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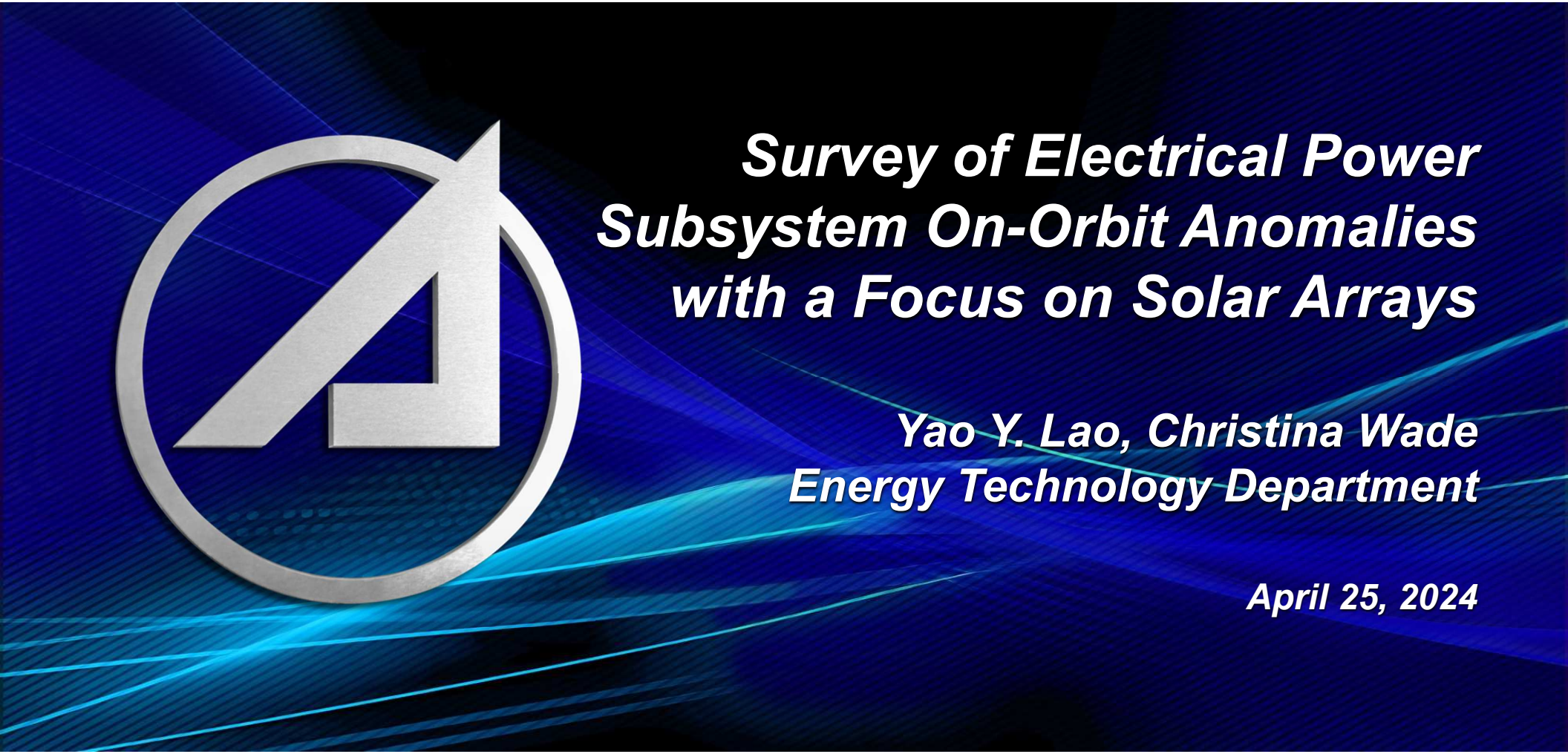

Survey of Electrical Power Subsystem On-Orbit Anomalies with a Focus on Solar Arrays

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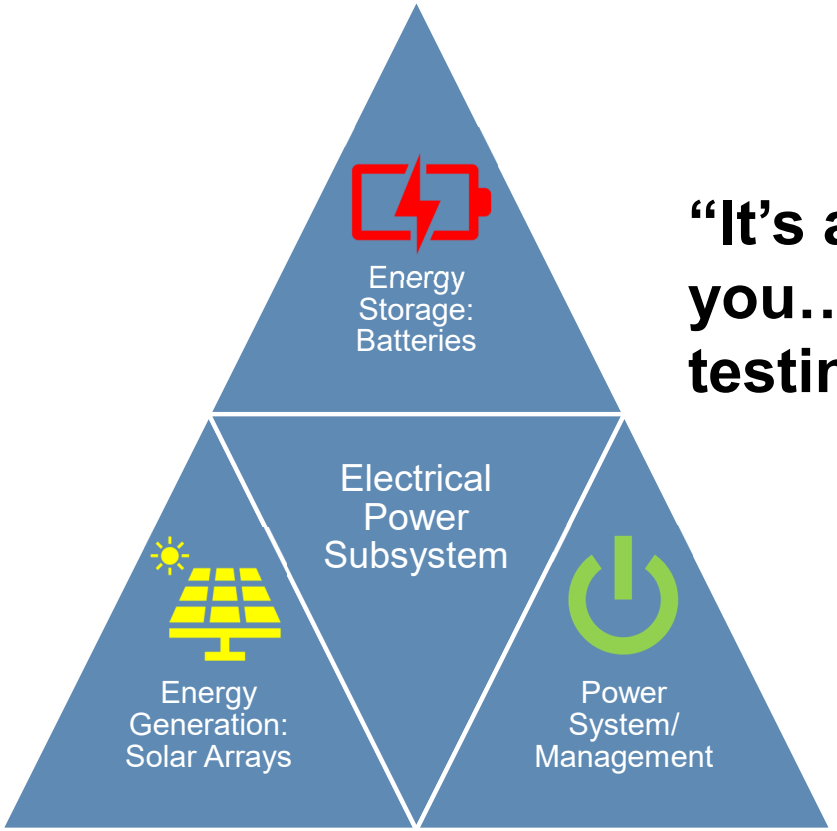
Energy Technology Department

April 25, 2024

Spacecraft Electrical Power Subsystem (EPS)

Complex subsystem working in sync to provide continuous and assured power



"It's always the simple stuff that kills you….It's not that they are stupid, with all the testing systems everything looked good."

James Cantrell, Main Engineer for the Skipper satellite

Skipper failed because its solar panels were connected backward (Associated Press 1996).

EPS is critical for the spacecraft's mission lifetime.

Understanding Common EPS On-Orbit Anomalies and Trends

Databases used for on-orbit anomalies

Seradata

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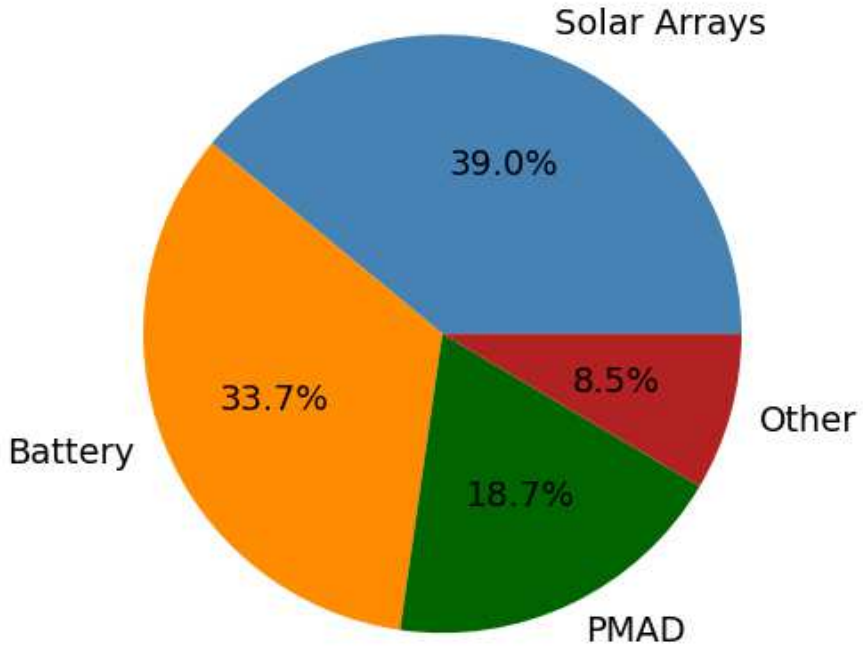
Database	Event histories for launch and spacecrafts since Sputnik in 1957.	Event histories for launch and spacecrafts since Sputnik in 1957.
Source	Public and private sources.	The Aerospace Corporation curated unclassified enterprise database, including program documents.
Anomaly Data	Satellite on-orbit anomalies categorized into subsystems, determined likely cause and categorized based on severity of the impact. **Additional insurance claims and loss values information when applicable.**	Satellite on-orbit anomalies categorized into subsystems with technical and descriptive reference documentation, issue tracking, severity of impact and lessons learned.

Taking lessons learned and apply to future missions in an agile environment can increase mission success and reduce cost.

Overview of On-Orbit EPS Anomalies

- 1,174 on-orbit space vehicle electrical power and distribution subsystem anomalies recorded between 1970 and 2024
- Including LEO, MEO, GEO, HEO, and others



Solar array anomalies make up the largest percentage in number of anomalies.

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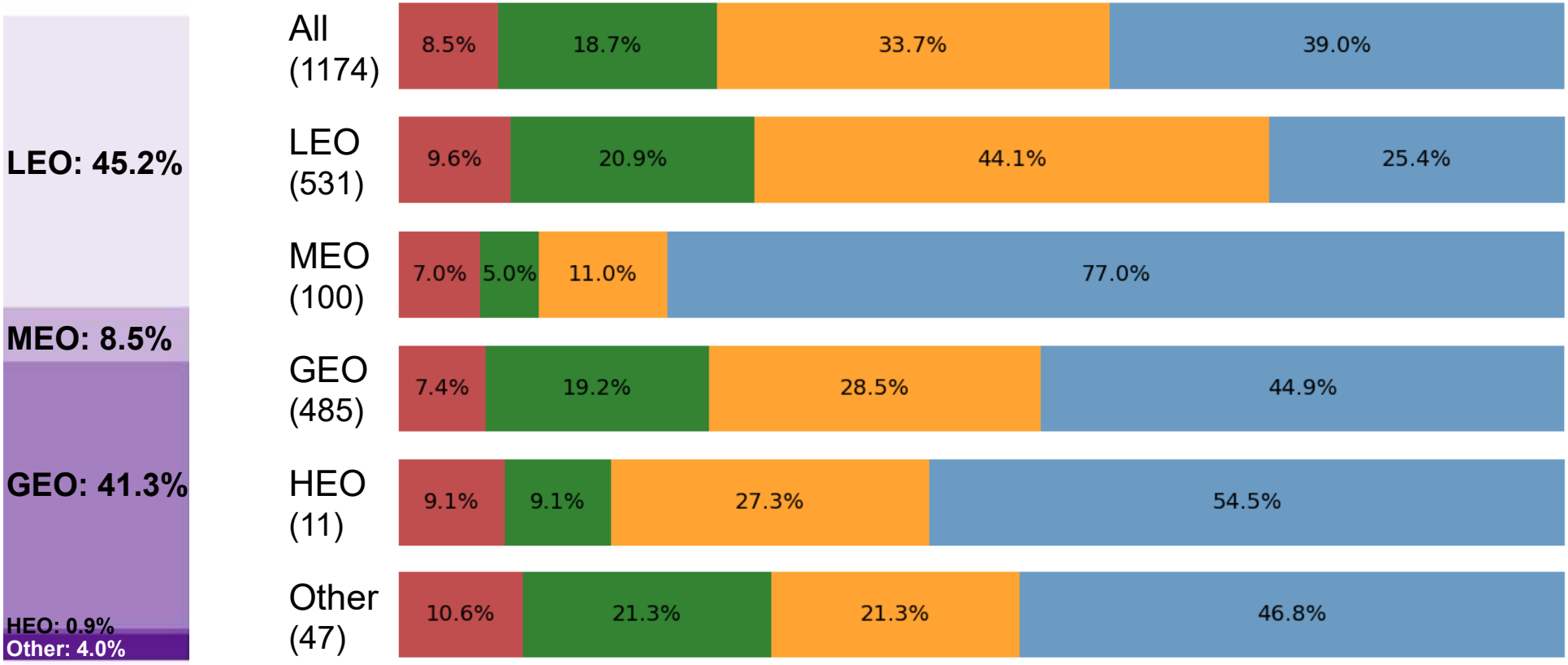
Source: Aerospace ASSET Anomalies Database

Orbit Environment Impacts Dominant Failure Modes

ASSET Database



Consider for your mission environment, what is the dominant failure mode to watch out for?

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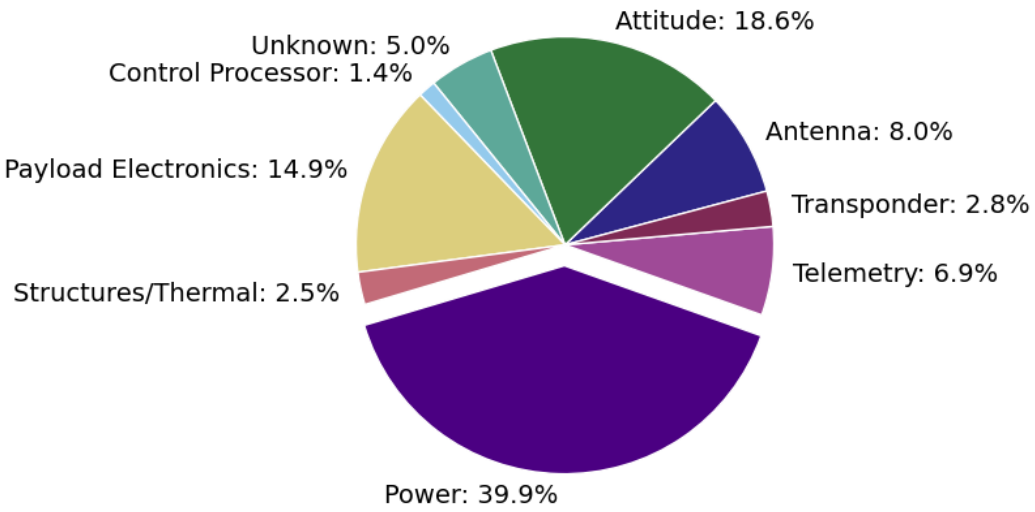
Source: Aerospace ASSET Anomalies Database

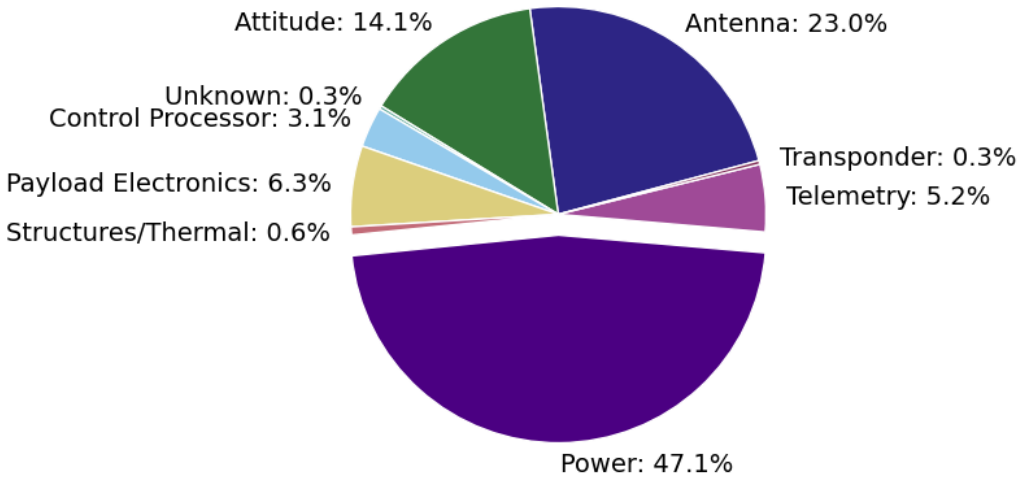
Number and Cost of Anomalies Resulting in Insurance Claims

Seradata Insurance Claims - excluding launch anomalies and insurance losses

Number of Claims by Anomaly Type (Total 436)



Value of Claims by Anomaly Type (Total $23.7 Billion)



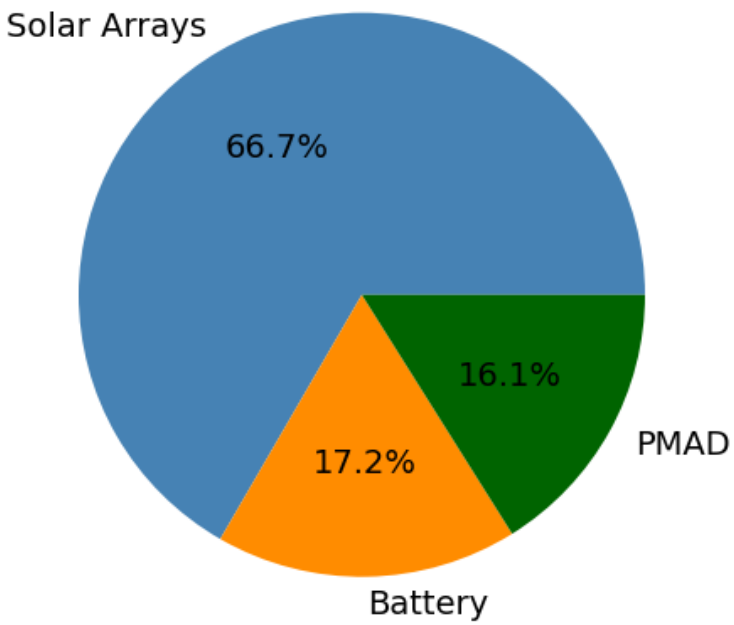
Power-related anomalies make up 39.9% of number of insurance claims but value at 47.1% - costly anomalies.

Source: Seradata database

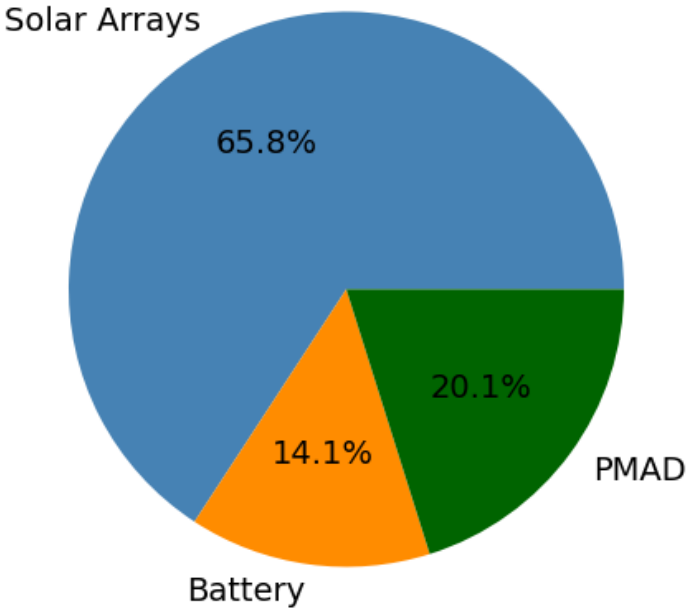
Breakdown of the EPS Anomalies by Number and Cost

Seradata Insurance Claims - excluding launch anomalies and insurance losses

Number of Claims by EPS Anomaly Type
(Total 174)



Value of Claims by EPS Anomaly Type
(Total $11.2 Billion)



Solar arrays made up of most of the insurance claims by number and cost.

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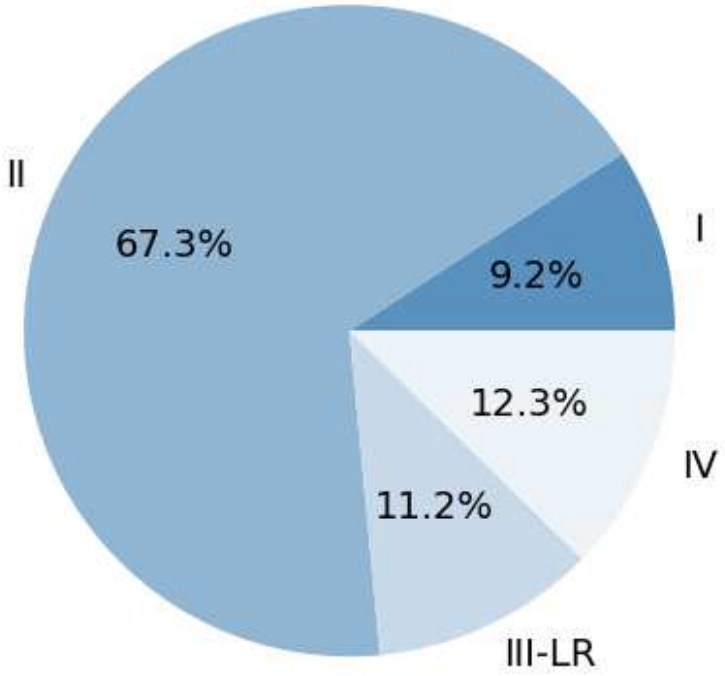
Source: Seradata database

Mission Impacting Anomalies Not All Captured by Insurance Claims

Impact of the other 484 Solar Array Anomalies



	Total	Insurance Loss (#)	Insurance Loss ($M)
I	55	2	31
II	404	114	7,319
III-LR	67	--	--
IV	74	--	--
Total	**600**	**116**	**7350**

CLASS I: Catastrophic. Total failure of the entire satellite due to an anomaly or failure of a system. Mission Capability remaining must be zero.
CLASS II: Major failures resulting in Mission Capability lost
CLASS III-LR: Major non-repairable failures that cause the loss of redundancy
CLASS IV: Minor /temporary/repairable failures that do not have a significant permanent impact

Majority of the solar array related anomalies do not result in insurance claims but impact mission.

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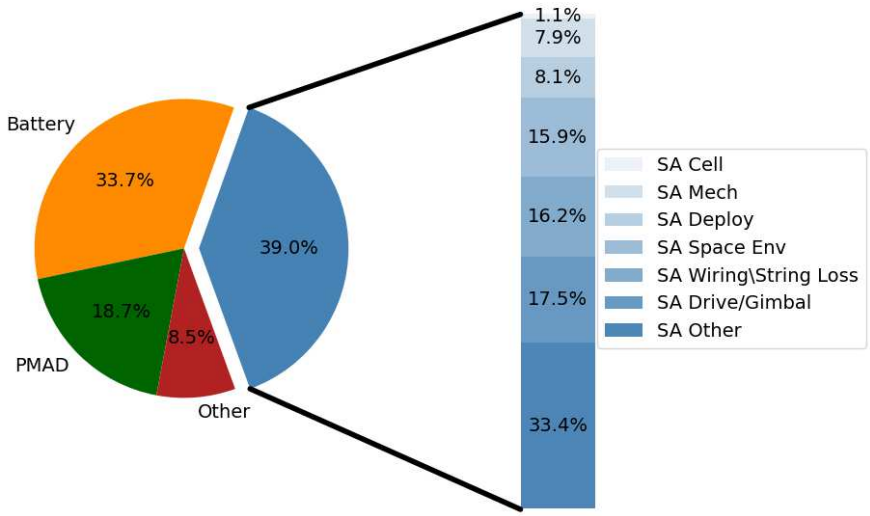
Source: Seradata database

Breakdown of Solar Array Anomalies by Categories



Cause	Description of Category
SA Other	**Not traceable to one specific cause, or otherwise undisclosed**
SA Drive/Gimbal	Anomalies with placement and movement of solar arrays, or issues with sun sensors
SA Wiring/String Loss	A fault with wiring or interconnects between cells/array. Including shorts and loss of strings
SA Space Environment	Degradation in performance due to space environment, including solar flare, radiation, darkening, ESD, etc.
SA Deployment	Anomalies with deployment, or issue traced back to deployment
SA Mechanical	An anomaly with mechanical equipment not related to deploy or drive
SA Cell	Cell level defects such as cracking

If you don't know what failed, especially when adopting new technology, consider having more diagnostic telemetry.

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Source: Aerospace ASSET Anomalies Database

Breakdown of Categorized Solar Array Anomalies by Orbit Environment

	LEO	MEO	GEO	HEO	Other
Cell	2	1	2	0	0
Mechanical	17	1	16	0	0
Deployment	16	1	19	0	1
Space Environment	8	7	42	**5**	**11**
Wiring/String Loss	16	2	**53**	1	3
Drive/Gimbal	**40**	12	26	0	2
Other	36	**53**	**60**	0	5
Total	135	77	218	6	22

Different solar array failure modes dominate in different environments.

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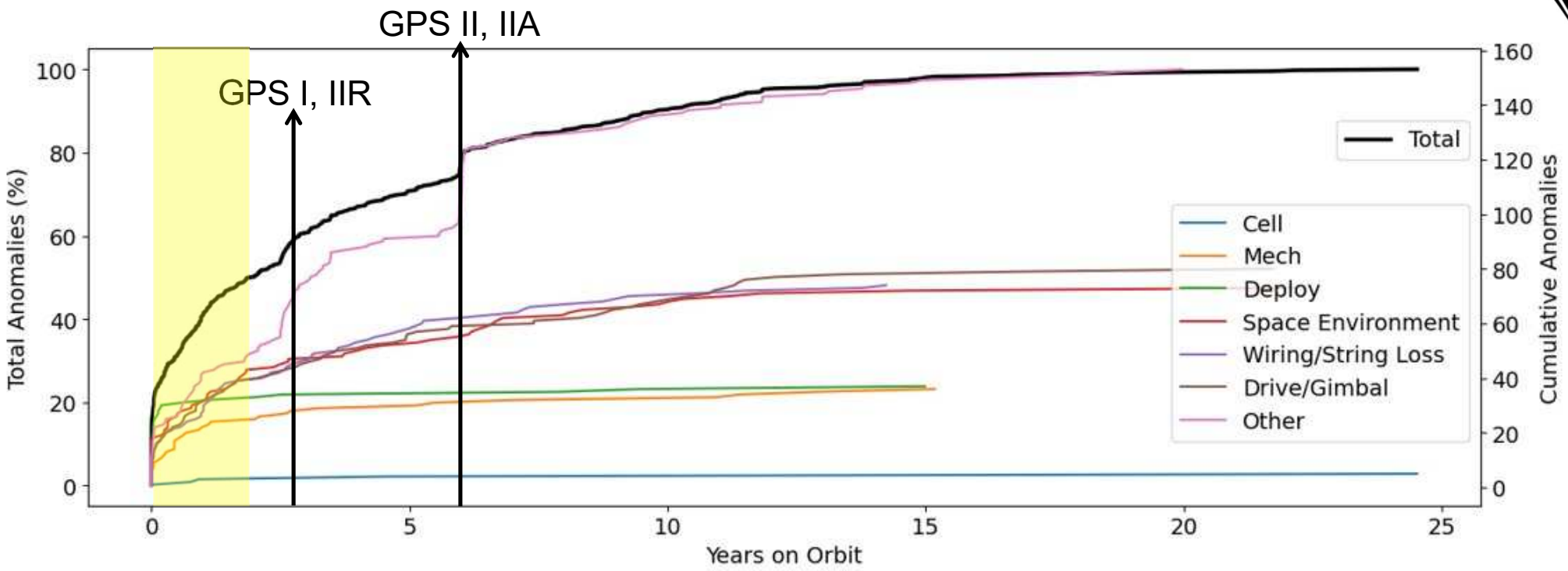
Source: Aerospace ASSET Anomalies Database

Cumulative Anomalies vs. Years on Orbit



Marvin, D. C., et al. "Anomalous Solar Array Performance on GPS." 1988.
Ferguson, D, et al. "Anomalous Global Positioning System Power Degradation from Arc-Induced Contamination." 2016.

50% of all solar array anomalies occur within 2 years after launch.

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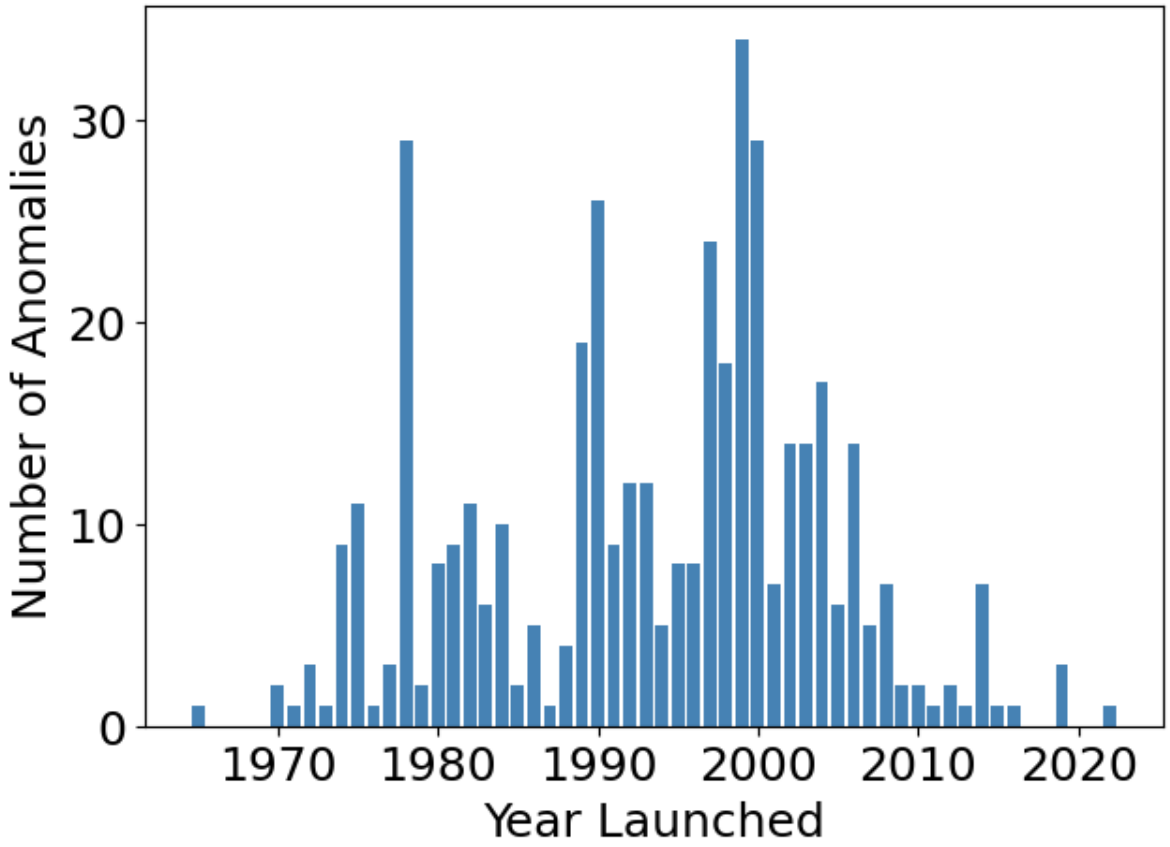
Source: Aerospace ASSET Anomalies Database

Solar Array Anomalies Through Time

Lessons learned from the past



Lecointe, Pascal. “Satellites failures in orbit Focus on power systems” *Space Power Workshop* (2005). Data from 1993-2004
Landis, Geoffrey A. et al. “Causes of Power-Related Satellite Failures.” *2006 IEEE 4th WCPVC* (2006). Data from 1990-2006
Landis, Geoffrey. Tabulation of Power-Related Satellite Failure Causes. *11th IECEC* (2013). Data from 1990-2013

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Source: Aerospace ASSET Anomalies Database

What do we take going forward?

- Space business is evolving rapidly
- Improve EPS performance and reliability in this changing business
  - Better situational awareness and anomaly detection
- Shared responsibility for space hygiene
  - Improve understanding of space environment and hardware application
  - Critically consider the most impactful failure modes for your mission
  - Improve modeling and simulation based on experience of on-orbit anomalies

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Acknowledgements

- Acquisition Analysis & Insights Department – ASSET, Seradata
- Christina Wade – Data analysis
- Solar group – Various discussions and insight

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EPS Anomaly Category Descriptions

- Solar Arrays:
  - Cell: Cell level defects such as cracking
  - Mechanical: Any mechanical anomaly not related to deploy or drive. Such as temperature sensors
  - Deployment: Anomalies with deployment, or issue traced back to deployment
  - Space Environment: Degradation in performance due to space environment, including radiation, darkening, etc.
  - Wiring/String Loss: Any fault with wiring or interconnects between cells/array. Including shorts and loss of strings
  - Drive/Gimbal: Anomalies with placement and movement of solar arrays, or issues with sun sensors
  - Other: Not traceable to one specific portion, or otherwise undisclosed
- Battery: All anomalies related to the batteries. I am not well-versed enough in batteries to be able to split it up into good categories.
- PMAD: Some of the anomalies within PMAD are ambiguously related to both the EPS subsystem as well as the subsystem to which power is being provided. Therefore, depending on how things are interpreted or assigned, the anomaly count for PMAD could be lower
  - Computer: Software anomalies relating to Power Management
  - Electronics: Power converters, etc.
  - Electrical Circuit: Shorts, other wiring/electrical circuit issues between EPS components
  - Distribution: Power system control board fault
  - Bus Other: Related to the power bus, but not specified
- Other:
  - System: Interrelated issue involving 2 or more parts of EPS. ie. Fault after eclipse, batteries ran too low and SA can’t make up deficit before next eclipse
  - Impact: Impact by micrometeoroid, etc.
  - Space Environment: Arcing, spacecraft charging, causing a fault in the power electronics
  - Other/Unknown: Unable to be traced to a specific part, or unspecified

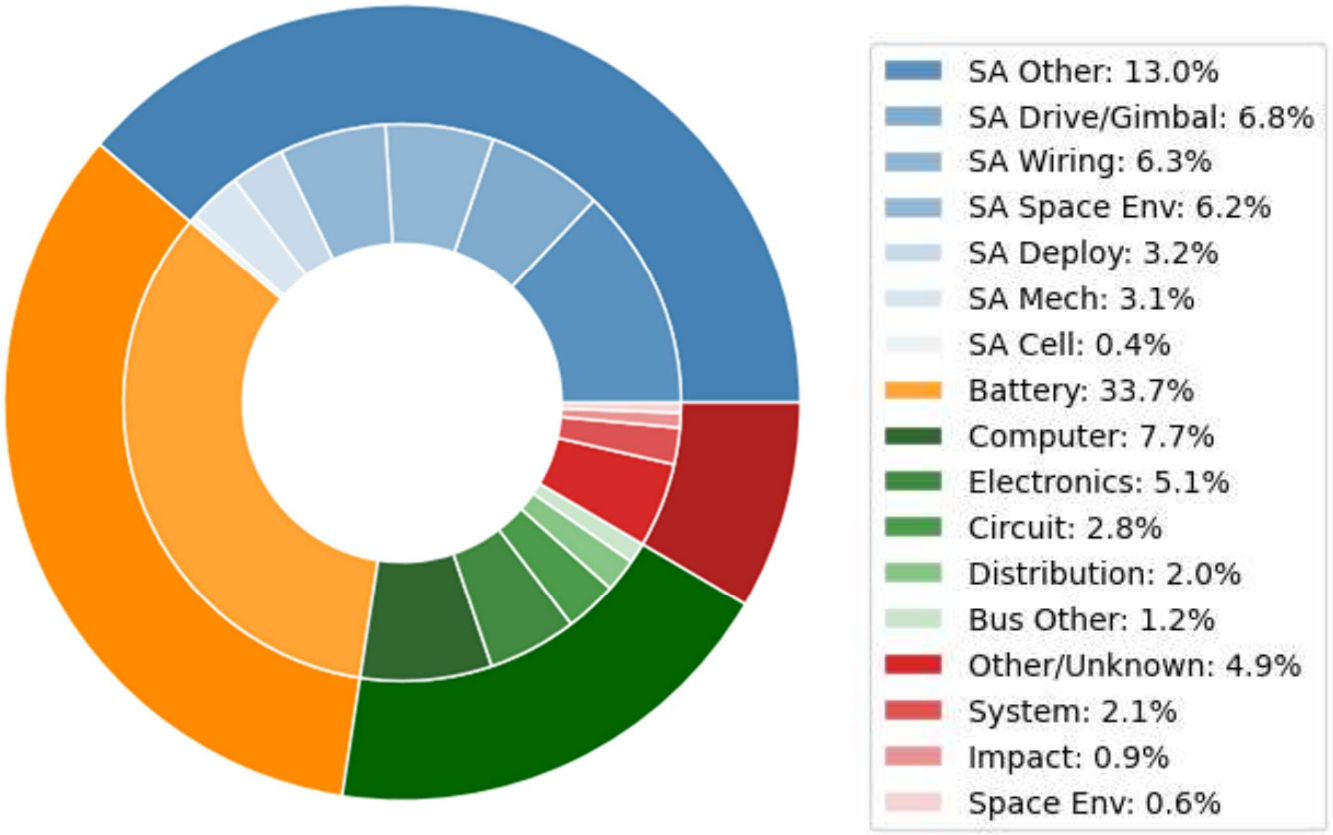
Process Used to categorize ASSET data

- There are 3 descriptive columns that can tell what caused the anomaly
  - "Title", "Cause Description", and "Abstract"
  - These three have varying degrees of information, and some are more vague than others
- Using key words in each of the three columns can broadly categorize many items
  - e.g., "Solar", "SA", "Panel" all are key words for Solar Arrays. "Distribution", "Bus" for PMAD. "Battery", "Batt" for Batteries
- Using acronyms commonly found in known categories as further key words
- Read individually entries and decided on the assigned category that best fit the description
  - Future work: explore natural language processing to categorize anomalies

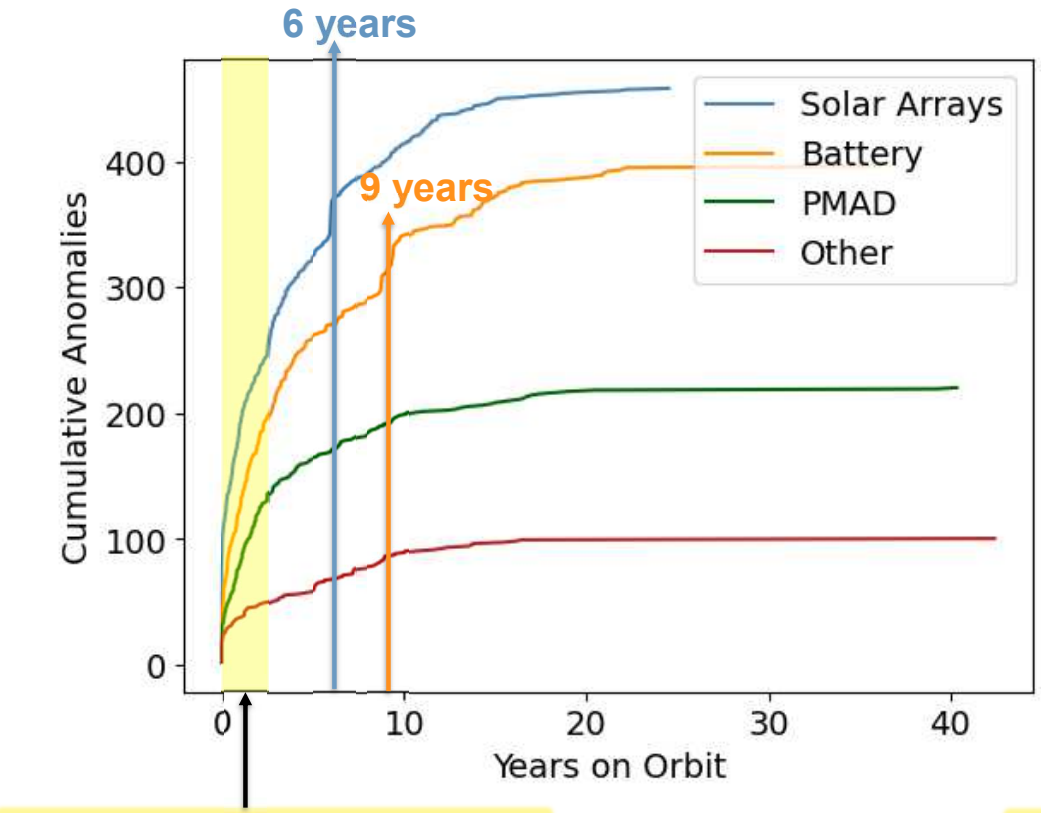
Common Types of EPDS Anomalies Categorized

	Cause	# Incidents	Percent of total Anomalies	Description of Category
Solar Array	SA Other	153	13.00%	Not traceable to one specific cause, or otherwise undisclosed
	SA Drive/Gimbal	80	6.80%	Anomalies with placement and movement of solar arrays, or issues with sun sensors
	SA Wiring/String Loss	74	6.30%	A fault with wiring or interconnects between cells/array. Including shorts and loss of strings
	SA Space Environment	73	6.20%	Degradation in performance due to space environment, including radiation, darkening, etc.
	SA Deployment	37	3.20%	Anomalies with deployment, or issue traced back to deployment
	SA Mechanical	36	3.10%	An anomaly with mechanical equipment not related to deploy or drive
	SA Cell	5	0.40%	Cell level defects such as cracking
Battery	Battery	396	33.70%	All anomalies related to the batteries
PMAD	Computer	90	7.70%	Software anomalies relating to Power Management
	Electronics	60	5.10%	Power converters, etc.
	Electrical Circuit	33	2.80%	Shorts, other wiring/circuit issues between EPS components
	Distribution	23	2.00%	Power system control board fault
	Bus Other	14	1.20%	Related to the power bus, but not specified
Other	Other/Unknown	58	4.90%	Unable to be traced to a specific part, or unspecified
	System	25	2.10%	Interrelated issue involving 2 or more parts of EPS
	Impact	10	0.90%	Impact by micrometeoroid, etc.
	Space Environment	7	0.60%	Arcing, spacecraft charging, causing a fault in the power electronics
	Total	**1174**		

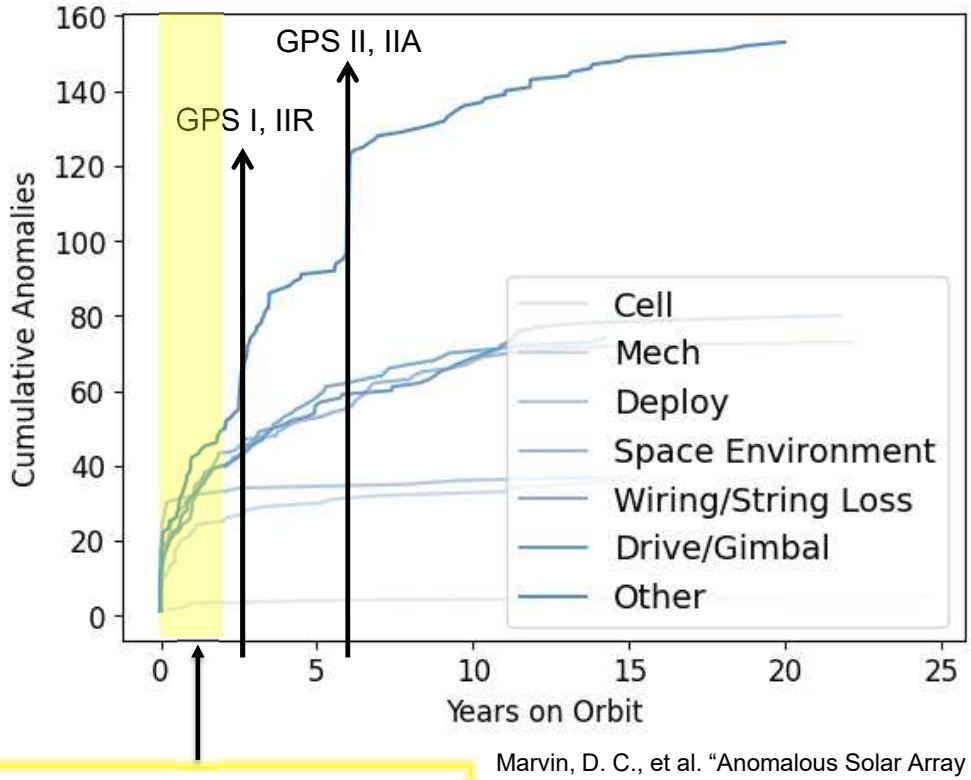
Breakdown of EPDS Anomalies by Categories



Cumulative Anomalies vs. Years on Orbit



50% failures in first 2.5 years



50% failures in first 1.9 years

50% of all EPS and solar array anomalies occur within 2.5 years after launch.

Marvin, D. C., et al. “Anomalous Solar Array Performance on GPS,” 1988.
Ferguson, D, et al. “Anomalous Global Positioning System Power Degradation from Arc-Induced Contamination.” 2016.

Source: Aerospace ASSET Anomalies Database

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Solar Array Anomalies Through Time (normalized to # of launches)