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Data processing and visualisation in the Rosetta Science Ground Segment

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ABSTRACT

Rosetta is the first space mission to rendezvous with a comet. The spacecraft encountered its target 67P/Churyumov-Gerasimenko in 2014 and currently escorts the comet through a complete activity cycle during perihelion passage. The Rosetta Science Ground Segment (RSGS) is in charge of planning and coordinating the observations carried out by the scientific instruments on board the Rosetta spacecraft.

We describe the data processing system implemented at the RSGS in order to support data analysis and science operations planning. The system automatically retrieves and processes telemetry data in near real-time. The generated products include spacecraft and instrument housekeeping parameters, scientific data for some instruments, and derived quantities. Based on spacecraft and comet trajectory information a series of geometric variables are calculated in order to assess the conditions for scheduling the observations of the scientific instruments and analyse the respective measurements obtained.

Images acquired by the Rosetta Navigation Camera are processed and distributed in near real-time to the instrument team community. A quicklook web-page displaying the images allows the RSGS team to monitor the state of the comet and the correct acquisition and downlink of the images. Consolidated datasets are later delivered to the long-term archive.

1. Introduction

Rosetta is a cornerstone mission in the science programme of the European Space Agency (ESA). After a cruise phase of ten years with two asteroid fly-bys and a hibernation period of two and a half years the spacecraft approached comet 67P/Churyumov-Gerasimenko in the year 2014. Rosetta entered bound orbits around the comet in September and deployed the Philae lander on the surface on 12 November 2014. Since then the spacecraft has escorted the comet through its perihelion passage at 1.24 AU in August 2015 and it will continue operating until September 2016.

First scientific results were presented in special issues of the Science magazine for the Rosetta orbiter [1] and the Philae lander [2]. A large amount of articles reporting important new results in cometary science have since been published, for example in a special feature of Astronomy & Astrophysics [3].

The spacecraft is controlled by the Rosetta Mission Operations Centre (RMOC) which is located at the European Space Operations Centre (ESOC) in Darmstadt, Germany. RMOC consists of the Flight Control and Flight Dynamics teams and their respective ground segment infrastructure. Spacecraft operations in the early comet phases of the mission are described by Accomazzo et al. [4].

The Rosetta Science Ground Segment (RSGS) is located at the European Space Astronomy Centre (ESAC) in Villanueva de la Cañada, Spain. Its role is to plan and coordinate the scientific observations based on the requests from the Rosetta principal investigators and instrument teams and then deliver consolidated instrument operation timelines to RMOC. The science planning process is described by Vallat et al. [5] and the operational implementation by Pérez-Ayúcar et al. [6]. The support given by RSGS for the operations of the Philae lander was summarised by Ashman et al. [7].

In this paper we describe the telemetry data processing system implemented at the RSGS and explain geometric computations relevant for supporting the planning and analysis of science observations. The processing and distribution of Rosetta Navigation Camera images is discussed and visualisation tools are presented.

2. Context and concept

The diagram in Fig. 1 is a simple representation of the relations between different entities involved in the Rosetta mission, with a focus on the interfaces between RSGS and RMOC.

RSGS provides relevant planning information to the instrument teams and in turn receives observation requests. Depending on the stage of the planning process, the requests range from high-level

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science objectives [5] to detailed instrument operation timelines [6]. RMOC commands the spacecraft and receives telemetry data via the ground station network.

There are two operational file transfer mechanisms installed between the RSGS and RMOC ground segments. The Data Disposition System (DDS) is mainly used for telemetry data requests and delivery, while operation requests and auxiliary planning files are exchanged via the File Transfer System (FTS).

Fig. 2 includes a conceptual drawing of the data processing and information system implemented in the RSGS in order to support science planning and data analysis. The main types of information considered are processed telemetry data as well as geometric quantities derived from planning files specifying the spacecraft trajectory and attitude. The central component of the system is technically implemented by means of a relational SQL data base.

Processing tasks are executed automatically in near real-time based on the availability of the respective input data. The information in the system can be retrieved by using a number of visualisation and reporting tools implemented for various purposes. In addition, the concept also allows the users to directly access the data base with customised programs for specific applications, which assures high flexibility without the need of formal development cycles causing delays and overheads.

The main users of the products generated by the system are members of the RSGS and the Rosetta instrument team community. Some items are only available internally to the RSGS and to other ESA entities. The term 'product' is used in this paper to denote information regularly processed by the system and stored in the data base – and not only to items that are systematically exported and made available in the form of 'product files'.

The emphasis of the system design is for usage during the active operations of the mission. However, many of the generated products are pertinent for later data analysis purposes and can be transferred to the long-term archive. For the image data of the Rosetta Navigation Camera regular archive deliveries are made during the course of the mission.

3. Telemetry data requests

Telemetry data are not automatically distributed to the RSGS after downlink from the spacecraft, but need to be requested by sending files to the DDS (cf. Fig. 1). The strategy for telemetry request submission was designed in order to meet the following main requirements:

- Completeness: All telemetry data packets shall be retrieved by the RSGS system (for the data types considered).
- Timeliness: For usage in a near real-time context the data shall be available in the RSGS system 'shortly' after they were

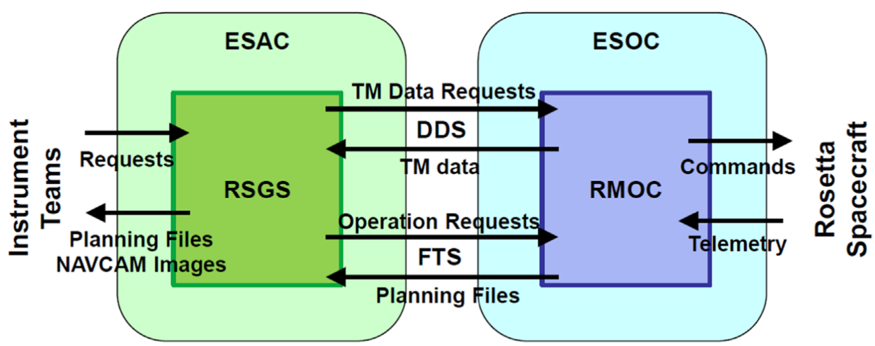


Fig. 1. Simplified diagram of the interfaces between the Rosetta Science Ground Segment (RSGS) and the Rosetta Mission Operations Centre (RMOC). For the system elements described in this paper the following 'Planning File' types sent from RMOC to RSGS are relevant: Comet trajectory (CORB and CORL), attitude (CATT), and shape (CSHP); Rosetta spacecraft trajectory (RORB and RORL) and attitude (RATT and RATM); Lander trajectory (LORB and LORL); schedule of ground station passes (FECS); and timeline of pointing blocks reserved for navigation and spacecraft maintenance (PTSL).

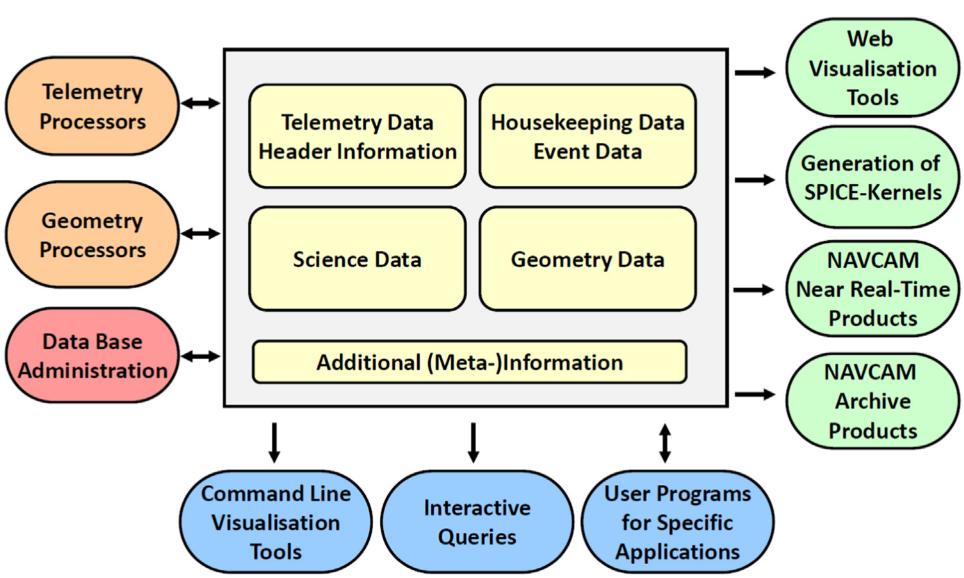


Fig. 2. Conceptual drawing of the information system. Processors generating the data products are listed on the left. Operational tools and applications exploiting the information stored in the system are shown on the right. Direct user access and informal applications are depicted at the bottom.

downlinked from the spacecraft and ingested in the RMOC ground system.

- Uniqueness: For efficiency and clarity the same telemetry packets shall (nominally) only be requested, transferred, and processed once.

The DDS interface offers two possibilities regarding the temporal reference of the requested time periods: by on-board generation time or by ground reception time of the telemetry packets. The second option was chosen for the implementation of the operational requests in the RSGS system. After the end of each ground station pass, the telemetry data are requested by ground reception time for the time period corresponding to that pass.

The Rosetta ground station pass schedule is typically updated once per week by the Flight Control team based on the latest information on pass allocation as communicated by the ESA Tracking Network (ESTRACK) and the NASA Deep Space Network (DSN). The schedule is sent to RSGS via FTS in the form of the so-called Flight Events and Communications Skeleton (FECS) file. After reception in the RSGS server infrastructure, the pass schedule information is extracted and ingested into a data base table by assigning a sequential pass identifier. Previously ingested passes are deleted if their end time is still in the future (and therefore the corresponding data requests have not yet been sent) and if the respective time period is covered in the validity range of the newly received FECS file.

The types of telemetry data to be requested can be selected by adding their corresponding Application Process IDentifiers (APID) to a configuration table. The system periodically checks whether the end time of the next scheduled and unrequested ground station pass plus a configurable waiting time has been reached. The waiting time is added in order to account for a possible latency in the availability of the data in the RMOC system. The corresponding request files in XML-format are then generated for all configured APIDs and sent to the DDS, which in turn transfers the corresponding raw telemetry data files to the RSGS server infrastructure.

No specific action is taken in case scheduled passes are cancelled on short notice without communication via the FECS. In the system this simply results in a pass identifier with no corresponding telemetry data. For robustness to the insertion of new passes on short notice (i.e. without communication via the FECS), the requested time periods are defined as continuous. For each pass (known by the system) the beginning of the request period is set to the end time of the previous request instead of to the start time of the pass. In this way unexpected passes and data dumps are also covered in the requests, albeit without a unique pass identifier.

Occasionally network problems or other technical issues with the server infrastructure lead to a failure of the file transfer between RSGS and RMOC. A bookkeeping table is used in order to register the arrival of data files for each of the requests sent to the DDS. Furthermore a web-page was set up for visually monitoring the file transfers via the information stored in the bookkeeping table. Requests for which no data files were received after one hour are displayed in red colour. Procedures are in place for manually resending the corresponding requests, either for individual files or for the complete set of files (all APIDs) corresponding to one ground station pass.

Operational telemetry data requests are configured for all science data and all housekeeping data of the Rosetta orbiter instruments, as well as for (selected) spacecraft housekeeping and event telemetry types.

4. Telemetry data processing

The execution of telemetry processors is triggered by the availability of raw telemetry data files transferred by the DDS to the RSGS server infrastructure in response to automatic data requests sent by the system (cf. Section 3). The processors to be launched for each type of raw telemetry are specified by APID in a specific configuration table. Various processors can sequentially be executed on the same input files. After all tasks are completed, the raw telemetry files are moved to a storage directory structure.

Most of the telemetry processors were set up in the present form towards the end of the Rosetta cruise phase. Regular data requests were reactivated after hibernation exit in January 2014. Some products were added at a later stage. In these cases the data were normally back-processed for the whole duration of the mission in order to have a complete record available in the system.

4.1. Header information

All telemetry packets sent by the spacecraft contain header information for identification and timing in a standardised format [8]. In the raw telemetry data distributed by the DDS, an additional header with information generated by the RMOC ground system is present [9]. For all housekeeping and science data types, for which automatic data requests are configured in the system, useful meta-information from these headers is systematically extracted by a specific processor and stored in data base tables per APID.

Table 1 summarises the information made available in this manner. In addition to the time stamps in UNIX time and spacecraft clock time read from the headers, the 'packet header processor' also computes and stores the corresponding UTC time as an SQL datetime variable. For the Rosetta mission the ground reception time is not included in the header added by the DDS to the telemetry packets for distribution. As explained in Section 3 the RSGS system requests the data by ground reception time after each scheduled ground station pass. The corresponding pass identifier is included in the name of the request file sent and the corresponding data file received. The packet header processor reads the identifier from the name of the data file and accordingly assigns the ground station pass information for each extracted telemetry packet.

The unprocessed data packets themselves are not stored in the data base. Housekeeping and science data processors run on the binary raw telemetry files. In an extension of the packet header processor, the packet data field could also be ingested in order to create a full raw data archive. For the present system such a facility was not required. It would increase the complexity of the implementation.

Table 1
Information extracted and stored by the packet header processor. Packet data field and source packet headers come from the spacecraft. The DDS header is added by the RMOC ground segment.

Item	Source
UNIX time stamp – seconds	DDS header
UNIX time stamp – microseconds	DDS header
Ground station ID	DDS header
Virtual channel	DDS header
SLE (space link extension) type	DDS header
Time Quality	DDS header
APID (application process ID)	Source packet header
Sequence counter	Source packet header
Packet length	Source packet header
Spacecraft clock time – high counter	Packet data field header
Spacecraft clock time – low counter	Packet data field header
PUS (packet utilisation standard) version	Packet data field header
Packet type	Packet data field header
Packet subtype	Packet data field header
SID (structure identifier), also known as P1Val	Packet data field
UTC time stamp	Telemetry processor
Sequence counter break flag	Telemetry processor
Spacecraft time order break flag	Telemetry processor
Ground station pass ID	Telemetry processor

The data base tables containing header information extracted from instrument science data telemetry packets are systematically used for assessing the generated and downlinked data volume. The total data volume per time period of interest can conveniently be determined by means of a simple and fast SQL query. The packet length extracted from the source packet header indicates the number of bytes contained in the packet data field (including its header). Adding six bytes (per packet) for the source packet header itself then gives the total data volume transmitted from the spacecraft. The cumulative data volume graph shown as an example in Fig. 3 was also created with a single SQL query to the packet length information in the header information table.

4.2. Housekeeping data

Spacecraft and instrument housekeeping telemetry data is encoded in a standard format following specifications of the relevant interface control documents. Processors for housekeeping telemetry can therefore efficiently be implemented in a generic way. In the RSGS system the parameters listed below are processed for information and analysis purposes. Specific configuration details for the items of interest are extracted from a data structure known as the Mission Implementation Base (MIB) in the ESA ground segments.

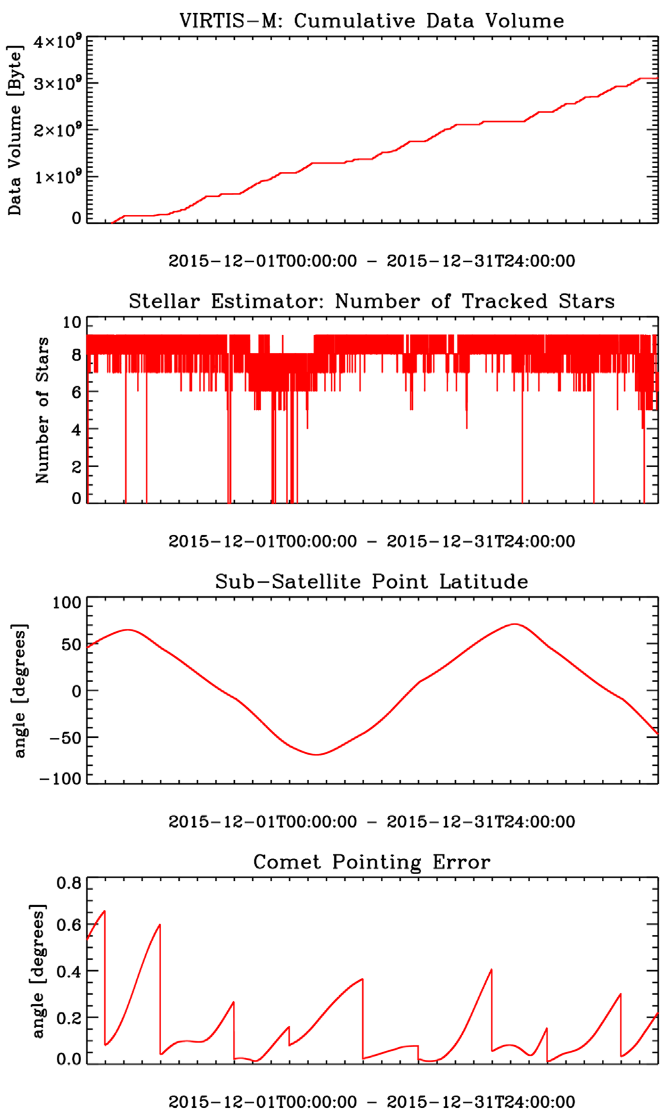


Fig. 3. Visualisation of time series for the period from 1 to 31 December 2015. From top to bottom: Cumulative data volume generated by the VIRTIS-M sensor (Section 4.1). Spacecraft housekeeping telemetry parameter 'number of tracked stars' (Section 4.2). Geometric variable 'sub-satellite point latitude' (Section 5.1). 'Comet pointing error' derived from trajectory files (Section 5.4).

- Solar array orientation angles ($+Y$ and $-Y$-panels).
- High Gain Antenna (HGA) orientation angles (elevation and azimuth).
- Estimated spacecraft attitude (four quaternion elements).
- Number of stars tracked by the stellar estimator.
- Instrument power consumption (as reported in spacecraft housekeeping data).
- Temperatures of the navigation camera detector and optics.
- Mode numbers for the sensors of the ROSINA instrument.
- Time offset for 'fine datation' correction.

The generated products are stored in the system in appropriate data base tables. As an example, Fig. 3 includes a graph depicting the number of stars identified by the operational star tracker and used for spacecraft attitude determination by the on-board estimator. The generic housekeeping processor (as well as all specific telemetry processors mentioned later in this paper) store time stamp information in all variants listed in Table 1, i.e. spacecraft clock time, UNIX time, and UTC in SQL datetime format.

The last item in the list above is of a technical nature and only available internally. It reports an offset which needs to be applied to correct the time stamps of certain types of spacecraft housekeeping data [10]. A feature for applying this 'fine datation' correction was implemented in the generic housekeeping processor. Among the parameters listed above, application of this procedure is configured for the orientation angles of spacecraft structures and the spacecraft attitude quaternions.

4.3. Instrument data

The processing of instrument science data is not within the scope of the RSGS activities. Data in the format of time series are nevertheless processed for two sensors and stored in the system for internal analysis purposes.

SREM is a standard radiation environment monitor incorporated in a number of ESA spacecraft [11]. It is sensitive to highly energetic particles with thresholds of 0.5 MeV for electrons and 10 MeV for protons. In the RSGS system the data are processed to the level of detector counts only and no higher level products such as particle fluxes are derived.

The COPS sensor is part of the ROSINA instrument [12]. It consists of two gauges measuring the pressure at the position of the spacecraft in the comet environment. While this information is of high scientific interest, the corresponding data are technically transmitted and downlinked as housekeeping telemetry. Consequently, the standard housekeeping format is applicable and the generic housekeeping telemetry processor is employed.

4.4. Derived products

The telemetry processors typically read the binary raw telemetry files received from the DDS as input. However, the system concept and implementation also allows processors to query information from the data base and to generate further products based on already processed results.

An example of such a derived product is the deviation between the spacecraft attitude as measured by the on-board estimator and the planned attitude as specified on ground and commanded to the spacecraft. For the computations the measured attitude is available in the form of processed housekeeping information as listed in Section 4.2. Operational files containing the commanded attitude profiles are distributed by RMOC via the FTS (cf. Fig. 1) and transformed by a component of the RSGS system into so-called SPICE-kernels (which are further described in Section 5).

The 'attitude deviation' processor is launched after each run of the housekeeping telemetry processor for the relevant APID. For each time step the difference angle between measured and commanded pointing direction is calculated for the spacecraft *X*-, *Y*-, and *Z*-axes. The latter one is the most relevant since it corresponds to the nominal boresight direction of the remote sensing instruments. The deviation angles are an indicator for the inertial pointing accuracy and stability. Exploitation of the information for quantitative data analysis purposes requires expertise on the functioning of the attitude control system and inspection of further telemetry parameters such as the number of tracked stars.

In the case of Rosetta, the attitude deviation product is mainly relevant for the inertial pointings employed with stellar calibration observations. For comet nucleus observations the pointing uncertainty induced by trajectory offsets is by far the dominant factor (cf. Section 5.4).

4.5. Event telemetry

Event telemetry generated by the spacecraft and instruments is distributed by the RMOC ground segment via the DDS in the same way as housekeeping and science data. Within the scope of the system described in this paper only event data files of the spacecraft star trackers are processed. The corresponding product was implemented after repeated problems with attitude acquisition occurred owing to the perturbation of the star tracker software by the presence of a very large number of dust particles appearing as 'false stars'.

Ultimately the star tracker problems led to a fundamental change of the mission operations concept, in particular regarding the trajectory planning process [5]. The occurrence of anomalous star tracker events is one of the criteria used by RMOC for assessing safety of spacecraft operations as a function of the distance to the comet. Visibility of the event information to the RSGS team and the Rosetta community is important for monitoring this process and for further analyses. The events are filtered to discard the nominal ones and only retain the anomalous star tracker events.

4.6. Time correlation

Command timelines for spacecraft and instrument operations are generated in the RMOC and RSGS ground segments in UTC time. On the spacecraft, however, activities of its sub-systems and instruments are triggered in terms of the counts of the on-board clock. Also the telemetry is recorded with respect to on-board clock counts.

The time correlation is a linear relation between ground time in UTC and spacecraft clock counts. Timelines of commands scheduled in UTC are converted to spacecraft clock time before upload to the spacecraft. Likewise, the spacecraft clock time stamps of telemetry packets are converted to UTC in the ground system by applying the conversion.

New time correlations are performed by the Flight Control team when the arrival times of specific telemetry packets indicate that the quality of the current time correlation exceeds an accuracy limit in the order of 5 ms. The coefficients of the linear time correlation relation are distributed by RMOC via the DDS in a format equivalent to telemetry data. Regular requests of the corresponding APID are configured in the RSGS system (cf. Section 3). The received data files are automatically processed and the extracted information is stored in the system.

In general, the data processing applications described in this paper make use of the time stamp information in UNIX time

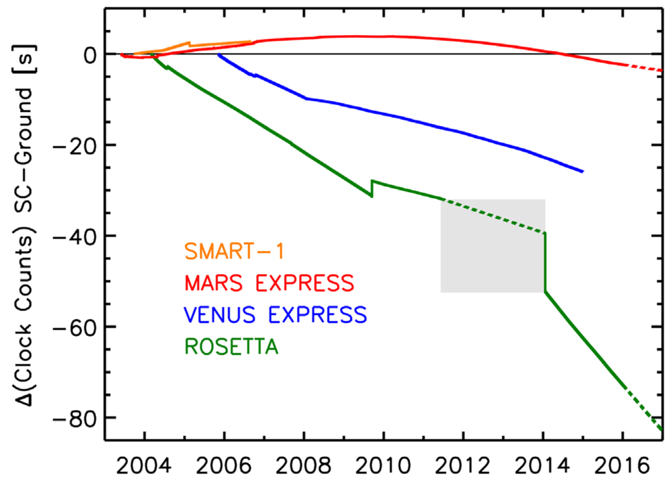


Fig. 4. Clock drift for planetary mission spacecraft derived from the piecewise linear fits of successive time correlations. The grey square corresponds to the Rosetta hibernation phase. At wake-up the difference between the pre-hibernation time correlation and UTC amounted to roughly 13 s. The jump of 3.5 s in September 2009 was due to the reconfiguration and switch to another clock after a safe mode. (The abscissa labels are centred on the beginning of the respective year.)

already included in the DDS-header for each telemetry packet (cf. Table 1) and there is no need to compute the time conversion. For some instruments, however, time stamps in spacecraft clock time can also be contained in the packet data field of the science telemetry which is not processed in the RMOC ground system. In these cases, the time correlation needs to be applied explicitly when processing the science telemetry data.

Fig. 4 illustrates the evolution of the clocks on board of several ESA spacecraft. The graph depicts the offset accumulated between the spacecraft clock counts and UTC time seconds during the course of the missions. This offset can be interpreted as the error which would be made if no time correlation was performed at all and the clock counts were taken as seconds. In this sense, the Rosetta clock was set at launch and now in 2016 after twelve years in space it is about 75 s slow. Changes of the clock speed and hence the time correlation can be caused by different thermal regimes and ultimately by ageing of the oscillator.

5. Geometry information

In addition to the processing of telemetry information, the system also comprises processors for computing time series of geometric quantities based on trajectory and attitude files. Depending on the periods considered, this information serves for science planning purposes or for supporting data analysis after acquisition.

Fundamental input are spacecraft and comet trajectory and attitude files generated by Flight Dynamics and delivered to RSGS via the FTS (cf. Fig. 1). In an intermediate step, which is not described in this paper, these files are converted to the native data format ('kernels') of the SPICE software package [13]. Routines from the SPICE library are used for many of the computations in the geometry processor.

At Long Term Planning (LTP) level the product files (CORL, RORL, and PTSL) span periods of several months and are released well before start of execution. At Medium Term Planning (MTP) level the spacecraft pointing plan for successive periods of four weeks used to be available and Flight Dynamics released a first version (RATM) of the spacecraft attitude file. However, in a revision of the mission planning scheme this step was removed and the corresponding files are no longer applicable from spring 2015 onwards (cf. [5,6]).

At the Very Short Term Planning (VSTP) level the Flight Dynamics products (CORB, CATT, RORB, and RATT) are released twice a weak. These file versions include a prediction for the near future and reconstructed trajectory information for the past. In the VSTP case, the availability of the respective SPICE-kernels triggers the automatic execution of the geometry processor. The VSTP files are cumulative and span the complete mission since the beginning of 2014. Hence at each run of the geometry processor the results of the previous run are overwritten and only one VSTP-level data base table is maintained. New sets of LTP (and previously MTP) level files are much less frequent. The geometry processor is then launched manually and for each LTP (and previously MTP) period a separate results table is created.

By default the sampling interval of the information computed by the geometry processors is configured as 60 s. In order to use common tools and equivalent implementations for data access, the time information is technically stored in UTC and UNIX time in the same formats as used in the telemetry processors (cf. Table 1). In addition, the ephemeris time (more precisely the Barycentric Dynamical Time, TDB) is also computed and stored for each time step.

5.1. General geometric quantities

The most basic variables characterising the conditions for scheduling science observation for a given spacecraft trajectory are summarised in the following list:

- Distance from Rosetta to the comet-centre.
- Phase angle with respect to the comet-centre, i.e. the angle Sun–comet-centre–Rosetta.
- Angular size of a 2 km radius sphere (as a rough estimate for the extent of the nucleus with respect to the instruments' fields of view).

For trajectory visualisation and detailed investigations, information on the spacecraft state vector is also available.

- Rosetta position vector in the Comet-centred Solar Orbital (CSO) frame.
- Relative velocity of Rosetta with respect to the comet (modulus of the relative velocity vector).

The location of the spacecraft in body-fixed reference frame is an important piece of information for science planning. It is best expressed in terms of the coordinates of the sub-satellite point, which is defined as the intersection between the Rosetta to comet-centre line with the surface.

- Latitude and longitude of the sub-satellite point. (See Fig. 3 for an example of the latitude evolution during a one month period.)
- Local time at the sub-satellite point.

The pointing direction of the spacecraft is characterised by computing the series of variables listed below. In the LTP variants of the set of quantities, the pointing timeline is specified according to the content of the PTSL file (cf. the caption of Fig. 1). It then includes pre-defined pointings for spacecraft navigation, but no specific pointings for science observations. In the MTP and VSTP variants, the full payload pointing plan is taken into account.

- Nadir off-pointing, i.e. the angle between the spacecraft to comet-centre vector and the spacecraft $+Z$-axis.
- Comet centre X- and Y-positions in spacecraft reference frame.
- Off-pointing of the $+Z$-axis with respect to the Sun direction and perpendicular to that direction.
- Pointing direction of the $+Z$-axis in J2000 inertial frame (right ascension and declination).
- Coordinates (latitude and longitude) of the intersection of the spacecraft $+Z$-axis with the surface of the comet nucleus.

Based on the directions to Sun and Earth, the predicted orientations of spacecraft structures are computed for planning purposes.

- Solar array orientation angle ($+Y$- and $-Y$-panels).
- HGA orientation angles (azimuth and elevation).

For a range of geometric configurations there are two solutions for orienting the HGA towards Earth and occasionally a flip between the two is required. One solution is chosen in the computations and a detailed modelling of the antenna movement is not attempted.

Information on the rotation state of the comet nucleus is provided by Flight Dynamics in the form of continuous attitude quaternion files (CATT). This format makes it possible to express any type of complex rotation pattern. However, it is convenient to transform the information into a number of quantities that are easier to interpret. The automatic derivation of the set of data products listed below was implemented in particular because prior to comet encounter and characterisation many of its properties were unknown and the choice of the comet-fixed coordinate system was not well-defined.

- Instantaneous comet rotation period.
- Pointing direction (right ascension and declination) of the instantaneous comet rotation axis in the J2000 inertial frame.
- Components of the instantaneous rotation axis vector in body-fixed reference frame.

For a set of pre-defined landmark coordinates the following variables are computed which allow the users to assess the observation conditions.

- Observation angle, i.e. the angle between the local surface normal and the vector from the landmark to the spacecraft.
- Visibility flag indicating whether the line of sight between Rosetta and the landmark is unobstructed.
- Illumination angle, i.e. the angle between the local surface normal and the vector from the landmark to the Sun.
- Illumination flag indicating whether the landmark is illuminated, i.e. whether the line of sight between the Sun and the landmark is unobstructed.
- Local time at the position of the landmark.
- Phase angle with respect to the position of the landmark, i.e. the angle Sun–landmark–Rosetta.

5.2. Instrument specific quantities

For the science planning of various instruments, specific quantities were included in the computations in order to support the respective liaison scientist and instrument teams. For assessing the suitable observation strategy of the VIRTIS-M instrument [14] the projected angles defined below are computed. Depending on the geometric configuration, it can be more appropriate to operate in ‘pushbroom-mode’ or to use the internal mirror of the instrument for scanning.

- Direction of movement of the sub-satellite point: Angle between the projections of both the sub-satellite point velocity vector and the spacecraft to Sun vector into the plane perpendicular to the line of sight from spacecraft to comet.
- Comet spin axis: Angle between the projections of both the comet spin axis and the spacecraft to Sun vector into the plane

perpendicular to the line of sight from spacecraft to comet.

The Rosetta Plasma Consortium (RPC [15]) contributes several instruments to the spacecraft payload: ICA [16], IES [17], LAP [18], MIP [19], and MAG [20]. For these sensors the computation of a series of geometric variables and checks was implemented. A detailed description is given in the technical note [21].

- Comet and Sun directions (azimuth and elevation) in the ICA reference frame.
- Flags indicating whether the comet and Sun are in the ICA field of view.
- Comet and Sun direction (azimuth and elevation) in the IES reference frame.
- Flags indicating whether the comet and Sun are in the IES field of view.
- Angle between the vector from LAP2 to LAP1 and the vector from the spacecraft to the comet-centre.
- Flags indicating whether the LAP1, LAP2, and MIP sensors are located in the solar wind wake or the comet flow wake (with respect to the spacecraft body or movable structures).
- Angle between the $+Z$-axis direction of the MIP reference frame and the vector from the spacecraft to the comet-centre.
- Angles between specific vectors defined by the LAP and MIP teams and the direction from the spacecraft to the Sun or the comet.

In support of the Radio Science Investigations (RSI [22]) the following variables are calculated. The first two are relevant for evaluating the conditions for the bi-static radar experiment and the third one for limb sounding observations.

- Angle Earth–Comet–Rosetta.
- HGA footprint size, i.e. the spatial dimension corresponding to the antenna lobe diameter (0.98° for a signal drop of 3 dB) at the distance of the comet nucleus.
- Shortest distance ('impact parameter') between the Rosetta to Earth vector and the comet-centre.

CONSERT [23,24] is a radar instrument with components on the Rosetta orbiter as well as on the Philae lander. As a consequence, lander related quantities are particularly relevant for assessing the geometry and also the comet shape model is important.

- Distance from Rosetta to Philae and visibility flag indicating whether or not the line of sight between the two is obstructed (by the comet).
- Relative velocity of Rosetta with respect to Philae (the component along the connection line).
- Geometric conditions listed for landmarks in Section 5.1, but referring to the landing site.
- Section length of the Rosetta to Philae connection line through the comet nucleus.
- Coordinates (latitude and longitude) of the point defined by the intersection of the Rosetta to Philae connection line with the surface. (The point closest to Rosetta is chosen in the case of multiple sections.)
- Velocity of this point on the surface.
- Angles Rosetta-comet-centre–Philae and Rosetta–Philae–comet-centre.
- Angle between the spacecraft $+Z$-axis and the connection line from Rosetta to Philae.

5.3. Trajectory independent quantities

The quantities listed in this section are independent of the Rosetta trajectory around the comet which is defined during the course of the mission in the science planning process. The variables are stored in a separate data base table which is only updated after the release of Flight Dynamics products for new LTP planning periods with possibly slightly improved ephemeris data for the orbit of the comet around the Sun.

- Distance from the comet to the Sun (and vector from Sun to comet in ECLIPJ2000 frame).
- Distance from the comet to the Earth (and vector from Earth to comet in ECLIPJ2000 frame).
- Angle Sun – Comet – Earth.
- Angle Sun – Earth – Comet, useful for identifying conjunction periods.
- Latitude of the sub-solar point, indicating the 'comet seasons'.
- Distance from Rosetta to the Sun (and vector from Sun to Rosetta in ECLIPJ2000 frame).
- Distance from Rosetta to the Earth (and vector from Earth to Rosetta in ECLIPJ2000 frame).

For the mission phases after comet encounter the Rosetta positions in the last two items of the list are virtually identical to the values for the comet. The interest of these entries is mainly for the cruise phase since they describe Rosetta's journey through the solar system before reaching 67P/Churyumov-Gerasimenko.

5.4. Trajectory offset and pointing error

Navigation of the Rosetta spacecraft with respect to the comet nucleus is a complex and difficult process. Owing to the limited precision of manoeuvres and unpredictable variability in the gas drag exerted on the spacecraft, the actually flown trajectory inevitably deviates from the predicted one. The commands for controlling the attitude of the spacecraft (with respect to the inertial J2000 reference frame) are generated on ground with the best navigation knowledge available at that time. An offset between the predicted trajectory (which served as a basis for command generation) and the actually flown trajectory therefore leads to an offset in spacecraft pointing with respect to the comet nucleus direction. See Section 4.3 in Vallat et al. [5] for a more detailed description.

The navigation and commanding process is carried out by the Flight Dynamics and Flight Control teams at VSTP level. Normally, the planning periods alternately comprise three and four days consistent with a weekly working scheme. The set of VSTP files released for a given planning period contains the predicted trajectory which has been used for the command generation for this upcoming VSTP period, a further prediction of the trajectory into the future, and a reconstruction of the trajectory for past VSTP periods based on the new navigation information available. A specific processor was developed which computes the trajectory offset and the resulting 'comet pointing error' from successive versions of the VSTP level spacecraft and comet trajectory files. The processor is automatically executed upon availability of a complete set of SPICE trajectory kernels for a new VSTP period.

- Along-track, across-track, and radial component of the difference vector ('error') between predicted and reconstructed position of the spacecraft relative to the comet. The radial error is defined positive if the reconstructed radial distance component is larger than the predicted. The along-track error is positive if the spacecraft is 'ahead' on its trajectory with respect to the prediction.
- Total position error, i.e. the modulus of the vector above.
- Comet pointing error, i.e. an angular off-pointing indicator calculated from the along- and across-track errors and the distance between spacecraft and comet-centre.

Fig. 3 includes an example graph for the comet pointing error. The three and four day pattern of the VSTP periods can be clearly seen. Typically, the comet pointing accuracy is best at the beginning of the commanding periods and then degrades as the trajectory deviates from the prediction. Information on the performance in the recent past is an important piece of information for the pointing design and uncertainty mitigation strategies for upcoming observations. Note that the error discussed here is relevant for pointing specifications with reference to the comet position, but not for inertial pointings such as those used for stellar calibration observations. For those the inertial pointing stability as quantified by the 'attitude deviation' product discussed in Section 4.4 is relevant.

6. Information access

This section summarises a number of operational tools which make use of the information generated by the telemetry and geometry processors. Furthermore, the concept also allows users to connect to the system directly for interactive work or customised applications (cf. Fig. 2).

6.1. Time series visualisation

Most of the information types processed by the telemetry and geometry processors are in the form of time series. Consequently, appropriate visualisation tools are required. A web-interface for accessing the quantities described in Sections 4 and 5 was implemented by re-using components of earlier developments. The tool is available to RSGS as well as to the Rosetta instrument team community. Some of the data items are not disclosed externally, though.

During development, care has been taken to define equivalent time formats for telemetry and geometry information in order to use common software. The variety of accessible data types includes spacecraft and instrument housekeeping parameters, derived quantities, science data products, events, data volume, and geometric variables. The example graphs shown in Fig. 3 for different information types have been generated with this web-tool. In the interface the user can select the relevant item and specify the time period of interest. If required, the ordinate range to be displayed can also be adapted.

Most of the quantities are read directly from data base tables as stored by the processors. However, there are also cases where a 'post-processing step' is implemented by means of the employed SQL query. This is for example done for obtaining the cumulative data volume from the row entries including the telemetry packet sizes.

For further investigations and analysis, the web-tool also offers the functionality of downloading the displayed data for the selected time period in csv-format.

6.2. Data volume reports

The telemetry packet headers, which are systematically processed and ingested into the system, include the complete information on the science data volume generated and downlinked from the spacecraft (cf. Section 4.1). Reports per instrument can conveniently be created by querying the respective data base tables. A specific web-page was set up for listing the data volume by UTC-day periods. In addition, an equivalent page is also available for the data volume downlinked per ground station pass, based on the pass identifier stored for each telemetry packet. Here the corresponding time range of the telemetry packets in on-board generation time can be displayed by 'mouse-over' the data volume numbers. The reporting pages are generated dynamically upon access by the user and therefore always reflect the latest state in terms of information processed by the system.

For checking the status of data downlink from the spacecraft, a dedicated web-page was set up in order to display for each instrument the on-board time stamp of the last telemetry data packet available in the system. Similar reporting tools can be implemented with small effort for other information items of interest. For example, a web-page was created for listing the time correlations (cf. Section 4.6) carried out in the RMOC ground segment.

6.3. SPICE-kernel generation

The geometry calculations of Section 5 rely on the availability of spacecraft trajectory and attitude in the form of SPICE-kernels. Conversely, the system also provides information for the generation of such kernels. As listed in Section 4.2, the orientation angles of solar arrays and high gain antenna are extracted from spacecraft housekeeping telemetry. The values are read by the respective RSGS system component [25] and transformed into 'C-kernels'. Updated kernels with newly available information are created once per week and released via a public ftp-server. Knowledge of the orientation of spacecraft structures is for example important for the analysis of RPC sensor data or for radio science investigations (RSI).

6.4. Interactive access

In addition to the formal tools explained in the previous subsections, the information system is also open for direct user access – either by connecting to the data base in command line mode for interactive work or by means of user-developed customised programs (cf. Fig. 2).

Such applications include three-dimensional visualisations of the comet and spacecraft orbit in the solar system or the Rosetta trajectories around the comet nucleus. Further graphs generated by user programs retrieving information from the system are shown in Fig. 5. Plots of the spacecraft ground track on top of a digital elevation map of the comet surface were frequently used in discussions regarding the design of close fly-by trajectories. Finally only the two close fly-bys included in the graph have been realised (so far) because of the star tracker problems encountered during execution.

The position of the Sun and the comet as well as of the spacecraft body and structures in the field of view of the RPC sensors is useful for planning as well as for data analysis purposes. An analogous application is the simulation of comet position and solar panel orientation in the field of view of the Philae CIVA camera [26]. This was used for validating the pointing design for the Rosetta 'selfies with comet'. See Figs. 3 and 4 in Ashman et al. [7] and the cover image of [3].

Expert users with specific privileges can run the geometry processor with study trajectories and make use of the functionalities of available tools for analysis. The results of these runs are not displayed via the externally accessible visualisation tools, but on equivalent internal versions. The geometry computations implemented in the processor were extensively used for testing pointing specifications. In addition to the (one-dimensional) time series visualisation, plotting the pointing direction with respect to the comet nucleus in two angular dimensions proved to be very helpful for checking the implementation of scans and rasters, especially in the early mission phases in order to become acquainted with the pointing interface. Another example is graphs of the spacecraft pointing direction in inertial J2000 frame for the visualisation of slews between stellar pointings.

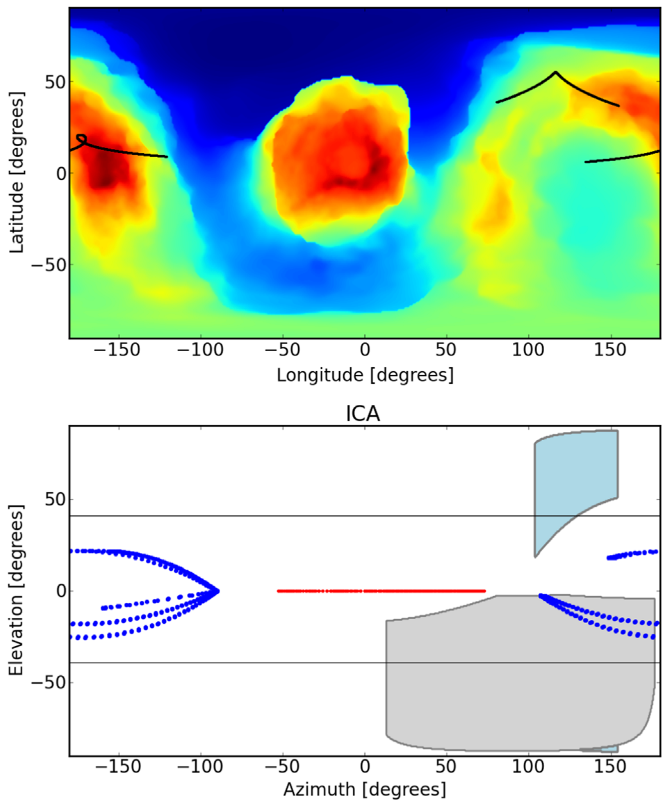


Fig. 5. Examples of graphs created with user programs accessing the information in the data base. Top: Ground track overlaid on a digital elevation model of the comet nucleus (based on Flight Dynamics shape model #6 released in August 2015). The colour scales range from a centre distance of 0.47 km (dark blue) to 2.65 km (dark red). The ground track is plotted for periods during which the spacecraft distance was less than 20 km in the year 2015. The black lines correspond to the close fly-bys on 14 February (at $-170°$ longitude) and 28 March (at $120°$ longitude). Bottom: Positions of the Sun (red dots) and the comet nucleus (blue dots) in the reference frame of the RPC-ICA sensor for the period from 1 to 10 July 2014. The horizontal lines indicate the elevation limit of the sensor field of view. The grey area depicts the directions obstructed by the spacecraft body and the light blue area the directions blocked by the solar panels (when oriented perpendicular to the spacecraft *X*-axis). (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this paper.)

6.5. *Opportunity analysis*

For planning and scheduling scientific observations in planetary missions it is essential to identify the periods with appropriate geometric conditions. As described in Section 5, the relevant quantities are systematically calculated at various stages of the planning process and stored in data base tables. Opportunity windows for specific observations can therefore easily be found by means of simple SQL queries with the relevant conditions. Any subset of the available variables can be combined logically in order to restrict the results as needed.

Let us consider as an example the objective of deriving the surface composition during the Global Mapping Phase in September 2014. Spatial resolution and illumination constraints, respectively, can be translated into upper limits on the spacecraft distance (50 km) and the phase angle (70°). The relevant planning period is LTP001 and we consider the nominal trajectory plan A for the pre-landing phases. The query

```
SELECT utc FROM tra_ltp001_a WHERE d_ros_com < 50.   AND a_phase < 70.
```

delivers a list of time steps for which the required conditions are met. Taking into account the sampling interval, this can easily be reduced to the opportunity windows for scheduling the observations:

$$[2014-09-12T00:11:00,\ 2014-09-15T14:01:00] \quad \text{and}$$

$$[2014-09-19T03:37:00,\ 2014-09-22T16:31:00].$$

The complete procedure described here was implemented in a short user program with in the order of 20 lines of code. The system was used in this way in order to support the science planning activities of the RSGS liaison scientists and instrument teams.

6.6. *Feedback with uplink*

Part of the information processed by the system is also exploited for comparison with the corresponding uplink information, e.g. for confirming the execution of instrument observations and checking the data volume estimates used in the planning process. These RSGS components are presented by O'Rourke et al. [27].

7. Navigation camera images

The images acquired by the Rosetta Navigation Camera (NAVCAM) are essential for determining the position of the spacecraft with respect to the comet nucleus and hence for navigating the spacecraft in the comet vicinity. The NAVCAM data are processed in the Flight Dynamics system at RMOC for these critical spacecraft operations purposes.

In the RSGS system the NAVCAM data are processed in order to provide visibility of the comet properties and their evolution to the Rosetta team at ESAC, for distribution to the Rosetta instrument team community, for outreach purposes, and finally for delivery to the long-term archive and publication.

NAVCAM images required for spacecraft navigation are scheduled by the Flight Dynamics team. In addition, context images for scientific observations can be requested by the ALICE instrument [28] team. These NAVCAM Context Image Requests (NCIR) are communicated by the RSGS to RMOC with a specific interface file. Since August 2015 the RSGS also schedules additional images via this interface for improved comet activity monitoring and for calibration purposes.

For redundancy there are two identical NAVCAMs installed on the Rosetta spacecraft. For both of them the respective image and housekeeping telemetry data APIDs are configured in the RSGS data processing system, although nominally only the NAVCAM-1 unit is used during the comet escort phase.

7.1. *Data processors*

NAVCAM image telemetry data are handled with a specific processor extracting the image as well as the corresponding meta-information such as the integration time, gain, and filter element used. The dynamic range of the camera is 12 bits and therefore pixel saturation occurs at a digital number value of 4095. Two pixels are stored in three bytes in the raw telemetry and one telemetry packet corresponds to one image row. The information is assembled into images of the commanded window size with two bytes per pixel.

The processor can cope with partial images, either due to the loss of telemetry packets because of bad weather or other ground station problems, or because at the end of a ground station pass the downlink of an image is not yet completed. In the latter case, the image is automatically completed in the next run of the processor (provided that the remaining data have been downlinked in the meantime). For this purpose the processor checks for each encountered image in the telemetry data stream whether for the same acquisition time a (possibly partially) processed image is already available in the system. If yes, the existing image information is read in and merged with the newly processed data.

Missing rows are padded with zeros so that the processor always delivers an image of the commanded size. The number of missing rows is reported as a quality indicator. The position of the missing rows in the image is evident from the assigned zero values since the digital numbers read from the CCD are always larger than a positive offset (bias). Context images have low downlink priority and under some circumstances it can occur that only a few rows are downlinked during several consecutive ground station passes. A number of passes and runs of the processor are then required to complete the image.

The processor also computes a series of geometric quantities such as the comet distance, the sub-satellite point coordinates, and the inertial pointing direction of the camera boresight at the time of image acquisition.

NAVCAM housekeeping data are processed by the generic telemetry processor (cf. Section 4.2). The temperature of the CCD detector and the camera optics is extracted, stored in the system, and included in exported image product files. The temperature information is useful for the quantitative radiometric calibration of the images.

In addition, data acquired in the NAVCAM point target tracking mode are also treated with the generic housekeeping telemetry processor. This camera operating mode was only used occasionally during the mission. Consequently, it was not required to include the product in the configuration of the automatic pipeline. The processor was launched manually on the respective raw telemetry files. The data consist of continuous time series of the position, velocities, and magnitudes of point sources identified and tracked within the NAVCAM field of view.

7.2. Quicklook visualisation

A quicklook web-page was implemented to visually monitor the state of the comet and check the correct acquisition and downlink of the NAVCAM images. The tool is only available internally to members of the ESA Rosetta mission teams. A screenshot of the web-page is shown in Fig. 6. The user can rapidly display the data for the last two days, or select past images by adjusting the start and end dates accordingly. The system contains all images acquired during the course of the Rosetta mission including the complete cruise phase.

The most important image acquisition parameters are listed and also the number of missing rows is displayed to easily identify incomplete images and data loss. The images are shown in reduced size, but full-size images can quickly be downloaded and displayed in appropriate viewer software. Grey scale converted images in PNG-format as well as the original data in FITS-format are available.

Housekeeping parameters and data acquired in the point target tracking mode can be displayed with the time series visualisation tool presented in Section 6.1.

7.3. Product file export and distribution

NAVCAM image product files are distributed in two versions (cf. Fig. 2) – a few hours after downlink from the spacecraft within the Rosetta community and later in the form of consolidated archive datasets for public access.

7.3.1. Near real-time products

Immediately after processing the telemetry data, product files are exported for near real-time distribution via an sftp-server accessible to the Rosetta instrument team community. The file export task is configured in the system in a way analogous to the telemetry processors. In this step different data sources are combined. The images and associated meta-information are taken from the results stored by the image data processor. The temperatures of detector and optics at the time of image acquisitions are read from the respective table populated by the housekeeping data processor. Further information such as the names of the mission phases is extracted from additional tables which are maintained manually.

Product files are generated in a format complying with the Planetary Data System (PDS) standard. The chosen variants are binary image files with accompanying detached PDS-label files. The product version number keyword in the label files is set to V0.1 in order to distinguish these products from the archive versions generated later. For convenience also a FITS-format version is provided with meta-information included in its header. Users of the near real-time products include in particular the ALICE team for context images supporting the analysis of their instrument data. Images made available shortly after acquisition are also regularly used for outreach purposes and displayed on the Rosetta blog [29] after some processing to reduce the presence of artefacts.

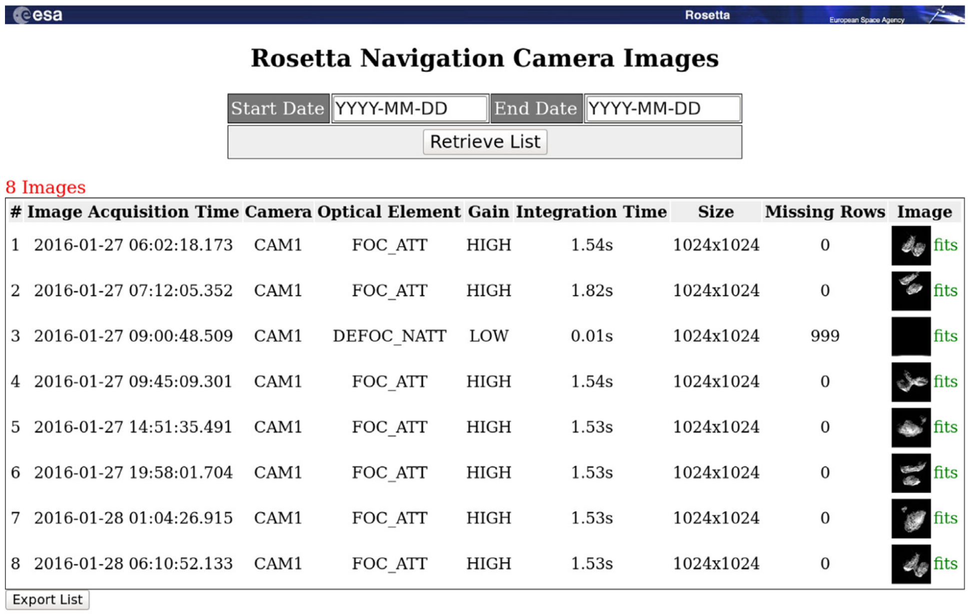
A label keyword indicating the observation type is assigned as 'context image' for images scheduled via the NCIR-interface and as 'navigation image' otherwise. By default the comet 67P/Churyumov-Gerasimenko is specified in the target keyword.

7.3.2. Archive products

At a later stage, datasets of image product files are generated for delivery to the Planetary Science Archive (PSA). At this time the reconstructed spacecraft trajectory is available and the values of the geometry dependent keywords in the label files are recalculated. In addition, the information on the observation type and the target reported in the corresponding label keywords is checked and revised – in particular by identifying the images scheduled for calibration purposes. Furthermore systematic completeness checks of the number of acquired versus the number of scheduled navigation and context images are made. Missing and incomplete images are documented along with the operational reasons for the absence of data.

The datasets are defined by MTP planning periods. The employed data export tool creates the required directory structure for the collection of the product files into datasets following the PDS3 standard. For each image, file versions in binary format and FITS-format are provided, both with a corresponding PDS-format label file. In addition, the datasets also include browse images of reduced size in JPG-format. The dataset structure is completed by the archive scientist and then passed to the PSA for archive ingestion and publication [30]. Detailed information about the structure of the datasets and the content of the product and label files is given in the NAVCAM Experiment to Archive Interface Control Document (EAICD) [31]. The product version number is specified as V1.0 for this release. The Rosetta data archiving process is described by Barthelemy et al. [32].

Initially the datasets were published with a delay of six months with respect to the end of the covered time period. Later this time was gradually reduced to one month. An example for the citation of Rosetta NAVCAM datasets (here for MTP013) is given as number [33] in the reference list. At the moment only uncalibrated datasets are available in the archive. In the relevant terminology these are denoted as 'Level 2' data. The generation and distribution of radiometrically calibrated images is foreseen. The corresponding 'Level 3' datasets are planned to be released during the course of the year 2016.



#	Image Acquisition Time	Camera	Optical Element	Gain	Integration Time	Size	Missing Rows	Image
1	2016-01-27 06:02:18.173	CAM1	FOC_ATT	HIGH	1.54s	1024x1024	0	fits
2	2016-01-27 07:12:05.352	CAM1	FOC_ATT	HIGH	1.82s	1024x1024	0	fits
3	2016-01-27 09:00:48.509	CAM1	DEFOC_NATT	LOW	0.01s	1024x1024	999	fits
4	2016-01-27 09:45:09.301	CAM1	FOC_ATT	HIGH	1.54s	1024x1024	0	fits
5	2016-01-27 14:51:35.491	CAM1	FOC_ATT	HIGH	1.53s	1024x1024	0	fits
6	2016-01-27 19:58:01.704	CAM1	FOC_ATT	HIGH	1.53s	1024x1024	0	fits
7	2016-01-28 01:04:26.915	CAM1	FOC_ATT	HIGH	1.53s	1024x1024	0	fits
8	2016-01-28 06:10:52.133	CAM1	FOC_ATT	HIGH	1.53s	1024x1024	0	fits

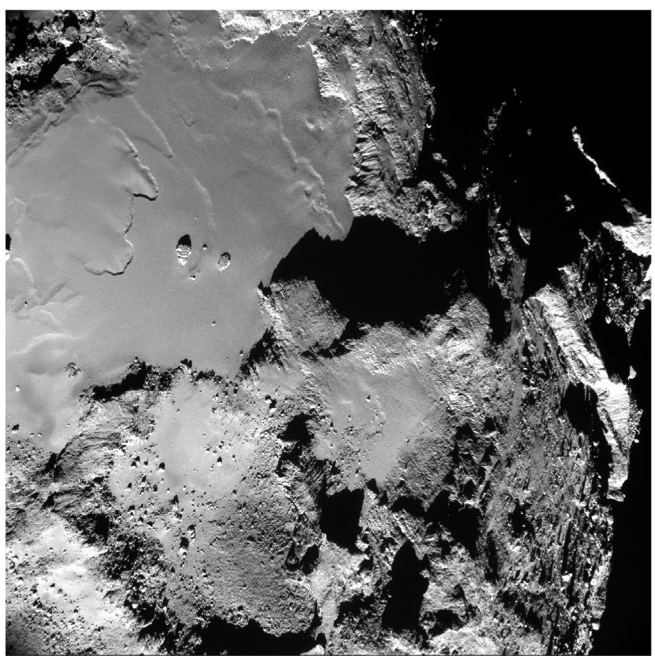


Fig. 6. Top: Screenshot of the NAVCAM quicklook web-page. Start and end dates were left unspecified here, which by default shows the images acquired on the previous and the current day. The graph was generated in the morning of 28 January 2016. Clicking on the thumbnail-sized previews opens the full-sized images in PNG-format for display or download and the links labelled *fits* give access to the data files in FITS-format. Bottom: NAVCAM image of the surface of comet 67P/Churyumov-Gerasimenko acquired on 14 February 2014 at 16:12 UTC while the spacecraft was at a distance of 17 km from the nucleus centre. The smooth terrain towards the upper left is the region known as Imhotep.

8. Miscellaneous

8.1. Programming languages

The telemetry and geometry processors are written in the C language. Reasons are computational efficiency and the availability of libraries for data base access as well as SPICE routines. In addition to the standard SPICE package, extensive use is also made of the Digital Shape Kernel (DSK) sub-system for problems involving the comet shape model and for spacecraft wake computations.

The data base at the core of the system is MySQL. Web-interfaces are implemented in PHP with some JavaScript functionalities. Telemetry request and process handling scripts are written in Perl. The generation of NAVCAM products by exporting the data base information is also realised in Perl. An exception is the creation of files in FITS-format which was added at a later stage. This is achieved with Python making use of the routines provided by the astropy module [34]. Informal user programs were typically developed in Python.

8.2. Version control

All elements of the processing pipeline and the visualisation tools are under version control using CVS. The PDS-format label files for the NAVCAM image products include the keyword PIPELINE_VERSION_ID. For traceability the relevant processors, configuration files, table structures, and export scripts are CVS-tagged with the respective pipeline version number.

Table 2
Log information generated by the NAVCAM image processor. The example corresponds to the last execution before the screenshot of the quicklook web-page for Fig. 6 was created.

Date	Time	Severity	Message
2016-01-28	09:50:30	info	Started camproc v0.6 on file R_0460_GRT_2110_2016-01-28.dat
2016-01-28	09:50:34	warning	Merged with an existing image of 1004 missing rows at 2016-01-27T09:00:48
2016-01-28	09:50:34	info	Found 2053 telemetry packets
2016-01-28	09:50:34	info	Ingested 3 CAM1-images into tables cam_-meta and cam_image
2016-01-28	09:50:34	warning	Encountered 2 sequence counter breaks
2016-01-28	09:50:34	info	Finished processing file R_0460_GRT_2110_2016-01-28.dat

8.3. *Log information*

The telemetry data requests scripts (Section 3), the telemetry processors (Sections 4 and 7), and the geometry processors (Section 5) generate log information in an identical format. Table 2 shows an example of the log information generated by a run of the NAVCAM image processor. During execution the log-entries are directly written into data base tables from where they can conveniently be accessed by means of a Log-Viewer web-tool.

8.4. *Usage in other missions*

Many of the elements of the data processing pipeline and visualisation tools are based on earlier developments carried out for the Venus Express mission. The same generic housekeeping telemetry processor was employed in that project for the following parameters: solar array orientation angles (used for the subsequent creation of SPICE C-Kernels), reaction wheel angular momentum, measured spacecraft acceleration, and the number of tracked stars. Also, the spacecraft attitude deviation was determined from on-board estimated quaternions in the same way as for Rosetta (cf. Section 4.4). Customised processors following the same concept were set up for spacecraft data with different structure such as memory pointers and housekeeping data with high sampling rate ('8 Hz memory cell'). Science data products for the Venus Monitoring Camera (VMC [35]) and magnetometer [36] instruments were generated with specific processors. Furthermore quicklook web-pages were available for these instruments in order to monitor the correct acquisition and downlink of the data.

The housekeeping telemetry processor is also used in the Mars Express project. The processed parameters include the orientation angles of the solar arrays (for the creation of SPICE C-kernels) and quaternion elements for computing the derived spacecraft attitude deviation product in the same way as for Rosetta and Venus Express.

9. Conclusion and perspectives

In the Rosetta Science Ground Segment an integrated information system is used for telemetry and geometry data processing applications. Regular tasks are fully automated and carried out in near real-time. The system contains information for periods in the past, the present, and in the future. It comprises information relevant for planning purposes in the uplink chain and also for analysis purposes derived from telemetry data after downlink. Engineering, geometry, as well as science data are considered.

Among the very large number of housekeeping parameters generated by the spacecraft only a small number were selected and are currently processed and stored in the system. The effort to include all available parameters would be relatively small since the format of the raw data as well as the conversion relations to engineering values are standardised. In an extended system it is advisable to process all parameters systematically in order to be flexible for applications requiring new types of information. However, finding a particular parameter and acquiring a good understanding of its significance often requires the consultation of the experts in the Flight Control team. Therefore only those parameters that are well understood by the members of the Science Ground Segment should be made visible and available for general use.

Science data are systematically considered in the system for data volume analysis purposes, but only for two sensors the data are processed to extract the information content. Nevertheless, the images acquired by the Navigation Camera are also of high scientific value and the data structure is equivalent to a science instrument. The processing, quicklook visualisation, product file creation, distribution, and archiving of NAVCAM images can therefore serve as an example case for the treatment of science instrument data in such a system.

The concept also foresees the ingestion of planned instrument operation timelines into the same information system in order to close the loop between uplink and downlink information. At the present time this could only be realised in a limited way for the NAVCAM context images scheduled via the RSGS. For the future it will be useful to spend some effort on the definition of a common data model for instrument operation timelines and processed time series of telemetry data in order to fully exploit the synergies of combined analysis and visualisation tools.

Because of limited development time and resources some components of the system could not be implemented in a way that meets all user requirements. An example is the available time series visualisation tool, which is simply a web-interface to a previously developed command line tool for generating the graphs. Appropriate and modern web-technologies should be used in order to develop a more interactive and dynamic interface. Functionalities should for example include overlays of various quantities in the same view, as well as scrolling and zooming in the timeline. For housekeeping parameters some components of the mission operation ground segments at ESOC offer these features. However, the emphasis of the concept followed here is on the combination of different information types from a variety of sources to achieve a comprehensive view. A generic time series and timeline visualisation tool is therefore recommended as a dedicated module of the Science Ground Segment infrastructure for planetary missions.

An important feature of the concept is the direct user access to the data base. This is geared towards mission scientists who generally have a detailed understanding of the information content and at the same time have sufficient computer literacy to program their own applications.

The functionalities described in this paper have been extensively used by members of the RSGS and the Rosetta instrument team community for the preparation of science observations and for data analysis throughout the pre-landing and comet escort phases of the Rosetta mission.

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