Engineering a Solution to Jupiter Exploration

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The Europa Jupiter System Mission (EJSM) would be an international mission with the overall theme of investigating the emergence of habitable worlds around gas giants. Its goals are to (1) explore Europa to investigate its habitability, (2) characterize Ganymede as a planetary object including its potential habitability and (3) explore the Jupiter system as an archetype for gas giants. NASA and ESA have concluded a detailed joint study of a mission to Europa, Ganymede, and the Jupiter system with conceptual orbiters developed by NASA and ESA. The baseline EJSM architecture consists of two primary elements operating simultaneously in the Jovian system: the NASA-led Jupiter Europa Orbiter (JEO), and the ESA-led Jupiter Ganymede Orbiter (JGO). JEO and JGO would execute an intricately choreographed exploration of the Jupiter System before settling into orbit around Europa and Ganymede, respectively. EJSM would directly address themes concerning the origin and evolution of satellite systems and water-rich environments in icy satellites. The potential habitability of the ocean-bearing moons Europa and Ganymede would be investigated, by characterizing the geophysical, compositional, geological, and external processes that affect these icy worlds. EJSM would also investigate Io and Callisto, Jupiter's atmosphere, and the Jovian magnetosphere. By understanding the Jupiter system and unraveling its history, the formation and evolution of gas giant planets and their satellites would be better known. Most importantly, EJSM would shed new light on the potential for the emergence of life in the celestial neighborhood and beyond. The EJSM baseline architecture would provide opportunities for coordinated synergistic observations by JEO and JGO of the Jupiter and Ganymede magnetospheres, the volcanoes and torus of Io, the atmosphere of Jupiter, and comparative planetology of icy satellites. Each spacecraft would conduct both synergistic dual-spacecraft investigations and stand-alone measurements toward the overall mission theme and goals.

The two-spacecraft architecture of EJSM would provide for significant and unique science opportunities for complementary and synergistic science, which could not be accomplished by either spacecraft alone. Such advances could come in the areas of magnetospheric studies, Jupiter atmosphere monitoring, satellite remote sensing, and rings and small satellite studies. Such unique science includes characterization of the spatial and temporal variability of the magnetic field, Jovian atmospheric and ring studies through spacecraft-to-spacecraft radio occultations, and satellite and Jupiter remote sensing incorporating a range of viewing geometries.

An international team of scientists and engineers has defined a comprehensive mission concept that is a balance between cost, risk, and science value. By using proven functionality and leveraging lessons learned from numerous flight missions, the engineering teams have defined the two flight systems (JEO and JGO) that could be designed, fabricated, tested, and operated by two well experience organizations, NASA and ESA, using their own assets and processes. EJSM's synergy arises from having two spacecraft which would simultaneously operate in the Jupiter system and acquire simultaneous observations of targets where this is scientifically valuable and complementary observations of other targets for which the JEO and JGO would have been separately optimized.

The expansive Jupiter system is scientifically rich and is best studied using multiple elements. To explore the system in detail, two flight systems, performing an intricate choreographed dance to explore the system from every perspective, are envisioned. Though both would examine the whole system, one would focus on the inner two Galilean satellites and the other would focus on the outer two. Both flight elements would perform multi-year studies of the Jupiter system, including the giant planet's magnetosphere, rings and atmosphere, and the Galilean moons. JGO would focus on Ganymede and Callisto, while JEO would focus on Io and Europa (but also study Callisto and Ganymede up close). This architecture would allow JGO to stay outside the most intense radiation belts and, thus, be designed for a lesser radiation tolerance requirement. JEO and JGO would each carry approximately 11 instruments. Complementary instrumentation would allow for each flight system to study the whole system from different perspectives and provide data for synergistic science. The remainder of this discussion would focus on JEO and on the approaches taken by NASA to enable the JEO spacecraft and instruments to function within the intense radiation belts at Jupiter.

Launched in early 2020, JEO would use chemical propulsion and Venus and Earth gravity assists to arrive at Jupiter approximately 6 years later. After an Io gravity assisted Jupiter orbit insertion, JEO would

Figure 1: The JEO current flight system design uses radioisotope power to operate 11 instruments while in the Jupiter system and makes many flybys of all four Galilean satellites before entering a tight circular orbit at Europa.

perform a tour of the Jupiter system using gravity assists of the Galilean moons to shape the trajectory and to permit science measurements. The current mission design for JEO would have a 30-month Jupiter system tour that includes 4 Io flybys, 9 Callisto flybys, 6 Ganymede flybys, and 6 Europa flybys. JEO would enter orbit at Europa and spend the first month in a 200-km circular orbit and then descend to a 100 km-circular orbit for another 8 months. The JEO Europa Science scenarios are designed to obtain Europa Science objectives in priority order. The JEO would end when the flight system impacts Europa's surface.

Flight System

The conceptual flight system design is very similar to other large orbital spacecraft (e.g. Cassini, Mars Reconnaissance Orbiter). The similarity of the science objectives and instrumentation requires flight systems with very comparable functionality. The conceptual flight system design for JEO is shown in Figure 1.

Primary design drivers on the spacecraft architecture are Jupiter's radiation environment, planetary protection, high propulsive needs to get into Europa orbit, powering and communicating with a spacecraft that is a large distance from the Sun and Earth and the accommodation of the instrument payload. To meet the JEO science objectives, the JJSDT recommended a payload consisting of remote-sensing and in-situ instruments and use of the spacecraft X-band and Ka-band spacecraft telecommunications systems for radio science. While all instruments are assumed to be independent standalone instruments, mechanical integration of instrument electronics into a shared Science Electronics Chassis (SEC) is assumed as a means to reduce radiation-shielding mass and to facilitate efficient payload thermal management.

JEO's remote sensing model payload would consist of a Laser Altimeter, an Ice Penetrating Radar, a Visible-Infrared Spectrometer, an Ultraviolet Spectrometer, a Thermal Instrument, a Narrow-Angle Camera, and a Camera Package containing medium-angle and wide-angle cameras. The in-situ model payload would consist of an Ion and Neutral Mass Spectrometer, a Magnetometer and a Particle and Plasma Instrument.

Most remote sensing instruments in the model payload would nominally view in the nadir direction when in orbit around Europa. Because JJSDT analysis indicates that nominal nadir pointing of the remote sensing instruments would address the science objectives, spacecraft-provided scan platforms are not baselined.

The EJSM proposes to explore one of the most intriguing planetary systems in our solar system, with particular emphasis on exploring Europa. This small icy moon has particularly intrigued scientists, with glimpses from the Voyager and Galileo missions suggesting it as a potential harbor for life. The radiation environment of 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.

To learn more about Europa, the JEO, has been put forward to get closer, stay longer, and look deeper into Europa than previous missionsever 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 2). Concerns with withstanding the radiation environment have naturally driven all considerations of a mission to Europa since studies began in 1996.

We now believe that the radiation challenge is reasonably well understood and has 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…

- Understanding the magnitude and variation of **radiation** in the Jupiter system, including modulation of this environment by shielding and other factors,
- Availability of affordable **radiation hardened**

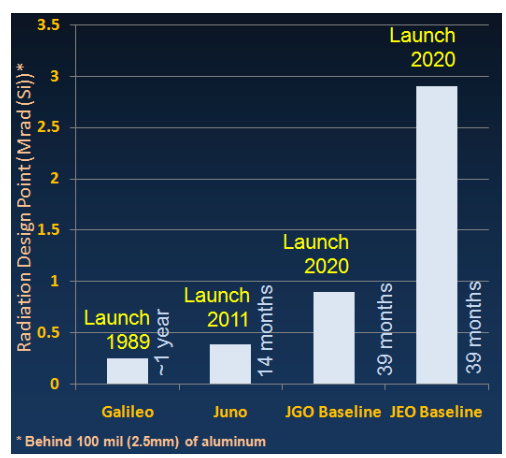

Figure 2. Estimated radiation dose levels unprecedented for NASA/ESA missions. Graphic shows the design point for each mission during the and the design lifetime.

technology that is capable of performing the required 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 would build upon this foundation to confidently manage radiation concerns and balance their impacts across the system.

Understanding

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. In surviving many times its design dose through two extended missions, Galileo provided not only a superb radiation data set, but also information that has enabled modeling 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 electron, proton and heavy ion 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 validate averaging of cumulative effects 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 within this shadow, JEO would accumulate radiation effects at a substantially lower rate, on average, than would otherwise been suggested.

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 this confidence is significantly higher than for Juno where the local environment isn't as well characterized (there is little Galileo data inside 4 R_J where Juno will travel).

Two additional factors would determine the cumulative exposure ultimately experienced by spacecraft components. These are trajectory and shielding, both of which could 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 could 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 in hand, integrated with trajectory tools, we have the capability 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 models.

Overall then, there is very good reason to believe that uncertainty in the environment is a contained problem enabling a systematic engineering approach that balances trajectory and shielding sensitivities.

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 Department of 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 require for a mission such as JEO, that could not be addressed by alternate means. . Work is ongoing to develop and issue an Approved Parts and Materials List (APML) and worst-case database (WCDB) to facilitate early development work on JEO using these hard parts.

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, and allowing for 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.. There is one FPGA currently approved and appearing on the JEO APML, with others under consideration for approval.

Options also exist for mass storage, with a mixed strategy envisioned at the present that would use standard technologies, for the science tour phase, until radiation dose had accumulated past their capability, while more hardened but less dense alternatives serviced the latter part of the mission at Europa. 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 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, using suitable mitigations. This characterization and assessment continues.

Accompanying these developments have been similar strides in understanding the physical phenomena of radiation effects effects in parts based on silicon and other emerging semiconductor materials.. 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, annealing and single event susceptibility. This 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, instead of establishing 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 for 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.

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 and 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 success, 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, etc.

Understanding and Evaluating

The Jet Propulsion Laboratory (JPL) and the Applied Physics Laboratory (APL) 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 would 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 for 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 APL to confront remaining development and operational risks as early as possible prior to Phase A development.

The objectives of this plan were 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].

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 which could fly on JEO begins in earnest, and validation data for refined analysis techniques is gathered.

Also included in the plan were 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 would require 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 the concurrent engineering process that would be followed on JEO depends on excellent communication across all parts of the engineering and management team. System modeling and analysis activities would ensure the timely flow of up-to-date design 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 could 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 the proposed JEO mission.

Design guidelines are also being developed as part of risk mitigation activities. Already, 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). Electronic parts on the APML are verified for applicability above 300 krad, and all would meet the applicable reliability, quality, and radiation requirements specified in JEO's Parts Program Requirements (PPR).

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" [8].

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.

Summary

The challenge associated with operating a spacecraft for long periods within the radiation belts of Jupiter is significant. The promise of incredible science is well worth the risk though, *when* the risk is identified and controlled. To be managed within reasonable resource limits, a system level engineering 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 in a committed, disciplined manner 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.

Acknowledgement

The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration and in conjunction with the JohnsHopkins University – Applied Physics Laboratory.

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