Identifying Failed Solar Array Strings on the International Space Station

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Thank You

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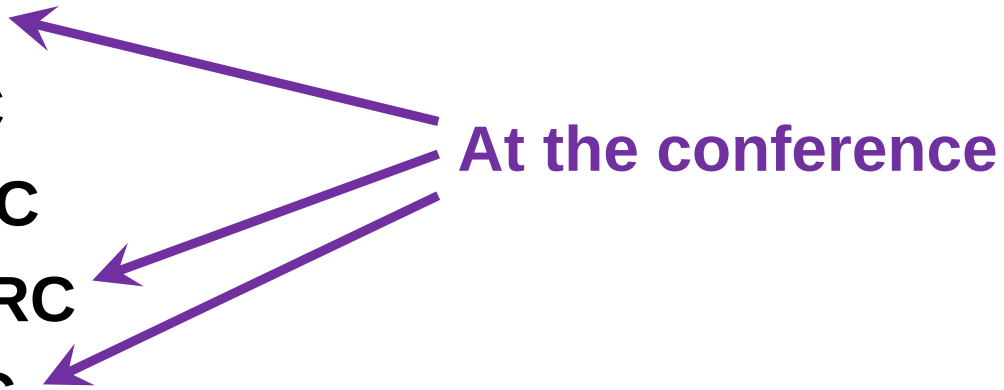
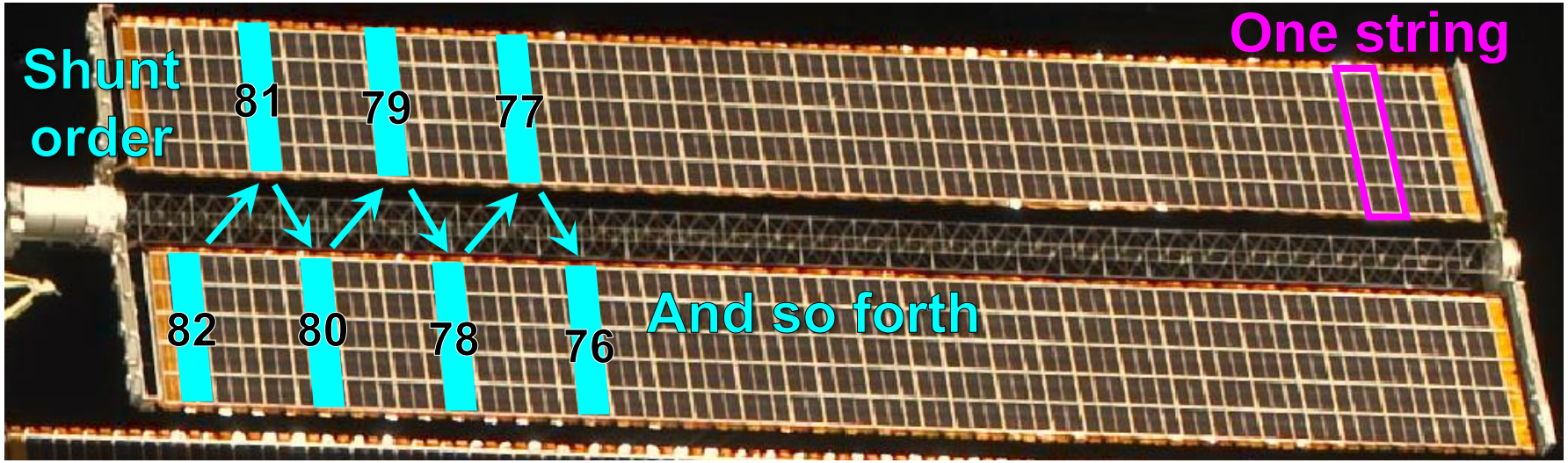


Background: ISS SAW Operation

- Each of the power channels on the ISS consists of 82 solar array strings across two blankets to generate electrical power.
- When less power is needed, strings are shunted in a set order.
- A shunted string contributes no electrical power to the EPS and thus heats up due to the solar flux (conservation of energy).



← Right Blanket

← Left Blanket

All string numbering in this presentation will follow the shunt order.

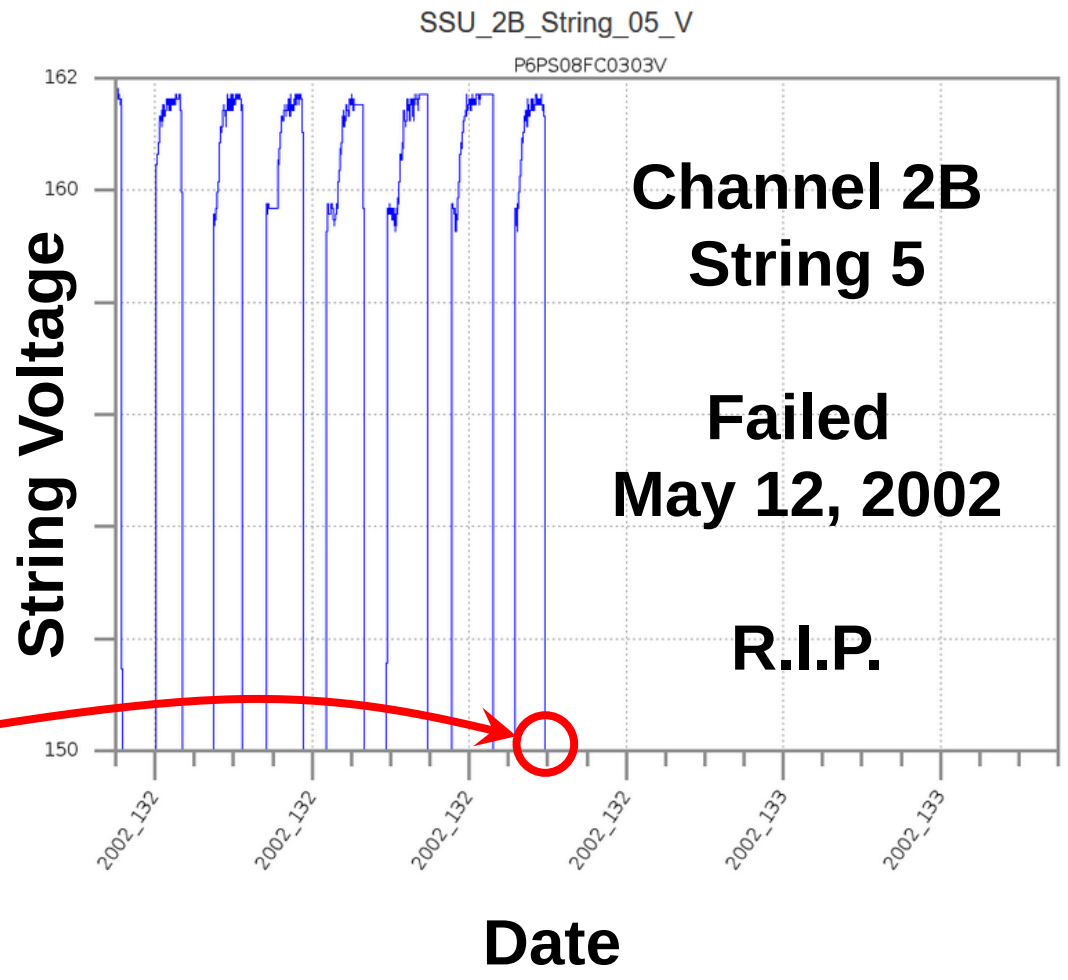
Why Identify Failed Strings?

- A failed solar array string on the ISS can cause a drop of usable electrical power by around 300W (~160Vdc at ~2A).
- Knowledge of string failures is needed to make accurate predictions of power capability for upcoming missions.
  - Power margins are getting tighter due to higher ISS utilization and older solar arrays.
- There are multiple methods to identify a failed solar array string. Each method has different strengths and limitations.

Sensors and Instrumentation

- **No sensors on wing. Sensors are in the shunt regulator:**
  - **Full wing voltage and current**
  - **Shunt current (1x each blanket)**
  - **Voltage for the number of active strings**
  - **String voltages for 22 strings (out of 82 on the channel)**

- **If a string voltage sensor reads ~0V and stays there, the string is likely failed.**



Visual Inspection

- **Photograph surveys of the arrays can show areas that have been damaged.**

- **Compare successive photo surveys to find date when damage occurred.**

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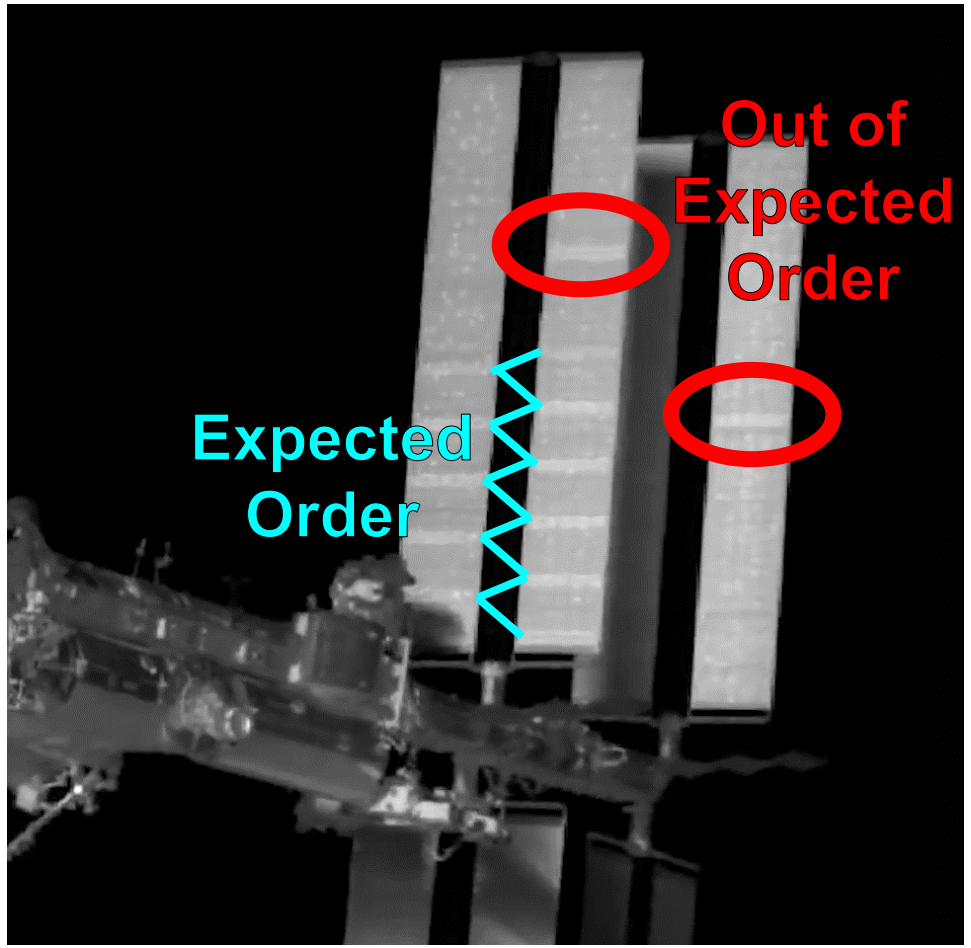
Visible damage does not guarantee the string has failed.

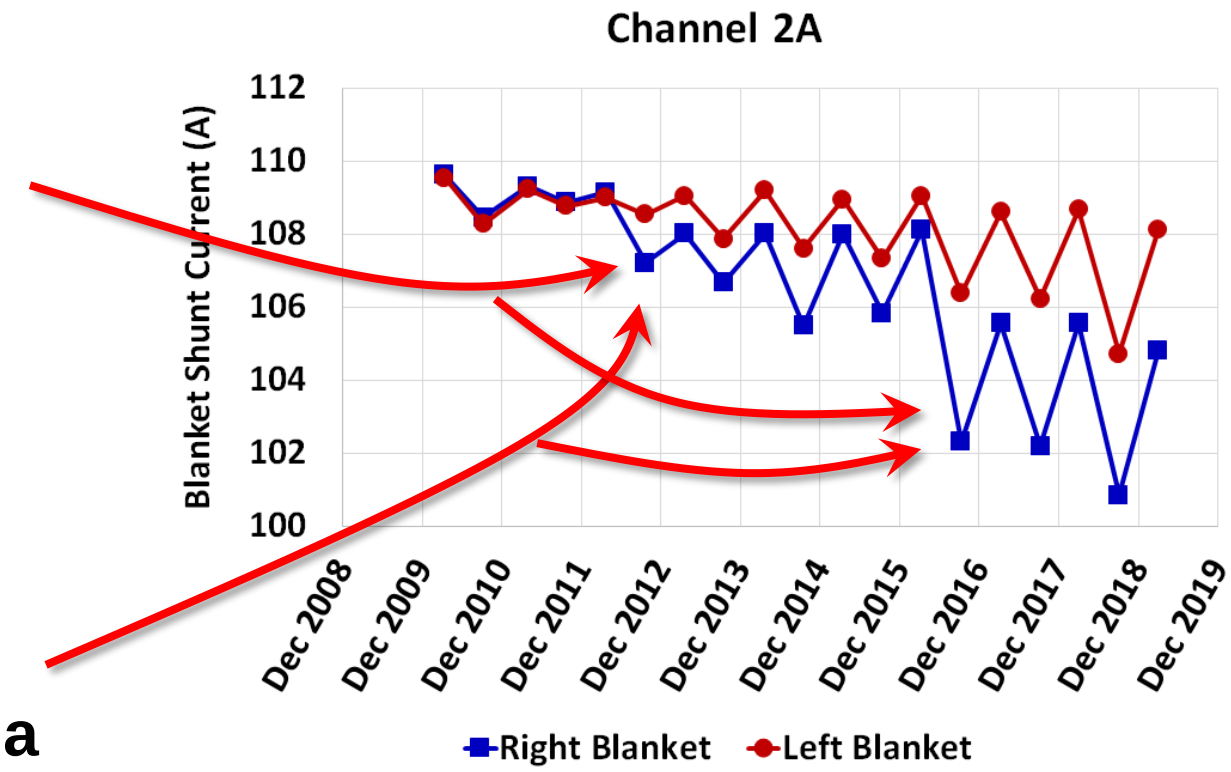
Infrared Imagery

- Observe infrared images/video of solar arrays for hot strings.
  - A hot string out of the expected shunt order is likely failed.
- Infrared imagery available:
  - STS-135 rendezvous + docking and departure + fly-around by TriDAR system in July 2011



Total and Delta Shunt Current

- **Observe the total blanket shunt current during a shunt test**
  - **An unexpected drop in shunt current suggests a failed string**
- **Observe a change in the delta between Left and Right Blankets**
  - **Diverging, re-converging, or crossing lines indicate a possible string failure**



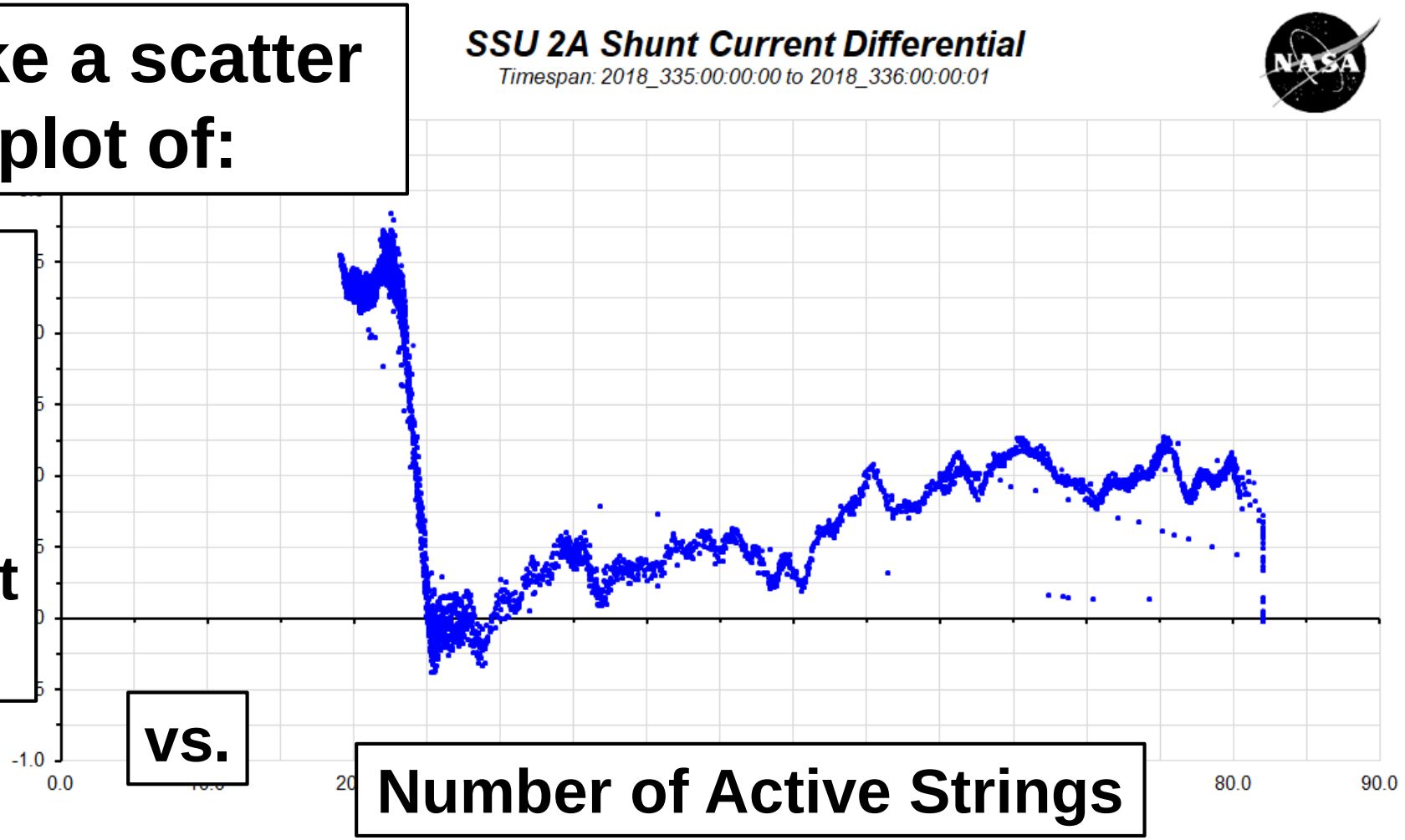
Whalen Method

Make a scatter plot of:

Shunt Current Difference

(Left - Right Blankets)

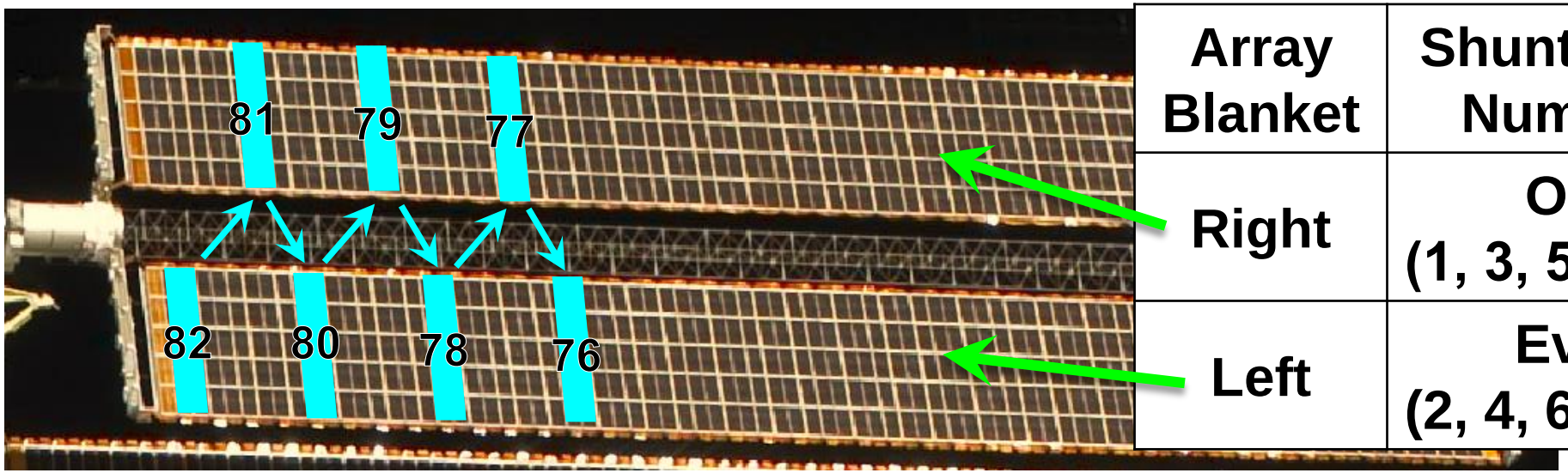
vs.



Number of Active Strings

ISS SAW String Shunting Order

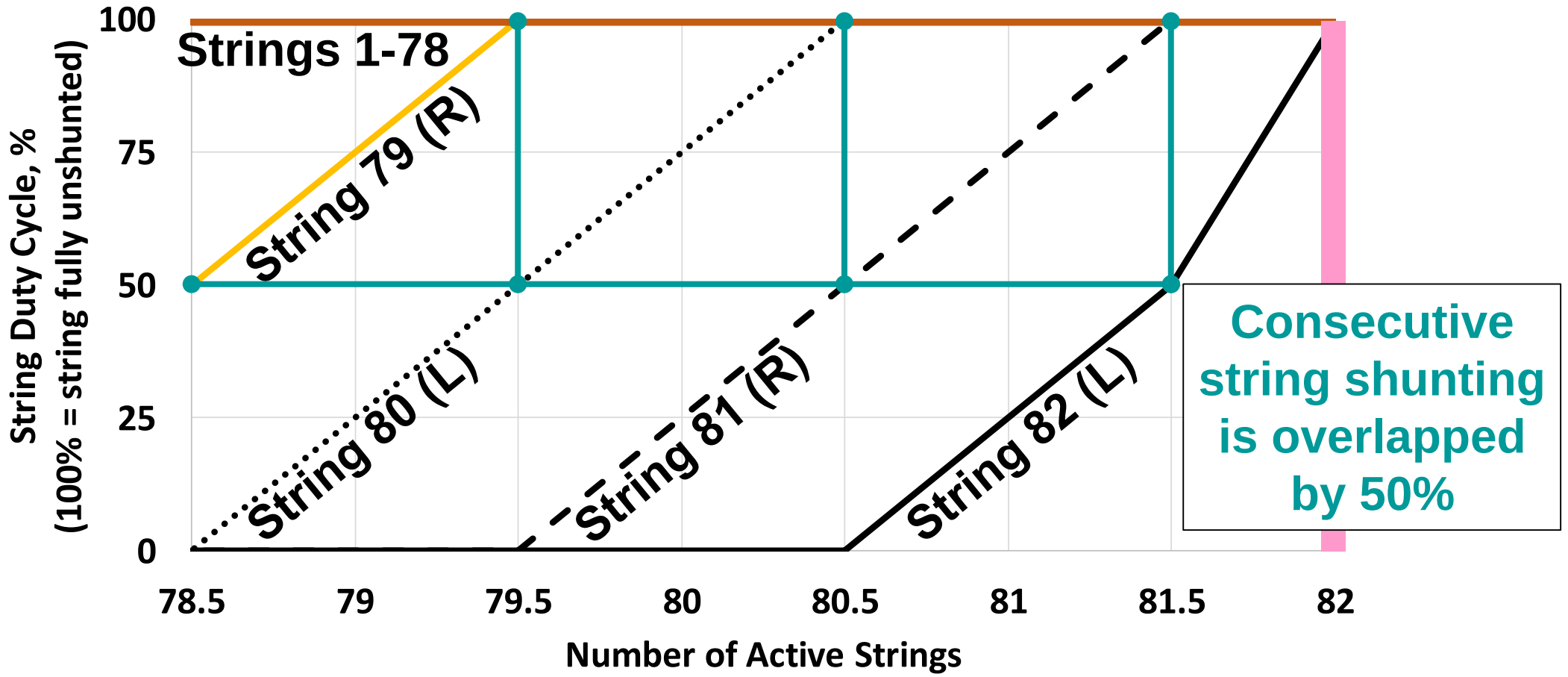
- When less power is needed, strings are shunted in a set order.
- Consecutive strings in the shunt order alternate blankets.
- Each blanket has a shunt current sensor.



Array Blanket	Shunt Order Numbers	Shunt Sensor
Right	Odd (1, 3, 5, … 81)	1
Left	Even (2, 4, 6, … 82)	2

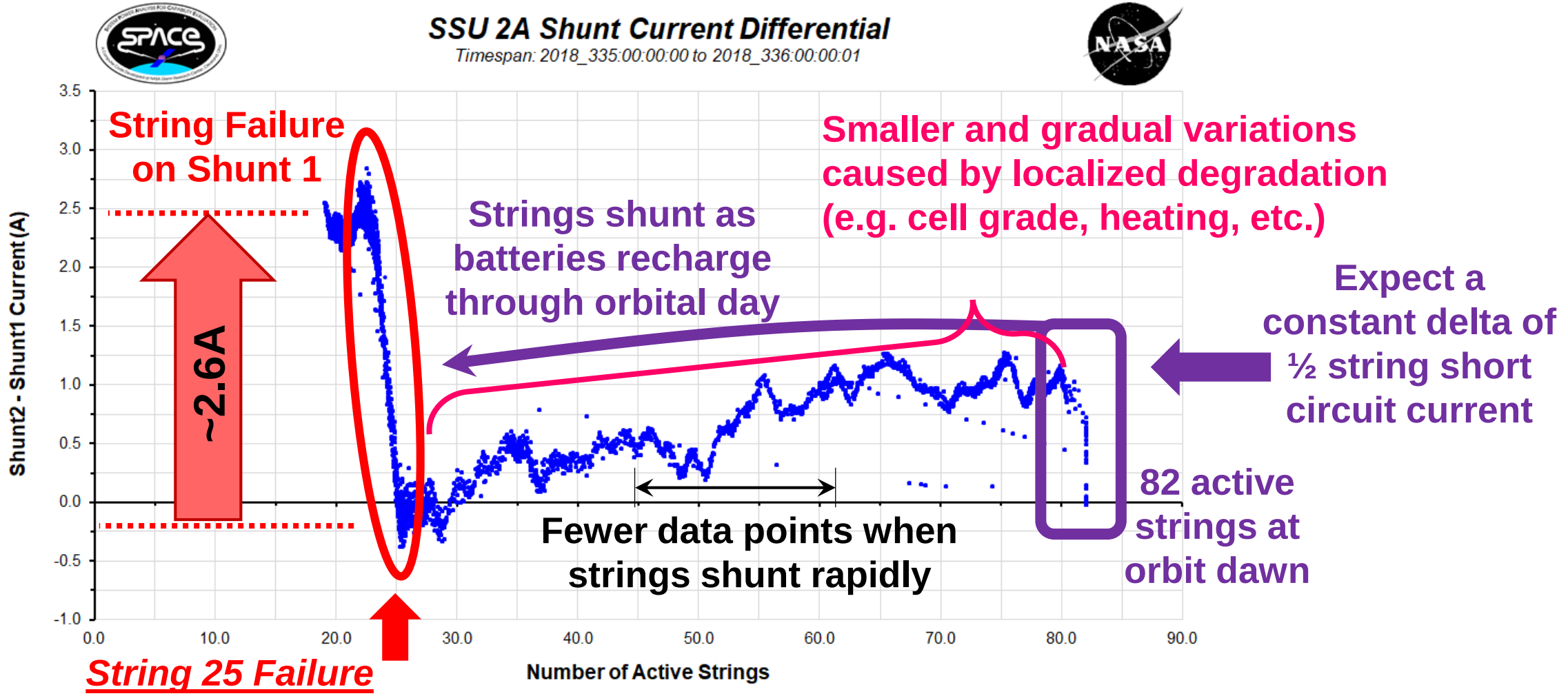
Consecutive shunt order strings alternate shunt current sensors.

ISS String Shunting Overlap



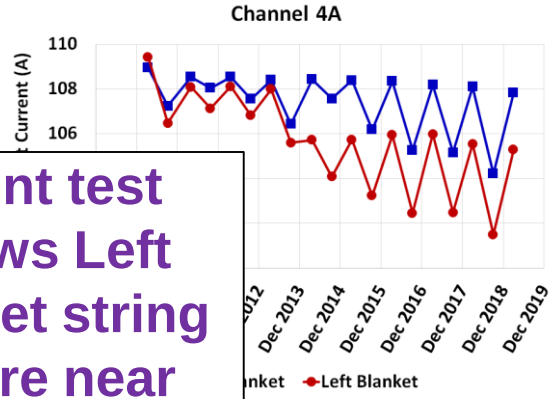
Total shunt of even strings is always ½ string more than odd strings.

Reading Whalen Plots



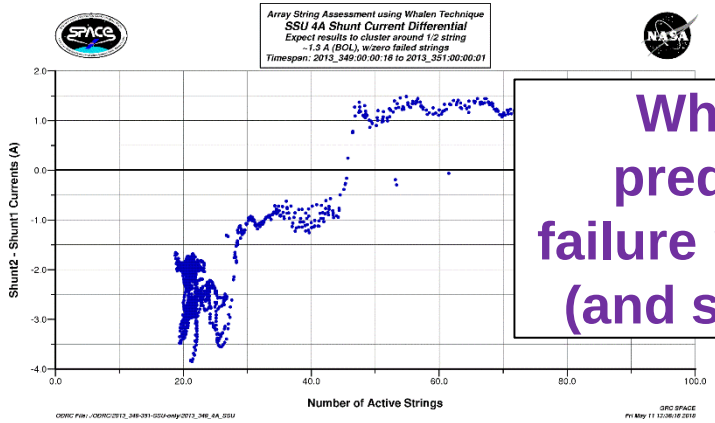
Validation of the Methods

Visible damage observed on string 46 (photo Oct 2018)

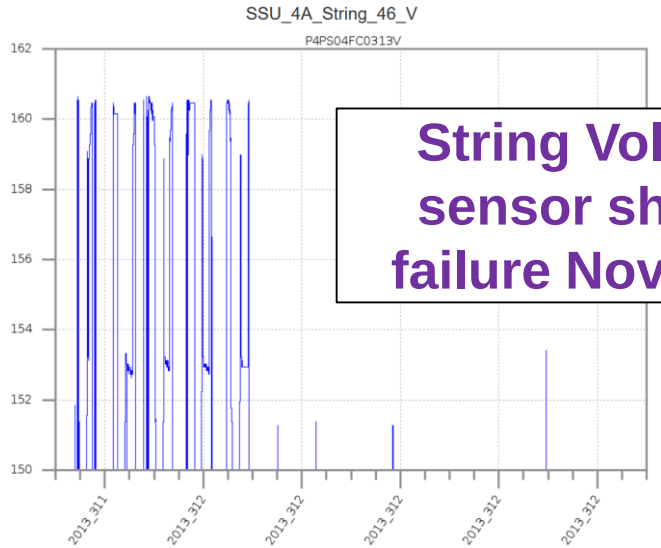


Shunt test shows Left Blanket string failure near end of 2013

Channel 4A String 46 (Left Blanket)



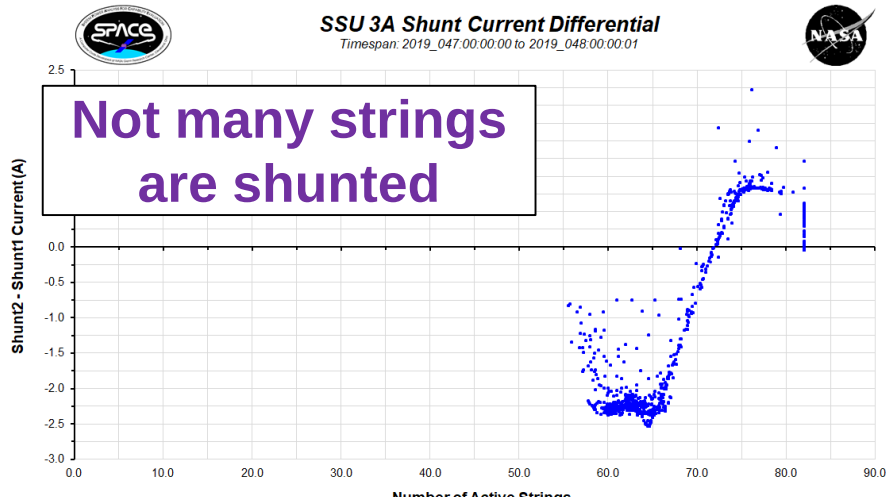
Whalen method predicts string 46 failure near end of 2013 (and string 28 earlier)

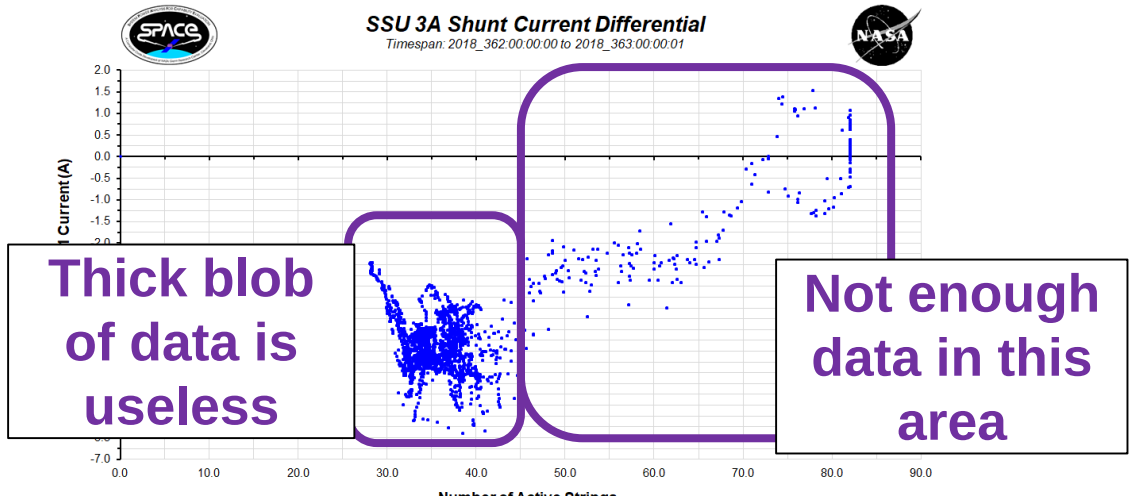


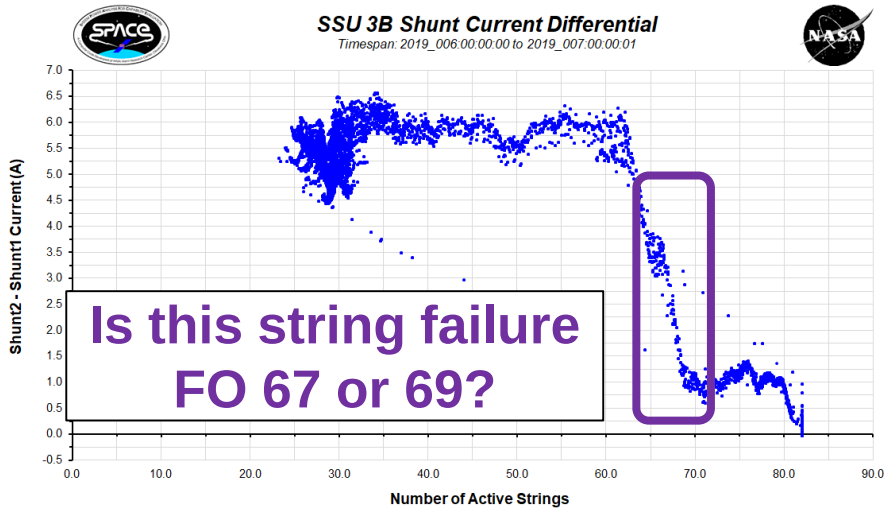
String Voltage sensor shows failure Nov 2013

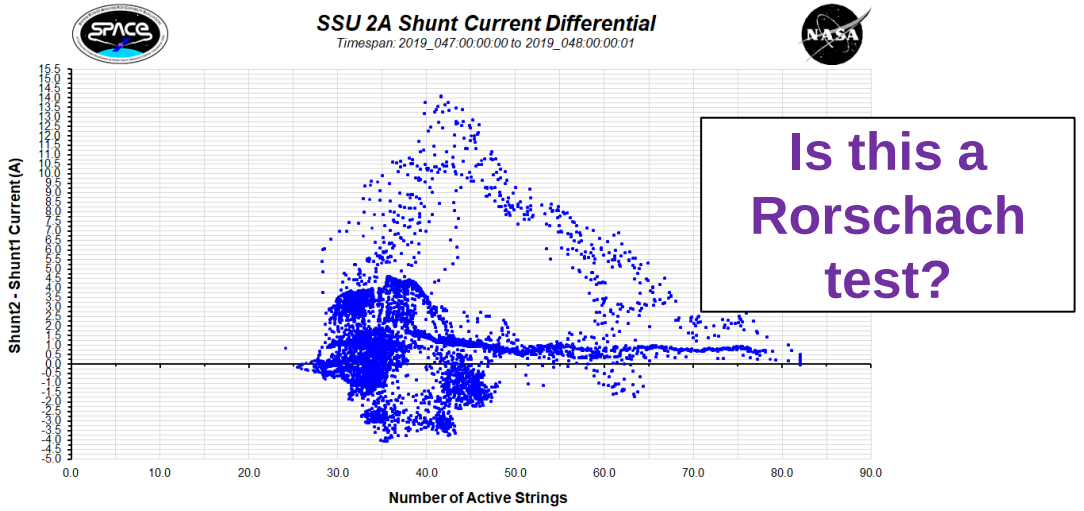
String failures and failure dates must align across the methods.

Bad Data for Whalen Method







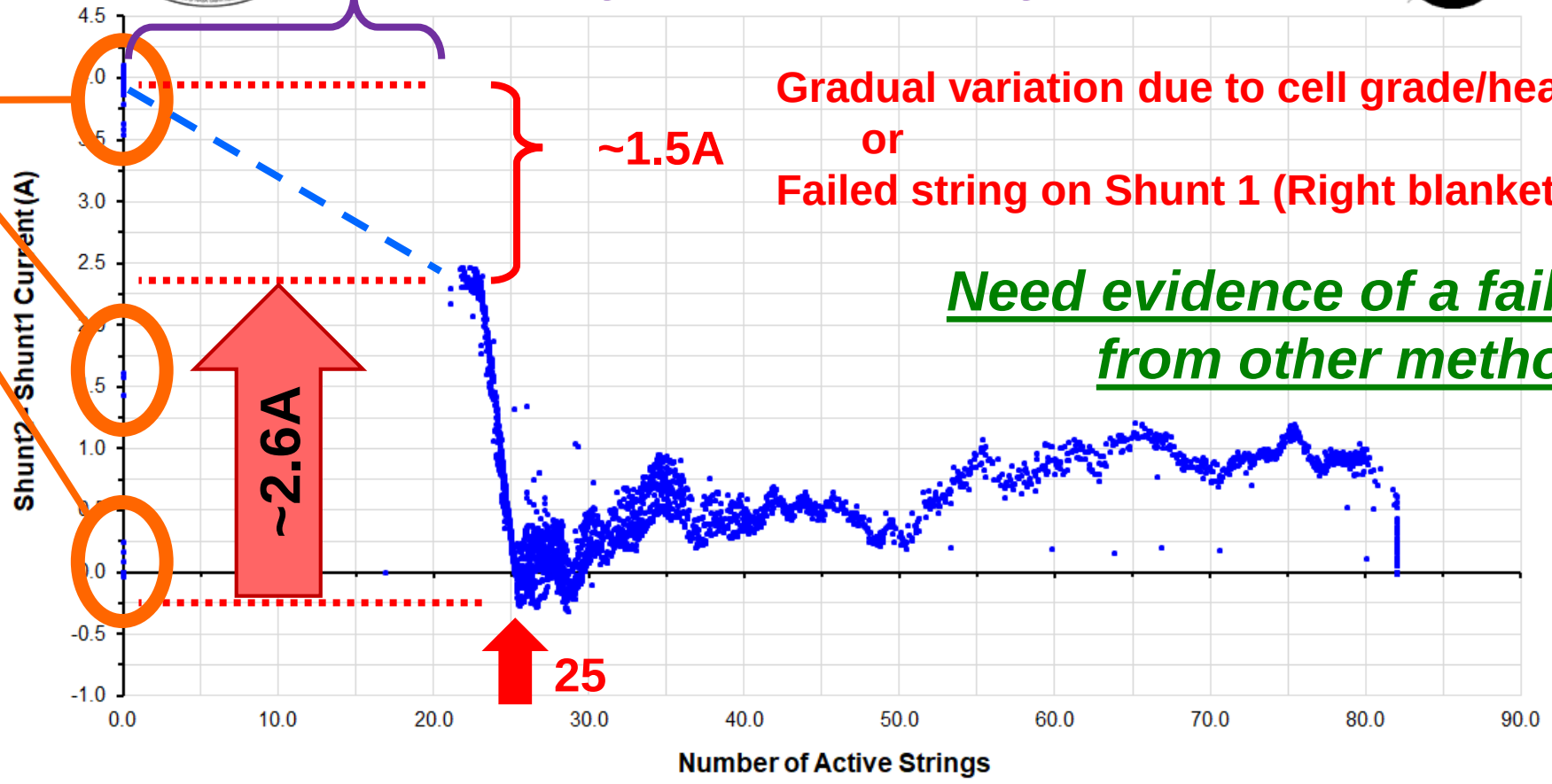


Strings Low in Shunt Order

Can the Whalen Method be used to find string failures in this region?

Shunt Test

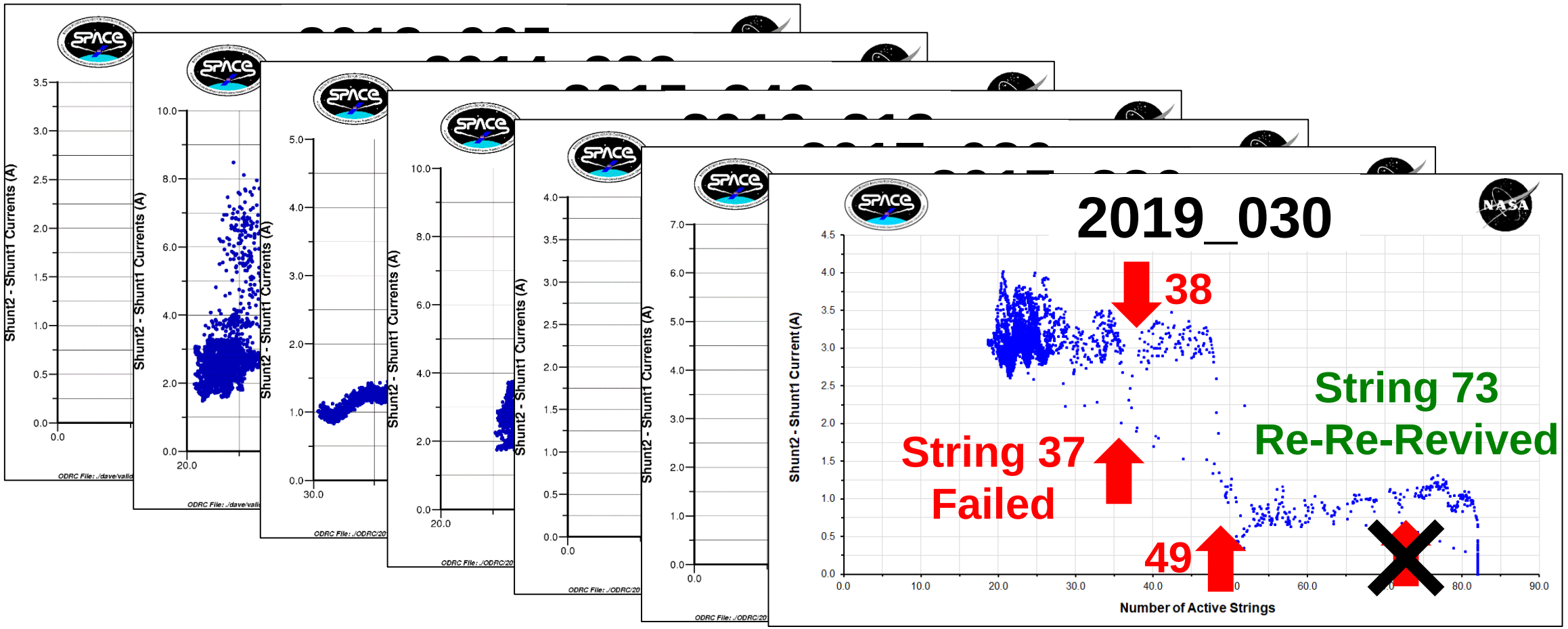
All strings set to shunt



Gradual variation due to cell grade/heating/etc.?
or
Failed string on Shunt 1 (Right blanket)?

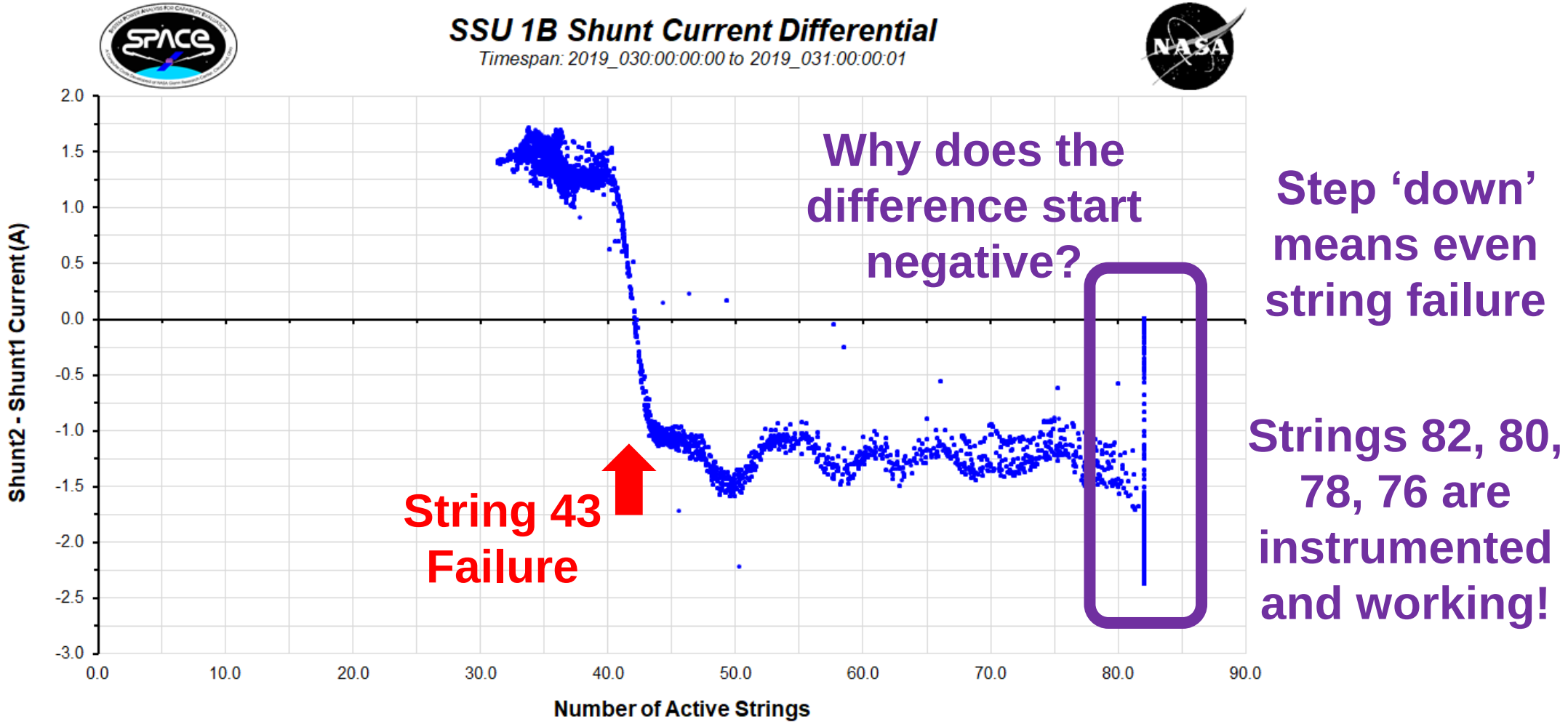
Need evidence of a failed string from other methods.

Intermittent Failure



For analysis, intermittent string failures are always assumed failed.

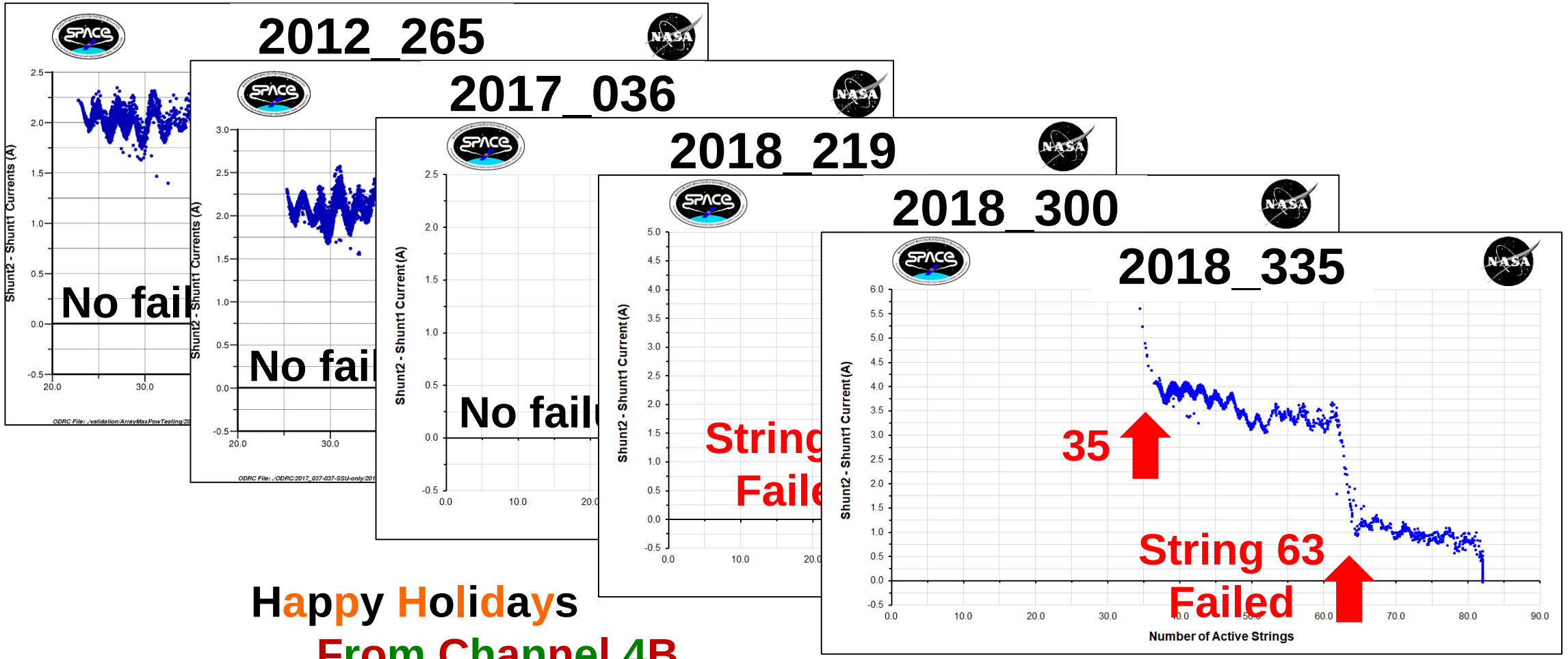
Odd Shunt Current



Step 'down' means even string failure

Strings 82, 80, 78, 76 are instrumented and working!

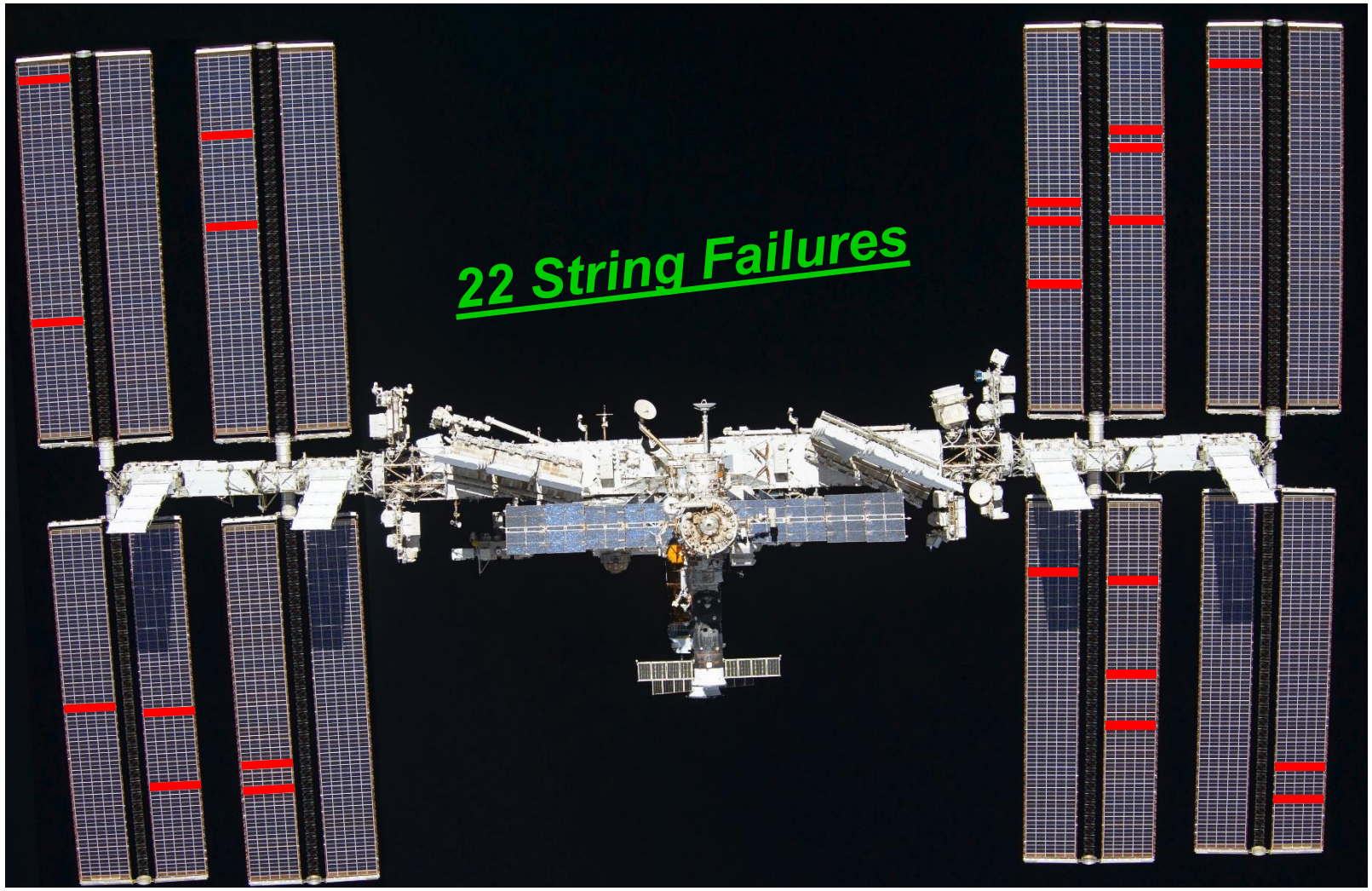
No Failures?



Happy Holidays

From Channel 4B

Failed Strings on the ISS



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Comparison of the Methods

Method	Advantages	Limitations
Instrumented String	• Know for sure if string is failed	• Only 22 out of 82 strings are instrumented
Visual Inspection	• Photo surveys occur regularly	• Difficult to determine if damage causes failure
Infrared Imagery	• High knowledge of identifying string failures	• Only one data set in July 2011 • Can be difficult to place failure
Total and Delta Shunt Current	• Long history of tests • Near-identical conditions across tests	• Does not tell which string failed • Tests occur only 2x per year
Whalen Method	• High knowledge of identifying string failures • Can be used to find string failures on most days	• Cannot detect failures late in the shunt order • Number of active strings is calculated from bus voltage • Data sometimes unclear

Possible Q&A

- **Is there any effort to try to find the causes of string failures?**
  - **We'd like to, but this would prove difficult. It might be possible to find the exact date of many string failures and look at what happened that might have caused damage on the string. Photography surveys of the arrays have shown MMOD or arcing damage on known failed strings, but sometimes there is no visible damage at all.**

- **What mechanism can cause the intermittent strings to fail and revive?**
  - **We don't know for sure. It is possible that it is temperature related, but there are no temperature sensors on the array strings. The bi-annual shunt tests occur under fairly consistent conditions and the intermittent strings have been failed and revived across these tests. This is especially puzzling for Channel 2B string 72, which has been observed as a failed string in so many of the methods.**

- **Why do the Total Blanket Shunt Current data points look weird?**
  - **The power tests changed methodology a little in 2011, so it is difficult to compare older and newer results. The SSU shunt current sensors saturate at 110A. Recent tests are run twice per year around the equinox. However, the Earth (and thus the ISS) is closer to the Sun during the Spring tests in early March. The varying intensity of the solar flux results in higher shunt currents in Spring and lower shunt currents in Fall, creating a zig-zag pattern.**

Possible Q&A (cont.)

- **What are more of the factors that cause the small, gradual variations of shunt current in the Whalen method?**
  - **There are several. Some of them include: differences in solar cell grade, localized heating due to different view factors to vehicle radiators, blanket warping, localized degradation and contaminants, sensor imperfections, and manufacturing defects. These ups-and-downs are usually consistent across Whalen plots of the same channel from day-to-day.**

- **How many new string failures were found making this presentation?**
  - **Four new string failures were identified between submitting the abstract for this presentation and the presentation itself. There may be further string failures. We are still looking at telemetry.**

- **Which strings have voltage instrumented in the Sequential Shunt Unit (SSU)?**
  - **The following 22 strings for each channel have voltage sensors downstream in the SSU. Shunt order: 1, 3, 5, 7, 12, 17, 22, 27, 32, 37, 41, 42, 46, 51, 56, 61, 66, 71, 76, 78, 80, and 82**

- **Is the rate of string failures increasing in recent years?**
  - **Yes, however this is somewhat skewed as recent years have more arrays and strings on orbit.**