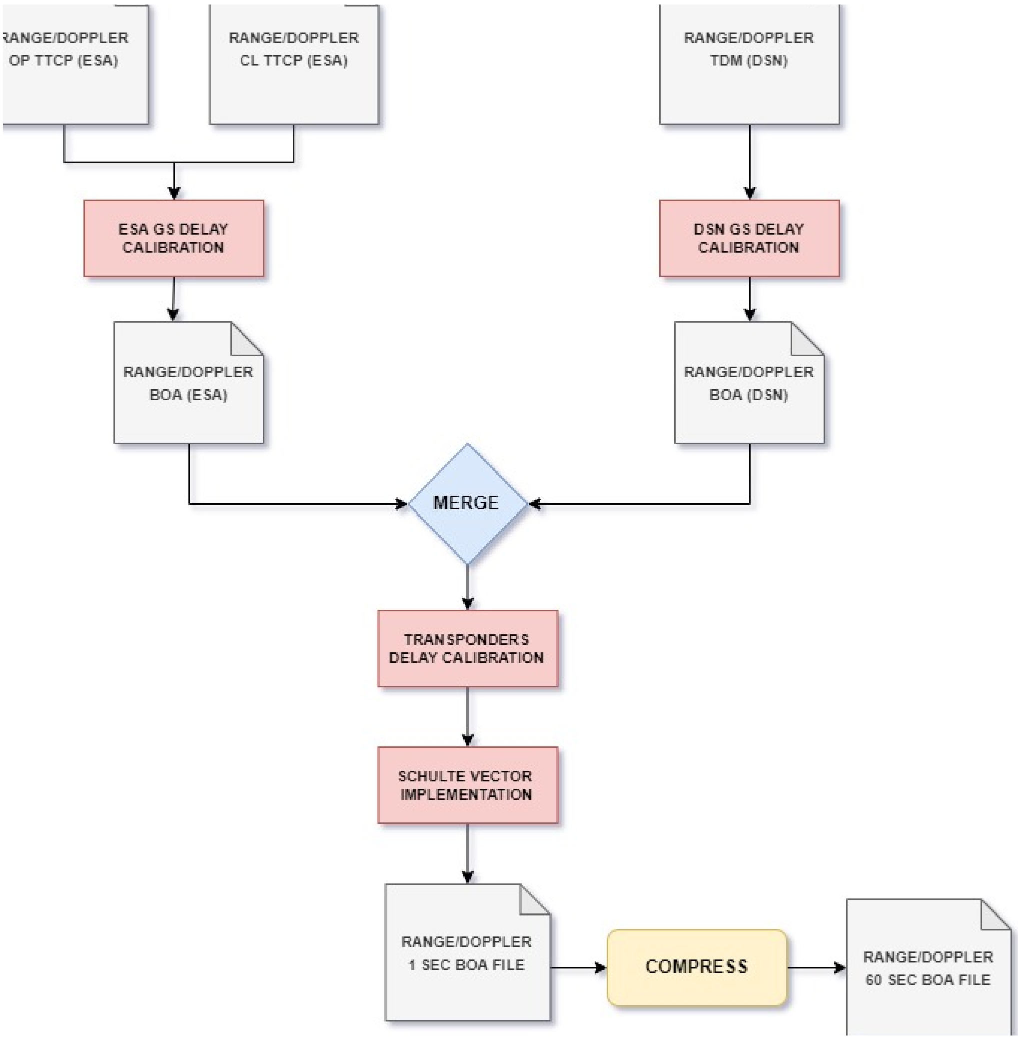


Figure 12: Antenna geometry & Hardware electronics Calibration pipeline

B.1.2 Med

The second calibration phase corrects all the effects introduced by Plasma, Ionosphere and Troposphere. The main calibration process, in this phase, is the elimination of all the dispersive noise (mainly Plasma and Ionosphere) through the application of the multi-frequency link technique, which will be described in detail in paragraph **Error! Reference source not found.**. The input file of this calibration process is the 1 second-sample BOA file corrected with the ground station and transponders' delays. The observables are manipulated through the multi-frequency link in order to remove some undesired effect, however, according to the kind of multifrequency link we may have different results:

1. In case of a full triple link, the multifrequency algorithm is sufficient to eliminate Plasma and Ionospheric effects.

2. In case of an uncomplete link, we still have a smaller correction but some effect may be taken into account through some external information, such as the ionosphere CSP files from which we can estimate the ionosphere-introduced delay and remove it from the observables

Once the multifrequency algorithm has been applied, the observables are then calibrated again with the removal of the contribution given by the troposphere. Similarly to ionosphere, also the troposphere contribution can be estimated thanks to a set of CSP files where relevant information about troposphere itself are stored. After the calibration of the tropospheric effect, the output file is the final BOA file containing the fully calibrated observables. **Error! Reference source not found.** shows the block diagram pipeline of the media calibration process. In the following paragraphs, the different media calibration procedures are described in deep.

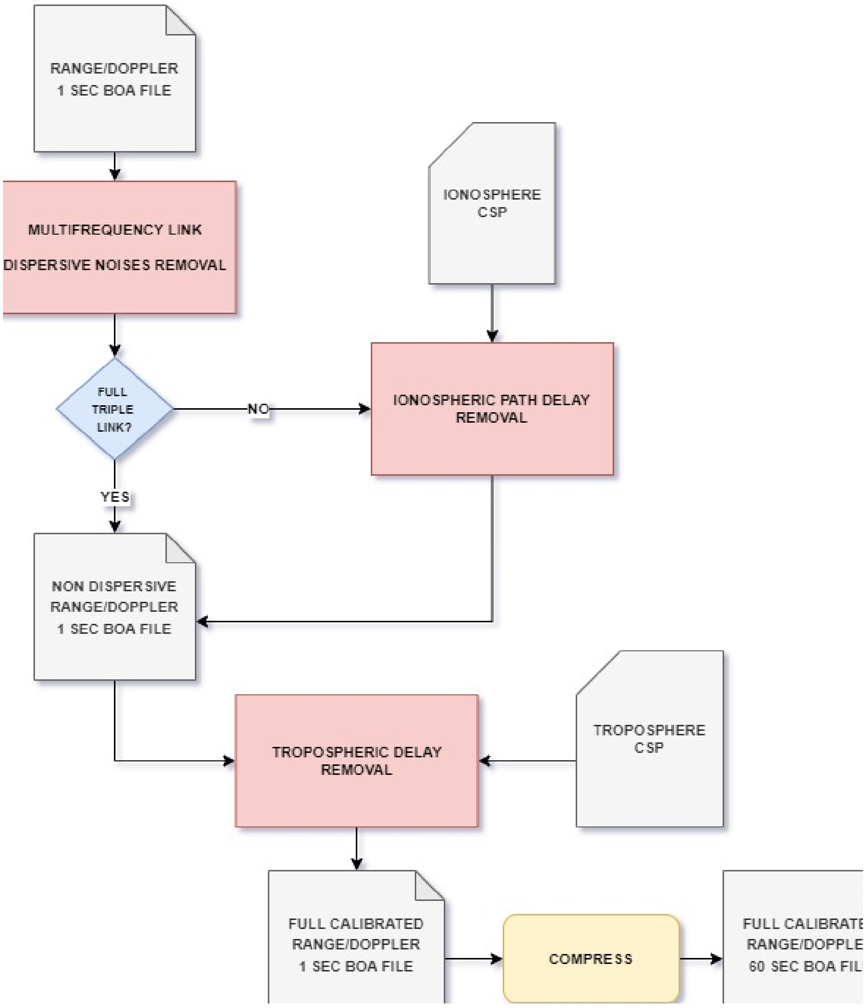


Figure 13 Media calibration pipeline.

B.1.2.1 Multifrequency link

The multifrequency algorithm is responsible for removing the non-dispersive noises (the noises which depend on the carrier frequency, i.e. coronal and interplanetary plasma, Earth ionosphere) from either Doppler or range data, using a linear combination of data coming from different bands.

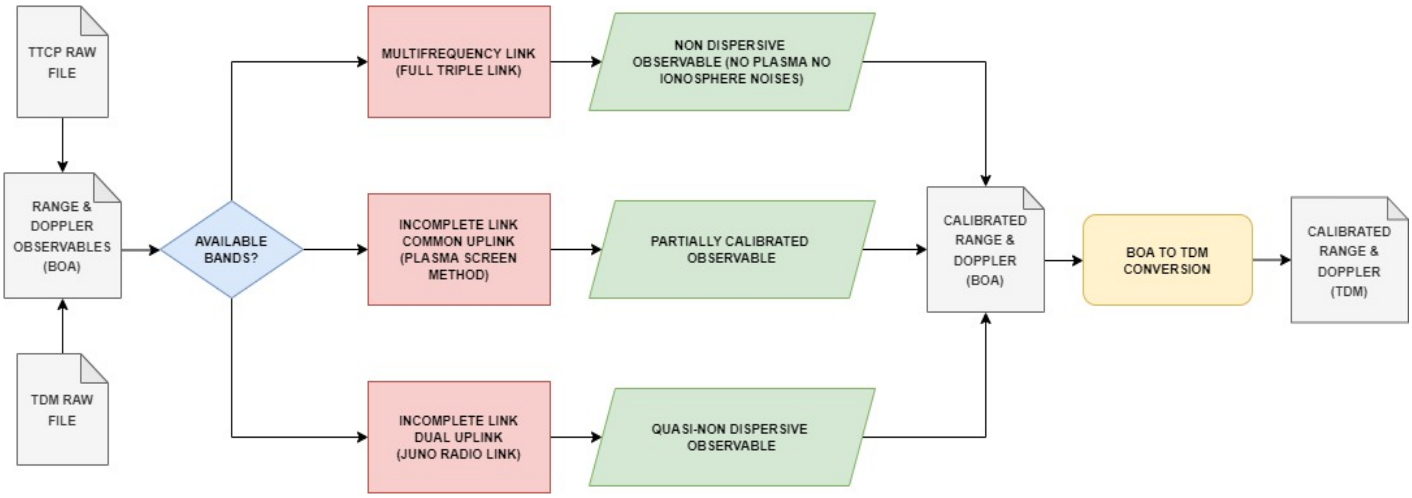


Figure 14: Multifrequency Link Block

The software can run various calibration schemes with respect to the number of bands available.

B.1.2.1.1 Full triple link

When the input consists of three different bands (BepiColombo's full radio link is active), the software processes the X/X, X/Ka, Ka/Ka observables using the full multifrequency link equations, which provide a total calibration of both uplink and downlink plasma and ionospheric noise.

Three observables are needed for a complete removal of the dispersive noise, since the sky observable actually received by the ground station y_{OBS} is the sum of three operands:

$$y_{OBS} = y_{ND} + \frac{P_U}{f_U^2} + \frac{P_D}{f_D^2}$$

For the sake of accuracy in the orbit determination process, the so-called "non-dispersive" observable y_{ND}, free from the interplanetary medium and Earth ionosphere influence, must be isolated from the uplink (P_U) and downlink (P_D) contribution affecting the signal due to the propagation through the dispersive medium.

Using three observed sky frequencies (or range data) makes possible the construction of a 3x3 equation set that can be easily inverted in order to calculate y_{ND} :

$$y_{X/X} = y_{ND} + y_U + \frac{y_D}{\alpha^2_{X/X}}$$

$$y_{X/Ka} = y_{ND} + y_U + \frac{y_D}{\alpha^2_{X/Ka}}$$

$$y_{Ka/Ka} = y_{ND} + \frac{y_U}{\beta^2} + \frac{y_D}{\beta^2 \alpha^2_{X/Ka}}$$

Where the α coefficients indicate the turn-around ratios used in phase-coherent two-way radio links (f_D/f_U), and β the Ka/X uplink frequency ratio. y_U and y_D are equal to P_U and P_D divided by f_U^2.

The system finally results in:

$$y_D = \frac{y_{XX} - y_{XKa}}{\alpha^{-2}_{XX} - \alpha^{-2}_{XKa}}$$

$$y_U = \frac{y_{XKa} - y_{KK} - y_D \cdot \left(\alpha^{-2}_{XKa} - \beta^{-2}\alpha^{-2}_{KK}\right)}{1-\beta^{-2}}$$

$$y_{ND} = y_{KK} - \beta^{-2}\left(y_U + \alpha^{-2}_{KK} \cdot y_D\right)$$

Using this algorithm, the dispersive noise contribution to the error budget becomes negligible, at least for observables received sufficiently away from superior solar conjunction conditions (signal impact parameter must be longer than 4-5 solar radii). The calibrations gets less and less accurate as the SEP angle narrows, since several higher-order effects in the solar wind and corona (magnetic refraction, diffraction, dispersive displacements of the RF beams) become non-negligible.

B.1.2.1.2 Dual uplink incomplete link

Whenever the probe needs to save power it is possible to shut down the X/Ka cross-link, while retaining a good degree calibration by using the “incomplete link – dual uplink” calibration scheme, that uses only the X/X and Ka/Ka information.

Only one of the two-way plasma contributions can be removed with the available data, so this calibration scheme generates a near-optimal observable y^*, that also contains the lowest possible amount of the other noise contribution.

The most effective calibration is achieved choosing the uplink plasma signal as the one to be removed:

$$y^* = \frac{\beta^2 y_{KK} - y_{XX}}{\beta^2 - 1} = y_{ND} + \frac{\left(\alpha^{-2}_{KK} - \alpha^{-2}_{XX}\right)}{\beta^2 - 1} y_D \cong y_{ND} + 0.02 y_D$$

Thanks to the Ka/Ka band the calibration is still very effective and its performance is very close to the triple link one.

B.1.2.1.3 Single uplink incomplete link

A third scenario is considered, although it is not encountered during normal operations of the mission, but can be used to provide a minimum level of calibration in case of MORE KaT failure or during BepiColombo’s operations on ESA ground stations (currently not capable of a Ka-band uplink). This calibration is referred to as “incomplete link – common uplink”, and can achieve noise levels only slightly better than the X/Ka band alone.

With this type of combination, only one of the plasma noise contributions can be computed analytically (the downlink one, P_D) so the other must be modelled.

Two alternative hypotheses can be made to design the expected uplink noise content: the simplest is to assume that the charged particles are concentrated in a single layer with no thickness (similar to the Ionospheric Point (IP) model used for ionospheric calibration), so the signal is affected by the same plasma content in both transmission legs, with the only difference being a delay between the P_D and P_U time series, depending on the supposed position of the layer, that varies with the SEP angle

SEP < 90° $$y_U(t) = y_D\left[t - \left(RTLT - 2\frac{AU}{c}\cos(SEP)\right)\right]$$

SEP > 90° $$y_U(t) = y_D(t - RTLT)$$

Regardless of which of these two cases applies, the incomplete link scheme is unable to determine the very first segment of the uplink plasma shift (as there is no corresponding downlink signal to be used to infer information on the uplink plasma noise).

Hence that portion of radiometric data will not be calibrated for the uplink plasma contribution, and must be discarded.

The second algorithm that can be used for this type of link statistically determines the uplink plasma using the correlation function of electron content distributions between two points in space at different distances from the Sun, starting from the downlink plasma time series.

A Wiener filter transfer function H(ω) is constructed in the frequency domain by dividing the uplink-downlink cross-correlation spectrum S_{UD} by the downlink autocorrelation spectrum S_D:

$$H(\omega) = \frac{S_{UD}(\omega)}{S_D(\omega)} = \int_0^L g_n(\eta)\, e^{-2i\omega(L-\eta)}\, d\eta$$

Where η is the coordinate along the LoS, *L* the ground-station to spacecraft one-way light-time, and

$$g(\eta) = \left[1 + \eta^2 - 2\eta\cos(SEP)\right]^{-2}$$

After computing the filter transfer function, the time-domain convolution

$$y_U(t) = y_D(t) * F[\mathrm{H}(\omega)]$$

yields the uplink plasma estimate to be used to calibrate the sky observable.

Considering the plasma content as spread throughout the entire line of sight theoretically guarantee a better calibration, especially for wide SEP angles (approaching this condition the layer hypothesis becomes an unfit representation of the interplanetary environment), but the application of both common uplink algorithms to Cassini's Doppler data showed a very marginal difference in calibration effectiveness between the two.

Finally, it has to be noted that when the common uplink calibration scheme is used, a preliminary removal of ionospheric noise is advised.

Input	Doppler or range observables transmitted using various bands available on the spacecraft
Output	A single "synthetic" observable (referred to a user-defined band, typically X/X) that is (to some extent, depending on the input) free from dispersive noises

B.1.2.2 Tropospheric noise calibration

The main tropospheric calibration procedures are depicted in the figures below:

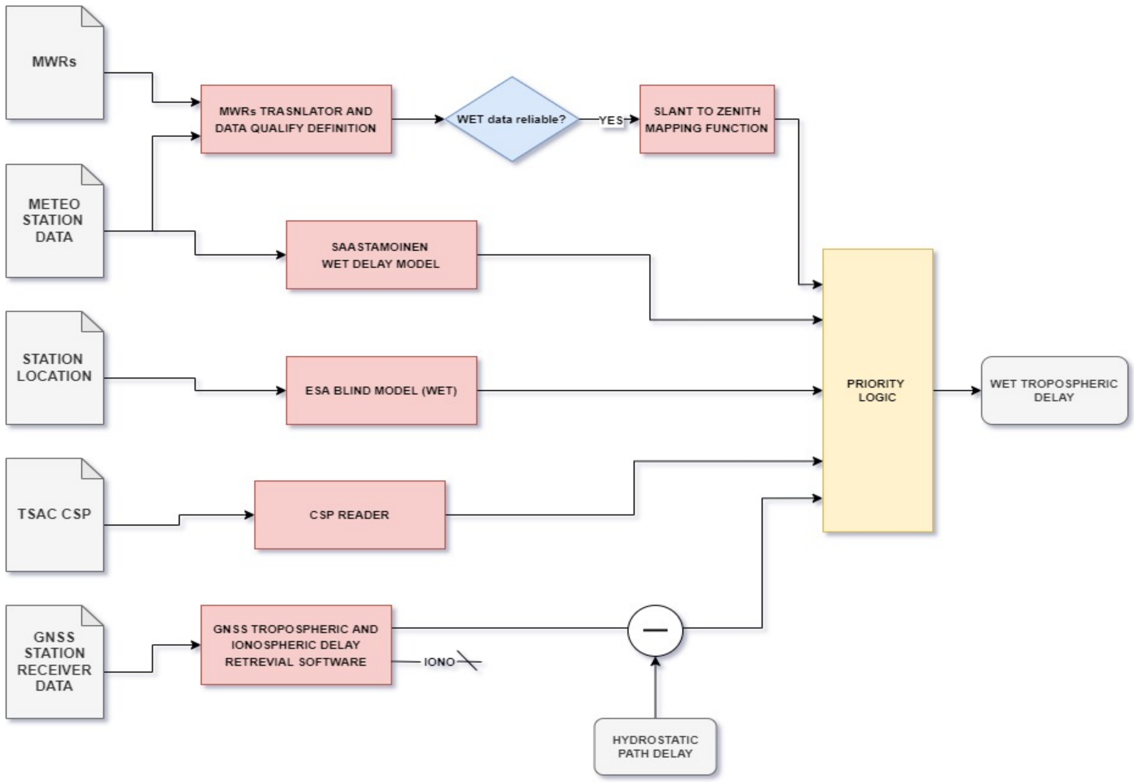


Figure 8: Wet tropospheric delay calibration block

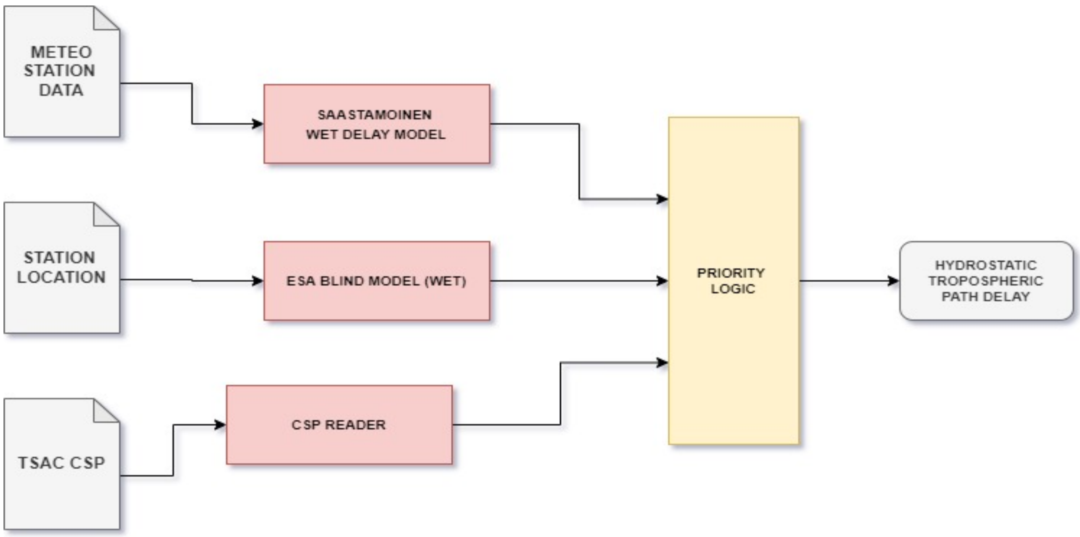


Figure 9: Hydrostatic tropospheric path delay calibration block

The TSAC/MVR to TDM Troposphere Translator is used by the UniBo Team for the conversion of the tropospheric data provided by the Tracking System Analytic Calibration (TSAC) group and from the radiometers, to the TDM format.

This library includes:

- TSAC identifier
- MVR identifier
- Validator
- A Tropospheric/MVR Reader that loads data fields in a workspace.
- TDM writer

Input	TSAC ionospheric calibrations, conforming to the Command Statement Processor (CSP) English-like command language used by the Orbit Determination Program (this language is described in [RD.07]. Tropospheric calibrations are currently given by a normalized power series representing the seasonal variations plus punctual corrections as computed by processing GPS observables. Two series are given for each station or complex: the "dry" and "wet" components of one-way zenith range delay in meters. The format for the JPL WVR calibrations is a tabulated ASCII (TBC) **Error! Reference source not found.**
Output	TDM file containing 'wet' and 'dry' delay information in 'km' units with six decimal figures (TBC) and ancillary data [RD.04], [RD.05].

B.1.2.2.1 Troposphere models

Both components of the troposphere path delay are obtained using simple formulations based upon the International Standard Atmosphere and statistical observations of atmospheric parameters such as pressure, temperature, density, and their influence on the media refractivity.

The two models in use by the pre-processing software are the ESA GALILEO Blind model and the Saastamoinen model. Both consist of a wet and a hydrostatic formulation, with a non-negligible difference in accuracy between the two.

In fact, while the hydrostatic equilibrium assumptions fits the dry part of the troposphere, the water vapour content is quite unstable, resulting in a relatively poor accordance of the model with actual data, although the wet path delay represents only a small fraction of the total.

The Saastamoinen model is very popular for atmospheric path delay computation, carried out starting from the ideal gas law and rewriting the pressure and temperature as function of the surface values and the lapse rates.

The dry atmosphere is considered in hydrostatic equilibrium, while the gravity is a function of the height rather than a constant: a differential equation can be constructed for the dry refractivity index, that can be integrated yielding

$$\mathrm{ZHD} = \frac{0.0022767\left[\frac{\mathrm{m}}{\mathrm{hPa}}\right]\cdot \mathrm{p_0}}{1-0.002266\cdot\cos 2\varphi - 0.00028\left[\frac{1}{\mathrm{km}}\right]\cdot \mathrm{h}}$$

given the surface pressure $\boldsymbol{p_o}$, the geodetic latitude $\boldsymbol{\varphi}$ and the height $\boldsymbol{h}$.

For the wet part of the computation, the Saastamoinen model reads (with $\boldsymbol{T_o}$ and $\boldsymbol{e_o}$ as surface temperature and water vapour content):

$$\mathrm{ZWD} = 0.0022768\left(\frac{1255}{273.15+\mathrm{T_0}}\right)\mathrm{e_0}$$

Using the readings of a meteorological station placed nearby the tracking facility, the path delays are computed with this model. Whenever these data are unavailable, a "blind" formulation (that makes some assumption about these values depending upon the station coordinates and the season) is needed.

The ESA Blind model is based upon the ECMWF ERA15 collection of atmospheric data statistically weighted and gathered in a world map (resolution: 1.5 degrees in latitude and longitude, 31 height layers, 6 hours intervals in a single day), that can link the station location to a mean value of these atmospheric values, and hence to path delays.

Each meteorological parameter (pressure, temperature, water vapour pressure, etc. indicated as ***X***) is modelled using a seasonal contribution (dependent upon the day of the year ***DOY***), along with a diurnal contribution (relative to the hour of the day ***HOD***):

$$X_{seas}(DOY) = a_1 - a_2 \cdot \cos\left[\frac{2\pi}{365.25}\left(DOY - a_3\right)\right]$$

$$X_{diur}(DOY, HOD) = X_{seas}(DOY) - b_2(DOY) \cdot \cos\left[\frac{2\pi}{24}\left(HOD - b_3(DOY)\right)\right]$$

Using these parameters the path delays can be computed: the hydrostatic one is yielded by the Saastamoinen formula, while for the wet model:

$$ZWD = 10^{-6} \frac{k_3}{T_m} \frac{R_d}{g_m} \frac{e_0}{\lambda + 1}$$

where $\boldsymbol{k_3}$ is the refraction coefficient, $\boldsymbol{R_d}$ the gas constant for dry air, $\boldsymbol{g_m}$ the weighted mean gravity acceleration, $\boldsymbol{T_m}$ the mean temperature, $\boldsymbol{e_o}$ the surface water vapour pressure, $\boldsymbol{\lambda}$ the water vapour lapse rate.

This approach offers a good backup calibration whenever other methods are unavailable (one can note that every other calibration requires some kind of hardware on the tracking site: GNSS receivers, radiometers, meteorological stations).

Inputs	Meteorological station readings, station coordinates, date
Outputs	Zenithal wet and dry path delays.

B.1.2.2.2 Microwave radiometers calibration

When operated in optimal conditions, microwave radiometers provide information on the slant wet path delay with the highest obtainable precision, by measuring the brightness temperature of the sky crossed by the RF signal.

In 2002 and 2003 a series of gravitational waves experiments involving the Cassini spacecraft were scheduled. In order to satisfy the radio link stability requirements for these experiments, JPL developed a newly ultra-stable WVR in order to remove the troposphere effect within Doppler observables up to an Allan Deviation level smaller than $3 \cdot 10^{-15}$ s/s at 1000 s of integration time. This novel instrument was included in the so-called Advanced Media Calibration system (AMC).

The current technology of MWR available to ESA is the ATPROP Ka-band radiometer, which is equipped with a Dicke switch sensor and features fourteen channels: six in the water vapour line, one in the liquid water line, seven in the oxygen line plus an additional channel at 15 GHz and one at 90GHz.

The ATPROP MWR is a state-of-the-art instrument which allows the estimation of the vapour and the liquid content of the atmosphere, the temperature profile and the presence and the base of clouds, however it was not designed for radio science purposes, but for LEO and GEO telecommunications.

A new generation of radiometers (larger beam width, total power receiver paired with the Dicke switch, enhanced side-lobe suppression, and more precise pointing control) is currently under development to overcome the limitations of the ATPROP when applied to radio science.

The information output by this equipment is, however, very dependent on the weather conditions experienced by the site, and MWR readings become not reliable when clouds and precipitations (liquid water, in general) are present along the instrument LoS.

This behaviour implies the need for a quality check mechanism on the MWR information according to meteorological reports for the station site, obtained by various sources, including the MWR output file itself if a "meteo" field is present (JPL AWVR files currently report this type of information).

While the output format of NASA AWVR is well known, the one for next generation ESA MWRs is currently TBD, so the reading program logic can be liable for further modifications.

The quality algorithm must weight or reject MVR data in favour of GNSS calibration if the liquid water levels affecting the reading are beyond operational thresholds. The exact weighting criteria are still TBD.

Since the path delay obtained by the instrument is the one in the LoS direction (slant), a mapping function gives the corresponding value on the station zenith direction. This function requires at least the spacecraft elevation as input, and several formulations with different orders of complexity and required inputs are available.

Inputs	MVR path delay readings, meteorological condition on station site (clouds and precipitations), spacecraft elevation.
Outputs	Zenithal wet path delay.

B.1.2.3 Ionospheric noise calibration

The ionospheric path delay calibration pipeline is represented below:

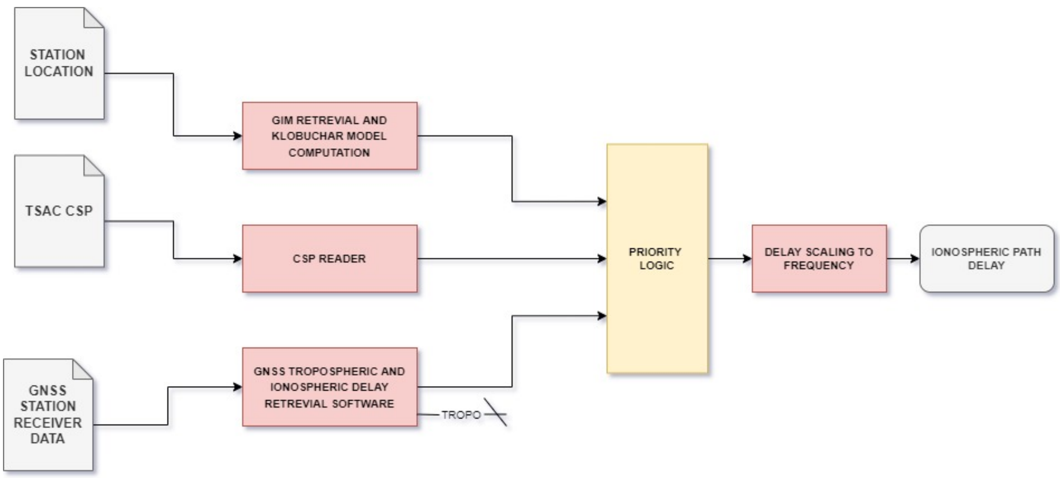


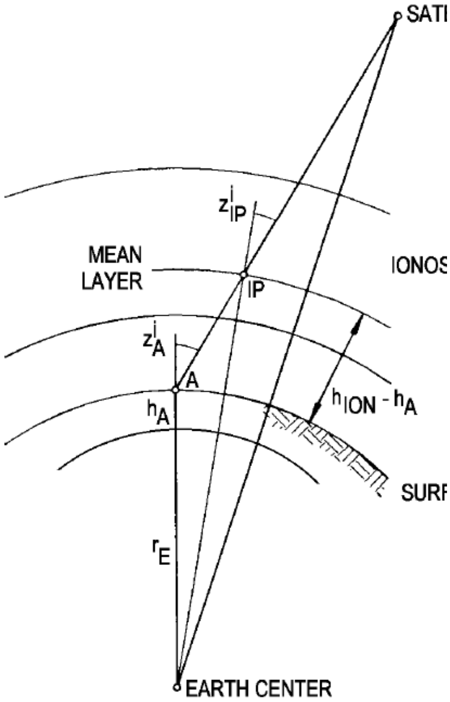
Figure 10: Ionospheric path delay calibration block

B.1.2.3.1 Ionosphere models

If neither GNSS data or TSACs are available, the ionospheric path delay can be modelled by means of the Hoffman-Wellenhof formulation, which is an improved version of the Klobuchar model.

With the assumption of a layer-wide ionosphere (placed at an average altitude of about 300-500 km, while it is in fact spread in a range of 50-1000 km), it is possible to define and place a so-called "Ionospheric Point"

(IP) that represents the point where the RF beam instantaneously crosses the ionospheric layer, and is affected by the whole ionospheric delay at once.



The proposed technique can be summarized by three steps.

The first step is the definition of the zenith angle between the station and the satellite:

$$cos\ z_A^i = \frac{\cos\varphi_A \cos\lambda_A \Delta X_A + \cos\varphi_A \sin\lambda_A \Delta Y_A + \sin\varphi_A \Delta Z_A}{\rho_A^i}$$

where $\boldsymbol{\varphi_A}$, $\boldsymbol{\lambda_A}$ are the station latitude and longitude, respectively and $\boldsymbol{\Delta X_A^i}$, $\boldsymbol{\Delta Y_A^i}$, $\boldsymbol{\Delta Z_A^i}$ are the geometric distance components.

Then the IP zenith angle is defined as:

$$sin\ z_{IP}^i = \frac{r_E + h_A}{r_E + h_{ION}} \sin z_A^i$$

Defining the Earth centred angle as (angles are expressed in semicircles):

the IP latitude and longitude can be obtained:

$$\lambda_{IP} = \lambda_A + \frac{\psi \cos \alpha_A}{cos\ \phi_{IP}}$$

Combining the coordinates of the IP with broadcast GIM maps (found in the IONEX IGS product, which contains the Vertical Total Electron Content of the ionosphere on a 73x73x13 space-time grid spaced by 2.5° in latitude and 5° in longitude, with a time interval of 2 hours) the total VTEC relative to the tracking station can be retrieved and used in the estimation of the delay using the first order approximation:

$$\delta_{ion} = \frac{40.30}{f^2} \cdot m_{ion} \cdot VTEC$$

Note that the delay is scales with the carrier frequency. This operation is conducted by a dedicated routine reported below.

A simple projection mapping function can be applied starting from the z_{IP} value (several more accurate mapping functions are implemented such as the geometric or the ellipsoidal ones [RD.08]):

$$m_{ion} = \frac{1}{cos\ z_{IP}}$$

The described program is also capable of estimating the second order component of the delay ($\propto f^{-3}$), using the geomagnetic coordinates of the IP.

With this formulation an abatement of about a half of the ionosphere noise level can be achieved.

Inputs	Station coordinates, spacecraft elevation and azimuth.
Outputs	Ionospheric path delay.

B.1.2.3.2 Ionospheric path delay scaling routine

If the ionosphere PD is calculated, its amount is valid only for a specific carrier frequency, due to its dispersive nature, and this frequency varies with respect to the source of the calibration.

GNSS retrieves delays on the L1 and L2 GPS bands, while JPL's TSAC files are referred to a standard S-band frequency. A specific routine homogenizes the various ionosphere information, scaling the values so that the output TDM is compiled with data at the same reference band regardless of the calibration used.

A further scaling to the actual observables uplink and downlink frequencies must be carried out inside the orbit determination program, since it is not possible to accomplish this task during the pre-processing stage if ramped uplinks are in use (uplink frequency values are dependent upon the RTLT calculated with the light-time solution).

Inputs	Ionospheric path delay.
Outputs	Ionospheric path delay scaled to a specific reference frequency.

B.1.2.4 GNSS Tropospheric and Ionospheric Software

By using GNSS observables and a dedicated software, it is possible to estimate Tropospheric and Ionospheric path delays affecting observables using a "double differences" approach, applied to a network of GNSS receivers.

This is possible since a GNSS signal traveling towards a receiver positioned nearby the deep space equipment crosses the same atmosphere of the probe RF signal.

A GPS antenna ***A*** that tracks a satellite ***j*** receives a pseudo-range code P_A^j modulated on a carrier with a phase L_A^j . Both are the combination of several contributions:

$$P_A^j = \rho_A^j + c\left(dt_A - dt^j\right) + \delta_{rel,A}^j + T_A^j + I_A^j + K_A^j + M_A^j + \delta_{tide,A} + \varepsilon_A^j$$
$$L_A^j = \rho_A^j + c\left(dt_A - dt^j\right) + \delta_{rel,A}^j + T_A^j + I_A^j + B_A^j + K_A^j + M_A^j + \delta_{tide,A} + w_L + \varepsilon_A^j$$
,

with:

- **ρ** is the geometric range between satellite and receiver
- **dt** is the clock offset with respect to GPS time
- **T** is the tropospheric delay
- **I** is the ionospheric delay, scales with the band (L1 or L2)
- δ_{rel} is the relativistic error
- δ_{tide} is the receiver position offset due to solid and polar tides
- **K** represents instrumental errors
- **M** is the multipath effect, scales with the band
- w_L is the "wind-up" effect on the polarization of the wave
- **B** is the phase ambiguity

By inverting these equalities one can retrieve ***I*** and ***T*** data, but in order to do so a removal of the other phenomena must take place. Several can be removed using dedicated prediction models or information by IGS, CODE and similar agencies.

This calibration however has its own level of accuracy and this is directly reflected into the accuracy of the overall estimation. This problem can be addressed by comparing observables received by different stations and transmitted by different GNSS spacecraft: this approach performs a direct removal of several noise terms so no additional error is transferred to the result.

The double difference method implies that two GNSS receivers ***A*** and ***B*** are in view of two satellites ***i*** and ***j*** at the same time, and then calculates:

$$\nabla\Delta P_{AB}^{ij} = \left(P_A^i - P_B^i\right) - \left(P_A^j - P_B^j\right) = \nabla\Delta\rho_{AB}^{ij} + \nabla\Delta T_{AB}^{ij} + \nabla\Delta I_{AB}^{ij} + \nabla\Delta\varepsilon_{AB}^{ij}$$
$$\nabla\Delta L_{AB}^{ij} = \left(L_A^i - L_B^i\right) - \left(L_A^j - L_B^j\right) = \nabla\Delta\rho_{AB}^{ij} + \nabla\Delta T_{AB}^{ij} + \nabla\Delta I_{AB}^{ij} + \nabla\Delta\varepsilon_{AB}^{ij} + \nabla\Delta B_{AB}^{ij}$$

In the described estimation software, the ionospheric delay is removed previously from the non-differenced data, and the phase biases are removed thanks to dedicated algorithms such as the LAMBDA method.

Since every addend is now a differential value, we need to know with a high degree of accuracy the information for these values with respect one of the stations, which is caller *Master,* while the other one is regarded as *Rover*.

In this application a network of receivers will be constructed, consisting of the Deep Space tracking centre as the rover station, while several EUREF or IGS sites will be our Master stations (accurate information is available for each one of them inside the IGS products). Also the satellite ***j*** is considered as reference, and is usually chosen among the ones at highest elevation over the rover site.

Once the double-differenced observables are created, the estimation of the desired time series is carried out by a linearization of the geometric distance ρ around a guess value for the rover station position

$$\nabla\Delta\rho_{AB}^{ij} = \nabla\Delta\rho_{AB,0}^{ij} + \left(e_{x,A}^{ij}dx_A + e_{y,A}^{ij}dy_A + e_{z,A}^{ij}dz_A\right) - \left(e_{x,B}^{ij}dx_B + e_{y,B}^{ij}dy_B + e_{z,B}^{ij}dz_B\right)$$

If A is the reference station, then the error components for its positions are zero.

Bringing the initial guess value for the geometric distance at the left-hand side along with the random error term, and then using an equation for every satellite in view at a certain instant, for each of the four observables (P1/C1, P2/C2, L1, L2) we have the final set:

$$\begin{bmatrix} \nabla\Delta R^{1j}_{P1,AB} \\ \vdots \\ \nabla\Delta R^{ij}_{P2,AB} \\ \vdots \\ \nabla\Delta R^{ij}_{L1,AB} \\ \vdots \\ \nabla\Delta R^{nj}_{L2,AB} \end{bmatrix} = \begin{bmatrix} e^{1j}_{x,B} & e^{1j}_{y,B} & e^{1j}_{y,B} & m(el^{1j}_{A}) & -m(el^{1j}_{B}) \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ e^{ij}_{x,B} & e^{ij}_{y,B} & e^{ij}_{z,B} & m(el^{ij}_{A}) & -m(el^{ij}_{B}) \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ e^{ij}_{x,B} & e^{ij}_{y,B} & e^{ij}_{z,B} & m(el^{ij}_{A}) & -m(el^{ij}_{B}) \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ e^{nj}_{x,B} & e^{nj}_{y,B} & e^{nj}_{z,B} & m(el^{nj}_{A}) & -m(el^{nj}_{B}) \end{bmatrix} \begin{bmatrix} \mathrm{dx}_{B} \\ \mathrm{dy}_{B} \\ \mathrm{dz}_{B} \\ \mathrm{ZTD}_{A} \\ \mathrm{ZTD}_{B} \end{bmatrix} .$$

The Zenith Tropospheric Delay for the rover and Master station have been isolated using the identity

$$\nabla\Delta T^{ij}_{AB} = \left(m(el^{i}_{A})ZTD^{i}_{A} - m(el^{i}_{B})ZTD^{i}_{B}\right) - \left(m(el^{j}_{A})ZTD^{j}_{A} - m(el^{j}_{B})ZTD^{j}_{B}\right)$$

$$m(el^{ij}_{A}) = m(el^{i}_{A}) - m(el^{j}_{A})$$

where $\boldsymbol{m}$ is the mapping function.

The equation set is finally solved for the tropospheric delay using a Kalman filter or a least squares approach. Note that the same methodology can be followed for the ionospheric delay estimation.

The software can be divided in two stages:

- The PRE-PROCESSING section:
  - automatically retrieves all needed IGS products, such as SP3 and RINEX files, if available for the tracking station, and loads the relative data (observables, satellites orbits, station locations…) into memory
  - calibrates the GNSS phase and pseudorange observables for ionospheric delay (or tropospheric, depending upon the computation), antenna phase offsets, solid tides and other undesired effects
  - performs the “double difference” operation on the observables
  - performs cycle slips detection and phase biases removal
- the PROCESSING section:
  - linearizes the position of the rover
  - builds the set of equations for each timetag of the tracking pass
  - solves the set through Kalman filtering, estimating the path delay

Depending on which delay is required as output, the other one can be considered as a parameter and removed from the double differenced observables using a calibration.

The tropospheric path delay represents the sum of the dry and wet contributions, because when using GNSS processing it is not possible to discriminate between the two components: this separation must be performed by comparing the output with the result of a hydrostatic model (even before the creation of the final equation set). Furthermore, by isolating the mapping function for each satellite-station combination, the path delay computed with this routine is zenithal, to be later mapped onto BepiColombo’s elevation value.

Inputs	Time span of tracking data and station name. If the tracking station GNSS receiver is not listed in the IGS network, the relative RINEX data and station coordinates must be provided. Users can also define which stations are part of the computation network.
Outputs	Ionospheric and Total Tropospheric Path Delays affecting radio signals received by the station.

B.1.2.4.1 TSAC CSPs

TSACs are CSP cards emitted by the JPL and cover NASA DSN stations, providing path delays. These data can be used by the pre-processing software if the observables are received by a DSN complex.

CSP cards consist of three fields: the DRY path delay, computed by a Saastamoinen model, the WET path delay, computed by differencing the GIPSY GNSS s/w output with the above results, and the ionospheric path delay also computed by GIPSY.

A dedicated reader routine is used to load the information into the workspace.

B.1.2.5 Calibration Priority List

According to the features of the various troposphere calibration schemes reported in this document, and their accuracies, a priority system can be defined to choose which method is to prefer.

The amount of hydrostatic delay can be modelled with good accuracy by the Saastamoinen model, so this source is to be preferred against the blind model if meteo-station data are available.

If the tracking station is covered by JPL TSAC files, this information is the same of the Saastamoinen model for the hydrostatic component.

DRY PATH DELAY PRIORITY

a) **TSAC / SAASTAMOINEN (whichever is available)**
b) **ESA GALILEO Blind Model**

MWRs are at present the best source of calibration for the wet path delay, but their values are not reliable if clouds or rain are present during the pass, so the GNSS program output have the highest (on average) “all-weather” accuracy.

Since the wet path delay field of TSACs is compiled using GIPSY (the GNSS software used by JPL), this calibration card shares the same level of accuracy.

Saastamoinen and blind models are the least accurate methods (as explained in the relative sections above) so they should be used only as backup.

WET PATH DELAY PRIORITY

a) **MWR (if reliable)**
b) **GNSS / TSAC (if available)**
c) **SAASTAMOINEN Model (if meteo data are available)**
d) **ESA GALILEO Blind Model**

For ionosphere calibration the best accuracy is achieved by the multifrequency link plasma calibration, as already stated, so the ionosphere block should be bypassed if the full triple link (or the “dual uplink” incomplete link) is available. Otherwise, the GNSS calibration is to be preferred.

IONOSPHERIC PATH DELAY PRIORITY

a) **MULTIFREQUENCY LINK (bypass ionospheric calibration)**
b) **GNSS SOFTWARE / TSAC**

c) **KLOBUCHAR MODEL**

B.1.3 BOA to TDM conversion

At the end of the various calibration processes the calibrated BOA files are converted to TDM files. The TDM structure is composed by an initial header, which gives some general information about the entire file. The information given by the header are common to all the different subsections of the file itself. After the header we can find some subgroups, which may contain different kinds of data observables, and each of this group is labelled with a specific header and presents a group of data of different kind. The TDM file's format will be discussed in deep in section **Error! Reference source not found.**.

B.2 On-ground calibration

Before launch, different tests have been conducted on the two transponders to measure the delays they introduced at different ambient conditions. While the KaT also provides an in-flight calibration system, for the DST the on-ground measurements are the only reference used for the data calibration process.

All the data collected during the on-ground calibration campaign are stored into the technical documents reported below:

Reference ID	Title	Content	Version
BC-ALS-MO-0000XX	DC Magnetic Test Report of MORE KaT EQM	Measurement of the magnetic signature of the MORE KaT EQM	MEMO
BC-ALS-RP-00066	BepiColombo ETA MPO Thermal Analysis Report	Thermal analysis report for MPO	Issue 6
BC-ALS-RP-00287	Functional and Performance test report and engineering evaluation – COMMS INTEGRATED SYSTEM TEST (IST)	Test report for COMMS integrated system (IST)	Issue 4
BC-ALS-RP-00318	Functional and Performance test report – COMMS TBTV TEST RESULT	Test report for COMMS subsystem during MPO TBVT campaign	Issue 3
BC-ALS-TN-00058	ETA Radio Science Experiment RF Performances Technical Note	Test report for performances of BepiColombo RSE	Issue 5
BC-ALS-TR-00096	BepiColombo PFM ETA Alignment measurement test report	Test report for alignment measurements for PFM	Issue 4
BC-MRE-PL-00017	MORE KaT EM TEST PLAN	KaT test plan for Engineering Model	Issue 2
BC-MRE-RP-00147	MORE KaT S/N 003 FM EMC TEST REPORT	Test report, EMC KaT for MORE	Issue 1
BC-MRE-TP-00144	MORE KaT Test Plan and Procedures	Test plan and procedure for the KaT	Issue 1
BC-MRE-TR-00136	MORE KaT Test Report	Test report, KaT for MORE in Initial Performance Test IPT, Vibration Test, Thermal Vacuum TVAC, EMC Test, Final Performances Test FPT	Issue 1
BC-MRE-TR-00171	KaT FS Test Report	Test report, MORE KaT flight spare from qualification model	Issue 1
BC-MRE-TR-00184	MORE KaT PENALTY TEST – TEST REPORT	Test report, MORE KaT Penalty Test Matrix	Issue 1
BC-MRE-UM-00150	MORE KaT FM User Manual	User manual for the KaT	Issue 3
BC-TAR-TR-00097	BepiColombo X-X-Ka	Electrical Test Report for DST	Issue 1

	Transponder FM1 Electrical Test Report		
ESA-GRST-SYS-TN-0005	Methods and practices for deriving the station delay for ranging calibration measurements	Ground station delay determination, ranging measurement systems	Issue 2
GAIA-ESC-TN-0053	DSA Ground Station Delay Measurement	This document describes the DSA Ground Station Delay Measurement	Issue 1_draft

B.3 In-flight calibration

The calibration procedure described in detail in section 3.1 for the MORE case in intended as the in-flight calibration procedure.

B.4 Science Data Quality Control

This section describes the different processes by which the archive data products are validated.

B.4.1 Validation

Prior to the delivery of the data to the archive, every data product is validated to check that it conforms to a basic set of requirements, as defined in the BepiColombo Archiving Guide [AD.02]. This is done using the NASA's PDS4 validate tool, and a set of XML Schema and Schematron files.

In addition, the SGS performs completeness and integrity checks on the MORE science data to ensure that they comply with the specifications described in this EAICD. Visual inspection is used as necessary to check the content.

B.4.2 Instrument Team Validation

In parallel to SGS archive validation activities, PI teams routinely assess archive products as part of the operational quality control. In addition, PI teams use archive products for their analysis throughout the mission lifetime. This enables rapid detection and correction of issues in the archive data.

This section will include details of the validation performed by the PI team on the science data, as part of the routine operational quality control.

B.4.3 Science Reviews

Formal science reviews of the data will be organised by the SGS, in coordination with the Project Scientist. These are the so-called Peer Reviews. The Peer Review committee will include independent planetary scientists knowledgeable in each discipline to assess the quality of the data against well-defined scientific criteria. A preliminary schedule of the reviews can be found in the BepiColombo Archiving Plan [AD.01]. Additional review will be organised as necessary.

There will be a preliminary review approximately 2 months before Launch and 2 months prior to the start of the science phase. This review will contain sample data and documentation in the format of the final archived data set. The sample data will be produced using datasets from the flight instrument checkout activities that differ from the final data set only in specific values and sizes. Data formats and data processing and archiving methods are identical.

ANNEX C DATA DELIVERY SCHEDULE

The data delivery performed during the mission is composed by:

Delivery date	***Data content***	***Data timespan***
2021-05	Raw files: - ESA/TTCP - ESA/RDEF - GNSS/CSP - TDCS/CSP	From beginning of mission to 2021-05-27
2022-03	Raw files: - ESA/TTCP - ESA/RDEF - GNSS/CSP - TDCS/CSP	From 2021-05-27 to 2022-03-09

Table 3 Data delivery table.

This part of the document is meant to be updated with new information throughout the mission.

END OF DOCUMENT