Modeling Science Objectives within a Probabilistic Risk Assessment

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SUMMARY AND CONCLUSIONS

The Radiation Belt Storm Probes (RBSP) mission is being designed to help us understand the Sun's influence on Earth and near-Earth space by studying the Earth's radiation belts on various scales of space and time. NASA has designated RBSP as a risk class C mission (Explanation of risk classifications for NASA payloads, can be found in NPR 8705.4, Appendix A). As a result, the pair of spacecraft (including the instrument suites) are designed to be largely single-string. However, there is a fair amount of functional redundancy implemented within the overlapping performance characteristics of the science payload. Various instruments' spectra provide surrogate measurements while others have inherent dependencies that need to be modeled across various phases of the mission. This paper discusses how the science objectives for full and partial mission success requirements are mapped in the Probabilistic Risk Assessment (PRA) to show a more accurate robust risk picture for the mission.

1. INTRODUCTION

Designing spacecraft missions is a complex task of balancing many objectives with constraints such as system reliability, performance, and cost. RBSP is a two-spacecraft mission. The two spacecraft (including their instrument payloads) are largely single-string designs. Despite the initial appearance that all instruments on both spacecraft must work for the entire mission, some functional and performance overlap is built in to the selection of the instruments to provide limited backup science capability. This paper examines the process of using reliability modeling techniques to show the value of this functional redundancy at the mission design level.

1.1 Mission Overview

The Radiation Belt Storm Probes mission is part of NASA's "Living with a Star" Program and is managed by Goddard Space Flight Center (GSFC). The primary scientific objectives of the RBSP mission are to investigate the following about populations of relativistic electrons and ions in the region known as the Radiation Belts: How they are formed; How they change in response to variable inputs of energy from the Sun.

Additionally, space weather data will be collected and broadcast nearly continuously during the mission. The RBSP mission uses two spacecraft which will be launched on a single launch vehicle into nearly identical orbits which have a low-inclination, are highly-elliptical, and have an apogee which is lower than geosynchronous orbit. The mission is designed to include a 60-day commissioning period followed by a 2-year science operations phase. The two RBSP spacecraft are nearly identical and are both primarily single-string. The RBSP spacecraft diagram is provided in Figure 1. (1)

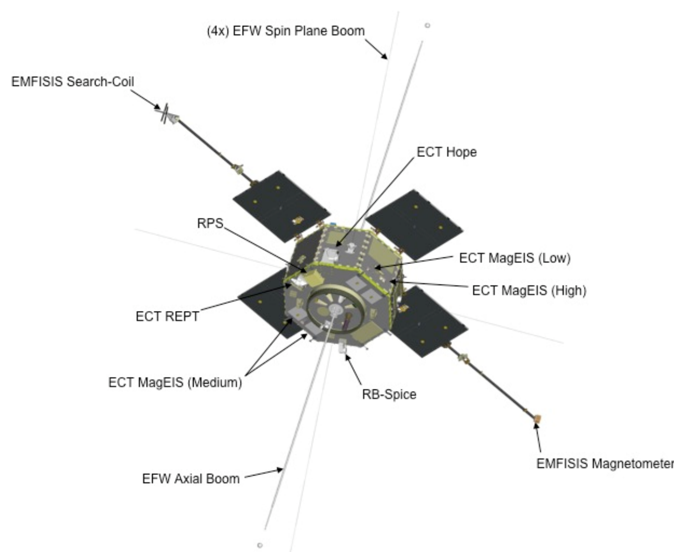

Figure 1: RBSP Spacecraft Diagram

1.2 Science Overview

The two spacecraft each fly five primary science instruments:

- *Energetic Particle Composition, and Thermal Plasma Investigation* (ECT). Directly measure the near-Earth space radiation particles to determine the physical processes that produce radiation enhancements and loss.

- *Electric and Magnetic Field Instrument Suite and Integrated Science Investigation* (EMFISIS). Understand the origin of plasma waves that energize space particles to radiation levels; measure the distortions to the Earth's magnetic field that control the structure of the planet's radiation belts.
- *Electric Fields and Waves Investigation* (EFW). Study electric fields in space that energize radiation particles and modify the structure of the inner magnetosphere.
- *Radiation Belt Science of Protons, Ion Composition, and Electrons Investigation* (RBSPICE). Determine how space weather creates what is called the "storm time ring current" around Earth and determine how that ring current supplies and supports the creation of radiation populations.
- *Proton Spectrometer Belt Research Investigation* (PSBR). Provide the Relativistic Proton Spectrometer (RPS) instrument as Government Furnished Equipment; measure high energy space radiation particles and compliments the energy ranges provided by the other science investigations.

The mission science objectives are to be achieved by obtaining the following particle, field, and wave measurements: high-energy electrons, medium-energy electrons, high-energy protons, medium-energy protons, medium-energy ion composition, low-energy ion/electron composition, 3-D magnetic field, 3-D wave magnetic field, 3-D wave electric field, 3-D electric field, and plasma density. Various combinations of these measurements, and the instrument(s) required to obtain them, are needed in order to meet the baseline and threshold science objectives.

The mission success criteria for RBSP are defined by NASA (2). To meet baseline mission success, the RBSP mission is required to take all science measurements on both spacecraft for one year, and all science measurements on at least one spacecraft for a second year (two years, in total). To meet threshold mission success, selected scientific measurements are required on both spacecraft for nine months and are required for all selected measurements on at least one spacecraft for an additional three months (one year, in total). These requirements are described in more detail in Table 1. The number ("0," "1," or "2") denotes whether or not the measurement is required, and if it must be obtained on one or both spacecraft. So, for example, in order to meet the baseline science objectives, all measurements must be obtained by both spacecraft. There are a total of seven ways to achieve threshold science. Not all of the science measurements are required for the various threshold science tracks; measurements that are not required are denoted by a "0."

The mapping of instruments to science measurements is provided in Table 2. Primary instruments must be used to obtain baseline science objectives; primary, secondary, or tertiary instruments may be used to obtain threshold science objectives.

Table 1: Baseline and Threshold Science Mission Success Criteria

Measurement	Baseline	Threshold						
		1		2		3	4	
High energy electrons	2	2^A		2^A		2^A	2	
Medium energy electrons	2	2		2		2	2	
High energy protons	2	0		0		1	1	
Medium energy protons	2	0		0		1	1	0
Medium energy ion composition	2	1	2	0	1	0	0	1
Low-energy ion/electron composition	2	1	0	1	0	0	0	
3-D magnetic field	2	2		2		2	2	
3-D wave magnetic field	2	0		1^B		0	1	
3-D wave electric field	2	1^C		1^B		1^C	1	
3-D electric field	2	1^D		1^D		1^C	2	
Plasma density	2	1		1		1	2	

[A] Either 1-4 MeV electrons or 3-10 MeV electrons are required to achieve Threshold Science
[B] High resolution wave form data are required to achieve Threshold Science
[C] 2D will suffice to achieve Threshold Science
[D] For Threshold Science, the third axis can be derived instead of directly measured

Table 2: Instrument-to-Science Measurement Mapping

Measurement	Primary Instrument	Secondary Instrument	Tertiary Instrument
High energy electrons	ECT/REPT (<2 – 10 MeV)	ECT/MagEIS-H (1-4 MeV)	
Medium energy electrons	ECT/MagEIS-M/L (40 keV - >4 MeV)	RBSPICE (30 keV – 1 MeV)	
High energy protons	ECT/REPT (<20 - >75 MeV)	RPS (50 MeV - 2 GeV)	
Medium energy protons	RBSPICE (7 keV – 5 MeV)	ECT/MagEIS-H (0.1 – 1 MeV)	
Medium energy ion composition	RBSPICE (20 –300 keV)	ECT/MagEIS (65-350keV - total ions)	ECT/HOPE (50 eV-50 keV)
Low energy ion/electron composition	ECT/HOPE (50 eV-50 keV)	RBSPICE (20-300 keV)	
3-D magnetic field	EMFISIS/MAG (DC – 10 Hz)	ECT (reconstruct mag field direction "per spin"): MagEIS azimuthal, HOPE (or RBSPICE) polar If we have E, we can use Vdrift from HOPE to estimate Bmag From measurement of direction, we have 1st order correction to magnetic field model and can estimate Btotal	EFW could provide full 3D measurement (less accuracy) PSD and direction if EMFISIS/MEB fails
3-D wave magnetic field	EMFISIS/WAVES (10 Hz – 10 kHz)	EFW (10 Hz – 12 kHz)	
3-D wave electric field	EMFISIS/WAVES (10 Hz – 10 kHz)	EFW (1 Hz – 6 kHz)	
3-D electric field	EFW (DC – 10 Hz)	ECT/HOPE (vxB)	
Plasma density	EMFISIS/WAVES	EFW	ECT/HOPE

2. *MODELING EFFORT*

The information in these tables was the basis of the reliability model, which was implemented in SAPHIRE version 6.75. (3) The modeling effort was accomplished with the development of a mission-level PRA. This PRA included both spacecraft and their instruments, and all of the mission success criteria. This section shows the progression of the modeling effort.

The initial RBSP PRA was very limited in scope. It represented only the baseline mission success criteria (no thresholds), included only the operational phase of the mission (no launch, deployments, or check-outs), and included only the two spacecraft busses (there were interfaces to the instruments, but not the instruments themselves).

By the mission's preliminary design review (PDR), the RBSP PRA represented both the baseline and the threshold mission success criteria in a generic fashion. Two SAPHIRE "projects" were created (one for the baseline mission success criteria and one for the threshold criteria). The two spacecraft were modeled to the board level and the instruments were included as single basic events. Two "projects" were created to enable the same model (and specifically the same basic events) to be used over different time periods.

At the mission's critical design review (CDR), the PRA modeled both the baseline and the various threshold mission success criteria using five separate SAPHIRE "projects" (again, to allow the use of the same basic events for varying time periods):

Deployment/Check-out (DC)
Baseline, year 1 (B1)
Baseline, year 2 (B2)
Threshold, first 9 months (T9)
Threshold, final 3 months (T3)

These models were connected mathematically (shown in Figure 2 below), but, as with the PDR model, the actual failures did not propagate from one project to the next. In the DC project, the failure of both spacecraft to separate from the launch vehicle (or each other) or the failure of certain deployments resulted in an immediate "Loss of Mission" (LOM) end state. If all separations and deployments occurred successfully, then an end state of "Baseline-Yr1" was reached. This probability was used as the initiating event probability for the sole event tree in the B1 project. If both spacecraft and science objectives were met for a year, then an end state of "Baseline-Yr2" was reached. This probability was then used as the initiating event probability for the B2 project's sole event tree. If a failure occurred which resulted in not being able to reach the second year of the baseline mission success criteria, then the end state "Not-Baseline" was reached. All of the "Not-Baseline" probabilities were summed, with the total probability of "Not-Baseline" being used as the initiating event probability for each of the T9 project event trees (one for each threshold criteria, seven total). Once the mission passed successfully into its second year, all "Threshold" criteria have been met, so the B2 project never results in a LOM end state. The only end states resulting from the B2 project are "OK" (meaning that there has been complete mission success for the entirety of the two years) and "Generic-Threshold" (this means that baseline mission success objectives were not achieved, but the mission was successful for longer than any of the threshold criteria require).

Once there has been a failure which results in the baseline success criteria not being met during the first year, the mission is now only capable of meeting the threshold criteria. As mentioned above, the "Not-Baseline" end state probabilities were summed and used as the initiating event probability for the T9 Project event trees. It was not possible to account for when the failure occurred during the first year, so the conservative assumption was made that all failures occurred on day 1 of the B1 project. Therefore, the mission time for the T9 model was 9 months, rather than varying based on when the initial failure (which resulted in the "Not-Baseline" end state in the B1 project) occurred.

The two threshold projects each contained seven event trees, one for each set of threshold criteria. Each event tree asked if the two spacecraft busses operated successfully for the time period, then asked if the particular threshold success criteria were met. The resulting probability of meeting the threshold success criteria for 9 months was then used as the initiating event probability for the appropriate event tree in the T3 project (e.g., the "Thresh-1A-3mo" end state probability from the T9 project was used as the initiating event probability in the Threshold 1A event tree in the T3 project). If the threshold criteria were not met in the T9 project, then the LOM end state was reached.

Similarly in the T3 project, each event tree asked about the two spacecraft busses, then asked if the threshold criteria were met. If they were met, then an end state of "Thresh-X" was reached. This was the probability of achieving that set of threshold criteria. If the criteria were not met, then LOM was reached.

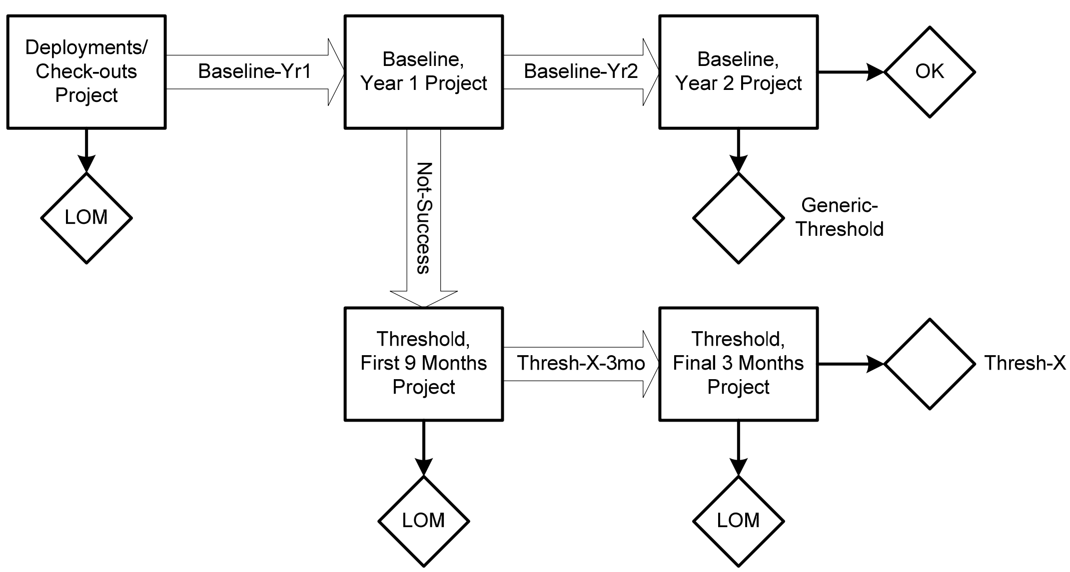

Figure 2: SAPHIRE Project Relationships

If summed together, all of the final end states from all of the projects (not the transitional end states which were used as initiating events in another project) equaled to 1. The probability of meeting baseline mission success criteria for two years was equal to the "OK" end state probability, and the probability of meeting or surpassing a set of threshold criteria was the sum of the "Gen-Threshold" end state probabilities and the various individual "Thresh-X" end state probabilities.

2.1 Discussion of Modeling Issues

The RBSP mission involved two spacecraft, with multiple paths toward "minimum" success that changed with time. This, combined with modeling software limitations, made for an extremely complex model which still did not completely and accurately reflect the probability of mission success.

Most of the PRA modeling software available is designed for modeling a static system – one that does not change with time. Most spacecraft missions are dynamic – probes are ejected, appendages are deployed, and mission success criteria change with time, among other considerations. Unfortunately, dynamic changes are difficult to capture accurately in a static setting. This is similar to the difficulty of communicating a 3D image in a 2D format – there are ways to approximate 3D into 2D, but it is far from a perfect rendering. Some software exists which can simulate a dynamic system (e.g. GoldSim (www.goldsim.com)), but its use in a reliability setting is still in its infancy while also being cost-prohibitive for this project.

To model this dynamic mission in a static setting as accurately as possible, several obstacles had to be overcome. There needed to be a way to separate the various success criteria (baseline and threshold). However, since these involved different time periods, there was no way to include them in a single SAPHIRE project while still using the same basic event in each "phase." Duplicating basic events and fault trees for differing time periods would be unwieldy. Splitting baseline and threshold into two projects wasn't sufficient, as the mission success criteria (even within baseline or threshold) changed with time. So they were split again (B1, B2, T9, and T3), with the deployments and checkouts project added to the beginning in order to capture the entire mission.

While splitting the model up into different projects solved the problem of using the same basic events over different time periods with different success criteria, it added three problems: there was no way to determine when a failure had occurred during the B1 project, specific component failures could not be carried over from one project to the next, and individual component probabilities of failure over time were cut into small pieces instead of accurately reflecting the entirety of the mission time. Each of these issues had the potential of "double counting" failures, making the final probability of mission failure to be an extremely conservative upper bound estimate of the actual probability of mission failure. Additionally, the number of different mission success criteria alone made modeling difficult.

2.1.1 Failure Timing

There was no way to know when the failure occurred in the B1 project which caused it to reach the "Not-Baseline" end state. It could have occurred on Day 1, it could have occurred after six months, or it could have occurred on Day 364. If the modeler assumes that it occurred on Day 1, then there is little-to-no overlap between the B1 project and the T9 project. Assuming that it occurs during month six of the mission adds overlap, as the "mission time" clock resets to 0 when the T9 project begins. Assuming a failure on Day 364 of the B1 project (or any day after nine months has elapsed) really shouldn't be included in the initiating event probability for the T9 project as the T9 success criteria are only valid for the first nine months of the operational phase of the mission.

2.1.2 Carrying Over Failures

In reality, a failure which occurs during the DC phase of the mission (whether it causes LOM or not) would still exist in a later phase of the mission. By separating the mission into several projects, this information is lost. To a certain extent, it is accounted for in the initiating event probability (essentially a conditional probability) which is determined by the previous phase's end states, but the exact failure is not (and cannot be) carried over.

Some analysts account for this by including separate phases in a single project, adding different events for each mission phase, as seen in Figure 3 below. In phase I, one can simply ask if component A AND component B fail. In phase II, one must ask first if component A (or B) failed during phase I, THEN if it failed during phase II (continuing on for subsequent phases). This accurately captures failures in each phase, but increases fault tree size and complexity significantly. Since the fault trees were already large and complex, this methodology was not utilized.

2.1.3 Component Age

The final modeling issue was that the component failure rates weren't calculated over the entire mission time, but rather over smaller mission subsets (i.e., 60 days for the DC project, one year for the B1 and B2 projects, 9 months for the T9 project, and 3 months for the T3 project). Effectively, this makes the components seem "younger" in the later projects. This could have been alleviated to some extent by "aging" the components in the later projects through Bayesian updating of the component failure rates.

2.2 Science Issues

Accurately modeling eight different mission success criteria (baseline and seven threshold) was difficult. Initially, an attempt was made to model the criteria based on the various scientific measurements that were being taken (i.e., magnetic field measurements, electric wave measurements, etc.). Given that there were 11 distinct scientific measurements being taken, any of which could fail, this quickly became unwieldy (the permutations equaling to 2^{11} or 2048).

In the end, the two baseline projects looked at the scientific measurements (since failure of any instrument would send the mission into the threshold success criteria arena, the various permutations were not relevant). The two threshold projects, however, asked in separate event trees whether the individual threshold success criteria were met. This increased the number of event trees, but greatly reduced their complexity.

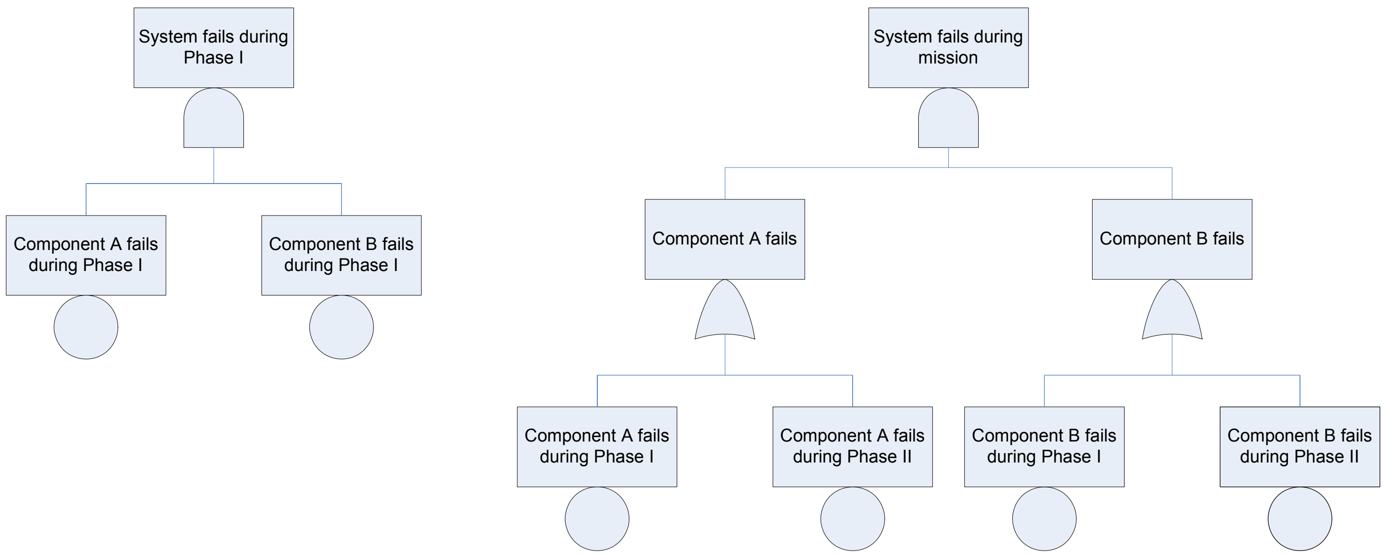

Figure 3: One Method for Capturing Failures in Various Mission Phases

3. CONCLUSIONS AND RECOMMENDATIONS

This paper has discussed how the PRA was used to model the baseline and threshold mission success requirements to provide a more robust and accurate picture of the mission risk while highlighting the difficulties encountered with using the existing tools to model the dependencies and phase issues. Despite the modeling issues, the PRA was used both to assist and validate the instrument-to-science measurement mapping, and to make the case for a mission with a single-string spacecraft and instrument architecture by showing improved mission reliability numbers due to instrument functional redundancy. The experiences with modeling the RBSP mission also emphasize the importance of understanding tool limitations and the need for more dynamic modeling tools.

For future missions the process of laying out the instrument dependencies and overlapping capability will play a vital role in generating the specifications early in the mission design phase. Incorporating this as functional redundancy for science return is value we can add to the process of improving the mission robustness.

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