Optimization of Debris Shields on the NISAR Mission's L-Band Radar Instrument

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ABSTRACT

The NASA-ISRO Synthetic Aperture Radar (NISAR) space mission is a collaboration between NASA and the Indian Space Research Organization (ISRO), launching in the 2020s to a polar orbit of 747km altitude. The mission will provide spatial and temporal measurements of land surface changes (e.g. ice sheets, vegetation, earthquakes). Many of the SAR electronics boxes are mounted on the exterior of the structure. Their single-wall box lids efficiently radiate heat for thermal control, but are not very efficient debris shields. The initial design showed an unacceptably high impact risk as estimated with NASA's ORDEM3 debris model and Bumper impact analysis tool. Each box has a different role in instrument functionality, and this was captured in a reliability model used to optimize the distribution of shield mass among the boxes: total added mass was minimized while maintaining a threshold of functionality and survival probability that was acceptable to the project.

1 INTRODUCTION

The NASA-ISRO Synthetic Aperture Radar (NISAR) space mission is a collaboration between NASA and the Indian Space Research Organization (ISRO). Work is underway on the spacecraft and its SAR science payload, for a launch in the early 2020s to a polar Earth orbit of about 747km altitude. The mission will provide spatial and temporal measurements of land surface changes having high societal impact, such as ground displacement (earthquakes, landslides, ground subsidence) and changes in ice sheets and land vegetation. Many of the L-band SAR electronics boxes are mounted on the exterior of the spacecraft for thermal control and for lack of volume within the structure. The box lids function well as radiators, but are not very efficient debris shields. Unfortunately, a more-efficient double-wall debris shield would impede the transport of heat out of the boxes. Two sets of identical electronics on opposite sides of the spacecraft provide vertical- or horizontal-polarization radar measurements. Different combinations of transmitted and received polarizations are used for different types of measurements. The data acquisition modes are such that one set of boxes will always be facing into the velocity direction, where it will be exposed to near-head-on impacts by space debris at speeds of about 15km/s.

The impact risk was estimated using NASA's ORDEM 3.0 debris model (excluding the high-density particle population) and Bumper impact analysis tool. Debris impact estimates for the initial L-band radar design showed an unacceptably high probability that the science instrument would not survive to complete even a minimally acceptable science campaign. Mitigation of this risk presented several challenges. The design had to be modified to increase the chance of impact survival without compromising the thermal requirements and it had to be done within a tolerable allocation of mass. The various electronics boxes all play a role in science data acquisition, but some boxes play a more critical role than others. These differences were captured in a reliability model reflecting the minimum hardware and the minimum acquisition time required to meet the threshold of acceptable science acquisition. This model evaluated a database consisting of box survival probabilities as a function of shield thicknesses, to determine an optimal apportionment of shield mass to the various boxes. After increasing the shield-mass allocation to achieve acceptable reliability, and after optimization of the distribution of this shield mass among the box lids, the number of damaging hits during the full duration of the mission dropped from about 15 for the initial (baseline) design to about 2 hits in the optimized design. Although the analysis predicts that NISAR is likely to lose the use of two boxes over the course of its 3.25-year mission, it will still have a 95% probability of achieving the minimum acceptable threshold of science data return. In contrast, the baseline design had only a 4% chance of achieving the threshold science return.

2 ELECTRONICS BOX SURVIVAL

2.1 Observatory Structure and Orbit Attitude

The NISAR observatory consists of a spacecraft bus to which are mounted solar arrays, a Radar Instrument Structure (RIS), and a boom-deployed reflector. The observatory body and solar arrays are shown in Fig. 1. Initial calculations of impact risk to NISAR instrument electronics showed that the risk was dominated by the

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external electronics boxes of the L-band electronics, which are:

TRM (Transmit/Receive Module), Qty. 12 per side.
qFSP (quad First Stage Processor), Qty. 3 per side.
SSP (Second Stage Processor), Qty. 1 per side.
DSPPCU (Digital Signal Processor Power Conditioning Unit), Qty. 1 per side.

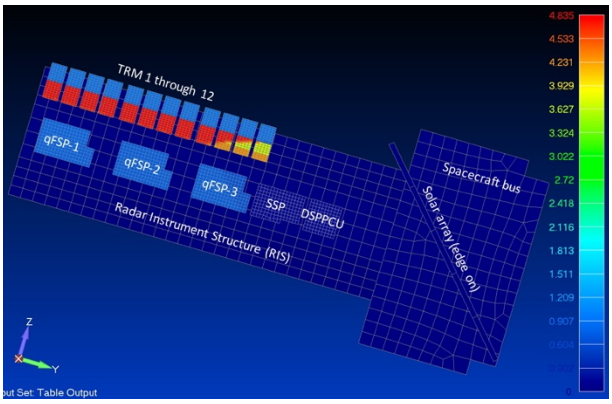

Figure 1. Main body of the NISAR observatory (boom and reflector not shown), with color contour plot of perforating impacts to the external L-band electronics. See text for details.

This set of boxes, seen in Fig. 1, works together to provide the necessary transmit and receive functionality of the L-band radar. An identical second set of boxes, arranged in essentially a mirror image of the first, occupies the opposite side of the RIS. Fig. 2 shows an isometric view of a portion of the end of the RIS, including some of the TRMs and qFSPs and a partial view of the octagonal cross section of the RIS.

The observatory flies such that one set of boxes is facing into the velocity direction (a.k.a. the ram direction or ram side), and the other set is on the opposite, wake side. In Fig. 1, the observatory velocity is along the (+)X axis, pointing out of the page, and the nadir direction is straight down. This orientation, in which the RIS is canted 16.3° up from horizontal and pointed to starboard, is called the "right-looking" science acquisition attitude. A spacecraft rotation of 180° around the nadir-pointing vector puts the instrument in the "left-looking" attitude. The instrument will always be in one or the other of these two attitudes, but the science team has not yet determined the fraction of time spent in each. NASA's "Bumper" impact risk analysis code [1] was used to estimate the expected number of perforations of the single-wall box lids in the NISAR debris environment. Bumper uses a finite element mesh of the observatory as its input. This model can be rotated into the proper flight orientation and exposed to the debris environment at NISAR's orbit. The mesh elements that represent the external electronics box surfaces are assigned a specific type of shield geometry, which in this case is a single wall of aluminum 7075-T651 (excepting portions of the TRMs that are Al 6061). Elements representing the rest of the observatory are assigned as shadowing material, meaning that those elements are assumed to stop any debris. For example, the gradation of impacts to some TRM boxes in Fig. 1 is a result of shadowing by the solar array.

2.2 Electronics Box Failure Criterion

Impact damage is typically quantified through the use of a Ballistic Limit Equation (BLE), an equation that relates impactor and target configurations and conditions to a given level of damage. Quantification of the possibility of impact-induced failure of all the individual components inside each electronics box would be exceedingly complex and time-consuming, so instead, the onset of box wall perforation is equated with functional failure of the electronics within the box. The equivalence is obviously not exact, in that a perforation could occur and yet not damage the electronics within, or an impact could dislodge a spall fragment into the box and cause damage without there being an actual perforation of the wall. The assumption that all spall causes failure was considered to be an excessively conservative bound on the impact risk. Support for this assertion is found in a series of impact tests on functioning electronics boxes by Putzar et al. (summarized in Tab. 4 of that paper) [2], in which no failures from spall were noted. In addition, most of the tests resulting in smaller-diameter perforations also did not cause functional failures. Thus, box perforation was chosen as the proxy for functional failure of the box electronics, and is considered to yield a moderately conservative result.

The top surface of each of the qFSP, SSP, and DSPPCU boxes, and of a portion of the top of each TRM, is a lid of aluminum that serves as a passive radiator that removes heat from the box. The need for heat rejection precludes the use of a double-wall shield geometry to protect against debris impacts. To identify the conditions under which perforation occurs, the BLE known as the Cour-Palais single-wall equation was used [3]. It delineates either the onset of detached spall or the onset of perforation, depending on the chosen value of a scaling constant applied to the box wall thickness in the BLE. For perforation, a penetration depth into the wall must be $t/1.8$, or slightly more than half the wall thickness t. At this depth, the impact crater meets the bottom of the spall crater, resulting in a through-hole.

2.3 Impact Analysis

The boxes, including lids, were initially all to be made of aluminum 6061-T6, but the lid material was changed to Al 7075-T651 for most of the lids because the 7075 material's higher hardness provides a better debris shield for essentially the same amount of mass. (Material properties provided to Bumper code are Density = 0.102 lb/in^3, Speed of Sound = 16500 ft/s, Brinnell Hardness Number = 150.) The use of an Aluminum/Beryllium (Al/Be) alloy, which is harder and stronger than aluminum, was also investigated. Bumper runs with Al/Be lids showed a considerable reduction in the number of perforations for a given shield mass. However, the single-wall ballistic limit equation was empirically derived from tests on aluminum walls, and the equation's applicability to Al/Be could not be established. Al/Be was therefore dropped as a shield option.

The impact analyses considered impacts only to the lids of the boxes. Impacts to the qFSPs, SSP, and DSPPCU occur almost exclusively on the lid, because the sides are essentially parallel to the direction of the incoming debris (so any impact on the sides is just a glancing blow). On the TRMs there is one side that is facing into the debris stream at a 45^{o} angle (because the TRMs are mounted on the +X/+Z octagon face of the RIS). This side is the shadowed surface at the bottom of each TRM module in Fig. 2, facing roughly in the direction of the qFSPs. Perforation-induced failure of this side was deemed unlikely because of the internal construction and because there are several connectors on this surface. (The connectors themselves were not evaluated for impact-induced failure.) For the top TRM surface, only the portion having a single wall was evaluated for impacts (HPA and ESS sections in Fig. 2). The portion with a double-wall and few components beneath it (FES in Fig. 2) was not evaluated. The HPA segment of the TRM was originally designed with a lid of 0.200" Al 6061, and this was retained in the final design. Only for the ESS portion of the TRM module was the lid thickness included in the optimization process, which resulted in a design change from 0.060" Al 6061 to 0.100" Al 7075.

2.4 Box Failure Probability: Debris and Meteoroid Impacts to the Ram and Wake Sides

Bumper provides a separate perforation estimate for each box, for the specified environment. The NISAR environment spec is derived from the current NASA debris environment model, ORDEM 3.0 [4,5], but the high density (HD) debris population of ORDEM 3.0 has been removed because of questions concerning its validity in the region of NISAR's orbit [6]. (We should note that the NASA Orbital Debris Program Office does not condone this or any other alteration of the model.) Risk results were derived using this environment specification. To provide a comparison of risk levels with other current NASA missions and with missions evaluated under the full ORDEM3 model and the older ORDEM2 environment, Tab. 1 shows perforations of individual boxes having 1mm or 2mm lid thicknesses, for the different environments. Conditions are for a full 3.25-year mission in which the electronics face into the ram direction.

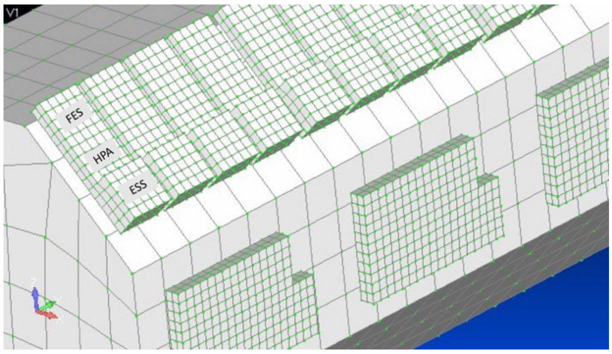

Figure 2. Detail of the Mesh Representing the TRMs and qFSPs.

The color contour plot in Fig. 1 shows perforating impacts to the external L-band electronics at the optimal wall thickness configuration described below. Impact values are in units of impacts per m^2; e.g. in a yellow area one would expect on average to experience about 3.9 perforations/m^2 over the 3.25-year mission, for the ORDEM3 model excluding HD particles. The total area of single-wall surfaces is 1.3 m^2. The analysis yields an estimate of 2 damaging hits for the mission design environment (no HD).

Orbital debris is generally more likely to approach a spacecraft from the forward-facing hemisphere, and this is particularly true in NISAR's orbit. Almost all the debris is traveling in nearly the opposite direction from NISAR (resulting in head-on collisions). For the optimal shield design, there are very few perforating debris impacts to the wake side of the observatory. This is seen in Tab. 2, which also indicates that the risk from meteoroids [7] is negligible in comparison to the risk from ram-side debris. For this reason, the shield optimization analysis only considered the threat from ram-side debris.

The expected number N of each box's perforations for a 27-month mission (for threshold science) was obtained by scaling the Bumper results for the 3.25-year mission linearly with time. It is assumed that the chance of MMOD impacts is constant over the time interval of the mission (which is approximately true) and that impacts are mutually independent, so an exponential probability distribution exp(-N) is justified. Note that the perforation count N for each box is a function of the debris model and box lid thickness. The database of N for different thicknesses for each box was interpolated with a spline to use in the optimization analysis. Fig. 3

shows an example of reliability (i.e. the survival probability) for a DSPPCU for 27 months.

Table 1. Perforations vs. Lid thickness of Boxes on Ram Side, for 3.25yr NISAR mission; Different Debris Models; Aluminum 7075-T651 lids

	\ Lid Thickness					
	1 mm (0.040”)			2 mm (0.080”)		
Component	**ORDEM3**	**ORDEM3 no HD**	**ORDEM2**	**ORDEM3**	**ORDEM3 no HD**	**ORDEM2**
TRM1	3.59E+00	1.11E+00	3.92E-01	9.24E-01	1.94E-01	5.50E-02
TRM2	3.59E+00	1.11E+00	3.92E-01	9.24E-01	1.94E-01	5.50E-02
TRM3	3.59E+00	1.11E+00	3.92E-01	9.24E-01	1.94E-01	5.50E-02
TRM4	3.59E+00	1.11E+00	3.92E-01	9.24E-01	1.94E-01	5.50E-02
TRM5	3.59E+00	1.11E+00	3.92E-01	9.24E-01	1.94E-01	5.50E-02
TRM6	3.59E+00	1.11E+00	3.92E-01	9.24E-01	1.94E-01	5.50E-02
TRM7	3.59E+00	1.11E+00	3.92E-01	9.24E-01	1.94E-01	5.50E-02
TRM8	3.59E+00	1.11E+00	3.92E-01	9.24E-01	1.94E-01	5.50E-02
TRM9	3.59E+00	1.11E+00	3.92E-01	9.24E-01	1.94E-01	5.50E-02
TRM10	3.52E+00	1.09E+00	3.78E-01	9.05E-01	1.90E-01	5.29E-02
TRM11	3.10E+00	9.64E-01	2.91E-01	7.92E-01	1.68E-01	3.99E-02
TRM12	2.77E+00	8.64E-01	2.21E-01	7.06E-01	1.51E-01	2.93E-02
qFSP1	5.88E+01	2.17E+01	5.97E+00	1.46E+01	3.45E+00	9.21E-01
qFSP2	5.52E+01	2.05E+01	5.01E+00	1.37E+01	3.26E+00	7.70E-01
qFSP3	5.34E+01	1.98E+01	4.88E+00	1.32E+01	3.14E+00	7.48E-01
SSP	4.00E+01	1.48E+01	3.89E+00	9.88E+00	2.36E+00	5.92E-01
DSPPCU	2.73E+01	1.01E+01	2.66E+00	6.75E+00	1.60E+00	4.01E-01

Table 2. Perforations of NISAR electronics with optimal shields, evaluated with ORDEM3-without-HD and MEM (MM) environment models; 3.25-year mission

BOX	**Material**	**Thick-ness (mils)**	**area (m^2)**	**Ram OD HITS w/OUT steel**	**Wake OD HITS w/OUT steel**	**Ram MM HITS**	**Wake MM HITS**
TRM HPA (average)	6061-T6	200	0.0235	1.73E-02	3.19E-08	6.98E-05	1.00E-05
TRM ESS (average)	7075-T651	100	0.0225	1.06E-01	1.18E-07	4.38E-04	6.17E-05
qFSP (average)	7075-T651	230	0.1674	1.27E-01	2.48E-08	2.44E-04	3.68E-05
SSP	7075-T651	300	0.1358	2.13E-02	1.08E-08	6.43E-05	1.04E-05
DSPPCU	7075-T651	300	0.0921	1.44E-02	6.80E-09	4.05E-05	6.78E-06
Total				1.89E+00	1.89E-06	6.93E-03	9.88E-04

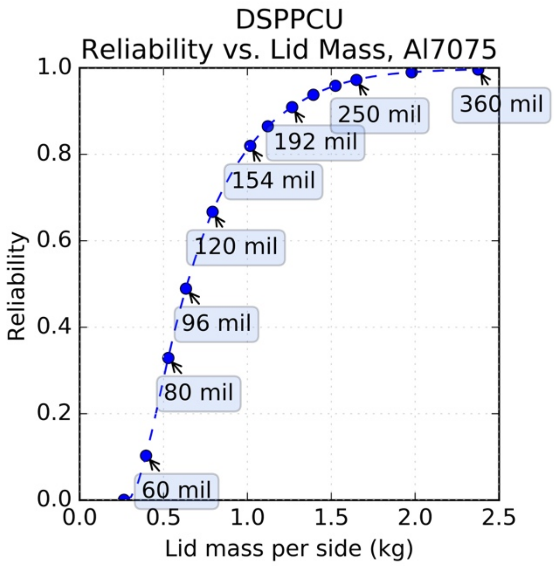

Figure 3. Reliability (probability of survival) vs. mass for DSPPCU for different lid thicknesses. (1000mil =25.4mm)

3 Shield Optimization for Threshold Science Mission Success

3.1 Design Optimization

A reliability model of the SAR instrument's MMOD impact survival probability, quantified in terms of the boxes' survival likelihood, was used to determine how best to distribute shielding to meet the requirement of at least a 95% probability of achieving the threshold science mission. This optimization is needed because the instrument has multiple modes of operation, and because the various boxes contribute in different amounts to the acquisition of data. For example, at least one SSP and DSPPCU are critical for all operating modes, so these boxes need to receive more shielding than the TRMs, each one of which produces 1/12th of the signal from the ground swath being mapped. Simply increasing the thickness of all lids by the same amount would not be an efficient use of mass. A block diagram showing signal and power interconnections is shown in Fig. 4. The reliability model was implemented in a computer script optimization algorithm to determine optimal thickness for each box lid such that the probability requirement for the threshold science mission is met, using the least additional shield mass.

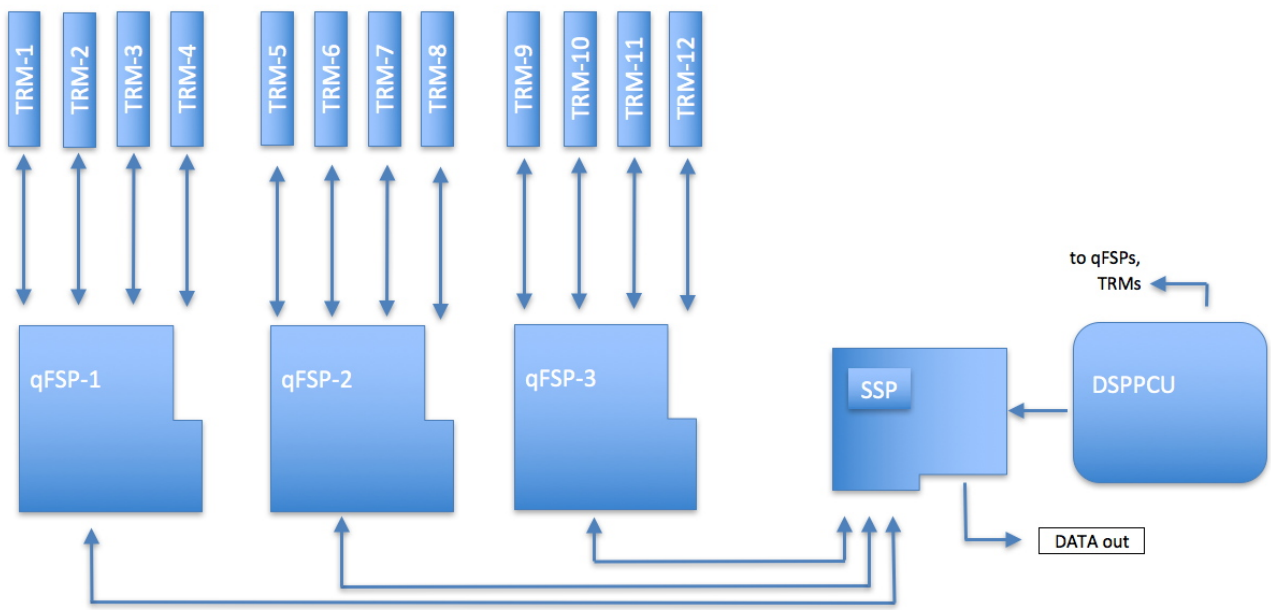

Figure 4. L-Band SAR Block Diagram showing signal and power interconnections.

Further optimization was then done to improve the probability of a more extensive science return. The spline fits to values of box perforation vs. lid thickness (a sample of which is shown in Tab. 1) were used as input to the optimization calculation. The resulting optimized lid thicknesses are shown in Tab. 3. The damaging hits to each box from MMOD are given in Tab. 2. A description of the optimization process follows.

Table 3. Design Results for Box Lids

Box	Baseline Lid Thickness, Al 6061 (mil)	Threshold Science Optimum, Al 7075-T651 (mil)	Dual Pol. Mission, Al 7075-T651 (mil)
DSPPCU	125	301.6	300
SSP	125	120	**300**
TRM (ESS)	60	106.1	100
qFSP	125	224.2	230
Mass (kg)	0	12.2	14.9
Prob. threshold science	4%	95%	95%
Prob. dual pol receiving	2%	54%	94%

3.2 Success Criteria and Probabilities

The lid thicknesses were chosen with respect to two probabilities: (1) probability of threshold science success and (2) probability of survival of the dual polarization receiving mode during the threshold mission. Lid thicknesses of each component type were first numerically optimized to reach a 95% probability of threshold science for a minimal amount of additional mass. This optimized solution was then adjusted to ensure adequate survival probability of the dual polarization ("dual-pol.") receiving mode.

3.3 Threshold Science

Threshold science success criteria are as follows:

- *Duration*: 3 months of post-launch commissioning activities followed by 24 months of science observations (27 months total)
- *Coverage*: For loss of up to four TRMs (loss of one third of mapping swath), global coverage can be maintained by changing from a 12-day to an 18-day repeat orbit.
- *Science Targets*: All.

Translating these criteria in terms of electronics box survival, threshold science requires:

- Both DSP-PCUs *and*
- Either of the two SSPs *and*
- At least 2 of 3 ram-side qFSPs *and*
- At least 9 of 12 ram-side TRMs *and*
- All wake side qFSPs and TRMs

Some simplification and engineering judgment were used to put these criteria into a probability equation. For example, the survival of sciences from sets of four TRMs depend on individual qFSPs, but this detailed dependency is not part of the survival criteria. Also, particular number criteria such as "9 of 12 TRMs" are from expert judgment rather than from detailed mission analyses that the Project could not afford to spend time on. Because the success criteria are partly formed of human judgment, the mathematical probability models to calculate them are also simplified to an appropriate level. They do not capture all event combinations that may conceivably lead to threshold science failure but do capture many of the main effects. Further assumptions were made in order to simplify computation. First, average penetration rates were used for TRMs and for qFPSs on a given side (ram/wake). For example, rather than using twelve slightly different penetration rates for TRM #1 through #12 on the ram side, the average penetration rate was used for each ram side TRM. Second, it was assumed there is no need to explicitly model the flip of the spacecraft between right-looking and left-looking attitudes, which will be determined from the choice of science targets. This simplification is reasonable on the one hand because a common lid thickness is used for all boxes of a type, regardless of observatory side. On the other hand, the simplification does not account for the possibility that the two corresponding boxes on opposite sides are both damaged while successively occupying the same position. For example, suppose TRM #7 on the ram direction fails during the mission. After a yaw flip, the corresponding TRM #7 on the opposite side also fails in the ram position. This situation is not captured by the present model; only the first failure in a particular position (e.g. "ram side TRM #7") is modeled. The chances of two opposite boxes failing while occupying the same position is the product of their individual failure probabilities – typically a small number. Such effects are neglected in the probability model. Although a much more detailed probability model could be used, such complexity was not justified given the uncertainty and human judgment in setting success criteria.

With P(A) indicating the probability of survival of box (A), the probability of achieving threshold science is given by Eq. 1.

$$P(\text{threshold mission}) =$$
$$P(\text{DSP-PCU}_{\text{ram}}) \cdot P(\text{DSP-PCU}_{\text{wake}}) \cdot$$
$$[1-(1-P(\text{SSP}_{\text{ram}}))\cdot(1-P(\text{SSP}_{\text{wake}}))]\cdot$$
$$\sum_{k=2}^{3}\binom{3}{k}\cdot P(\text{qFSP}_{\text{ram}})^k\cdot(1-P(\text{qFSP}_{\text{ram}}))^{3-k}\cdot$$
$$\sum_{k=9}^{12}\binom{12}{k}\cdot P(\text{TRM}_{\text{ram}})^k\cdot(1-P(\text{TRM}_{\text{ram}}))^{12-k}\cdot$$
$$P(\text{qFSP}_{\text{wake}})^3\cdot P(\text{TRM}_{\text{wake}})^{12} \quad (1)$$
where
$$\binom{n}{k}=\frac{n!}{k!(n-k)!}$$

The computer script implementation of this probability could be set to maximize survival for a given shield mass, or minimize shield mass for a given survival probability. The optimization solution for different delta (Δ) mass budgets is shown in Fig. 5.

Optimization was constrained by requiring that all instances of a given component type will have the same lid thickness. For example, the SSP on the wake side will have the same thickness as the SPP on the ram side, even though the ram side sees a much higher debris fluence. This was done to avoid having two versions of a given component (which would require two iterations of various analyses and tests), and because the required mass balance of the spacecraft could more easily be maintained. It also acknowledges that the time history of the spacecraft attitude has not yet been planned.

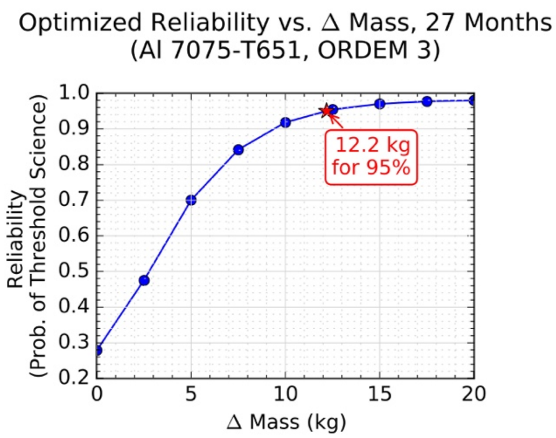

Figure 5. Reliability for Different Mass Budgets

3.4 Dual Polarization Receiving Mode

Note that threshold science requires either dual pol. transmit or dual pol. receive mode. Dual pol. transmission requires only one of the SSPs to survive, whereas dual pol. receiving requires the use of both SSPs. Dual pol. receiving is desirable for its scientific value if it can be ensured for a reasonable mass cost, so a second case was evaluated:

- Both DSP-PCUs *and*
- ***Both SSPs*** *and*
- At least 2 of 3 ram-side qFSPs *and*
- At least 9 of 12 ram-side TRMs *and*
- All wake side FSPs and TRMs

The probability equation for this dual pol. science return is similar to Eq. 1, with modification to the terms involving the SSP:

P(dual pol. Receive) =
P(threshold mission) * $[P(\text{SSP}_{\text{ram}})* P(\text{SSP}_{\text{wake}})]$
$/ [[1 – (1 - P(\text{SSP}_{\text{ram}}))] * [1 – (1 - P(\text{SSP}_{\text{wake}}))]\}$ (2)

This equation yields a probability of only 54% for lid thicknesses optimized only for threshold science. By taking the additional step of thickening the lids of both the ram- and wake-facing SSP lids from 0.120” (3mm) to 0.300” (7.6mm), which adds about 3.5kg, the chance of maintaining a dual pol. receiving capability increases to 94% for the 27-month mission. Tab. 3 shows a comparison of probabilities for the baseline design, the optimized solution for threshold science criteria, and for SSPs thickened to ensure a functional dual polarization receiving mode. Other lid thicknesses were rounded slightly to reach practical dimensions for fabrication while maintaining 95% probability of threshold science.

4 CONCLUSION

Addressing the threat to the NISAR L-band radar from MMOD was an atypical challenge because of the large number of exposed electronics boxes and the constraints on shield design imposed by thermal requirements. The task was further complicated by the complex and varied ways in which the boxes work together to produce the different types of science observations, such that loss of a box might not produce a total functional loss of the instrument. Successfully quantifying and reducing the risk required a determination of the minimum acceptable combination of surviving boxes that would produce a successful science campaign, for which the probability of survival was described mathematically. This equation was then used to optimize the shield design for the most efficient use of mass that produced the desired level of reliability.

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