ALBA

Results of the Alba mission

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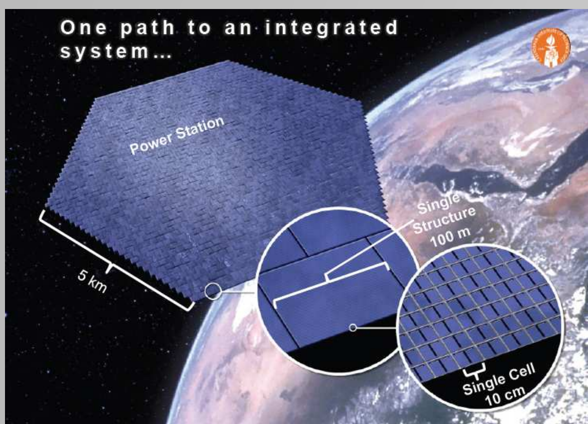
and Harry A. Atwater

Caltech
Space Solar Power Project

Colorized photo by Charles Sommer

Background: Caltech SSPP, SSPD-1, and Alba

Caltech's Space Solar Power Project (SSPP) seeks to develop and demonstrate novel technologies needed to realize cost-effective space-based solar power

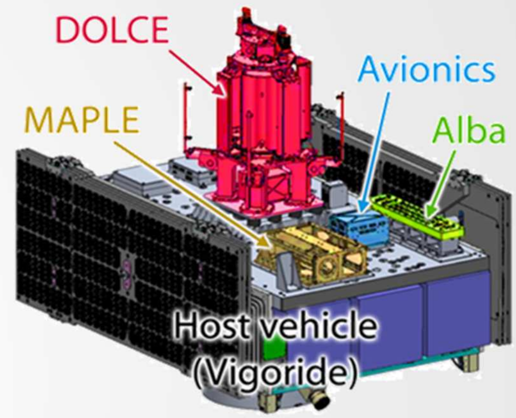


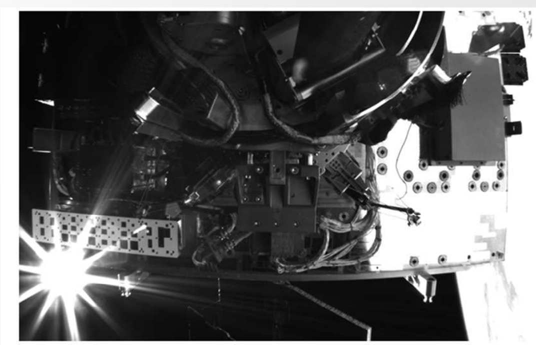
Ultralight photovoltaics
(Atwater Group)

Wireless power transmission
(Hajimiri Group)

Deployable space structures
(Pellegrino Group)

https://spacesolar.caltech.edu





*Our first mission, SSPD-1, flew 2023, to demonstrate advancements in these technology areas, in low-earth orbit. **Alba** sought to test novel solar cells.*

ALBA DESIGN SUMMARY

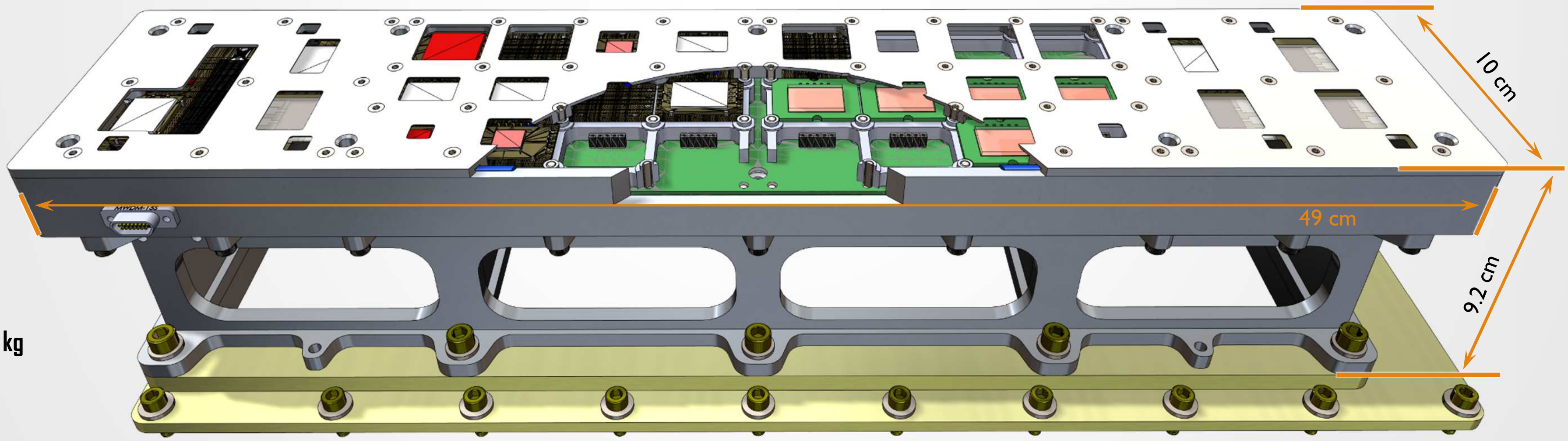
Science Payload

32 research solar cells
w/ precision I-V sweep and temperature data logging

Underlying architecture:

AMU
(Aerospace Measurement Unit)

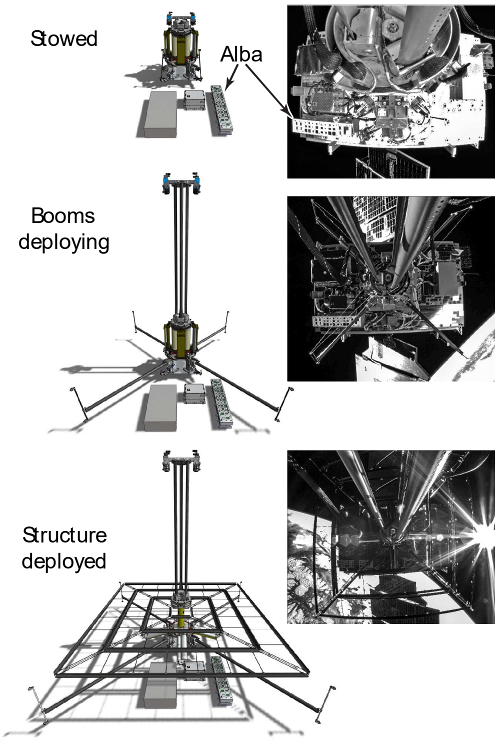
Modular high-precision solar cell measurement platform developed by Colin Mann et al @ Aerospace Corp, generously licensed for Alba



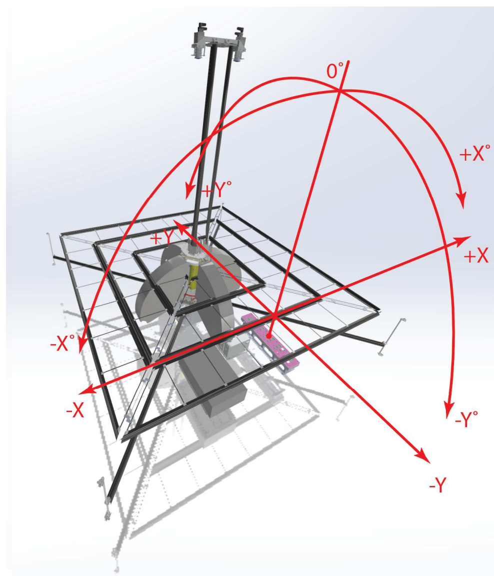
Mass: ~3 kg

OPERATING PLAN

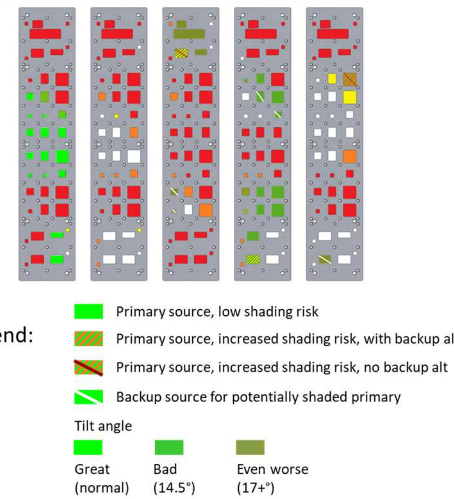
Alba will be located beneath DOLCE deployed structure

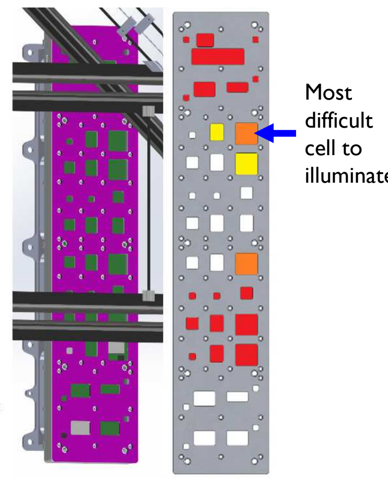


Dealing with shading…



θ	0°	4°	17°	14.5°	18.3°
cos(θ)	1	.9975	.9563	.9681	.9494



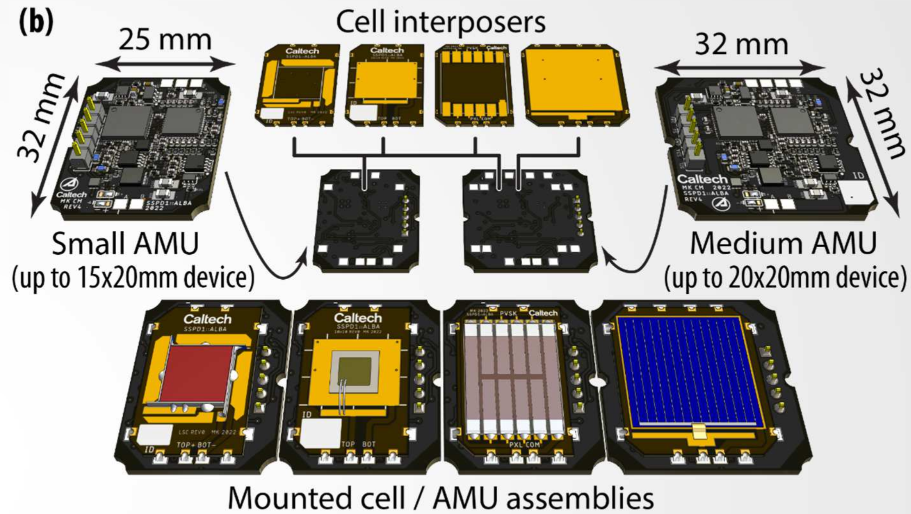


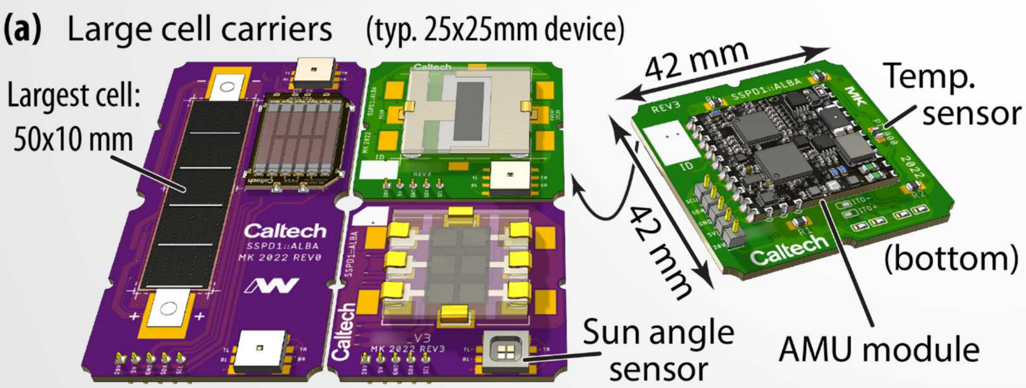
Example: Angle 5
X=-18°, Y=-3° (θ~18.3°)

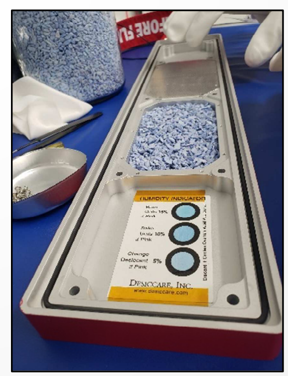
We planned to command the spacecraft to specific sun-pointing angles on a regular schedule, to provide consistent usable illumination throughout the mission

Unfortunately, the host spacecraft was unable to do this.

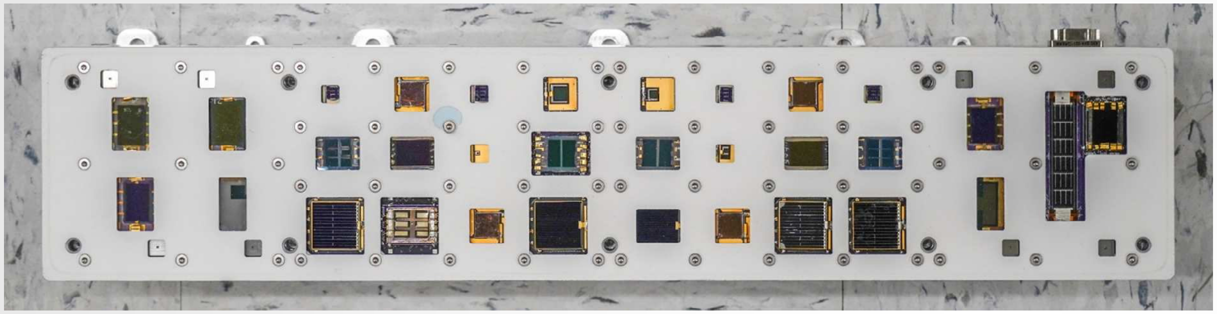
CIRCUITS AND KEY COMPONENTS

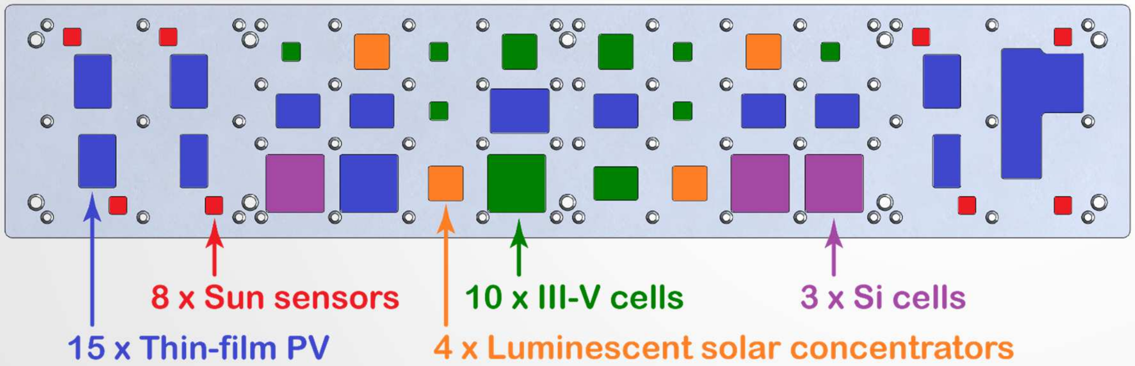






FINAL CONFIGURATION





Manifest includes:

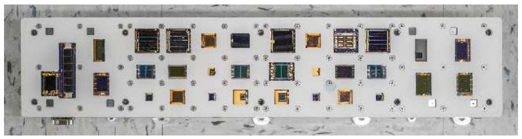
- Low-cost diffused GaAs
- Rad-tolerant nanowire III-Vs
- Luminescent solar concentrators (LSCs)
- Thin-film perovskites
- Thin-film CIGS
- Modern low-cost Si
- Modern III-V multijunction space-grade CICs
- 8x sun angle sensors (unfortunately non-op)

ALBA

FROM LAB ... TO ORBIT

TIMELINE: DELIVERY, LAUNCH, AND INITIAL FLIGHT OPS

Oct 30: Final Alba test/calibration @ Caltech

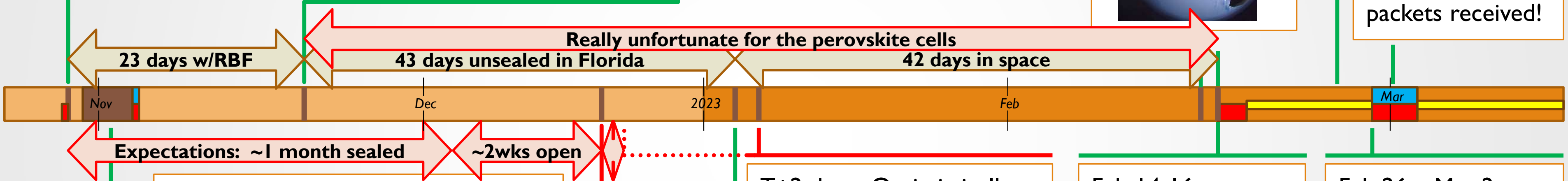


Vehicle assembly: RBF cover removed @ KSC Florida

Feb 13: First photo from host

First partial download of I-V data!

First Alba telem packets received!



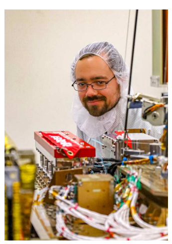
Dec 18: Originally planned launch date

T+2 days: Optimistically planned Alba turn-on date

Feb 14-16: First on-orbit Alba power on, runs for ~49 hours w/o telemetry working

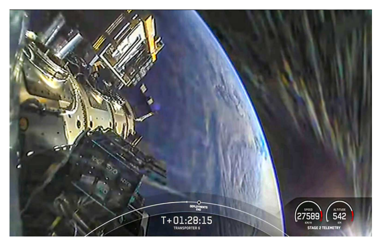
Feb 26 – Mar 2: Second Alba power on, runs for ~99 hours w/ partial telemetry downlink

Oct 31 – Nov 2: Caltech team integrates Alba onto Vigoride @ Momentus HQ.



Minor issues found and resolved, limited testing performed

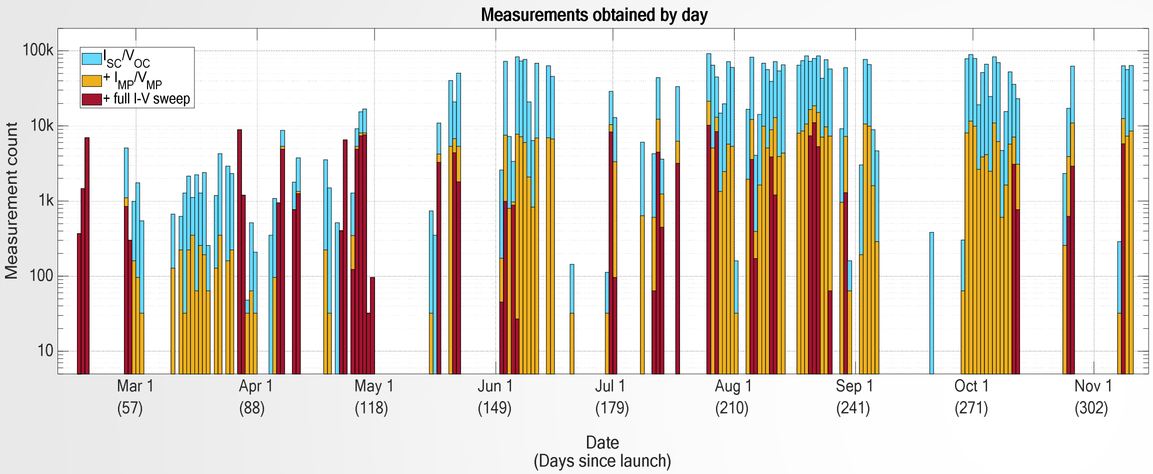
Jan 3: SpaceX Transporter 6 launch successfully delivers SSPD1 aboard Vigoride to orbit!

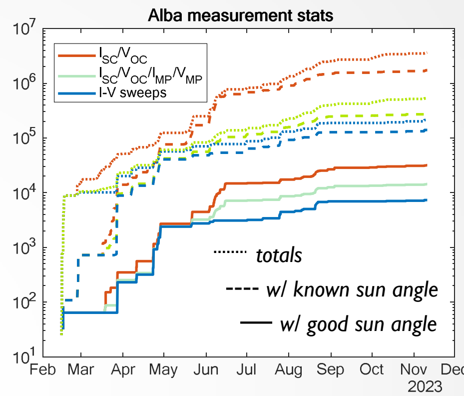


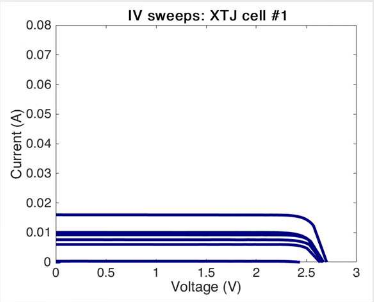
Legend for Alba ops

- Alba on, recording I-V files (red)
- Alba on, downlinking telemetry data (blue)
- Efforts to downlink I-V file data (yellow)

DATA FROM SPACE!   FINAL STATS



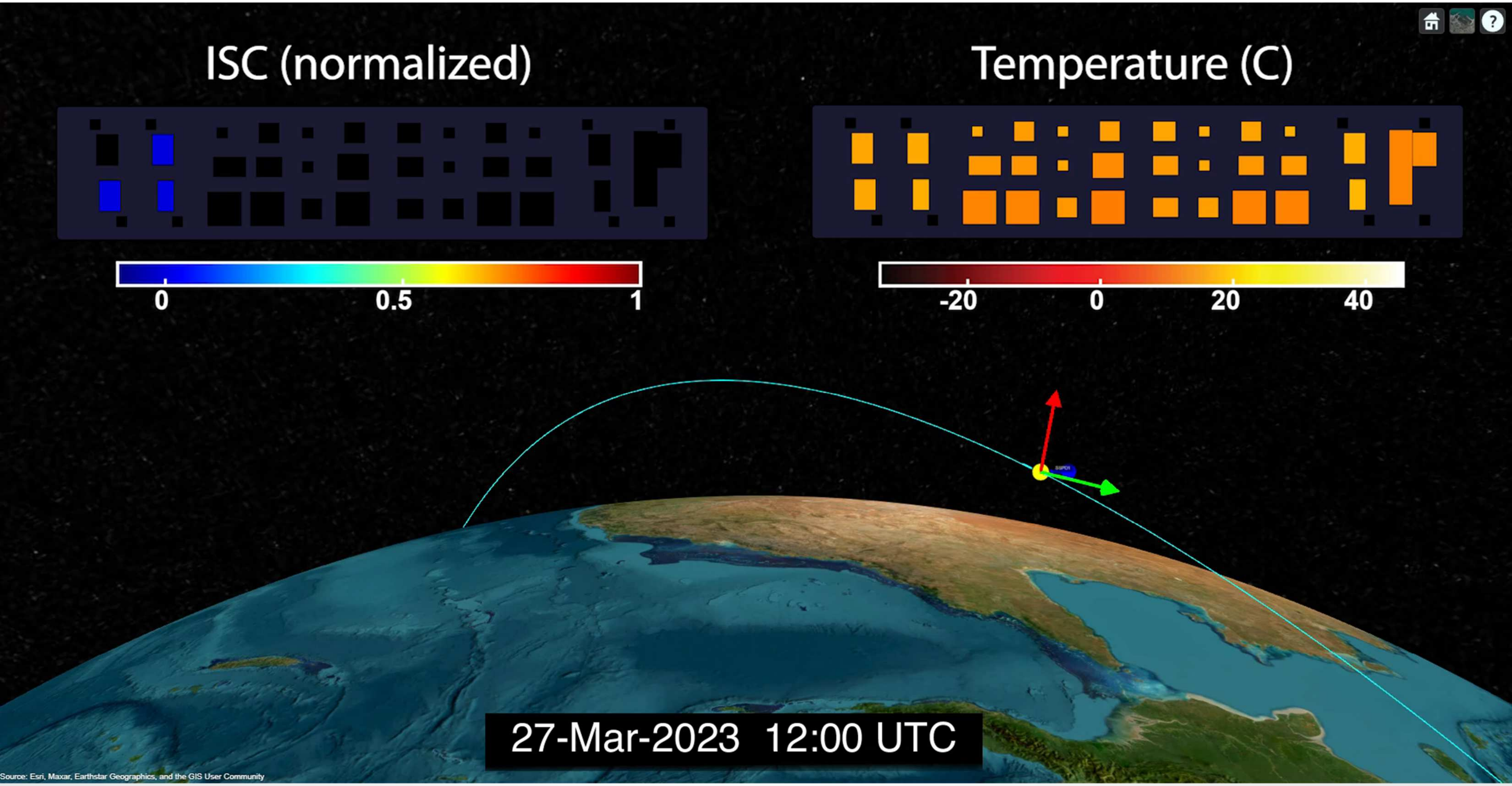




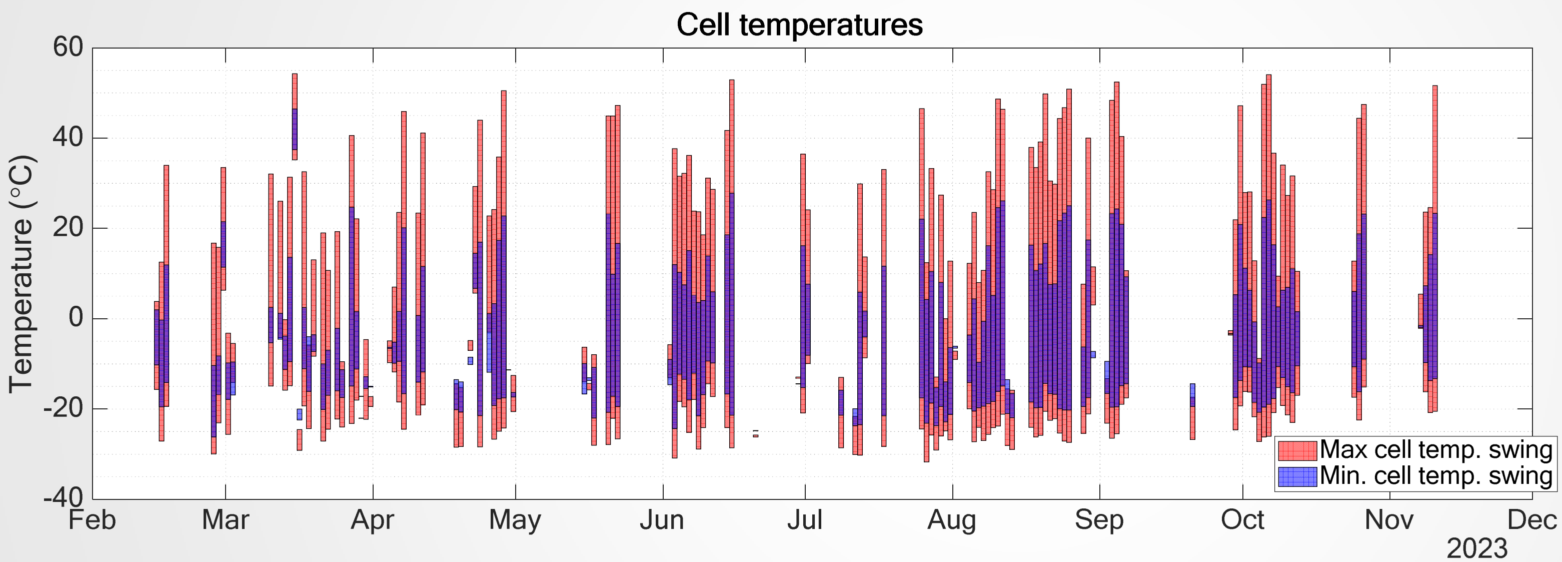
example data animation (3J cell) – through June only!

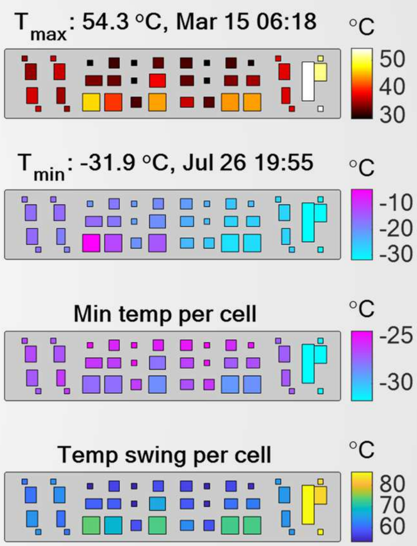
- **Alba largely functioned as designed and returned a great deal of data!**
- Unfortunately, our sun angle sensors didn't work, nor was the host able to provide sun-pointing, so we faced uncertainty as to how to calibrate and analyze solar cell performance.
- Luckily, we were able to determine sun angle from the host's attitude data instead.
- There were lots of other problems too, but we worked through them.
- We developed lots of programs to process and analyze the results

Data type	TOTALS
V_{OC}/I_{SC}/Temp	**3,577,321**
with known insolation	1,725,190
sun incidence <10°	31,739
I-V sweeps	**212,778**
with known insolation	139,304
sun incidence <10°	7,303


ISC (normalized)
0
0.5
1
Temperature (C)
-20
0
20
40
27-Mar-2023 12:00 UTC
Source: Esri, Maxar, Earthstar Geographics, and the GIS User Community

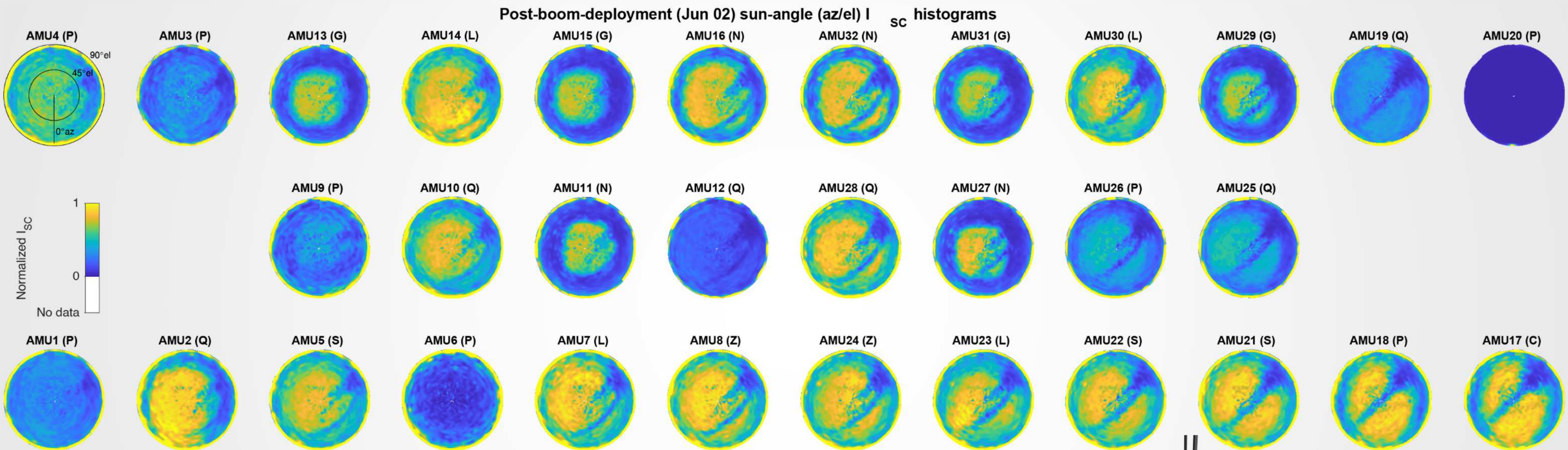
Temperatures experienced



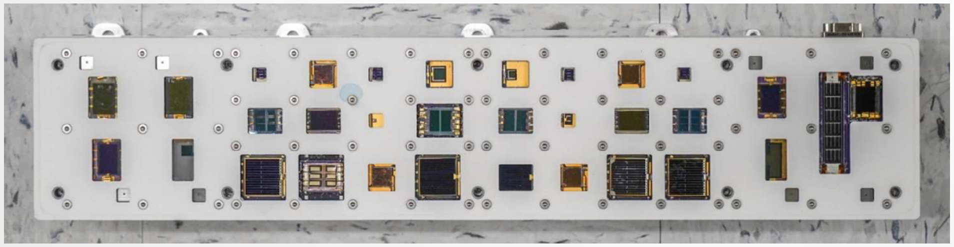


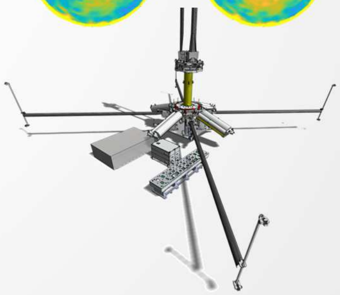
- **Operating temperatures turned out to be quite mild vs. expectations**
- Cells were thermally isolated, but contained within large thermal mass enclosure

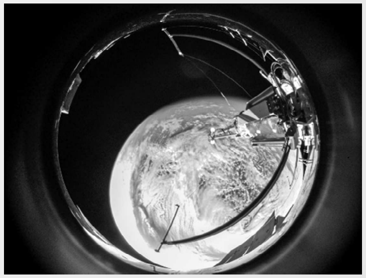
SHADING HISTOGRAMS (MID-MISSION):



Plots are laid out according to cell location on Alba

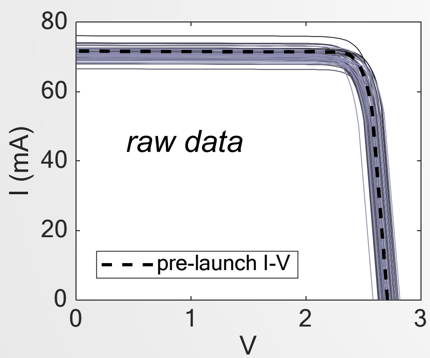


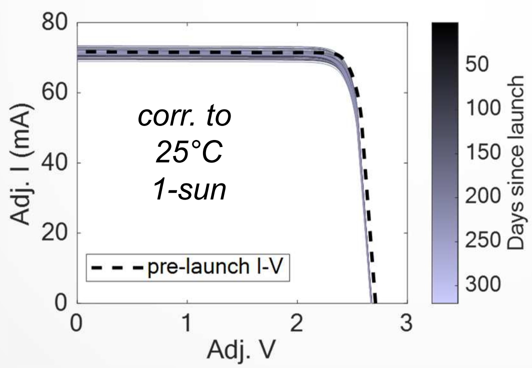


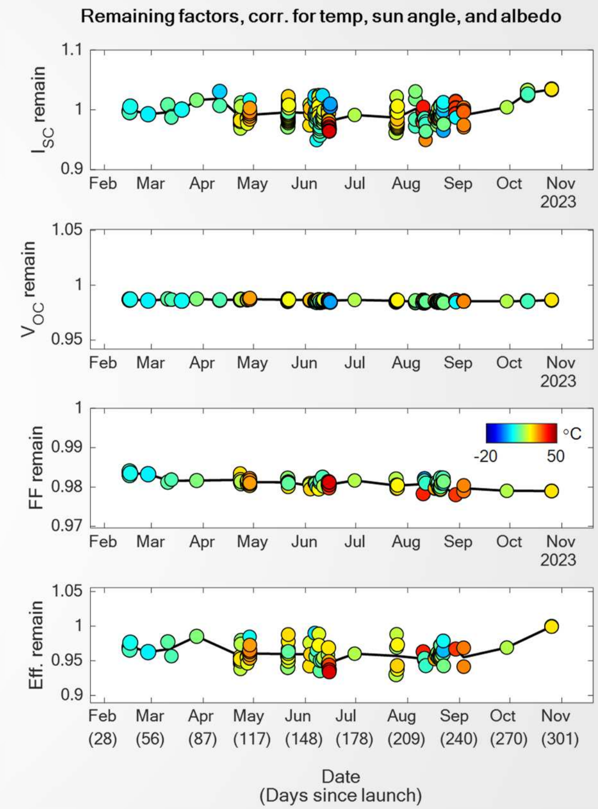


Reference cell data -- after all processing

- Control cells: Commercial 3J III-V CICs
- Rather large insolation uncertainty: ~±5%
- Excellent Voc and FF resolution after correction to 25C 1-sun
- Expected >99.8% remain power (based on modelled radiation environment), which is consistent with observed performance



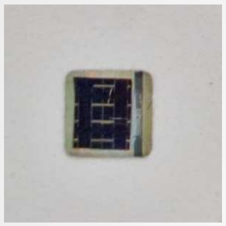




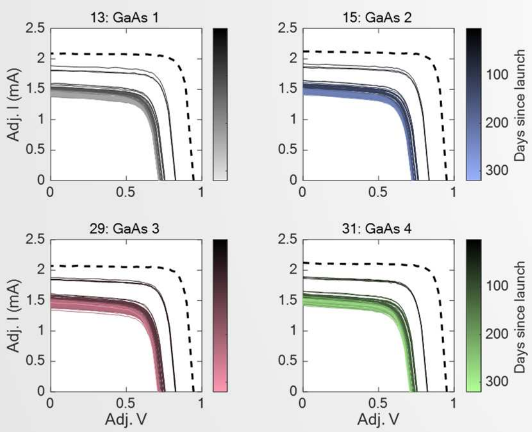
Note: Apparent reduction in Voc and FF was almost certainly caused by errors in ground (pre-flight) I-V measurements – affecting the 3J cells only. (We only had a single-zone simulator, which can't accurately bias all three junctions. We calibrated with isotype of current-limiting junction.)

Diffused-junction GaAs results -- degradation due to solar storm

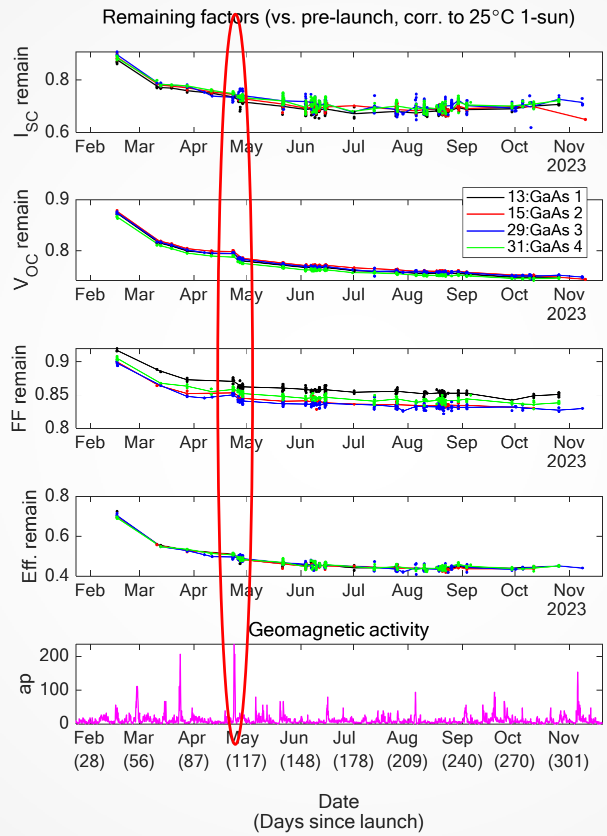
These cells had absolutely no shielding!



Mission I-V data
(Adj. to 25°C 1-sun)



- - - pre-flight measurement



We didn't have any dosimetry or particle fluence sensors, but can see correlation with solar storm

Severe Solar Storm Creates Dazzling Auroras Farther South

By Associated Press | April 24, 2023

An intense solar storm has the northern lights gracing the skies farther south than usual

An aurora borealis, also known as the northern lights, is seen in the night sky in the early morning hours of Monday, April 24, 2023, near Washtucna, Wash. An intense solar storm has the aurora borealis gracing the skies farther south than usual. (AP Photo/Ted S. Warren) TED S. WARREN

CAPE CANAVERAL, Fla. (AP) — An intense solar storm has the northern lights gracing the skies farther south than usual.

A blast of superhot material from the sun late last week hurled scorching gases known as plasma toward Earth at nearly 2 million mph (3 million kph), the National Oceanic and Atmospheric Administration said Monday.

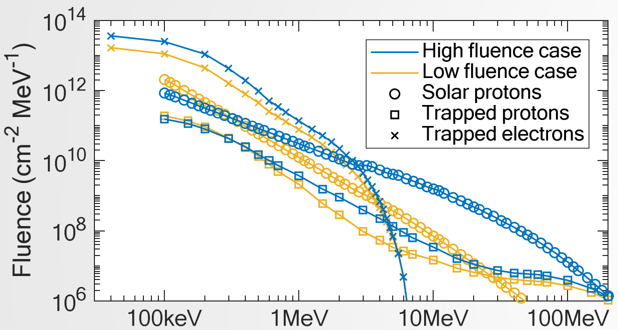
Earth felt the brunt of the storm Sunday, according to NOAA, with forecasters warning operators of power plants and spacecraft of the potential for disruption.

Auroras were reported across parts of Europe and Asia. In the U.S., skygazers took in the sights from Wisconsin, Washington state, Colorado, California, New Mexico and even Arizona — mostly a reddish glow instead of the typical green shimmer.

"I don't want any expectations of these green curtains moving back and forth" so far south, said Bill Murtagh, program coordinator at the NOAA Space Weather Prediction Center in Boulder, Colorado.

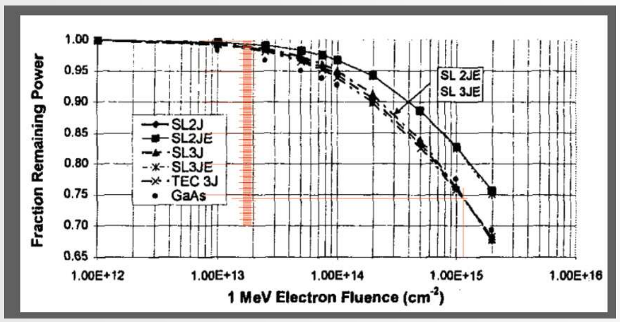
Radiation fluence and damage models for GaAs cells

- Used models on SPENVIS to calculate typical fluence spectra (AP-8, AE-8, ESP-PSYCHIC) for this mission
- Apply EQFLUX and MC-SCREAM methods to estimate expected degradation of "GaAs" solar cell



Remain factor	Power	Voltage (VOC)	Current (ISC)
Flight data	**.442**	**.709**	**.703**
"High fluence" case	.742 | .684	.972 | .878	.864 | .823
"Low fluence" case	.624 | .568	.854 | .831	.770 | .737

EQFLUX *MC-SCREAM*



GaAs solar cell radiation handbook

First-order estimates predict less damage for unshielded cells

1. Lower-energy particles (plasma) can damage unshielded cells
2. GaAs damage estimates are based on different cell architecture than flown (polarity, diffused vs. epi, ...)

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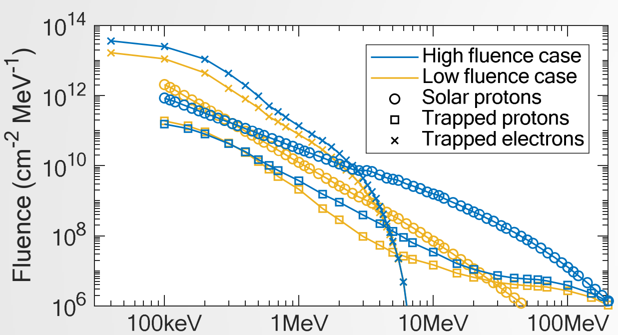

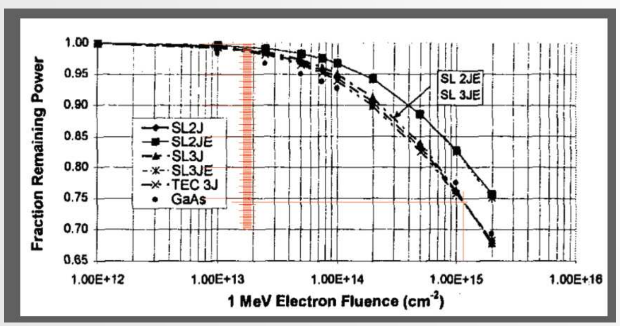

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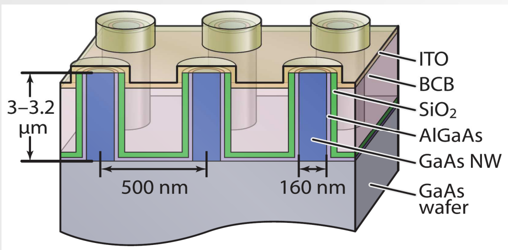
High fluence + 1mil glass	.925 | .929	.958 | .973	.967 | .972
Low fluence + 1 mil glass	.975 | .990	.986 | .996	.991 | .996

First-order estimates predict less damage for unshielded cells

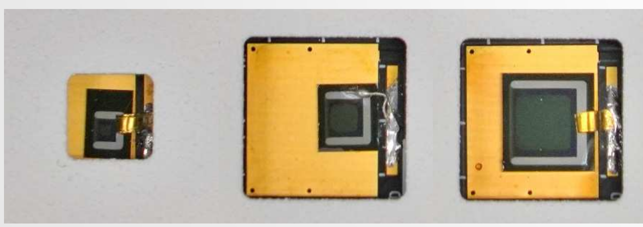
1. Lower-energy particles (plasma) can damage unshielded cells
2. GaAs damage estimates are based on different cell architecture than flown (polarity, diffused vs. epi, ...)
3. Shielding is... probably important

III-V NW CELLS…

NW cells exhibited remarkable radiation tolerance in prior ground testing…



(3) unshielded GaAs NW cells were flown



1x1 mm   2.5x2.5 mm   5x5 mm

ACS Nano   Article

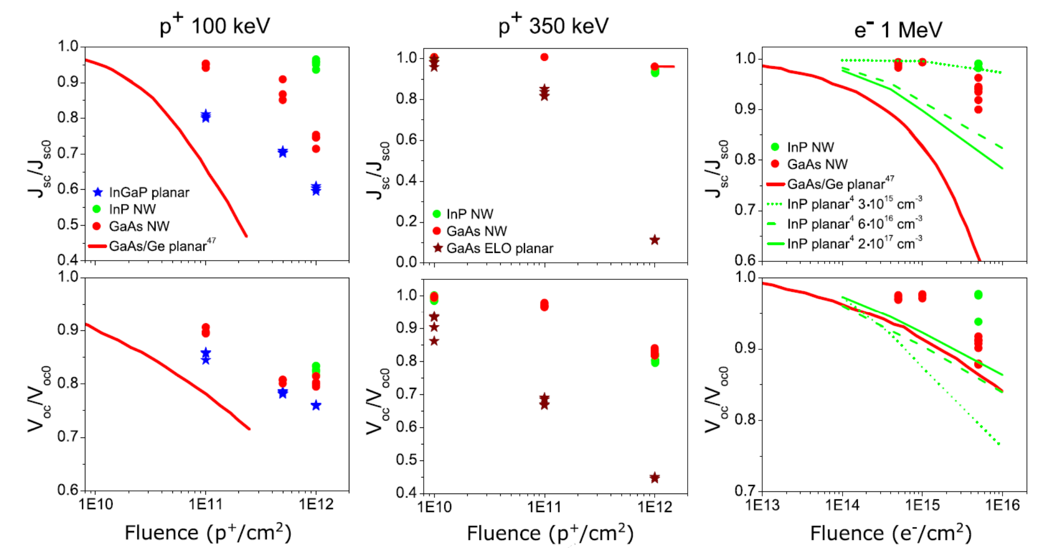
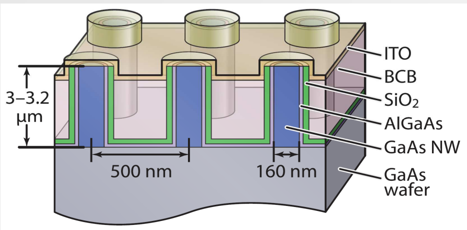


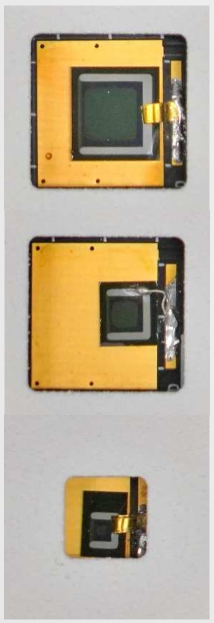
Figure 2. Solar cells performance after irradiation experiments. Degradation of the characteristic parameters (J_{sc} and V_{oc}) of different solar cells architectures tested under irradiation with 100 keV p^+ (left panels), 350 keV p^+ (center panels), and 1 MeV e^- (right panels). The points show the performance of the different solar cells included in each test. Data for the degradation of planar GaAs/Ge solar cells (red lines)[47] and for planar InP solar cells (green lines)[4] have been included for comparison.

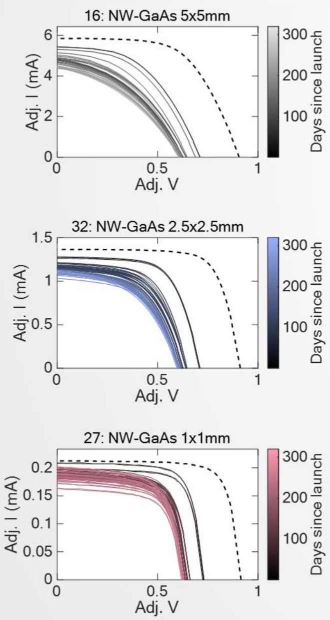
Radiation Tolerant Nanowire Array Solar Cells
Pilar Espinet-Gonzalez, et. al. *ACS Nano* **2019** *13* (11), 12860-12869
DOI: 10.1021/acsnano.9b05213

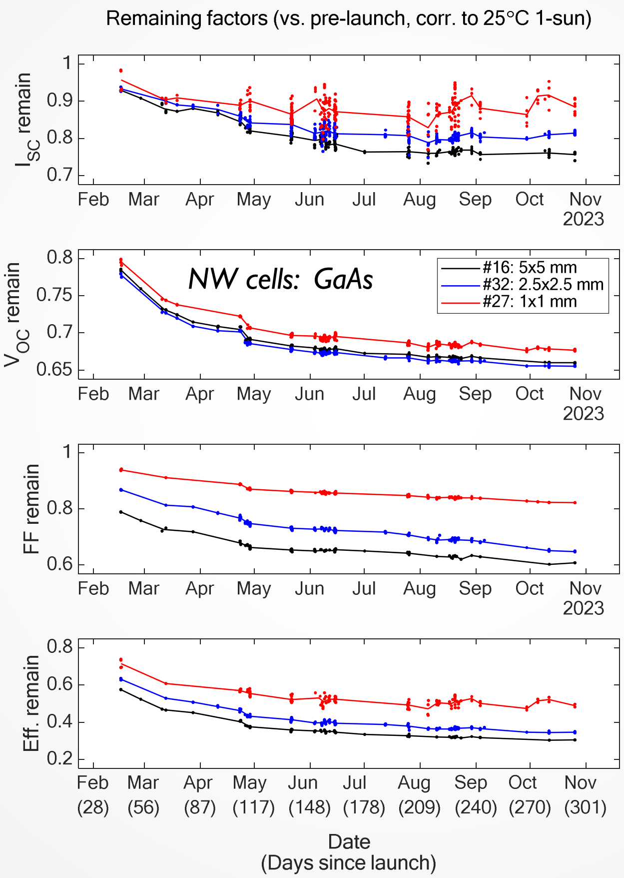
III-V NWs

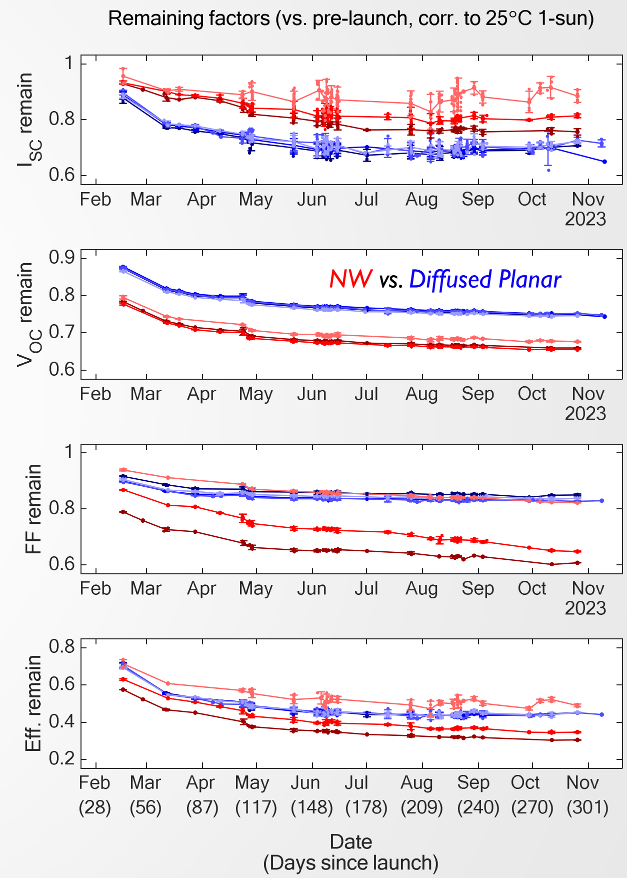
- However, comparing to planar GaAs cells, the NW cells degraded faster in V_{OC}
- We also observed an area-dependent FF degradation, suggesting loss of conductance











III-V NWs

- We speculate this may indicate mechanical damage to the front ITO layer
- Lumped-element circuit model of resistor grid w/ discrete diodes constructed to represent cell
- Certain fraction of resistors deleted to represent cracking of ITO layer
- Results seem consistent over all three cell sizes, at pre-flight, first, and last flight measurements

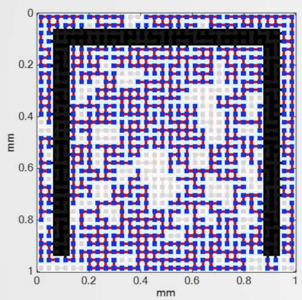
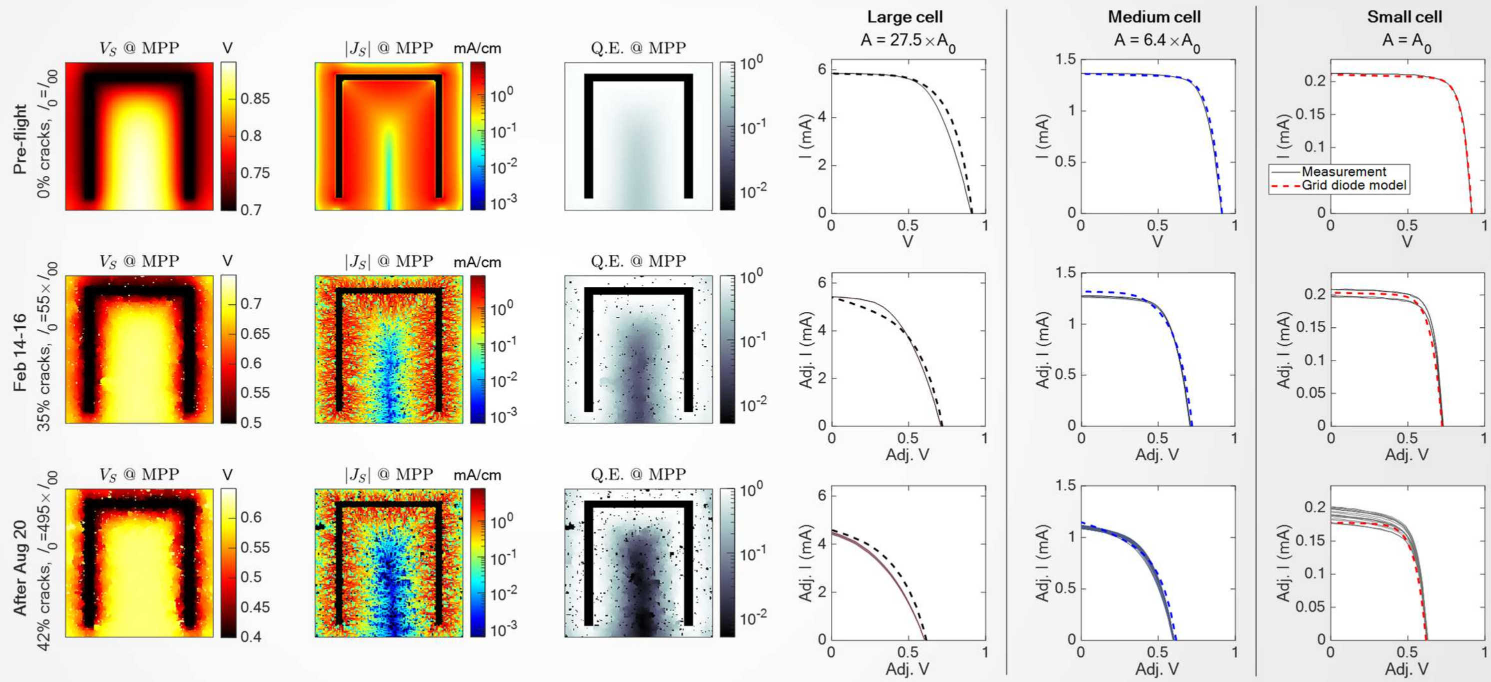
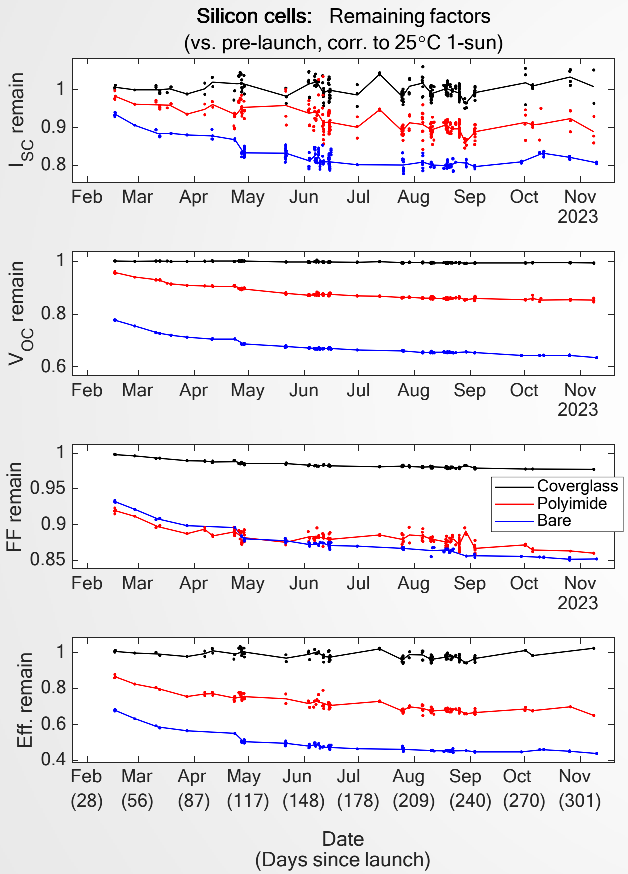


Illustration of lumped-element circuit model for small cell.

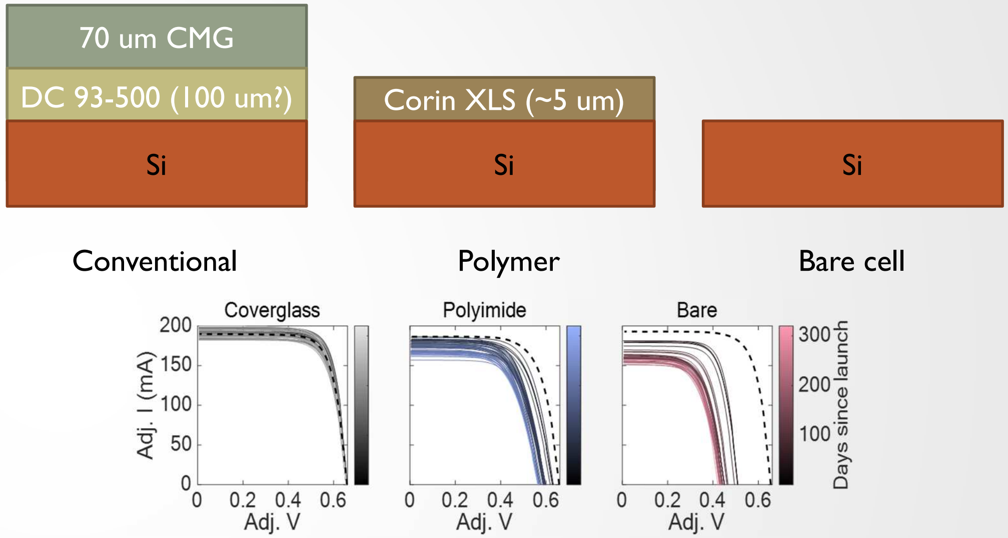


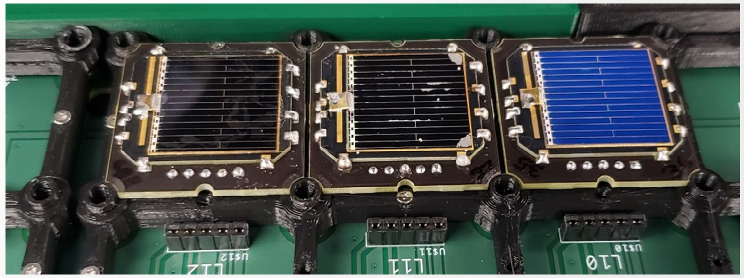
- However, we did not observe significant ITO damage with prior temp cycling in cryostat
- Cannot be certain what caused the area-related FF degradation

Si cells: 2x2cm PERC

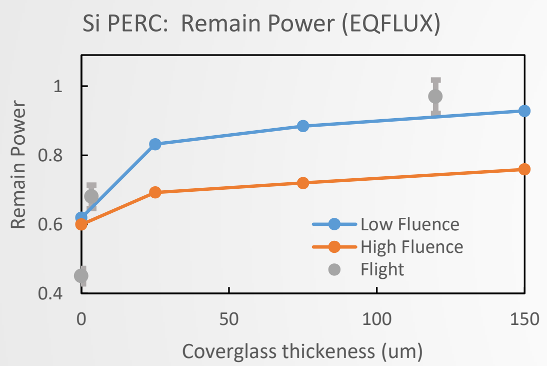


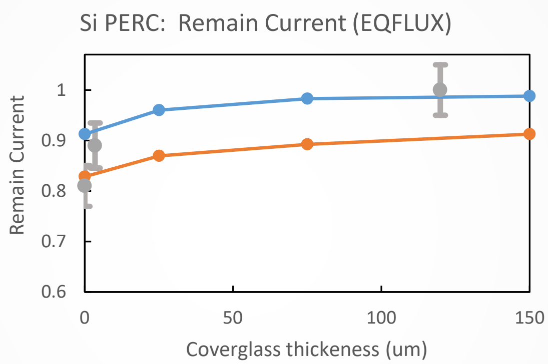
Three different approaches to shielding

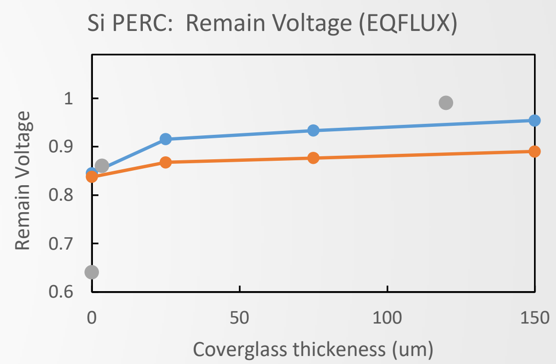




SI RADIATION PREDICTIONS: EQFLUX

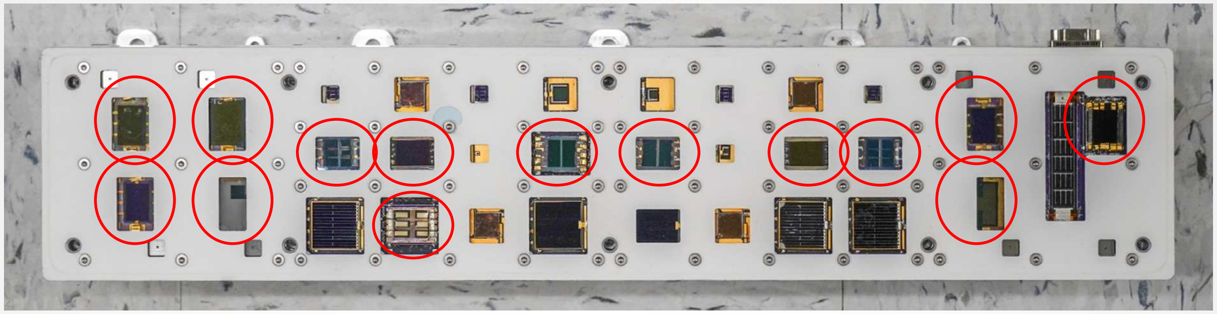






Degradation reference: Romain Cariou, et al., Investigation of p-Type Silicon Heterojunction Radiation Hardness, JPV (2024). DOI: 10.1109/JPHOTOV.2023.3333197

PEROVSKITES



A variety of perovskite cells were sourced from collaborators

Mounting methods included

- Conductive adhesives
- Brass spring clips w/ indium

Substrates included

- Glass slides
- Polymer (PET) films

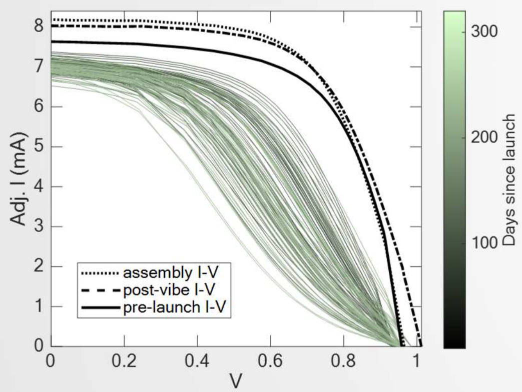
Rear-side encapsulation included

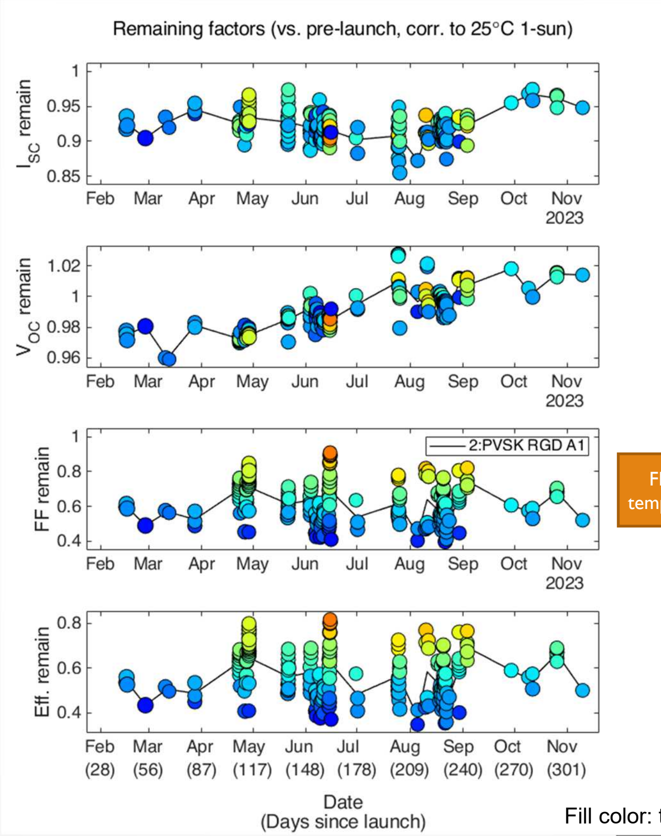
- Glued-on coverglass or plastic films
- Deposited layers (or just rear metal)

- The perovskite cells generally degraded during handling and testing prior to flight, but most were performing well at time of delivery
- Degradation varied substantially, even between nominally identical cells

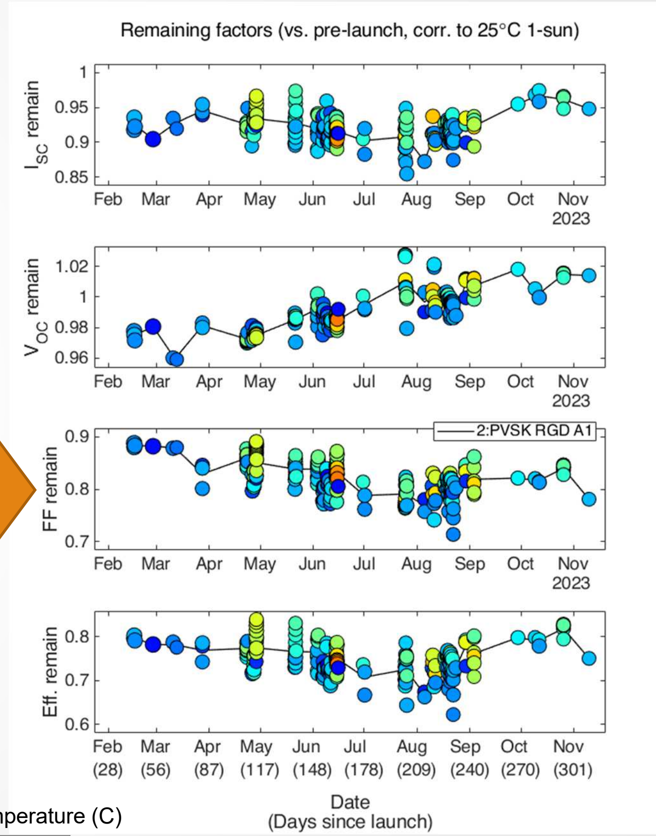
Perovskite highlights – highest remaining efficiency

- Rigid glass superstrate
- No back glass
- Single-pixel device
- Brass-clip connections





FF tempco

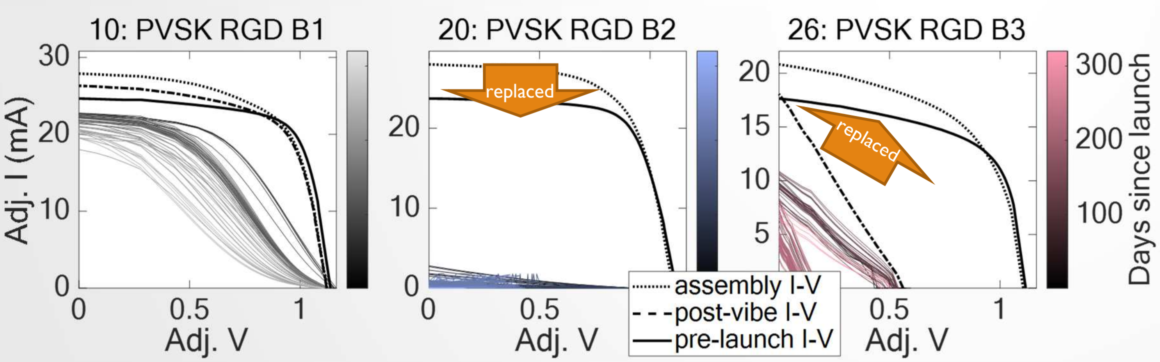


Fill color: temperature (C)

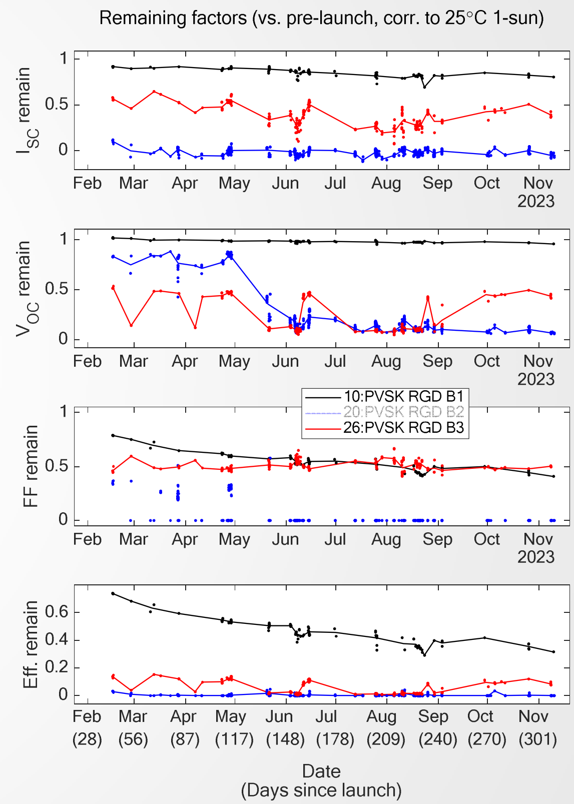
-20° 50°

Perovskites – (3) nominally identical cells

- Rigid glass superstrate
- No back glass
- 8-pixel device (all parallel)

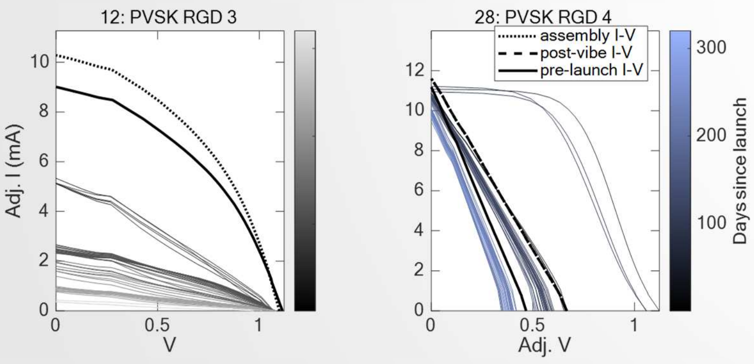


adhesive *clips* *adhesive*

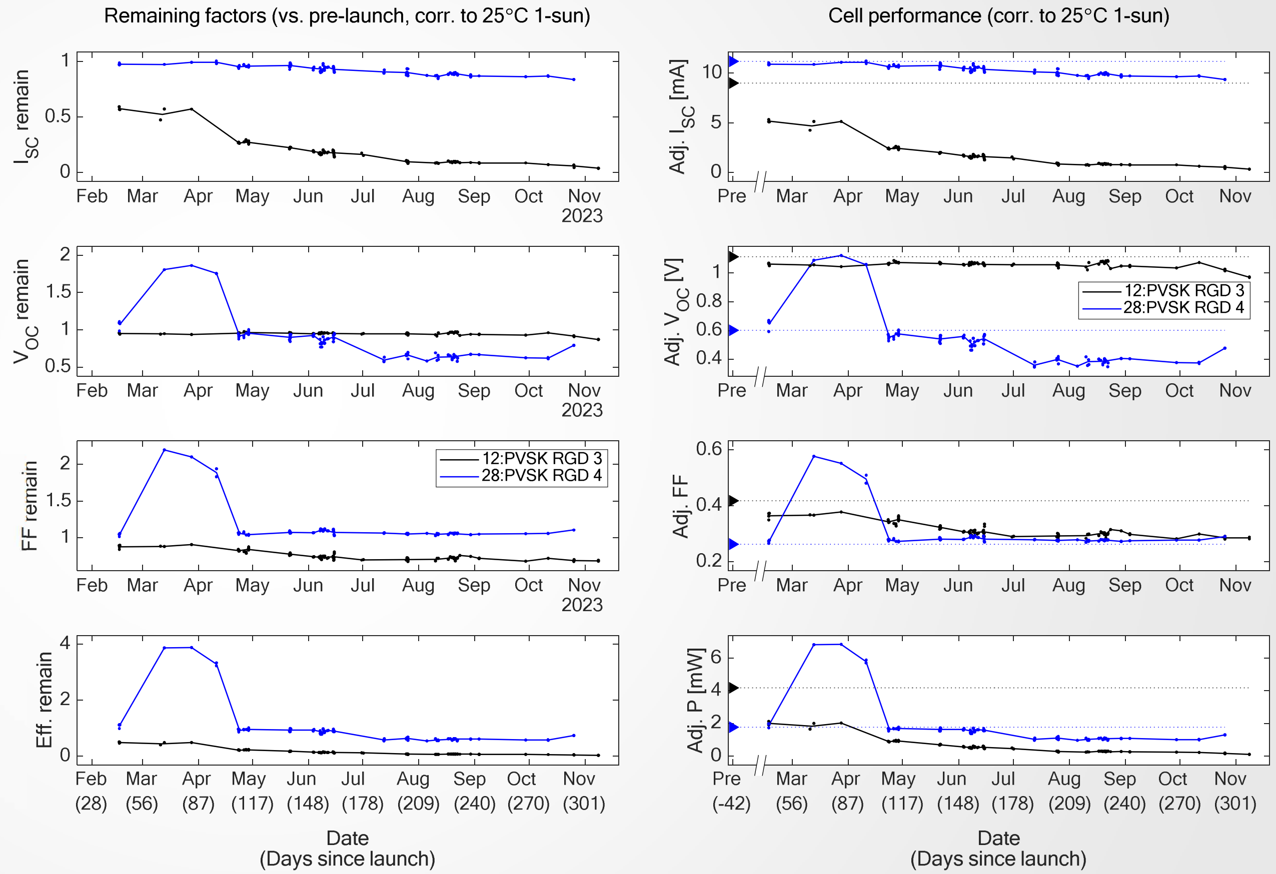


Perovskites – momentary resolution of shunt

- Rigid glass superstrate
- With back glass encapsulation
- 6-pixel devices (all parallel)

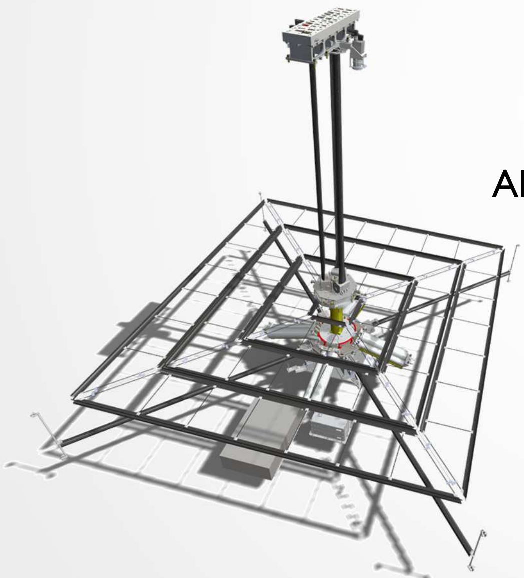


clips *adhesive*



EXPERIENCE AND LESSONS LEARNED

- Measuring solar cells in space is within reach for academic research, thanks to the AMU architecture!
- Despite intermittent faults, all 32 AMUs remained operational throughout the mission
- Flight testing is very time-consuming, but can inspire and benefit a broad range of emerging technologies
- We are working to publish full mission details and results ASAP



Also…

It is best to locate solar cells away from sources of shading, such as trees, buildings, or ultralight deployable space structures

Acknowledgements

- The Caltech SSPP team and Atwater Group members
- Collaborators who have provided cells for Alba!
- Colin Mann, Don Walker, Pilar Espinet Gonzalez and others @ Aerospace Corp
- Collaborators at JPL, NREL, and NASA who participated in the perovskite proton radiation study

Caltech
Space Solar Power Project

A failed attempt to photograph Vigoride5/SSPD1 passing over Death Valley (May 2023)

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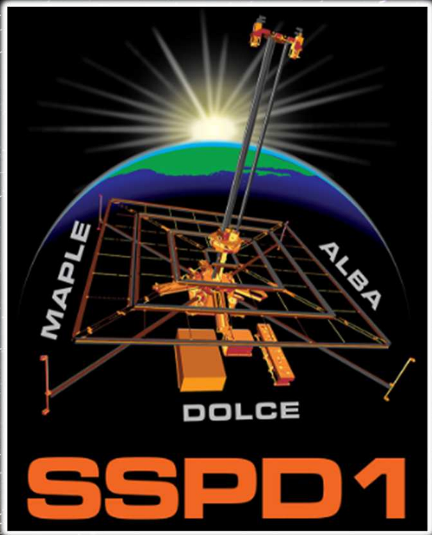


MacGillivray Freeman's
CITIES OF THE FUTURE

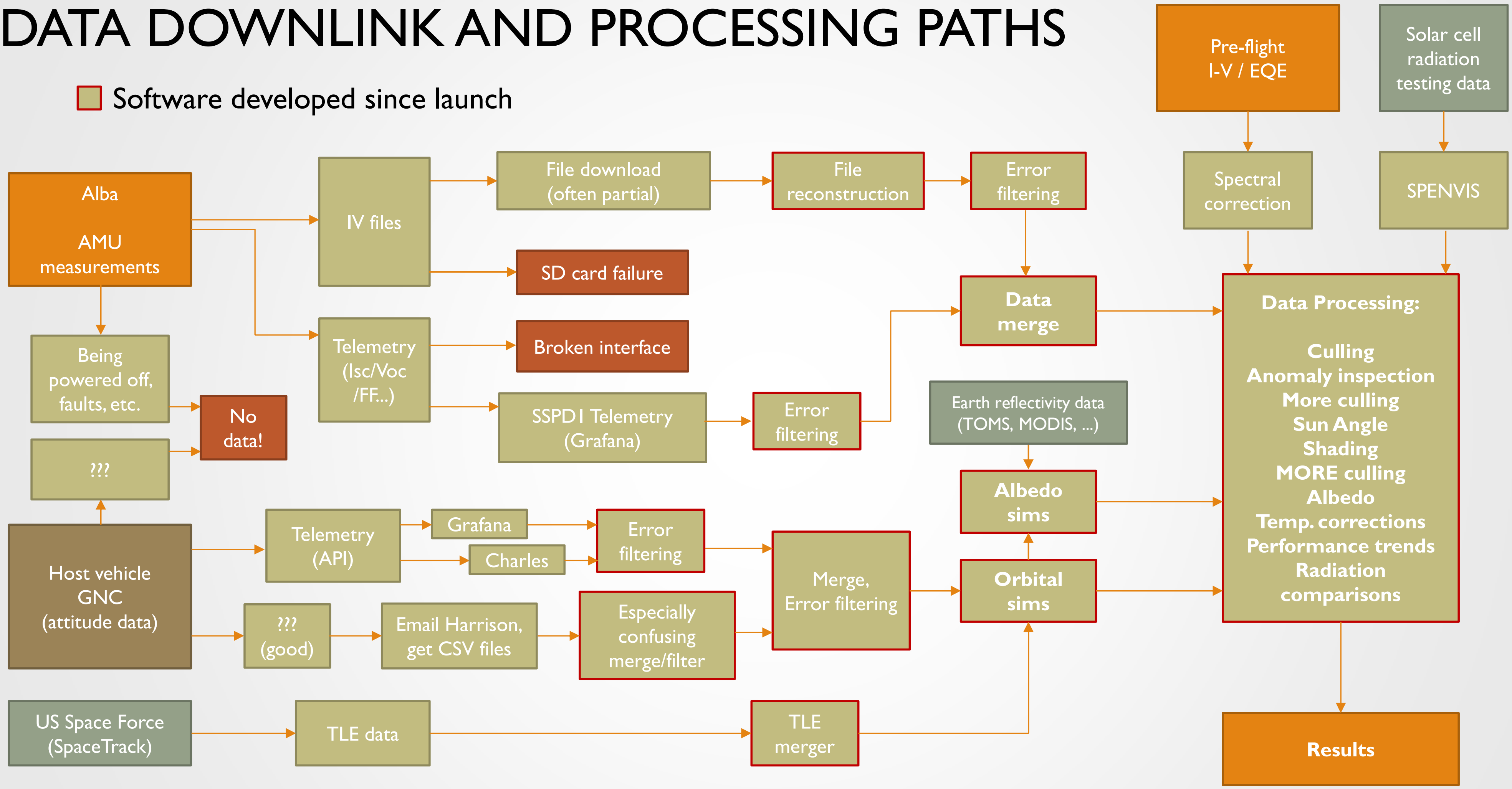
Caltech
Space Solar Power Project

A failed attempt to photograph Vigoride5/SSPD1 passing over Death Valley (May 2023)

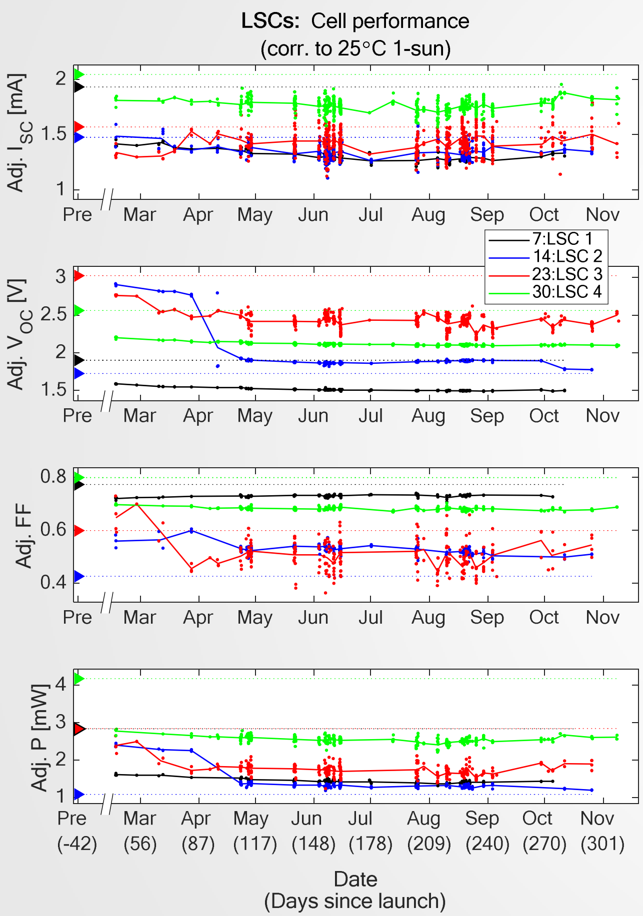
ATWATER RESEARCH GROUP

DATA DOWNLINK AND PROCESSING PATHS

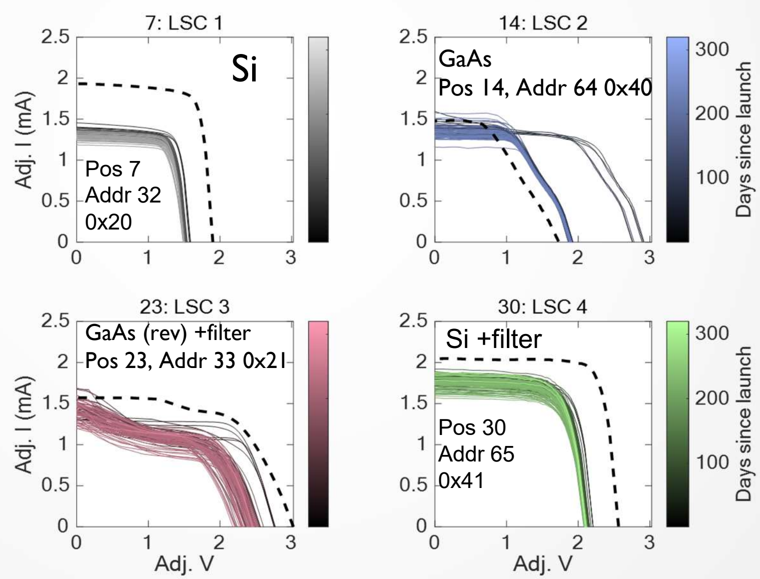
Software developed since launch

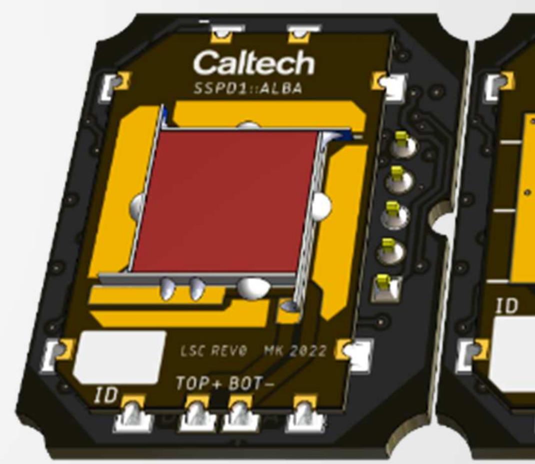


LSC RESULTS



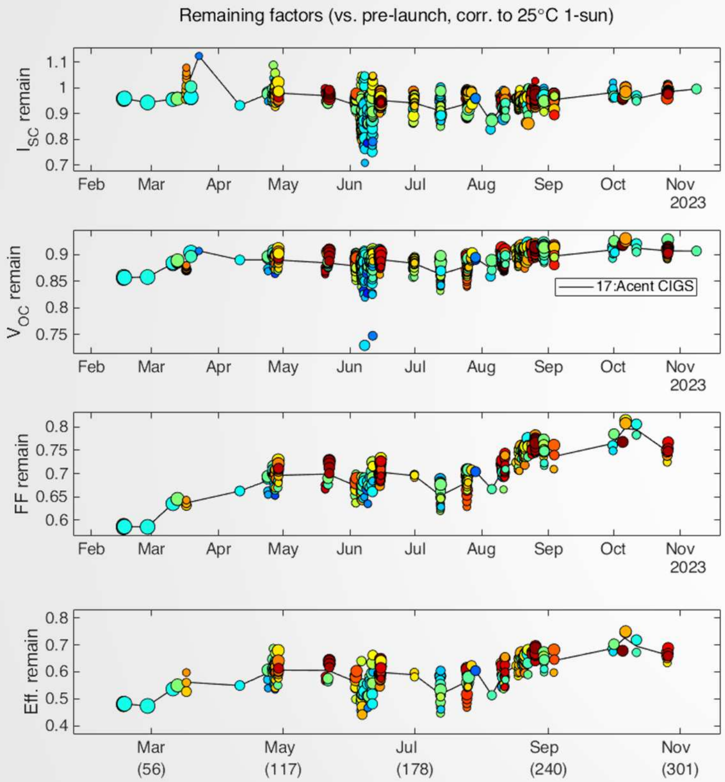
- It appears that the primary issues with LSCs were mechanical
- Shunting of subcells – particularly for GaAs, which were thinner
- Detachment of cells from waveguide – current mismatch
- Moderate voltage degradation for both types; current degradation for Si

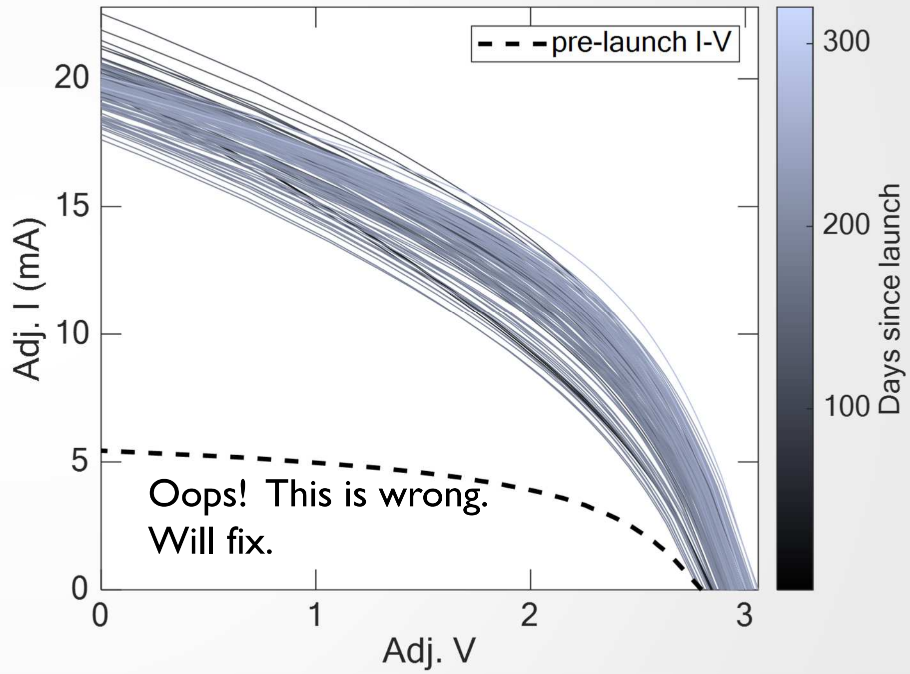




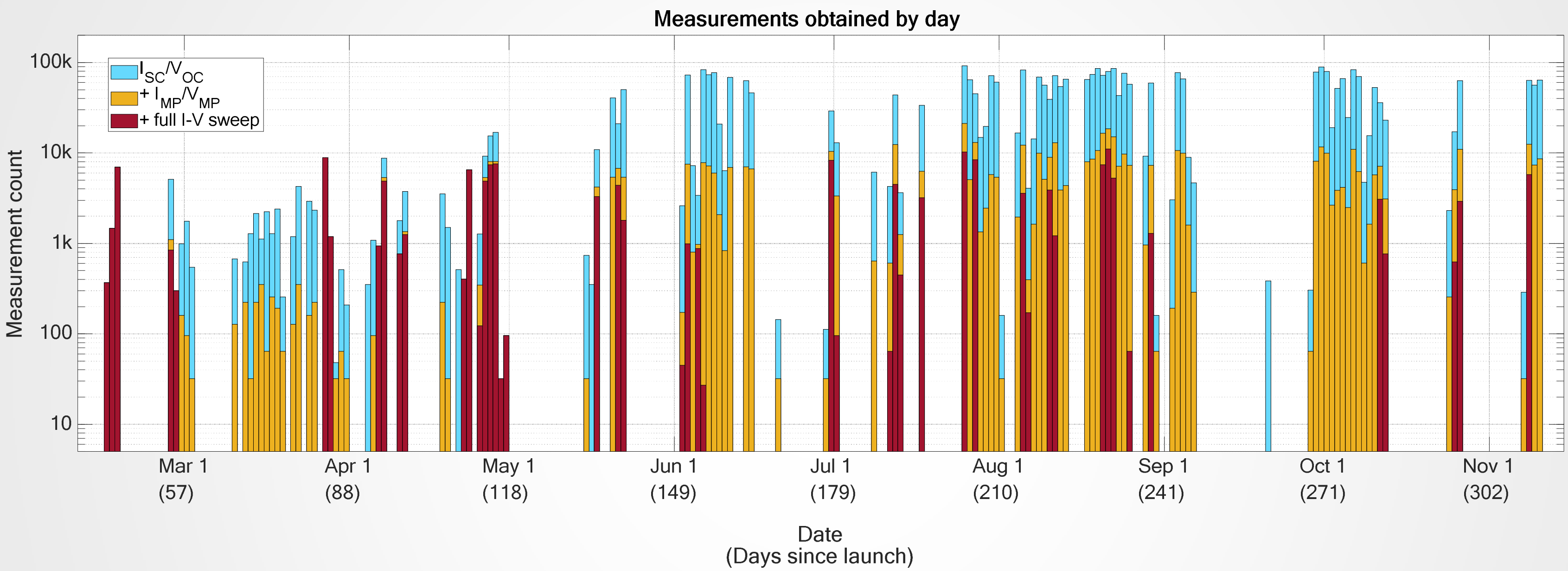
LSCs comprise (4) series-connected cells

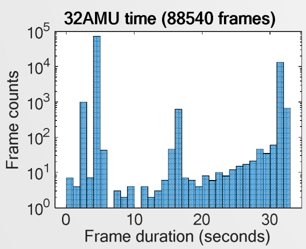
CIGS RESULTS



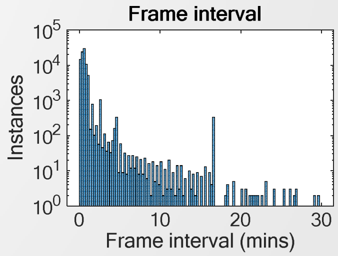


ALBA DATA STATS

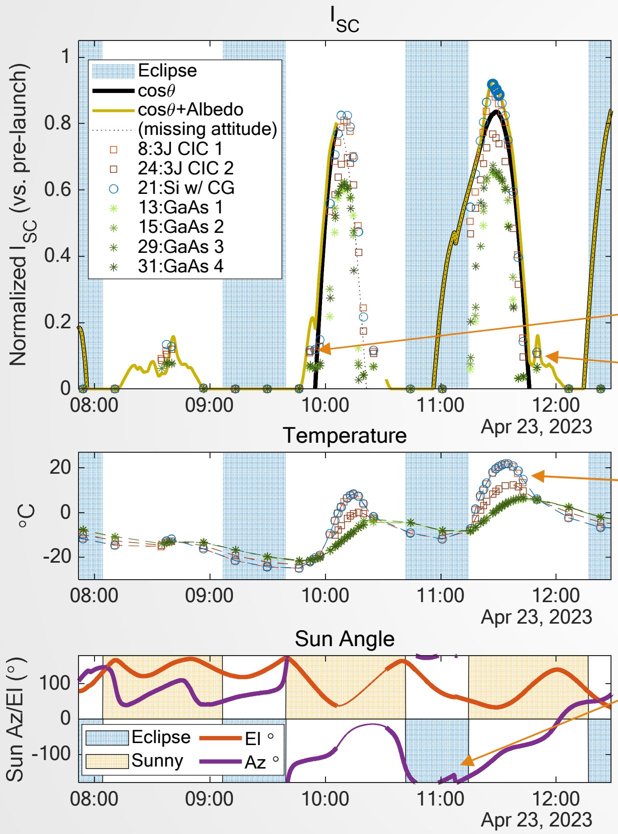





```
Calculated 08-Nov-2023 22:20:54, using timeout threshold 30 minutes:
Total operational time:  44.193 days
Number of operational intervals:  348
First data point:  14-Feb-2023 21:15:51
Final data point:  06-Oct-2023 16:04:35
Longest continuous interval:  58.653 hr
Shortest continuous interval: 17 sec
```



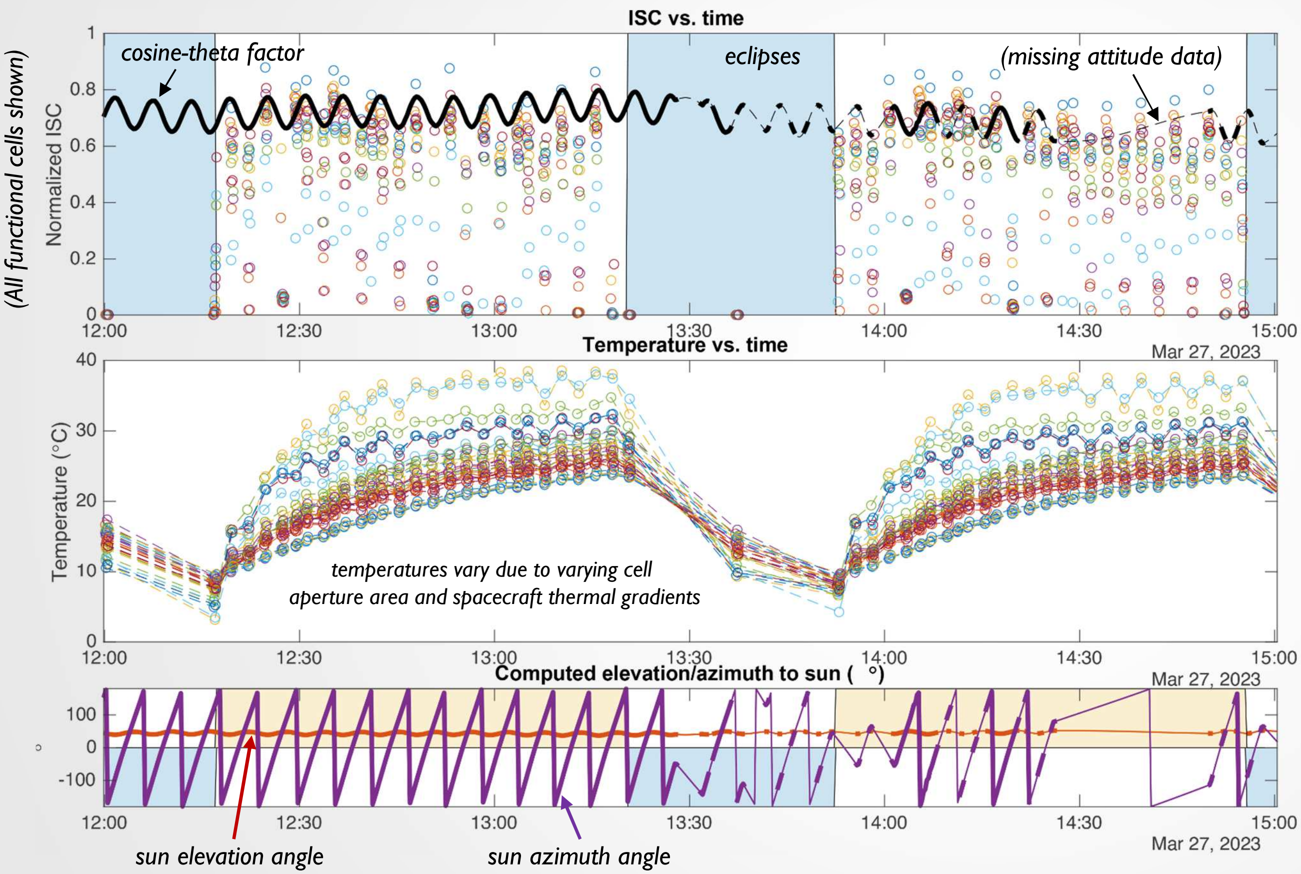
More typically, attitude data agrees somewhat well

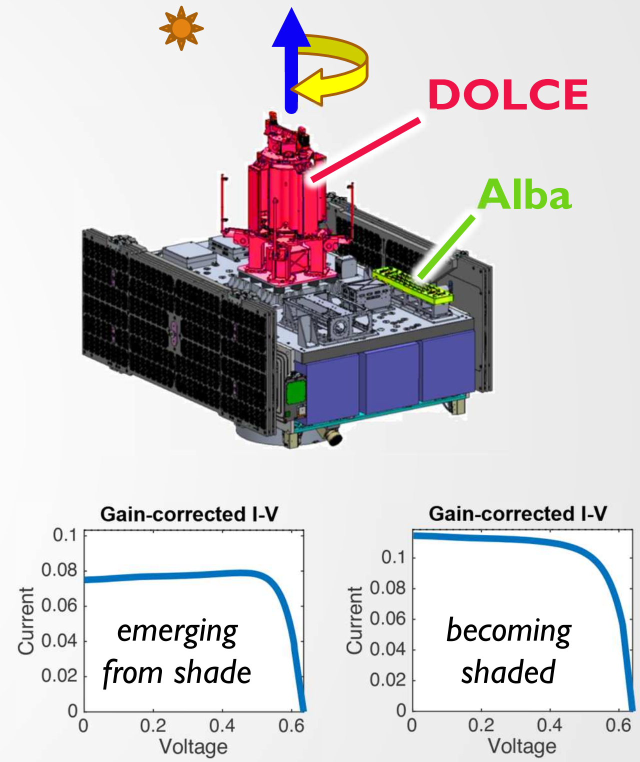


This example shows key typical behaviors:

- Reasonable agreement between non-degraded reference cells I_{SC} and cosθ envelope
  - (degraded cells track proportionally)
- Some shading evident far off normal
- Agreement is even better when albedo is considered (more on this later)
- Alba's self-regulation of data acquisition is evident—frequent measurements when illuminated, less frequent in darkness.
- Occasional abrupt angle changes – suspected due to articulation of solar panels
- Note: only measurements taken as near normal-incidence as possible are selected for analysis (bold; more on this later)

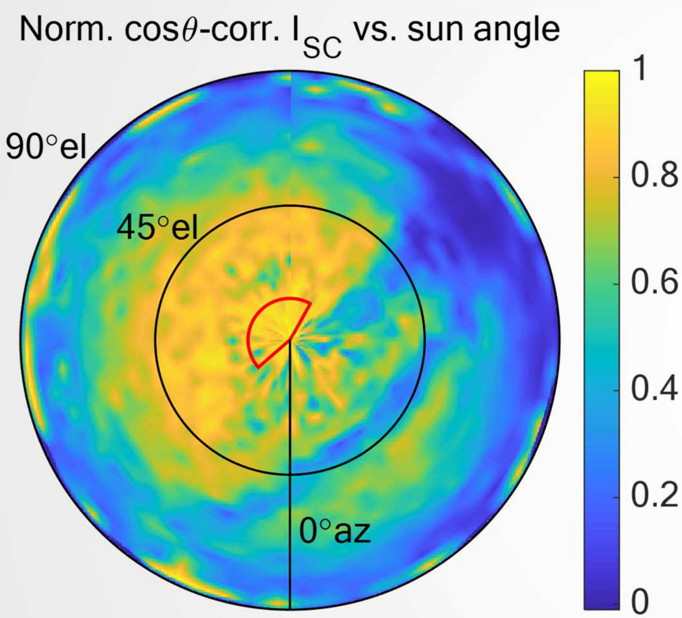
DETERMINING SHADING ANGLES

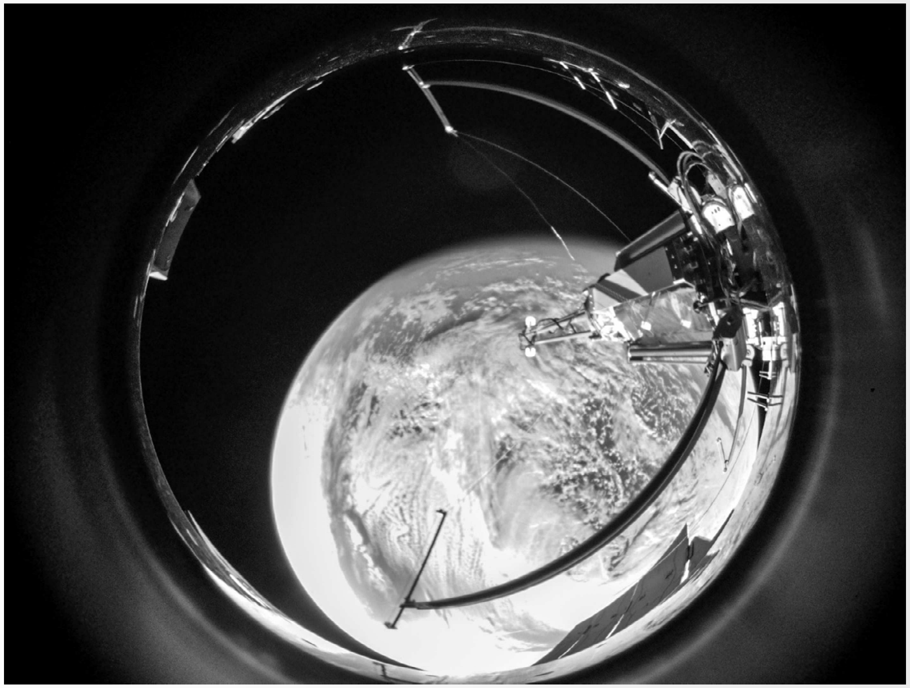




Attitude data is used to cull data from transient illumination conditions

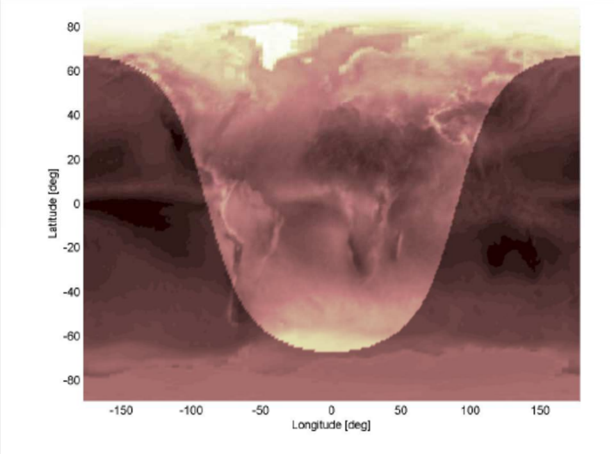
Choosing the acceptance angle (per cell, per mission phase)



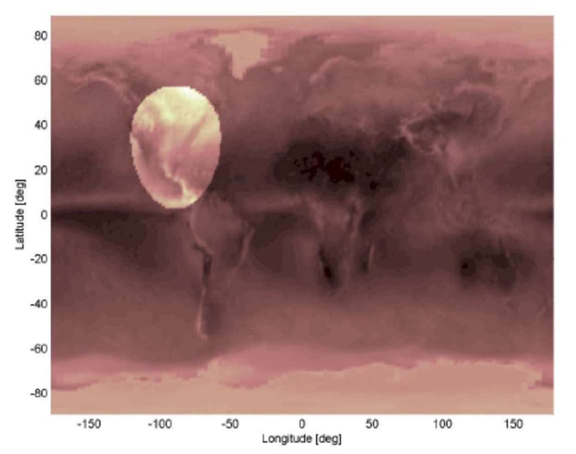


ALBEDO

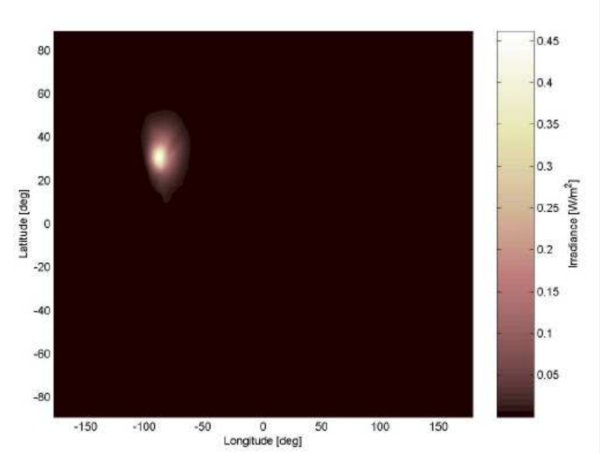
Sunlight reflected from Earth



Solar illumination



Satellite field of view



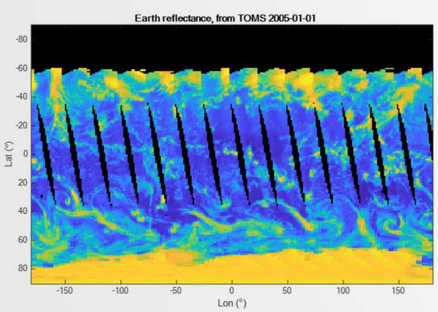
Albedo factor

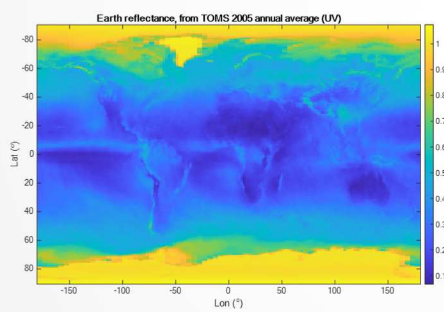
- I implemented a simplified approach to calculate Albedo illumination on Alba's solar cells
- Reference: "Spacecraft Attitude Determination with Earth Albedo Corrected Sun Sensor Measurements," Dan Bhanderi, 2005

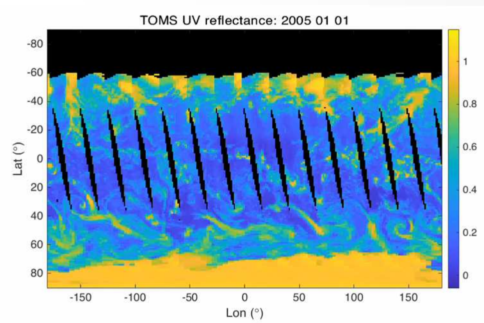
ALBEDO CORRECTION: DATASET

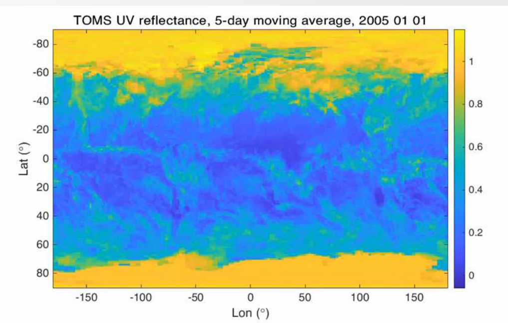
For simplicity, I used an earth reflectivity data set from the TOMS program

THE GOOD	THE BAD
• Easy to track down and import data for calculations	• Provides UV reflectance (~380 nm) – wrong band for solar cells!
• Adequate spatial resolution for this application (180x288px)	• From 2005 instead of 2023
• Daily data sets allow albedo calcs to capture seasonal variation	• Daily passes don't cover the whole globe… averaging and interpolation necessary









It appears I could get time-resolved multi-band reflectance data for 2023, from MODIS MCD43 ?

- Daily full-globe coverage (I think? Haven't accessed!)
- Several bands available (12; 405 – 965 nm)
- 2023 data

- Incredibly confusing!
- 500m resolution?
- Black sky? White sky?

- Don't even know which product to use!
- Download/import alone would be PITA
- Need geophysicist advice, where to even start?

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