Space Environment Impacts on GEO COMSATs

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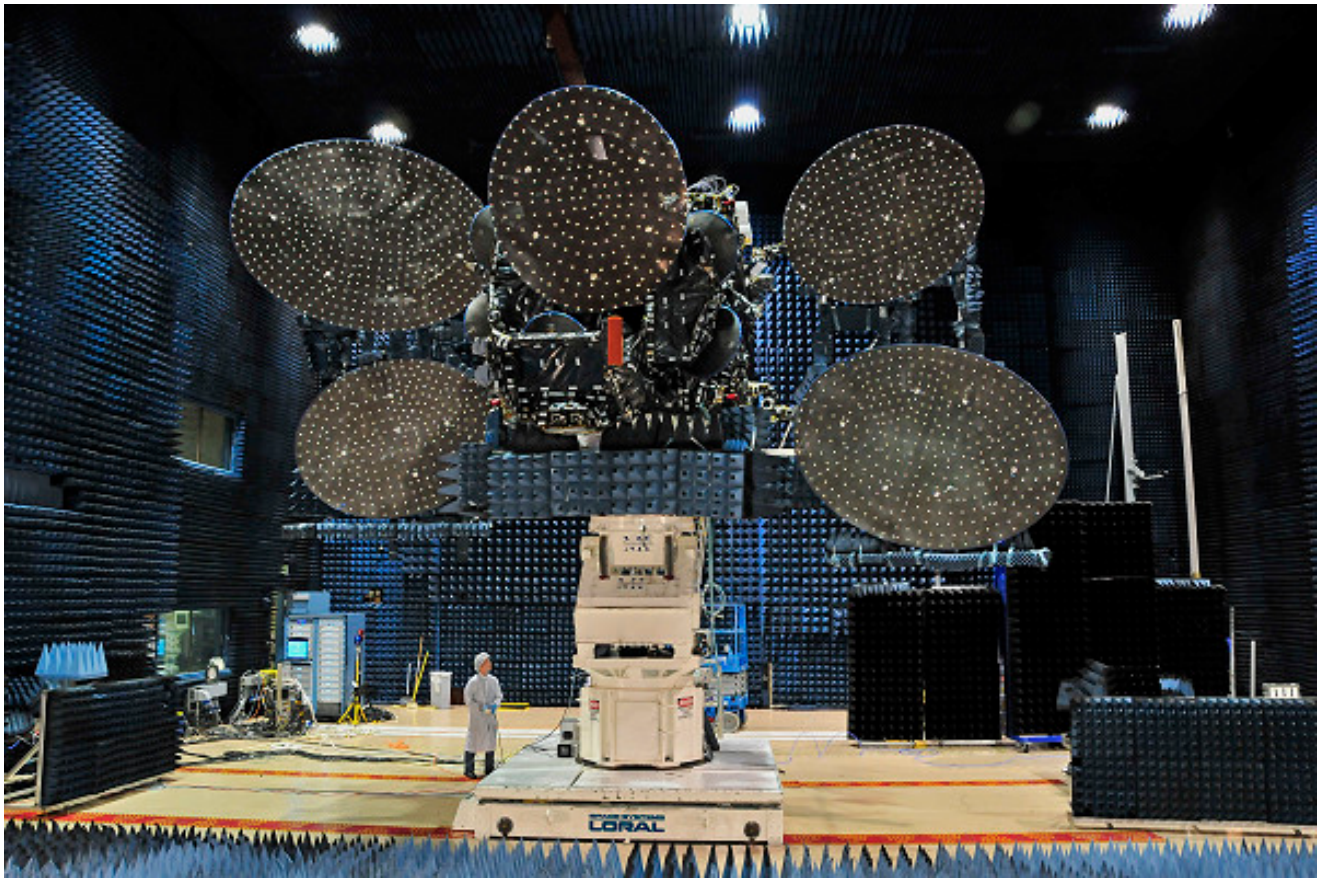
Geostationary Satellite



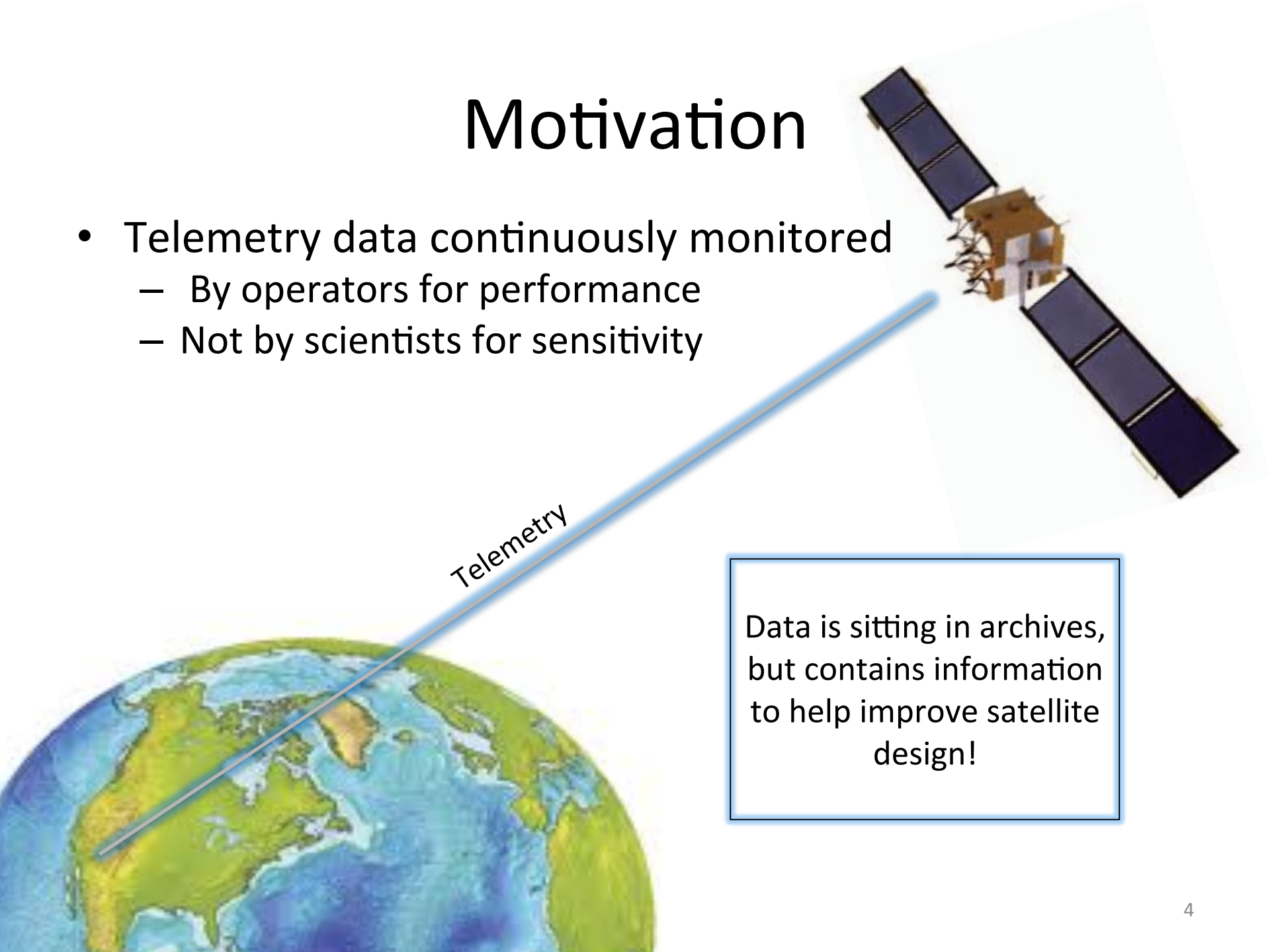
Telstar 14R– Space Systems/Loral

Outline

I. Motivation
II. Enabling factor: Satellite Operators' data
III. Investigation of Known Anomalies
    I. Amplifier Anomaly Study
    II. Solar Array Degradation
IV. Telemetry Algorithm

Motivation

- Telemetry data continuously monitored
  - By operators for performance
  - Not by scientists for sensitivity



Data is sitting in archives, but contains information to help improve satellite design!

Motivation

- **How sensitive are communications satellites to the radiation environment? Can we quantify?**
  - To understand how space weather causes anomalies must have **both** space weather data and satellite telemetry
  - Hard to get access to telemetry!
- **Strategy**: partner with operators, focus on key components (amplifiers and power systems)
- First-of-its kind MIT/industry collaboration w/Inmarsat in 2011
  - Producing important findings
  - Other operators now also participating

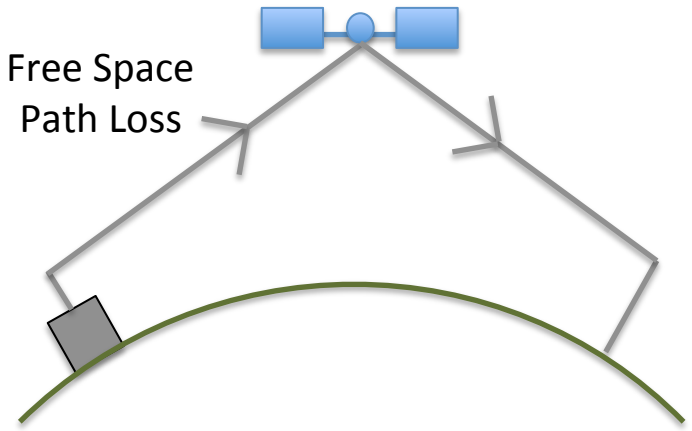
Satellite Operators

Operator	Inmarsat	Telenor	ARABSat
Headquarters	United Kingdom	Norway	Saudi Arabia
Number of Satellites	10	4	3
Number of Bus Types	3	3	2
Data Time Range	1991 – 2012	1997 - 2012	1996 - 2011
Years of Data	22	16	17
Telemetry Obtained	SSPA current and temperature; solar panel current, total bus power; anomaly and SEU list	TWTA current and temperature; solar panel current and total bus power; anomaly and SEU list	Solar panel current and total bus power

Currently obtaining data from Intelsat as well!

What are power amplifiers?

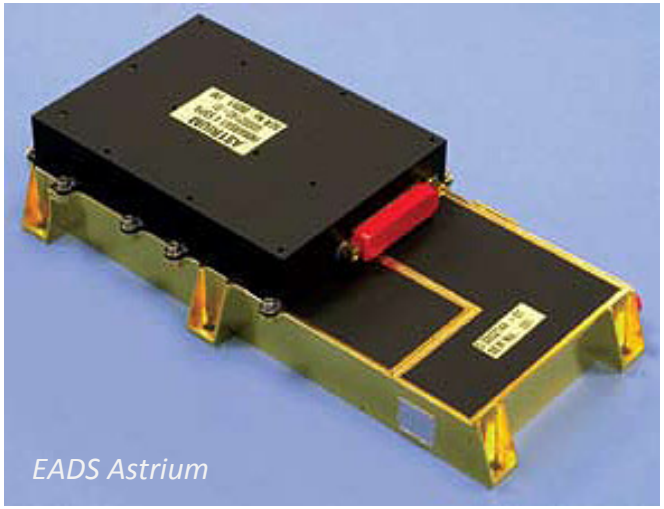
- Key components in satellite comm systems
  - Strengthen uplink signals that are weakened from free space path loss [1,3,4]
  - Amplifier units consume ~85% of the spacecraft bus power [1,2]



- Two primary types: solid state power amplifiers (SSPAs) and traveling wave tube amplifiers (TWTAs)
- Technologies have evolved over past decades

Components

- Solid State Power Amplifier (SSPA)
- Traveling Wave Tube Amplifiers (TWTA)
- Solar Panels
  - Silicon, Gallium Arsenide



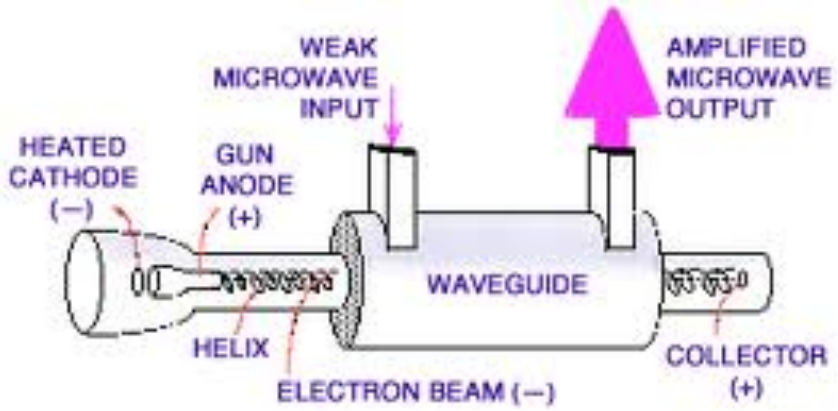
TWTAs vs. SSPAs

TWTA Technology

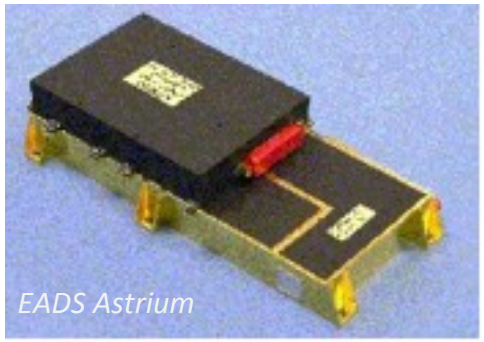
- Traveling wave tube (TWT) and electrical power conditioner (EPC)
- Used for high power + high freq.
- Provide better efficiency [10]
- 1992-2006 69% COMSATS used TWTAS [5]

SSPA Technology

- Field effect transistor (FET) and EPC [1]
- Less complex and cheaper [7,8]
- Historically used at L + S band
- Competitive in 1980s, new GaN technology is increasing market popularity [4]



TWTA [6]

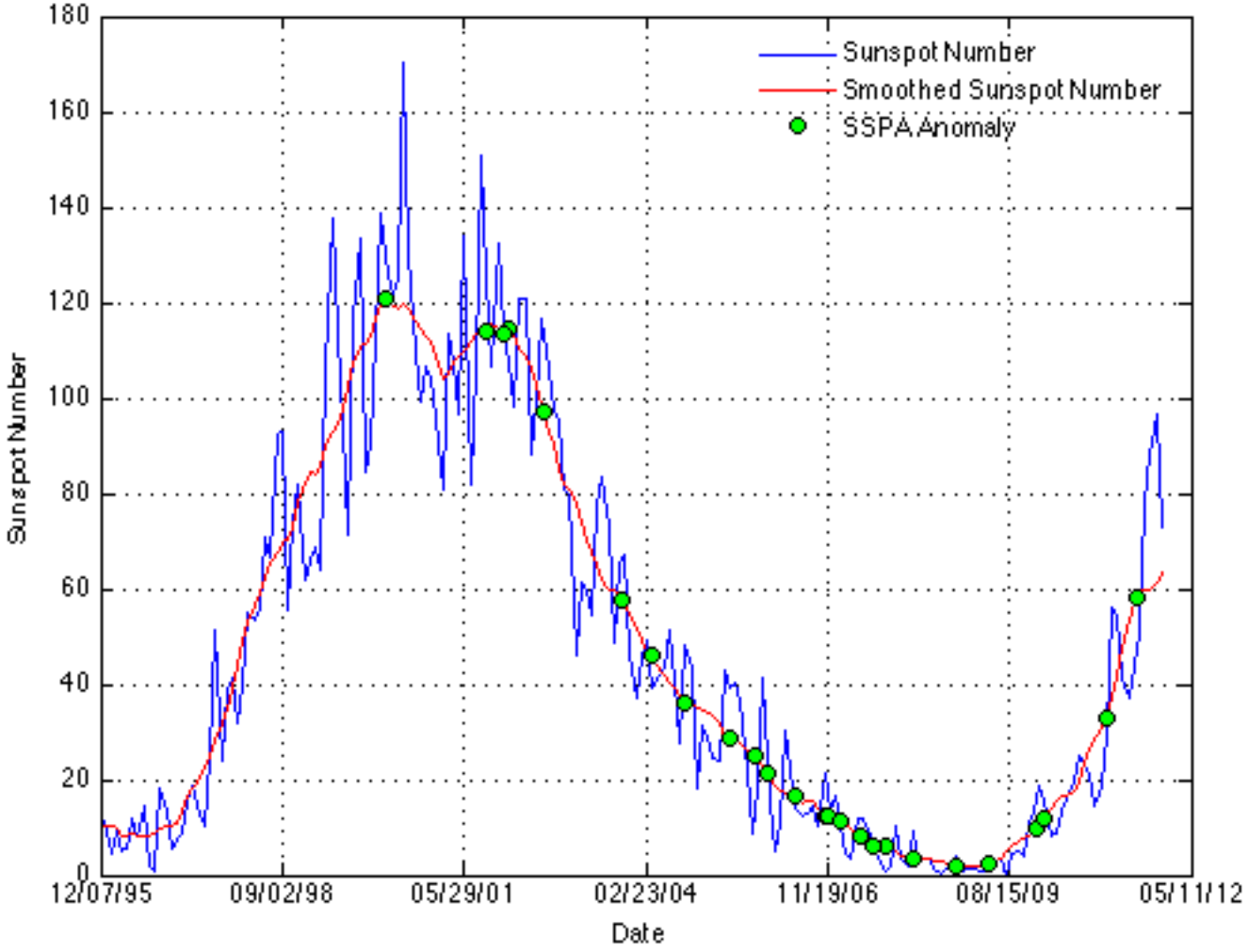


SSPA [9]

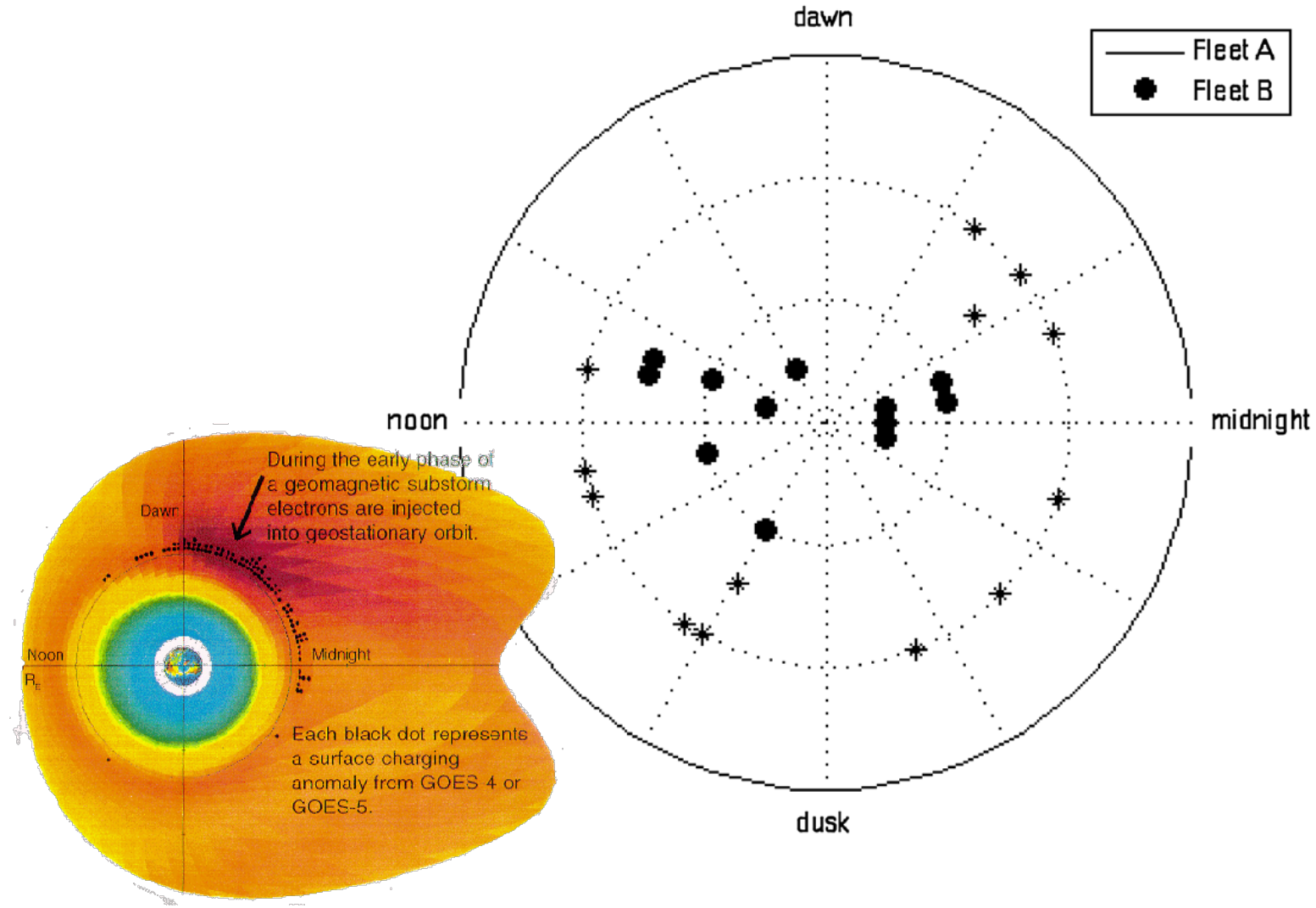
Amplifier Anomaly Study

- Analyzed solid state power amplifier (SSPA) currents from 8 Inmarsat satellites (1996-2012)
  - Amplifiers are the workhorse of the COMSAT
  - Redundancy is implemented in design
  - For 8 Inmarsat satellites, with hundreds of SSPAs, 26 anomalies over 16 years (with little to no impact on customers)
    - This is impressive performance, but we would still like to understand what caused the anomalies – was space weather a factor?
- ***Can the occurrence of anomalies be predicted?***
- ***Can we reduce the number of anomalies?***

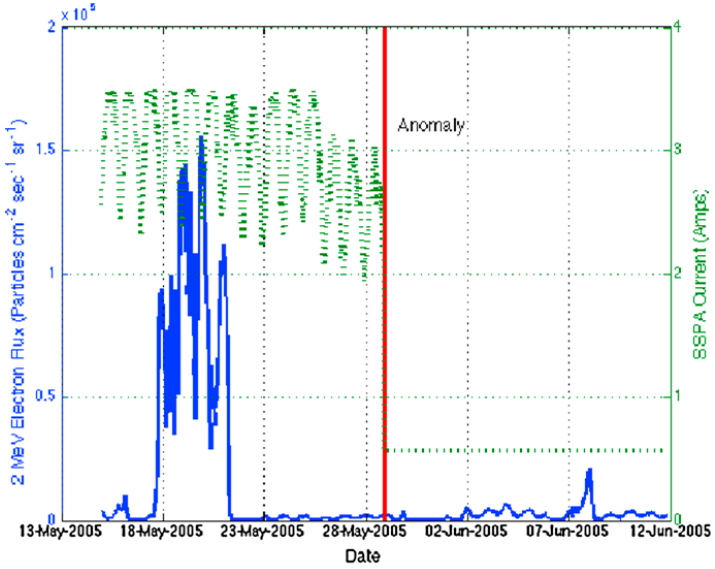
11 Year Solar Cycle

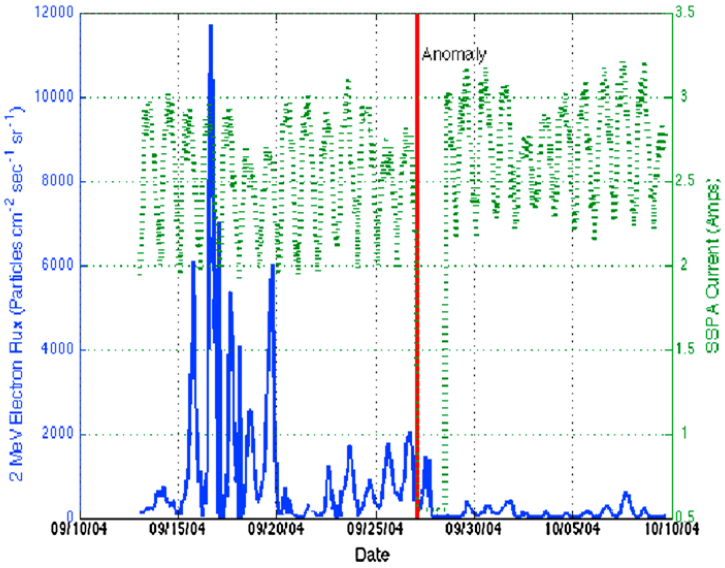


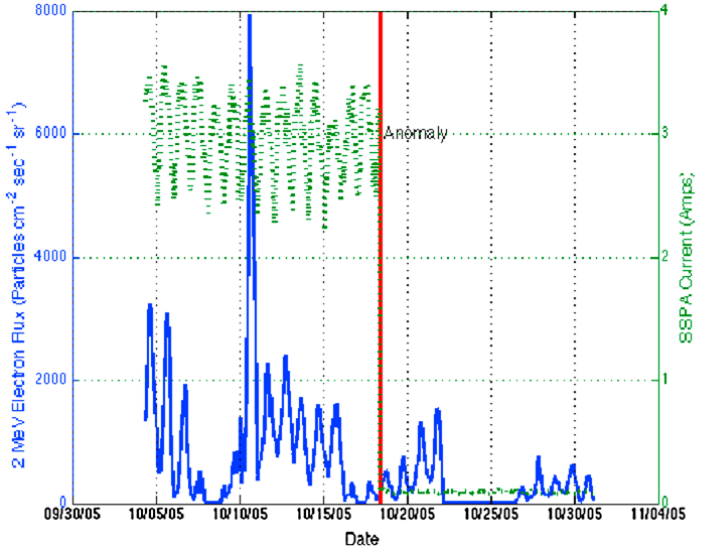
Surface Charging and Local Time

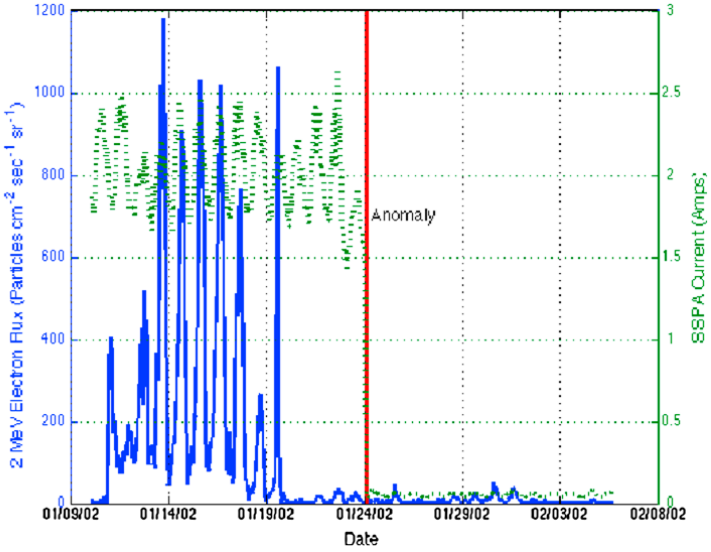


2 MeV Electrons and SSPA Currents

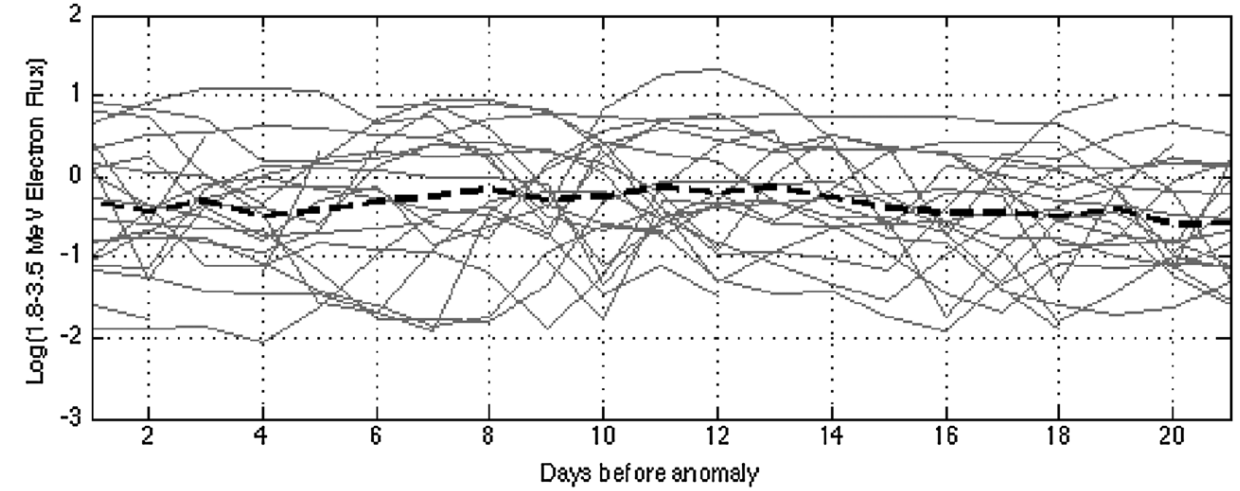


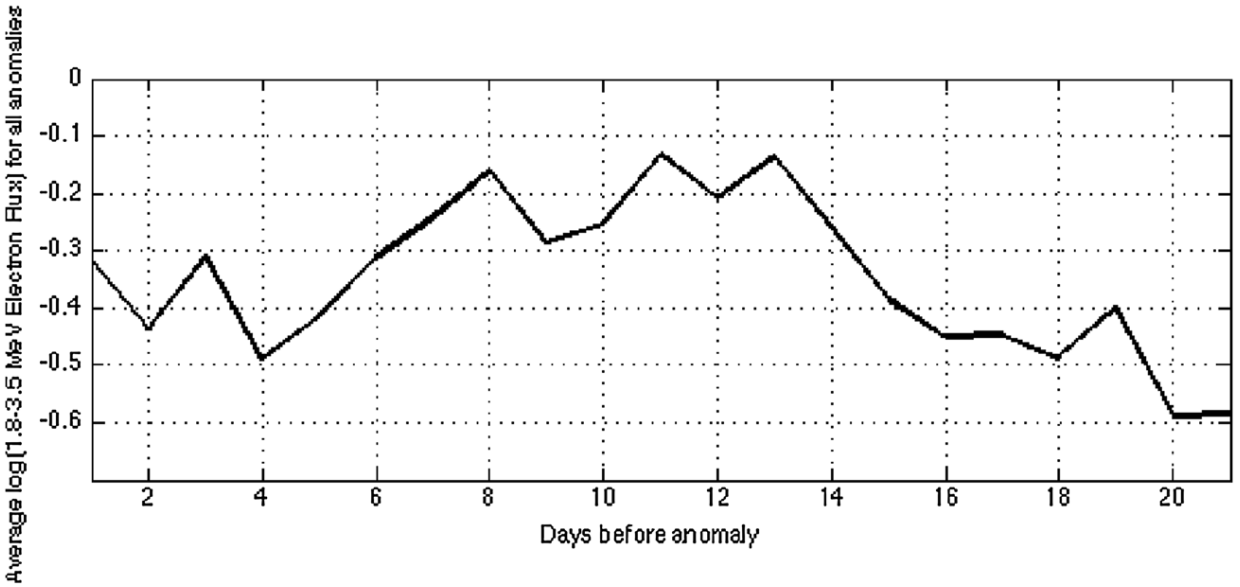






Superposed Epoch of High Energy Electron Flux





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    II. Solar Array Degradation
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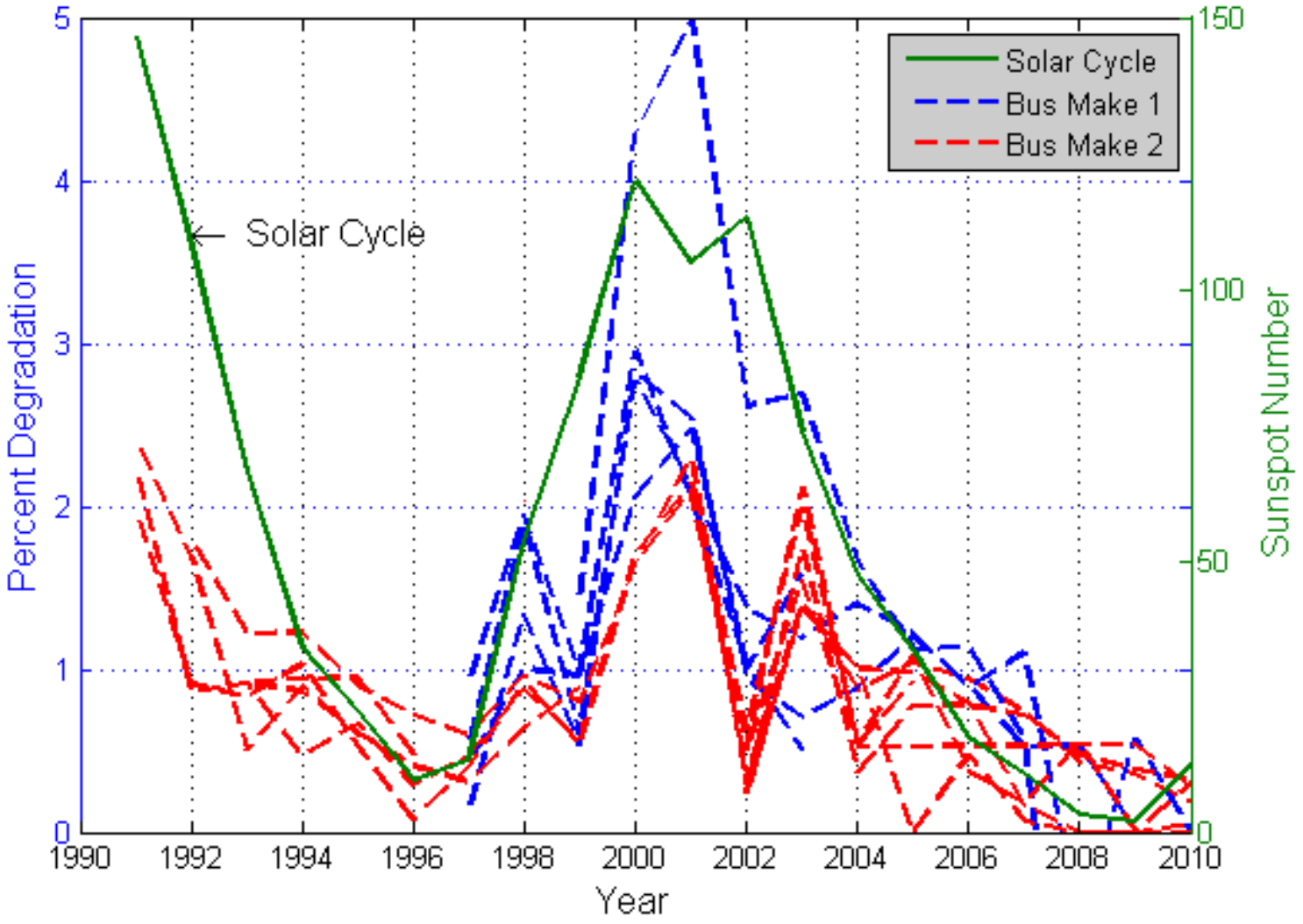
Solar Array Degradation Study

I. Solar Arrays and the GEO Radiation Environment
   I. Degradation mechanisms
   II. Solar cell performance parameters
   III. Silicon vs. GaAs solar cell technology
II. Annual Solar Array Degradation
III. Solar Array Degradation over SPE

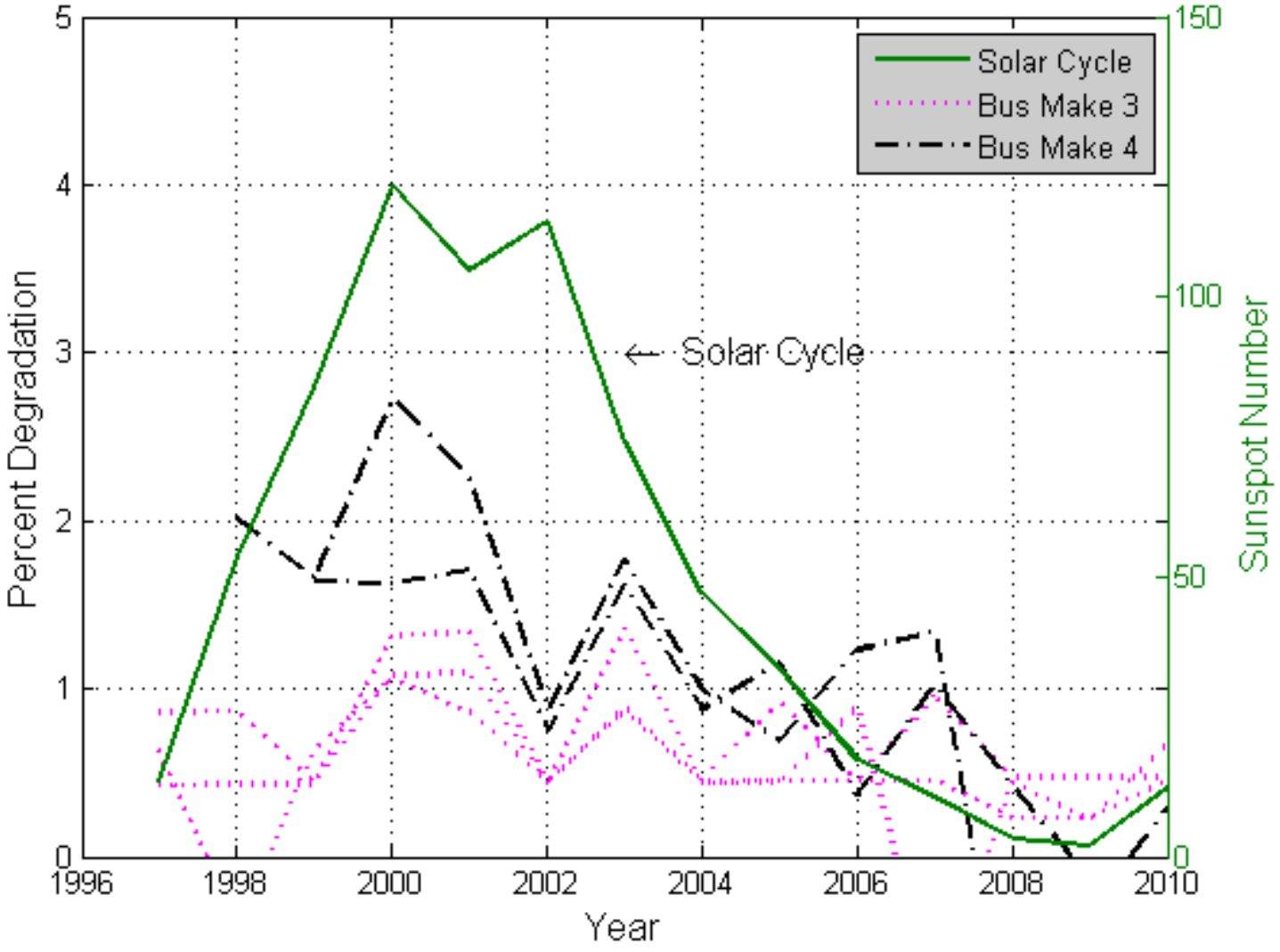
10 MeV SPE > 10,000 pfu

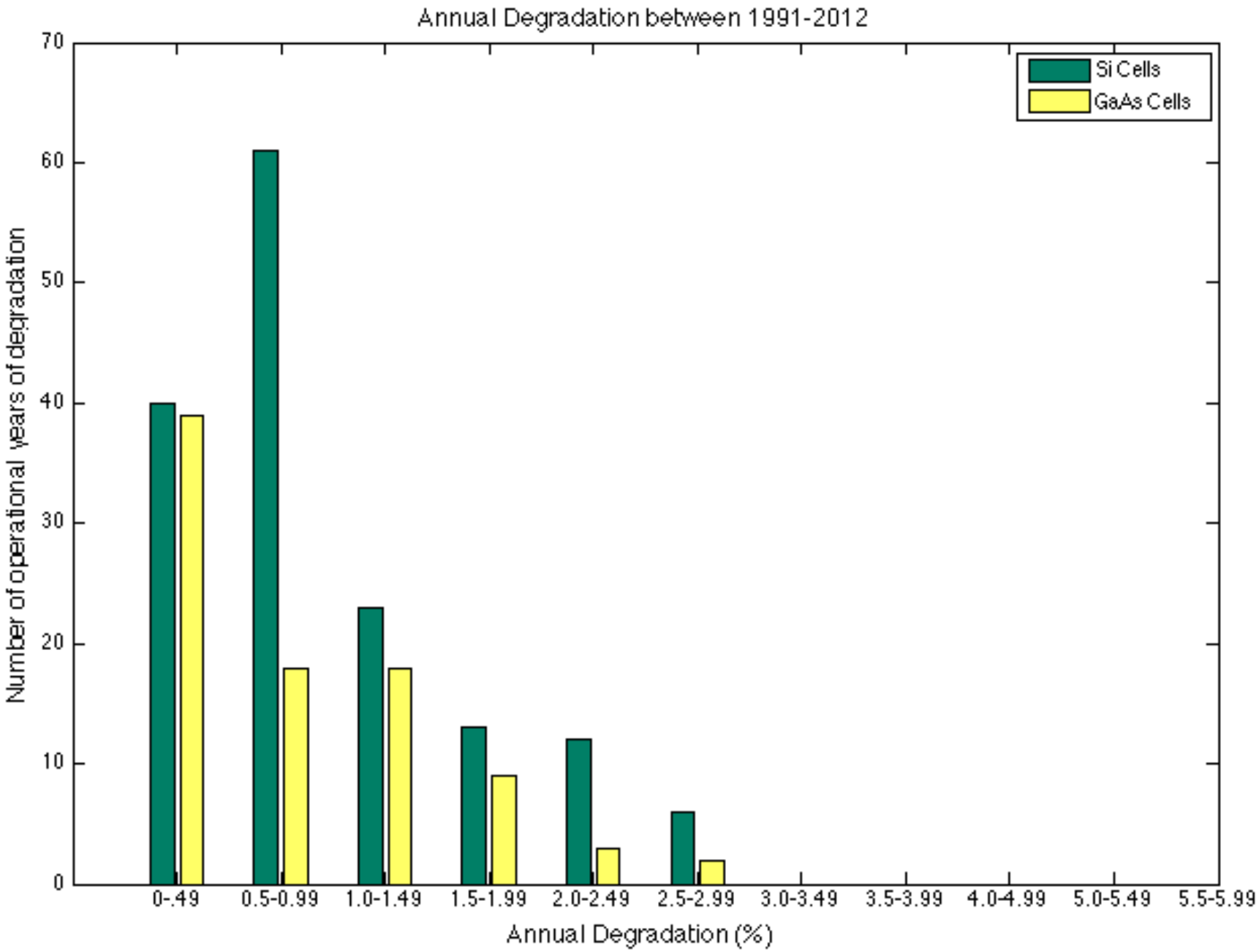
SPE	SPE Start Date	SPE Start Time	SPE End Date	SPE End Time	10 MeV Proton Flux > 10,000 pfu
1	July 14, 2000	10:45	July 15, 2000	12:30	24,000
2	Nov. 8, 2000	23:50	Nov. 9, 2000	15:55	14,800
3	Sept. 24, 2001	12:15	Sept. 25, 2001	22:35	12,900
4	Nov. 4, 2001	17:05	Nov. 6, 2001	2:15	31,700
5	Nov. 22, 2001	23:20	Nov. 24, 2001	11:15	18,900
6	Oct. 28, 2003	12:15	Oct. 29, 2003	6:15	29,500

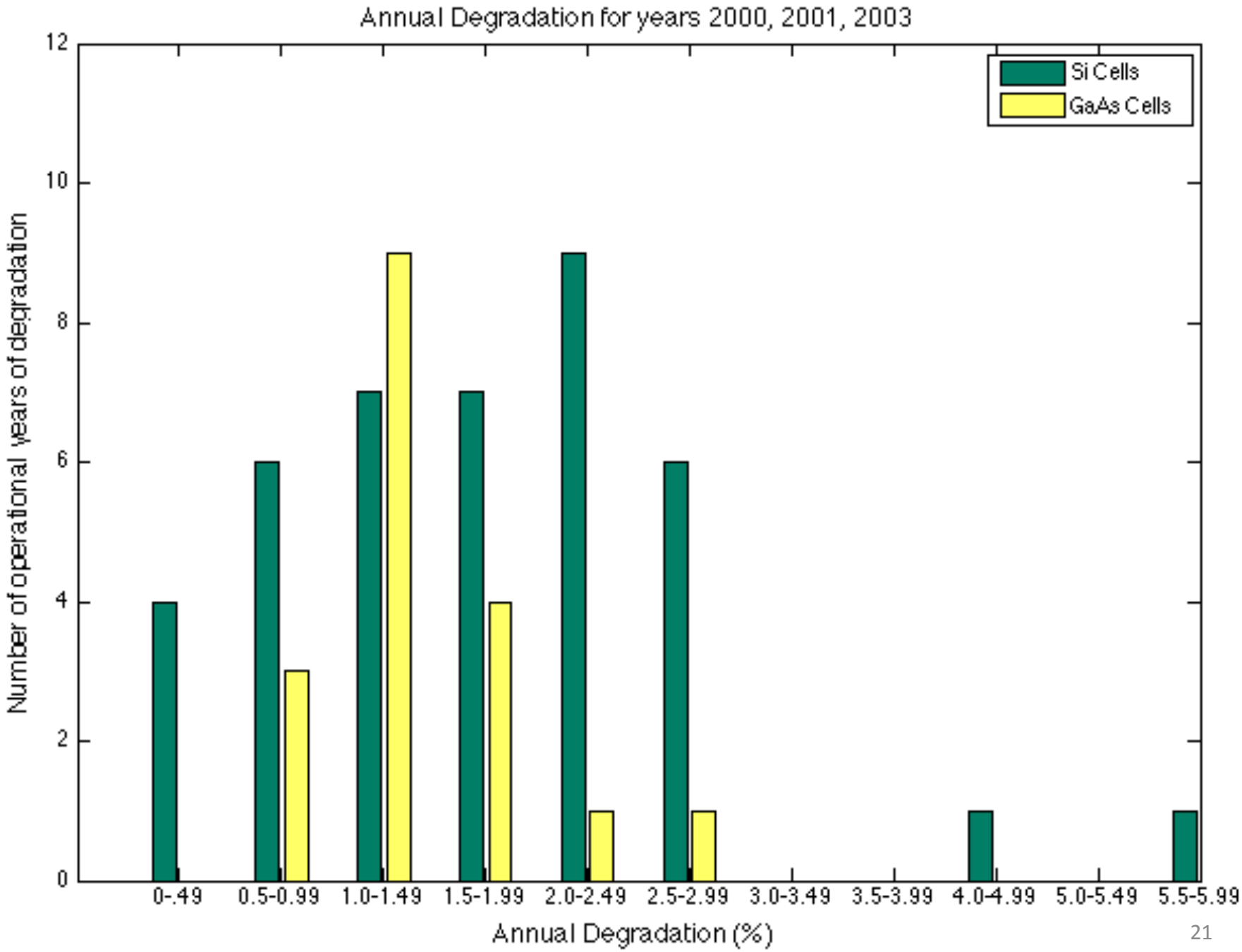
Annual Degradation for Si Cells



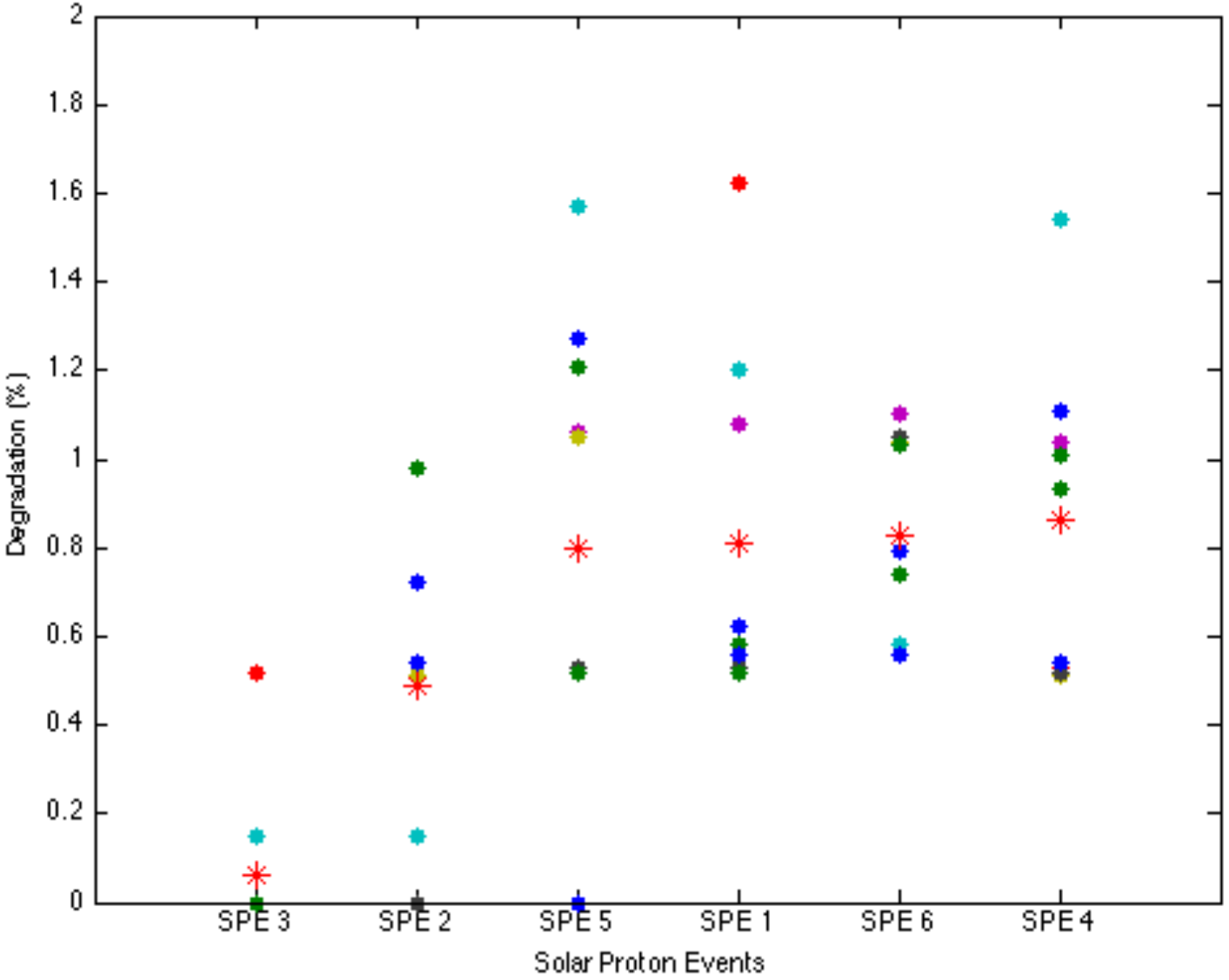
Annual Degradation for GaAs Cells



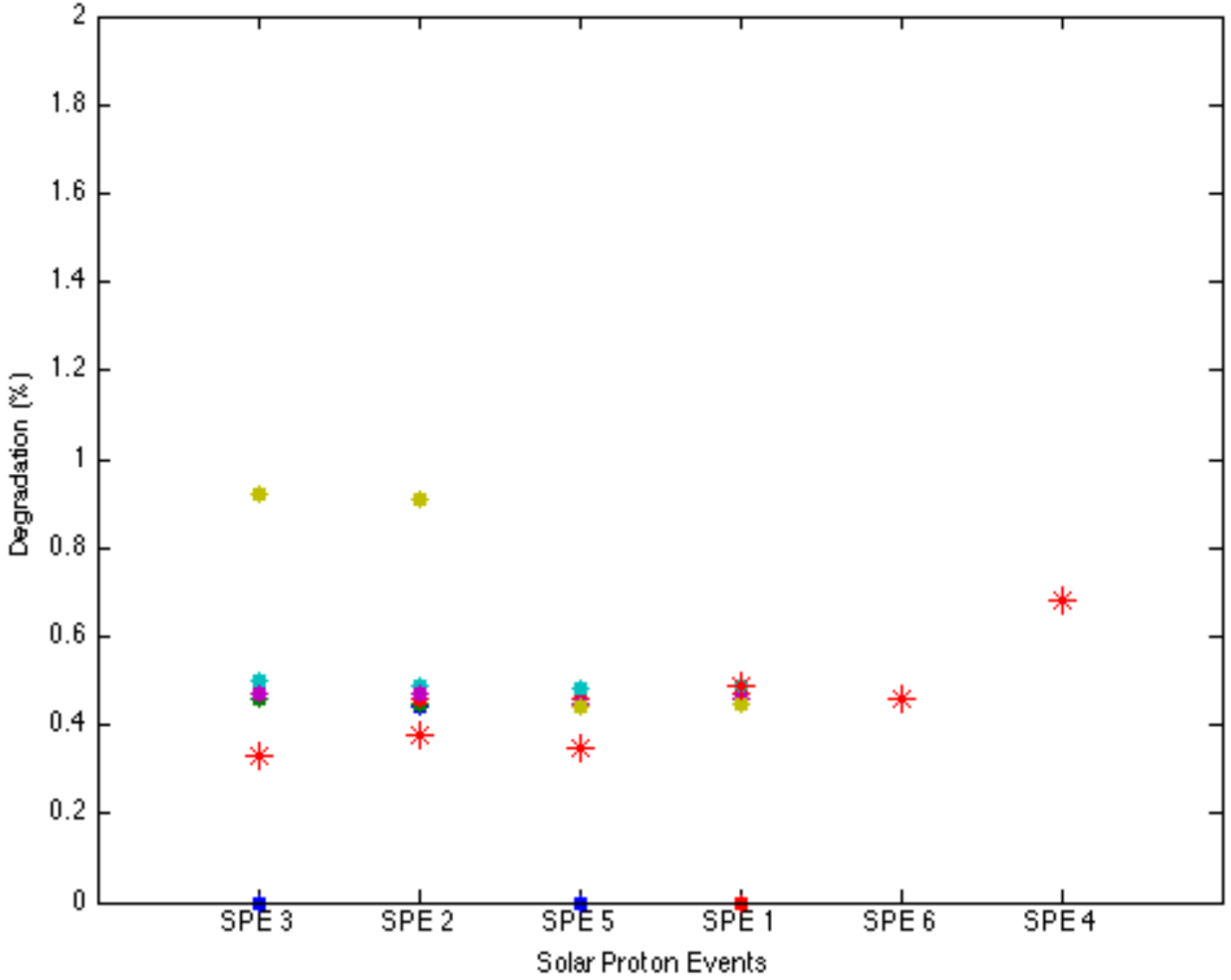

Annual Degradation between 1991-2012
Si Cells
GaAs Cells
Number of operational years of degradation
0
10
20
30
40
50
60
70
0-.49
0.5-0.99
1.0-1.49
1.5-1.99
2.0-2.49
2.5-2.99
3.0-3.49
3.5-3.99
4.0-4.99
5.0-5.49
5.5-5.99
Annual Degradation (%)


Annual Degradation for years 2000, 2001, 2003
Si Cells
GaAs Cells
Number of operational years of degradation
0
2
4
6
8
10
12
0-.49
0.5-0.99
1.0-1.49
1.5-1.99
2.0-2.49
2.5-2.99
3.0-3.49
3.5-3.99
4.0-4.99
5.0-5.49
5.5-5.99
Annual Degradation (%)

Silicon Cell Degradation over 6 SPEs



GaAs Cell Degradation over 6 SPEs



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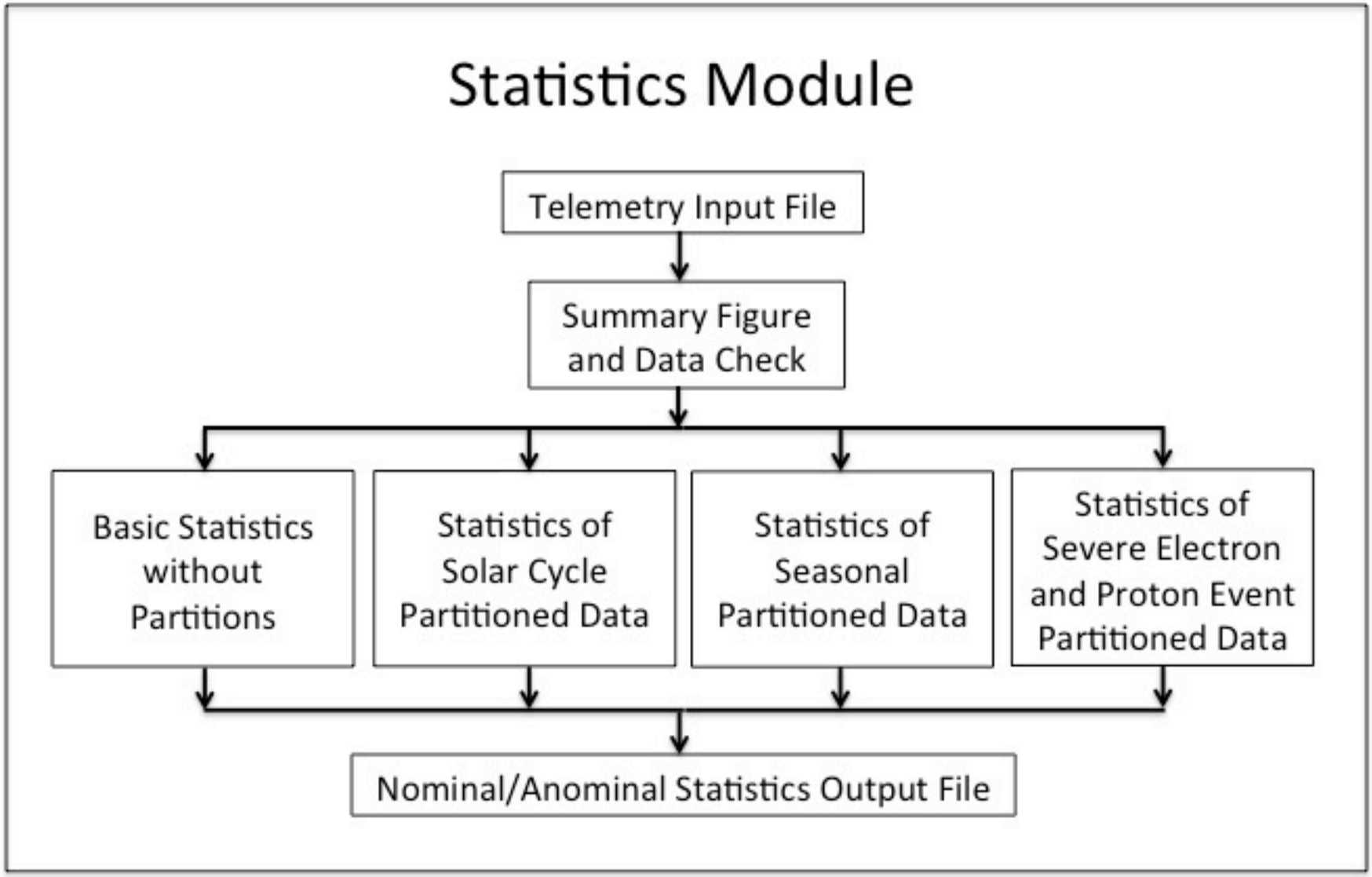
Telemetry Algorithm

Can we identify and explain odd behavior even if there may not have been an anomaly?

- Input: telemetry feed (i.e. amplifier current, amplifier temp, total bus power, etc.)
- Statistics Module
  - Partitions data over environmental events (solar cycle phases, seasons, Extreme 2 MeV Electron events, 10 MeV SPE > 10,000 pfu)
  - Compares anomalous activity with nominal
- Traffic Module
  - Calculates periodicities of the telemetry file
  - Are any periodicities in response to the environment?

Statistics Module

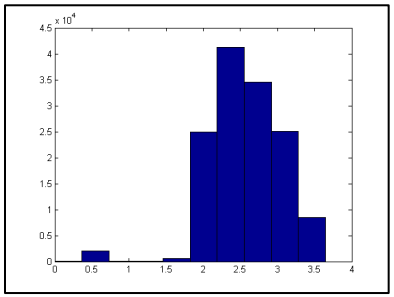
- Partitions data over environmental events
  - Solar cycle phases
  - Seasons
  - Extreme 2 MeV Electron events
    - Obtained from GOES > 2 MeV daily fluence
      - 73 Events greater than 3 sigma fluence since 1987
      - 46 Events greater than 4 sigma fluence since 1987
  - 10 MeV SPE > 10,000 pfu
    - Obtained from NOAA SPE List
    - 6 Events between 2000-2003
- Compares anomalous SSPA activity with nominal SSPA activity


Statistics Module
Telemetry Input File
Summary Figure and Data Check
Basic Statistics without Partitions
Statistics of Solar Cycle Partitioned Data
Statistics of Seasonal Partitioned Data
Statistics of Severe Electron and Proton Event Partitioned Data
Nominal/Anominal Statistics Output File

Statistics Module

Telemetry Input File

Summary Figure and Data Check



Basic Statistics without Partitions

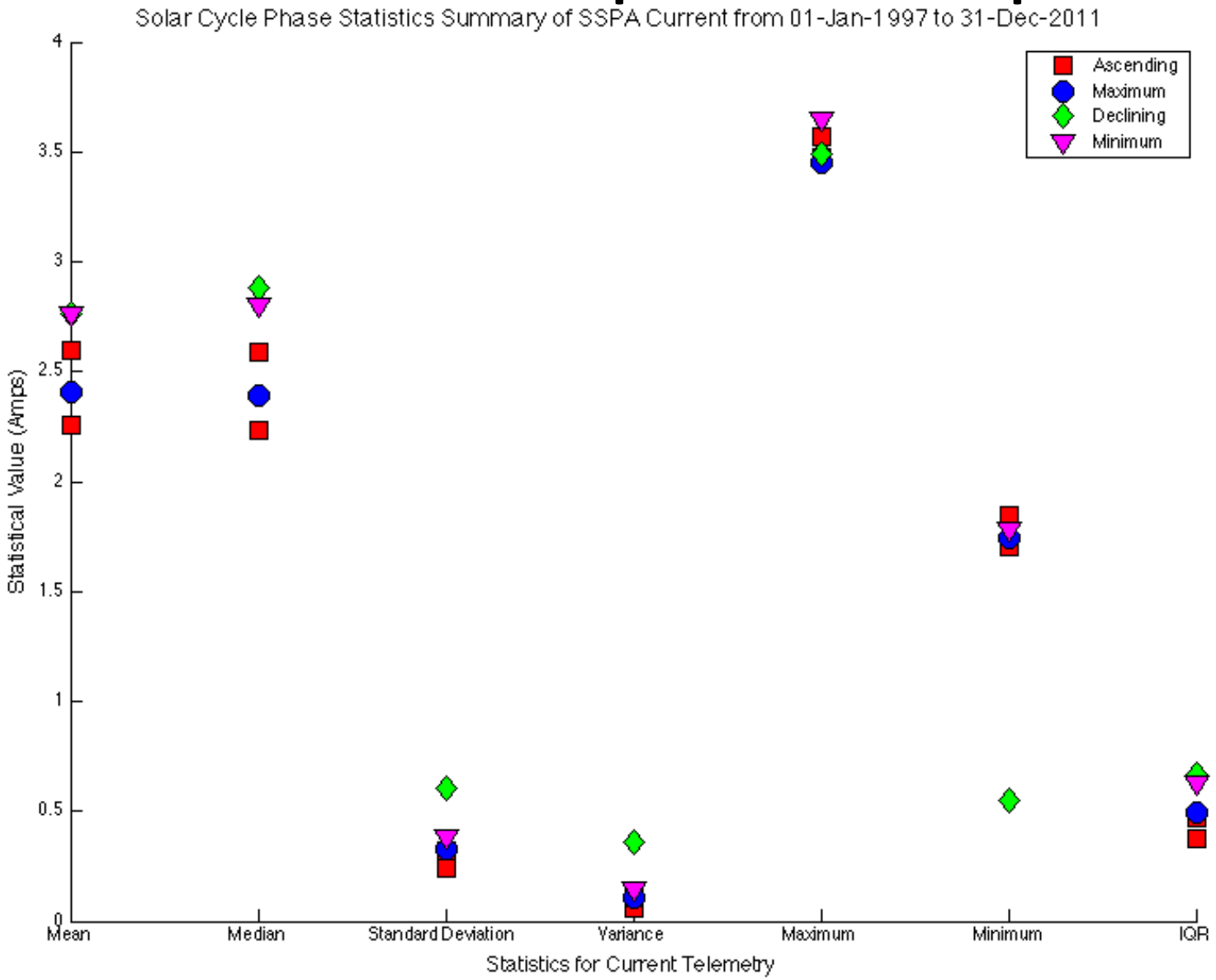
Statistics of Solar Cycle Partitioned Data

Statistics of Seasonal Partitioned Data

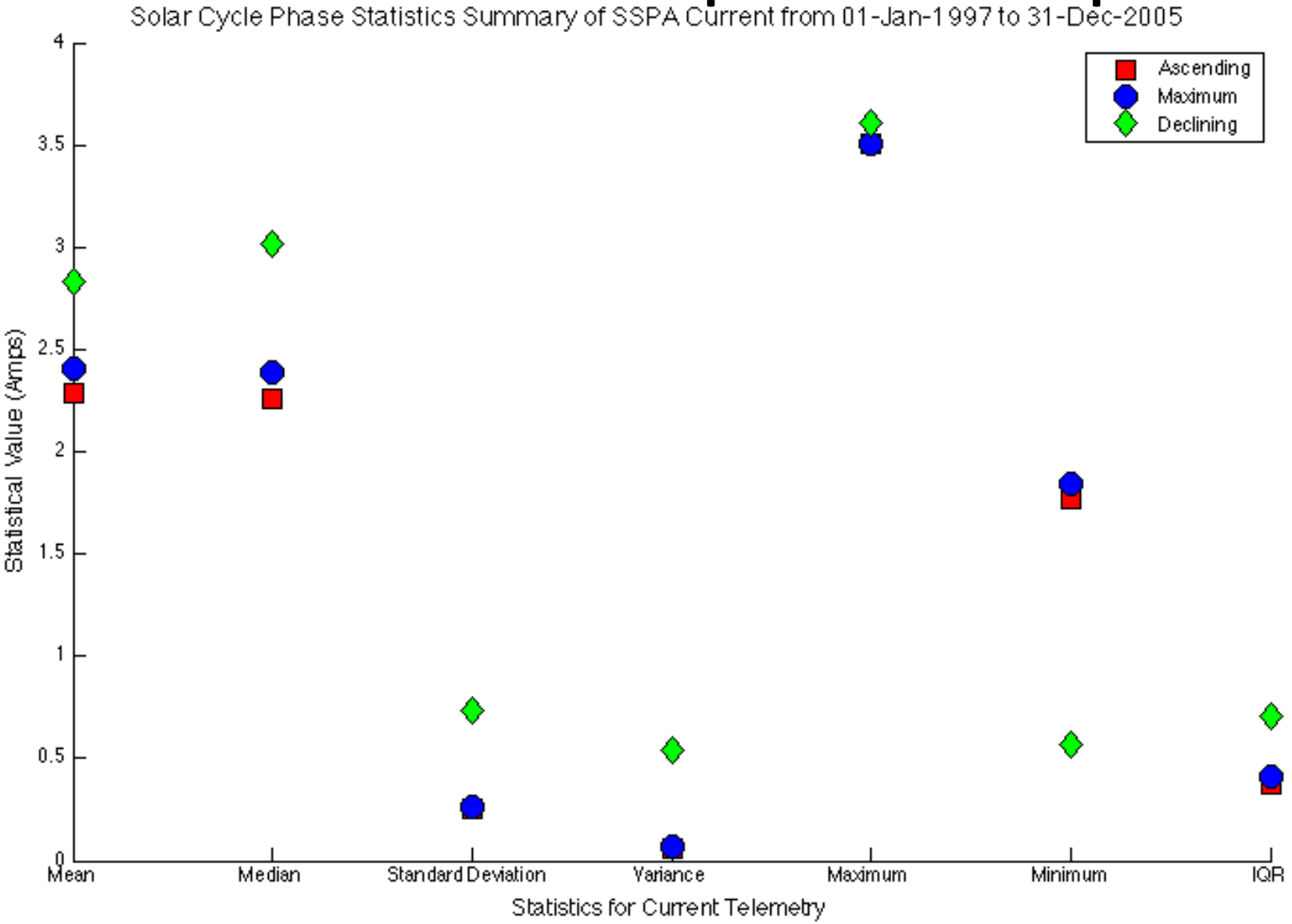
Statistics of Severe Electron and Proton Event Partitioned Data

Nominal/Anominal Statistics Output File

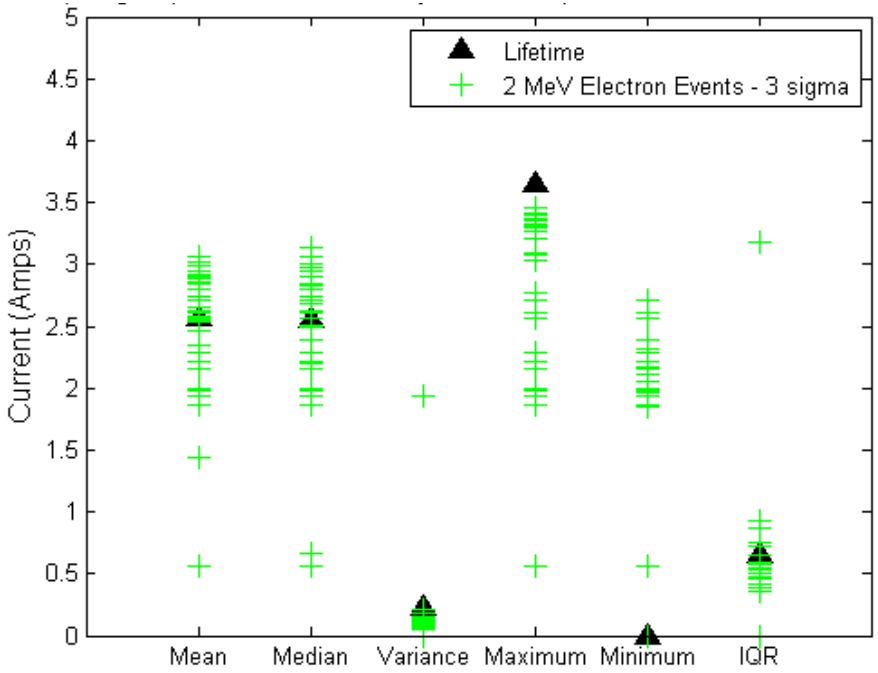
Nominal Amplifier Output

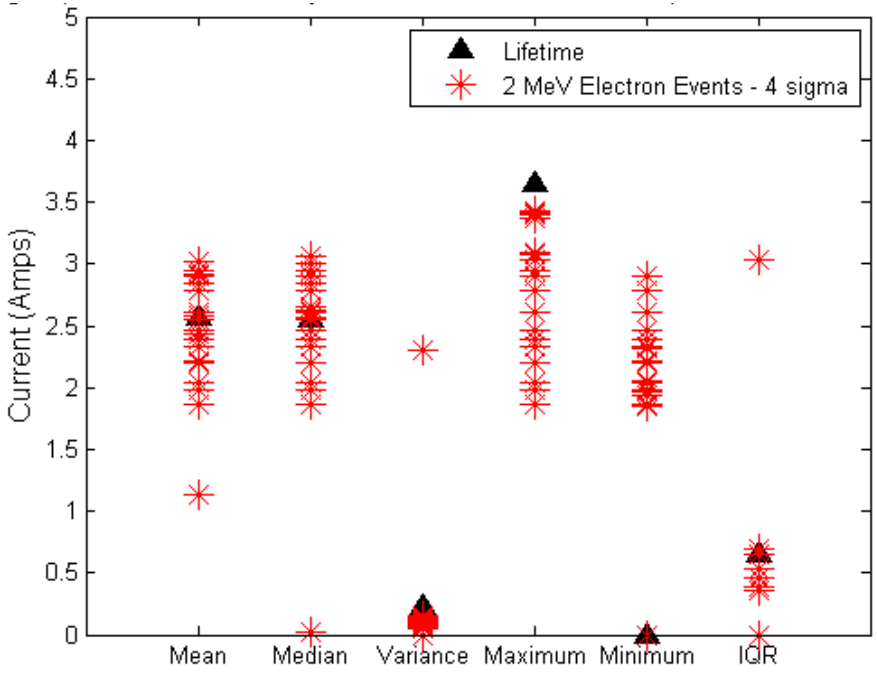


Anomalous Amplifier Output



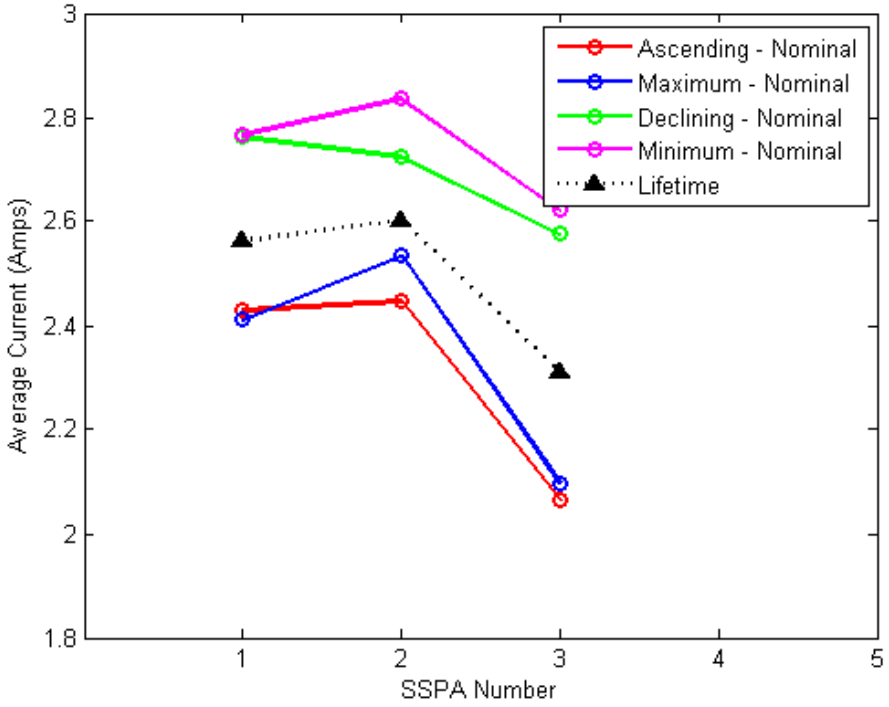
Average Current during 2 MeV Electron Events for a Nominal Amplifier



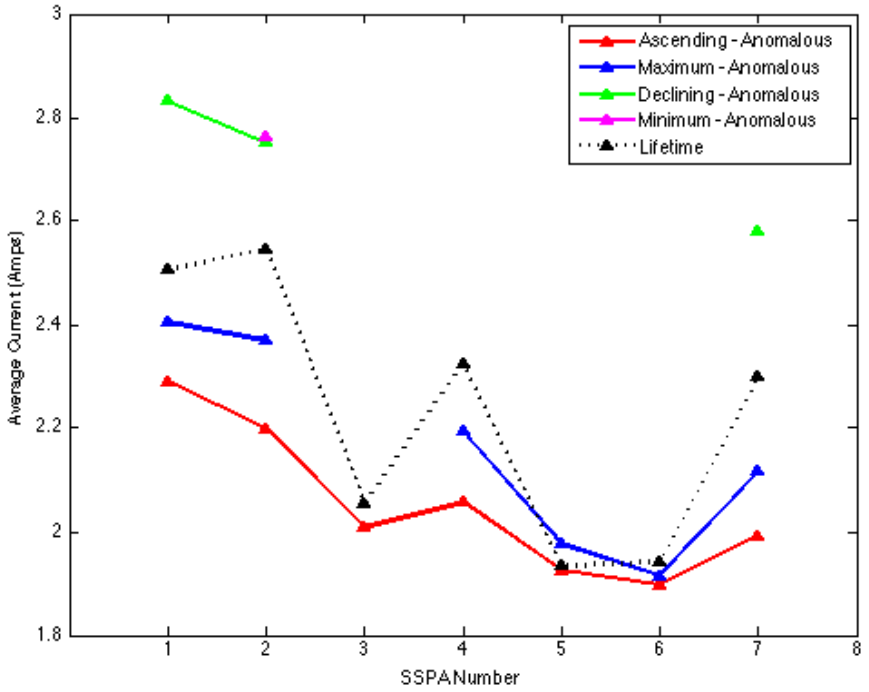


Average Current over Solar Cycle Phases

Nominal SSPAs

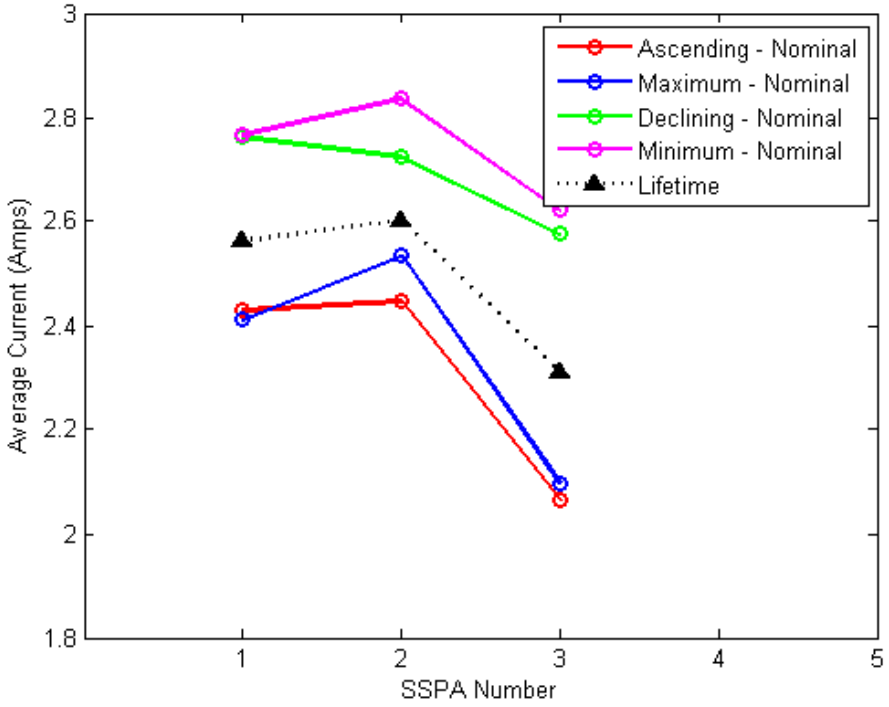


Anomalous SSPAs

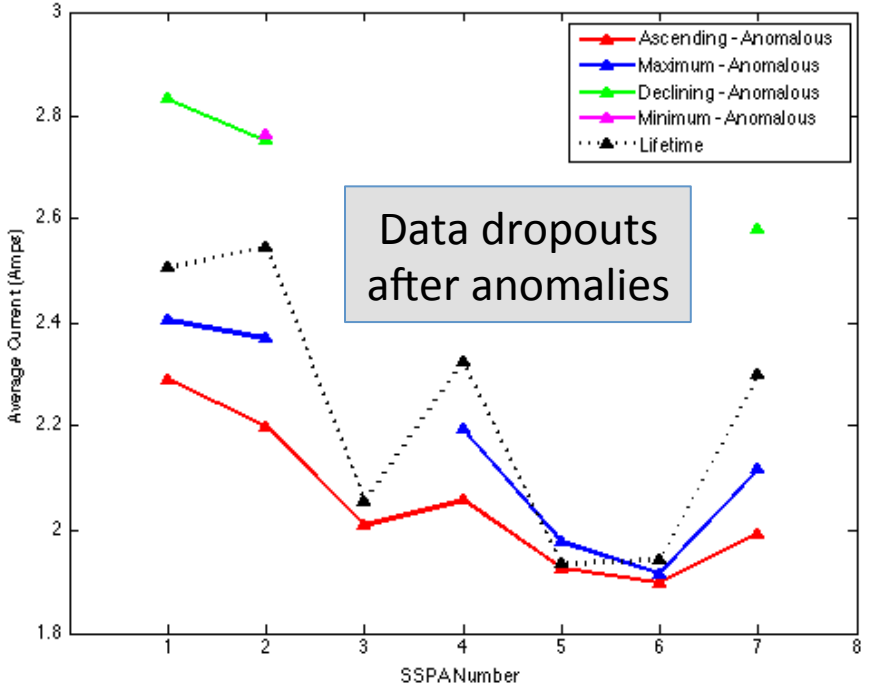


Average Current over Solar Cycle Phases

Nominal SSPAs



Anomalous SSPAs

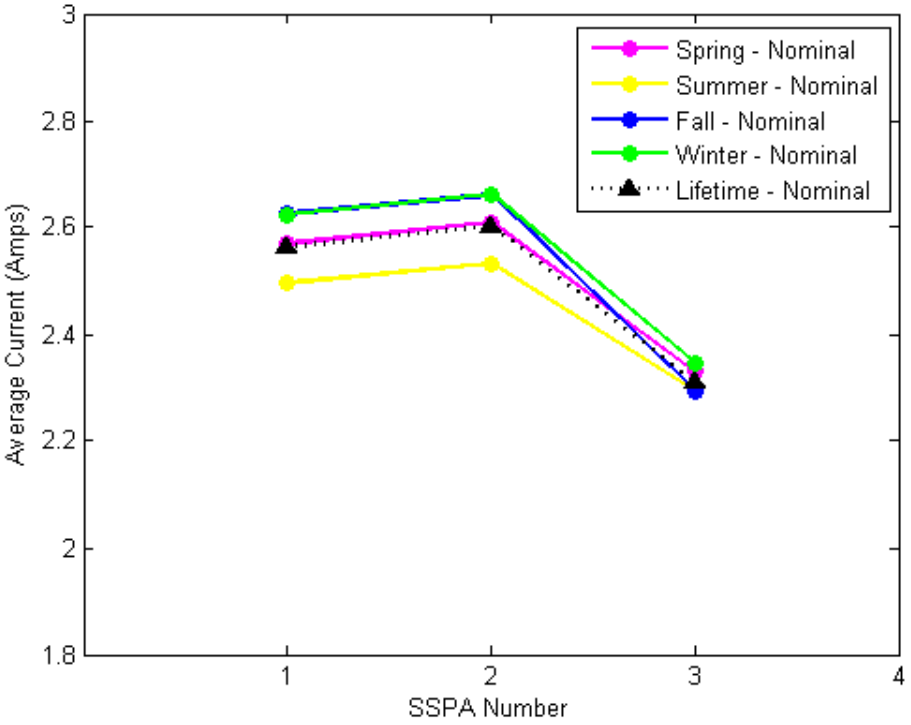


Data dropouts after anomalies

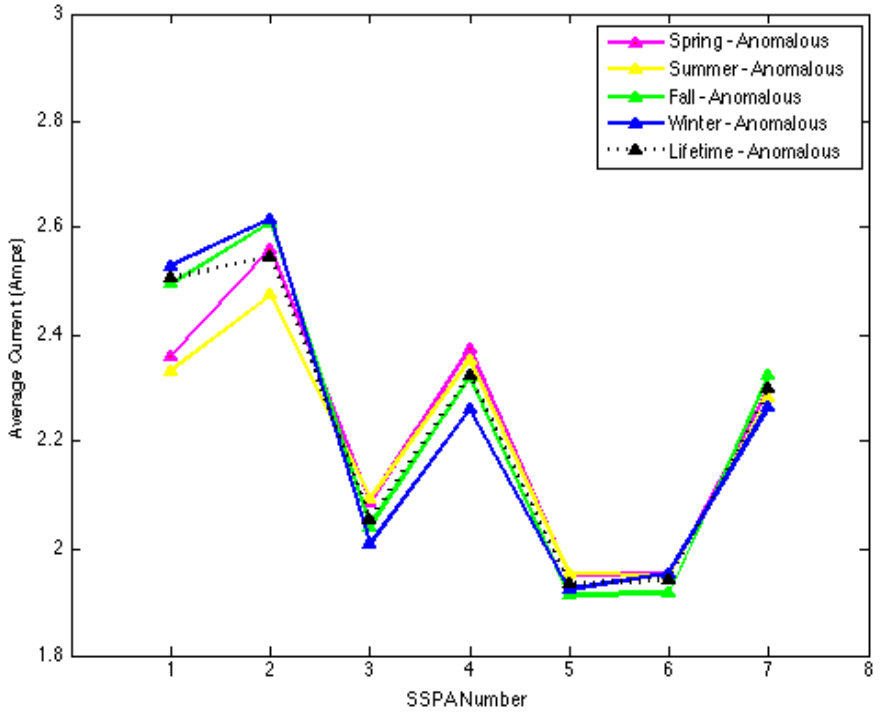
What is causing the deviation between ascending/maximum and declining/minimum phase?

Average Current over Seasons

Nominal SSPAs



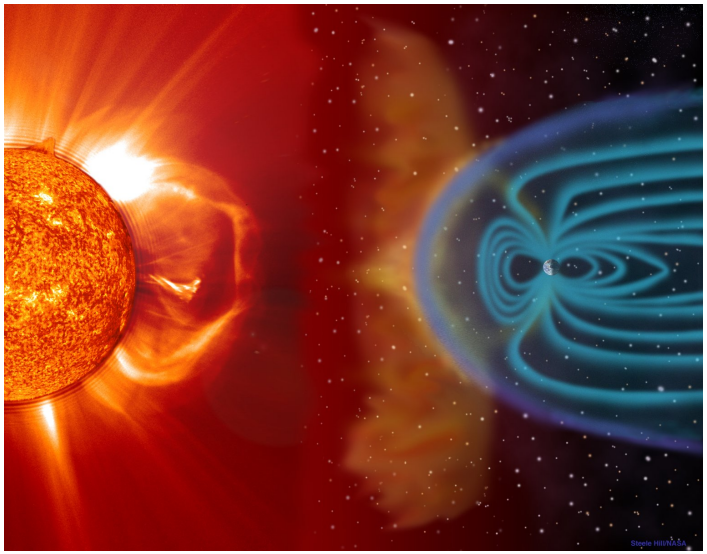
Anomalous SSPAs



We do not expect a recurrent deviation in seasonal partitioned data

Summary and Future Work

- Future Goals for Analysis:
  - Amplifier Study
    - Continue to investigate internal charging mechanisms
  - Solar Array Degradation
    - Improve statistics and define Solar Degradation vs. SPE curve
  - Telemetry Algorithm
    - Run telemetry for remaining buses
    - Determine cause of deviation between ascending/maximum and declining/minimum phases
    - Plot the current partitioned over severe environmental events



Acknowledgements

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[4] Kaliski, M. (2009), "Evalution of the Net Steps in Satellite High Power Amplifier Technology: Flexible TWTAs and GaN SSPAs", IEEE International Vacuum Electronics Conference, 28-30 April 2009.

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[7] Escalera, N., (2008), Ka-band, 30 watts solid state power amplifier. In *Microwave Symposium Digest. 2000 IEEE MTT-S International* (Vol. 1, pp. 561-563), IEEE.

[8] Sechi, F., and M. Bujatti (2009), *Solid-State Microwave High-power Amplifiers.* Artech House, M.A.

[9] SSPA Image http://www.astrium.eads.net/en/equipment/l-band-sspa.html.