DOI: 10.13009/EUCASS2017-540

Examination of Spacecraft Anomalies Provides Insight into Complex Space Environment

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Abstract
Spacecraft operations are affected by a variety of natural and manmade features that create significant ambiguity as to root cause determination for many anomalies and failures of satellites. The natural space environment comprises dynamic radiation, energetic atomic particles, and particulates (micrometeoroids and orbital debris) that vary temporally and spatially across relevant Earth orbits. Some of the failure mechanisms are further obfuscated by intricate local interactions, the fact that failures are often the result of more than one environmental effect, and lack of diagnostic sensors onboard spacecraft. At the same time, manmade influences on spacecraft anomalies and failures include design, manufacture, integration/installation, parts quality, testing completeness, and operations. These manmade aspects of the anomaly/failure attribution process are equally daunting as much of the relevant information is either not collected or not widely distributed for a variety of reasons. This paper details these dimensions of the anomaly/failure attribution process and provides data from a variety of operational examples to illustrate quantitative and specific actions to enhance the anomaly/failure attribution process short-term and long-term.

1. Introduction

Spacecraft operations are affected by a variety of natural and manmade features that create significant ambiguity as to root cause determination for many anomalies and failures of satellites. The natural space environment comprises dynamic radiation, energetic atomic particles, and particulates (micrometeoroids and orbital debris) that vary temporally and spatially across relevant Earth orbits. Some of the failure mechanisms are further obfuscated by intricate local interactions, the fact that failures are often the result of more than one environmental effect, and lack of diagnostic sensors onboard spacecraft.

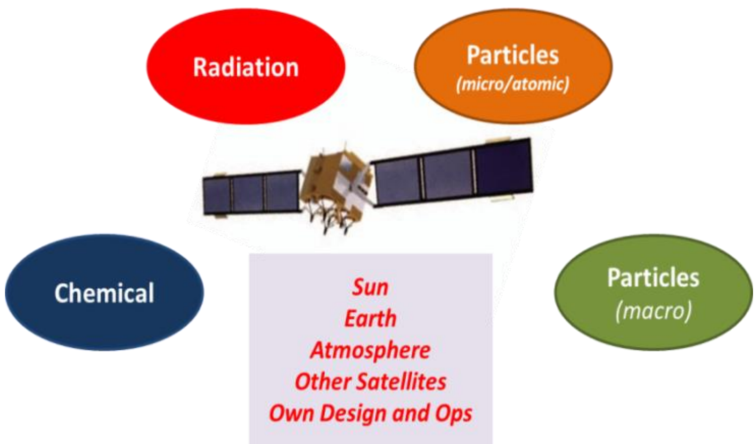

Figure 1. Space environmental effects come from a variety of sources.

At the same time, manmade influences on spacecraft anomalies and failures include design, manufacture, integration/installation, parts quality, testing completeness, and operations. These manmade aspects of the anomaly/failure attribution process are equally daunting as much of the relevant information is either not collected or not widely distributed for a variety of reasons.

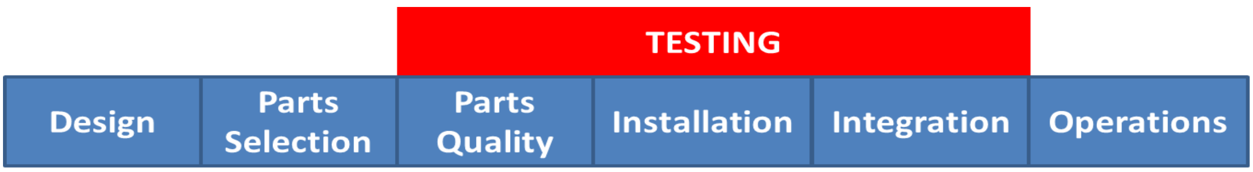

Figure 2. Testing can provide the most benefit to mitigating manmade anomalies/failures.

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2. Natural Triggers

The table below summarizes the four families of natural triggers while differentiating effects for low Earth orbit (LEO) and geosynchronous orbit (GEO).

Table 1. Natural environmental triggers can be organized into four general categories.

Source	Environmental Trigger	LEO	GEO
Radiation	**Ultraviolet (UV) Degradation**	Affects sunlit polymers	
	Electrostatic Discharge (ESD) ***Function of plasma***	Low to High Fcn (inclination)	High
Micro-"Particle" **(p^+, e^-, ions)**	**Single Event Upset (SEU)**	Moderate to High Fcn (inclination)	High
	Total Dose	Low to Moderate	
	Displacement Damage	Low to Moderate	
Chemical Process (Driven by Radiation)	**Contamination**	Function of design and proper testing (also as the result of ESD)	
	Atomic Oxygen (AO)	High (below 650km)	None
	Atmospheric Drag	High (below 750km)	None
Macro-"Particle"	**Micrometeoroid**	Low	Moderate
	Orbital Debris	Moderate – High Fcn (alttitude)	Low - Moderate

The simplest direct radiation effect is ultraviolet (UV) radiation that degrade exposed polymers in LEO and GEO. Charging of the spacecraft components and surfaces from the plasma environment that fuels electrostatic discharge (ESD) can create transient electrical signals and permanent damage to surfaces where charges are violently equalized. ESD is a significant hazard in GEO but is a function of inclination in LEO (i.e., satellites in higher inclination orbits are more susceptible to ESD). Charged particles present a greater threat as they become trapped in the Van Allen radiation belts: more protons in the inner belt affecting LEO and more electrons in the outer belt affecting GEO.

The sub-atomic and atomic particles (electrons, protons, and ions) can cause electronics to change state quickly but temporarily (i.e., single event upset), damage functionality over time through total dose, and create a permanent flaw in electronics by disruption of the material (i.e., displacement damage). Chemical processes include one internally-generated issue (i.e., contamination to external surfaces from outgassing or normal effluent releases) and two externally-induced effects (i.e., atomic oxygen in low-LEO eroding polymers and the expansion of the atmosphere increasing the drag on low-LEO satellites).

The larger natural particles, micrometeoroids and space debris, pose the last family of space environmental effects. Micrometeoroids are generally much smaller and less dense than space debris but are traveling upwards of 40-70km/s while space debris generally impacts spacecraft in the 4-14km/s range. The source of much of the natural effects are driven by the Sun. The figure below highlights how the solar activity, that follows a roughly 11-year cycle, drive many of the significant perturbations to spacecraft. Solar storms produce both high and low energy charged particles that arrive at the Earth at different times as shown in the top panel of the figure.

During periods of high solar activity there are more coronal mass ejections (CMEs) that bathe satellites in more charged particles. Increased solar activity also increases atmospheric drag in LEO but also causes more charged particles to be trapped in the outer radiation belt. However, trapped charged particles in the inner belt peak at solar minimum.

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Galactic cosmic rays (GCR, that actually are high energy protons and atomic nuclei originating from out of the solar system) and auroral charging are also a maximum at solar minimum. While solar activity and CMEs are related, solar activity is highly correlated with the 10.7cm solar flux component.

ESD events are likely during periods of decreasing solar activity and when a satellite comes out of eclipse (i.e., from dark into light). The effects of UV degradation stay fairly constant and do not vary significantly across the solar cycle.

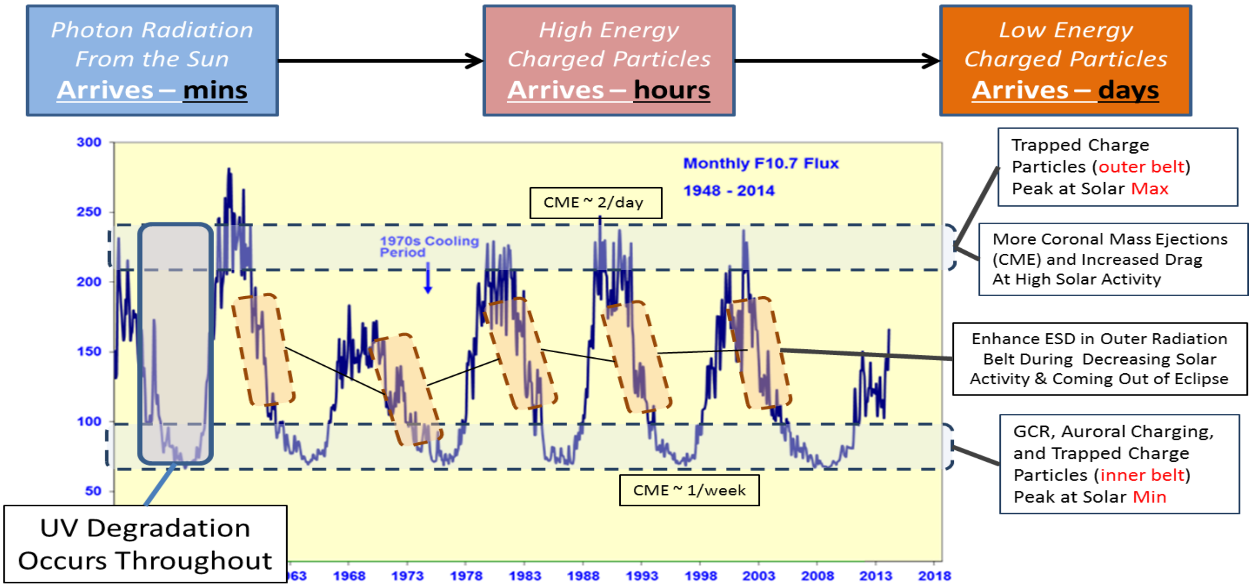

Figure 3. The solar dynamo is the catalyst for many of the space environmental effects deleterious to spacecraft operations.

3. Manmade Causes of Anomalies/Failures

Many of the techniques and procedures applied to reduce the chances of satellite anomalies and failures are collected under the banner of mission assurance (MA). MA lessons learned provide insights that can enhance anomaly resolution operations. It can be said that on-orbit performance of space systems provides a valuable feedback loop for MA activities that basically extends the enhanced understanding gained from component, system-level, and operational testing sequences into the ultimate of operational testing (i.e., on-orbit operations). While hardware assurance (HwA) has been practiced for decades and is still vitally important, software assurance (SwA) is increasingly critical as more complex, autonomous systems are being deployed and cyber security risks proliferate.
From an engineer's perspective, there are several high-level suggestions that apply to design and testing:[1]

- <u>Sign errors</u>: having the wrong sign may be fatal since it is not just wrong, it is the opposite so may create an amplifying error, therefore, watch and control the possible impact of sign errors;
- <u>Last-minute changes</u>: avoid alterations to design and testing; however, if essential then ensure that it is a simple change;
- <u>Sensitivity to computer glitches</u>: make sure the entire spacecraft does not fail if the computer has an anomaly;
- <u>Scrutinize current surge protectors</u>: ensure the safety and rating of devices meant to protect against electrical spikes;
- <u>Do not ignore anomalistic testing results</u>: understand all anomaly/failure signatures that you encounter during testing, do not just assume that they will never happen on orbit; and
- <u>Maintain current/complete system documentation with operators</u>: ensure that operators can get access to accurate, detailed technical information about onboard systems to help troubleshoot issue when they occur.

[1] Paul Cheng and Patrick Smith, "Why Satellites Fail Lessons for Mission Success", Aerospace TOR-2009 (8617)-8704, 2013.

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There are number of space system-specific issues that, if known, will enhance anomaly troubleshooting:[2]

- Flexible solar arrays are susceptible to thermally-induced vibrations.
- Ensure that design isolates faults.
- Check start-up circuit behavior, especially at low temperatures.
- Ensure critical systems are tolerant of transient power loss.
- Identify all exposed circuits to preclude inadvertent short circuits.
- Guard against subtle timing conflicts in fast circuits.
- Do not dismiss test anomalies as random events – find out why they occurred!
- Remember that tests are for verification, not discovery.
- Ensure that HW and SW engineers communicate with each other.

While it is hardly high tech or a surprise, an important mitigation mechanism for operationally-induced anomalies and failures is training. Satellites are getting more and more capable; with that increased functionality also comes potentially more complex operations and more opportunities for user error. In addition, awareness and diligence are critical for accurate anomaly and failure reduction. People must maintain a culture of safety and compliance starting with design and running all the way through operations and retirement.

Unfortunately, studies have shown that for all domains (not just space safety) it is human nature to stop reporting anomalies after potentially deleterious events have not led to a disaster. This is called the normalization of variance. In a study on the NASA Space Shuttle Program by NASA, it was found that the overall downward trend in reported in-flight anomalies is undoubtedly due, in part, to a decrease in the number of near-misses actually occurring during flights as technology matured. However, it is unlikely that the spikes reflect an increase in true near-miss frequency. Rather clear failures (Challenger and Columbia) trigger a burst of attention to identifying near-misses but this vigilance decreases over time so that near-misses are less noticed because of the follow-on successful outcomes. Anomalies begin to be ignored and deemed as successes rather than indicators of vulnerability. This may lull operators into false sense of security.[3]

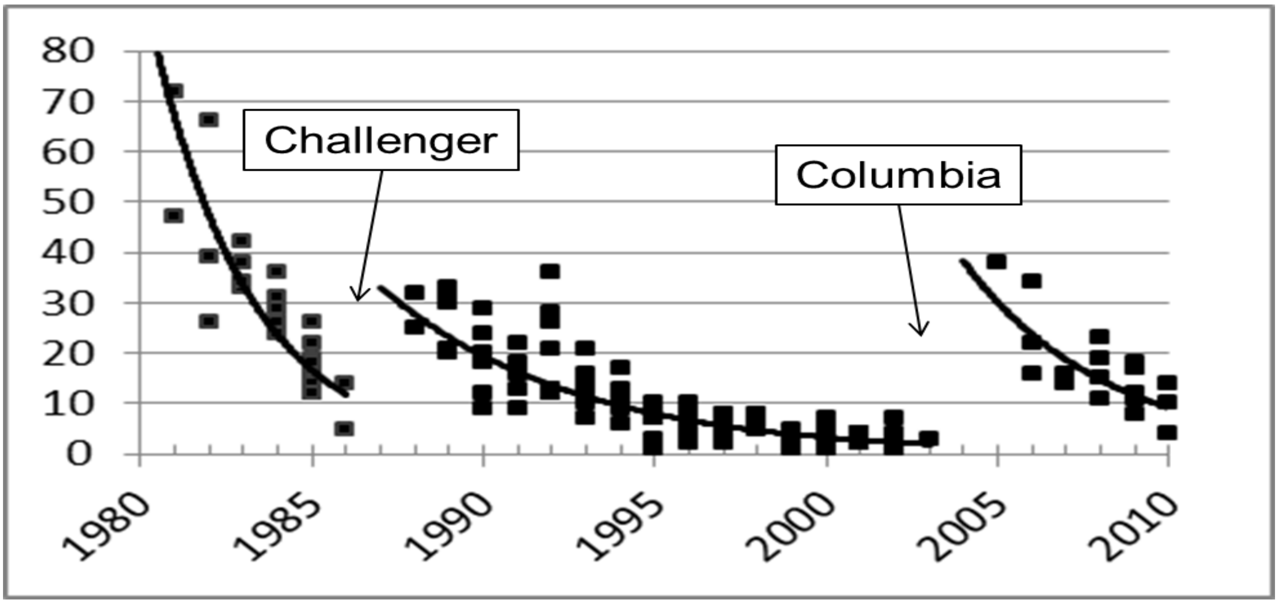

Figure 4. Anomalies often go unreported as they are distanced from the last major failure. Source: Dillon 2008.

[2] Cheng, P., “Five Common Mistakes Reviewers Should Look For,” Aerospace Report No. TOR-2007(8617)-1, 29June 2007.

[3] Dillon, R.L. and Tinsley, C.H., “How near-misses influence decision making under risk: A missed opportunity for learning. *Management Science*, 2008, 54(8): 1425-1440.

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4. Outline of Selected Anomaly Scenarios

Now that all of the natural and manmade anomaly/failure triggers have been reviewed, several of these will be examined in detail to provide perspective on how daunting this overall process can be over time. Three scenarios will be discussed to show how a detailed investigation into a specific anomaly or failure will occur. The following three anomaly/failure modes are impact-induced electromagnetic pulse (EMP), physical contamination, and possible LEO debris events.

Impact-induced EMP: High velocity impacts from micrometeoroids can actually create electrical surges that look much like an ESD event. Work done by Stanford University and Kyushu Institute of Technology trace the disassociation of mass in an impact crater into a plasma that then discharges in a complicated series of events.[4] The figure below taken from a research paper published by Stanford University shows the overall process and implications for this proposed phenomenon.

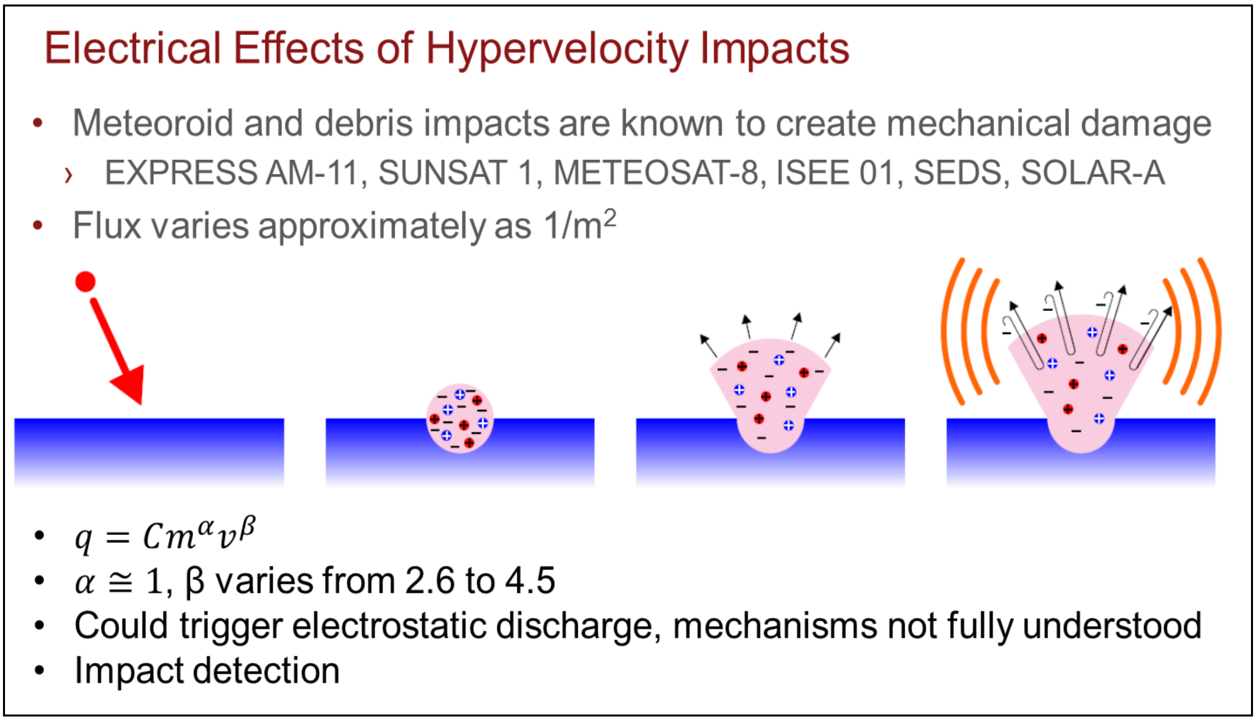

Figure 5. The root cause of an electrical failure being caused by a physical impact helps to remind the community of the difficulty in satellite anomaly attribution. (Source: Goel, 2015)

This type of failure is especially difficult to diagnoze as the trigger is a particle impact creating an electric anomaly similar to ESD. The first clue may be that the indicators of ESD (i.e., decreasing solar activity and coming out of terminator) are not present while there is a significant high-speed micrometeoroid flux. Withour some type of flash detector or onboard accelerometer, the final attribution will be circumstantial (i.e., disproving other options but not necessarily proving the root cause).

Physical Contamination: Contamination is "undesirable matter" that degrades system performance. Contamination can lead to severe mission degradation or failure, if not accounted for carefully. For example, the Boeing 702 had a solar concentrator failure from the outgassing of nonmetallic spacecraft materials. Self-contamination lessons learned are that total mass loss (TML) from materials used is less than 1% and CVCM (collected volatile condensable

[4] Stanford and Japanese papers on impact-induced EMP. Ashish Goel, Close, Sigrid, "Electrical Anomalies on Spacecraft Due to Hypervelocity Impacts," 978-1-4799-5380-6/15/$31:00c 2015 IEEE and Shinya Fukushige, Yasuhiro Akahoshi, Keiko Watanabe, Toshikazu Nagasaki,Kenshou Sugawara, Takao Koura, and Mengu Cho, "Solar-Array Arcing Due to Plasma Created by Space-Debris Impact," IEEE TRANSACTIONS ON PLASMA SCIENCE, VOL. 36, NO. 5, OCTOBER 2008.

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materials) is less than 0.1% are not necessarily adequate standards for optical systems.[5] For optical systems, contaminant morphology is crucial in hardware design review. Venting design and outgassing strength are closely tied to system performance. Space radiation exacerbates the degradation effects of contaminant films. Molecular contamination preferentially affects top junctions of solar arrays limiting current output. There is more transmission degradation after contaminant films are irradiated with protons. The inability to keep the coverglass clean prior to launch can potentially result in additional degradation upon space radiation exposure.

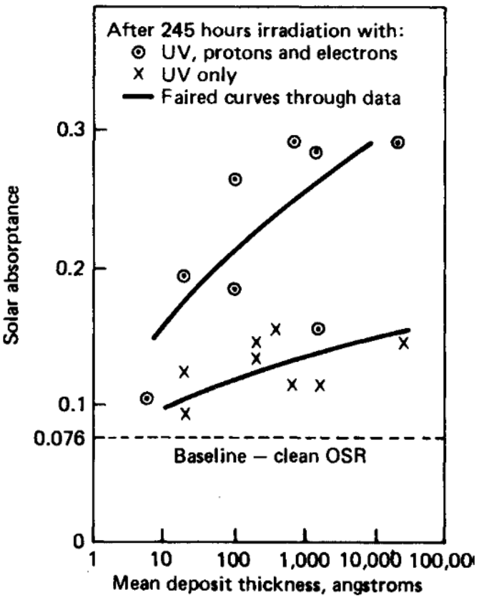

Figure 6. Contamination effects will get even worse when followed with ultraviolet exposure or sub-atomic particle flux.

The figure to the right shows the change in solar absorptance for optical solar reflectors (OSR) from contamination highlighting the synergistic effects of other space environmental phenomena such as UV and charged particles. The x-axis is the depth of contamination.

A key indicator typical of contamination is a gradual degradation of a surface's reflective/absorptive characteristics. This could be an optic, solar array, thermal control subsystem, etc. The synergistic effects of UV and proton exposure may add to complicating a diagnosis as these contributors occur more periodically even though the actual contamination may be gradual. However, episodic contamination may occur from thruster firings, especially in GEO orbits where the plasma conditions can enable recontact of charged effluents.

<u>LEO Debris Events with Indicators</u>: The ability to sense whether or not a satellite was disrupted by an orbital debris impact is not as easy as it might seem. The likely debris impactor to on operational satellite in LEO will be a smaller fragment, since there are more of them: there are over 500,000 fragments in LEO larger than 5mm-1cm versus 18,000 cataloged objects). Anomalies or failures from a debris impact will likely be a fast-acting effect (i.e., not a slow, steady reduction in performance). However, having a rapid reduction in solar power that might be attributed to a debris particle destroying a portion of a solar array may look identical to a reduction in power due to short in a solar array due to a charging event.

The difficulty in discerning between the two root causes is amplified by the fact that there are few diagnostics sensors on spacecraft to measure an impact and the uncertainty of the effects of a particular impact on the overall mission of a spacecraft. The sequence of parameters that may not be known well enough to confidently attribute a cause of an anomaly as a debris are summarized in the figure below.

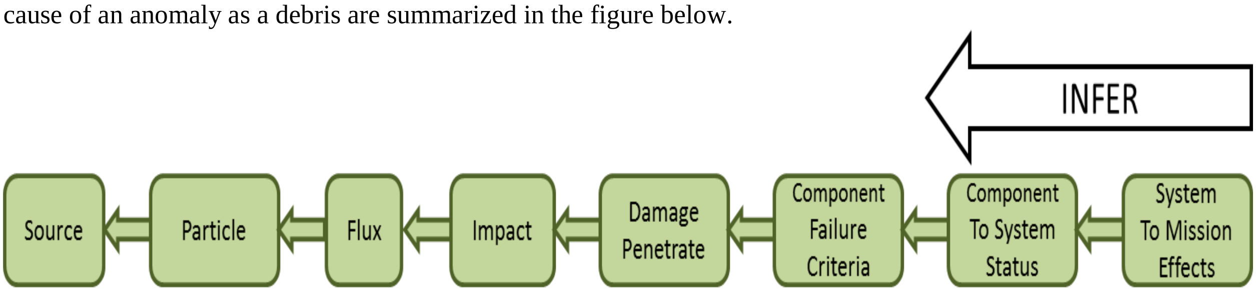

Figure 7. The ambiguity of translating a change in mission performance to an impact, flux, particle, or even, eventually, a source requires a significant amount of information that is often not known.

A test that has become more suggestive of a debris impact is summarized in the table of impact indicators provided in Appendix A. However, it is a straightforward requirement (though problematic in reality) that a debris impact can really only be verified by visual inspection or by having two independent, related observables occur simultaneously. For example, if the solar array power output drops by 20% instantly while an angular perturbation is detected for the entire spacecraft then particulate impact is likely to be the root cause.

[5] J.A. Neff, C.R. Mullen, L.B. Fogdall, "Effects of a Simulated Synchronous Altitude Environment on Contaminated Optical Solar Reflectors", J. Spacecraft & Rockets, **23**: 386-390,1986.

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Another example is that a satellite ceases communicating at the same time that 50 pieces of debris are generated. The sequence is very important, however, as early reports of the Hitomi spacecraft failure in 2016 attributed the loss to a debris impact since the satellite was tumbling and debris was produced. However, fairly soon after the event the Japanese operators stated clearly that the satellite was spinning before the satellite liberated the debris and that the debris creation was due to the rapid rotation of the spacecraft caused by a software glitch that cause the satellite to increase the spin rate of the satellite rather than dampen it.[6]

5. Summary

This quick tutorial of spacecraft anomalies attribution has highlighted the difficulty in this process based on lack of information for a variety of reasons:

- Lack of spacecraft (system, subsystem, and component) design information;
- Inconsistency between the design and the final state a satellite was launched;
- Lack of diagnostics on a spacecraft to unambiguously characterize an anomaly's root cause[7];
- The complexity and variability of failure modes such as impacts, charging, contamination, etc.;
- Inconsistent and unclear motives to share anomaly details; and
- The fact that failures often are the result of more than one trigger.[8]

A useful set of guidelines for assisting anomaly attribution exercises comes from the world of accident investigation best practices. Accident investigators often say to ask "why" seven times.[9] As a practice, I personally say to ask "why" three times to unearth useful information. A hypothetical example from Wayne Hall's blog is in the box to the right. This deliberate questioning takes time and discipline but can produce excellent results!

Q1: Why did the train not stop? A1: **The brakes failed** to apply when commanded by the operator. Q2: Why did the brakes fail? A2: part X in the braking system failed. Q3: Why did part X in the braking system fail? A3 It was installed improperly at the last maintenance period. Q4: Why was part X installed improperly? A4: The maintenance installation procedure was incorrect. Q5: Why was the maintenance procedure incorrect? A5: The procedure was not updated when a new part manufacturer was selected to build part X. Q6: Why was the procedure not updated? A6: **The process for updating maintenance procedures did not allow for a change in part manufacturer.** Q7: Why did the process not allow for a new manufacturer: A7: It was not foreseen that a new part manufacturer would make a part that needed new installation procedures.

For this boxed example, the proximate cause of the accident was a braking failure, but the root cause was an inadequate process to account for new part manufacturers and the corrective action is to update the maintenance procedure change process to ensure that when a new part is introduced, the maintenance procedures are updated properly.

We almost always choose the first accessible solution (even though the first solution stated is usually wrong) so we should consider multiple alternative/options. The Devil's Advocacy rule for accident investigators calls for not coming to a conclusion too soon; ensure that you question any and all decisions. Do not start making theories too early. Stay away from quick conclusions and let the facts lead to the conclusion, not the other way around. It is easy

[6] "Chain of Onboard Failures Responsible for Sending Hitomi Observatory into Deathly Tumble", Spaceflight 101.com, 3 March 2017.
[7] This may actually be getting even worse as more cubesats are deployed that are trying to field so much capability in such a small volume and mass.
[8] This is a special phenomenon called a binary failure that is detailed in Castet, Jean-Francois and Saleh, Joseph H., "Beyond Reliability, Multi-State Failure Analysis of Satellite Subsystems: A Statistical Approach," Reliab Eng Syst Safety (2009), doi:10.1016/j.ress.2009.11.001.
[9] Wayne Hale's Blog: Accident Investigations; Posted 1OCT2016.

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to overlook evidence once your mind (consciously or subconsciously) believes it has reached a conclusion. A coherent means to do this is to have all data examined by a dis-interested third party that is well-qualified to evaluate it. In essence, creating a cognitively diverse team guards against groupthink.

There will always be conflicting and confusing information so strive to be able to tolerate ambiguity even while formulating important decisions. A good decisionmaking process will always give some credibility to options which are less likely and cannot be completely ruled out. Absolute certainty is not something that engineers or accident investigators deal in.

All of these recommendations provide the basis for the final conclusion that anomaly attribution tradecraft will only be improved through more regular and substantive interactions between the wide range of stakeholders concerned with spacecraft mission performance: designers, space physicists, engineers, operators, policymakers, insurance specialists, etc. A powerful means to make this happen is a focused workshop. Just such a Spacecraft Anomalies and Failures (SCAF) Workshop has been conducted for the last four years in the United States. The format and focus of this successful gathering has been adopted by the International Association for the Advancement for Space Safety (IAASS) to hold the inaugural International SCAF Workshop in Toulouse, France on 16-17 October 2017.

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[7] R. Kataoka and Y. Miyoshi, Space Weather, Vol 4, S09004, doi:10.1029/2005SW000211, 2006.