Some not-so-intuitive lessons from key on-orbit failures and anomalies since 2005

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Outline

- Purpose
- Upfront view of forthcoming lessons
- Recent Failures on GSFC and related missions involving EEE parts
- Other noteworthy failures
- Failure Space Venn Diagram
- Takeaway/lessons

Purpose

- Objectively review recent history of major on-orbit failures and anomalies for low-risk-tolerant missions
- Provide linkage back to parts and components as applicable
- Characterize any actual or apparent trends
- Provide recommendations to ensure that our processes properly account for experiences
- Establish broad lessons of interest to the community

Lessons forthcoming

- Neither part upscreening or use of MIL-SPEC or rad-hard parts provides protection against a poor or overly-sensitive design, i.e., “high-reliability parts” do not mitigate risks of a weak design. Furthermore, there is no longer a clear distinction in general between a “high-reliability” part and a “low reliability” part. Radiation effects cannot always be mitigated at the part level.
- Before applying screening tests to parts for flight, be sure none violate the part’s datasheet rated limits
- There is no indication that any level of part screening affects mission reliability or lifetime
- Components that have demonstrated performance issues tend to continue to do so
  - In some cases proper context indicates problem areas (e.g, temperature profile)
  - Some tend to skew the overall reliability estimates for particular component types
- Over-reliance on piece-part level screening or use of MIL-SPEC parts leaves an opening for manufacturing flaws not addressed by the MIL-SPECs
  - One unique parts manufacturing issue led to major anomalies or failures on at least four missions, for parts that are compliant to Level 1 equivalent MIL-SPECs
- A weak linkage between mission operations activities/teams and engineering development and testing teams can leave a hole for a repeat of problems
  - When an on-orbit part failure is indicated with confidence on-orbit, the development and testing records for the parts in question should be reviewed as a top priority
- Beware of agendas that may be in force from subject matter experts on ARBs
  - Be sure that the caveats associated with failure theories are understood
  - Be sure that there is a clear rationale for de-prioritizing open items on the fishbone or cause tree
- Take note of and capture risks for items with unexplained out-of-family performance in I&T
- A smart use of fault-tolerance can go a long way when parts or components are used that have a spotty or uncertain history

Recent Major GSFC and related Mission Failures and Anomalies

- STEREO (IMU-A)
- Several "A&B type" RWA failures (FUSE, Kepler, …)
- SAC-D (failed converters just after primary lifetime)
- SMAP (weak design + radiation hit)
- LandSat-8 (TIRS) (MLCC problem #1)
- SDO (MLCC problem #1)
- Commercial Bird 1 (MLCC problem #1)
- Commercial Bird 2 (MLCC problem #1)
- GOES-17 ABI (loop heat pipes – new technology)
- DSCOVR (IMU-A)
- GPM RWA failure

Reaction Wheel failures from past 15+ years

- ”A & B wheel” failures
  - FUSE (2001 – 2007)
  - TIMED (2007)
  - Kepler (2012, 2013)
  - Hayabusa (2005, 2008)
  - DAWN (2010, 2012)
- Global Precipitation Measurement (GPM) mission reaction wheel failure (2019) (no performance effect)

STEREO

- Launch: 10/2006
- Early IMU-A failures
  - First IMU-A failed in 4/2007
    - Cause attributed to shorting of connector due to contamination
  - Second IMU-A failed in 1/2014
    - x-axis gyro failed (failed current control, but limited telemetry to understand further)
  - Third IMU-A failed in 10/2014
    - Telemetry very limited, but may have been similar problem to the first failure
- These were older units that have been updated in later revisions of IMU-A
- After the last failure, a reset occurred and shortly thereafter the spacecraft was lost, in its heliocentric orbit.

SAC-D (Aquarius)

- Launched in June of 2011 on a 3-year mission
- The project (managed by Argentine Space Agency) selected DC/DC converters from a non-QML manufacturer with whom we have limited experience, and screened the hybrids to Level 1 requirements (commensurate with Class A missions)
- About a year into operations, the first converter failed on-orbit.
- Multiple converter failures occurred over time, but fault-tolerance in system design maintained system function over the required lifetime.
- Mission was extended, but four years after launch, the power supply ended up failing after all converters ended up failing.
- Failure investigation began with the assumption that the parts failed due to manufacturing and quality flaws, linking them to screening observations.
- Unfortunately, the investigation did not consider the screening levels performed on the parts relative to the data sheet levels
- All the converters flown had a 500g constant acceleration limit in their datasheets, but all were tested to 3000g constant acceleration, and unfortunately, they passed the screens
- The construct of a hybrid DC/DC converter is inconsistent with the extreme accelerations demanded by MIL-PRF-38534, which were designed for a different type and construct of part.
- Ultimately, the overtesting applied to the parts in screening severely degraded their useful life

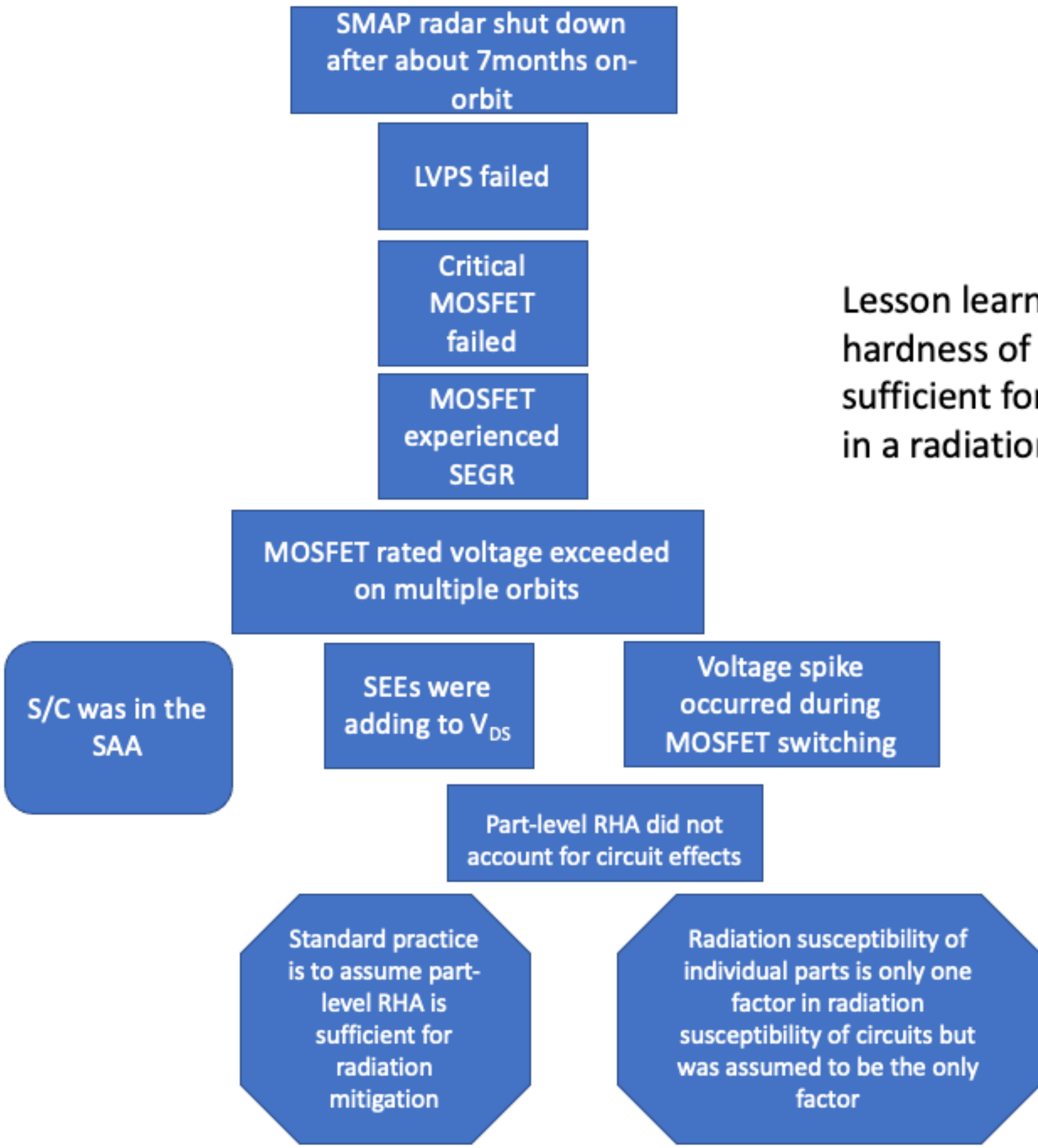
SMAP

- In 2015, several months into the science phase of NASA's Soil Moisture Active Passive (SMAP) mission, the SMAP active radar (SAR), the primary payload, stopped gathering science measurements shortly after the spacecraft entered the South Atlantic Anomaly (SAA). After a month and a half of troubleshooting and attempts to restart the radar, NASA declared a Type A mishap and convened a NASA Mishap Investigation Board (MIB). In parallel, the implementing center, JPL, convened its own failure review board (FRB). (The JPL board was very effective at getting to the detailed technical causes).
- Being Class C, the project followed the guidelines in NPR 8705.4, suggesting that single string designs are acceptable, but that risks can be mitigated through the use of "high reliability parts".
- The project depended on the radiation-hardness of all the parts in the system, but did not consider the circuit effects that combined with the single event effects in the SAA.
  - These circuit effects coupled with radiation effects to exceed the rated voltage within the rad-hard part, ultimately resulting in single event gate rupture.
- Fortunately, the mission has been able to continue with almost full success on the passive radiometer, even without the function of the radar.

See https://llis.nasa.gov/lesson/27701 for proximate cause details

SMAP failure Event and Causal Factor Tree

Goddard Space Flight Center



Lesson learned: radiation hardness of piece parts is not sufficient for reliable operation in a radiation environment

LandSat-8/TIRS on-orbit SSM anomaly

Starting approximately 10 months after launch of LandSat-8 an anomalous trend was noted in the –EV MCE (mechanism control electronics) current on the TIRS A side electronics. Over time the –EV MCE current began to grow at an exponential rate and an anomaly investigation commenced. A lengthy investigation could not confirm root cause, however it was suspected at the time that a conductive anodic filament (CAF) created a short path within the A side electronics. To prepare for possible loss of MCE, tests were conducted to understand SSM drift without positive feedback control.

Following the recommendations from the A side ARB investigation, TIRS was swapped to the B side electronics to collect optimal science for the 2015 growing season. Approximately 5 months after resuming nominal operations on the TIRS B side, indications of an anomalous current have been observed in the +EV MCE current.

TIRS on-orbit anomaly cont'd

- In preparation for TIRS-2, GSFC SMA was reviewing anomaly history of TIRS, noting the behavior and open items on the fishbone
- SMA was concurrently performing reverse bias capacitor testing to support projects using the Express Logistics Carrier (ELC) on ISS.
- Behavior of the on-orbit leakage currents on TIRS bore a striking resemblance to the reverse bias capacitor performance in our ground testing
- A thorough examination was performed of the capacitor polarities in all related components on TIRS
  - Polarity was correct at all levels
- SMA requested that spare boards be brought out of storage to be powered up
- Not long after power-up, the board started to exhibit the leakage current reflective of the on-orbit behavior
  - Many attempts were made to power cycle the boards, induce recovery, or otherwise affect the profile, with mixed results
- We placed a thermal camera over the board to watch for hot spots

TIRS on-orbit anomaly cont'd

- After weeks of operation, noticeable locations of excessive temperature rise were seen on the board
- These were located in the vicinity of some RC filters feeding into amplifiers on the board
- Probe measurements were taken at points on the bank of filters that indicated reduced voltage (and hence current leakage) at at least two of the caps.
- GSFC Parts Branch brought in a thermal camera with high spatial resolution that identified that the hot spots were unequivocally located on two of the capacitors themselves.
- The focused heating combined with the fact that the capacitors are hand-soldered ceramic caps (not recommended for handsoldering) gave a strong indication that they are cracked.
- Inspections of the board and x-rays performed did not show signs of cracking
- The process then began to remove the suspect parts from the board for failure analysis and replacement.

TIRS on-orbit anomaly cont'd

- This is the first instance we have seen of cracked capacitors making it through I&T undetected and becoming anomalous on-orbit
  - In this case, the cracks are internal to the parts and they may not have even formed until the hardware had been on-orbit for a while, or the crack may have propagated over time.
- C-mode Scanning Acoustic Microscopy (C-SAM) was performed on the anomalous parts on the boards, which subsequently showed signs of delamination internal to the parts that lined up with the hot spots on the parts.
- Fortunately, we had hundreds of spares from the LDC (1011-BY) that enabled some lot-based views.
- A large-scale effort to perform C-SAM was undertaken, resulting in discovery that about 50% of the parts have delaminations internal to the pristine parts, in many cases similar to that present in the anomalous parts.
- While the hot spots line up with the delamination features, in general such features have not been established as failure or degradation mechanisms, but they are indicators that there may be a lot problem

Investigation

- Investigation revealed that this specific problem was discovered in at least one classified mission years ago, but proper warnings did not make their way into the NASA community.
- We began an immediate process of performing C-SAMs on spare parts that we had on hand, first to determine whether there was lot dependence, and next to start exonerating applications on GSFC projects
  - Lot dependence was established
  - Many more lots clear of the problem than those that exhibit the problem
  - Many lots, however, do exhibit the problem, but none to the extent of the TIRS lot.

SDO capacitor failures

- In 2007, during EMI testing, engineers found that a clock on the EVE instrument MEGS-A board was functioning improperly. It was further discovered that a generic bypass capacitor was leaky, exhibiting a resistance of approximately 1.5kohms.
- The part was externally inspected and photo-documented. No anomalies were noted. As received, the capacitor retained some conformal coating left after board removal.
- Leads were attached without clamping and using brief contact with the soldering iron. The capacitor was potted for cross sectioning. Re-testing with a hand-held DVM following potting found that the capacitor was no longer shorted. Electrical bridge testing was repeated, confirming that the device was functioning properly.
- Initial cross sectioning at the 5-percent cross section level found a delamination spanning between capacitor terminations. The anomaly was examined microscopically and photo-documented. Cross sectioning continued to approximately the 10-percent level, at which the delamination was fully revealed and seen to extend from termination to termination of the capacitor.
- Ultimately, the part was replaced and the rest of the lot remained in place

SDO capacitor failures (cont'd)

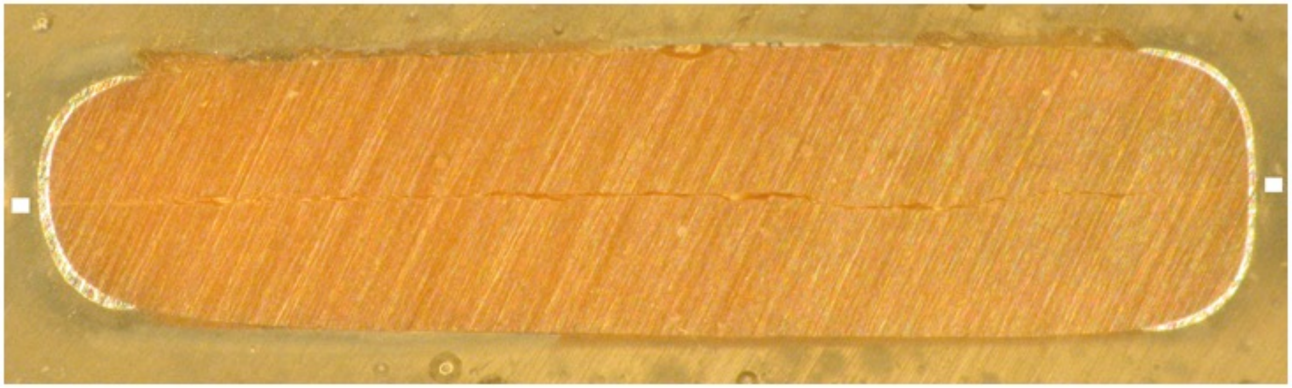


Figure 1. A delamination spanning between terminations was found at the 10-percent level. Square dots in the image above mark the ends of the crack. Note that the cross section plane is near the end of the part and does not reveal the electrodes.

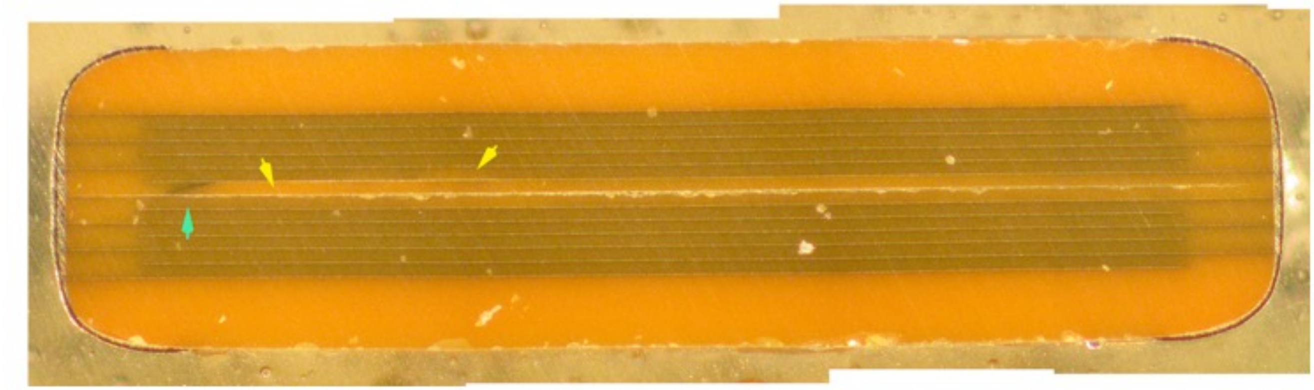


Figure 2. The 21-percent level with polish first reveals the electrode structure and simultaneously revealed a diagonal crack, marked by a green arrow, bridging between the center, and an adjacent electrode. This location is considered a likely candidate for the failure site. Yellow arrows mark a difference in layer color later shown to be caused by internal light reflection from a discontinuity in the dielectric. EDS found no material difference between the layers.

SDO capacitor failures (cont'd)

- In May of 2014, the MEGS-A board in the EVE instrument experienced a voltage drop, prompting ops to move it into safe mode
- Problem was ultimately traced to a CDR35 capacitor from 0509 LDC.
- Many attempts were made to power cycle the board to clear the short, as had been done for other capacitor-related shorts
- Ultimately, MEGS-A was shut down after several unsuccessful attempts
- Unfortunately, the on-orbit problem was characterized as a random capacitor failure and no further announcement ensued to open up a cross-cutting review
- During the TIRS investigation, a parts engineer recalled a discussion with one of the LASP engineers concerning a capacitor failure, which prompted us to open some records associated with SDO/EVE.
- Review of the original FA from 2007 and the details of recovery efforts for EVE, indicated that the problem appears to be related to our current ceramic capacitor problem
- The part number and lot date code were then found in one of the recent C-SAM batches we had tested and declared to be an implicated lot.
- The parts in the MEGS instrument were all handsoldered
  - MEGS-B had parts from the same LDC, but they were handsoldered by a different organization
  - MEGS-B exhibited no anomalies or failures

Other similar failures

- In 2018, two separate commercial spacecraft suffered failures related to this problem.
- The same component was taken out in both spacecraft, ending both missions very early.
- In 2021, two DoD missions that were subject to the same problem reached their demise as well.

Six separate spacecraft experienced catastrophic failures or serious anomalies due to a single parts manufacturing problem affecting MIL-SPEC level 1 ceramic capacitors, in which the particular flaw is not detectable by the MIL-SPECs, and the affected caps are within spec.

Fault Tree from alert

Leakage Current trips safehold in TIRS

Loss of resistance in at least one MLCC

Conductive path across opposing electrodes

Internal crack in part

Silver Migration

Longstanding manufacturing flaw

Past Observations entirely blamed on handsoldering

Weakness in ceramic

MIL-SPEC not perceptive to manufacturing flaw

MIL-SPEC tests overtest without ability to perceive subtle signs of overstress

Root Cause 1: MIL-SPEC Level 1 Assurance is neither necessary nor sufficient to assure parts to be good for use. Additionally, in some cases, weaker parts may be overtested without knowing overtest has caused overstress

Root Cause 2: Per standard Agency and GSFC practices, parts were tested in non-flight conditions. Testing at the piece part level did not expose the manufacturing flaw, which only appeared after installation. Piece-part testing per the MIL-SPEC was ineffective and gave a false sense of confidence.

JUNO and MMS HV801 part failures

- HV801 is a high voltage optocoupler often used in HV power supplies operating at about 7 kV.
  - Hand produced
  - Rated to 8 kV (1 kV for each of the LEDs inside)
  - Above about 3 kV, there is extreme sensitivity to even the most subtle material and workmanship defects, and material breakdowns occur that often lead to part failure
  - This was discovered in an extreme way during MMS mission development, which had the most extreme applications, with 300 parts in use at up to around 7 kV. Years of effort went into working with the manufacturer for improving the parts (during MMS development and more so afterwards) and then ultimately cherry picking the parts with the best characteristics, lacking a fool-proof screening process
  - Ultimately it was recognized that we were pushing the boundaries on the usage of these parts, so the designs were resilient to multiple failures
  - JUNO and MMS have experienced a pair of HV801 failures on-orbit each, but both designs are fault-tolerant, and MMS made operational adjustments based on I&T experiences, so neither had a performance impact on the respective missions.
    - MMS had an expectation that multiple failures were likely to occur, limiting the life of the mission; however, mission has been operating since March 2015 with full operating performance, aided by operational adjustments.

GOES-17 ABI failure

GOES-S, now GOES-17, launched on March 1, 2018, reaching geostationary orbit on March 18, 2018. On April 13, the Optical Port Cover was opened, and subsequently the two loop heat pipes (LHPs) in the ABI instrument's radiator/LHP cooling system began to self-start every day when entering the hot phase of the orbit. The LHPs would run for three hours and then shut down after sunlight no longer entered the port. These self-starts were not planned, although self-starts were considered normal in LHP operations. About two weeks later, the flight controllers commanded the LHP startup heaters for the first controlled start of the LHPs on GOES-17. Shortly after startup it became clear that the LHPs were underperforming. Many attempts to improve the performance continued over several months, supported by a failure review board, followed by an independent review team.

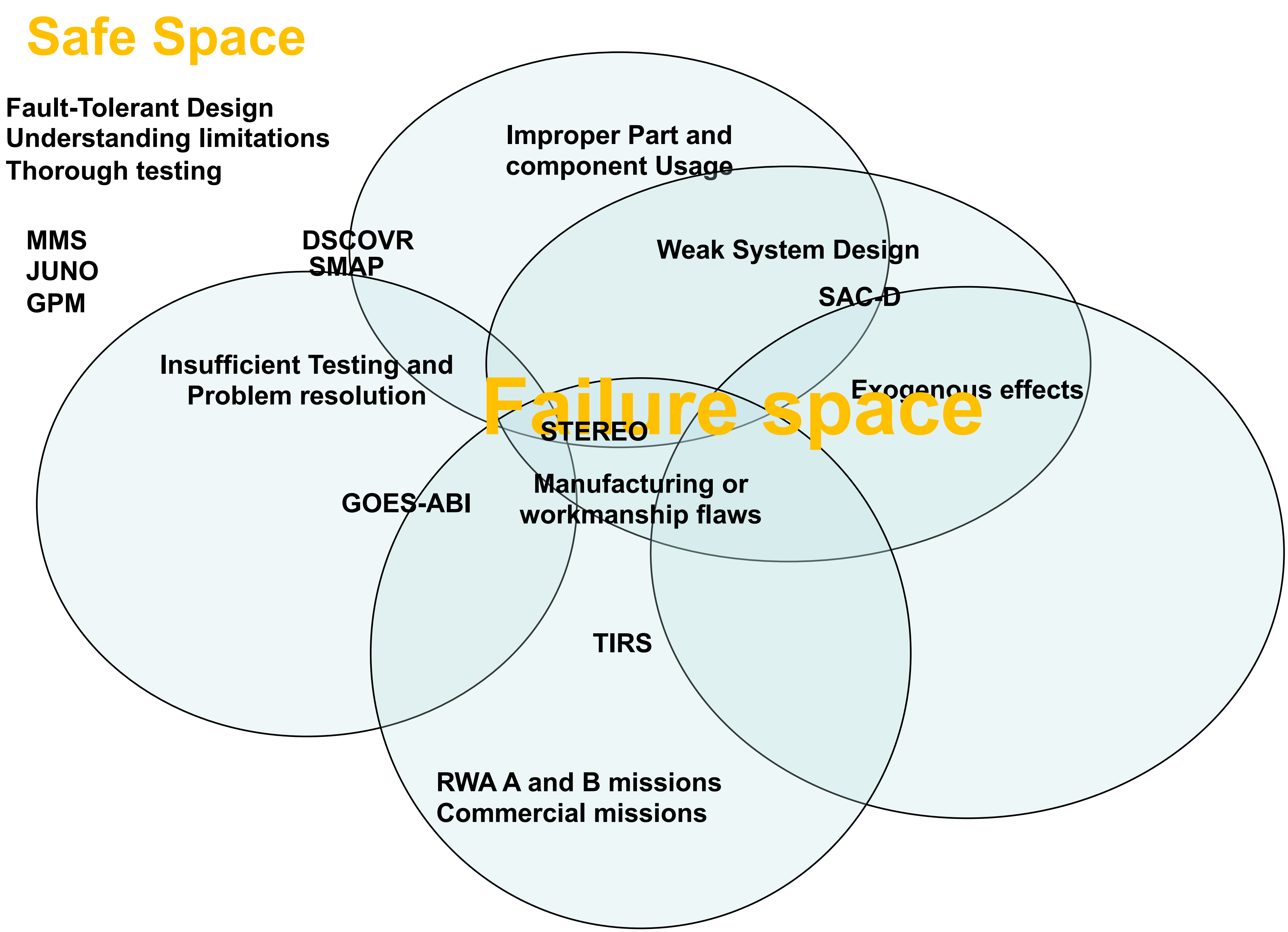
In reviewing the development processes leading up to launch, the following items were noted:

1. Out of uncertainty for the power and thermal requirements, a newer propylene based LHP technology was selected without full knowledge of the differences in implementation relative to the two previous space flights on JAXA missions
2. The performance of the GOES-17 LHPs was out of family with those of the other instantiations. The project made significant efforts to understand, but ultimately the LHPs were accepted since they met the spec. Unfortunately, no risk was captured to maintain the proper attention.

DSCOVR IMU failure

- DSCOVR launched to L1 in 2015 on a mission with 2-year design life. The spacecraft was a resurrection of the mothballed TRIANA spacecraft that had been in storage for 8 years after initial cancellation. Many of the parts and components at the time of launch were over 15 years old.
- Mission was extended after 2 years, but in 2019, one of the IMUs showed the signs of pending failure. Interestingly, the IMU-A (as that from STEREO) had been replaced during the later development period.
- The investigation prompted a deeper look into the temperature influence on the lifetime of IMU-A that was not well understood within GSFC
- Fortunately, the flight software was rewritten to accommodate a gyro-less mode and the spacecraft is fully operational again.

Venn diagram



Takeaways from Recent Failures

- Neither part upscreening or use of MIL-SPEC or rad-hard parts provides protection against a poor or overly-sensitive design, i.e., "high-reliability parts" do not mitigate risks of a weak design. Furthermore, there is no longer a clear distinction in general between a "high-reliability" part and a "low reliability" part. Radiation effects cannot always be mitigated at the part level.
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