The U.S. Rosetta Project: Preparations for Prime Mission, 2014

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Abstract—In 2014, the International Rosetta mission will place a spacecraft in orbit around comet 67P/Churyumov-Gerasimenko and deliver a lander to the comet's surface. The National Aeronautics and Space Administration's (NASA) contribution to the International Rosetta mission, designated the U.S. Rosetta Project, includes several instruments, tracking support, and science support for some non-US payloads. In July 2011 the spacecraft was placed in a long-duration hibernation mode planned to last approximately 37 months to conserve electrical power. Rosetta will rendezvous with 67P/Churyumov-Gerasimenko in 2014. On the eve of the mission's arrival at its target, this paper highlights three issues related to Rosetta's looming prime mission: (A) measures taken in 2009 to prepare the US Rosetta Project for the long-duration hibernation mode; (B) risk reviews conducted in 2013 to prepare the US Rosetta Project for exit from hibernation; (C) ESA and NASA preparations for use of NASA Deep Space Network (DSN) assets related to keyword files. [1,2]

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1. INTRODUCTION

ROSETTA, the third of ESA's cornerstone missions within its Horizon 2000 science program, will place a spacecraft in orbit around comet 67P/Churyumov-Gerasimenko, deliver a lander to the comet's surface, and perform detailed scientific study of the comet including chemical /mineralogical analyses, surface morphology studies, gas/dust interactions studies, and global characterization of asteroids encountered during transit to the comet. The science objectives of the Rosetta mission are to study the origin of comets, the relationship between cometary and interstellar material, understand the origin and evolution of the solar system, and perform asteroid science *en route.*

The Rosetta spacecraft was launched from the Guiana Space Centre on 2 March 2004 in an Earth-escape trajectory with a complicated set of gravity assists including Earth swing-bys in March 2005, November 2007, and November 2009, and a Mars swing-by in February 2007 to accumulate the delta-V needed to match the spacecraft's heliocentric orbit with that of the comet. This trajectory provided for flybys and science opportunities at asteroid 2867 Steins in 2008 and asteroid 21 Lutetia in 2010 [1]. The present mission plan calls for rendezvous with 67P/Churyumov-Gerasimenko on 22 May

[1] 978-1-4799-1622-1/14/$31.00 ©2014 IEEE.
[2] IEEEAC paper #2432, Version 5, Updated October 7, 2013

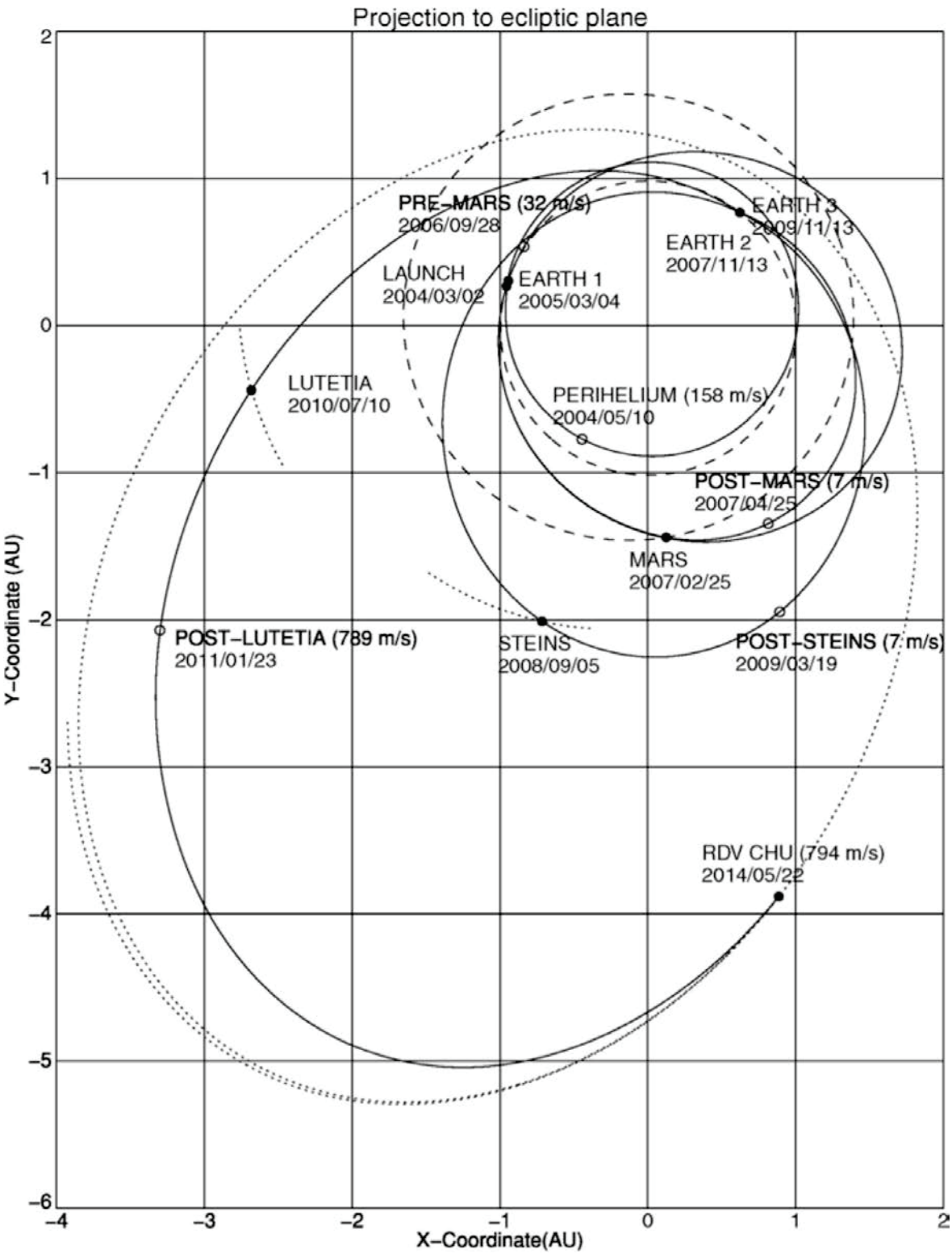

Figure 1. Trajectory of the Rosetta Mission. Hibernation takes place at aphelion (lower left area of the trajectory, for approximately 40 months, after the post-Lutetia maneuver.

2014, and delivery of the Lander on 11 November 2014. The comet science phase lasts for approximately 18 months. The end of the primary mission is planned for December 2015 [2].

The National Aeronautics and Space Administration's (NASA) contribution to the International Rosetta mission is designated the U.S. Rosetta Project. The U.S. Rosetta Project consists in part of three instruments: Alice (an

ultraviolet spectrometer), IES (the Ion and Electron Sensor, a plasma instrument), and MIRO (the Microwave Instrument for the Rosetta Orbiter). A fourth instrument, ROSINA, the Rosetta Orbiter Spectrometer for Ion and Neutral Analysis, is a European investigation with a U.S. hardware contribution consisting of a portion of the electronics package for one of the sensors known as the Double Focusing Mass Spectrometer (DFMS). These elements comprise the NASA hardware contribution to the payload of the International Rosetta Mission. In other contributions to the mission, NASA provides tracking support for ESA by way of its Deep Space Network (DSN). In addition, NASA supports an interdisciplinary scientist (IDS) and Co-Investigators (Co-Is) on non-U.S. payload instruments: the Optical Spectroscopic and Infrared Remote Imaging System (OSIRIS); the Visible and Infrared Thermal Imaging Spectrometer (VIRTIS), and Radio Science. Details of the instruments and of NASA's role can be found in the instrument description papers [3, 4, 5, 6, 7].

The spacecraft trajectory post-Lutetia has taken the Rosetta spacecraft to beyond five astronomical units (AU) from the Sun, with the comet encounter at just under four AU, resulting in reduced power from the solar arrays. For example, at 5.25 AU the total solar array power is expected to be just 395 W [8]. To limit power consumption Rosetta is being operated in "hibernation mode" where most electrical systems were turned off except for critical systems such as heaters, the on-board computer, and the radio receiver. The spacecraft is spin-stabilized with the solar arrays facing the sun, rotating at about one and a half revolutions per minute. A hibernation mode test was performed successfully in January 2010. The Rosetta spacecraft entered into hibernation on June 8, 2011 and will operate in this mode until January 20, 2014.

Preparations made by the U.S. Rosetta Project for this phase of the mission, underway for more than two years, included: comprehensive risk mitigation reviews, characterization of the instrument(s) thermal environment, final flight software updates, close-out of cruise anomaly investigation(s), cross-check of instrument concerns with the Rosetta spacecraft team in Europe, and practice with the DSN of 'wake-up' from hibernation activities. Science team preparations included ramp up of operations process definition, software for measurement planning, and enhanced support for prime mission planning activities. The mission must emerge from hibernation ready for prime mission science. Instrument concerns entering this phase of the mission included guarantees of a stable thermal environment, and some mechanical issues with long-duration and cold non-activity with certain doors. This paper summarizes the science team planning, operations and tests performed to prepare the U.S. Rosetta Project for long-duration hibernation on-board the Rosetta spacecraft.

2. 2009 HIBERNATION PREPARATIONS

Alice

The Alice instrument [3, 4, 7] will obtain spectra of the nucleus and the coma in the 700-2050 Å bandpass (ultra-violet and extreme ultra-violet wavelength regions). This investigation will: (1) directly determine the volatilized helium (He), neon (Ne), argon (Ar), and possibly krypton (Kr), and the nitrogen (N2) content of the nucleus to provide information concerning the temperature of formation and the thermal history of the comet since its formation; (2) directly determine the production rates and spatial distributions of the key parent species, water (H2O), carbon monoxide (CO), and carbon dioxide (CO2), thereby allowing the nucleus/coma coupling to be observed and interpreted without significant ambiguities; (3) obtain unambiguous atomic budget measurements of carbon, hydrogen, oxygen, nitrogen and sulfur in the coma to derive the elemental composition of the volatile fraction of the nucleus; and (4) study the onset of cometary nuclear activity. Additional objectives include (5) mapping the cometary nucleus at far-UV wavelengths and characterizing the presence of icy UV absorbers on its surface; (6) studying the photometric properties of small grains in the coma as an aid to understanding the size distribution of cometary grains and how they vary in time; and (7) mapping the time variability of O II, C II, and N II emissions in the coma and ion tail around perihelion to connect nucleus activity to changes in tail morphology and structure, and coupling to the solar wind.

Two anomalies (described as "upset" or "reset" events) occurred—first during Payload Checkout 8 (PC8) in July 2008 and then during PC 10 in September 2009. The PC8 event occurred during Alice initial activities just after the high voltage (HV) ramp-up during the Interference Campaign (IC). PC10 occurred after Alice had completed one perpetual pixel list observation. In both incidents, data in the event, command, and housekeeping files indicated Alice experienced some kind of power restart. Alice was operating in programmable read-only memory (PROM) consistent with having a reset since there would be no subsequent on-board control procedure (OBCP) command to tell Alice to switch to electrically erasable programmable read-only memory (EEPROM).

Table 1. Alice operations and consumables: October 2010.

Launch	2004 March 2
Operation time	2400 days (57600 hours).
Alice powered ON	~150 times for a total of ~2250 hours
HVPS turned ON	~120 times for a total of ~1500 hours
acquisitions	4034 acquisitions for a total of 1342 hours of exposure time.
Aperture door flaps to date	~1050 in flight, ~1350 total
	Qualified for >10,000 in mission. Expect a total of ~1100 flaps before comet arrival

Both in flight and ground efforts to reproduce the upsets or determine the underlying cause were pursued. A repeat of the PC8 Interference Campaign timeline during which Alice first experienced an upset event was done on the spacecraft during PC10. All instruments participating in the campaign, ALICE, MIRO, OSIRIS and VIRTIS, successfully executed the same commands, operations proceeded as expected and no upset event occurred. The execution of the IC timeline happened 10 days before the PC10 upset event with several Alice power cycles during the interim, suggesting that the second upset event was unrelated to the interference test. Long-duration ground testing running version 2.07 flight software on the software test bed testing each of the four EEPROMs has been ongoing since December 2009. After running for 6896 hours, all tests completed nominally and no upset anomalies occurred. Long-duration flight testing during PC12 in which Alice was run for 24 hours in each of the four EEPROMS to test upset frequency did not reproduce any upset events.

Analyses into external factors that may have contributed to the upset events were pursued. An investigation of interference from other instruments possibly contributing to the resets revealed that during the PC8 incident, OSIRIS, MIRO and VIRTIS were on during the upset event but under minimal operations, being in either susceptible or standby mode. During the PC10 incident, no other instruments were active. Investigations into high energy particle events potentially causing the upset/reset events revealed that data from the Rosetta Standard Radiation Environment Monitor (SREM) indicated no unusual particle flux activity and analysis of the National Oceanic and Atmospheric Administration (NOAA) space weather data showed no unusual activity.

Operational mitigation steps have been implemented to minimize the impact if Alice experiences another upset/reset event. Commands inserted in the timeline before selected Alice exposures include: (1) Reset HV set point to the nominal value so that after a restart, the HV is set to a safe, low, but non-operational value allowing any acquisitions following a restart to proceed nominally; (2) Set housekeeping rate to a more frequent value if desired; and (3) Set time synchronization command if desired.

Other strategies were developed in addition to the operational mitigation steps already planned:

1) Intentionally command power on resets more frequently to ensure instrument response to power cycling is controlled and Alice is put in an expected state. If an anomalous upset event occurs, this operational precaution should contain the duration that Alice is placed in an unexpected state.

2) Verify which flight software versions were running when the incidents occurred and determine that changes between software versions would not contribute to an upset/reset event. The long-term duration testing on the software test bed utilized v2.07 and was unable to reproduce the upsets, but it appears that earlier software versions were executing when the upset events occurred during PC8 and PC10. The differences between software versions were studied to eliminate the possibility that software changes would be a potential cause of the resets.

Ion and Electron Sensor (IES)

The Rosetta Ion and Electron Sensor (IES) instrument [5, 10] is a plasma instrument consisting of electrostatic analyzers, one each for electrons and ions. Each analyzer covers an energy/charge range from 1 eV/e to 17 keV/e with a resolution of 4%. In general, IES measures the flux of ions and electrons as a function of energy, direction, and time in 256 bins over an azimuth range of 90 degrees and polar angle of 360 degrees (less spacecraft obstructions). Thus IES collects plasma data roughly in 2.8 π steradians of space, and samples plasma velocity space. At comet C/G, IES will investigate (1) the solar wind interaction with the cometary nucleus, (2) the processes that govern the composition and structure of the cometary atmosphere, and (3) the interaction between the solar wind and the cometary atmosphere. With the asteroid fly-by data now in hand, IES has obtained limited data in the solar wind with which to correlate with science objectives related to sputtering and ion implantation, electrical charging of the surface, and wake effects.

IES has experienced occasional communication link errors with the Plasma Interface Unit (PIU) during instrument checkouts in flight, resulting in unexpected multiple "IES PIU Link Error" event messages transmitted to the PIU. The PIU is the interface through which IES and the other Rosetta Plasma Consortium (RPC) instruments communicate with the spacecraft. Two of the incidents occurred in flight during memory dumps during Payload Checkout 10 (PC10) in September 2010 and Payload Checkout 12 (PC12) in April 2010, and one during a memory load during PC12 Engineering Qualification Model (EQM) ground testing in March 2010.

The PC10 link reset resulted in a burst of 64 event messages transmitted from IES to PIU causing PIU to go into a loop whereby PIU repeatedly transmitted the IES memory dump rather than IES science to the spacecraft even after IES rebooted twice. Nominal operations were restored by ground based commanding to reboot PIU. A risk mitigation strategy limiting the number of event messages from 64 to 10 was implemented after the PC10 incident and was in place for PC12. The PC12 link reset resulted in 10 event messages transmitted from IES to PIU. PIU did not go into a loop and no reboot was required. The link reset during EQM testing in preparation for PC12 resulted in three link error event messages. Unlike the incidents during PC10 and PC12, the link reset occurred during a memory load rather than a memory dump. This incident was attributed to noise during testing as the memory load commands leading up to the reset had checksum problems not previously experienced. After

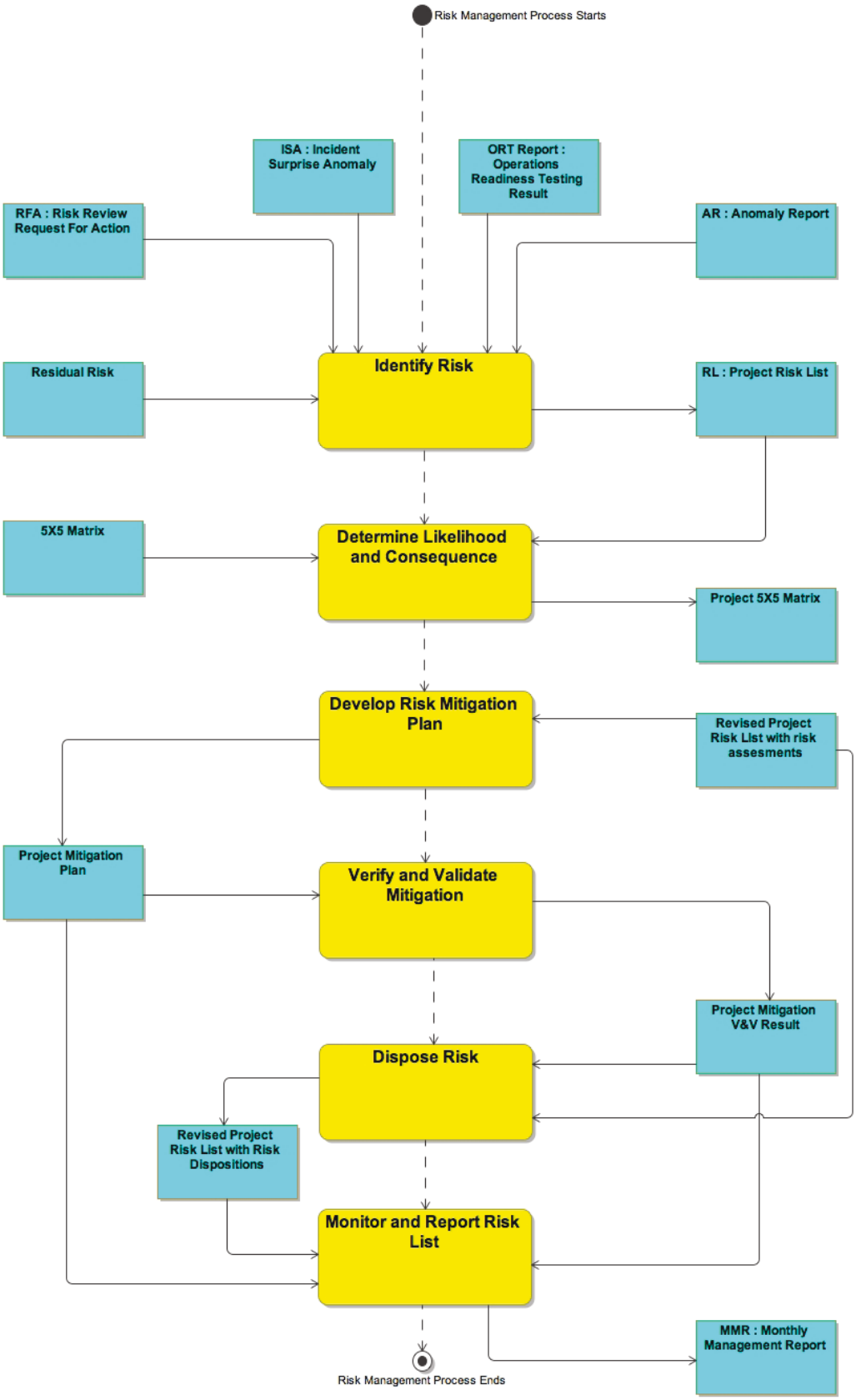

Figure 2. The Rosetta Mission risk management process.

stopping execution, a rerun of the identical test sequence resulted in successful operations with no checksum errors or link resets.

Telemetry analysis for the first link reset during PC10 showed that IES had triggered a communications link reset when a memory dump link packet was being sent. The IES PROM software allows up to four seconds for a link packet to be sent to the PIU. If not completed within that period of time, IES PROM software resets the interface between IES and PIU. The four second cadence was seen in the command sequence and telemetry timeline as the link resets occurred. While the link was unavailable IES queued up the event messages and when the link was re-established approximately 1 minute from the initial reset, the event messages were transmitted to the PIU and then to the spacecraft. The root cause for why it took so long is unknown.

Mitigation efforts to address concerns regarding loss of science and spacecraft safety as a result of the error event messages were pursued. The concern regarding the loss of science data is due to the inability of the PIU to handle a burst of event messages which resulted in loss of science data transmission, requiring ground intervention to restore nominal operation. Another concern expressed by mission operations personnel was the ability of the spacecraft command and data handling (CDH) system to handle such a burst since safing occurred as a result of a burst of event messages on the EQM and in flight on the Venus Express spacecraft which has the same fundamental spacecraft CDH system as Rosetta. These concerns were addressed by limiting the number of event messages to a manageable number.

The team settled on a strategy to limit the number of event message queue to 10 since such a number of event messages in rapid succession has been sent successfully several times in the past and did not cause anomalous behavior. For the EEPROM mode, the strategy was implemented by an update of the software code that was successfully tested on the EQM under induced link resets. The software updates was uploaded to the spacecraft during PC12. As the PROM code cannot be updated, the implementation is carried out by updating two variables in SRAM after the PROM code is copied to it. The steps to update the variables will be performed each time IES operates in PROM mode. The PROM mode strategy was successfully tested on the EQM by inducing link resets and successfully validated in flight during the unintentional PC12 link reset incident.

Overall, the risk mitigation strategy implemented and validated successfully reduced the effects of the IES-PIU communication link resets. However, to further reduce exposure to risk, memory dumps may be minimized since the link reset incidents in flight occurred while doing memory load dumps of the EEPROM content. One option is to forego the memory dumps after files are loaded to EEPROM and be satisfied with the checksums as verification for the EEPROM load. If memory dumps are desired, the frequency of EEPROM updates may be limited.

Microwave Instrument for the Rosetta Orbiter (MIRO)

MIRO (the Microwave Instrument for the Rosetta Orbiter) [6] will obtain spectra of the nucleus and the coma in the microwave region of millimeter wavelengths (190 GHz, ~1.6 mm) and sub-millimeter wavelengths (562 GHz, ~0.5 mm). This scientific investigation addresses the nature of the cometary nucleus, outgassing, and development of the coma as strongly interrelated aspects of cometary physics. MIRO will measure the near-surface temperatures of at least one asteroid and the comet 67P/Churyumov-Gerasimenko, thereby allowing estimation of the thermal and electrical properties of these surfaces. In addition, the spectrometer portion of MIRO will allow measurements of water, carbon monoxide, ammonia, and methanol in the gaseous coma of comet 67P/Churyumov-Gerasimenko. These measurements will allow study of the process of icy cometary sublimation (change from the frozen state, ice, to a gas) in time and distance from the Sun. The data from MIRO, along with data from other instruments on the orbiter and the comet lander, will give scientists a better idea of how comets formed, what they are made of and how they change with time.

During routine MIRO command sequence testing in 2010 MIRO generated less than 10% of the expected science. The cause of the problem was identified as incorrect parameters in some of the software patches used for implementing new processes on-board Rosetta. At the time the fault occurred there was no MIRO hardware on Rosetta's spacecraft test bed, however, an engineering model (EM) of the MIRO was subsequently integrated onto the Rosetta spacecraft test bed.

The MIRO team has also been investigating problems related to phase lock loss (PLL) on the EM test bed on and off for several years. In 2008 frequency synthesizer power dropped out for >50ms. Analysis and tests have not produced a conclusion concerning why the PLL was losing lock, and a new effort was undertaken to further characterize the problem more recently.

During extended periods of operation in CTS / Dual Continuum mode, the software would detect PLL lock failures reported by the hardware, and attempt to automatically fix them by toggling the LO frequency prior to starting a new CTS scan. When this happened, the software was not able to successfully bring the PLL back into lock, and proceeded to then start each 5-second CTS scan despite the lack of PLL lock after toggling the LO frequency 3 times. Once this problem occurred, the SW/HW remained in this state of constant unlock until the next instrument calibration, which happens every 37 minutes. It was

observed that the subsequent instrument calibration was then able to resolve the PLL lock problem, and the instrument resumed normal operation from that point. The PLL lock problem then resurfaced after some period of time, always to be fixed at the time of the next instrument calibration. The testing done over the 3 day period of 03-31-10 to 04-02-10 consisted of long stretches of normal operation, interrupted by short periods (<35 minutes) where PLL lock would be lost. None of the above behavior was ever observed on the spacecraft instrument. The PLL problem exhibited itself on the test bed only.

This puzzling behavior was finally understood when the MIRO engineering model was shipped to Europe to be tested together with the spacecraft EQM. A loose pin was discovered in one of the MIRO EM connectors. After the connector was repaired and tightly attached to the EQM the PLL problem never showed up in subsequent testing.

Rosetta Orbiter Spectrometer for Ion and Neutral Analysis (ROSINA); electronics package for the Double Focusing Mass Spectrometer (DFMS)

ROSINA (Rosetta Orbiter Spectrometer for Ion and Neutral Analysis) is a state-of-the-art mass spectrometer [9] with two redundant sensors using different technologies for simultaneous and independent mass detection and verification. The ROSINA instrument is capable of making mass detections to 300 AMU (atomic mass units), and of resolving mass to and accuracy of one in three thousand (on the 1 percent level). The primary measurement objective of ROSINA is to determine the elemental, isotopic, and molecular composition of the atmospheres and ionospheres of comets, as well as the temperature and bulk velocity of the gas and the homogeneous and inhomogeneous reactions of gas and ions in the dusty cometary atmosphere and ionosphere. One of the most exciting measurements will be the carbon dating of the nucleus, or the determination of the C_{12}/C_{13} ratio and the D/H ratios in organic molecules. ROSINA will also provide gas pressure measurements important for the health and safety of other instruments, notably Alice, which will use ROSINA detections of significant increases in gas flux to close its aperture door, and IES, when high voltage (HV) must be turned off to avoid arcing during high pressure conditions.

ROSINA consists of (1) two separate spectrometers, (2) a velocity and temperature sensor and (3) a common data processing unit. The mass spectrometers employ different and complementary measurement techniques. The DFMS uses magnetic analysis to achieve high mass resolution and high dynamic range. The Reflectron Time of Flight (RTOF) spectrometer uses time of flight analysis to achieve high sensitivity over a broad mass range. The velocity and temperature sensor determines the flow velocity and temperature of the cometary gas in the coma. The NASA hardware contribution to ROSINA consists of a significant portion of the electronics package for the DFMS sensor.

The baseplate of the Rosina instrument is conductively coupled to the spacecraft deck for thermal control. Thermal control of the detector head is accomplished radiatively to the deck and to space through a gap in the multi-layer insulation (MLI) blanketing. Thermal sensors monitored by the spacecraft control survival heaters to maintain the detector head to within flight allowable limits.

The most sensitive element in the detector head is the Linear Electron Detector Array (LEDA). Preliminary thermal models indicated that under certain conditions during hibernation mode the LEDA temperature could decrease below the minimum flight allowable temperature of -55 degrees C. Additional thermal modeling was performed to reduce temperature predict errors due to instrument/deck thermal conduction factors and other thermal model uncertainties.

Two particular cases were studied using the improved thermal model over a range of sun incident angles and solar distances: A worst-case cold thermal environment with the LEDA powered off and with only a survival heater on at detector head, and a worst-case hot environment with the detector, RDP heater and a survival heater on. The improved thermal model provided temperature predicts over a wide range of solar distances and sun incident angles. The data from the improved model indicates that the LEDA can be maintained above the minimum non-operating temperature limit if the spacecraft thermal control surface (spacecraft deck) is maintained above -47 degrees C. In addition, the data indicate that the LEDA in operation exceeds the minimum flight allowable operating temperature of -20 degrees C. Strategies were developed to modify the turn-on sequence of other instruments within Rosina to guarantee a temperature of > -20 degrees C for LEDA turn-on.

3. 2013 RISK REVIEWS

Through the summer of 2013, the US Rosetta Project conducted table top risk reviews of the NASA hardware contribution of Alice, IES, and MIRO. These reviews involved the following personnel: the Project Manager (PM), the project's Operations System Engineer (OSE), each instrument's Systems Engineer (SE), the project's Mission Operation Assurance Manager (MOAM), the effected US instrument Principal Investigators (PIs), and a three member independent review board. By necessity of funding, timing, and inclination, given the extensive hibernation readiness preparations conducted in 2009, these reviews were qualitative in nature but were used to help the US Rosetta Project focus on areas of future risk and adjust resources to prevent the occurrence of specific risks.

Strategy

Project staff reviewed the status of residual risk, Requests For Action (RFA) from prior risk reviews, and archived

Incident Surprise Anomalies (ISA)/Anomaly Reports (AR). The project team identified general areas of risk and concerns at the following strategic points as follows:

(1) Prior to the S/C wake-up from hibernation.

(2) At the start of Comet Approach.

(3) At the start of Global Mapping and Close Observation.

(4) Prior to the Lander Delivery.

(5) At the start of Comet Escort.

Concurrent with these strategic points, specific risks were solicited from all US instrument teams. The result was a 55 point questionnaire sent to each team in advance of the review. These risk review questions were categorized into the following types:

(6) Anomaly Analysis

(7) Anomaly Response

(8) Contingency Planning

(9) Documentation

(10) Ground Software Interface

(11) Operational Interface Agreement

(12) Operations Procedure

(13) Operations Readiness Test

(14) Programmatic

(15) Residual Risk

(16) Resources

(17) Schedule

(18) Staffing

(19) System Engineering

(20) Training

Conclusions

The Risk Review Board's overall assessment concluded that the instrument teams have done an excellent job preparing for the upcoming comet operations, and the instruments are ready except for a few small issues that are currently being corrected, and one major issue, that of the rollout of the Rosetta Science Ground Segment (SGS).

A set of thirteen risk items were identified from the risk reviews. Among the thirteen risk items, US Rosetta project has five yellow risks, some of which involved contingency plans, schedule for prime mission, and manpower impacts of the Project's continuing uplink development. The US Rosetta Project has eight green risks, some of which involved funding and staff for prime mission data analysis, and the upset/reset problems of the cruise phase. Ten out of thirteen risk items have mitigation plans and the rest of three risk items are categorized as "watch/accept" as follows:

(1) Item 1 (US Payload): Major Anomaly that compromises orbiter measurement objectives, including those of the lander, propulsion system, or reaction wheels

(2) Item 2 (IES only): Survival of the Rosetta Plasma Consortium's Power Interface Unit (PIU) upon exit from hibernation

(3) Item 3 (Alice only): Survival of the aperture door upon exit from hibernation.

The risk priorities and possible mitigations are now under discussion with the each team, and will be shared with European partners to provide input to ESA's Rosetta Comet Operations Readiness Review (CORR), conducted in fall of 2013.

In particular, concurrent with the risk reviews, the fully implemented Rosetta Science Ground Segment (SGS) uplink system was re-engineered, due to its complexity and ambitious development plan, to a minimum SGS uplink system. This re-engineering required additional labor resources as follows: 1) instrument teams' uplink process updated to include additional manual steps and more time for the team to prepare the instrument observation plans; 2) more time built into the uplink operation schedule to accommodate a longer turnaround time for re-iteration or re-plan of instrument observations.

4. ESA/NASA COLLABORATION ON DSN KEYWORDS, 2006-2014

The Rosetta ground segment is a complex system involving, among other things, use of NASA assets at the Deep Space Network (DSN). Cross-agency interfaces, between NASA personnel at JPL, the DSN, and personnel at the ESA Science and Operations Center (ESOC) for operation of the DSN to support Rosetta, include many key points (figure 3), but none perhaps of more significance than the process of generating the DSN keyword files (DKF).

To produce a Nominal Sequence of Events (NSOE), any flight project must work with the DSN Network Operations Project Engineer (NOPE) to define a limited number of

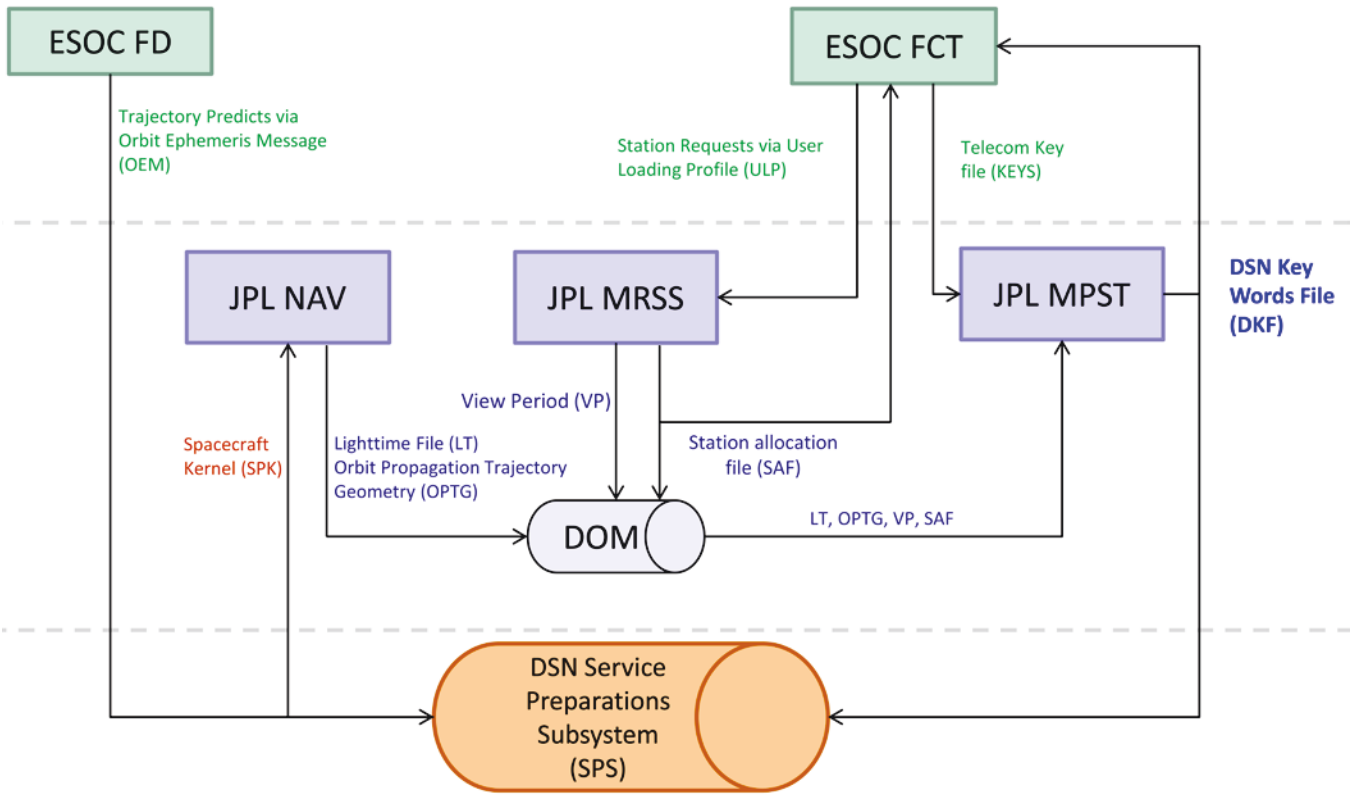

Figure 3. Rosetta DSN interfaces. DKFs are found in the far right of this vast diagram of interfaces. Boxes represent operational personnel (green at ESA, blue at JPL) who generate file products. The light blue oval is the DOM repository for file products used by JPL personnel. The orange oval is the DSN portal used for file product submission and processing.

template sequences well in advance (weeks to months) of the time of operation. This feature is useful when the sequence does not change from pass to pass. NSOEs can handle up to 36 different static files, and are time-relative in order. A mission uses a template over a large number of passes. Such a template is for missions that do the same thing every day. The dynamics of orbit are not amenable to a template; the timing, geometry and spacecraft operations is not the same every pass. When events vary from pass to pass and multiple state changes need to be made, including multiple uplinks, tracking modes and telemetry rate changes DKFs are the most common method used to convey inputs for DSN operations.

Use of DSN Keyword Files (DKFs) was first discussed in the second of the project's IEEE papers in 2006 [12]. In 2006, one method for flight projects to provide inputs for standard commands to the DSN were conveyed by means of a NSOE file. First with Mars Express (MEX), and later with Rosetta, NASA requested ESA devote manpower to support the use of newly defined keyword files. ESA acquiesced for the more complicated MEX mission, but demurred in the case of Rosetta, deeming the manpower requirements not commensurate with the labor savings for the less complicated (at the time) Rosetta mission.

In the 2006 paper we discussed the cost benefits to JPL of making these command files autonomous, that keywords were introduced into the process to reduce the labor demands of creation of the NSOE files. In 2006, we spent some time outlining the series of events, many of them manually intensive, required to generate these files. A key problem with this process, for ESA, was the complexity, learning curve, and time-consuming nature of the creation of the keyword files themselves. The process for ESA was codified in a paper about MEX for the AIAA in 2008 [33].

Eight years later, the driving force for the keyword file generation is now ESA. DKFs are used with nearly every mission. Rosetta ended up using DKFs only for Delta Difference One-Way Range (DDOR) pre-hibernation. ESA has requested the use of KEYS to DKFs for such missions as MEX (the first non-NASA mission to use this process) and Venus Express (VEX). In this section we want to explore this critical element of inter-agency commanding, and how its importance/significance has ballooned for Rosetta.

Recap: Generation Process for DKFs

A keyword file is essentially a collection of the parameters needed, with advance knowledge of the necessary modes required, for station operation with a particular pointing configuration. A keyword file may contain multiple telecom configuration blocks. DKFs allow for rapid implementation

of changes, and allow the DSN facilities greater flexibility in allocation of station resources. An abbreviated form of the complex process of creating such a file is outlined below (see also figure 3). For the complete process, see the 2006 paper [12].

(1) The process starts with a Navigation solution for Rosetta. The Flight Dynamics (FD) group at ESOC (ESA's primary navigation group for the Rosetta mission), and the upper green box on the left in figure 3, deposits predict trajectories in a DSN portal, the large orange cylinder of figure 3, that automatically converts the files into a standard SPICE-kernel format (for more about JPL's SPICE kernel protocol, see, for example, [12]).

(2) The JPL Navigation (NAV) team uses the converted trajectory to create Orbit Propagation and Timing Geometry (OPTG) files (if needed) and Light Time files. The light time file contains Earth-centered spacecraft one-way light time. Light time and OPTG files will be mainly used by the JPL Mission Planning and Sequencing Team (MPST) – the right-most blue box in figure 3.

(3) The JPL Multi-Mission Resource Scheduling Services (MRSS) team, the central blue box in figure 3, will use the converted files in the portal (orange box of figure 3) to output DSN view period files to support the MPST. View periods define intervals when Rosetta is visible from each Deep Space Station and specify limits for each station transmitter. Based on requirements provided by the Flight Control Team (FCT) at ESOC, MRSS also negotiates and schedules the specific DSN stations and equipment to support Rosetta and produce the DSN station allocation file. Included in the station allocation file are the configuration codes for all the hardware equipment to be used during the scheduled DSN antenna tracks.

(4) These station allocation files, along with navigation information, and science pointing requests, are in turn used by the Rosetta Ground Segment at ESA to prepare sequences and commands for Rosetta.

Relevance of a JPL Sequence-Generation Program Named SEQGEN

The critical software used by the MPST team (right-hand side blue box in figure 3) for DKF generation process is called SEQGEN (for sequence generator). SEQGEN was a piece of software originally written at JPL for the Voyager mission, then extended to multi-mission capability for the Mars Observer and Galileo Missions circa 1998. SEQGEN models (a) the spacecraft telecom states, (b) the DSN station equipment states and, (c) the interactions between them and then generates a set of commands which facilitate the DSN tracking of the spacecraft [34]. SEQGEN requires mission specific adaptations, and the U.S. Rosetta Project relies on the MEX adaptation of SEQGEN. This is possible since the MEX and Rosetta (and VEX) spacecraft telecom architectures are similar enough that the same models in SEQGEN are applicable.

(5) A portion of the sequences and commands for Rosetta referenced in bullet (4) above accounts for the status of the Rosetta telecom system. Rather than providing MPST with a strip of actual commands from the telecom system, Rosetta controllers learned to send a 'telecom key file' (KEY file, not the DKF) that represents the spacecraft telecom system as it pertains to the DSN.

(6) The JPL MPST reformats the KEY file for ingestion into the SEQGEN software, along with the Light Times, OPTG, and station allocation files. Output from SEQGEN is adapted with additional software to extract the specific data needed to generate the DKF product.

Implementation for Rosetta Prime Mission

Reasons ESA has become a strong proponent of DKFs for Rosetta include the fact that in prime mission, Rosetta enters a unique combination of orbits and navigation pointing configurations, and will be executing complex scenarios. Once Rosetta has reached the comet target, there will be daily multiple contacts with the spacecraft, using ESA and DSN stations. During these contacts the spacecraft will maneuver around the comet, perform science observations, and downlink data at varying telemetry rates. There will be frequent Radio science observations including bi-static radar and gravity measurements. The activities during the DSN station passes will vary for each track and include spacecraft maneuvers during some passes. The command specification for the DSN with more complex activities are expected to be more amenable with the DKF. Finally, though orbiting a comet, the Rosetta profile of operations with the DSN is expected to be similar to that of MEX.

Additional functionalities and costs associated with this more robust Rosetta configuration included the following. The Rosetta team at ESOC now generates a KEY file for the JPL MPST team for DKF generation. This represents an additional accepted cost for the US Rosetta Project, as it is personnel at JPL that perform the ingestion of the KEY file into SEQGEN for the generation of the DKFs. Updates to the interfaces required to produce the DKF were defined and documented by members of the Rosetta flight control team (FCT) at ESOC, and the JPL MPST and MRSS teams. Different scenarios for Rosetta spacecraft activities during DSN passes were identified, and the required keywords for implementation of these in the KEYs file were defined.

Additional costs for the FCT at ESOC included development of the new software to generate the KEY file

with the spacecraft telecom parameters. The new ESOC file products required testing by the MRSS and MPST teams at JPL to verify files could be properly ingested by the relevant software, and that the expected output be generated. Several iterations of test file products produced by ESOC and JPL were generated, exchanged and reviewed in 2013. At JPL, the NAV, MRSS and MPST team members as well as the DSN DDOR Subsystem engineer and DSN NOPE provided various inputs for file generation and testing.

Output from the SEQGEN runs for the Rosetta test files, that included all the different test scenarios for DSN pass activities, were checked to ensure that any usage with the MEX adaptation were still valid under the Rosetta prime mission use conditions. A missing functionality from the MPST DKF generation process tool set was the ability to specify the transition between multiple carrier and subcarrier modulations. This capability was needed infrequently for MEX and multiple telemetry modulations were modified manually. A script was created for Rosetta to add this capability and remove the manual work and has since been successfully used and validated in flight on MEX using a MPST generated MEX DKF.

5. SUMMARY

The U.S. Rosetta instruments exhibited several anomalies in the years preceding spacecraft Deep Space Hibernation Mode. The U.S. Project Office jointly with the instrument teams took up an extensive effort to resolve all the anomalies before the spacecraft was commanded to sleep. After studying the problems the teams tried to duplicate the errors on test beds and in a few cases on the actual spacecraft to assure that the proposed solutions resolved the anomalies. The solutions to the anomalies were thoroughly tested and documented. The U.S. Project Office conducted reviews of all the solutions to the anomalies with participation of software, hardware and mission assurance experts. Finally, all the Office of Mission Success documentation: Incident, Surprise and Anomaly Reports were dispositioned and closed.

In the months prior to exit from hibernation, the U.S. Rosetta Project prepared to wake up in 2014 with a qualitative but detailed questionnaire focused on the phases of the prime mission including close observation and mapping, landing phase, and comet escort phase. Residual risk was reviewed, Incident, Surprise and Anomaly Reports from 2009 were reviewed, and the current uplink and downlink process, contingency plans, and software-PI interfaces were discussed and reviewed. This process resulted in some yellow risks, some green risks, a few watch/accept risks, and items to fold into the ESA Rosetta Comet Operations Readiness Review process in fall of 2013.

The US Rosetta project, JPL's DSMS, together with the ESA ground segment have an ongoing collaboration, underway for many years, to develop keyword files appropriate for commanding Rosetta with NASA Deep Space Network assets. End to end tests on this eight-year old 'new' way of commanding the DSN were conducted in 2013, incorporating new functionalities including the ability to specify the transition between multiple carrier and subcarrier modulations, and testing new software to generate a KEY file by ESOC, and conversion of those KEY files via SEQGEN at JPL to generate a DKF.

Taken together, between preparing for hibernation, reviewing instrument needs for post-hibernation measurement activity, and preparations for operation of the DSN for the Rosetta Prime mission, the US Rosetta Project has been declared ready. Accordingly, we are looking forward to successfully observe this magnificent comet, and for the first time, land on and escort it through perihelion.

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Mr Andrea Accomazzo has been a staff member at the European Space Operations Centre (ESOC) of the European Space Agency (ESA) since 1999. He has served the agency in the Mission Operations Department of the Operations and Infrastructure Directorate for the Rosetta and the Venus Express missions as Spacecraft Operations Manager. In his professional career he has been involved in the early design of the guidance, navigation, and control system for the ESA Vega launch vehicle and in the design of the Active Descent System of the Rosetta lander Philae. He is the Head of the Solar and Planetary Missions Division at ESOC, as such also responsible for the design and conduct of the flight operations of the Rosetta mission on behalf of the ESA Science and Exploration Directorate.

Mr. Arthur B. Chmielewski is the US Rosetta Project Manager. He has managed several flight projects at JPL: the Space Technology 8 mission, Mars Telecommunication Orbiter Rendezvous Experiment, Space Technology 6 mission, Gossamer Program, Inflatable Antenna Flight Experiment and the Cryocooler Flight Experiment. He was also a Project Element Manager on Deep Space 1 mission and a power system engineer for Galileo, Ulysses and Cassini spacecraft. He was responsible for development of 9 space instruments and several new technology devices. He also managed a flagship pre-project - space radio astronomy mission ARISE. In the two years at NASA Headquarters he managed the space experiments program In-STEP. He has degrees in mechanical engineering and computer science from University of Michigan and USC.

Mr. Adans Y. Ko currently is the Mission Operation Assurance Manager for U.S. Rosetta and Voyager Projects at JPL. He was the Multi- Mission Ground System and Services (MGSS) Software Architect for Advanced Multi-Mission Operation System (AMMOS), was responsible for Ground System software architecture for the current and future AMMOS. He has published numerous papers in the area of mission operation system and system architecture. He was a development manager for the AMMOS Mission Planning and Sequencing Subsystem (MPS) over 10 years. He has in-depth knowledge of the Multi-mission Ground Data System uplink tools, which include mission planning, sequence generation, and sequence flight software. In the private sector, he was a project manager for credit card systems for the Navy at CitiBank Development Center, Los Angeles, CA and a Principle Engineer for e-Commerce Consulting at MarchFirst Consulting Firm, in Los Angeles, CA. He received a NASA "Turn a goal to reality" award for his work on technology infusion of AMES planning and scheduling technology to AMMOS planning and sequencing legacy system. He has also received NASA's Exceptional Service Medal for his work on Voyager's Onboard Computer Command Subsystem for missions to Uranus and Neptune. He got his B.S.C.S. degree from Utah State University, Logan, Utah in 1982 and his M.B.A. degree from University of California, Los Angeles in 1993.

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Dr. Matt Taylor was born in London, gained his undergraduate Physics degree at the University of Liverpool, and a PhD from Imperial College London. His career has focused on in-situ space plasma measurements, working in Europe and US on the four spacecraft ESA Cluster mission, leading to a post at ESA which started in 2005 working in the area of project science for Cluster and the ESA-China Double Star mission. His studies have focused on energetic particle dynamics in near-Earth space and in the interaction of the Sun's solar wind with the Earths magnetic field, particularly focusing on how boundary layer interactions evolve, leading to 70 first or co-authored papers. Most recently he was appointed the project science position on the Rosetta mission. "Since early on in my career I have enjoyed working with groups or teams of scientists towards a common goal, encouraging them to work with one another and to support their activities. For the first time we will fly with the comet and actually land on it! The Rosetta mission is a breakthrough in space science and exploration and really demonstrates what international collaboration can achieve."