SP-1291
June 2009

→ MARS EXPRESS

The Scientific Investigations

European Space Agency

OPERATIONS AND ARCHIVING

Spacecraft and Payload Data Handling

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The success of a scientific mission is determined by the quality of the scientific results. The prompt delivery of instrument and ancillary raw data to the instrument teams and of reduced and calibrated data to the scientific community is therefore a key element in the mission design. This chapter describes the flow of data from the spacecraft through the ground segment via the instrument teams to the final scientific archive. Several software tools and standards are used to support data dissemination. The functionality of the individual tools is explained, the interfaces to the individual groups are discussed, and examples of the graphical user interfaces are shown. Finally, the chapter provides a brief introduction to each of the currently available datasets.

1. Introduction

A large number of teams and individuals are involved in processing data from the byte packages on the Mars Express (MEX) spacecraft, to provide scientifically useful, reviewed datasets to the scientific communities. Although the various teams have different responsibilities, all of them aim to deliver complete, accurate sets of information. The information dealt with is diverse, covering, for example:

— spacecraft and instrument documentation;
— ancillary data such as spacecraft event information, instrument mounting alignments;

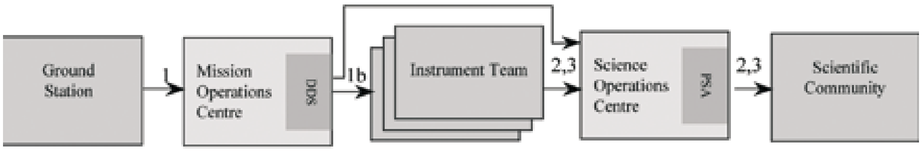


Fig. 1. The data flow from the ground station in New Norcia, Australia, to the scientific community. The numbers above the arrows indicate the data processing levels. Iterations that might occur in the data flow are not indicated.

— spacecraft orbit and attitude information;
— environment information such as spacecraft temperature or electron densities;
— spacecraft anomalies;
— instrument housekeeping and scientific data;
— instrument calibration information;
— science operations planning information; and
— geometric and positional information.

The ground segment includes the receipt of the spacecraft data, delivery to the Missions Operations Team at the European Space Operations Centre (ESOC) in Darmstadt, Germany, and the provision of all spacecraft and instrument data to the instrument teams. ESOC provides data that have been corrected to remove any errors arising during transmission from the spacecraft to the ground station.

Each instrument team obtains spacecraft and ancillary data of interest and instrument data from the Data Distribution System (DDS) located at ESOC. The ongoing data distribution, analysis and validation depend on the internal structure of each team, the data volume and the type of housekeeping and scientific data. The data path varies for each team, and is described individually in the relevant chapters of this volume. The instrument teams reformat their raw and calibrated data into more user-friendly formats following the Planetary Data System (PDS) standard (JPL, 2006). Also the ancillary data originating from the Mission Operations Centre (MOC) is formatted following the PDS standard by the archive team of the Mars Express Payload Support Team (MEXPST). The datasets are delivered online to the ESA archive team. After a first syntactical check, the datasets are peer-reviewed and are ingested into the Planetary Science Archive (PSA) after they have been successfully reviewed. Scientists, engineers and the public can access and search the PSA server and retrieve datasets or individual data products.

Figure 1 illustrates the flow of data between the relevant parties. The darker shaded boxes within the MOC and SOC PST represent software applications that are available online, in the case of the DDS for the experimenter teams, and in the case of the PSA for the entire scientific community. The numbers above the arrows indicate the data processing level of the data products, as defined in Table 1. The processing levels indicate the level of data reduction.

The handling and flow of data from the Beagle 2 instruments were planned to be in parallel to the Mars Express orbiter instrumentation data flow (Pullan et al., 2004). The Beagle 2 Lander Operations and Control Centre (LOCC), Leicester, UK, was prepared to process all instrument data into PDS-compatible format after downloading from the DDS at the MOC. After a proprietary period, it was planned to enter all the data into the PSA.

This chapter provides an overview of the flow of data from level 1 to level 3. As the processing of data at levels 2 and 3 are instrument dependent, see the individual instrument chapters in this or earlier ESA publications for details. Section 2 gives an overview of the processing of level 1 data and the Data Distribution System (DDS) that allows the experiment teams to download level 1a data on request. Section 3 introduces the science archiving process and the PDS standard. Section 4 describes the dissemination of scientific data to the scientific community, and finally, Section 5 summarises the datasets available at the time of writing.

Table 1. Data processing levels as used within the Mars Express archive plan (ESA, 2001).

Data processing level	*Data processing level description*	*Created by*	*CODMAC level*	*PDS type*
Level 0	Raw telemetry data as received at the ground receiving station or ground test GSE	Spacecraft	1	Raw
Level 1	Level 0 data that have been cleaned and merged, time ordered, and in packet format	Telemetry processor	1	Raw
Level 1a	Level 1 data that have been separated by instrument	As requested by the DS	1	Raw
Level 1b	Level 1a data that have been sorted by instrument data type and instrument mode. These data are in scientifically useful formats, e.g. as images or spectra that are still uncalibrated.	Experiment team	2	Edited
Level 2	Level 1b with calibration and corrections applied to yield to scientific units	Experiment team	3	Calibrated
Level 3	Higher-level data products developed for specific scientific investigations	Experiment team, Interdisciplinary scientists, other teams	4 5	Resampled derived

2. The Ground Segment

2.1 Overview

Mars Express was launched on 2 June 2003 on a Soyuz–Fregat from the Baikonur Cosmodrome in Kazakhstan. After a cruise phase of about six months, the spacecraft was captured by, and later orbited the planet with an inclination of 87°, an orbiting period of 7.5 h and a pericentre of about 250 km.

The definition, design and implementation of the Mars Express ground segment are the responsibility of ESOC in Darmstadt. The Mars Express data processing system is part of the ESOC Operations Control Centre (OCC), which is the central facility responsible for operating the spacecraft. In order to reduce costs, risks and development time, Rosetta, Mars Express and Venus Express share nearly identical data management systems.

The major components of the data processing system are as follows (see Fig. 2):

— The Mission Control System (MCS), which supports the exchange of telemetry and telecommand data between the OCC and the spacecraft via dedicated communication lines and appropriate interfaces with the ground stations.

— The MCS, which is based on the ESOC SCOS-2000 infrastructure, provides the capability to process housekeeping (HK) data in real time for spacecraft control purposes. This includes command verification and out-of-limit detection. The MCS timestamps the telemetry (TM) data by converting the onboard time to Coordinated Universal Time (UTC), with an accuracy below 2 ms. Housekeeping and telemetry data, including parameters and event messages, are processed by the MCS using calibration curves to convert them into the engineering and/or functional parameter values needed to monitor the status of the spacecraft platform and payload, and to recover from anomalies if any. It also provides a command system that is capable of controlling the spacecraft. During nominal operations, commands are calibrated, pre-transmission validated and transmitted to the ground station(s) for uplinking in real time. The OCC maintains a complete history of all commands requested,

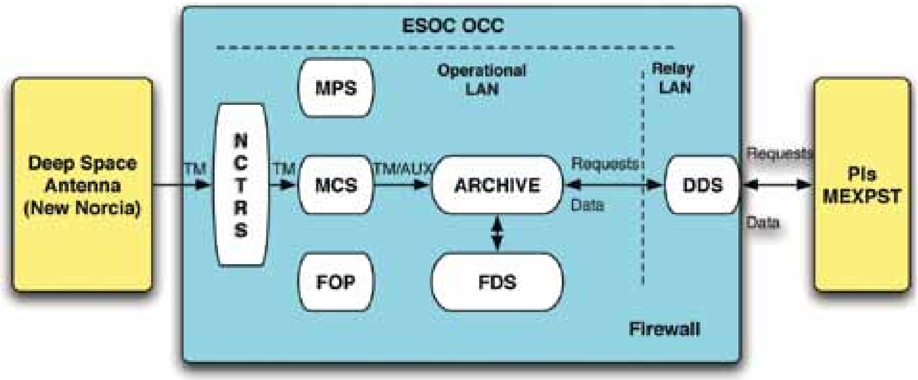


Fig. 2. The Mars Express Operations Control Centre (OCC).

transmitted and verified. The MCS also has facilities for managing the operational database and for maintaining the onboard software.

- The Data Distribution System (DDS) is based on the Generic Data Disposition System (GDDS), and allows remote access by the scientific community for the near-real-time and/or offline inspection of mission data. The system also provides facilities for the regular daily production of raw data media (RDM) for the permanent archiving of raw telemetry and auxiliary data. For Mars Express the DDS will be used to store instrument telemetry data on recordable compact discs (CD-Rs), which are sent to authorised members of the Mars Express scientific community. The DDS system is described in more detail below.
- The Mission Planning System (MPS) is an offline system that provides tools for the advance planning of the mission operations, based on inputs from the Principal Investigators, the Science Operations Centre (SOC) and the operations staff at ESOC. The final outputs of this system take the form of machine-readable schedules for commanding the spacecraft and the two ground stations. Unlike other data system components, the MPS is mission-specific.
- The Flight Operations Procedure (FOP) system is used by the Mission Operations Team to prepare spacecraft operational procedures and command sequences, which can then be imported into the operational database.

2.2 Collection of Telemetry Data

The Mission Control System interfaces with the ground stations to receive and transmit telemetry (TM) and telecommand (TC) data in a controlled and error-free manner. A no-break data link connection is always established when the ground station is in real-time contact with the spacecraft.

The Mars Express MCS receives the telemetry data from the ground stations via a generic infrastructure system called the Network Controller and Telemetry Receiver System (NCTRS), which serves as the ground station interface with the MCS.

The NCTRS receives the telemetry data as delivered by the ground station equipment, which has already performed some basic checks and has ‘time stamped’ it with Earth Reception Time (ERT). It then passes the housekeeping and science telemetry data to the relevant MCS for more specific processing and for archiving. The NCTRS gathers all the telecommands sent from the MCS and forwards them to the relevant ground station.

The NCTRS is also used for acquiring and locally storing tracking data such as antenna angles, range and Doppler measurements made at the ground station. These are then made available to the Flight Dynamics System via the File Transfer System (FTS) and to authorised Principal Investigators (PIs) via the DDS system.

The files generated by the OCC, such as antenna pointing information and ground station schedule files, are also transferred via the NCTRS to the ground station.

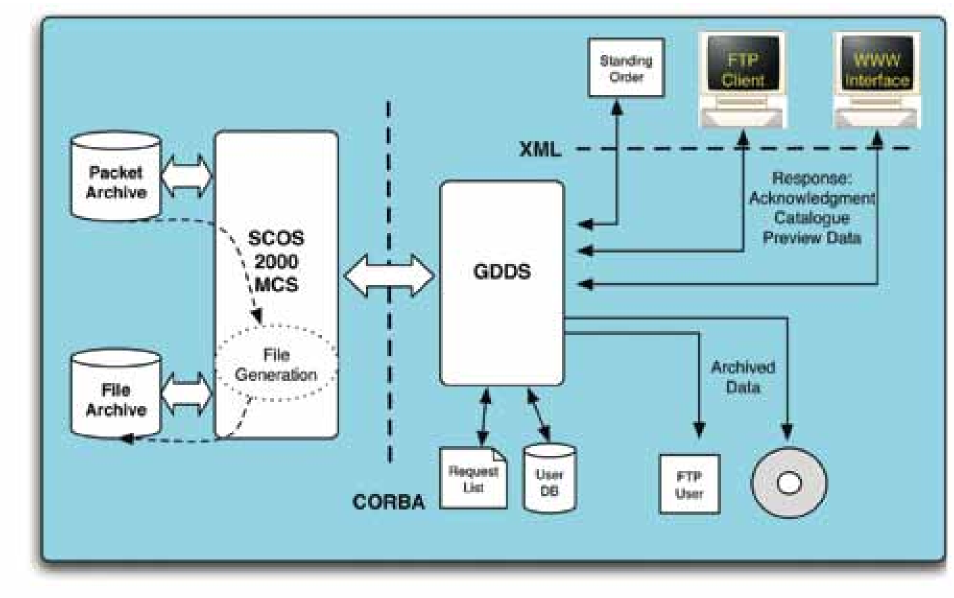


Fig. 3. Generic Data Disposition System (GDDS) architecture.

2.3 Dissemination of Raw Data

The Mars Express OCC offers telemetry, both housekeeping and scientific data, and auxiliary data in near-real-time and/or offline mode to the PIs. Following receipt or generation at the OCC, the data can be accessed from remote computers on a call-up basis.

Mission products include payload science data, all platform and payload housekeeping data and auxiliary data (e.g. TC history, station visibility, spacecraft orbital position, attitude, etc.; DDID, 2002). HK and science TM data (both real-time and playback) are extracted and stored as raw data, which are chronologically ordered and sorted by spacecraft and payload. They include quality data and additional timing data so that the PIs are able to correlate the data with respect to UTC.

In addition, the science data, housekeeping data and consolidated auxiliary data are transferred onto CD-ROMs, which are mailed to each PI on a weekly basis. A common data interchange standard based on the Standard Formatted Data Unit (SFDU) concept is used in order to allow for efficient data distribution.

Finally, the OCC archives all Mars Express level 1 data for all payloads for a period of ten years after the end of the mission. Archived data include all raw telemetry and auxiliary data.

The MCS is on the operational LAN and can be accessed by operational staff at ESOC (i.e. there is no remote access). External access to mission data is via the DDS, which allows a secure connection between the outside world (such as the Mars Express PIs) and the ESOC-protected operational LAN.

2.3.1 Dissemination of Mission Raw Data via the Mars Express DDS

The DDS is based on the Generic Data Disposition System (GDDS, 2002). It enables PIs and other external users to submit requests for data to be extracted from the mission archives supported by the SCOS-2000 spacecraft control system kernel. These requests are expressed in a format based on XML (extended mark-up language; Thompson et al., 2001). Figure 3 provides an overview of the GDDS.

The Mission Control System, based on SCOS-2000, maintains a mission archive comprising two main elements: a packet archive containing historical telemetry, telecommand and derived data, and a file archive that typically includes flight dynamics and planning data. A file generation process within SCOS-2000 can also be invoked to generate file-based summary data from packet data, e.g. command history reports.

Fig. 4. Sample screenshot from the GDDS web interface.

Requests for data to be extracted from the mission archive may originate in three ways:

— scheduled ‘standing orders’;
— submission via a web-based interface; or
— request files sent using the File Transmission Protocol (FTP).

All requests comprise a list of items to be retrieved, and are expressed in a recursive query language defined in XML, which is used internally within the system, and also exposed to the user on the FTP interface. This allows multiple filters to be applied to the data being retrieved. The requested data can be from three sources: telemetry, auxiliary and catalogue data.

These requests are managed by a central DDS server, which interfaces with the MCS to initiate archive retrievals via a Common Object Request Broker Architecture (CORBA) based interface. Archive retrievals performed on the MCS interface are relatively low level, and several individual retrievals may be performed to satisfy a single request. The GDDS server maintains a request list, and collates the retrieved data for a single delivery in response to each request.

Requests must be identified as originating from a previously authorised external user. The DDS maintains a database of these authorised users, together with address information for the delivery of retrieved data.

Three methods of archive data delivery are supported: online via a web-based interface; via an FTP server; and on CD-ROM (only available for Mars Express PIs, and following agreed recording and distribution schemes).

The DDS web-based user interface is designed to allow authorised users to view the catalogue of data held in the mission archive, and to generate and submit retrieval requests, for delivery using the FTP server or online. Figure 4 shows a screenshot of a data request.

All responses from the DDS server to the web-based interface are also transferred as XML files. These may include request acknowledgements, catalogue data and online data retrieval.

Online data retrieval is only available in response to a request originating from the web-based interface, and is designed for previewing small amounts of data only. This enables a user to verify that it is the required data, before requesting a full FTP transfer. The data are embedded as a byte stream in the XML response.

3. Scientific Processing and Data Archive Preparation

3.1 Overview

Following the success of the visits of the Giotto spacecraft to the comets P/Halley and P/Grigg–Skjellerup (during its extended mission), Rosetta, Mars Express and SMART-1 are ESA's next planetary missions. All the data from the International Halley Watch campaign – including the Giotto data – have been archived using NASA's Planetary Data System (PDS) standard. The PDS is the *de facto* standard for most US planetary missions. It was therefore decided early in the mission development to use the PDS standard for Rosetta, Mars Express and SMART-1.

To ensure maximum commonality, ESA has introduced the Planetary Science Archive (*www.rssd.esa.int/PSA*) for all planetary missions. The PSA is the official interface of all engineering, housekeeping and scientific data for the scientific community after the experimenters' proprietary period has come to an end. All necessary services are offered to the scientific community via an online interface.

The initial requirements, system tests and further development of the PSA are basically driven by the PSA Scientific Advisory Group, a mission-independent group representing a range of instrument categories and disciplines within the European scientific community.

This section describes the PDS standard and the PSA system and gives an outline of the planned archive process.

3.2 The Planetary Data System (PDS) Standard

The PDS standard is a set of guidelines published in the PDS Data Standards Reference (JPL, 2006). The guidelines cover the archive process as well as details of predefined data types, an object description language, a data dictionary, rules on labelling data products, catalogue templates and the organisation of logical or physical volumes. The PDS standard is compliant with the reference model of the Open Archival Information System (OAIS; CCSDS, 1999).

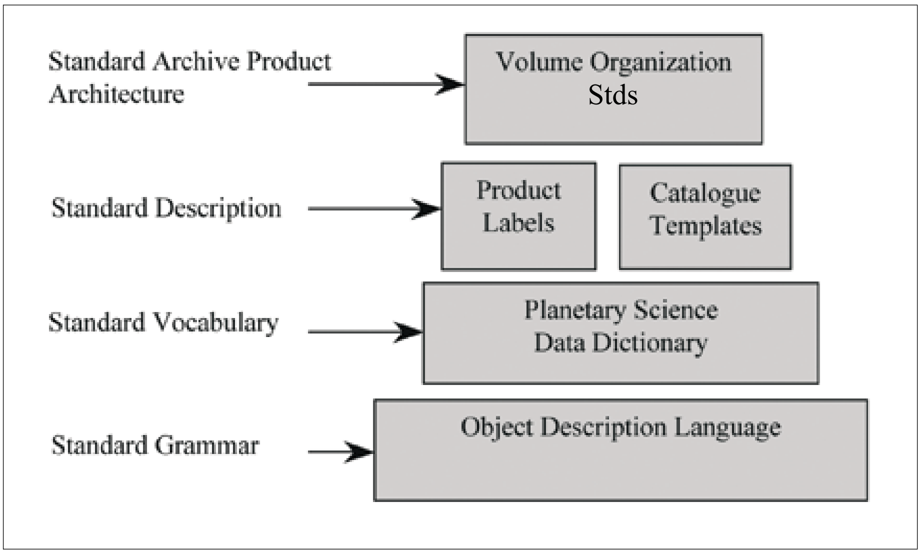
As a general rule, each data product must be labelled and linked to a data file. The label is either attached to the data file itself or detached in a separate file, called a label file. Documents are classified as products and a label is required. Each self-contained unity, called a dataset, must contain a default set of documentation in ASCII format, referred to as catalogue files. Figure 5 sketches the parts of the standard, and indicates the hierarchical structure of the standard.

The glue for all data products is the standard grammar, the object description language (ODL). The ODL requires that all metadata be given as a *keyword = value* pair. For example,

```
INSTRUMENT_HOST_NAME     = MARS_EXPRESS
```

is a valid description of the spacecraft name. The keywords on the left side of the pair must be defined in the Planetary Science Data Dictionary (PSDD; JPL, 2002). A lookup for the keyword *instrument_host_name* results in

Fig. 5. Hierarchy of the Planetary Data System (PDS) standard.




```
NAME = INSTRUMENT_HOST_NAME
  STATUS_TYPE               = APPROVED
  GENERAL_DATA_TYPE         = CHARACTER
  UNIT_ID                   = NONE
  STANDARD_VALUE_TYPE = STATIC
  MAXIMUM_LENGTH            = 60
  DESCRIPTION = "
     The instrument_host_name element provides the full name of
     the host on which an instrument is based.  This host can be
     either a spacecraft or an earth base.  Thus, the
     instrument_host_name element can contain values which are
     either spacecraft_name values or earth_base_name values."
  STANDARD_VALUE_SET = {
     "ROSETTA",
     "ROSETTA LANDER",
     "MARS EXPRESS",
     "BEAGLE 2",
     "SMART 1",
     "2001 MARS ODYSSEY",
     "24-COLOR SURVEY",
     "AMES MARS GENERAL CIRCULATION MODEL",
     "ARECIBO OBSERVATORY",
     "CLEMENTINE 1",
     ….
   }
```

The basic elements of the archive are of course the data products. The standard foresees a small number of simple, predefined data types for these products, but also allows the definition of user-defined structures or combined structures. Bearing in mind that one of the purposes of the archive is the long-term preservation of the data, the reduced number of available data types can seen as an advantage, as it enhances the simplicity of the data in the long term. Data producers are forced to design easy data types and structures, which in turn simplify access to data products. These data types include matrix, image, spectrum, table and histogram, to name just a few.

The standard description foresees a label for each data product. This label contains *keyword = value* pairs that describe the data type, structure and any another metainformation necessary to access the data and to interpret it. The following block shows an excerpt from the OMEGA data product label:

```
PRODUCT_ID                          = "ORB1879_2_DATA"
PRODUCT_TYPE                        = EDR
STANDARD_DATA_PRODUCT_ID            = "OMEGA DATA"
PI_PDS_USER_ID                      = BIBRING
MISSION_NAME                        = "MARS EXPRESS"
MISSION_PHASE_NAME                  = "MR Phase 6"
INSTRUMENT_NAME                     = "Observatoire Mineralogie, Eau, Glaces, Activite"
PRODUCER_INSTITUTION_NAME           = "IAS"
INSTRUMENT_ID                       = OMEGA
INSTRUMENT_TYPE                     = "IMAGING SPECTROMETER"
^INSTRUMENT_DESC                    = "OMEGA_DESC.TXT"
^INSTRUMENT_CALIBRATION_DESC        = "OMEGA_CALIBRATION_DESC.TXT"

DATA_QUALITY_ID                     = 3
DATA_QUALITY_DESC                   = " from 0 to 3 depending on
                                        missing lines and compression errors"

MISSING_SCAN_LINES                  = 0
CHANNEL_ID                          = (IRC,IRL,VIS)
SOFTWARE_VERSION_ID                 = "OMEGA 4.5"
TARGET_NAME                         = MARS
ORBIT_NUMBER                        = 1879

PRODUCT_CREATION_TIME               = 2005-09-14T23:57:13.000
START_TIME                          = 2005-07-02T20:41:36.043
STOP_TIME                           = 2005-07-02T20:51:38.091
SPACECRAFT_CLOCK_START_COUNT        = "68351355.13762"
SPACECRAFT_CLOCK_STOP_COUNT         = "68351957.00685"

MAXIMUM_LATITUDE                    = -54.238
MINIMUM_LATITUDE                    = -70.102
EASTERNMOST_LONGITUDE               = 184.354
WESTERNMOST_LONGITUDE               = 161.580
SLANT_DISTANCE                      = 2526.525
```

The PDS standard also requires a set of catalogue files. A catalogue file is a label file that contains textual information in ASCII format for at least:

- dataset description (dataset catalogue file);
- spacecraft description (instrument_host catalogue file);
- instrument description (instrument catalogue file);
- mission description (mission catalogue file);
- references (reference catalogue file);
- personnel information (personnel catalogue file);
- dataset collection description (dataset collection catalogue file, optional); and
- target information (target catalogue file, optional).

In addition, the standard requires a well defined directory structure. All catalogue files, for example, need to be accessible from a directory named *CATALOG*. The top-level directory must contain a file named *VOLDESC.CAT* that describes the whole archive volume. The next block gives an example of a typical *VOLDESC.CAT* file:

```
PDS_VERSION_ID                    = PDS3
RECORD_TYPE                       = STREAM
RELEASE_ID                        = 0001
REVISION_ID                       = 0004
OBJECT                            = VOLUME
  VOLUME_SERIES_NAME              = “MISSION TO MARS”
  VOLUME_SET_NAME                 = “MARS EXPRESS ASPERA3”
  VOLUME_SET_ID                   = “USA_ESA_PSA_MEX_ASPERA3”
  VOLUME_NAME                     = “MARS EXPRESS ASPERA-3 VIRTUAL VOLUME”
  VOLUME_ID                       = “MEXASP_3100”
  VOLUME_VERSION_ID               = “Version 1”
  PUBLICATION_DATE                = 2005-01-31
  VOLUMES                         = 1
  MEDIUM_TYPE                     = “ONLINE”
  VOLUME_FORMAT                   = “ISO-9660”
  DATA_SET_ID                     = “MEX-M-ASPERA3-2-EDR-NPI-V1.0”
  DESCRIPTION                     = “
Data from the Neutral Particle Imager (NPI) instrument of the Analyzer
of Space Plasmas and Energetic Atoms experiment, 3rd edition (ASPERA-3),
aboard the Mars Express spacecraft.  The ASPERA-3 Principal Investigator
is Dr. Rickard Lundin, Swedish Institute of Space Physics (IRF), Kiruna,
Sweden.  The primary source for ASPERA-3 data is the ESA Planetary
Science Archive (PSA).”

  OBJECT                          = DATA_PRODUCER
    INSTITUTION_NAME              = “SOUTHWEST RESEARCH INSTITUTE”
    FACILITY_NAME                 = “N/A”
    FULL_NAME                     = “N/A”
    ADDRESS_TEXT                  = “6220 CULEBRA RD., SAN ANTONIO, TX  78238”
  END_OBJECT                      = DATA_PRODUCER

  OBJECT                          = CATALOG
    ^MISSION_CATALOG              = “MISSION.CAT”
    ^INSTRUMENT_HOST_CATALOG      = “INSTHOST.CAT”
    ^INSTRUMENT_CATALOG           = “ASPERA3_INST.CAT”
    ^DATA_SET_CATALOG             = “ASPERA3_NPI_EDR_DS.CAT”
    ^PERSONNEL_CATALOG            = “PERSON.CAT”
    ^DATA_SET_RELEASE_CATALOG     = “ASPERA3_NPI_RELEASE.CAT”
    ^REFERENCE_CATALOG            = “REF.CAT”
    ^SOFTWARE_CATALOG             = “ASPERA3_SOFTWARE.CAT”
  END_OBJECT              = CATALOG

END_OBJECT                = VOLUME
END
```

Documentation is found below the directory named *DOC* and software is archived below the *SOFTWARE* directory. Software products might include visualisation, analysis or calibration routines.

The standard is also intended to overcome operating system dependencies and to direct the archive designers towards human readability.

To test a dataset against these standard rules, a software package was provided to all instrument teams to ensure the accuracy of datasets for keywords, keyword values used, file names, directory names and other constraints.

3.3 The Scientific Archive Process

The archive process starts with discussions and agreement on the Archive Generation, Validation and Transfer Plan, also called the Mars Express Archive Plan (ESA, 2001), which is based on the Science Management Plan (ESA, 1997) and ESA’s general archiving rules (ESA Council, 1989). The Archive Plan gives the scope of the scientific data archive in relation to the overall mission, and summarises the mission, experiments and groups involved in the archiving efforts. It lists the datasets that are produced by each team, together with contact information for the team members.

Within the Mars Express mission, the experimenters are responsible for the design and implementation of the scientific datasets. The initial version of the Mars Express Archive Plan, which contained a first draft of the data types and the expected data volume, was prepared by ESA's archive team and was issued one year before launch.

As the PDS standard gives enough information for the experimenter teams to start preparing their archive design, the ESA archive team acts as a consultant for the experimenters. Each experimenter team defines its archive design in the Experimenter to Archive Interface Control Document (EAICD), which contains full details of the archive's directory structure, the data types and the label keywords used. The EAICDs were issued soon after launch and updated when required.

Throughout the entire process of data preparation and archiving, members of the Data Archive Working Group (DAWG) hold regular meetings and teleconferences to discuss issues of common interest and to keep each other informed on the progress in design and implementation.

The volume of the scientific archive of Mars Express was originally estimated to be of the order of 1 terabyte (TB;10^9 bytes) for the nominal mission phase, but this has already grown to 2.5 TB.

Electronic data handling is the aim, for the ingestion of data from the experimenter teams into the PSA, and the delivery of data from the PSA to the scientific community.

The members of ESA's archive team keep in close contact with their PDS colleagues in the United States. The PDS Geosciences Node in St Louis and the PDS Navigation and Ancillary Information Node (NAIF) at the Jet Propulsion Laboratory (JPL) in Pasadena, support MEX-related archive and ancillary activities. For Mars Express, the archive will contain the NAIF auxiliary data kernels that will be produced by NAIF software from the corresponding ESOC auxiliary files.

Besides the spacecraft data prepared by several teams at ESOC and the experimental scientific data, the PSA contains geometric, positional, illumination and mission phase information. Individual working groups discuss these topics, and agree on the content and format of corresponding data products, which are often implemented by the experimenter teams and delivered as part of their instrument datasets.

Because the continuous (e.g. daily) delivery of data from the instrument teams to the archive team would require tremendous technical and data validation efforts by all the parties involved, the delivery schedule is based on longer time periods. The three archive phases, as they are known, are the data collection, archive preparation and archive validation phases.

During the data collection phase, the experimenter teams receive their data from the DDS, distribute the data among their co-investigators and other team members, and perform data analysis and validation. The data collection phase will never be longer than the proprietary period, which is usually six months for ESA's planetary missions. All the data from one collection phase are processed into PDS-compliant datasets over the next three months, the archive preparation phase. After automatic data pre-validation, the experimenter team will ingest its datasets electronically into the PSA. The ESA archive team will run software validation tools to check for syntax errors and ensure that the delivered datasets are complete. The archive team will also manually check the completeness of the delivered documentation and calibration information. For the first and last deliveries of a mission, a team of ESA internal and external scientists and engineers will be called in to conduct an independent scientific peer review of the completeness and accuracy of the delivered datasets. For intermediate deliveries, scientists will get together via teleconferences to conduct *ad hoc* reviews of individual deliveries. Three months after delivery to the PSA, the datasets will be made available to the scientific community. It will be obvious to scientific users of the PSA whether or not a dataset has been successfully peer reviewed.

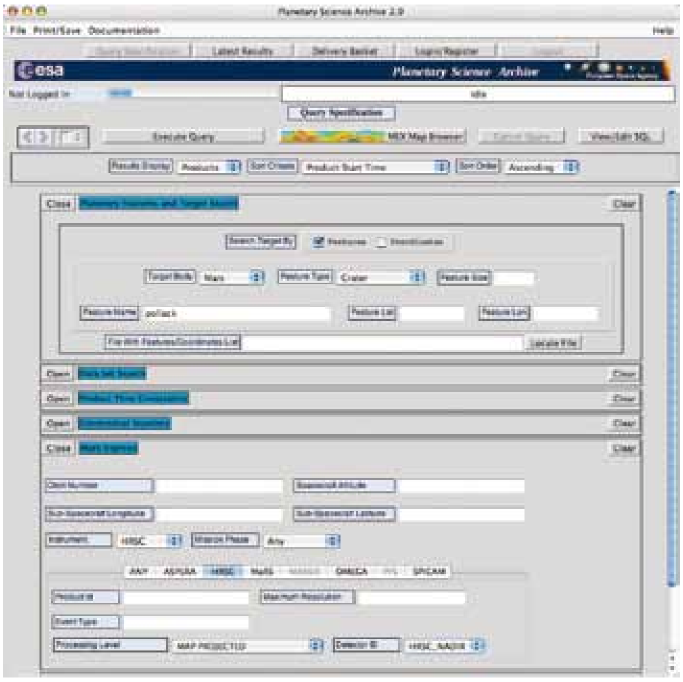
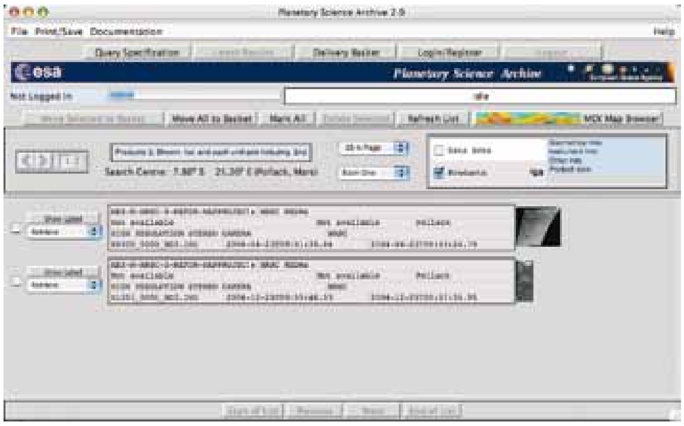


Fig. 6. The PSA query user interface. In this example the HRSC instrument is selected and all HRSC data covering the crater Pollack. Only map-projected data and data from the nadir channel are requested.

Fig. 7. The result of the query defined in Fig. 6. Product information is presented as a list of main label parameters, as well as an icon that gives immediate access to quicklook information. The data product can be downloaded directly from the 'Retrieve' option on the left.



4. Planetary Science Archive Services

The Planetary Science Archive (PSA) is an online archive where users can search for and access data via the internet.

Several experiment teams expressed the need to offer additional data services on top of the delivery of PDS-compliant datasets. Investigations into the potential of online data archiving showed that re-using the ISO and X-ray Multi-Mirror Mission (XMM–Newton) scientific data archive architecture would have several advantages. In particular, the architecture has been used for several years by hundreds of scientists around the world, and would cost considerably less than it would to develop a new one. Thus the decision was made in 2002 to build on the expertise of the Research and Scientific Support Department (RSSD) Science Archives Team at the European Space Astronomy Centre (ESAC) in Villafranca, Spain.

In April 2002, a PSA user requirements workshop was held for 2.5 days, resulting in a well defined set of requirements (PSA, 2002). To guarantee the balanced capture of the requirements of the different scientific fields involved in planetary missions, scientists and engineers from a range of disciplines were invited: spectroscopy, plasma, lander, radio science, radar, atmospheres, dust, imaging, probe/lander orbiter coordination and science operations. The members of the User Requirement Working Group will form the PSA Scientific Advisory Group.

The PSA will support several user groups. *Standard users*, typically scientists or engineers, can query the PSA to find data on a specific topic, a dedicated instrument keyword or a location on a planetary body. Standard users have full access to all public data in the database. *Expert users* can access a restricted set of scientific data, e.g. experimental data that are not yet open to the public, perhaps due to a proprietary period, for example, or uncertainties in the data validation. Potential expert users include members of experiment teams or of the Science Operations Team. The third group of potential users includes members of the *general public* who may be interested in using simple queries to find the most interesting and easy-to-interpret data. Educators are supported in this group of users.

Besides the technical objectives of the PSA – covering the electronic ingestion of data from the experimenter teams and the delivery of data to the scientific community – there are several major scientific objectives, including:

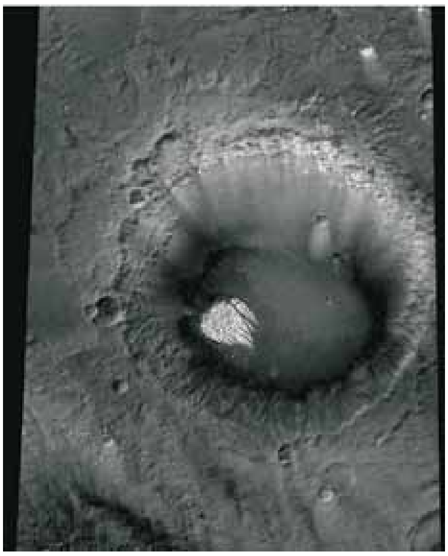


Fig. 8. The postcard image (quicklook) that is displayed when the user selects the icon in Fig. 7.

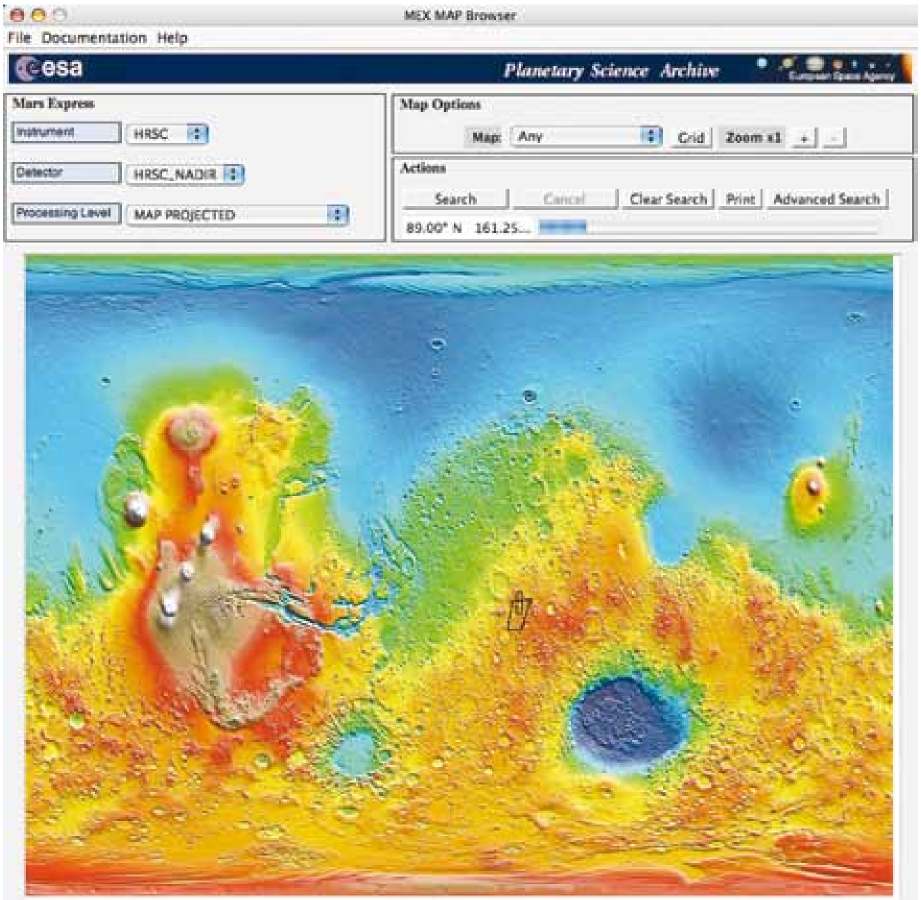


Fig. 9. The map-based results panel. It corresponds to the query defined earlier and the parameter-based result panel shown in Fig. 7. The footprints of the products are plotted near the equator at about 25°E.

— increasing the scientific return of the mission;
— central organisation and long-term preservation of all data;
— easy access and search functionality;
— single entry point to information on all of ESA's planetary missions;
— compliance with the PDS;
— direct data download;
— delivery basket download; and
— interoperability with other planetary archives, e.g. the PDS online archive, and with other documentation databases.

The PSA offers the following user-support functionalities:

— automatic ingestion and validation support;
— single entry page for all planetary missions;
— common look-and-feel for all planetary missions;
— dataset browsing tool (FTP-like);
— 2D map search and view; and
— notification management.

Figures 6–9 provide screenshots of the available PSA user interfaces, demonstrating some of the capabilities of the services available. To locate data of interest, a user can use the parameter-based interface (see Fig. 6), a map-based interface or a dataset browser interface. A parameter-based query leads to parameter-based listing of results, as shown in Fig. 7. A map-based query leads to a map-based display of resulting footprints, as shown in Fig. 9. The user can toggle between the available result displays. If quicklook information is provided within a dataset, the individual quicklook images can be immediately accessed from the result panels. The dataset browser interface provides FTP-like access to all available Mars Express data. A more detailed user manual is available from the PSA web page.

5. Available Mars Express Datasets

5.1 General Dataset Characteristics

All datasets have an identical top-level directory structure as required by the PDS standard explained in section 3. Due to the common archive approach, including discussions and agreements with the instrument teams, a minimal set of keywords is used within all data labels.

The INDEX directory of each dataset contains a minimum set of ASCII index files formatted as PDS TABLE objects, to be used for information lookup or further data processing. The file INDEX.TAB contains a single line for each data product of a dataset, with basic identification information. The GEO_MARS.TAB file contains geometrical information for each data product, providing a representation/projection of each data product/observation on the surface of Mars (i.e. footprint). A common concept was developed for all instrument types (ESA, 2007) to allow uniform data retrieval. The BROWSE.TAB file is optional and present in case browse images are available in the dataset. It provides the mapping between the data products and their corresponding browse products.

The DOCUMENT directory of each dataset contains the Experiment to Archive Interface Control Document (EAICD). This is the basic document of each dataset and should be the entry point for new users. The file MEX_ORIENTATION_DESC.TXT defines the different orientations of the Mars Express spacecraft and their use within the datasets. The file MEX_POINTING_DESC.TXT defines the spacecraft pointing modes and their uses. Individual datasets might contain other documents; users are advised to read the EAICD for detailed information. The file AAREADME.TXT at the root of each dataset provides further high-level information, which new users are also advised to read.

Changes, updates, corrections of errors and other important information are documented at several locations, especially in the file ERRATA.TXT in the root directory of each dataset. Information is appended to the ERRATA.TXT to ensure that modifications to the dataset are fully transparent to users.

The planetocentric coordinate system is used for all Mars Express datasets, with longitudes increasing from 0° to 360°E, and latitudes between –90° and +90°. The reference frames of the spacecraft, instruments and detectors are defined in the frame kernels of the SPICE datasets (see section 5.8). In the following, the terms 'reduced' and 'calibrated' are used synonymously.

5.2 ASPERA-3 (Analyser of Space Plasmas and Energetic Neutral Atoms)

ASPERA-3 comprises four sensors: the Electron Spectrometer (ELS), the Neutral Particle Imager (NPI), the Neutral Particle Detector (NPD), and the Ion Mass Analyser (IMA; Barabash et al., 2004). Data from each sensor are archived in individual datasets. The following datasets are currently available from ASPERA-3 and are produced at the Southwest Research Institute, San Antonio, Texas. All sensor data are stored in ASCII format with a varying, sometimes large, file sizes.

The dataset MEX-M-ASPERA3-2-EDR-ELS-V1.0 contains the raw experimental data records of the ELS sensor from launch to the end of the nominal mission. It provides the *in situ* electron measurements in the energy range 0.05–20 keV in two kinds of data product: the ELS Science low-range data and the ELS Science high-range data, both given in counts per accumulation unit. A data quality indicator based on the state of the instrument is available for each set of scan measurements. The data structure for all products is a spreadsheet in ASCII format, which is effectively a table containing comma-separated columns. The CALIBRATION directory contains the high-range and low-range calibration tables providing for each ELS sensor the conversion values from counts to number fluxes. Deflection voltages to centre energies for the scan values are also given. The DOCUMENT directory contains supplementary information on flight performance, sensor frame definitions and usage, sensor numbering and calibration reports.

The dataset MEX-M-ASPERA3-3-RDR-ELS-V1.0 contains the reduced experimental data records of the ELS sensor from launch to the end of the nominal mission. The values are given as Differential Number Flux (DNF) as a SPREADSHEET object. The CALIB directory again contains the high- and low-range calibration tables with details explained in the file CALINFO.TXT.

The dataset MEX-M-ASPERA3-2/3-EDR/RDR-NPI-V1.0 contains the raw as well as the reduced experimental data records of the NPI sensor from launch to the end of the nominal mission. The measured energetic neutral atoms (ENA) count rates per second in the range 0.1–60 keV are given in a single type of data product, again using the SPREADSHEET structure. The provision of count rates allows for the analysis of the ENA as well as the UV signal, which are intermixed. The CALIBRATION directory contains a calibration table defining the values for converting from count rate to number fluxes for the ENA component only.

The dataset MEX-M-ASPERA3-2/3-EDR/RDR-NPI-EXT1-V1.0 contains the NPI data described above from the extended mission phase 1.

The dataset MEX-M-ASPERA3-2-EDR-IMA-V1.0 contains the raw experimental data records of the IMA sensor from launch to the end of the nominal mission. The measured ion count rates per accumulation are given in a SPREADSHEET structure. The CALIBRATION directory contains the mass channel data calibration table providing background noise values and the correction ratio for each of the mass channels. The energy step table provides the centre energy for each energy step, and the fraction of noise dependent on the energy step. The azimuth sector table provides the efficiencies and geometric factors for each of the sectors. The use of the calibration tables is described in the CALINFO.TXT file.

5.3 HRSC (High Resolution Stereo Camera)

The HRSC instrument consists of two cameras, the Super-Resolution Camera (SRC) and the High Resolution Stereo Camera. The HRSC is a push-broom scanning instrument with nine CCD line detectors mounted in parallel in the focal plane (Neukum et al., 2004; Jaumann et al., 2007). The scan line data from each orbit and for each line detector are collected and stored in one IMAGE object.

The SRC is a framing device and the resulting observations are stored in an IMAGE object, one for each observation. All HRSC and SRC data are stored in VICAR format with an attached PDS label. The BROWSE directory contains a JPEG image of each data product. As the data products can be of considerable size (up to 5 GBytes), users are advised to check the browse images before downloading. All HRSC datasets contain this browse information.

All HRSC datasets are produced at the German Aerospace Center (DLR) in Berlin, Germany, in cooperation with the Department of Earth Sciences at the Freie Universität Berlin.

The dataset MEX-M-HRSC-3-RDR-V2.0 contains the radiometrically calibrated data from orbit 10 to the end of the first mission phase extension. The SOFTWARE directory contains the source code of MINIVICAR, a small subset of the VICAR image processing system with additions to allow for HRSC data processing. The MINIVICAR package provides a functionality to display the HRSC images, and convert them into other image file formats, and can process the radiometrically calibrated images to higher data processing levels.

The dataset MEX-M-HRSC-5-REFDR-MAPPROJECTED-V2.0 contains the geometrically calibrated and map projected data from orbit 10 to the end of the first mission phase extension. Images are presented in a sinusoidal equal-area map projection for latitudes between –85° and +85°E. Images at the poles are presented in stereographic projection. More detailed information can be found in the file DSMAP. CAT in the CATALOG directory, and in the references provided there.

The dataset MEX-M-HRSC-5-REFDR-DTM.V1.0 contains the Digital Terrain Model (DTM) as 8-bit orthoimages for the nadir channel and the four colour channels, and 16-bit DTM, the latter with a height resolution of 1 m. The spatial resolution of the DTM is about twice the stereo resolution (up to 50 m). The map projection is polar-stereographic for polar areas, and sinusoidal elsewhere.

5.4 MaRS (Mars Express Radio Science) Experiment

The dataset approach for the radio science experiment differs from those for the other instruments. The MaRS team provides one dataset including several data processing levels for each observation. For example, the dataset MEX-M-MRS-1-2-3-PRM-0117-V1.0 contains all data levels for an observation with sequence number 117 obtained during the nominal (prime, PRM) mission. Several hundreds of datasets are available for the nominal mission. More information about the MaRS experiment can be found in Pätzold et al. (2004).

The data processing levels provided in the datasets are as follows. The first data level contains the raw tracking data from either New Norcia or the Deep Space Network for both closed- and open-loop. The next data level contains the reformatted and further processed data in ASCII format. The third data level contains calibrated data products: distance to the target, observed and predicted frequencies, residuals of both frequencies, corrections for Earth’s atmosphere, signal level and the differential Doppler. For bistatic radar products coordinates are also available.

The data from each of the different processing levels, and from each of the ground stations used, are included in separate directories with appropriate naming.

The CALIBRATION directory contains calibration information for the ground stations used, both open- and closed-loop. The BROWSE directory contains JPEG images containing four-panel plots that allow preliminary data quality checks. The DOCUMENT directory contains a large amount of supplementary information ranging from the operational notebooks to ground station antenna documents.

5.5 OMEGA (Observatoire pour la Minéralogie, l’Eau, les Glaces et l’Activité)

The dataset MEX-M-OMEGA-2-EDR-FLIGHT-V1.0 contains the raw experimental data records as well as geometry data from launch to the end of the nominal mission. The data records from the two mapping spectrometer channels (Bibring et al., 2004), the visible and near-infrared channel and the short-wavelength channel, are three dimensional and physically stored using the QUBE object comprising two spatial and one spectral dimension. The backplane of the QUBE contains dark current information for each CCD pixel. Several sideplanes of the QUBE contain supplementary instrument housekeeping information such as temperatures, voltages, scan mirror positions and more detailed timing information. One QUBE corresponds to one observation. A geometry data product is provided for each observation, providing the observation geometry of each pixel for each of the OMEGA channels. Explanations and definitions of the 51 geometry parameters can be found in the EAICD.

The SOFTWARE directory contains all versions of a data reduction pipeline to calibrate the raw data records into radiances and several other data structures. Users of OMEGA data are advised to check regularly for software updates. The software package contains necessary calibration data such as bias, flat field and photometric data, and explains instrument-specific and environmental aspects and takes them into account during the reduction.

The OMEGA dataset has been produced at the Institute d’Astrophysique Spatiale (IAS), Orsay, France.

5.6 PFS (Planetary Fourier Spectrometer)

The dataset MEX-M-PFS-2-EDR-NOMINAL-V1.0 contains the raw experimental data records from the PFS spectrometer (Formisano et al., 2004) from launch to the end of the nominal mission, produced at the Istituto Nazionale di Astrofisica (INAF-IFSI) in Rome, Italy. The data from the short-wavelength channel (SWC, 1.2–5 mm) and the long-wavelength channel (LWC, 5–45 mm), are contained in this dataset and separated via an appropriate directory naming scheme described in detail in the document MEX-PFS-PSA-ICD-25.pdf (EIACD for the PFS instrument).

The two channels can be operated in instrument calibration and instrument measurement modes. For each mode, the raw measurements, the housekeeping data and geometry information are provided in separate files using the TABLE structure. Data files, comprising calibration, housekeeping and measurements, from both the SWC and LWC, are stored in separated subdirectories of DATA directory, while the geometrical information for each scientific measurement is stored in the GEOMETRY directory, which has an identical structure.

The DOCUMENT directory contains extensive calibration documentation for both the SWC and the LWC. It discusses the calibration steps as well as external influences on the measurements, and includes the user manual for the PFS instrument.

5.7 SPICAM (Spectroscopy for Investigation of Characteristics of the Atmosphere of Mars)

The raw data from the infrared (IR) and the ultraviolet (UV) spectrometers of SPICAM (Bertaux et al., 2004) are archived in two different datasets, all produced at the Service d'Aéronomie, IPSL, CNRS in Verrières-le-Buisson, France.

The datasets MEX-Y/M-SPI-2-UVEDR-RAWXCRU/MARS-V1.0 and MEX-Y/M-SPI-2-IREDR-RAWXCRU/MARS-V1.0 contain the raw experimental data records from the UV and IR channels, respectively, from launch to the end of the nominal mission. The instrument data are stored in an ARRAY of COLLECTIONS containing for each record a header and the data. The data part of a UV record represents five bands of the UV CCD, recorded during one measurement. The data part of an IR record represents the spectrum points recorded by each of the two detectors during one measurement cycle. The DOCUMENT directory contains a calibration document for each sensor, explaining how to process the data, and referring to the calibration files in the CALIB directory. The BROWSE directory contains PNG quicklook spectro-temporal images for each UV band and each IR detector. Both datasets provide further geometry parameters in the GEOMETRY directory for each observation. The parameters include, for example, line-of-sight information for specific CCD locations, specific operational modes and specific targets. Detailed information can be found in the SPICAM_GEOMETRY and SPICAM_POINTING files within the DOCUMENT directory.

5.8 MARSIS (Mars Advanced Radar for Subsurface and Ionosphere Sounding)

The raw experimental data records of MARSIS (Picardi et al., 2004) are processed at the INFOCOM Department of the University of Rome 'La Sapienza' to produce the MEX-M-MARSIS-2-EDR-V1.0 dataset. This contains data that have been edited to remove corrupted or duplicated packets, and provides auxiliary information to locate them in space and time.

The data products in MEX-M-MARSIS-2-EDR-V1.0 are made by an aggregation of frames, which are a collection of received echoes with or without onboard processing applied. Each data product contains frames acquired through a single operational mode, instrument status and onboard processing scheme. The storage representation is a binary TABLE object containing timing, housekeeping and measurement values.

Users of this dataset are mainly radar scientists interested in redoing the entire processing of the received signal. The fact that unprocessed subsurface sounding echoes do not show any obvious indication of subsurface interfaces means that they are of little use to geologists.

Subsurface sounding data are further processed at the INFOCOM Department to produce the MEX-M-MARSIS-3-RDR-SS-V1.0 dataset, i.e. data that have been calibrated, range-compressed and corrected for ionospheric distortion. They are therefore the dataset of choice for geological analysis of the structure and layering of the martian subsurface. Data products in this dataset have the same structure as those in the MEX-M-MARSIS-2-EDR-V1.0 dataset, with ground-processed frames substituted for instrument raw frames.

These datasets contain data from the deployment of the antenna in May 2005 to the end of the nominal mission. Data acquired in the extended phases of the mission are named MEX-M-MARSIS-2-EDR-EXTx-V1.0 for experiment data records and MEX-M-MARSIS-3-RDR-SS-EXTx-V1.0 for subsurface sounding processed frames, where ‘x’ denotes the number of the extension (‘1’ for the first extension, and so on).

The Department of Physics and Astronomy of the University of Iowa provides the calibrated data relating to the ionospheric soundings.

The data products of MEX-M-MARSIS-3-RDR-AIS-V1.0 are calibrated ionospheric sounding data stored in binary format using the TABLE object. One data product contains a list of vectors representing the power received by the instrument in time after transmission. The BROWSE directory contains one overview frequency–time spectrogram for each pericentre pass, as well as several delay time versus frequency plots covering all transmit/receive intervals of one pericentre pass.

5.9 SPICE (Navigational and Ancillary Information)

The dataset MEX-M-SPICE-6-V1.0 contains navigation and ancillary data in the form of SPICE kernel files (Semenov et al., 2005). The instrument description kernels (IK) give descriptive and operational data for an instrument. I-kernels are available for all ASPERA-3 sensors, the HRSC camera, the OMEGA spectral imager and the PFS spectrometer. The frame definition kernels (FK) contain information to define reference frames, sources of frame orientation data and interconnections between these and other frames within the SPICE system. F-kernels are available for the Mars Express spacecraft, its instruments and most of its subsystems, such as the solar arrays and the high-gain antenna. The spacecraft clock kernel (SCLK) contains the onboard clock calibration data required to perform a mapping between ephemeris time and the onboard time. The leap seconds kernel (LSK) is a non-mission related kernel and provides the leap seconds and other constants required to perform transformations between UTC and ephemeris time.

The C-kernels describe the spacecraft pointing, containing a transformation traditionally called the C-Matrix, which is used to determine the time-tagged pointing angles. For Mars Express, the flight dynamics team provides one predicted attitude data file that is continuously updated in precision and time interval. Only in very rare cases is a reconstituted attitude file provided. These files are converted to C-kernels by the MEXPST team, with the support of the NAIF team. The filenames of these kernels are prefixed with ‘ATNM_P’. The reconstituted C-kernel is prefixed with ‘ATNM_RECONSTITUTED’.

SPK-kernels describe the ephemeris of one object against another. One SPK kernel prefixed with ‘ORHM’ describes the ephemeris of the spacecraft during cruise. During the nominal mission, there is typically one orbit file provided per month, prefixed with ‘ORMM’. Several Phobos and Deimos ephemeris kernels are provided, originating from ESOC, JPL or the HRSC instrument team. Ephemeris data for the ESA New Norcia station and the NASA DSN stations are also provided.

The DOCUMENT directory contains further information on the processing and use of the kernels provided.

6. Conclusions

The data flow and data integrity from the spacecraft to the payload team and to the scientific community are well defined. All the tools and services from the OCC to the PSA are operational, stable and in continuous use. The PSA released the first scientific data to the scientific community at large, and will provide a continuous support to scientists worldwide.

Acknowledgements

The data path from the spacecraft to the scientific users is accompanied by hundreds of engineers and scientists, including – and our apologies to those we have forgotten to mention – Pedro Osuna, Jesus Salgado, Guillermo San Miguel, Aurele Vrata Venet, Esther Parrila, Markus Fels, Phil Brabbin, Alessandro Ercolani, Angelo Rossi and Maud Barthelemy.

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