RADIATION FACTS AND MITIGATION STRATEGIES FOR THE JEO MISSION

Submitted by
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I. Introduction

The Europa Jupiter System Mission (EJSM) proposes to explore one of the most intriguing planetary systems in our solar system. The radiation belts of Jupiter, however, also make this system one of the most technically challenging to visit, especially when Europa, revolving in the midst of this harsh environment, is included. This small icy moon has particularly intrigued scientists, ever since glimpses from the Galileo mission suggested it as a potential harbor for life.

To learn more, the Jupiter Europa Orbiter (JEO), one of two EJSM spacecraft, has been put forward to get closer, stay longer, and look deeper into Europa than Galileo ever could. In making this journey though, JEO would also need to tolerate substantially more radiation than its predecessor or other planned missions to the Jupiter system (Figure 1). Therefore, this concern has naturally driven all considerations of a mission to Europa since studies began in 1996.

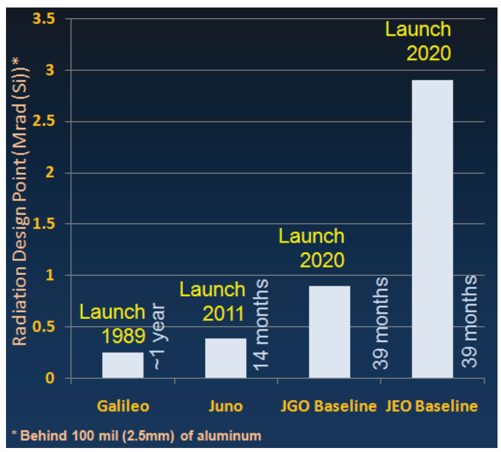

***Figure 1**. Estimated radiation dose levels unprecedented for NASA/ESA*

We now believe that these concerns are reasonably well understood and have been reduced to manageable form. This judgment rests on a body of evidence collected through a number of related efforts over the last decade regarding…

- Magnitude and variation of **radiation** in the Jupiter system, including modulation of this environment by shielding and other factors,
- Availability of affordable **radiation hardened technology** that is capable of performing a rewarding mission, accompanied by an understanding of radiation effects on their performance and reliability, and
- **Analysis techniques** for understanding and correlating these combined factors with other system considerations to intelligently inform engineering decisions.

This understanding is summarized here, followed by a description of the plan through which JEO builds upon this foundation to confidently manage radiation concerns and balance their impacts across the system.

II. Understanding Radiation

While there are many types of radiation and consequent effects on spacecraft, the dominant problem for a mission to Jupiter, beyond what is normally experienced on spacecraft in general, is the cumulative dose (both ionizing and displacement damage). JEO would accumulate significant radiation dose in two stages: initially, as it uses gravity assists in the inner Jupiter system to shape the trajectory for Europa arrival; and then for the remainder of the mission, once it has settled into tight circular orbit around Europa. We are fortunate that both parts of this journey lie within the region of Jupiter's radiation belts well traveled by Galileo during its eight-year stint at Jupiter. In surviving many times its design dose through two extended missions, Galileo was able to provide, not only a superb radiation data set, but also information that has enabled characterization of the moderating affect of Europa on its local environment. In addition, seven flybys of Jupiter to date by other spacecraft have supplemented and supported this information. Much of this data has been incorporated into environment models [1], giving us an understanding of the environment around Jupiter and Europa that is good enough to characterize the dose for a Europa mission.

These models indicate, for instance, that elevated radiation levels (e.g., from solar events) can be intense, but are short-lived, lasting on the order of days at a time. Therefore, with allowance for spatial variation, the statistical average dose provides a reasonable estimate of radiation exposure over a mission, as both random variations and "weather" average out over time with a familiar statistical residual.

For some radiation effects, the momentary flux, rather than long-term accumulation, is the issue of concern. This applies, for example, to flux dependent noise in sensors. For such cases, temporal variations are significant, but the same models that justify averaging of cumulative effects and tell us what to expect from the background flux also provide insight into the intensity and duration of flux peaks.

These models also tell us that Europa casts a "radiation shadow" [2], thereby substantially reducing radiation on one side as it orbits Jupiter. Consequently, while in orbit about Europa spending about half its time well within this shadow, JEO would accumulate radiation effects at a substantially lower rate, on average, than the location within Jupiter's radiation belts would otherwise suggest.

While there is still more data to be incorporated into the models, predictions are not expected to change substantially. Thus, confidence in the estimated dose which would be seen by JEO is good, unlike when Galileo was designed, and it is significantly higher than for Juno where the local environment isn't as well characterized (little Galileo data inside 4 R_J where Juno will travel).

Two additional factors determine the cumulative exposure ultimately felt by spacecraft components. These are trajectory and shielding, both of which can be manipulated to good effect. For instance, limiting time spent in the worst regions might seem the easiest way to reduce dose, but this must be traded against science and gravity-assist opportunities in the satellite tour. The latter, in particular can be tailored to reduce exposure duration, but usually at the expense of system mass, which might have been used for radiation shielding. The best-shielded environment for sensitive system elements is consequently an interesting interplay between shielding and trajectory designs. With good environment and shielding models now *both* in hand, we have the tools to explore mission designs with reduced radiation exposure that might not otherwise have been considered. Just as importantly, we can forestall unforeseen threats to exposure that might result from a less overt coupling of these two models.

Overall then, there is very good reason to believe that uncertainty in the environment is a contained problem.

Radiation Hardened Technology

Besides gaining a good understanding of the Jovian radiation environment, the past decade or so has also seen great strides in the development, characterization, and understanding of radiation-hardened electronic parts, which would directly benefit the proposed JEO concept. These advances are the product of efforts like X2000, JIMO, and Mars Technology within NASA, as well as vital work by the Departments of Defense (DoD) and Energy (DoE), and by numerous industrial contributors.

Because of this work, there is now available to designers a rich assortment of part types that are hardened to 300 krad (Si) or greater. Indeed, many of the most commonly used parts are available at 1 Mrad (Si) and above. Assessment of this has revealed no major omissions, relative to what both instrument and engineering designers would typically expect for a mission such as JEO, that cannot be addressed by alternate means.

Three notable areas of investigation have been FPGAs, mass storage devices, and detectors, but in each case, viable approaches have been found that require no further technology development. FPGAs, for instance, are most easily dealt with by replacing them with custom ASICs, perhaps in conjunction with microcontrollers, having made appropriate programmatic adjustments to accommodate the different design life cycle. The book is not closed on FPGAs, for which there may yet remain acceptable options, but in any event, ASICs are a known alternative good to 1 Mrad and better.

Options also exist for mass storage, with a mixed strategy envisioned at the present that would use standard technologies until radiation dose had accumulated past their capability, while more hardened but less dense alternatives serviced the latter part of the mission. The parts required for this strategy are available, and the science objectives of the mission are achievable within the storage capacities available by this method in conjunction with other data transport features.

Detectors present a much more varied situation, especially since both reliability and data quality are at stake. However, through various modeling and analysis studies, it has been concluded that in each likely family of sensors, there are plausible options capable of meeting science objectives, given suitable mitigations. This characterization and assessment continues.

Accompanying these developments have been similar strides in understanding the physical phenomena of radiation effects. In fact, the development of hardened parts and the understanding that makes this possible go hand in hand.

From these advances, plus long prior experience, we now have in hand, not just the bounds within which parts are expected to perform, but also a better understanding of the changes they are undergoing, how these changes might progress differently under varying circumstances, and what the characteristics of degradation are beyond specified performance limits. Moreover, test methods are being modified to provide greater statistical insight into these effects, all the way to part failure, where appropriate.

These understandings, including better appreciation for such phenomena as low dose rate effects, temperature- and bias-dependent exposure and annealing, and single event susceptibility can be used to refine expectations, produce better assessments of margins, develop mitigating techniques, and better direct project resources. Similar gains are being made in the understanding of detector noise, degradation, and reliability.

There remains work to do, but not so much to close gaps in the availability of radiation-hardened parts as to complete the catalog of information needed to follow through with orderly engineering development. This is a routine situation.

Analysis Techniques

Integrating all of the information about environment, mission and system design, operations plans, and so on is the third element of understanding upon which JEO stands. One example of this has already been discussed, regarding the give and take between tour designs and shielding to find trajectories that balance radiation concerns with other resources and objectives. This is enabled by analysis techniques that provide measurable sensitivities of radiation effects to design changes.

Traditional radiation design methods have exercised such capability sparingly, choosing instead to establish opaque radiation design margins (typically pass/fail), which were accommodated locally for the most part, while holding other considerations at a distance. True margins and the associated performance effects beyond were largely unknown, so sensitivity to design change could not be clearly assessed.

Statistical modeling of lifetime, as might be done for any other system resource, is the lever needed to shift analysis into a domain where integrated consideration of cross-system interests is approachable. Drawing from parts and environment data, circuit analyses, system architecture, operations plans, and other engineering data, such modeling allows systems engineers to identify and focus their efforts in areas of significant impact to the mission, whether science return, resources, or reliability.

Moreover, added insights into system behaviors beyond the bounds of normal performance are intrinsically necessary for any mindful approach to fault tolerance and robust operations. These analysis techniques would consequently be important to the overall preparedness and integrity of the systems engineering effort.

The analysis tools needed to exploit such modeling have been available, but without the necessary data and systems engineering processes to deploy them. This has turned, however, in recent years, such that plans presently in place are closing this gap. The result would be an approach that augments traditional design and analysis with new insights, wherever discerning sensitivity analysis can inform better design. Better design ultimately translates into a more balanced use of resources, larger margins, and reduced risk.

III. Plans

A comprehensive approach has been developed to handle the radiation risks inherent in missions to Europa.

Because of significant technology and engineering developments, a conservatively designed yet scientifically comprehensive Europa mission is viable today. Indeed, further technology development is not essential, so options considered henceforth could be limited to those offering enhancements to science return or reductions in cost, as weighed through objective analysis of benefits versus risks.

The fruits of these developments, however, have gone beyond their individual technological contributions. Just as importantly, they also include a deepened appreciation of the need for a well-integrated, system-wide approach to the radiation problem, if implementation or operational risks to the scientific objectives of JEO are to be handled effectively.

Four primary facets of this system-wide approach have been identified for action:

- **Data** - parts, materials, environment, shielding, trajectories, science data values…
- **Tools** - models, trade studies, analyses, training material…
- **Processes** - test and design guidelines, structured system architecture decomposition, incorporation of lessons learned from Juno, Radiation Belt Storm Probe (RBSP), Galileo, and others…
- **People** - peer reviews, advisory boards, working groups, radiation systems engineers…

Taken together these efforts systematically address radiation issues through the structured identification, analysis, understanding, communication, and retirement of critical risks relative to mission return, while ensuring that energy and resources are invested where they are needed.

The steps involved in exercising this approach, described further below, can be summarized, as follows:

- Understanding and evaluating
- Planning
- Applying Resources
- Executing
- Preparing for Unknowns

Continual risk management is critical to the evaluation and evolution of a detailed implementation plan for JEO. Therefore, this sequence of steps would be reiterated often, as instruments are selected, priorities are refined, resources are allocated, new technical data becomes available, the mission concept matures, and so on.

Understanding and Evaluating

The Jet Propulsion Laboratory (JPL) has extensive experience designing spacecraft and instruments that operate in harsh environments. This experience informs us though that understanding and evaluating the radiation challenge can be difficult and time-consuming. Therefore, mining the rich vein of prior experience with radiation is a good way to gain an early advantage on this issue.

We are especially fortunate to have the opportunity to learn from experts who designed, built, tested, and operated Galileo, and who analyzed the data from its flight. Vital lessons learned from Galileo's radiation-related anomalies — not to mention a wealth of experience regarding operation in this environment — have been summarized [3] and assimilated as part of the JEO mission risk mitigation strategy.

Current projects such as Juno and RBSP (both scheduled for launch in 2011) also provide an abundant set of experiences; and there are experts in industry, academia, and government who have dealt with various aspects of the issue over many years and many missions. Assembling the results of this extensive experience and expertise to provide a view of the unique JEO situation is not an isolated exercise. Rather, continuing engagement by experts has been and would remain important to understanding the efficient use of JEO resources.

One product of this expertise is that we now know the environment for a Europa mission relatively well, as described above. The Galileo experience also provides insight into the conservatism of its design methodology. Large radiation design margins were appropriate when the environment was not well characterized, but a byproduct of this was that actual margins overall were not well characterized, resulting in wide variation across the system and impaired expectations for actual performance, as ultimately manifest during flight. By understanding Galileo's design practices and part technologies in the context of actual experience, JEO could adopt more discerning design criteria that better exploit newer part technologies, updated design and analysis practices, more accurate environment predictions, and better modeling capabilities. The resulting improvement in our ability to objectively evaluate sensitivities in the design enables a more strategically balanced application of resources across the system, while ensuring ample attention to its weakest elements.

An important aspect of this understanding and evaluation, of course, is the characterization of parts and materials needed to support the JEO design methodology. Besides knowing the exposure below which nominal operation is assured, the nature, rate, and statistics of degradation beyond this level are of vital interest in the assessment of system robustness. Such insight enables realistic assessment of margin, while also providing the useful information for proactive accommodation of performance changes. This characterization begins with early radiation testing of sample parts and materials, continues with validation of modeling and analysis techniques, and is carried into flight operations through the correlation of observed effects with on board dosimetry.

It is clear then that this process of understanding and evaluating radiation issues is ongoing and would not end at Preliminary Design Review, or Launch, or even Europa Orbit Insertion. The nature of decisions guided by these evaluations would change dramatically throughout the project life cycle, but the usefulness of continually improved understanding only grows.

Planning

Understanding developed over the years in Europa mission studies has led to decided clarity in the direction for near term efforts to target the radiation issue. Thus, in 2007, a four-year Risk Mitigation Plan (RMP) [4] was established in partnership between JPL and the Applied Physics Laboratory (APL) to confront remaining development and operational risks as early as possible prior to Phase A development.

The objectives of this plan are to begin the early retirement of selected radiation concerns (parts and materials selection, electronics design, radiation-induced effects on sensors and detectors…), and to get an early start on needed long-lead design items and supporting infrastructure capabilities (data gathering, model development, guideline documentation…).

This plan was reviewed with practicing engineers and scientists, including experts drawn from other radiation design experience, as described above, who gave it their approval. This plan was also presented as a part of the Europa Explorer Final Report [5] and reviewed by the Science, Technical. Management and Cost (STMC) review panel commissioned by NASA Headquarters. The STMC endorsed the plan (with a few suggested additions) and recommended to NASA that money be identified specifically to begin its execution.

In 2008, the JEO study team began executing the plan as documented in the RMP. This plan is developed around each of the aspects — data, tools, processes, and people — cited above as essential to a well-integrated systems approach to the problem. Data collection is a therefore a substantial part of this effort, as characterization of parts likely to fly on JEO begins in earnest, and validation data for refined analysis techniques is gathered.

Also included in the plan are steps to institute the processes and tools of a system-level radiation-hardened-by-design approach utilizing a system model to estimate the effects of the Jovian radiation environment on instruments and other spacecraft components. This systematic methodology incorporates science instruments as inseparable parts of the system as a whole. Successful JEO mission development requires tight interaction between mission designers and instrument developers, especially during the early risk mitigation and system trade periods.

Finally, the organizational elements needed to manage, coordinate, and advise radiation design efforts are being put in place. The management structure to oversee the effort has been defined. Processes, guidelines, and training needed to sustain the effort are under development. Critical insight of key people is also ensured by leveraging concurrent work on Juno and RBSP. Members of both project teams have been incorporated into the JEO team to facilitate good communication, and additional crossover personnel would be utilized as JEO moves forward.

Applying Resources

The mitigation strategies outlined above clearly come at a price. However, their effects on cost and schedule are fully incorporated into the base implementation plan for the JEO mission, not into reserves. The 2008 JEO Mission Study Final Report [6] describes the accommodation of these effects from a few key viewpoints.

From an **organizational** perspective:

- Conventional management and engineering is greatly augmented through the addition of a sizable, experienced team focused on management and technical implementation of the overall approach to radiation issues. Deputy Project Manager and Deputy Project Systems Engineering positions established for leadership of this effort ensure it receives the highest level of attention.
- An External Advisory Board of Radiation Experts is established to provide independent review and guidance to the effort.
- Specific reviews at all appropriate levels and project phases are added to handle topics specific to radiation.

From a **schedule** perspective:

- The traditional project schedule is expanded with provisions to ensure instrument and system readiness, given the additional scope of the effort.
- Instrument-specific interaction periods and associated reviews are added prior to the start of Phase B after the selection of instrument providers to ensure system-wide convergence of the integrated design for radiation.

From a **cost** perspective:

- Additional systematic costs are added for increased systems engineering oversight, acquisition and characterization of hardened parts, extended part testing, refined analyses, potential redesigns to accommodate the radiation environment, and operational and behavioral augmentations to system robustness.

Executing

The RMP identifies and documents very specific near-term actions. These are apparent in present operational plans and are readily apparent in ongoing implementation activities.

Progress against the plan is assessed regularly, both through peer reviews and through formal reviews, including reviews with the Radiation Advisory Board. Updates or revisions are identified and incorporated back into an updated plan. Thus, the plan is viewed as a living, responsive vehicle for the management of overall effort, as mandated by JEO's commitment to continuous risk management.

Success of this approach depends on excellent communication. System modeling and analysis activities ensure the timely flow of information into the process; and the results of actions and other updates are communicated to the project team via documents, databases, review packages, videos, and so on. To the extent possible, this material is released to the public via the project website and public meetings and forums.

Preparing for Unknowns

No matter how well the effort is planned today, there would be unanticipated obstacles, things that go wrong, or new issues that arise. Reserves and margin are what allow a project to react to these unknowns, so all projects carry a level of cost, schedule, and technical resources reserves commensurate with their risk posture. Planned reserves for JEO are substantially higher than typical for budget, schedule, power, and mass, in order to accommodate extra unknowns related to radiation.

This cautious approach is also carried forward into mission plans. For example, the operational strategy is to achieve the primary Europa science objectives within the first few months in orbit at Europa. Moreover, no single Europa science data set would be critical, as redundant passes over the same terrain would provide redundant scientific data.

For much of the tour science, numerous opportunities exist, as currently understood, and no tour science has yet been identified as critical. Nonetheless, even though the final tour would likely have very similar characteristics, the current tour would be only an example. Once satellite flyby science is worked directly with the selected science team, individual flybys may become important, even though there could be multiple flybys of each target body. However, the Jupiter system tour would occur prior to Europa orbit, and hence well before the heaviest accumulation of radiation dose. Moreover, the present sample tour, upon which current dose estimates are predicated, already includes forays into the most intense environment near Io, so ample conservatism regarding radiation remains in mission plans, even under tour design uncertainty.

Current Efforts

Several activities are presently under way to execute radiation risk planning commitments. An overarching concern of this multi-year plan has been the definition of an approach by which radiation risks could be addressed broadly across mission and system design in a more systematic manner. Through quantitative modeling of risks in the context of system resources and science value, mission and system designs could be refined to contain radiation impacts at manageable levels while preserving quality science. This systems engineering approach, summarized in "Radiation Challenges and Risk Mitigation for JEO Mission" [7], improves upon traditional processes and provides a revealing method for characterizing mission lifetime beyond the radiation design point — a important tool for good risk management on JEO.

Design guidelines are also being developed as part of risk mitigation activities. Already, 27 design documents and tutorials are available for engineering and instrument providers to use in understanding radiation effects and mitigating risks to their designs. These have been delivered to NASA as part of the 2008 JEO Mission Study, and public versions have been made available via the Outer Planets Flagship Mission website: http://opfm.jpl.nasa.gov.

The JEO team has also begun preparation of the Approved Parts and Materials List (APML) for JEO. Electronic parts on the APML are categorized at four radiation levels: 50-100, 100-300, 300-1000, and ≥1000 krad, and all would meet the applicable reliability, quality, and radiation requirements specified in JPL's Parts Program Requirements (PPR) [8].

The APML also lists approved materials, describing radiation effects on their properties. Material selection guidelines regarding radiation susceptibility and reliability have been documented separately in a report entitled "Materials Survivability and Selection for Nuclear Powered Missions" [9].

Other concerns being addressed in near term activities are radiation effects on detectors and other key instrument components, where sensitivity and noise are key considerations for data quality. Sensor degradation can appear in many forms, partly from cumulative effects, but also in direct response to the radiation flux itself. The result in extreme cases, if not properly addressed, could be severe limitations on the lifetime of an instrument. Therefore, the JEO team has undertaken several pro-active measures to handle this issue for the instrument development community, including tests and analysis of candidate detectors.

In May 2009, NASA issued a Request for Information (RFI) to solicit responses from the community for 1) organizations that may provide radiation expertise, and 2) principal investigators who may be interested in submitting instrument proposals to an upcoming Announcement of Opportunity (AO).

In support of such efforts, the first two in a series of Instrument Workshops (June 2008 and July 2009) have been conducted to engage potential instrument providers early in the formulation cycle. Workshop objectives included helping instrument developers understand radiation design constraints, preparing developers for the systems engineering design approach, and describing requirements on parts and material selection.

The 2009 Instrument Workshop, held at APL, emphasized key design information and a description of the technical approach and plans adopted by JEO. In addition, special sessions were conducted to introduce and connect the instrument providers with the radiation experts. On display were 18 posters and 20 information booths from organizations declaring their expertise in response to JEO needs. Details of the workshops, so far, including the presentations made there, are available at the OPFM website.

A third Instrument Workshop is considered for the summer of 2010. Updated design information releases would continue during pre-phase A as part of a strategy to reduce cost and risk for both engineering and instrument providers.

IV. Summary

The challenge associated with operating a spacecraft for long periods within the radiation belts of Jupiter cannot be underestimated. The promise of incredible science is well worth the risk though, *if* the risk can be identified and controlled. To be managed within reasonable resource limits, a system level approach is needed to balance available resources, bolstering the weakest areas and adjusting the design as a whole for best results, rather than focusing on local concerns. It is important to establish these design methodologies early in conceptual development, and carry them forward with conviction through development and operation.

Early risk assessment and mitigation activities are also essential to controlling cost and risk. The JEO team has been pro-active in deploying a comprehensive risk mitigation plan, now in its second year, to retire most radiation risks prior to the Phase A development. The JPL/APL team has capitalized on prior deep space experience, significantly leveraging this technical expertise. Experience gained from Juno and RBSP would aid the proposed JEO mission during Phase A/B development; and the Galileo orbiter, in particular, has provided both a wealth of radiation data and an invaluable demonstration, well beyond anyone's expectations, of the practicability of operating a scientific spacecraft in the most intense regions of Jupiter's radiations belts.

Given the many steps taken to subdue the radiation issue, the design outlined in the 2008 JEO Mission Study report is well in hand and would allow this system to perform admirably well past its prime mission.

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