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DOCUMENT

L1 Mission Reformulation

JUICE - JUpiter ICy moon Explorer

Technical & programmatic review report

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1 INTRODUCTION

The EJSM/Laplace was selected as a Large-class candidate mission in the Cosmic Vision 2015-25 programme and underwent an assessment study (phase 0/A, 2008-2010) under the assumption of an international cooperation including ESA and NASA where ESA would provide the Jupiter Ganymede Orbiter (JGO) and NASA would provide the Jupiter Europa Orbiter (JEO). Both spacecraft would be launched and operated independently. The JGO spacecraft would perform flybys of Callisto and Ganymede, before finally arriving at an orbit around Ganymede. The JEO spacecraft would perform flybys of all 4 Galilean moons (Io, Europa, Ganymede and Callisto), before arriving at a circular orbit around Europa for detailed investigations.

Following the recent announcement of the US Planetary Science Decadal Survey, and the evolution of the NASA budget, NASA withdrew from the joint mission, and a mission to Europa by the JEO spacecraft will not be executed as conceived. The purpose of this study phase "Reformulation Study" was to investigate whether parts of the original science goals of the EJSM/Laplace mission could be recovered by a single spacecraft mission based on the results of the JGO study and led by ESA. The most significant changes to the original JGO mission profile consisted in the addition of 2 flybys of Europa and the inclusion of high inclination orbit phase around Jupiter.

This study was conducted in parallel with the mission reformulation studies of the competing mission concepts, IXO/Athena and LISA/NGO, with the following common boundary conditions:

- The mission will be led by ESA
- ESA Cost at Completion (CaC) below 850 M€ (E.C. 2011).
- International cooperation limited to the provision of non-critical specific spacecraft or payload units.
- Provision of scientific instruments by Member States and/or partner agencies.
- A target launch date in 2022.
- Technology Readiness Level (TRL) of the space segment ≥ 5 before the final mission adoption (by early 2014).

This review report is based on the outcome of the Phase 0/A industrial study of the EJSM JGO spacecraft with three Contractor teams, and is updated with the review of the outcome of the Reformulation phase.

This Review is intended to assist in the down-selection of the L-class candidate missions to be carried forward into the next study phase, which would be a Definition Study, aiming for completion of Phase B1. The Review focused on the technical issues of the mission, and an evaluation of the science return was excluded from the scope. The Review was conducted in accordance with the applicable Procedure (SRE-PA/2011/080 dated 30 August 2011).

The major findings of the Review Board are summarised in this report.

2 MAJOR FINDINGS – TECHNICAL SYSTEM

2.1 Design & Definition

The collection of mission requirements that drive the mission design was found complete.

The following design drivers were identified and need to be revisited for the Definition Phase:
- The overall mission design and mission analysis with a focus on system mass.
- The required data volume to be returned by the mission, including the baseline architecture for telemetry downlink and radio-science.
- Various autonomy & operations issues related to operability and access to spacecraft.

The complete technical background available from the envelope of the industrial studies provides a good level of detail for an Assessment Study, including critical analysis (e.g. radiation analysis).

2.2 Resources: Mass and Power

The Industrial Studies declared an available System Margin in excess of 20%. However, the Board has identified a number of underestimated subsystem masses, specifically:
- The structural dry mass index presented is at about 17 – 20%. However, the JUICE structural mass index is heavily influenced by the peculiar spacecraft configuration (very large propellant tanks). Hence a dry mass index of about 22 – 23% is considered more appropriate at this stage.
- The mass of various equipment items was underestimated, and/or discrepancies appear between assumptions in the different Industrial Studies (e.g. propellant tanks, magnetometer boom, PCDU, avionics, harness), resulting in an uncertainty on system margin.
- The power required by the platform varies by 15% between the Contractors, which also translates into an uncertainty on power subsystem mass.

A further impact on the system mass could result from the payload, which, once selected, could require increased resources (e.g. volume) than currently estimated.

The mass required for radiation shielding is also an area of uncertainty (see section 2.6).

Concerning power aspects:
- The solar array mass efficiency (in terms of W/kg) assumed by the studies is deemed credible.
- The estimated power demand includes a 20% margin, which is deemed sufficient at this stage, also covering an ECSS-E-ST-20C requirement that a 5% margin be available on the supply side at FAR.
- However, consumers with large uncertainties on power demand were identified, including the communications system (in need of more detailed design, see specific discussion in section 2.4), the heaters (based on preliminary thermal design), and the payload. The power required by the platform must therefore be consolidated through a better definition of system modes.

With respect to the estimated propellant mass, it was found that the manoeuvre efficiency has not been fully analysed yet. However, the Board expects that further detailed design and analysis will confirm the capability of performing navigation thrusts in any direction during most of the mission, as well as a force-free RCS layout as required for safe flyby manoeuvres, with small impact on propellant mass. At this point in time the estimated propellant was considered consistent and adequate for the specified mission profile.

The above findings led the Board to re-calculate a dry mass budget using other missions (BepiColombo, LISA Path Finder) as proxies, and including an updated shielding mass as needed for the reference mission scenario.

During the reformulation phase the performance of the launcher was studied with Arianespace, which resulted in an additional launch mass of 350 kg. This launcher performance is consistent with the performance agreed for BepiColombo. Furthermore a slightly different interplanetary trajectory was found, which does not need a deep space manoeuvre, as was originally the case for the 2022 launch option, reducing the required Δv by 300 m/s. To accommodate the increased radiation exposure resulting from the updated radiation model and from the additional Europa flybys, the industrial teams increased the nominal shielding mass from 88 to 155 kg. Based on the arguments in section 2.6, the Board considered an additional 28 kg for shielding necessary. Considering also an increase of the solar array mass estimated by the Board of 10 kg (see section 2.3), this results in an overall nominal dry mass increase of 105 kg since the updated mass that was established as outcome of the review of the Assessment Phase.

This mission scenario is compatible with a maximum dry mass of about 1900 kg, while the above mass increase brings the nominal spacecraft dry mass to about 1650 kg, yielding a System Margin in the order of 15%. In addition, it is noticed that the launch mass is affected by a high wet-to-dry mass amplification factor, due to the large Δv. Therefore at the current mission definition level the system mass is regarded as **high risk**.

Ways of increasing the System Margin have been identified and prioritised:

1. Increased A5 performance: the following improvements that are already planned and are on-going by Arianespace are of relevance for the this mission (mass estimates are w.r.t. GTO performance of 10 t):
    a. MPS propulsive law tuning and uncertainties reduction (Q4 2011: +90 kg),
    b. New Vulcain2 operating point called R2F/R3F (Q4 2011: +70 kg),
    c. LV drag reduction (Q4 2011: +15 kg),
    d. Optimization of RLH2 residuals /Step 2 (Q2 2012: +55 kg)
    e. Development of the evolution A5 ME to be decided in 2012
2. Mission design i.e. launch slot with longer cruise,
3. Reduction or suitable optimization of flybys; currently a budget of 10 m/s is assumed per flyby, which amounts to a total of 270 m/s due to flybys alone. This could be reduced by performing fewer flybys.
4. Only as a last resort: different final Ganymede orbit.

To bring the current mass margin of 15% on dry mass to 20%, either an additional launcher performance of 230 kg, or a reduction of Δv by 130 m/s, or a dry mass reduction of 90 kg, or a suitable combination of these three parameters is required. The planned improvements of the launcher performance (+230 kg into GTO) are equivalent to about 120 kg for the direct escape trajectory used by JUICE. Furthermore due to recent progress of mission analysis, the cost of the Europa phase in Δv has been reduced by 40 m/s. The combination of these two already brings the available dry mass within 10 kg of the target value, including 20% margin.

2.3 Solar Arrays

The availability of solar cell technology optimised for Low Intensity Low Temperature (LILT) was originally evaluated to be a medium risk because it was understood that some cells could contain defects implying a significant impact under LILT conditions, but would pass room temperature acceptance testing. During the intervening period, the on-going technology development activity has increased confidence that nominal cell performance under LILT conditions can be assured. The confidence arises from adaptations to the cell contact metallization and additional passivation layers that reduce the incidence of problematic defects and limit occurrences to cases which can be screened out during room temperature testing. Nevertheless, the risk status is maintained at **medium risk** until this is confirmed.

Parallel developments are expected to result in the release of at least one generation of improved cell technology (3G30) before the procurement for Laplace will be initiated. However, the system studies carried out by industry have baselined the current generation of solar cells (3G28) and do not rely upon availability of improved performance. This represents an additional margin. It is expected that the technological improvements made to the 3G28 cell will be directly transferable to later generations, but also this point is pending confirmation.

The changes to the mission profile that have been evaluated since the previous Mission Review (cf. issue 1 of this report) lead to both an increased power demand and a more severe radiation environment. The increased power demand is counter-balanced by the increased solar illumination intensity for the new sizing case, which is associated with a closer proximity of Jupiter to the sun (53 W/m^2 instead of 46 W/m^2 in the previous case).

In comparison with the Earth orbit environment, the radiation environment in the Jupiter system is characterised by a particle energy spectrum shifted to higher energies, especially for electrons and a more intense particle flux overall. However, after the attenuating effects of shielding upon the raw particle spectrum are taken into account, this does not lead to physically different effects at the solar cell level (though the raw spectrum impacting e.g. cover glass coatings will be higher and will need to be tested as representatively as possible). At the time of writing there are still discrepancies between the two available models of radiation-induced solar array degradation for the Laplace mission, but the baseline approach used in the studies, which is based on the 'equivalent fluence' approach, is anyway the more conservative of the alternatives.

In order to mitigate the impact of the more severe radiation environment upon solar array performance, it is possible to apply a thicker cover glass shielding (100 to 150 µm instead of 75 µm) for each cell, which would effectively attenuate the radiation arriving at the solar cell back to the level originally considered. The increased cover glass thickness would also be more in line with standard manufacturing processes but implies an increased mass of 0.2 kg/m^2 for the 150 µm case, leading to around 10 kg in total. In principle it would also be possible to achieve the same effect by increasing the solar array area – with both options being feasible, practical considerations determining which would imply more additional mass and which would be preferable in the context of a specific design.

Qualification of the solar array assembly for the Laplace extreme thermal environment (see section 2.7: low temperatures in the order of –230°C) shall be performed as part of the Implementation Phase, to verify that the composite materials withstand such low temperatures, and that the assembly remains intact after thermal cycling to such extreme conditions. No concerns were raised about the availability of suitable materials withstanding such conditions.

2.4 Communications

During the Reformulation study, no updates of the communication subsystem were performed. The cancellation of the second spacecraft, the JEO, introduces intrinsic simplifications due to the deletion of the inter-spacecraft link. Simplifications of the Radioscience implementation resulting in the potential implementation of a dual band MGA in support of radio-science, were also discussed by one Contractor, which would allow for a better segregation of the Radioscience related network from that of the main telemetry, and should be pursued in the Definition Phase.

Based on the established daily data downlink volume requirement of at least 1.4 Gb of science data, the Board finds that the use of X-band alone would be sufficient. Due to mass constraints possibly requiring reductions of Δv or a reduction of the time spent in a high radiation environment resulting in a reduction of the Ganymede phases, a higher science telemetry rate may however become necessary. It is recommended to continue with the trade-off comparing X-band only and a combined X-band and Ka-band science downlink capability.

The industrial studies assume that Radioscience could be carried out in parallel to telecommunications, however it is noted that this is not currently possible using ESA ground stations. The costs for the upgrade of the baseline ESA groundstation (DS3, Malargüe) will be added to the JUICE CaC.

While the overall risk in this area is considered **low;** it is recommended to consolidate the data return requirements, and to revisit and optimize the communications subsystem design.

2.5 Autonomy and Operations

The operational complexity of the baseline mission is considered comparable to other ESA interplanetary missions, such as Rosetta and BepiColombo.

Access to the spacecraft needs to be guaranteed during all mission phases, but it is complicated by the large distances involved (up to 6.4 AU) and by the fact that the pointing of the High-Gain Antenna (HGA) is compromised during the Venus gravity assist (GA), as it is used as sunshield. The duration of the non-availability of the HGA for communications needs to be minimised. A detailed thermal analysis shall be carried out to establish the duration during which the HGA is needed as a sun-shield, and this duration shall be minimised. Additionally, in order to facilitate more efficient recovery from Safe Mode, a higher-level Safe Mode shall be developed providing an autonomous stable pointing of the HGA to the Earth.

The main engine is proposed to be used for all major manoeuvres, being most efficient. However, the need for the autonomous on-board capability of continuing a burn in case of main engine failure is not fully assessed, in terms of probability of mission success. A switch-over from one main engine to a backup main engine has not been used on any ESA mission so far, and adds complexity and risk of mass increase, in case the main engines would need to be mounted with gimbals. Also the impact of a degraded mission using the RCS thrusters as backup has not yet been sufficiently analysed.

The spacecraft needs to be capable of reliably performing time-critical manoeuvres. A more capable backup operating mode or a fast transition from a backup operating mode to an orbit control mode appears necessary. This has not been implemented on previous missions, but is not seen as a major new development.

The adoption of a redundant navigation camera specifically for the support of the earlier Jupiter moon flybys is recommended, in order to mitigate navigation errors due to the limited knowledge of the ephemerides of the moons. This results in a negligible mass increase and a very modest cost increase (no autonomous on-board navigation is required).

The risk entailed in the operations and autonomy aspects of the mission is regarded as **low**, although the complexity needs to be fully taken into account in the software development planning.

2.6 Radiation

The JUICE radiation environment has similarities to the GEO environment (electron dominated), but is more severe (higher density and higher energies). The risk can be mitigated by careful application of shielding strategies similar to near-Earth missions (GEO/MEO).

The radiation environment model that was used during the Assessment Phase was based on a combination of three models, which included at that time available parameterizations of Galileo measurement data (DG83, GIRE) and an analytical model based on a magnetic field model that was developed for Earth (Salammbô). The worst case envelope of these three models was used for the prediction of the environment during the Assessment Phase. Since 2008 a development was conducted which re-analysed all available *in situ* measurement data from all missions that visited the Jupiter system (gravity assist and the mission that orbited Jupiter, Galileo), but using primarily Galileo data. The locations of these measurements were first mapped into the Jupiter magnetic field and then parameterised This so called JOREM model was just concluded and validated (among others with comparisons of an independent development by JPL based on the Divine/Garret and GIRE models) at the beginning of the Reformulation Study and was therefore taken as the new baseline. The mean level prediction of the environment by JOREM is higher than the previously used model by about a factor of 2. Furthermore Europa flybys were added to the mission profile, increasing the total dose by about 25%. In comparison, the Callisto phase is only contributing about 9% to the total dose.

The Board recommends following a clear separation of the margin philosophy on radiation issues:

- External environment: a factor 2 applied to the mean environment model, accounting for modelling uncertainty and fluctuations. Additional work on calibration of environment models is recommended as a pre-requisite to the mission, however the scarcity of mission data available for calibration imposes a conservative standing. The board recommends following the observations by the JUNO mission, once it arrives at Jupiter (July 2016) and allowing for an update of the radiation environment based on latest data.

- Part-level radiation design margin: a factor 1 applied to radiation hardness. This is based on an increased effort on parts testing (i.e. increased statistical significance of test results), which in turn translates into a higher cost of parts.

Additional simulations on the radiation exposure of components were performed by the industrial teams during the Reformulation Phase, which provides additional accuracy of the estimated shielding mass. A radiation shielding of several levels was assumed, a thin “vault”, unit level shielding and spot shielding. Care must be taken on the consequence of excessive spot shielding, introducing mechanical and thermal loads on the components and PCB’s. Due to the early design of the mission, a Maturity Margin of 40% on the basic mass of shielding shall be used, covering (1) uncertainties on sectoring analysis e.g. modelling of radiation shielding, and (2) risk that the widespread application of spot-shielding, as assumed by industry, may not be possible or effective for a number of components, so that additional mass may be necessary for reverting to unit shielding.

A TID (Total Ionising Dose) of 240 krad for 10 mm Al solid sphere (before application of margins) shall be considered as reference outcome of the Reformulation. This translates into about 28 kg additional shielding (nominal) mass w.r.t. industrial estimates.

The above optimised shielding approach is recommended. However it has to be underlined that it requires critically early availability of detailed design models of spacecraft, platform equipment and instruments which are suitable for radiation shielding analysis, and updated shielding analyses to accompany design evolutions.

As a practical measure, the radiation hardness of components for typical GEO applications (50 krad) shall be assumed, i.e. double the expected TID to absorb uncertainties of the environment modelling, as proposed by industry and recommended by the Board in the first iteration. No particular availability issue is expected for parts with TID tolerance ≥50 krad, however the majority of parts on GEO Comsats (80 – 90%) are US-sourced parts. This may raise a concern on procurement lead-time as ITAR clearance may be required.

A radiation monitor should be embarked, with its response tailored to electrons in the 2 MeV – 30 MeV range. This will provide important information on arrival and after the Europa phase on the radiation dose budget of the mission, and allow adaptations if necessary. In addition, the data would be available for future mission design, and for limited science.

In summary, the radiation risk is considered **high**, requiring continued proper attention. Specifically, the Board recommends establishing tailored JUICE Radiation Hardness Assurance requirements, and implementing iterative shielding analysis and shielding configuration control during the early design phases. The planned TDA’s for characterization and screening of parts shall be pursued with high priority. Radiation characterizations shall also include effects on glasses, fibre optics and other optical and electro-optical components. A European radiation-tolerant Approved Parts and Materials List (APML) shall be established. The radiation shielding analysis shall be carried out with high priority in the Definition Phase.

2.7 Materials

The spacecraft would be exposed to long eclipses during the Jupiter tour and the Callisto science phase, which could last as long as 7.5 hours. Consequently, surface materials and appendages will be exposed to extremely low temperatures, resulting in potential risk to structural integrity for solar arrays and antennae/masts, and require therefore qualification to the order of –230°C. In previous projects (e.g. XMM-Newton solar array) hardware was generally tested to –205°C only.

It is recommended to identify available LHe (20 – 40 K) facilities and to perform conclusive tests of representative samples at lowest temperatures before the Implementation Phase ITT. This needs to be added to the Technology Development Plan. It is not anticipated that full-scale Acceptance Tests at LHe temperature would be required for the PFM solar arrays, however a test and qualification approach shall be established for the whole mission.

The overall risk is regarded as **medium**.

2.8 Electrostatic Charging

The environment is similar to GEO/MEO. Special measures for avoiding electrostatic charging will have to be taken, including standard mitigations such as early attention to surface finishes, using ITO Kapton on MLI on the back of the solar array, and standard anti-reflective coating with MgF_2 on the solar cells.

The following requirements on electric cleanliness of the spacecraft in support of scientific instruments (RPWI) were included in the baseline as studied at the outboard sensor location:

1. <50 dbµV/m below 45 MHz
2. No exposed electric potential on the spacecraft >1 V
3. Conduction of surface $>10^7\ \Omega/m^2$ and grounding of spacecraft outer skin

One potential instrument team desires more strict EMC requirements, including the establishment of an EMC board, which would potentially affect all hardware contributions (including instrumentation). This was however not accepted as a requirement during the study, as it would shift the emphasis of the mission to a plasma type mission, which was not supported by the Study Science Team.

The material properties for the JUICE environment shall be studied with respect to the charging and low temperature exposure (resistivity, SEE yields, cold conditions). In particular the proposed material for the Sub-Surface Radar antenna structure (S glass/Kevlar composite) was flagged as being highly susceptible to surface and internal charging; less resistive options shall be investigated. The plasma environment specification (including secondary electrons from surfaces) needs to be provided.

The risk is regarded as **low** if the standard design measures, including those specified above, are systematically adhered to.

2.9 Magnetic Cleanliness

The magnetic cleanliness requirements (measurement background <0.2 nT) are regarded as ambitious and are similar to typical magnetosphere missions, and are two orders of magnitude more stringent than for BepiColombo, however only slightly lower than those achieved for Rosetta. The Board recommends applying best practices for reducing the spacecraft field and providing knowledge by measurement, to a similar level as was performed with Rosetta and LISA PF, avoiding the involvement of a specific magnetic measurement facility (with the associated planning and cost impact). The recommended best practices should include:

- Early detailed magnetic cleanliness analysis.
- Application of magnetic cleanliness guidelines for design and procurement minimising the use of magnetic materials.
- The magnetic moment of all units being characterised, and a magnetic budget being maintained at system level.
- Application of local compensation, where needed.
- spacecraft harness routing being laid out such that the magnetic field is minimised/reduced.
- A magnetic test being carried out at spacecraft level in a standard cleanroom, similar to what was performed for Rosetta.

Following these steps Rosetta achieved a DC magnetic field level of 43 nT at the tip of a 1.5 m boom. Based on a scaling of these results, it is expected that a resulting field of the order of 1 nT at the tip of a 5 m boom (current baseline length) could be achieved, or 0.2 nT , if the boom was extended to ~8.4 m (to be confirmed by further analysis).

If the above design measures are systematically taken, and if the performance similar to Rosetta and Lisa PF is deemed acceptable, the risk is regarded as **low**.

2.10 Planetary Protection

With the planned Europa flybys, JUICE became a Planetary Protection Category III mission, which requires that the likelihood of inadvertent contamination of the Europa sub-surface ocean be demonstrated to be less than 10^{-4}. The proposed approach is to select proper trajectories and ensure sufficient reliability of the flight system to guarantee a failure likelihood with a consequence of a possible Europa collision to be $<10^{-4}$. In this study phase the focus is to analyse the probability of impact during the more critical Europa targeting, flyby and escape mission phases.

The following points were identified, which need to be addressed during the next study phase:

- A full failure tree analysis, including probabilities, to establish the likelihood of mission-critical system failures, which may cause loss of trajectory control of the spacecraft.
- Establish the likelihood of collision before and after the Europa flyby phase.
- A micro-meteoroid model specifically for the Jovian system that allows simulating the micro-meteoroid collision rate and likelihood of causing loss of spacecraft control.

From first principles considerations the suggested approach of proper trajectory planning and sufficient spacecraft reliability appears feasible, but it needs to be demonstrated during the Definition Phase. Additional cost of critical subsystems should be reserved for increased reliability by design.

The risk attached to the proposed approach is currently estimated as **low**. However, due to the open issues identified above, which cannot be quantified in the current study phase, it is recommended to keep a reserve at programme level for active bioburden reduction, until these risks are properly quantified.

No Planetary Protection concern is raised with respect to other targets of the baseline mission profile.

3 MAJOR FINDINGS – TECHNICAL PAYLOAD

The review focused on the status of instruments, which were listed in the JUICE model payload as per the Payload Definition Document (PDD). The preliminary instrument study reports that were made available (Declaration of Interest [DOI] reports) covered all instruments, with several model payload instruments being addressed by more than one study/team. No assessment of the science performance was carried out by the review.

3.1 Payload Resources and Redundancy

The content of the PDD, which was used as reference in the Industrial Studies, was frozen in February 2010 to ensure a consistent design of the spacecraft. In August 2010 the DOI reports of the instrument studies became available. The comparison between the two sets of documents indicates an increase in power and mass assumed for the individual instruments (the increased resources are taken into account in section 2.2 above); this trend needs to be monitored carefully.

Single-point failures (SPF's) were identified in a number of instrument designs, mostly related to mechanisms. In most cases only a small effort was made to study alternatives avoiding such SPF's or limiting their effect, e.g. through introduction of alternative solutions. It is recommended for the next phase to focus on these SPF's and to devise proper strategies minimising the impact of such failures.

Attention shall also be given to optimised instrument redundancy concepts (including optimization of redundancy, e.g. by sharing data processing, with a view at minimising the required resources).

3.2 Radiation and Plasma

The Jovian radiation environment was properly addressed by the DOI studies up to the Assessment Review, although radiation shielding guidelines need to be established at system level, No specific input from payload study teams was obtained during the Reformulation Phase, however the Board finds that the instrument implementation teams may follow the same approach with respect to the radiation environment as defined for the spacecraft (see section 2.6 above).

The integrated radiation analysis approach, suggested by the industrial studies for an optimised allocation of shielding mass, requires that a reasonably detailed level of instrument design and specifications of radiation tolerances becomes available at an early stage. It is therefore recommended that instrument development starts immediately after instrument selection.

A number of detector systems proposed by the DOI instrument studies are rather sensitive to relatively high-energetic electrons, which are present with high fluence in the Jovian radiation environment, and which can generate a large background signal. It is therefore recommended to carry out an analysis of the scientific performance of critical detector systems in the Jovian radiation environment as one of the highest priorities by the instrument teams. The consequences of the plasma environment on the electrostatic cleanliness requirements need to be addressed in more detail.

Instrument teams need to specifically also address the feasibility of making observations and measurements in the high background environment that is incurred closer to Jupiter, i.e. during the Europa flybys. The studies on science performance estimates need to be carefully monitored.

3.3 Yaw Steering

The spacecraft will continuously rotate around its yaw axis (nadir-direction) in the baseline operating mode during science measurements while in Ganymede orbit due to the need of having the solar panels continuously illuminated. This is referred to as *Yaw Steering* and has a direct impact on the instruments. Some of the instrument studies address the effects of yaw steering and discuss how to avoid loss of performance, or how to benefit from it. In the DOI reports, however the discussions mostly remain at a high level and more detailed analysis is needed to evaluate the impact on the scientific performances.

3.4 Payload Development Status

Significant instrument heritage is available, albeit specific issues on performance and sensitivity need addressing, mainly due to the environment of the Laplace mission. For JUICE, the overall risk was deemed **low** for instrument developments relying on proven technology, and **medium** for new developments. One instrument study appears to rely on a new sensor with low TRL and is therefore viewed as **high risk**, however an alternative instrument design has also been investigated and could be considered for the mission.

Several instrument teams envisage mechanisms, including a scanning platform, shutters and covers of optical systems, filter wheels, etc. The application of scanning mechanisms should be traded against optimised accommodations and/or additional sensor heads to ensure the required FOV.

It was noted that the selection of materials for lenses based on radiation hard glasses makes it more difficult to achieve achromatisation (cameras). Care must be taken with the assumed suppliers, as some radiation hard glasses are no longer in routine manufacture/stock.

4 MAJOR FINDINGS – PROGRAMMATIC ASPECTS

4.1 Overall Technology Assessment

No technology showstopper has been identified by the review. Overall, the mission does not appear particularly technology-intensive, and could be designed with current technologies, with the exception of the LILT solar cells (see discussion in section 2.3 above).

No specific development is required to enhance the radiation tolerance of parts and materials, but a statistical radiation hardness assurance approach is recommended for parts procurement.

Characterisation and screening of materials for low temperatures shall be added to the Technology Plan.

Specific developments that need to be started include:

- Sub-Surface Radar antenna structure (MARSIS heritage is judged unsuitable for extremely low temperatures and high charging radiation environment).
- 100 W Ka-band TWTA (only if current downlink telemetry approach is confirmed).

Several instrument study reports (DOI reports) indicate on-going or planned developments. Their planning must however be tuned with the available schedule resources. It is noted that viable backup options essentially appear to exist for all instruments. No ESA-funded TDA's are planned for instruments, with the exception of radiation-related characterizations and two ASIC developments, all of which are of general application.

In the following the major TDA's for JUICE are listed:

Title	TRL now	Status
LILT solar cells	4	Ongoing since 2009; finish expected 2012
SSR antenna structure	4	Ongoing since 2009, finish expected 2012
100 W Ka-band TWTA	3	Extension of 30 W TWTA available at TRL 9; if confirmed, start in 2013
Materials qualification at low temperatures	4	Only delta qualifications for extreme low temperatures foreseen; related activity started in 2011, additional activities may be necessary start in 2013

No major developments are being considered by the instrument teams.

4.2 Schedule

The schedule provided by the Contractors appears optimistic, taking what is viewed as considerable risk. A more realistic schedule, including key Agency milestones, was established by the Board, based on the following assumptions:

- Downselection by the SPC in February 2012, followed by a Definition Phase of 24 months.
- An instrument AO would also be issued shortly after the downselection, and is expected to be released in Q2/2012.
- Assuming a mission adoption by the SPC in June 2014, and typical ITT process duration, the kick-off (KO) of Implementation Phase (B2/C/D) nominally takes place in May 2015.
- 12 months for the build-up of the industrial consortium (Subsystem- and Equipment-level Subcontractors), through lower-level ITT's and selections; this is judged slightly optimistic and incompressible.

- 24 months for the procurement of LLI's; while considered adequate in duration, an optimistic start date of the parts procurement with respect to the finalisation of the electronic units design was assumed.
- 24 months for qualification of LILT solar cells; no schedule risk needs be considered for this, as the solar array design would be frozen earlier, independently on the outcome of the development.
- A classical 3-model approach (STM/EM/PFM) is assumed, without relying on h/w links between models.
- 36 months are assumed from PDR to start of PFM spacecraft AIT; this is considered challenging for s/w development and validation, due to the complexity of spacecraft autonomy and operations, requiring early definition of s/w requirements baseline.
- Radiation shielding and magnetic cleanliness are not considered to be schedule drivers, assuming that the outlined approaches (c.f. sections 2.6 and 2.9) are implemented.
- 32 months are assumed for the total PFM campaign, which is deemed adequate. However, procurement of PFM structure, thermal control, propulsion, harness and other equipment is assumed to occur prior to System CDR, which is considered a risk, especially with regards to the procurement of PFM/FM electrical units.
- For the development of the instruments, a total duration of 4 and 5 years from start to PFM delivery is assumed, respectively, for instruments with significant heritage and for new developments.

Based on the above assumptions, it is noted that the schedule is driven by the industrial team build-up, the procurement of the LLI, the electrical systems, and the flight s/w development. No meaningful de-scoping options were identified that would allow significantly shortening the schedule. The Implementation Phase, including 16 months contingency and a 4-month launch campaign, was found to last 7 years from KO to earliest launch readiness.

A longer than nominal contingency of 16 months was assumed, due to the limited launch opportunity window, which occurs roughly on a yearly basis, causing a delta of one year, if missed. A launch opportunity in 2021 could be available.

The instrument development times (4 or 5 years, see above) imply that the starting date of the instrument development must be soon after instrument selection, following the Announcement of Opportunity (AO) for JUICE. Currently the AO is assumed to be released as soon as the mission is selected for Definition Phase, which would be in February 2012. This constrains the possibilities for instrument (pre-) development.

A tentative schedule of the main milestones would be:

	Industry	**Instrument Teams**	**SPC**
February 2012			Approval of draft SMP[1]
March 2012	ITT for Definition Phase	Instrumentation AO	
September 2012	KO of Definition Phase		
June 2014			Mission adoption
September 2014	End of Definition Phase	MLA[2] signed	
October 2014	ITT for Implementation Phase		
Q2/2015	KO Implementation Phase		

There is sufficient contingency for meeting the baseline launch in mid 2022, and therefore the overall schedule for a 2022 launch is judged a **medium risk**. The Board stresses the need to approve a draft SMP in Q1/2012, such that the instrument AO can proceed.

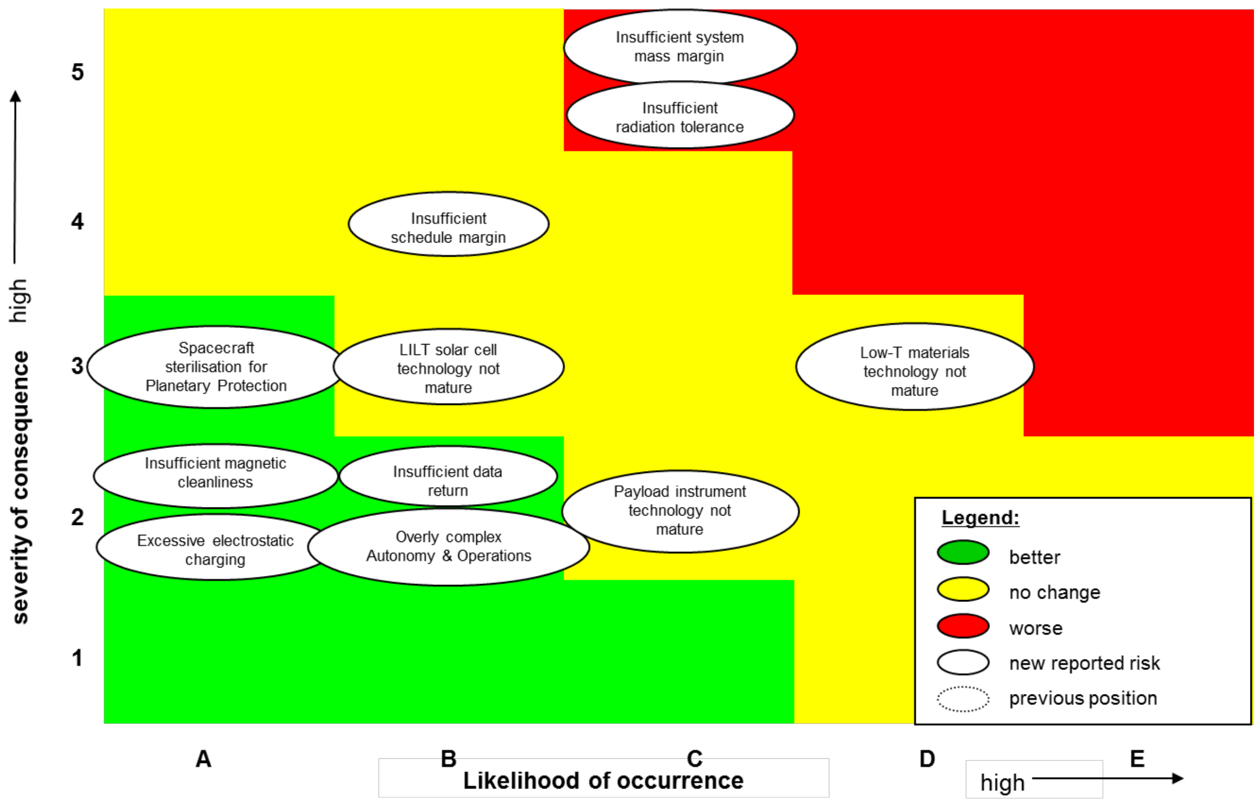
[1] Science Management Plan

[2] Multi-Lateral Agreement

5 RISK ASSESSMENT

Risks identified in this review have been assessed by the Board as detailed in the following table and figure.

#	Risk Description	Severity of Consequences	Likelihood of Occurrence	Risk
1	Insufficient system mass margin	5	C	High
2	LILT Solar Cell technology not mature	3	B	Medium
3	Insufficient data return	2	B	Low
4	Overly complex Autonomy & Operations	2	B	Low
5	Insufficient radiation tolerance	5	C	High
6	Low-T materials technology not mature	3	D	Medium
7	Excessive electrostatic charging	2	A	Low
8	Insufficient magnetic cleanliness	2	A	Low
9	Spacecraft sterilisation for Planetary Protection	3	A	Low
10	Payload instruments technology not mature	2	C	Medium
11	Insufficient schedule margin	4	B	Medium



6 CONCLUSIONS AND RECOMMENDATIONS

The Board finds that the establishment of mission requirements for JUICE/Laplace is complete, that the level of system definition is adequate at this stage of the development, and that the design approach is sufficiently robust with regards to the main technical challenges posed by the mission (namely: power availability and radiation at Jupiter).

The overall mission is regarded as **low risk** from a technical standpoint, as it could be implemented with a minimum of new technologies.

A realistic schedule, established by the Board including key Agency milestones, results in a **low** likelihood of not meeting the nominal 2022 launch opportunity.

In summary and based on the discussion above, the following recommendations are made:

1. Continue to improve the understanding of the **radiation environment model** and implement a factor of 2 margin on the mean model.
2. **Radiation shielding analysis** shall be carried out as soon as possible and a major effort shall be spent on shielding simulations in order to reduce uncertainty of this contribution to the system mass. Monte Carlo-based simulations are strongly recommended.
3. Tailored **Radiation Hardness Assurance** (RHA) requirements shall be compiled, and a radiation-tolerant Approved Parts and Materials List shall be established, specifically in support to payload instruments development. Component procurement shall be based on statistical RHA procedures, such that the component RDM could be reduced to 1, except for components where a higher tolerance margin is needed.
4. Monitor closely the evolution of the **dry mass**, with the aim of identifying possible mass reductions, and continue pursuing options for improved launcher performance and mission analysis. An incentive scheme with industry could help controlling the depletion of the mass margin for the Implementation Phase.
5. Characterization/qualification of materials used for structures and appendices (solar array composite, antennae and masts) with regards to exposure to extreme low temperature shall be followed carefully
6. **Instrument development** activities shall be started as soon as possible after selection by the AO, commensurate with the envisaged level of new developments, but specifically focusing on Jovian environmental issues at sensor and optics level.
7. Interfaces to the **Radioscience experiment** shall be consolidated before the Definition Phase.
8. Best practice approach on **magnetic cleanliness** shall be implemented from an early stage.
9. A **micro-meteoroid model** specifically for the Jovian system shall be developed to evaluate the effect on S/C reliability and need for potential additional protection of critical systems.