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DOCUMENT

MarcoPolo-R Preliminary Requirements Review (PRR) Technical Report

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Table of contents:

LIST OF ACRONYMS

AIV/T	Assembly, Integration and Verification/Testing
AO	Announcement of Opportunity
AST	ASTRIUM
CUC	Close-Up Camera
DD	Design and Development
EGSE	Electrical Ground Support Equipment
EID(-A/-B)	Experiment Interface Document (Part A/B)
ERC	Earth Re-entry Capsule
FM	Flight Model
GNC	Guidance, Navigation and Control
KO	Kick-Off
ITT	Invitation To Tender
LEOP	Launch and Early Operational Phase
LIDAR	Light Detection And Ranging
LGA	Low Gain Antenna
MGA	Medium Gain Antenna
MFSK	Multiple-Frequency Shift Keying
MP-R	MarcoPolo-R
MSRD	Mission and System Requirements Document
NAC	Narrow Angle Camera
NEO	Near-Earth Object
PFM	Proto-Flight Model
PRR	Preliminary Requirements Review
(E)QM	(Engineering) Qualification Model
RID	Review Item Discrepancy
SADM	Solar Array Deployment Mechanism
SATCS	Sampling, Acquisition, Transfer and Containment System
STM	Structural and Thermal Model
TAS	Thales Alenia Space
TDA	Technology Development Activity
TOM	Thruster Orientation Mechanism
TRL	Technology Readiness Level
V&V	Verification and Validation

1 INTRODUCTION

1.1 M3 mission in ESA Cosmic Vision plan

Following the Call for M3 mission proposals that was issued in July 2010, five mission candidates are today competing for M3 nominal launch slot in 2024:

- EChO, an Exoplanet Characterisation Observatory,
- LOFT, a Large Observatory For X-ray Timing,
- MarcoPolo-R, a Near-Earth Asteroid (NEA) sample return mission,
- PLATO, an Exoplanet mission devoted to PLAnetary Transit and Oscillations of stars,
- STE-QUEST, a Space-Time Explorer and Quantum Equivalence Principle Space Test.

M3 timeline is recalled in Table 1. With the exception of PLATO, for which an assessment study was completed in 2011, the other missions have recently completed their Assessment Phase (phase A). A Preliminary Requirements Review (PRR) of all candidate missions has been performed to review their status in support of the M3 selection. This document reports the results of the technical and programmatic review for the MarcoPolo-R mission candidate.

Event	Date
Selection of M3 mission candidates	*Feb 2011*
Industrial studies kick-off	*Feb 2012*
Industrial studies mid-term reviews with model payload	*Jul 2012*
Instrumentation AO	*Sept 2012*
Selection of instrument teams	*Feb 2013*
Industrial Phase A studies data package delivery for PRR	*Sept 2013*
ESA technical and programmatic reviews completed	Dec 2013
Public presentations, Science Advisory Structure assessment and SSAC recommendation for M3 selection	Jan 2014
M3 mission selection by the SPC	Feb 2014
Phase B1 completion for the selected mission	Nov 2015
M3 mission adoption by the SPC	Q1 2016
Industrial Phase B2/C/D kick-off	Sept-Oct 2016
M3 nominal launch	by 2024 (*)

Table 1- Timeline for M3 selection and implementation

(*) Compatibility of M3 implementation with a launch by 2022 was requested

1.2 M3 Reviews: Process and Objectives

The independent reviews followed a common procedure and have several objectives:

1) Assess the design maturity of the mission at the end of Phase A
2) Evaluate ESA Estimate at Completion (EaC)
3) Provide recommendations for the next phases

While objectives 1) and 2) serve the M3 selection process, the third objective is actually applicable only to the mission that would be selected.

For each mission candidate, the reviews were chaired by an experienced project manager and supported by a number of senior engineers and technical experts across the Agency, involving typically about 20 people per mission, with a natural dispersion depending on the mission needs and the review Chairman requests. The reviewers are independent of the study team, and the latter was supporting the review process on the request of the Chairman e.g. by providing the historical background and answering questions raised by the reviewers. For practical reasons, the reviews were conducted in parallel for the five missions and the reviewers were distributed in two panels:

- A technical and programmatic panel (also called Review Panel), assessing all technical aspects for the mission implementation, including: mission requirements and flow down to engineering level; spacecraft definition and technology readiness; science payload definition and technology readiness; launch aspects and launcher compatibility; ground segment and operations; spacecraft development plan (model philosophy, schedule for the spacecraft and payload elements) and the associated development risks.
- A cost panel, in charge of assessing ESA costs (EaC), taking into account the technical and programmatic findings

The input documentation is constituted of:

- ESA requirement documents (e.g. Science Requirements Document, Mission Requirements Document, Experiment Interface Documents, etc)
- The data packages provided by the two industrial contractors
- The data package provided by the instrument consortia

The Review Panel was specifically tasked with the following activities:

a- Confirmation of the Mission and System requirements:
  - Adequacy and completeness of ESA Mission Requirements
  - Adequacy, completeness and traceability of spacecraft, payload, ground segment and launcher requirements
  - Adequacy and completeness of interfaces definition

b- Confirmation of the mission technical feasibility:
  - Mission design justification and compliance with applicable requirements
  - Concept of operations, observing strategy and modes (where applicable), calibration aspects, driving requirements on mission, spacecraft and payload design
  - Validity and maturity of the spacecraft and payload design concept
  - Margin philosophy
  - Adequacy, completeness and credibility of system, spacecraft and payload budgets and

margins
- Availability of appropriate models and analyses in support to design definition
- Identification of critical technologies for the spacecraft and payload, identification of current technological maturity and availability of credible roadmap to achieve TRL 5 before adoption, critical review of ongoing technology development activities

c- Confirmation of the mission programmatic feasibility:
- Critical review of the spacecraft and payload development plans
- Adequacy and completeness of the proposed development and verification approach
- Model philosophy
- Realism and completeness of spacecraft and payload development schedule (incl. margins)
- Compatibility of payload need and delivery dates
- Critical path analysis
- Risk assessment and related mitigation plan
- Credibility and compatibility of technology maturation roadmap schedule with system schedule

The reviews were implemented through a series of meetings held throughout October and November. Towards the end of the review process, the major findings were presented to a common management board in the science directorate, who further challenged some findings and, in some cases, requested additional clarifications. A substantial effort was devoted to the harmonisation and cross-verification of the cost estimates.

This report provides a summary of the Review Panel findings. It is made public for the sake of transparency and for providing feedback to all teams who actively contributed to the mission assessment phase, namely: the study science team and the science community supporting the mission, the science instrument consortia, the industrial study teams, and ESA study team.

2 MARCOPOLO-R MISSION DESCRIPTION

MarcoPolo-R is a sample return mission to the primitive Near-Earth Asteroid (NEA) 2008 EV5. The spacecraft carrying the Earth re-entry capsule (40 kg), will be launched by a Soyuz-Fregat MT 2-1b from Kourou on a direct escape trajectory to asteroid 2008 EV5. The launch mass is ~ 1650 kg. The transfer is performed via electric propulsion and will reuse the Smart-1/Alphasat thruster system as flown.

The launch takes place in December 2022 (backup in December 2023, 2024, etc.). After one earth swing-by, the spacecraft will rendezvous with the NEA in January 2025. The proximity operations last for 180 days. This phase will include global observations of the asteroid with the main science instruments (MaNAC – narrow angle camera, MaRIS – visible/near-infrared and THERMAP – mid-infrared spectrometers) and will perform gravity field determination and hazard mapping at 5 km altitude. Five selected sampling site candidates are then characterized at high resolution from a hovering position at 250 m altitude in order to determine the most suitable and safest sampling site.

A few descent rehearsals will fully validate the critical operations before actually performing the sampling operation at the asteroid surface. Then the spacecraft, designed to cope with surface hazards (e.g. large clearance to the surface), navigates towards the final touchdown/sampling site and collects hundreds of grams of loose surface material. The sampling strategy is based on a "touch and go" approach to lower cost and risk. Therefore the spacecraft performs a soft touchdown of the surface, with the arm/boom, for a few seconds (in the order of 2-5 seconds) while collecting the sample, with the sampling tool and then takes-off immediately after that to move into a safe position away from the surface. Two more instruments are used during sampling operations: CUC (Close-up Camera) and VISTA-2 (dust and volatile measurements). The sample acquisition is verified and the sample is transferred to the re-entry capsule and sealed. If the sampling operation is not successful, the spacecraft will be capable to undertake 2 more attempts.

The spacecraft departs from the asteroid in July 2025 and returns to Earth in June 2027. The re-entry capsule is then released and lands in the Woomera test range in Australia where it will be recovered.

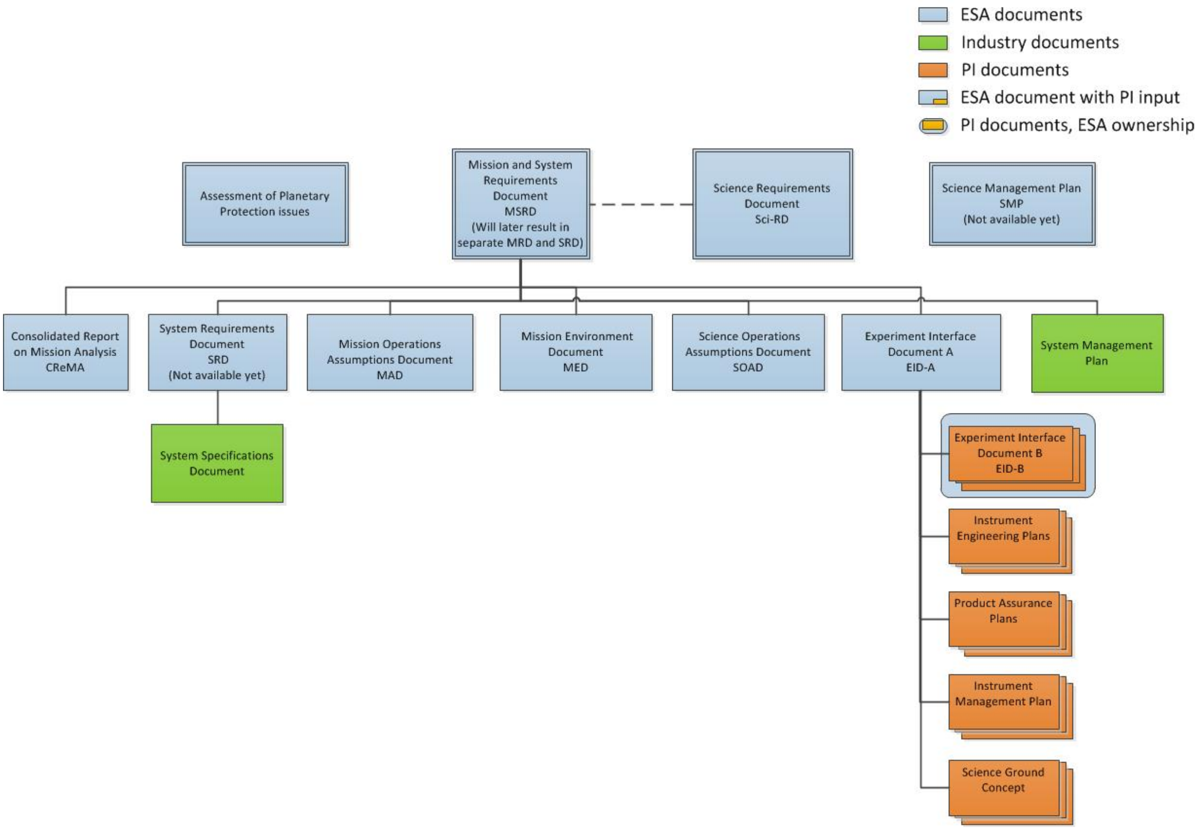
3 TECHNICAL REVIEW OUTCOME

3.1 Confirmation of the Mission and System requirements:

- *Adequacy and completeness of ESA Mission and Systems Requirements (MSRD)*
- *Adequacy, completeness and traceability of spacecraft, payload, ground segment and launcher requirements*
- *Adequacy and completeness of interfaces definition*

Mission/System

The ESA mission and system requirements are generally clear, complete and in line with the level required at PRR. The driving requirements for the key elements, SATCS, GNC and ERC, in particular are sufficiently defined and flown down to the spacecraft and its sub-systems. The requirements were properly fed into the relevant technology activities. They constitute a good basis for entering phase B1, with a few exceptions which are not considered to be critical (see paragraphs below) given their impact on the design (see **chapter 4.2**). The document tree is shown here below.



The EID-A is largely complete with respect to allocations and interfaces, and provided sufficient detail to enable the instrument definition in Phase A. However it seems to contain many detailed design requirements, which may have been inherited from earlier missions, and which will need further tailoring during phase B1. Also some high level interfaces definition will require further clarification. The EID-Bs from the instruments are not included in the documentation hierarchy. This shall be added to the EID-A and MSRD (Mission and Systems Requirements Document), prior to the issue of the Phase B1 ITT.

ERC (Earth Re-entry Capsule)

Most key system requirements are defined adequately for the ERC in the MSRD, i.e. the landing loads, the re-entry heat fluxes and mechanical loads, sample container sealing, etc., compatible with existing heat shield material capability and on-going development for crushable material. However, ERC requirements should be moved to a separate “ERC system” chapter in the MSRD. In addition the panel’s judgement is that a requirement on the knowledge of the landing ellipse after re-entry tracking and landing (e.g. at 3-sigma) shall be added to the MSRD to support and clarify for the ERC prime the existing ground recovery time requirement of 4 hours (currently: 2 hours as a goal, 4 hours as a requirement).

Mechanical

With regards to mechanical design and verification requirements, it is recommended that the ESA MSRD include more complete top level mechanical design requirements. At the moment, these requirements are quite generic and mainly limited to specifying launch loads and mass margins,

together with specific mechanical design and verification requirements for payload units (EID-A).
The flow-down of requirements to spacecraft, subsystems and equipment units by industrial study teams has not been completed at the time of the PRR. Both Astrium and TAS have provided a technical requirements document, but these have only served the purpose of place holders for the main mechanical requirements during the Phase A study. Considering the limited maturity of spacecraft and subsystem structural design that is expected at PRR, the requirements used are adequate at this stage.
Mechanical requirements for the payloads are provided in the EID-A. However, not all requirements are coherent with or correctly flowed-down from the Soyuz launcher manual. It is recommended to update these requirements in preparation for the next development phase, preferably in coordination with industrial study teams to ensure coherence also between requirements for payloads and spacecraft equipment. At payload level the mass margin philosophy is not always correctly applied or not clearly defined (e.g. not clear if baffles/MLI are included, inconsistent sum of all elements' mass) for some instruments (MaNAC (narrow angle camera) and MaRIS (visible/near-IR spectrometer)) at EID-B level. This should not be considered critical at PRR considering the total payload mass relative to the total launch mass and that the allocations for each individual instruments seem to be sufficient. However, this needs to be fully addressed in the next phase.

Thermal

The MSRD reflects all necessary thermal requirements for both the main spacecraft and ERC and they are flown-down properly to the lower level requirement documents, e.g. EID-A, environment document, and industry specifications. The environment requirements are not so stringent conditions (0.85 – 1.2 AU) compared to other planetary missions such as Bepi-Colombo, SOLO, VEX, MEX or Rosetta, but have to be harmonized as both Contractors used slightly different sizing aphelion/perihelion (e.g. 1.04 vs 1.2 AU (during cruise), 0.85 vs 0.88).

GNC

The overall GNC systems requirements (MSRD) are consistent with the system specifications documents provided by both industrial consortia. These requirements are compatible with state-of-the-art vision-based navigation capabilities. The MSRD maturity is generally consistent with the project phase and identifies a coherent set of key requirements. Some exceptions have been identified even though they have little impact on the design at this stage of the development.

The review panel has identified that the current MSRD is not consistent with regards to the number of sampling attempts and respective descent rehearsals. From the GNC point of view every time that the sampling is performed at a different sampling site, it is highly likely that descent parameters are different. Therefore, the operations rehearsal shall be repeated. This means that 2 more rehearsals shall be foreseen which has an impact of a few days in the schedule and a few kilos of propellant (delta-V of each descent is a few meters per second). This has nevertheless essentially been judged to be compatible with the current design as a lot of operational margin has been accounted for in the proximity operation timeline and mono-propellant delta-V allocation.
The touchdown accuracy requirements (R-SYS-240 and G-SYS-245) shall be reformulated considering the touchdown footprint radius or semi-major axis rather than a diameter to be self-contained and unambiguous. The correct definition was however used by the primes.

Mechanisms

ESA MSRD mission requirements are well established and comprehensive regarding touchdown, sampling and transfer mechanisms, which represent main mission design drivers.
The flow-down to detailed specifications has been performed consistently by Astrium, while TAS documentation (specifications as well as risk register) still remains at system level in terms of requirements definition and risk identification.
In the MSRD a consolidation is needed in terms of sample contamination requirement as it represents a design driver for the ERC sample container sealing system. Specifically, the requirement shall be formulated in terms of “leak rate” (which is more standard) rather than “ratio of contaminating particles”.
Other platform mechanisms (SADM (solar array deployment mechanism) and TOM (thruster orientation mechanism)) and payload mechanisms (mainly CUC and MaNAC focusing mechanisms as well as THERMAP flip mirror) requirements are quite generic and limited, which is deemed definitively not critical at PRR level given that the proposed design solutions are compliant with the need and that they are space-proven (SADM, Alphasat/Smart-1 TOM) or have ongoing development (CUC (ExoMars)).

Payload

Following the comment on the EID-A recorded at system level (see **Mission/system**), the panel recommends the tailoring of the document, in particular reducing the number of design requirements, clarifying some inconsistency and making it as much as possible a stand-alone document.
The EID-B’s contain many pages stating compliance to EID-A requirements (Thermap, MaRIS(p), CUC). While this is appreciated, the specific instrument interface requirements are not always well detailed.
NaNAC and especially VISTA documentation reflect the low maturity of the design at this stage. Given the objectives of the mission the risk is not considered to be critical, but mitigation measures shall be implemented right from the beginning of phase B1.

Operations

Overall, the requirements baseline, both on the spacecraft and on the Ground Segment, are considered to be at an adequate level of definition for what concerns Operations at this stage of the project. As part of the PRR requirements review, a single issue has been identified in this area. The current requirement for descent and touchdown in terms of communication with the ground is to fulfil Beagle 2’s recommendation and therefore use MFSK tones via LGA but this minimal approach heavily constrains the spacecraft operations and design as seen in phase A. Due to the nature of the spacecraft operations for this mission, requiring short ground response times and quick access for telemetry and telecommanding, in particular during Proximity Operations, a higher telemetry and telecommand capability is required. This has been already included in the MSRD as a goal. It is recommended to make it a requirement instead to increase robustness of the mission with respect to the minimal Beagle 2 recommendation.
It is also expected that the output of currently ongoing GNC studies will result in an expansion of the requirements baseline for MP-R, which will result in the improvement of the operational feasibility (see **chapter 4.2**).

3.2 Confirmation of the mission technical feasibility:

- *Mission design justification and compliance with applicable requirements*
- *Concept of operations, observing strategy and modes (where applicable), calibration aspects, driving requirements on mission, spacecraft and payload design*
- *Validity and maturity of the spacecraft and payload design concept*
- *Margin philosophy*
- *Adequacy, completeness and credibility of system, spacecraft and payload budgets and margins*
- *Availability of appropriate models and analyses in support to design definition*
- *Identification of critical technologies for the spacecraft and payload, identification of current technological maturity and availability of credible roadmap to achieve TRL 5 before adoption, critical review of ongoing technology development activities*

Mission/System

The mission/system design is credible and justified by the appropriate technical documentation and in line with the requirements. The overall mass budget is realistic and mass margins are adequate, including for the re-entry capsule. The required 20% system mass margin, appropriate maturity margins and an additional 5% launch mass margins for the 2024 worst-case launch are achieved (based on launch performances verified and approved by Arianespace analysis specifically made for MarcoPolo-R end 2013). For the nominal launch in 2022, the launch mass margin is above 10 %: Astrium with 1669 kg (12.5% margin) and TAS with 1624 kg (15% margin).

The table below shows the launch masses, mass margins (Based on specific LV performances analysis made by Arianespace) and mission duration for all opportunities (the asteroid proximity operations are always 180 days. The rest is cruise).

	Launch mass (incl. adapter) in kg		Launch mass margins in %		Mission duration (years)
	AST	TAS	AST	TAS	
December 2022	1669	1624	12.5	15	4.5
December 2023	1689	1618	8.5	12.5	4.5
December 2024	1701	1614	5.5	10.5	6.5

The interplanetary environment of the mission is milder than any previous ESA planetary mission, except Smart-1. Thus there is little environmental risk associated with the “standard” equipment. The critical phases of the mission are the asteroid touchdown and the Earth re-entry. As discussed in more details in paragraphs below, sufficient analysis and design iterations have been done for these critical areas to demonstrate that there is no high risk related to their implementation.

One non-compliance has been identified concerning the touchdown accuracy performance in the TAS descent strategy (see **GNC** and **operations**). The other two descent strategies (Astrium and GMV (TDA)) are compliant with the requirements (see **GNC**) leading to a high degree of confidence concerning the feasibility of that phase. The operational concept, backed up by appropriate technology activities focusing on GNC and optimisation of ground operations, has been sufficiently iterated with ESOC to provide confidence in its credibility (see **Operations**).

Technology readiness

All critical technologies have been identified for spacecraft and payload. All of them are addressed in dedicated technology activities which seem to progress well, namely GNC (GMV), sampling tool (AVS and Selex Galileo) and heat shield material (Astrium SAS). All of them have reached or are some months away to reach TRL5 with the exception of the touch and go mechanism for which the TDA is only about to start. Schedule margins are however adequate for this item and it seems realistic to reach TRL5 by mission adoption, given the specifications of the proposed design solution, either a robotic arm (TAS) or a boom (AST). The results of these technology activities must be however better communicated to the primes at the very start of phase B1 in order to cross-feed the system studies with the critical results of these technology developments and ensure direct harmonization at industry-level. The technology readiness aspects are addressed in more details in **chapter 4.3**.

ERC

The re-entry capsule design is sufficiently detailed and has sufficient margins in terms of system mass, aerothermodynamics and maturity margins, including the heat shield material which has higher margin levels as recommended for this element. The analysis of the robustness of its tracking and recovery operations (mostly navigation, optical and radar) is however limited to an analysis derived from Hayabusa landing performances. Since the capsule has no tracking beacons onboard, it is recommended to put extra effort on the analysis of the performances and robustness of the spacecraft Earth return ground-based navigation before release of the ERC from the spacecraft and re-entry tracking operations for this passive concept in the very early stage of phase B1 to ensure that the knowledge of the capsule landing ellipse is as accurate as claimed (see also comment in **chapter 4.1**). Alternatively, if this cannot be guaranteed and no satisfactory recovery operations can be designed for a passive capsule, a parachute must be added to slow down the descent and ease radar tracking. This adds complexity and cost to the mission would however save mass, as the capsule volume, thus mass, is driven by the volume required by the crushable material to absorb the impact energy at landing. It is noted that for the current design, the size of the capsule is compatible with radar and optical tracking, and that the actual landing ellipse knowledge error prior to re-entry after the last tracking should be small enough (5 kilometres, similar to Stardust (8 km at 3-sigma)) for envisaging efficient recovery operations. Nevertheless, the PRR panel recommends to further consolidate the ERC landing simulation and recovery operations in Phase B1 for confirming the parachute free design.

Mechanical

The spacecraft and subsystem structural design is considered satisfactory at PRR. The industrial study teams have proposed different structural configurations for the spacecraft.

Astrium proposes a re-use of the Solar Orbiter structure reconfigured and optimized for the MarcoPolo-R mission. Within the limits of this study phase the detail of this optimization is limited, but is essentially justified, e.g. deletion of propulsion tank rings. It should also be noted that the mass budget reported for MarcoPolo-R structure is based on limited changes to the relatively mature structure design of Solar Orbiter. As a mature design, this includes an appropriate and agreed level of margin for mechanical design loads, and therefore the reported mass budget should be considered reliable, even though the system study does not allow a detail design verification of the proposed structure design.

The TAS structure design is referenced to Herschel/Planck Service Module Structure. However, the similarities are quite limited in terms of dimensions and supported subsystem mass. In addition, the reported mass budget includes a very small allowance for miscellaneous items, e.g. brackets and cleats. The level of design verification possible at PRR, does not allow to confirm the feasibility of the proposed configuration in detail. The reported mass budget for the spacecraft structure should therefore be considered as optimistic. At system level, this has the possibility to absorb some system mass margin, and therefore as a constraint on the technical feasibility, but not a major blocking point as launch mass margins are superior to 10% in the TAS design.

Thermal

The payload and spacecraft thermal design is demonstrated by analysis and design as feasible and design margin is considered. This is valid for performance and budget. However it has to be noted that there is some flight operation constraint to find a working thermal design. During operation of the Solar Electric Propulsion the significant heat dissipation has to be radiated via performance-optimized radiators directed to deep space and at the same time the SA surface needs to be oriented in an optimal direction towards sun. During off mode of the electric propulsion system the radiators have to be controlled by heater power. This design has to be robust in a wide range of environment, in LEOP, direct escape, during cruising and Asteroid rendezvous. The LEOP analysis still has to be confirmed and the industry also has to use the required sun distance values as there is a slight discrepancy between both contractors to be clarified (see **chapter 4.1**). Nevertheless the panel judges the situation as not critical. In general the thermal design of the payload, platform and Earth reentry capsule is considered as feasible.

GNC

The GNC design and maturity are considered adequate to the mission achievement and project development phase. It features non vision-based absolute navigation which is a major improvement with respect to the previous Marco Polo concept in terms of technology maturity and cost as this was a schedule and cost driver. Now, only relative navigation is on-board, which is a mature technology.

As mentioned in **Mission/system** 3 descent strategies have been investigated by both system study contractors (Astrium and TAS) and by GMV in a dedicated TDA:

- The TAS design limits the use of relative navigation to the last descent phase. This basically makes the operations very complex but most importantly lead to non-compliance on the touchdown accuracy performance.
- ASTRIUM design is compliant with the requirements but only focused on navigation and guidance analysis during descent to asteroid, which indeed are the main contributors to GNC performance. However, the use of full GNC closed-loop performance simulations shall be recommended for the next phase.
- Major progress on the GNC have been achieved within a dedicated TDA led by GMV (NEO GNC 1 and 2). The NEO GNC 2 activity is almost completed. It has brought all the vision-based GNC and image processing software to a high maturity level and has demonstrated compliant and robust performances via extensive simulations. Currently, tests of the whole

closed-loop GNC descent towards the asteroid with relevant hardware – navigation camera, laser altimeter and flight processor in the loop – are on-going on a robotic bench with a meter scale 3D-printed model of an asteroid target and appropriate scaling.

The pre-descent navigation strategy is similar for both industrial studies. It relies on propagation of the position knowledge acquired by initial orbital determination by the ground. This position knowledge is updated one more time to the S/C just before the descent start is triggered. However, both approaches would benefit by following the enhanced navigation approach developed in the dedicated TDA. This approach allows simplifying ground operations and initialization of the descent operations. The panel recommends to consider the GNC enhanced navigation approach consisting of on-board pattern recognition of a minimal set of landmarks to initialize the on-board state estimations and triggering the start of the descent operations. This will allow reducing the performance dependency on the last ground command (which provides a guidance profile (initial orbital determination knowledge) and triggering of descent start). In addition, this dedicated study has demonstrated good performances with full close loop simulations and will raise the technology readiness level with robotic test bench validation in the coming months.

In the same dedicated TDA (GMV), the employment of a laser altimeter conclusively demonstrated increased performances, offering a higher measurement accuracy with a narrower beam width that allows higher surface resolution. On the contrary, the radar altimeter, baselined in both industrial designs, can ensure good performances only on smooth surfaces. Therefore, the landing site is strongly constrained to smooth surfaces and only in a region without any large obstacles. This region is not only the touchdown footprint but more generally in the wider surrounding of it, proportional to the altimeter beam width. The laser altimeter can guarantee higher and more reliable performance with little additional cost in terms of power and mass. In addition, the laser altimeter provides better performances at large range.

The spacecraft orientation with respect to the surface is based on vision-based image processing algorithms and careful selection and characterization of the landing site. Only an area with uniform slopes will be suitable for this approach. However tilted altimeters or an imaging LIDAR might be needed if an accurate knowledge of the surface in the surroundings of the landing site is needed. In addition, the needs to monitor the relative attitude during sampling operation would benefit from a direct measurement for collision avoidance purposes. The panel recommends to re-evaluate the slope requirements of a suitable landing site. The performances achievable within NEO GNC 2 shall be taken into account for this purpose as well as possible recommendations from the science team. In case a more demanding slope environment is defined the use of a laser altimeter and a LIDAR relative attitude determination shall be considered. If not, the current design is appropriate. The impact would be a cost increase but this is partly balanced out by merging this LIDAR with the “pure altimetry” function, which is the current concept in the dedicated TDA “miniaturized imaging LIDAR”.

Mechanisms

The sampling acquisition, touch and go, transfer and sealing subsystems are considered to be technically feasible for MarcoPolo-R based on the review of the designs presented and related specifications (e.g. stiffness, functions, transfer accuracy of the touch and go/transfer arm), delivered analysis (e.g. Monte Carlo for touchdown with sufficient test cases and delivered performances) and the separate TDA (e.g. sampling tools). The maturity of the presented designs is commensurate with a PRR level and the touch and go, sample, transfer and containment strategy is deemed to be feasible. In particular, several sets of soil have been successfully sampled during 3 seconds through a force of 20N with a brush-wheel breadboard. In addition this technology has been successfully tested by Honeybee Robotics (US) in a low gravity environment. However, it remains a key design driver for the mission. The following specific comments have been raised by the panel and shall be tackled by the respective primes and the TDA contractors (mostly sampling tool and touch and go) as there are a number of potential weaknesses with the proposed solutions, which could lead to design flaws if not addressed early. All of the issues below are addressed within the ongoing sampling tool and foreseen touch and go activities.

- TAS/Selex Galileo design: triggering of the sampling tool closure is challenging due to the specified soil properties and consequent sampling torque and forces. Penetration depth results are difficult to monitor. Alternatives shall be considered and a trade-off undertaken. Triggering sensors and strategy should be tested appropriately in the ongoing sampling tool development activity but this is currently foreseen.
- TAS/Selex Galileo design: compliance device shall be robust to lateral forces and torques occurring during (multiple) touchdowns, especially with respect to buckling of the blades. This could work as the touchdown resulting loads are not demanding but the level of analysis and definition is too low to confirm yet that it is a robust solution. In-depth analysis, well-justified material selection and very early testing are required within the touch and go activity.
- TAS/Selex Galileo and ASTRIUM designs: sampling tool closure systems have been proposed. These must take into account the possible presence of debris. A compression strength of 30MPa is considered for the pebbles, which could drive the closure strategy. With the Astrium sampling tool design (brush-wheel) straightforward solutions should be possible, as preliminary seen in the AVS sampling tool design and testing activity, but remain to be consolidated. In the TAS/Selex Galileo sampling tool the closure system design has not been demonstrated yet, neither by analysis nor by test. Therefore, this operation is at risk with a claw-like approach. However, a detailed design was made by Selex Galileo and testing is to be performed in the coming weeks.
- ASTRIUM design: during touchdown(s), it is not clear whether the transfer (pulley) mechanism has been fully designed to withstand the relatively high lateral loads (58 N on x and y-axis from Monte Carlo analysis) and torques. If not, this will add complexity and risks on its design and functionality. Lateral compliance of the boom could be considered.
- ASTRIUM design: It is not confirmed that the Eddie current damper solution is sufficient to absorb the touchdown energy. It is recommended to consolidate the design with a trade-off between different damping systems in the upcoming touch and go TDA.

Platform mechanisms proposed design is deemed appropriate considering the preliminary phase of the project. Payload mechanisms are poorly described, which may be considered acceptable at PRR level, however further consolidation has to be performed in the next phase of the project.

Payload

The instruments design and resources are considered adequate and not critical for the mission. The

payload mass is 33 kg for 4 key instruments (narrow angle camera, near-IR/visible spectrometer, mid-IR spectrometer and close-up camera) of relatively well-known use and design and one more instrument for which the sensor is well-known but with a less conventional accommodation (on the sampling boom).
The redundancy implemented in the instruments ranges from no I/F redundancy (CUC, partially THERMAP) to redundancy carried very far into the instrument (MaNAC). The panel recommends ensuring that the instrument redundancies are resource efficient while avoiding to drive the Platform Power and Data Handling architecture.

The review panel has raised the following specific comments:

- MaNAC: The design maturity of MaNAC is not sufficient for this stage of the project. Although the total mass is considered adequate for such an instrument, the mass budget lacks details and appears not to include some items. Tolerance analysis, thermo-elastic deformations, alignment, refocusing mechanism displacement, straylight analysis, mirrors manufacturing, filter information are required. A trade-off with other possible designs shall be presented. However, the above issues are not judged to be critical, provided that more design effort is put in place from the beginning of phase B1.
- CUC: The need to protect the instrument against dust during the sampling operation needs to be consolidated soon, as it may have an impact on the instrument mass and complexity.
- MaRIS: The presented instrument Mass budget (increased from AO) contains errors and may be incomplete. The mass budget needs to be clarified and re-assessed. The achievable spectral resolution performance needs to be clarified with respect to the requirements. A Thermo-mechanical and tolerance analysis shall be performed.
- VISTA: This sensor is to be mounted on the sampling boom. It is not resource-demanding but its accommodation and integration may be a challenge and it is overall poorly described.

Operations

While on the whole operational scheme there are no overriding technical feasibility concerns, the most challenging aspect of this mission, from an Operations point of view, are the operations in the proximity of the asteroid, and in particular the definition of the descent strategy. Both proposals present and elaborate operational concepts for this phase.
Taking into account the comment made in chapter 4.1 on the need for high telemetry and telecommand, the panel recommends however to include a pointing medium gain antenna. A medium gain antenna is already part of both designs and one of them already has a pointing mechanism. Most likely, a one-axis-mechanism operated in open-loop control will be sufficient. This does not have a major impact at system level. A more significant concern is that the TAS proposal for descent strategy is considered to involve a higher degree of operational complexity and has poorer results in terms of performance (see **GNC**).

Overall, Proximity Operations are considered to be challenging, however they are being thoroughly tackled by the NEO GNC (see **GNC**) and the Fast Operations Platform for small body GNC TDA studies, now underway at ESTEC and ESOC. The latter TDA is defining in details all operations required at ESOC to perform the mission, taking into account the inputs of the NEO GNC activity and building on the Rosetta approach. It is expected that as an outcome of these studies, results will be fed back into the design probably in the form of expanded S/C functional requirements. The

NEO GNC final outcomes will be available before the start of phase B1 whilst the Fast Operations Platform TDA will feed the Phase B1 throughout and will be completed in early 2015. After this step is completed, the Asteroid Proximity Operations could be considered consolidated and of medium complexity. It builds on the Rosetta operational building blocks, especially the orbital operational strategy, but is less critical as the asteroid has no off-gassing and the ground is not in the critical loop for descent and touchdown as opposed to Rosetta which Philae delivery fully relies on the ground-commanded operations. The operational complexity would be in addition much simplified if the recommendation proposed in the GNC chapter above is implemented (use of enhanced relative navigation to by-pass the last ground navigation update before descent) .

3.3 Confirmation of the mission programmatic feasibility:

- *Critical review of the spacecraft and payload development plans*
- *Adequacy and completeness of the proposed development and verification approach*
- *Model philosophy*
- *Realism and completeness of spacecraft and payload development schedule (incl. margins)*
- *Compatibility of payload need and delivery dates*
- *Critical path analysis*
- *Risk assessment and related mitigation plan*
- *Credibility and compatibility of technology maturation roadmap schedule with system schedule*

Spacecraft development plan/model/AIV-AIT

The spacecraft development plan is adequate. Both primes follow a PFM approach for the “standard” equipment but STM/QM/FM for innovative systems, e.g. sampling mechanism, touch and go arm, capsule and GNC SW/equipment for which test facilities have been already identified, and fit with the test specifications. It includes a complete hardware matrix with a detailed list of spare parts.

The development and verification approach is consistently defined by Astrium with the exception of the sine vibration test approach at unit level. This needs to be clarified as it may lead to over-testing of the flight model units. An inconsistency also exists in the allocation of random vibration qualification test to unit level models. When EQM units are procured, they should be used also for random vibration qualification testing. This is not completely clear and should be reassessed properly. TAS defined a consistent development and verification approach as well. Only the definition of verification levels is confusing and not in line with the applicable ESA standards (ECSS). They need to be reassessed in line with the expected activities. E.g. the Experiments are not a module and e.g. they are recalled under subsystem level. Further on, the ground segment is mentioned in the text, but it is not defined as a verification level. Either the ground segment should be defined or that terminology removed.

Spacecraft overall schedule

The Astrium schedule, with 6.4 year development time, is properly defined and quite complete for this phase of the project. It also includes (realistic) estimates of the procurement time of the subsystems and units, giving a good confidence on the assumed margins. The TAS schedule, also with 6.4 year development time, remains high-level. It does not include a detailed estimate of the procurement schedule of units and subsystems.

Based on the review of the provided schedule, critical path analysis (see below) and margins, the December 2022 launch date is considered to be feasible. The total development time (from phase B2 KO to launch) is 6.4 years including: 1-year phase B2, 2.3-year phase C, 2.1-year phase D, 0.5-year phase E1, 0.5-year contingency. This is realistic, similar to other projects of similar complexity and a little longer than for Solar Orbiter (6 years) and one year more than for Rosetta (5.5 years).
The backup December 2023 launch date can be met with robust margins, with a total of 7.4 year development time. Due to the nature of the mission (one launch window per year), it is however recommended to anticipate the phase B2/C/D KO by a few months as well as to speed up the procurement phase for the key elements, namely: GNC, sampling and touch and go mechanism and re-entry capsule in order to fully secure the 2022 opportunity.

Critical path

The critical path has been analysed. Both the touch and go arm and the GNC are considered to be the main schedule drivers; the former because the technology activity is starting only now and the latter because it involves intensive critical SW validation phases. Validation and Verification of the whole GNC chain is ongoing on a dynamic real-time test bench with flight processor and sensor in the loop. The whole GNC will be at TRL 5-6 in May 2014 so the GNC-related schedule risk is considered to be low. For the touch and go arm, appropriate test facilities have been identified, an adequate TDA is about to start and the overall design was judged to be non-critical (see chapter 4.2), but this particular sub-system requires a strong technology development effort in parallel to phase B1 to ensure that it is at the same level of maturity as the other technologies at start of phase B2. At the moment the risk is considered to be medium. Two contracts addressing both industrial designs are recommended.

Technology development schedule

ESA is taking care in an adequate manner and is currently well advanced in the development of the MarcoPolo-R required technologies as described in chapter 4.2, e.g. GNC validation by GMV, sampling tool development and tests, ERC heat shield material pre-qualification and crushable material tests, etc. The exception is the touch and go arm as indicated above which targets TRL 5 by mid-2015.

However, system primes need to be better informed of the current status of advancement as this is not yet shown into the industrial planning documentation. The following few remarks are not critical due to the above facts, but need to be mentioned. The required technologies to be developed are defined, but both industrial schedules and DD and AIV plan need to be complemented by dedicated schedules in a GANTT chart format for the technology development activities to be performed/continued in phase B1 in order to allow a proper start of the Implementation Phase and to reach TRL 5.

For Astrium, the technology readiness assessment and Development Plan seems to show a marginal development planning. By having a BB type of equipment available, TRL 5 should be reached, while it is here stated that the QM is used to bring the technology level from TRL 4 to 6 (e.g. radar altimeter). On the AOCS and GNC algorithms, Phase B2 is used to develop up to TRL 5, while the prerequisite is to be at TRL 5 at the end of B1.
In the TAS AIV Plan, the GNC during proximity is stated as a new development, but no specific

description of its intended qualification process was provided. A partial summary is provided in the technology Development Plan, but still insufficient.

More details on the model philosophy, the credibility and compatibility of the technology maturity activities as well as on the programmatic risk of the critical sub-systems can be found hereafter.

GNC

Both studies correctly indicated the GNC proximity operations as one of the technologies needing dedicated technology plans. However, only the ASTRIUM technology plan has identified possible hardware in the loop with robotic test benches to be used for the actual validation of the GNC and system level spacecraft electrical chain, as it is already done in GMV in the dedicated NEO GNC TDA. Even though both primes have defined an appropriate model philosophy for the GNC in their system AIV plan, only a placeholder is allocated for functional and performance GNC tests on a system test bench (integrating on-board computer and other QM units). These tests are specific to this mission and are critical. A clear description of such tests is missing (e.g. how to stimulate sensors, adequate test procedures). The review panel recommends to consolidate early the verification and validation strategy of the critical GNC at system level. It is also recommended to perform early development of the GNC proximity operations building on the upcoming "fast mission operations platform for NEO GNC" activity.

Mechanisms

Key mechanisms for touchdown and SATC are subjects of several on-going or shortly starting TDAs, which is deemed fully appropriate to mitigate associated risks listed in chapter 4.2. Model philosophy and proposed schedule are consistent with best practice and mission requirements for both contractors with the exception of the TAS-I SATCS QM model which is stated not to be a deliverable. This is to be clarified. In addition, the requirements and design are such that sampling tools are interchangeable with the system design, providing robustness to the industrial procurement approach.

Payload

The instruments model philosophy and development schedule are mostly compliant with the mission requirements. The lack of a complete Qualification Model for the NaNAC is however a risk of late discovery of the problems and may cause instrument delivery delay. The review panel recommends implementing a full MaNAC Qualification Model. The scheduled delivery of all payload models (except MaNAC QM) is fitting with the system-level requirements. All instruments have quite an extensive heritage at unit or component level. The following heritage is noted:

- MaNAC: SIMBIO-SYS (BepiColombo) for detector – VIRTIS (Venus Express), Frame Imaging Camera (DAWN) for electronic unit, etc.
- MaRIS: VIRTIS (Rosetta) for cryo-cooler – CHROMA FPA (Teledyne) for detector
- Thermap: MERTIS (BepiColombo) overall for electronics, optics – IRCAM (JEM-EUSO/ISS) for ULIS detector
- CUC: Clupi (ExoMars) for the whole system (including focus mechanism, detector, etc.)
- VISTA-2: GIADA (Rosetta) for the sensor (crystal microbalances)

Operations

From an operations standpoint, there are no major concerns on the programmatic feasibility of the mission. The only significant development related to operations is on-board GNC software, and there are sufficient support activities on-going (NEO GNC, Fast Operations Platform for small body) to build confidence that this is being addressed with ample schedule margin.

4 CONCLUSIONS AND RECOMMENDATIONS

The critical mission and system requirements have been defined and addressed adequately by ESA, the two system primes and in the dedicated technology activities of relevance to MarcoPolo-R. Many detailed recommendations to update the ESA documentation in preparation for the ITT for Phase B1 have been made by the review team.

The resulting design is appropriate and mass margins are robust. The overall interplanetary environment (~ 1 AU, asteroid) of the mission (except re-entry) is milder than any ESA planetary mission flown to date (except Smart-1), which keeps the environmental risk for the “standard” sub-systems low. The asteroid descent and touchdown and Earth re-entry operations have been simplified to the greatest extent even though they remain a medium operational risk intrinsic to the nature of the mission.

Most critical sub-systems and aspects have been through a satisfactory design iteration and are considered acceptable at this stage with a few exceptions. These exceptions, discussed in the relevant chapters, are: TAS GNC strategy, sampling tool closure system, touch and go compliance actuator and ERC ground recovery operations. For those, alternative design solutions are available mitigating the development and operational risk and appropriate testing activities are ongoing or foreseen to start shortly to address those issues. The associated specifications at component level are not demanding and the preliminarily identified components are space-qualified (touch and go arm motors and limbs, compliance actuator, etc.), but the identified weaknesses of these designs must be eliminated early in phase B1.

The payload design and maturity is judged overall to be adequate; particularly for THERMAP, MARIS, RSE and the CUC. Focused activities are however still required to define proper interfaces for phase B1 (e.g. thermo-mechanical tolerance analysis, review of spectral performance). The design maturity of MaNAC and VISTA 2 is considered to be low for PRR. Further design activities of these two instruments however have a limited severity for this mission given the current mass and volume allocation and known heritage.

The mission is considered to have an overall low to medium development risk. It is technologically demanding, but there is no high development risk associated with the proposed designs and all critical items have been or are being addressed appropriately in technology development activities of relevance to MarcoPolo-R. The mission is prepared to enter the ITT preparation for phase B1. For the relevant elements, TRL 5 has been reached (heat shield) or should be reached by KO of phase B1 (GNC, sampling tool). All other spacecraft parts are already mature.
In particular, the GNC design is being fully validated on dedicated optical and dynamic test benches and with mature algorithms, flight representative processor board and GNC hardware in the loop.

The dynamic test bench features a real chaser-to-target metrology stimulation allowing the use of sensors measurements in the loop through the recreation of relative trajectory and attitude profile by using robotic arms. Furthermore, the requirements have been relaxed with respect to the previous Marco Polo study, which allows to feature a more mature and cost effective navigation approach.
The sampling tools are being breadboarded and tested and initial test results demonstrate good performances. The re-entry capsule critical heat shield material has been tested successfully in the relevant environment and will reach the pre-qualification status shortly. The technology maturity of these elements is well-advanced. These results must however be directly communicated to the system primes right at the beginning of phase B1.
The touch and go mechanism TDA is planned but remains to be kicked-off and its schedule must be monitored very closely to ensure that this critical element can reach TRL5 by Mission Adoption and that its specifications are sufficiently well-defined to enter mission implementation/procurement phase. It is on the development critical path although its current design and development schedule are judged to be feasible.

The primes have defined a development plan in line with the specific needs of the mission, PFM for standard platform sub-system and full STM/EQM (or QM)/FM for critical technologies associated with relevant test facilities/EGSE. The GNC development is also a schedule driver and on the critical path, but the detailed V&V steps are well-defined and provide confidence into its development schedule, especially given the satisfactory performances and maturity reached at this stage. PFM system-level validation tests of the key GNC approach should however be consolidated.

The December 2022 launch date is considered to be feasible given the current development plan, schedule and status of key technologies. It leads to a total of 6.4 year development time, which is overall a little longer than for Solar Orbiter and one year longer than for Rosetta, and adequate for the complexity of MarcoPolo-R. Due to the mission launch constraints of one single 3-week window per year, the panel suggests to look into anticipation of the Phase B2 and speed up procurement of long lead items, i.e. GNC, SATCS and ERC in order to fully secure the 2022 opportunity, should it be required by the Programme needs.

With respect to the review objectives:

- <u>Confirmation of availability and completeness of the Mission and System requirements:</u>

  The documentation set was adequate for the Phase A and has established a firm baseline to start the preparation of the ITT documentation package for the Phase B1. Many detailed comments have however been made, therefore updates are required to the ESA documentation to be ready for the Phase B1 ITT.

- <u>Confirmation of the mission technical feasibility:</u>

  As discussed in the report and the above conclusions, the mission is technically challenging, mostly due to the two critical phases - asteroid sampling and Earth re-entry. Many issues were raised. However, they have been judged to be either non-critical or well-tackled by the on-going technology development. Subsequently no showstoppers have been identified

- Confirmation of the mission programmatic feasibility:

  Providing that the programmatic-related comments made by the panel are followed-up, the panel confirms that the mission is programmatically feasible.

Annex 1 – list of TDA of relevance to MarcoPolo-R

The touch and go activity, identified as the most critical one by the PRR panel, is highlighted in orange. Note that the previous activities of relevance to MP-R and already completed are not presented here (GNC development – step 1; ablative material development – step 1, etc.). The only activity proposed for implementation is an activity on sample sealing demonstration (leak tests, shock tests, etc.), see last row below. The other activities presented below are already ongoing.

Key capability	Activity Title	Budget	Duration	End date	Status	Deliverable	Current TRL	Targetted TRL
Asteroid descent and touchdown GNC	Assessment and breadboarding of a planetary Altimeter	900	16	Q1 2014	ongoing	Laser or radar altimeter breadboard/test	4	5
	Autonomous GNC Technology for NEO Proximity, Landing and Sampling Operations – Phase 2	500	18	Q2 2014	ongoing	GNC tests with HW in the loop for descent navigation. GNC/IP SW already developed, SW-in-the-loop tests performed. HW-in-the-loop tests about to start.	4	5
	Fast Mission Operations Platform for small body GNC	250	12	Q3 2014	RFQ	Optimization of ground segment/mission operations procedures specific to the mission need and harmonization of operations with GNC approach (above activity)	N/A (SW)	N/A (SW)
Asteroid touchdown, sample transfer	Touch and go mechanism breadboard design and test	750	18	Q3 2015	ITT	BB and test in microgravity-simulated environment of the asteroid touchdown and sample transfer mechanism (LAMA facility – DLR)	3	5
Sampling mechanism	Breadboard of a sampling tool mechanism for low-gravity bodies	2 x 750	21	Q2 2014	ongoing	BB and tests in microgravity of the sampling tool. Ground tests performed.	4	5
ERC heat shield	Delta-development of TPS for high heat loads	700	24	Q3 2014	ongoing	pre-qualification of the heat shield material. TRL 5 already achieved.	5	6
ERC crushable	Material development for a crushable TPS for the ERC	250	18	Q2 2014	ongoing	BB and tests for Pre-qualification of crushable material for the ERC. Existing materials. Need testing. Focus on material characterization	3/4	5
ERC aero	Marco Polo R earth re-entry capsule dynamic stability characterization	450	24	Q4 2014	ongoing	Validation of the ERC aerodynamic shape via tests	N/A (test)	N/A (test)
Sample sealing	Sample sealing system breadboard and testing (to be confirmed)	500	18	Q4 2015	Proposed	Breadboarding of the sample sealing system, integration into an ERC (simplified) STM and shock/leak tests	3	5