DOCUMENT

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M CLASS INTERNAL REVIEW REPORT

MARCO POLO

TECHNICAL & PROGRAMMATIC REPORT

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Issue: 1 Revision: 0

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1 INTRODUCTION

1.1 Board composition

The Marco Polo review board members are listed below:

Responsibility	**Board member**	**Comment**
Chair	Don Mc Coy	*Unable to attend*
Deputy chairman	Andrea Santovincenzo	
Secretary	David Agnolon	
Observers	Frédéric Safa	
	Thomas Passvogel	
	Renée Fontaine	*Unable to attend*
	Detlef Koschny	
	Jens Romstedt	
Mission analysis	Robin Biesbroek	
Thermal/re-entry aspects	Heiko Ritter	
Aerodynamics		*Olivier Bayle as support*
Mechanisms	Jean-Michel Lautier	
AOCS/GNC	Jacques Rouquet	*Remi Drai as support*
Payload #1 & AIV-T	Albert Haldemann	
Payload #2	Isabel Escudero	
Programmatics #1	Thorsten Siwitza	*Unable to attend*
Programmatics #2	Yves Bonnefous	
TOTAL board #	**9**	

1.2 Meeting dates

The review meetings took place on the following dates:

- Wednesday October 1st, 14:00-19:30 (BA 024)
- Wednesday October 7th, 14:00-18:30 (BA 024)
- Wednesday October 14th, 14:00-18:30 (BA 024)
- Tuesday October 20th, 09:00-12:50 (DB 124)
- Wednesday April 21st, 14:00-18:00 (BA 024)

1.3 List of documents

The following document packages were provided to the review board members:

- ESA-produced documents (requirements, mission analysis, operations, cost report, etc.)
- The technical and programmatics document packages produced by the three industrial assessment study contractors
- The technical and programmatics study reports produced by the payload teams having responded to the Declaration of Interest

The full list of documents available to the review board can be found in Annex 1.

1.4 Overview of review activities

In compliance with the objectives of the review, the board concentrated on identification of the major mission risks at technical, programmatic and financial level to provide an overall assessment of the feasibility of the mission within the schedule and cost constraints of the M-class.
An excel table was used to identify issues, describe them, analyse their risk in terms of severity and likelihood to occur, and eventually mark their overall criticality with a score of Low/Medium/High. For each risk the board produced a recommendation providing a set of mitigation strategies. The current report lists the issues which were acknowledged by the board as most critical. The annex 2 to this report describes issues of lower risk. Also for those issues, specific recommendations for consideration by the ESA study team have also been made in view of preparing next study/mission phases.

2 TECHNICAL REVIEW

2.1 Spacecraft design

2.1.1 COMPLETENESS AND CONSISTENCY OF THE MISSION REQUIREMENTS

Science and technical requirements from the Agency are in line with the level required for this phase of the mission and constitute a good basis for future phases.

In three requirement areas, the board has identified three major risks.

2.1.1.1 Landing accuracy

The present landing accuracy requirement (<3.5 m) is derived by consideration of maximisation of safety at landing in case of asteroid with rough surface. Such requirement has driven the design of the GNC system towards the choice of an advanced and immature absolute navigation technique based on visual recognition and automatic tracking of given landmarks on the asteroid surface.

The board has judged as unrealistic the possibility that this technology achieves TRL 5 by early 2012 (see section 2.3.1.1). To maintain a launch date in 2018, it has suggested relaxing the landing accuracy requirement by an order of magnitude. In such case a GNC system based on a more mature absolute navigation technology could be used. Landmark recognition performed through ground intervention rather than autonomously could be implemented. This reduction on performance will entail though an increase of risk of landing failure in case of rough terrain.

2.1.1.2 Safety requirements for ERC

There are currently no safety mission requirements that apply to the Earth Re-entry Capsule although in principle, safety and liability issues exist in connection with damage to people or properties at landing. ESA policy is currently incomplete as it is tailored to disposal of ATV and not directly applicable to the ERC case. Safety requirements from Australian authorities (landing site is Woomera) do not appear as problematic but nevertheless need to be further clarified as soon as possible.

The board has assumed that to achieve clearance from safety authorities to perform the re-entry, it will be enough to verify via probability analysis that:

- even in case of parachute failure or aerodynamic instability, the ERC still falls within the Woomera range perimeter,
- that the targeting manoeuvre has a very low probability of failure,
- that a total spacecraft loss of control prior to ERC separation leads to complete disintegration of Spacecraft into atmosphere.

Safety approval process may lead to mission delays, design modifications to return trajectory, spacecraft or ERC, extra cost due. The impact could be severe but the likelihood is low as there is sufficient time to take the necessary actions to mitigate this aspect. The overall risk is considered to be medium.

The board has recommended to initiate discussion with safety authorities to clarify requirements and required analyses as soon as possible

2.1.1.3 Asteroid soil specifications

The soil specifications for the sampling tool in the MRD is simplistic as it specifies only given values of mechanical properties. This entails a high risk to perform an incomplete qualification of the sample acquisition system

The board has recommended that soil properties are specified as ranges after discussion and agreement with the asteroid science community in order to develop and properly qualify a robust sample acquisition system.

2.1.2 CLEAR DEFINITION OF RESPONSIBILITY AND INTERFACES

Marco Polo was assessed during this review as an ESA-only mission. As such, no issue has been identified concerning external interfaces.

2.1.2.1 JAXA-led mission option

A short assessment was made of the alternative JAXA-led scenario in which ESA would provide only the re-entry capsule. For such scenario JAXA has specified a maximum mass of the ERC at interface of 20 kg. The current capsule mass from industrial design exceeds the constraint (e.g. 30 kg for Astrium in the ESA-led design). and several design uncertainties have been identified that would lead to mass increase (e.g. need of ballast mass, uncertainty on heat loads, potential density growth of TPS material, parachute mass underestimation, etc.). The ERC mass might be lower only if the JAXA design approach is followed which implies design choices which are not clear or shared at this stage (e.g. lack of internal structure, use of JAXA low-resource equipment such as beacons, parachutes for which there is no known equivalent in Europe, etc.).

This issue may have a severe impact as it could lead to the cancellation of the ESA contribution in this mission option and the likelihood is considered high as ERC mass growth is certain in future phases, therefore yielding an overall high risk.

The board has recommended that the ERC mass allocation be renegotiated as a condition for collaboration in case the JAXA-led option is being pursued further.

2.1.3 DESIGN ROBUSTNESS AND DESIGN VERIFICATION

The mission presents two areas that are new to the Agency: 1. asteroid landing in micro-gravity and 2. Earth re-entry from interplanetary hyperbolic trajectory.
As a consequence, the following mission elements require specific design and development effort:

- Guidance Navigation and Control subsystem for asteroid approach and landing
- Landing gear (legs)
- Sampling and Sample Transfer Mechanism(s)
- Earth Re-entry Capsule

For these subsystems the board has highlighted a few design issues which imply technical and programmatic risks
The rest of the spacecraft design is generally comparable in complexity to other ESA interplanetary missions like Rosetta, Venus Express, etc.

2.1.3.1 Absolute Navigation function for Landing

The present industrial designs show position errors which are typically 10 to 20 meters (without margins) assuming that landmark based navigation is used. It is therefore unrealistic to assume fulfilment of the 3.5 m landing accuracy mission requirement.
It is not clear if all the factors (e.g. illumination conditions, thruster execution errors, etc.) have been properly taken into account. In addition, some of the preliminary simulations that have been performed to validate the algorithms and assess performances are based on the Moon landing case for which previous work had been performed within an ESA technology development activity. Applicability of positioning error estimates to asteroid mission could therefore not be established at that stage, as the algorithms and more particularly the feature matching algorithms, will first need to be adapted to the asteroid case
If landing accuracies much lower than 100 m cannot be guaranteed, landing might not be possible or will be very risky in case of rough asteroid surface. Therefore the risk of not reaching the landing accuracy is considered to be severe and has a high likelihood yielding an overall high risk.

The board has recommended to analyse an alternative navigation technique including ground control in the loop (see also 2.1.1.1). This would need to be discussed with ESOC (Flight Dynamics) and simulations (industrial studies) shall be performed. Landing accuracy is likely to be significantly worse but possibly <50 m (Hayabusa's value), which would still lead to a feasible mission but increase the risk of failure at landing

2.1.3.2 FDIR strategy and safe mode definition

The definition of safe mode and FDIR strategy is presently very limited. Given the nature of the mission (high GNC performance and critical timeline) FDIR considerations may lead to heavy constraints on the approach and landing strategy with associated degradation of performance.
<u>At least</u> assessment of landing abort capabilities shall be performed in detail.
The risk severity is considered high. Nevertheless, no showstopper has been clearly identified by the board so the likelihood of occurrence is moderate. This is overall a medium risk area.

The board has recommended to consolidate the mission baseline and identify in particular ground outage as early as possible in the design phase to allow assessment of FDIR. It is also recommended to perform activities on robust collision detection and avoidance manoeuvres

2.1.3.3 ERC stability

The ERC stability in transonic is not sufficiently consolidated. To reduce risk, a supersonic parachute could be added which is problematic in terms of development time, testing and cost. In addition, the deployment approach does not seem to be mature (i.e. mortar accommodation). However, numerical analysis suggests stability for the proposed shape and configuration (subsonic parachute only) but this needs to be confirmed by test.
The board has investigated the issue and found that several wind tunnel test programs on similar capsules were performed in the US and Europe (e.g. ISL facility) indicating that the some shapes can be stable and providing confidence that a supersonic parachute can be avoided. Proper design of the backshell (i.e. spherical) and stringent control of the CoM may also ensure that the shape is stable.
The associated severe risk is to face an ERC configuration (aerodynamic shape) change in later phases causing schedule delay and increasing cost (i.e. addition of supersonic parachute available only in the US). However, thanks to early considerations of this issue it is unlikely that a valid solution with a subsonic parachute cannot be found, yielding an overall medium risk.

The board has recommended that: 1. strict control of the centre of mass should be implemented throughout the design; 2. The technology development plan shall include aerodynamic test campaigns in order to quantify stability parameters in transonic and to allow early freezing of ERC shape

2.1.3.4 Sampling tool shutter mechanism

The current design of the sampling mechanism includes a shutter to close the corer after penetration in the soil.
It has not been demonstrated via appropriate testing that the proposed sampling tool concepts are versatile enough against different soils properties. Ideally, soil samples that could be found on Earth should be specified for future testing. In addition, the sampling tool will have to be re-usable/settable up to 3 times. This might require the sampling tool to be "cleaned" after each attempt.
In case of inappropriate qualification, there is a risk of loosing the sample when closing the shutter leading to the loss of a major mission objective. Late investigation would lead to late design changes and sampling approach with associated high cost and schedule delay. Appropriate shutter development was however assessed to be possible by the board overall yielding a medium risk.

The board has recommended to emphasize shutter development as early as possible within the planned TDA and to perform testing with representative soil properties, noting that the associated risk is partially mitigated by experience gained in the ExoMars programme.

2.1.3.5 Sampling acquisition, transfer and containment (SATCS) system concept selection

The definition of the sampling and transfer mechanism has a major impact on the design, configuration and operations of the Spacecraft. Today two options exist:
1. Sampling after landing and permanence on the asteroid surface for a few minutes, leading to separation between the landing and the sampling function and
2 Touch-and-go approach with sampling mechanism within the landing gear, taking the sample at touchdown and leaving immediately the surface. This leads to coupling between the landing and sampling function.

Unless a decision on the approach is taken immediately by the Agency, there is a high risk of schedule delay as the spacecraft configuration will not be frozen and the limited resources of the future planned Technology Development activity will not allow maturation of two concepts.
Proper interfaces should be defined during next phase to ensure that both competitive definition studies will have clear feedback from the SATCS developed within the TDA.

The board recommends to take an early decision on the sampling approach and to discard the “touch and go” approach because this couples landing and sampling functions, increases risk and makes verification procedures more complex; In particular, the sampling capability relies on landing conditions and it is not robust enough against change of requirements for soil properties The problematic is identical for the landing gears.

2.1.4 COMPLETENESS AND CONSISTENCY OF RESOURCE BUDGETS

The design margin philosophy specified in the MRD (e.g. maturity, system margins, aerothermodynamics, etc.) has been fully respected by all contractors. The mass and power budgets are realistic at this stage of the project.
A launch mass margin around 10% (~160 kg) is achievable and it considered sufficient at this stage to cover potential uncertainty on the Soyuz performance into the specified hyperbolic escape trajectory. Such performance is today the result of ESA own model of the launcher and will have to be confirmed by Arianespace.. This risk is considered moderate as the ESA model has been validated with the GTO launch case

The board recommends to contact Arianespace as soon as possible to consolidate launcher reference performance and to maintain this launch margin across next design phase. No commitment on additional “optional” payload shall be taken..

2.2 Payload (science instruments)

The Marco Polo science payload is assumed to be provided by European Member States. The core payload is clearly defined and allows fulfilling all science requirements. It consists of a Narrow Angle Camera, a wide angle camera, a close-up camera, a near-infrared and visible spectrometer, a mid-infrared spectrometer, a laser altimeter, a neutral particle analyzer and a radio science experiment (the latter having no hardware other than the spacecraft telecommunication system).
The mass and power budgets of the proposed payload have been assessed as realistic
Although landing would require previous asteroid visual mapping, the success of the mission is not directly coupled to the scientific payload performance as the navigation camera could be used to identify an appropriate sampling site (at coarser resolution) and navigate towards it.
This has been positively noted by the board.

2.2.1.1 Narrow Angle Camera pointing accuracy

The NAC pointing accuracy requirement was changed in the late phase of the study by the payload camera team to 15 μrad while the industry studies assumed only 1.25 mrad. With ~ 2 ms exposure time the new requirement translates into a pointing stability requirement of 7.5 mrad/sec. This would become a major design driver as it would call for the need for innovative star tracker, optical bench, etc.. However, there seems to be a misunderstanding on what is meant by the payload team, thus making this requirement questionable.

The board has recommended to clarify as soon as possible with the payload team the need for such a stringent camera pointing requirement and to make the team aware of the design consequence

2.3 Technology readiness

Except for the recommendations in sections 2.1.3.3 and 2.1.3.4 above, the board has assessed the TDA plan as well structured and complete.
In a few cases achievement of TRL 5 by 2012 is considered not realistic and mitigation strategies have been proposed by the board as reported below

2.3.1 SPACECRAFT

2.3.1.1 Absolute Navigation function for Landing

Autonomous absolute navigation technique is still at a very low TRL (i.e. 2) today. R&D studies (MAGELLAN) have been initiated for lunar landing as the first application case. A stepwise series of technology activities has been duly proposed within the TDA plan for Marco Polo for a budget of 800 Keuro but the achievement of TRL 5 by 2012 with such budget is not considered realistic by the board. Taking into account that the descent rate on an asteroid will be slower than the descent on the lunar surface as well the benign dynamics environment in which the visual known landmark navigation (Magellan-like) will operate when compared to a lunar lander, the board has assessed that with the incremental verification and validation approach, both static and ground dynamics testing, the technology can be raised to TRL5 only by early 2013 and with an investment in the order of 2 Meuro. The lessons learnt from similar technology developments have been used to set such achievement date.
The risk associated with not reaching the required maturity in the given timeframe is a major schedule delay for GNC development (already a schedule driver) and the non-achievement of the required landing performance. This is considered to be a high severity risk with a high likelihood to happen.

The board has recommended to assume as baseline absolute navigation based on ground analysis of landmarks rather than autonomous. This would increase the chance of achieving TRL 5 by 2012. In addition higher budget should be foreseen for the associated TDA

2.3.1.2 GNC Proximity Sensors for Landing

Asteroid proximity operations require the use of a proximity altimetry sensor..
Different equipment suites have been baselined by contractors but such equipment either does not exist yet or its performance does not comply with the requirements. The availability of a proximity sensor is questionable and development effort will likely not permit to achieve TRL5 in due time
The risk associated with not reaching the required maturity in the given time is a major schedule delay for GNC development (already a schedule driver) and the non-achievement of the required landing performance. This is considered to be a high severity risk with high likelihood.

The board has recommended to investigate the purchase of JAXA sensor and analyse the impact on GNC performance of using a lower performance sensor (e.g. enhanced Beagle-2 altimeter).

2.3.1.3 ERC heatshield material

ERC mass strongly depends on new/ongoing ablative material development. Such development is well under control but there is the risk that final material performance (in particular density) will not be as assumed in the present design.
Good heritage exists in Europe on such materials. There is very little doubt that development will be successful but performance cannot be guaranteed yet. An activity to reach TRL 5 for the ablative material in the TDA plan for a value of 750 KEuro is foreseen but TRL 5 needs to be achieved for the overall heat shield.
Failure in developing the new ablative material with the required performance would lead to ERC mass increase and/or mission schedule delay. The risk level is medium as an ERC mass increase is tolerable up to about 50 kg with the current design providing no mass growth occurs on the main spacecraft. Overall the risk is considered medium.

The board has recommended: 1. to assess cost of the alternative US PICA material (suitable back-up) and its procurement constraints. 2. to implemented tight control of ablative material development. 3. to enlarge scope of TDA so to bring the whole heatshield technology to TRL5 by 2012

2.3.2 PAYLOAD

No criticality has been identified so as to the technology readiness of the instruments. The estimated TRLs are adequate, except for the close-up camera which maturity seems to be optimistic (e.g. ExoMars). The visible/near-IR infrared sensor ranges from 0.4-3.3 μm for science is not covered by current European detectors. Technology developments in the infrared detector industry are leading to covering the full range, but are not quite there, and may be quite expensive. There is thus a non-negligible schedule risk not to achieve TRL 5 by 2012. Overall, the technology development activities proposed by the payload teams have a poor level of definition. Those should be clarified in the AO in order to have an appropriate development approach with clear milestones.

3 PROGRAMMATIC REVIEW

3.1 Development plan and schedule risk

3.1.1 DEVELOPMENT PLAN

All contractors propose the following development plan:
- Main spacecraft: STM, PFM
- SATCS: EQM, FM (+ spares)
- Landing legs: QM, FM (+ spares)
- GNC: ATB, FM (+ spares)
- ERC: STM, QM, FM (+ spares)

- All other sub-system units: EM, PFM (+ spares)

This approach is judged feasible but it is highly recommended to also include QM for some of the units which will clearly require some delta-qualification (PCDU, IMU, STR, Navigation camera, all other mechanisms (HDRM, Antenna HDRM and pointing mechanism, spin ejection mechanism, etc.)).
In addition, this approach is only valid if the four most critical systems (SATCS, landing legs, GNC, ERC) are brought to TRL 5 by 2012, beginning of Phase B2.
Given the foreseen TDAs, this seems realistic (see section 2.3), except for GNC which development schedule has been assessed too optimistic. Schedule contingencies have been included in the GNC development schedule to account for this. The proposed verification approach is valid and does not require any new facility to be built.
For the most critical systems, the following verification tests are foreseen.

- SATCS: parabolic flight or microgravity-simulated testing (e.g. counterweights)
- Landing legs: drop tests in dedicated facility (DLR’s LAMA)
- GNC: real-time test bench with hardware in the loop, using dynamic test bench (e.g. robot arm or helicopter)
- ERC: stability wind tunnel testing, heat flux testing, balloon drop tests

3.1.2 SCHEDULE RISK

The time allocation for a number of tasks is quite realistic and in line with the Rosetta development for instance whenever comparable. From the beginning of Phase B (May 1997) to launch readiness (January 2003), the duration of the Rosetta development phase was 5 years and a half. Marco Polo includes a sampling system and a return capsule, while the development schedule is estimated at 6.5 years and 7.5 years for the backup launch date. Sufficient time is allocated for ESA implementation constraints. The schedule risk is considered as high in view of the complexity of the GNC system (as identified in the technical issues), the number of technology developments that need to be successfully implemented, the number of mechanisms to develop and validate during the implementation phase, and specific system verification aspects. It is also required to have a 6 month schedule contingency.
Overall, it appears challenging to meet the launch baseline date in November 2018. Nevertheless, by lowering the GNC requirements and efficiently initiating the technology developments at the beginning of the Definition Phase, the overall development time is estimated below 7.5 years with adequate margins. Therefore, the back-up launch date is considered realistic and achievable.

4 RECOMMENDATIONS, MITIGATION MEASURES

See section 2.

5 CONCLUSIONS

The review has confirmed the technical feasibility of the mission.

Several technical and programmatic risks have been identified but these can generally be mitigated

The main issue is that, driven by the landing accuracy requirements, the GNC sub-system for this mission requires a substantial delta-development with respect to ESA's state-of-the-art technologies. This leads to a high risk on performance, schedule and cost.

Relaxation of the landing accuracy requirement would allow reduction of those risks but efficacy of this mitigation approach cannot be properly quantified until a second design loop is performed.

Anyway, a higher risk of landing and/or sampling failure will have to be accepted due to the intrinsic uncertainty on the asteroid terrain roughness.
The schedule assessment has shown that a realistic launch date for the mission is late 2019.

ANNEX 1: LIST OF DOCUMENTS

The full list of documents available to the review board can be found thereafter.

Title	Reference	Issue	Issue date
Marco Polo Yellow Book (YB)	MP-RSSD-RP-016	D1-m	30/09/09
Marco Polo Science Requirement Document (Sci-RD)	MP-RSSD-RS-001	2c	29/09/09
Marco Polo Mission Requirement Document (MRD)	SCI-PA/2008.001/Marco-Polo	4.2	11/08/09
Marco Polo Planetary Protection Document (PP)	SCI-PA/2008.013/Marco-Polo	1.0	08/09/09
Marco Polo Mission Environment Document (MED)	SCI-PA/2008.014/Marco-Polo	1.3	03/07/09
Marco Polo - Consolidated Report on Mission Analysis (CreMA)	SRE-PA/2009.006/Marco-Polo	1.3	20/08/09
Marco Polo Payload Definition Document (PDD)	SCI-PA/2008.002/Marco-Polo	4.0	24/09/09
Margin philosophy for SCI-PA assessment studies	SCI-PA/2007.022	1.0	19/11/07
Soyuz-Fregat 2-1b from the Guyana Space Centre User's Manual	NA	1.0	XX/06/06
Marco Polo Mission Operations Assumptions document (MOAD)	SRE-PA/2009.028/Marco-Polo	1.1	28/05/09
Gravity Field Estimation of 1999 JU3 with Marco polo	SRE-PA/2009.023/Marco-Polo	1.1	22/06/09
Science Operations Assumptions Document (SOAD)	MP-RSSD-TN-001	1.0	11/05/09
Marco Polo Capsule retrieval Assumptions document	DOPS-MGT-TN-1002-OPS-HAS	1.1	23/07/09
Marco Polo JAXA-ESA Requirement and Interface Document	SRE-PA/2009.005/Marco-Polo	1.0	10/02/09
Marco Polo Technology Development Plan	SRE-PA/2009.037/Marco-Polo	2.0	30/09/09
Marco Polo TEC-SYC independent cost estimates (paper copy)	TEC-SYC/26/2009/CES/MvP	1.0	18/09/09
Marco Polo ground segment, operations cost report (paper copy)	DOPS-OS-RP-1001-OPS-HSA	2.0	10/07/09
Marco Polo Science ground segment cost report (paper copy)	MP-RSSD-RP-022	1.0	24/09/09

Table 1: ESA-provided documents

Title	Reference	Issue	Issue date
Requirements and constraints assessment	MP.ASU.TN-1.1	1	03/09/09
Mission analysis	MP.ASU.TN-1.2	2	03/09/09
Mission architecture options and trade-offs	MP.ASU.TN-2.1	2	02/09/09
Preliminary trade-off of critical technologies	MP.ASU.TN-2.2	1	16/07/09
GNC analysis	MP.ASU.TN-4.1	1	02/09/09

Landing structure and mechanisms	MP.ASU.TN-4.2	1	02/09/09
Sample acquisition, containment and transfer system	MP.ASU.TN-4.3	1	02/09/09
ERC design and analysis	MP.ASU.TN-4.4	1	30/09/09
Spacecraft detailed design	MP.ASU.TN-5.1	1	20/09/09
Programmatics, development plan and technology development	MP.ASU.TN-6.1	Draft B	02/09/09
Cost analysis report (paper copy)	MP.ASU.TN-6.2	Draft A	08/09/09
Executive summary	NA	Draft A	05/10/09
Final presentation	NA	1	17/09/09
CDF data exchange sheets	NA	Draft A	02/09/09
CAD models	NA	Draft A	02/09/09
FEM	NA		
GMM and TMM	NA	Draft A	30/09/09
Landing dynamics and transfer kinematics movies	NA	1	02/02/09

Table 2: Astrium-provided documents

Title	**Reference**	**Issue**	**Issue date**
Review of mission and systems requirements and constraints	MPL-OHB-TN-001	2	22/09/09
Consolidation of mission analysis	MPL-OHB-TN-002	2.1	22/09/09
Electric propulsion layout options	MPL-OHB-TN-003	1.1	22/09/09
Preliminary trade-off of critical technologies	MPL-OHB-TN-004	2	22/09/09
Mission architecture trade-off	MPL-OHB-TN-005	2.1	22/09/09
Detailed design report	MPL-OHB-TN-006	2.1	22/09/09
Design trade-off and analysis	MPL-OHB-TN-007	2.1	22/09/09
GNC subsystem analysis and design report	MPL-OHB-TN-008	2.1	22/09/09
Landing subsystem analysis and design report	MPL-OHB-TN-009	2.1	22/09/09
Sample acquisition and transfer subsystem analysis and design	MPL-OHB-TN-0010	2.1	22/09/09
ERC analysis and design report	MPL-OHB-TN-0011	2.1	22/09/09
Mission programmatics	MPL-OHB-TN-0012	1	07/09/09
Detailed cost analysis (paper copy)	MPL-OHB-TN-0013	1	08/09/09
Executive summary	NA	1	30/09/09
Final presentation	NA	1	09/09/09
CDF data exchange sheets	NA	1	
CAD models	NA	1	
FEM	NA	1	
GMM and TMM	NA	1	

Table 3: OHB-provided documents

Title	**Reference**	**Issue**	**Issue date**
Review of requirements	SD-TN-AI-1180	1	01/12/08
Consolidation of mission analysis	SD-TN-AI-1181	2	30/01/09
Mission architecture options definition and trade-offs	SD-TN-AI-1182	Draft	01/02/09
Detailed design report	SD-TN-AI-1186	Draft	10/09/09
Preliminary trade-off of critical technologies: GNC	SD-TN-AI-1204	Draft	01/02/09

Prelimi. trade-off of critical technos: Landing, sampling strategy	SD-TN-AI-1205	Draft	01/02/09
Preliminary trade-off of critical technos: SATS system	SD-TN-AI-1206	Draft	01/02/09
Preliminary trade-off of critical technos: ERC design, analysis	SD-TN-AI-1207	Draft	01/02/09
Analysis of the ERC critical technologies and behaviour	SD-TN-AI-1233	Draft	10/09/09
Touch and go legs design report	SD-TN-AI-1234	Draft	10/09/09
SATS system design report	SD-TN-AI-1235	Draft	10/09/09
GNC analysis for NEO proximity operations	SD-TN-AI-1236	Draft	10/09/09
Programmatics, development plan and technology development			10/10/09
Cost analysis report (paper copy)			10/10/09
Executive summary/Final Presentation			03/11/09
MDR presentation	NA		24/09/09
CDF data exchange sheets	NA		01/06/09
CAD models	NA		01/06/09
FEM	NA		10/10/09
GMM and TMM	NA		10/10/09
Landing dynamics and capsule dynamics movies	NA		10/09/09

Table 4: TAS-provided documents

	Type of instrument	Design Report	Cost Report
ATMS (Bowles, UK)	**Mid IR spectrometer**	**YES**	***Total cost known***
Laser Altimeter (Oberst, D)	**Laser altimeter**	***Very late funding, no report submitted***	
MAPIS (Barruci, F)	**Vis-near-IR spectrometer**	**YES**	**YES**
MPCS, WAC (Boehnhard, D)	**Wide angle camera**	**YES**	**YES**
MPCS, NAC “–“-	**Narrow angle camera**	**YES**	**YES**
MPCS, CUC “–“-	**Close-up camera**	**YES**	**YES**
NAC (Colangeli, I)	**Narrow angle camera**	**YES**	**NO**
NIMEIS (Le Blanc, F)	**Neutral particle analyser**	**YES**	**YES**
RAMON (Millilo, I)	**Neutral particle analyser**	**YES**	**NO**
THERMAP (Groussin, F)	**Mid IR spectrometer**	**YES**	**YES**
SCF (Brucato, I)	**Curation facility**	**YES**	**YES**
NSRF (Franchi, UK)	**Curation facility**	**YES**	**YES**
ACE (Aplin, UK)	**Elecric field measurement**	**YES**	**YES**
APXS (Klingelhoefer, D)	**Alpha particle x-ray spectrometer**	***Very late funding, no report submitted***	
ILMA (Cottin, F)	**Laser desorption mass spectrometer**	**YES**	**YES**
MASCOT (Richter, D)	**Lander package**	**YES**	**NO**
VISTA (Palomba, I)	**Contamination monitor**	**YES**	**NO**
VolDet (Grady, UK)	**IR spectroscopy & microscope**	**YES**	**YES**

Table 5: Documents produced by the DoI study teams (instruments)

ANNEX 2: TECHNICAL REVIEW – IDENTIFIED ISSUES

This chapter lists design, technology or programmatic issues raised during the Marco polo review, which are not considered critical but for which specific recommendations have been made in view of preparing next study phases and future mission implementation for the consideration by the Project Team.

GNC

Issue (title)	Issue description and analysis	Risk associated	Severity	Likelihood	Ranking	Mitigation proposed
Attitude and stability errors	Absolute and relative pointing error MRD requirements, i.e. respectively 260 arcsec and 5 arcsec/sec, correspond to state of the art AOCS. It is driven by local characterization using NAC at 200m altitude. However, PDD, v4.0 identified absolute pointing error of 15microrad, i.e. 3 arcsec, stability being confirmed around 5 arcsec/sec. It is important to note that: (1) firstly pointing error requirement could only be understood as an attitude measurement error and NOT an absolute pointing error, including not only attitude prediction error but also control and guidance errors; (2) secondly attitude measurement error of 3 arcsec, if proven feasible, will require operation of second star tracker (to cancel out STR boresight measurement noise of typically 20 arcsec), higher precision grade gyroscopes, together with an optical bench to minimize distortion between STR and NAC.	More demanding pointing requirements creeping in from science instruments leading to a much more complex design and higher technology requirements	High	Low (probably a misunderstanding at this stage)	Low/Medium	-Clarify science pointing requirements -Bear in mind that on-board attitude measurement accuracy, including thermo-mechanical distortion, lower than few hundreds arcseconds could NOT be achieved with state-of-the-art technology (both in terms of mechanical and AOCS). - Derive on-board pointing knowledge from ground a-priori accuracy.
Asteroid acquisition	*Omissis*.	Dependency on payload for critical spacecraft operations	Medium	Low (other solutions exist)	Low	Consolidate proposed concept, i.e. discuss with TEC-EC how it could be confirmed by suppliers, and avoid relying on payload camera nor implement specific GNC camera.
Spacecraft stability during sampling	GNC shall have the capability to compensate for torque generated by sampling mechanism up to 10Nm. Current predictions establish torque of typically few Nm. On the other hand, maximum reaction wheel torque does not exceed 0.0175Nm (0.2Nm in the case of Rosetta large RWs). reaction control torque will have to be provided by RCS system or/and with appropriate landing pad design or/and with anchoring concept TBD. Requirement implies that thruster with at least 10N thrust capability shall be considered. Propellant consumption and delta-V errors tend to increase with thrust magnitude. In that respect smaller thrusters will be preferable for operation at asteroid.	Problematic stability at sampling if bi-propellant excluded for contamination reason.	Medium	Medium	Medium/High	-Investigate whether it is acceptable to actuate thruster after landing. -Consolidate RCS definition considering torque and force authority during sampling but also deadband control issue: for given deadband control error, higher thrust will increase number of thruster actuation between deadband limit and consequently fuel consumption. -Evaluate if RCS system shall be pressurized or if blow-down control mode will be sufficient.
Insertion burn sequence	Approach timeline is very constraining for ground operation and in particular orbit determination between correction burns, i.e. 4 to 5 burns over 7 days. Not clear if modification of the sequence lead to major increase in delta-V and/or decrease in landing accuracy	Later consideration of operation constraints may bring to major redesign of the approach phase	High	Low	Low/Medium	- Coordinate with FD for definition of realistic operation scenario, identify time-critical constraints (insertion sequence) + Delta-V accuracy. - Investigate possible heritage of autonomous guidance and operations for rosetta asteroid fly-bys. - If proven necessary, introduce trade-off on vision based navigation.

Issue (title)	Issue description and analysis	Risk associated	Severity	Likelihood	Ranking	Mitigation proposed
Guidance function	Possible large increase of fuel consumption using position/velocity guidance instead of conventional thrust profiles has not been evaluated. At the same time, it is indicated by one of the contractors that there is no need for autonomous guidance algorithms for local characterization and landing phases. This need to be clarified by contractors.	Possible increase in fuel consumption	Low	Medium	Low	- Provide more detail trade-off during defintion phase.
Absolute Navigation function	*Omissis*	Need to couple vision-based navigation methods with inertial measurements may arise at a later stage	Medium	High	Medium	Ensure that inertial hybridization will also be addressed in future R&D activities, as mean to increase robustness of NPAL navigation technique in case of landmarks loss.
Absolute Navigation function	Development of an absolute navigation autonomous function based on extraction of natural landmarks on the surface and correlation with an existing database (built during the characterization phase) has been initiated in the frame of an R&D studies with the lunar landing as the first application case. One of them is called MAGELLAN for MAtching of Ground ELements and Landmarks for Approach Navigation. MAGELLAN absolute navigation function is further split in two categories of algorithms: (1.1) Feature matching algorithms to recognize and locate lunar landmarks, (1.2) Pose estimation algorithms to derive attitude and position data from multiple landmarks location in a single image. In particular, feature matching algorithms are mainly based on texture correlation. Adapting these algorithms to the asteroid case will not be straightforward and R&D activities have already been put in place. The main issues are that firstly the surface texture of an asteroid is very different from the lunar one, and secondly the very rough terrain makes it very hard to consider every local surface as a planar patch, as it is assumed for the lunar case.	More complex feature extraction algorithms than required for the lunar case	Medium	Medium	Medium	Adapt lunar case to the asteroid scenario and consolidate perfomance predictions
Absolute Navigation function	*Omissis*	Need to impose operational constraints for the descent and landing phase	Low	Medium	Low/Medium	- Possibility to correlate results with AutoNAV needs to be investigated. - Clarify illumination conditions and associated operational constraints. Perform similar sensitivity analysis, i.e. pitch angle and sun direction, for the asteroid case.

Issue (title)	Issue description and analysis	Risk associated	Severity	Likelihood	Ranking	Mitigation proposed
Absolute Navigation function	- Preliminary simulation results have permitted to identify some restrictive conditions and in particular on the initial position error when starting the absolute navigation function at gate altitude. Besides the fact that the acceptable initial error needs to be further characterised, it is a strong hint that there were simulation cases where the feature matching could not be completed due to high distortion between image and database. The simulations indicate that lunar algorithm can not be used directly and significant effort is needed to taylor approach, e.g. stereo-based 3D models matching. Some algorithms are highly non-linear and iterative, e.g. additionial refinement would be eventually necessary to minimize estimated pose error. However robustness and convergence of algorithms have not been thoroughly assessed, with the exception of a preliminary sensitivity analysis against sun illumination, camera pitch and attitude error performed for lunar landing case. Maximum time to determine attitude and position shall be established and associated operational constraints shall be clearly identified.	Need to implement more complex alternative means to increase algorithm robustness and/or to impose operational constraints for the descent and landing phase	Medium	Medium	Medium	Robustness shall be further evaluated and mechanisms to resume position and attitude determination after failed attempt shall also be investigated.
Absolute Navigation function	In the real mission, the landmarks selection will be done with the help and the verification of an operator prior to the descent (during the characterization phase), and probably with the help of an algorithm which would at least extract the sharpest features in the orbital images (e.g Harris edge, corner detector). It has to be noted that the absolute navigation function does not have to be fully autonomous and that ground could intervene in the selection of landmarks. Preliminary analysis for asteroid case shows that Harris detector may not be suitable for localizing landmarks. It reinforces the intervention of ground operator, rather than systematic detector. It is in contradiction with one of the industry conclusions that justify implementation of MAGELLAN as an autonomous function. Note that number of feature points used to fed pose estimation algorithm is not addressed. There is no discussion on degradation of performances caused by reduction of trackable landmarks. It should be of particular importance for the asteroid case. Note that the minimum number of selectable landmarks to achieve a given position accuracy will drive sizing of camera FoV. Therefore this analysis also needs to be conducted in support of camera specification.	The descent navigation function may require intervention of an operator and the whole approach has to be re-assessed (impact on spacecraft design to maintain ground communications as late as possible)	High	Medium	Medium/High	- Future R&D activities shall permit to better define selection criteria for landmarks in order to minimize pose estimation error, i.e. optimal number of landmarks and distribution. - Investigate intervention of ground operators to perform absolute navigation ("a-la-Hayabusa") - GNC analysis, including absolute and relative navigation, shall be used to consolidate navigation camera requirement.
Relative Navigation function	The relative navigation function will be used to control the vertical descent towards the landing site once it has been designated by the absolute navigation function. Relative navigation has been extensively studied. It is considered that NPAL-like design can be adapted to Marco Polo without major issues.	Need to implement major modifications to NPAL-like approach	Medium	Low	Low	Performances of the NPAL solution in case of featureless images (that could occur at very low altitude only) shall be carefully assessed. The images taken by Hayabusa at 40m altitude seem suitable for feature correlation, but this is obviously to be checked by simulation, once the detailed design of the relative navigation function is completed.
Relative Navigation function	The impact of initial conditions, i.e. position and velocity errors, on relative navigation performance has not been analysed in detail. It is agreed that residual position estimation error shall be negligible when compared with the initial error introduced by the absolute navigation function. However it will need to be further analysed. In this context, it is not fully understood why different contractors anticipate use of the absolute navigation function in support of relative navigation during final descent	GNC burden might be relaxed by removing absolute navigation requirement during relative navigation	Not applicable	Not applicable	Not applicable	Consolidate relative navigation performances by simulations and identify need for absolute navigation update during relative navigation phase.

Issue (title)	Issue description and analysis	Risk associated	Severity	Likelihood	Ranking	Mitigation proposed
	phase.					
Relative Navigation function	Need for autonomous orbit control proposed by two of the contractors (e.g. using Gauss functions) is not justified. Possible implementation for asteroid case appears very complex.	GNC burden might be relaxed by removing autonomous orbit control	Not applicab le	Not applicable	Not applicable	Option shall not be considered unless proven necessary, i.e. implement Rosetta orbit navigation/control approach
Navigation function	Navigation camera measurement noise has not been considered. Non-uniformity reponse of camera sensor, including fixe pattern noise for APS technology, will significantly affect images location. In addition, internal distortion effects and in general all possible thermal effects will degrade measurement accuracy.	Harsh requirements placed on camera sensor may increase development time or landing accuracy will be degraded	Medium	Low	Low/Medi um	- Realistic camera model, including all possible measurement noise and bias, shall be be considered for future GNC simulations. - Impact on performance of misalignments between navigation camera(s) and star tracker shall be evaluated.
Control function	There are two ways of performing an axial delta-V manoeuvre, the accelerometer method and the thruster pulse counting method. In both methods, the estimation of the actual delta-V is not perfect as there are a number of error sources and delta-V measurement accuracy lower than 1% can not be achieved. Any deviation from this rule of thumb requirement will severely impact AOCS and operation complexity, as well as fuel consumption and mass budget. This needs therefore to be identified early during the mission definition phase.	Delta-V increase and impact on mass	Medium	Medium	Medium	Establish preliminary delta-V magnitude and pointing accuracy for asteroid operations.
Control function	During descent and asteroid close operation, the spacecraft attitude will be heaviliy constrained and AOCS will have to retain the capability to perform vectorized thrust, i.e. thust in any spacecraft direction. Burn efficiency could be drastically degraded when compared to pure axial correction maneuvers. As a result fuel consumption increase and there shall be allocated in system mass budget.	Delta-V increase and impact on mass	Medium	Medium	Medium	Identify privileged thrust vector direction In spacecraft frame, i.e. vectorized thrust rather than sequence of axial and transverse burns.
Inertial Measurement Unit	*Omissis*	Need to implement accelerometers	High	Medium	Medium/H igh	Accelerometer requirement shall be clarified as it will most likely affect gyroscopes selection and development plan.
Navigation Camera	It is assumed that Marco Polo will benefit from VisNaV R&D activitiy currently on-going (TBC). Objective and scope of the activity are not sufficiently discussed. In particular detailled GNC analysis shall support definition of camera requirements in order to ensure that Marco Polo specific needs are adequately captured into VisNav generic requirements.	Need to do some major modifications to VisNav generic development leading to (high) extra cost and delays	High	Medium	Medium	- Ensure that GNC requirements for asteroid case are properly derived into solid unit requirements. - Identify any discrepancy in unit requirements with respect to submitted GNC concepts. Establish in particular common camera baseline acceptable to all contractors. - Taking benefit from active-pixel technology and computing power of LEON, consider adapting as much as

Issue (title)	Issue description and analysis	Risk associated	Severity	Likelihood	Ranking	Mitigation proposed
						possible STR design for navigation camera.
GNC Far Navigation Sensor	*Omissis*	Need to implement a far-range laser altimeter	High	Low	Low/Medium	Confirm vision-based navigation concept without need for far navigation sensor.

Mechanisms

Issue (title)	Issue description and analysis	Risk associated	Severity	Likelihood	Ranking	Mitigation proposed
Landing gears	1- Crushable damper are proposed as a baseline. This is a passive technology which is deemed as the most reliable and robust solution.However, resulting limitations have to be acknowledged. Limitations are: - Compression not recoverable, - Shortening of the legs after each landing, - Change of configuration/conditions/boundary conditions for each landing, - Remaining length not known, - Limited crushable length and therefore number of landings, - Still elastic energy stored with risks of bouncing, - Can't be tested before launch. 2 - In addition, the proposed design is not compatible with launch loads.Landing legs are mobile to deform upon landing and allow the crushable damper to operate. This mobility will not be compatible with launch loads. Compatibility with launch loads will require the use of springs or even launch locks which might jeopardise the landing because of elastic energy which is critical for landing in micro gravity.	Medium	Medium	Medium	Medium	1 - Implement monitoring of the remaining crushable length, - Perform more detailed Monte Carlo landing analysis, - Minimise the risk of bouncing (stored elastic energy). 2 - Only a limited mass and part of the landing leg can be mobile. TDA shall address compatibility of the proposed designs with launch loads.
Coupled GNC and touch down analyses	The GNC analysis stops at touch down whereas because of micro gravity and sampling tool counter reaction forces, the spacecraft stability has not been demonstrated during sampling. In addition, the feasability of disabling GNC elements during this phase has not been demonstrated either.	Underdimensioning of GNC	Medium	Low	Low	TDA on GNC shall cover the after touch down period including sampling. Need for GNC in addition of the use push down thrusters during sampling is to be analysed. Compability of GNC with sampling to be confirmed. Coupled landing/touch down/sampling/take-off analyses shall be performed and disabling/enabling operations of GNC elements shall be demonstrated.
Availability of building blocks technologies for mechanisms compliant with specific Marco Polo requirements	The availability of mechanisms building block for the development of mechanisms sub-systems shall be guaranteed for the performance of the TDAs..The following building blocks technologies are not readily available: - Brush DC motors, - Force and torque feedback sensors, - Volumetric sensors which can be reusable up to three times, - Pyro release nuts of back shield of ERC compliant with 80g re-entry deceleration. In addition, performances of mechanisms after long term non operation will have to be guaranteed. Mechanisms will be hibernating for years before operation. High temperature compatibility might be required.Operation above to 100oC will	Delay in achieving TRL 5 by phase B	Medium	Medium	Medium	In parallel of the performance of TDA activities, the required building block technologies shall be developed and qualified A specific work package (SATCS TDA) shall include activities related to the development and the qualification/delta qualification of building blocks (electric motor, force and position sensors, sealing, release nuts). These building blocks shall reach TRL6 at the end of

Issue (title)	Issue description and analysis	Risk associated	Severity	Likelihood	Ranking	Mitigation proposed
	require specific technologies developed in the frame of BepiColombo.					the TDA.
Reliability, redundancy, failure tolerance and FDIR for mechanisms	The mission relies mainly on mechanisms. All of them are SPF. However, still a standard redundancy approach is used. Mechanisms implementation and failure redundancy approach is based on existing ECSSs. For Marco Polo, it shall be clarified whether specific standards shall be implemented or re-defined for mechanisms in terms of: - Reliability, - Redundancy, - Failure tolerance, - Failure detection. The number of active elements shall be minimised.	Need to implement heavy redundancy requirements having a non-negligible system impact (testing, mass, etc.)	Low	Medium	Medium	In order to cover the risk associocted to the high number of mechanisms which are all SPF, it is recommended to implement the following requirements for mechanisms: - Redundancy related requirements in the mechanisms ECSS shall be enforced, - The number of active elements shall be minimised, - Redundant monitoring of all mechanisms operations and status (including latching…) shall be implemented, - The SATCS shall include force and torque feedback sensors, - If redundant motor is used, it shall be decoupled with a differential gear and not implemented in series.
Tool reaction upon sampling	During sampling, some counter torques and forces will be generated on the spacecraft. These forces will have to be compensated, maximal allowables to be defined and abort conditions clearly stated. In addition, force margins to be used for the design of mechanisms might lead to too high counter reaction. Also, according to the soil definition, the required penetration force, the induced torque and the resulting time to perform the sample collection are not clearly known.	Harsh requirements placed on the spacecraft control during sampling	Medium	Low	Low/Medium	Maximal (with margins) counter force and torque from the SATCS to the S/C shall be specified. This requirements might drive the duration of the stay on the asteroid. A specific work package dealing with sampling, GNC and landing gears design shall be implemented. Options for torque compensation are spikes or blades underneath the landing pad or the use of or the use of Reaction Wheels/thrusters during

Issue (title)	Issue description and analysis	Risk associated	Severity	Likelihood	Ranking	Mitigation proposed
						sampling shall be investigated. Maximal allowables to be defined and abort conditions clearly stated. In addition, force margins to be used for the design of mechanisms might lead to too high counter reactions.
Exposed parts	For the proposed designs, the following elements, not covered by MLI, might be exposed to direct sun illumination: - the inner part of the S/C (central tube), - the open sample container, - the open canister, - the canister lid, - the sealing O-ring, - the transfer mechanism. Possibility and criticality of direct sun illumination shall be checked.	Need to thermally protect mechanisms	Low	Medium	Low	Possibility and criticality of direct sun illumination shall be checked. Philosophy for using HT elements or thermal protection shall be assessed. Thermal requirements for the mechanisms shall be updated accordingly. If high temperature mechanisms, the some BepiColombo heritage could be reused and buts costs will have to be increased.
Thermal protection for mechanisms	None of the proposed designs have thermal protection. In addition, no demonstration of compliance with the requirement G-SY.ERC-1 : The ERC design should ensure that the sample is never exposed to temperatures higher than +40°C. For less than one minute +80°C is acceptable. Implementation of thermal protection including MLI might have serious impact on the design of the mechanisms. It shall therefore be demonstrated.	See above	See above	see above	See above	Suitability of ERC thermal design shall be demonstrated in next phase
Bouncing of ERC upon landing	Bouncing of the ERC was not addressed and the capsule is not designed for this. Conditions leading to bouncing of the ERC upon landing shall be identified. Should the risk of bouncing be too high, then the canister shall implement a spherical crash box.	Non-nominal landing leading to breaking of the sample canister or implementation of crushable with Volume and mass consequences	Medium	Low	Low	Assess the riks of bouncing upon landing on earth for the ERC during the next phase. Specific requirement shall be specified.
Suitability of sticky pad as back up sampling tool	Most of the back up sampling tools are sticky pad. Risk of loosing pebbles during transfer and having them stuck during capsule transfer and closing is deemed high. The location of the sticky pads combined with their limited capabilities to secure the sticked soil particles introduce a risk of interference during the transfer and the sealing of the ERC.	Complex interface/design/development for backup sampling tool, driving the whole SATCS design	Low	Low	Low	Potential solutions are: - Implement shaking tool, - Investigate alternative back up sampling tool solutions. To re-open the back-up sampling analysis taking into account interference and loss of pebbles during transfer

Issue (title)	Issue description and analysis	Risk associated	Severity	Likelihood	Ranking	Mitigation proposed
Free flying particles impact on mechanisms operation and ERC sealing	Landing, coring and sampling under micro gravity environment will inevitably generate free flying micro particle beneath and around the spacecraft which might endanger the sampling and sealing operations. Mechanisms shall be specified accordingly. Particle clouds not imaged in previous mission. Uncertainty on whether this would exist in the asteroid environment	Impact on design and testing	Medium	Medium	Medium	Perform specific simulations and tests to assess criticality. Identify specific requirements to define the phenomena and implement corrective actions.
Soil properties definition	The soil properties are defined but their interpretation in the asteroid environment (microgravity) is not straighforward. In addition, the range of soil properties seems to be narrow in view of the poor scientific knowledge for these bodies. - Grain Size: Sub-µm -> mm -> up to 3 cm (i.e. cm-sized fragments) - Shape: Very angular - Cohesion: 0.1 – 1 kPa - Compressive strength: 100 kPa (possibly up to 2 MPa, TBC), valid to a few cm depth - Shear strength: 1 – 2.6 kPa - Bulk density: <1.2 – 1.8 (max) - Angle of internal friction: 30° - 50° linked to the shape. Does similar materials exits on earth?	Major change in sampling tool design affecting the whole spacecraft system design (it is however unlikely that the proposed designs cannot cope with a slightly wider range of properties as shown in previous testing activities)	High	Low/Medium	Medium	- Science team should provide a complete set of solid samples for the performance of the TDA activities. - The sampling mechanism shall be tolerant to out of spec properties. - Time of sampling able to cope with duration of zero g flight on ground.
TDA "Capsule spin-ejection mechanism"	The capsule spin-ejection mechanism is not critical but some additional points need to be included in the foreseen TDA activity. Suitable concepts have been development in the past (Saab Ericsson) but the key personal and the built experience have been discontinued.	TDA delay	Low	Medium	Low/Medium	Shall include also Capsule HDRM, 12 months is short to reach TRL5, shall include delta-development of ground test facilities, shall address long term storage and standby periods before operation, EM needed to reach TRL5, include life test

ERC

Issue (title)	Issue description and analysis	Risk associated	Severity	Likelihood	Ranking	Mitigation proposed
ERC heatshield - material export license issues	*Omissis*	a. Material not available b. Schedule delays	a. High b. High	a. Very low b. Low	Low	Issue to be closed ASAP with involvement of export license expert in ESA-HQ.

Issue (title)	Issue description and analysis	Risk associated	Severity	Likelihood	Ranking	Mitigation proposed
ERC heatshield mass	*Omissis*	Potential ERC mass increase is about 2kg.	Low	Medium	Low	Plasma testing and material refinement (ongoing work within TRP). Until then a TPS mass margin of 40-50% seems more appropriate (for new development).
ERC turbulent heat fluxes not considered	Turbulent heat fluxes seem not to be taken into account by any of the teams. Convective fluxes only derived at stagnation point using Sutton-Graves formula. Criteria for transition to turbulence to be assessed. If turbulence cannot be exluded, TPS sizing needs to be updated.	Higher TPS mass	Medium	High	Medium	Perform detailed CFD to assess onset of turbulence
ERC heat flux blocking effects	The assumptions taken concerning blocking effect through pyrolysis gases (on convective and radiative heat fluxes) are not well explained and justified. It cannot be stated whether the taken assumptions are conservative.	Higher TPS mass	Low	Low	Low	Clarify issue in next design phase
ERC heat flux assumptions on backcover not clear	Assumption taken for the heat fluxes on the ERC backshield are not well justified and naturally have high uncertainties. Potentially required higher TPS mass on the back would have a negative effect also on the CoG.	Higher ERC mass	Low (mass of backcover TPS is very small)	Medium	Low	Perform testing in wind tunnel in late phase B
ERC sample temperature requirement	Fulfillment of ERC sample temperature requirement has not been demonstrated.	Mass increase if additional TCS required	Medium (mass increase)	low	Low	perform thermal analysis in early phases of next activity
ERC crushing material	The static and dynamic strenght of the proposed crushing material (Astrium) at elevated temperatures has not yet been assessed.	Change of material in later phases leading to delays	Low	Low	Low	

Payload

Issue (title)	Issue description and analysis	Risk associated	Severity	Likelihood	Ranking	Mitigation proposed
MPCS dust contamination	MPCS team states dust contamination as a critical point for mission ops envelope: this seems overstated since the dust environment is likely not worse than for Apollo, Stardust. Payload concern may be overstated; necessary investment should be evaluated by analogy to other missions that have flown in near-Earth environment (NEAR, SMART-1, Stardust, etc.)	Not applicable	Low	Medium	Low	Hold margin to the design, and even for the deeper study; initial study may be sufficient and may be lower cost.

Issue (title)	Issue description and analysis	Risk associated	Severity	Likelihood	Ranking	Mitigation proposed
MPCS inter-camera co-pointing requirement	co-registration among the different camera resolutions is not called out as a critical requirement. Proper science value from the different resolutions will require sufficient knowledge of how to tie the mapping at different scales together, which may or may not be affected by the co-alignment of the cameras relative to the spacecraft body.	Operations cost or accommodation complexity may be affected	Medium	Medium	Low	Re-assess alignment requirements in next phase
MPCS CUC TRL	MPCS CUC IDDR states focus mechanism with ExoMars development heritage as having TRL 5, proven concept and qualified for ExoMars. It has not yet been qualified for ExoMars, even understanding that TRL 5 on ExM needs testing in an appropriate Mars environment. ExM PanCam HRC focus mechanism was changed post instr. PDR (Oct 2008) from piezo to stepper motor approach. Breadboard was being modified still in April 2009. ExM PanCam reached TRL 5 overall, but HRC focus mechanism BB was only 85% complete for the TRL 5 criterion; TRL = 4 is fine, while stating 5 now needs more justification in the AO response than was provided in the IDDR. Also, cold vacuum performance testing may be needed to claim TRL 5 for Marco Polo.	Schedule risk to achieve TRL 5, Mass (resource) threat since 20% margin on this item may not be enough.	Medium (joint resource /schedule)	Low	Low	Start development activities as soon as possible
MAPIS and ATMS thermal control	Both IR instruments will need a cold radiator to perform well, which may produce an operational challenge, in particular if autonomous science targetting is conducted	Tractable problem, but may add some cost to either autonomy development, thermal qualification, or operations	Low	Medium	Low	Review, and potentially revise the thermal environment/interface requirements to/from the instruments, potentially prior to AO.
Payload mechanisms	TDA activities shall be clearly defined.	Missed to identify a payload mechanism which requires a substantial development effort	Low (payload development will start early enough)	Low	Low	AO should clearly require an accurate development plan with appropriate description of development steps
ATMS prisms coatings	ATMS KBr prisms coating survivability. KBr is moderately sensitive to handling and space environment, so the coatings are important. PA plan needs to account for this	Cost, AIT at system level, this instrument may need purging gas during system AIT and even on the launcher	Low	Medium	Low	Identify handling needs early.

Instrument masses

Payload	BEE [kg]	MM [%]	Allocation [kg]	Plausibility	Recommendation
NAC	8.9	20%	10.68	Straightforward camera design, with 'heritage' detector (APS) Mass risk is in the fixed focus limited at 200m range if the orbit needs to get closer, and in increased optics diameter to potentially account for need to image in dim light or low albedo regions May need a little more mass for own flash memory if bus is not sufficient to handle image data at full resolution.	AO allocation would be fine with 10.5 kg, if the operational requirements are truly frozen.
WAC	2.15	20%	2.58	Similar issues.	Perhaps the best approach to camera allocation for AO would be to advertise the sum of available mass (incl. MM 20%), i.e. ~13 kg to address all imaging requirements, and let the cleverest application win (single detector with focus mechanism versus multiple cameras)
Laser Altimeter	4	20%	4.8	Range of operations is much closer than BELA which is its heritage. While this may reduce optics size it may complicate the electronics more than anticipated. Also there is risk of needing more thermal control than planned to operate the laser in deep space environment, and more structural stiffness and/or thermomechanical stiffness to keep laser and receiving optics aligned.	MM 25%; AO alloc 5 kg.
VisNIR	3.6	20%	4.32	Design trade status suggests that maturity is not fully at phase B level (MM 20%)	MM 25 or 30%; AO alloc 4.5 kg, or trade against expectation of reduced spectral resolution
MidIR	3	20%	3.6	threat from platform stability (both thermomechanical and microvibrational) despite beam-shearing approach, so MM 20% may be insufficient since it affects the overall structure	AO alloc 3.8 kg, or allow for reduced spectral resolution.
NPA	2.2	20%	2.64	Good heritage, threats covered by 20% MM	Alloc okay at 2.6 kg.
CUC	1	20%	1.2	May need a little more mass for own flash memory if bus is not sufficient to handle image data at full resolution.	AO alloc 1.2 kg okay.
Total			**29.82**		Overall, most significant operationally is laser. Cameras probably can make savings by sharing resources, and the IR instruments can trade mass growth against reduction of scientific performance (i.e. less operational impact).