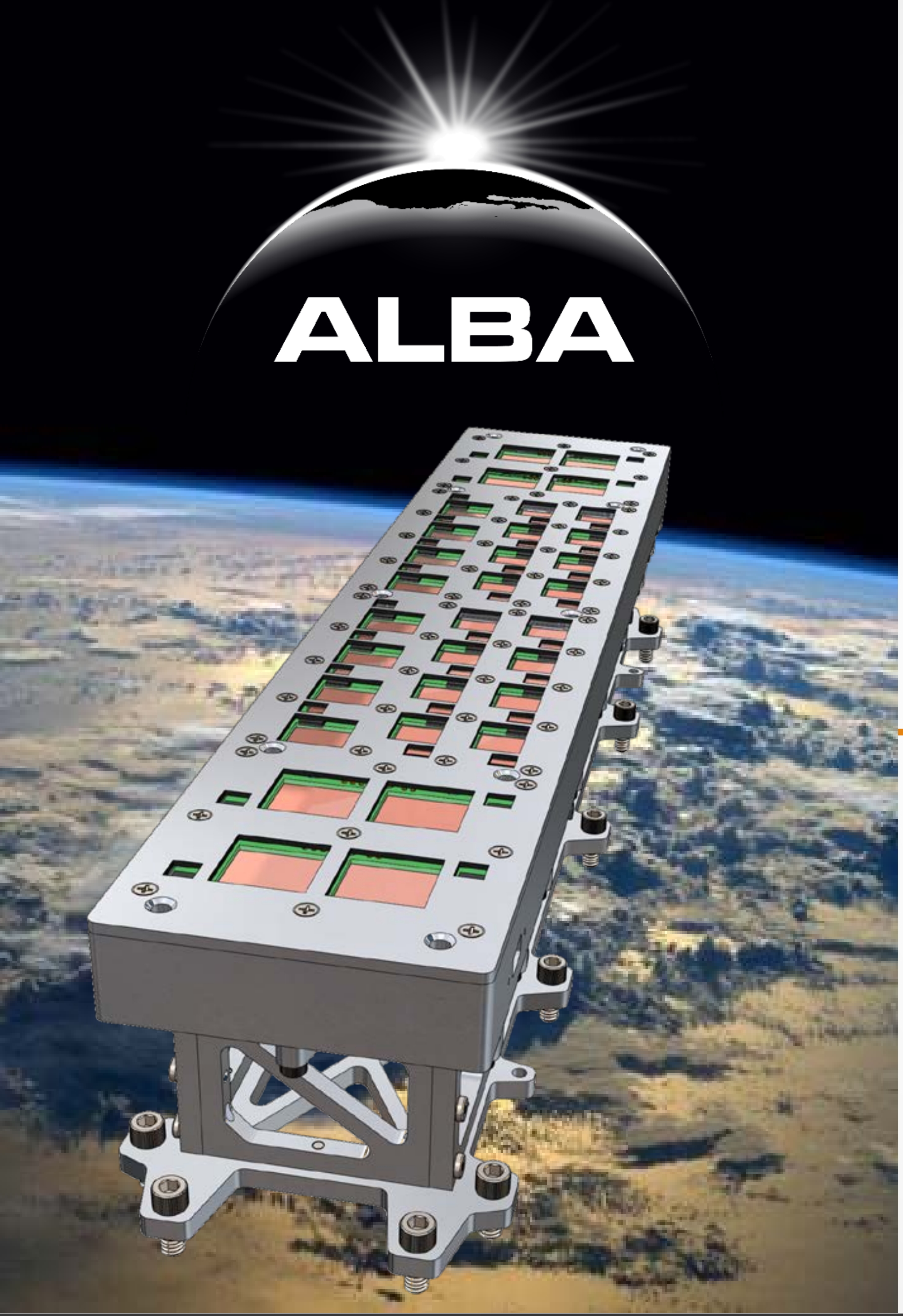


Alba: A Low Earth Orbit Testbed for Emerging Photovoltaic Technologies

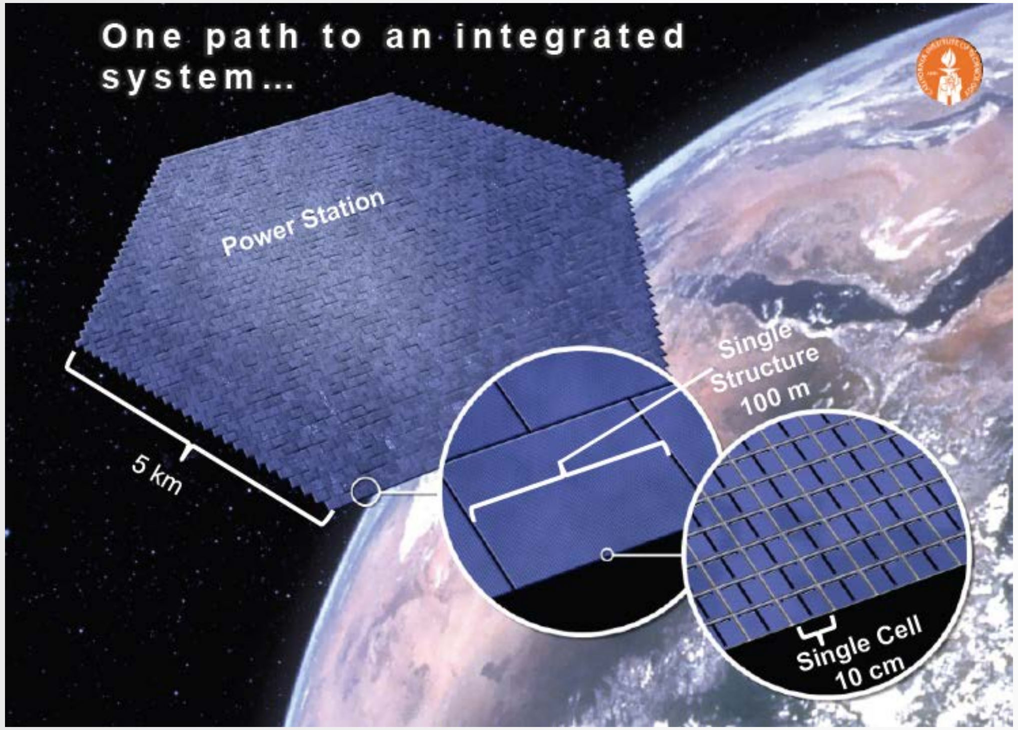
Michael D. Kelzenberg, Phillip R Jahelka, Andrew W. Nyholm, Sara Anjum, Megan Phelan, Catherine N. Ryczek, Samuel Loke, Pilar Espinet Gonzalez, Harry A. Atwater

Caltech
Space Solar Power Project

ATWATER
RESEARCH GROUP

BACKGROUND: CALTECH SSPP

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



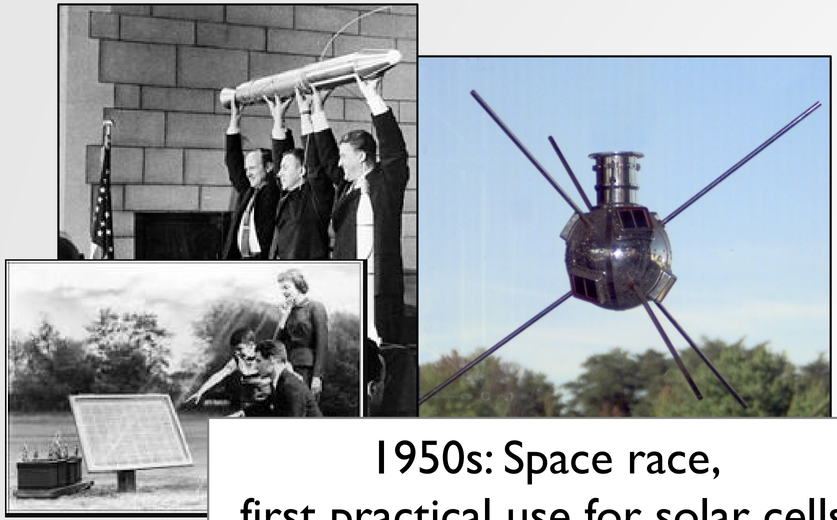
Ultralight photovoltaics
(Atwater Group)

Wireless power transmission
(Hajimiri Group)

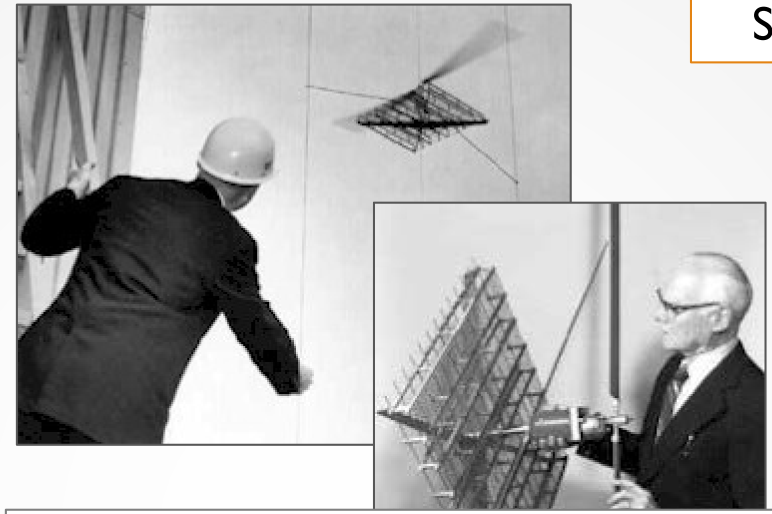
Deployable space structures
(Pellegrino Group)

https://spacesolar.caltech.edu

BACKGROUND: SPACE BASED SOLAR POWER

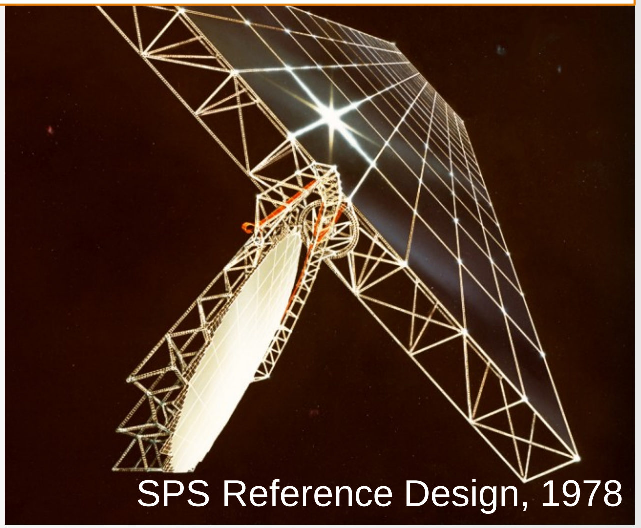


1950s: Space race,
first practical use for solar cells



1963: W. C. Brown invents the rectenna.

1968: Peter Glaser formally proposes SSP concept to NASA; studies follow.



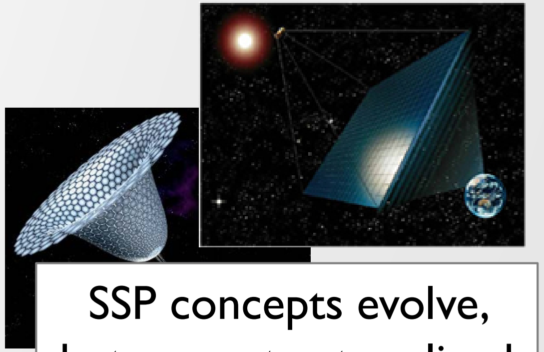
SPS Reference Design, 1978

1975: >30 kW transferred >1 mile

Present day…

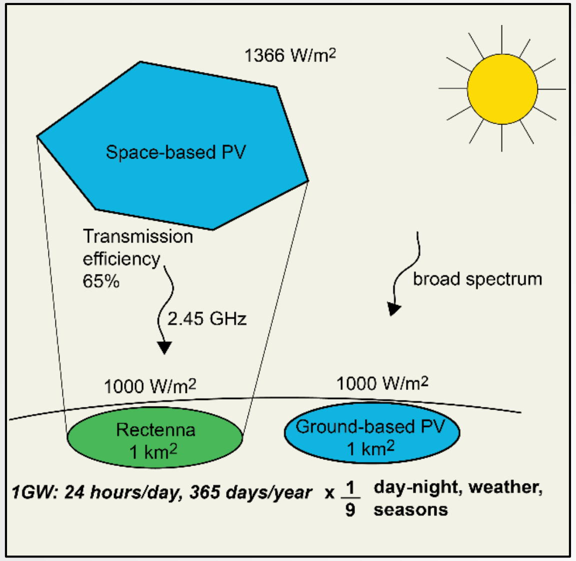
Spacecraft & PV technology matures

Crisis drives renewable energy growth, Terrestrial PV reaches TW scale



SSP concepts evolve, but are not yet realized

Promise of SSP



- Globally scalable source for renewable baseload power
- Dispatchable and predictable
- Based on proven technologies

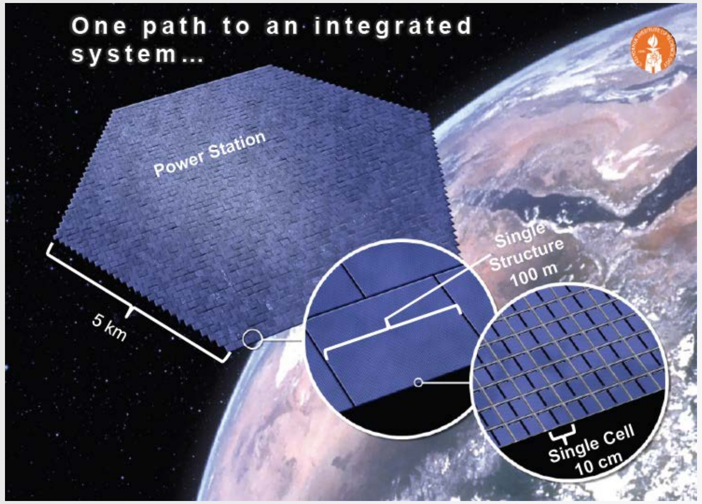
Challenges

- System cost:
  - Per watt?
  - Per kWh?
  - To deploy at viable scale?
  - Compared to alternatives?
- Risks:
  - Security and safety
  - Regulatory viability
- Vast range of design tradeoffs:
  - Wavelength (e.g., laser vs. RF)
  - Orbit and aperture architecture (duty cycle)
  - Lifetime and efficiency vs. cost and scalability
  - Modular vs. monolithic power stations

Our Motivation

We seek to develop ultralight, scalable technologies that could enable cost-effective space-based solar power

2015-2017: CALTECH SPACE SOLAR POWER INITIATIVE (SSPI)

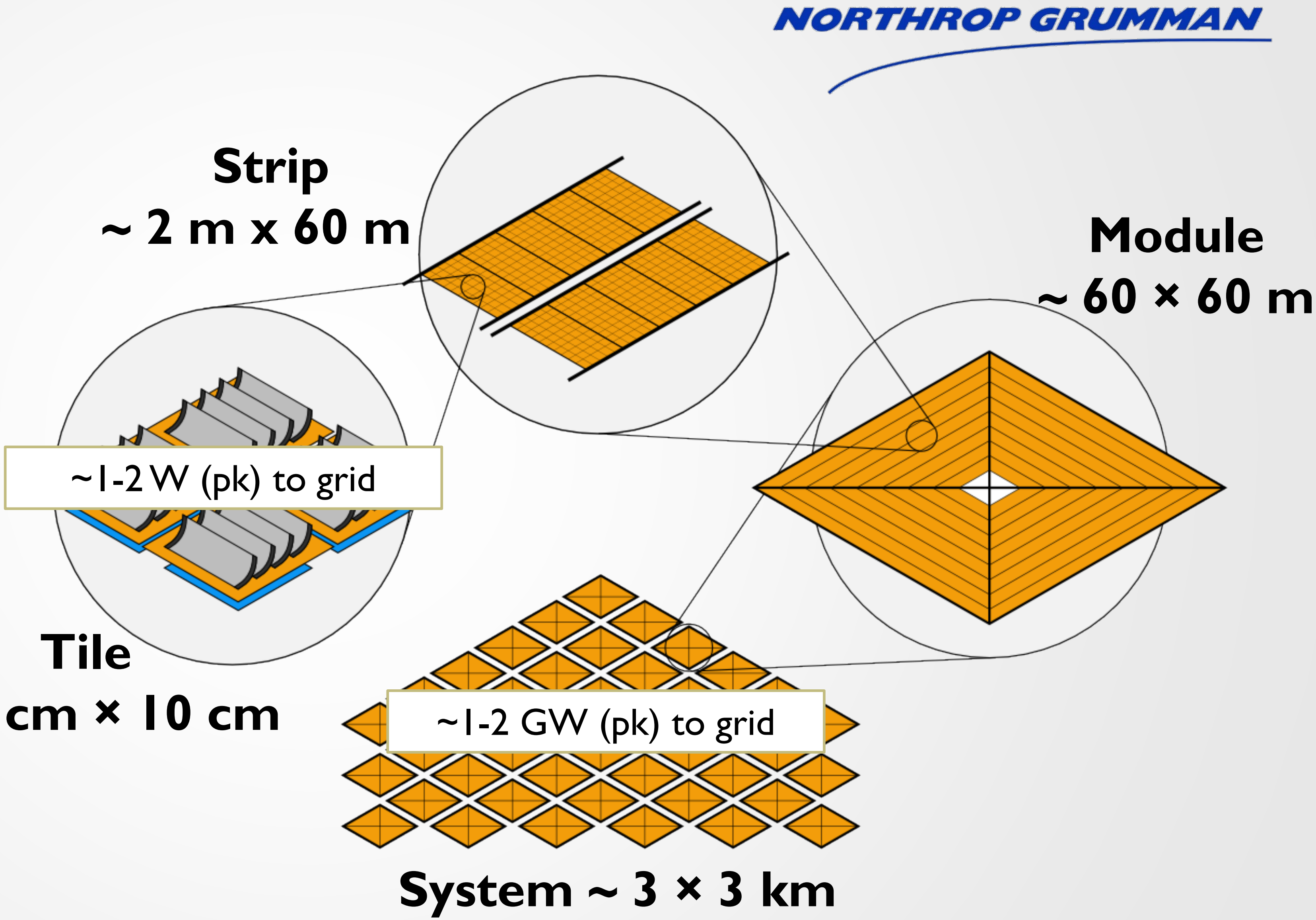


SSPI concept:

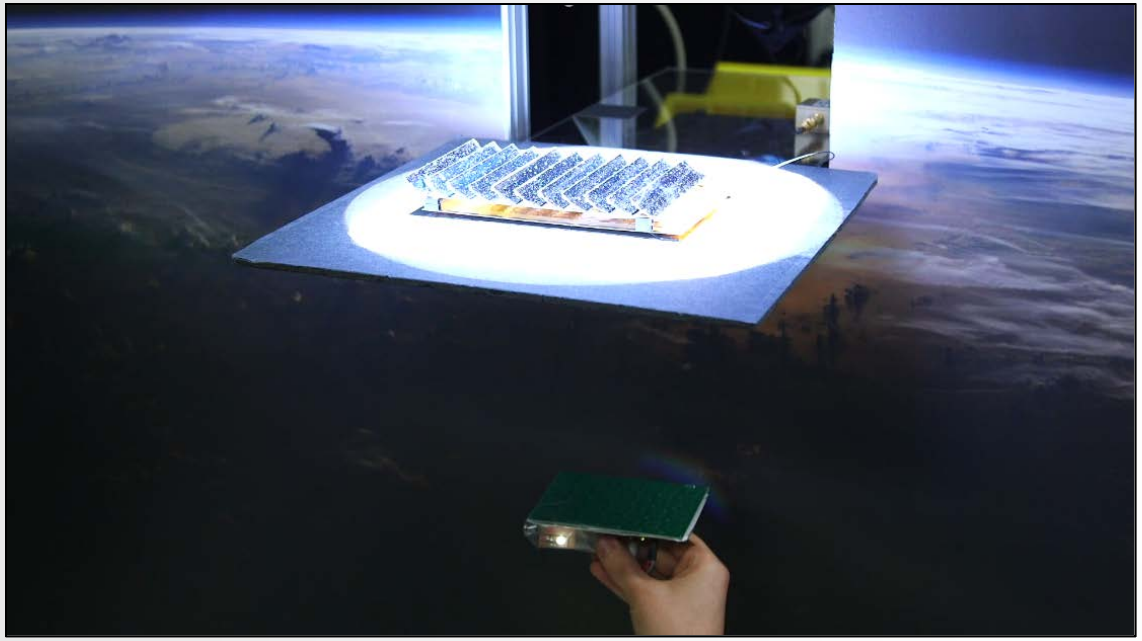
- GEO power station
- Area: ~10km^2
- Power Output: ~1-2 GW
- Peak ground power density: ~1 kW/m^2

PV Performance Targets:

- Efficiency > 30%
- Areal Mass: 40–200 g/m^2
- Specific Power: 2–10 kW/kg



SSPI Achievements

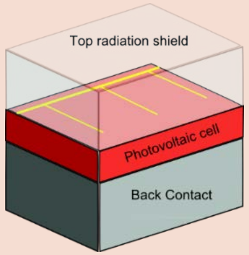


Integrated tile prototype

Deployable structure prototype

SINCE 2018: CALTECH SPACE SOLAR POWER PROJECT (SSPP)

spacesolar.caltech.edu

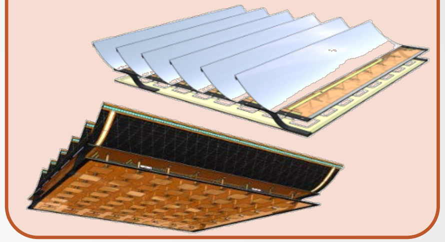


State-of-the-art space PV

- Efficient but costly III-V materials
- Requires radiation shielding
- Specific power < ~1 kW/g (module)

Prior work

Concentrators



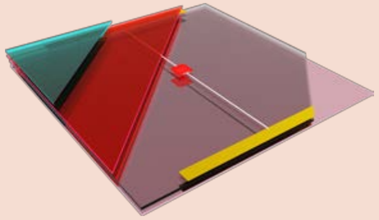
Concentrators improve specific power, but constrain system architecture

Tracking/pointing | One-sided PV | Deployment | Optical losses

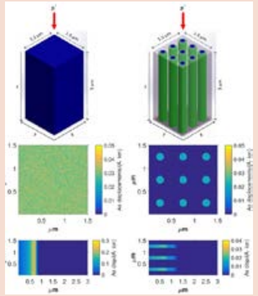
Flat-plate PV alleviates these constraints but requires new PV technology

Flat-plate concentration, new materials for space

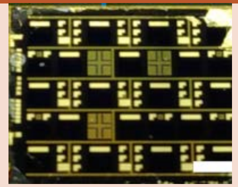
Luminescent concentrators



Fabrication and device-level innovation for proven materials

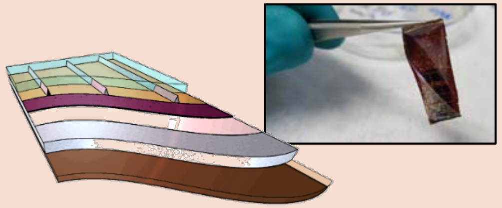


Rad-hard / low-cost III-Vs



Materials innovation: novel ultralight films

Thin-film (Perovskites)

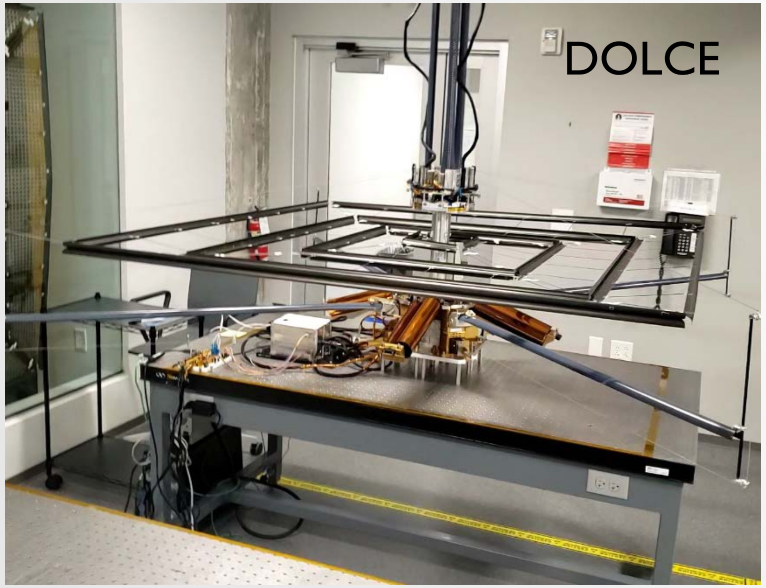


OUT OF THE LAB AND INTO ORBIT!

Our first flight mission, Space Solar Power Demonstrator One (SSPD1), comprises:

- DOLCE: Deployable On-orbit Lightweight Composite Experiment: demo deployment of ~2m structure
- MAPLE: MicrowAve Phased-array Low-earth-orbit Experiment: test RFICs, phase control, rectennas in space…
- Alba: Wait, we were doing acronyms? We chose 'alba' for dawn, invoking themes of sunlight and new beginnings

Alba is the Atwater Group's component of SSPD1, testing experimental solar cells in space



Emerging photovoltaic technologies of interest to SSPP being tested aboard Alba (and control devices):

- Low-cost scalable GaAs
- Rad-hard nanowire III-Vs
- Luminescent solar concentrators (LSCs)
- Thin-film perovskites
- Thin-film CIGS
- Modern low-cost Si
- Modern III-V multijunction space-grade CICs

CHALLENGES OF MEASURING SOLAR CELLS IN SPACE

Cost	Shared project resources across three SSPP research groups
Experiment complexity	Utilize flight-proven I-V measurement circuits developed for balloon/space applications
Spacecraft complexity	Operate mission as hosted payload on commercial vehicle vs. stand-alone cubesat
Risk management	Utilized space-rated central components (CPU/OS) + low-complexity risk diversification for our experiment

ALBA DESIGN SUMMARY

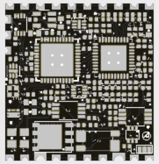
Science Payload

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

Underlying architecture:

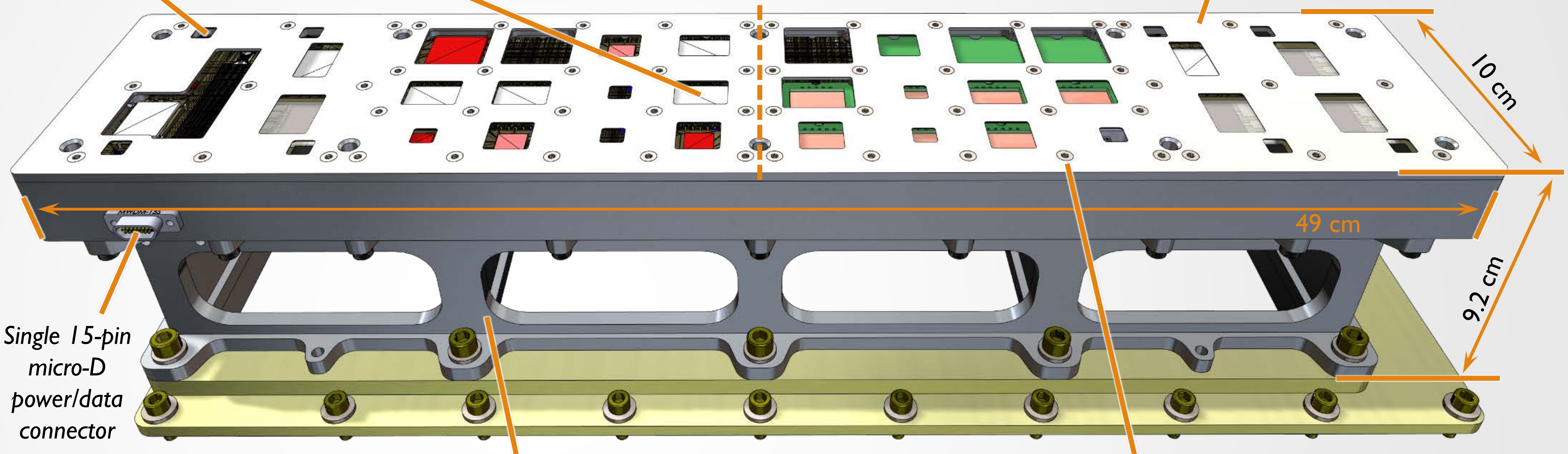
AMU

(Aerospace Measurement Unit)



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

- Low cost I-V sweep circuit
- Internal calibration
- Senses sun angle and cell temp
- Optional MPPT, cell heaters, …
- Simple I2C interface w/ C API



Mechanical*

- Dimensions:
  10.0 x 48.4 cm enclosure, 2.9 cm thick
  Envelope w/ standoffs: 11.0 x 48.4 x 9.2 cm
- As-flown mass: 3.0 kg

Electrical

- Power:
  2 x 5V, 2 x 80 mA max (2 x 40 mA typ)
  1 x 28V unregulated, up to 1.0 A (optional cell heaters)
- Data interface: 2 x I2C, up to 400 kHz, 3v3 or 5V

Mechanical specs don't include the Momentus-supplied adapter plate or associated hardware (yellow bottommost plate in image)

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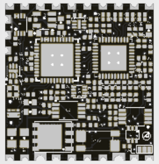

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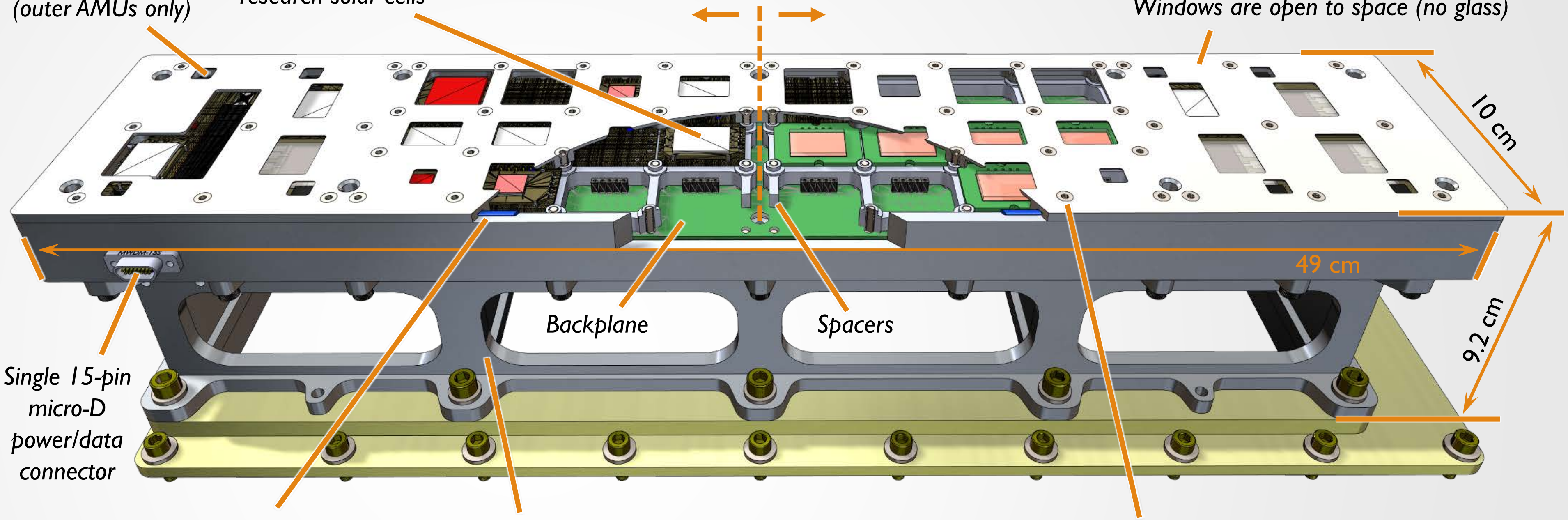

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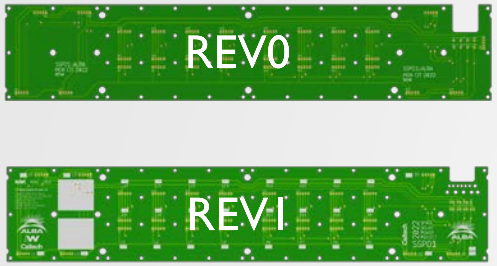
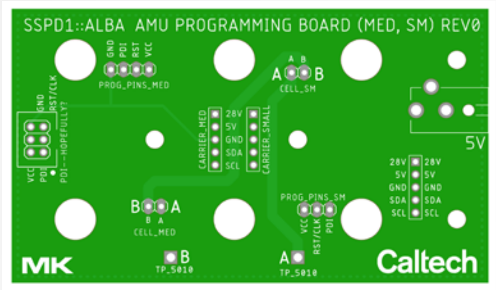
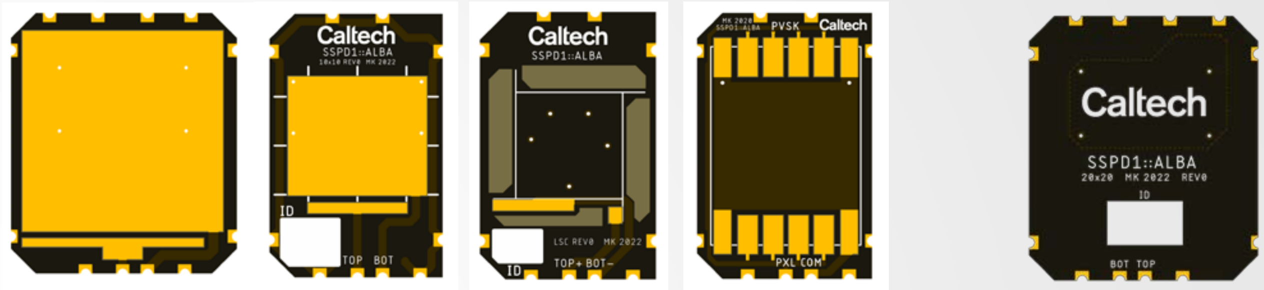
SUMMARY OF CIRCUITS FABRICATED FOR ALBA



Backplane



Programmer

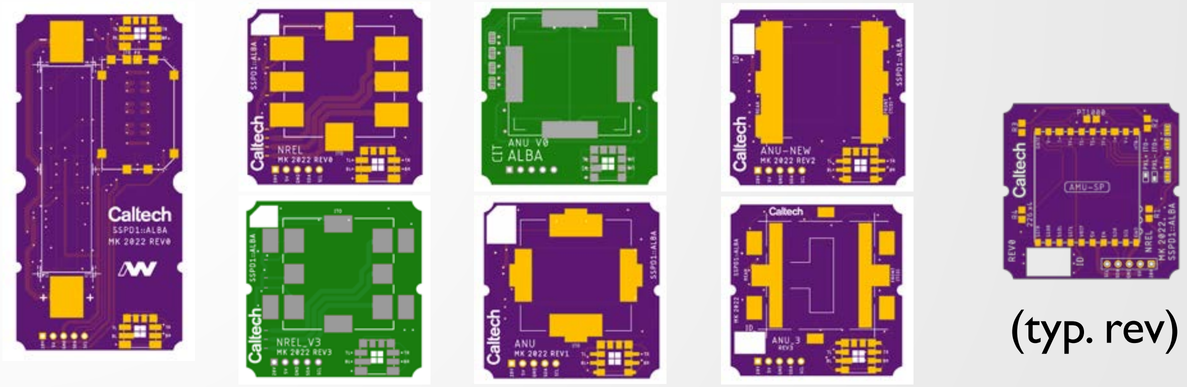


2cm cell | 1cm cell | LSC | PVSK | (typ. rev)

Cell interposers

SP | MD | SM

AMUs

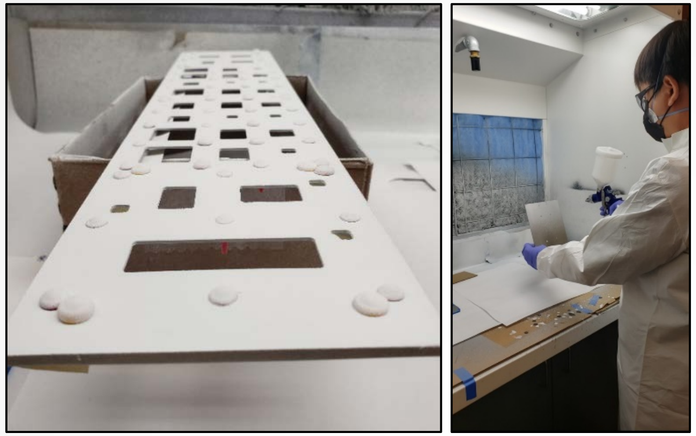


2SP | SP | (typ. rev)

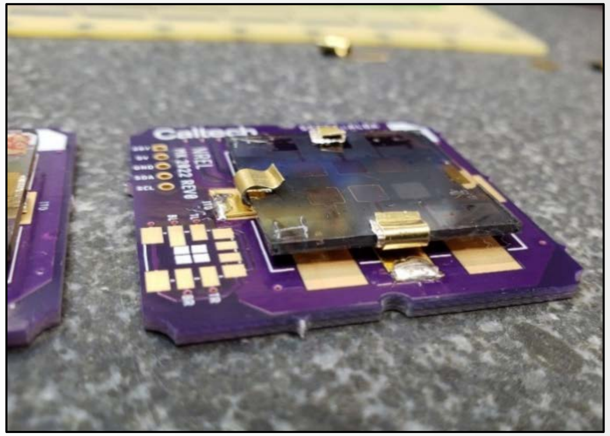
Cell Carriers

ALBA DEVELOPMENT HIGHLIGHTS

AMU & Cell Carrier PCB design

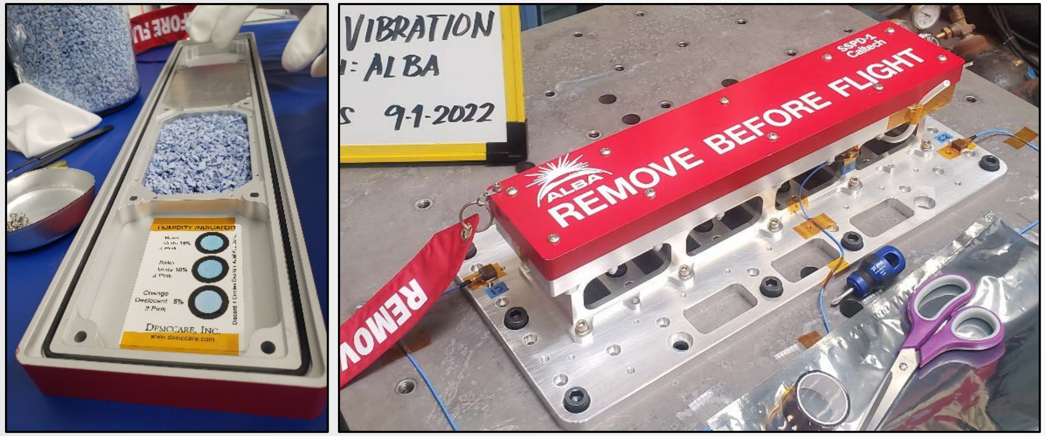


Front cover coating

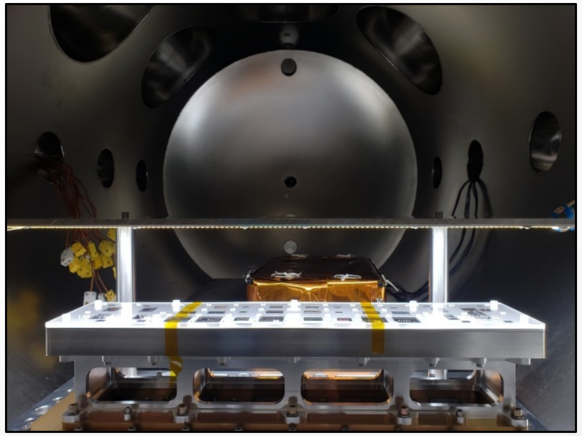


Cell mounting

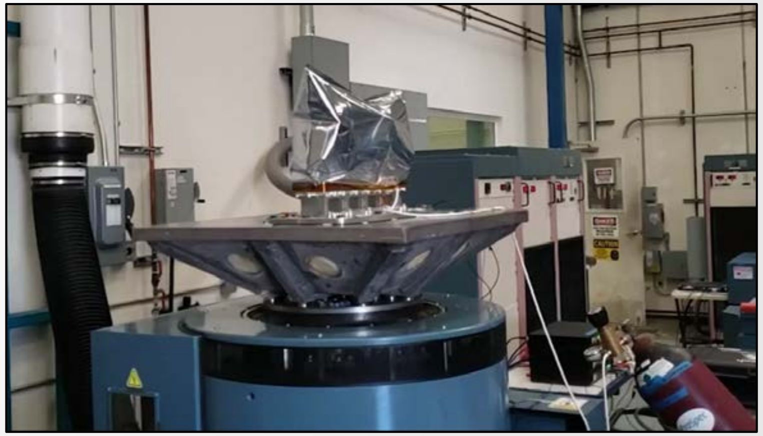
Assembly & test



RBF cover



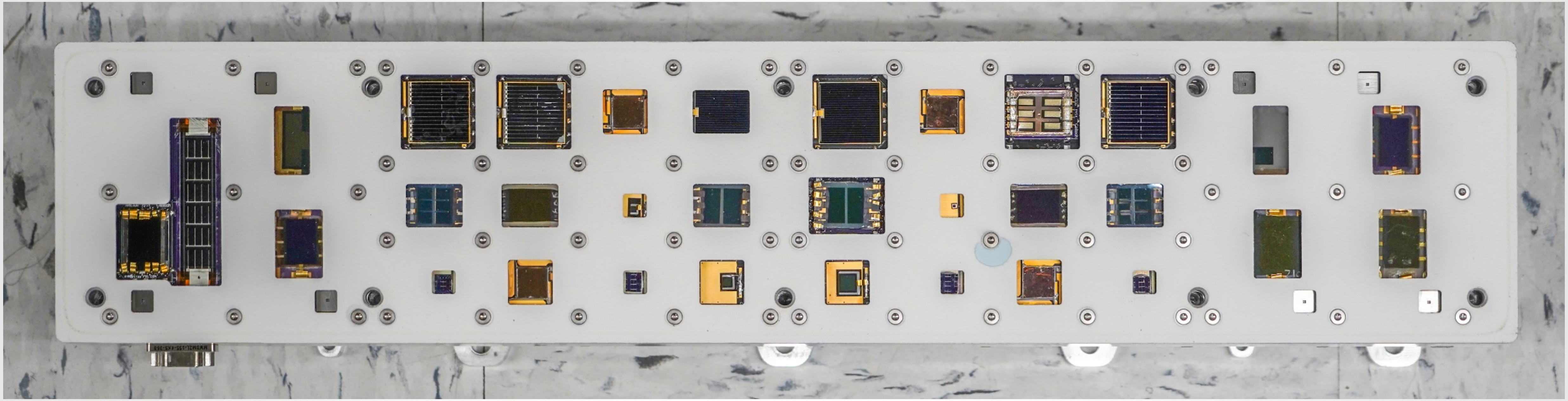
TVAC



Vibe test

INTEGRATED ON HOST VEHICLE

FINAL CONFIGURATION



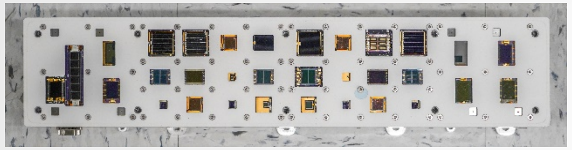
- Low-cost scalable GaAs
- Rad-hard nanowire III-Vs
- Luminescent solar concentrators (LSCs)
- Thin-film perovskites
- Thin-film CIGS
- Modern low-cost Si
- Modern III-V multijunction space-grade CICs

ALBA DESIGN PRINCIPLES

Autonomous	Automatically records I-V data when running. No input or commands necessary (other than startup).
Opportunistic	Detects when sunlight is present on the cells, records data more frequently when sunlight is favorable
Efficient/safe	Data generation, memory usage, and CPU usage are carefully throttled. Highly efficient non-compressed data structure.
Risk diverse	Utilizes two independent power/data busses (split) Utilizes two different ways to return data over the link

TIMELINE: DELIVERY, LAUNCH, AND INITIAL FLIGHT OPS

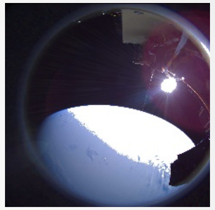
Oct 30: Final Alba test/calibration @ Caltech, flight SW on RPi Steele 202 Solar Simulator, AM0 I-V data recorded



Alba is complete with 32 functional AMUs, but unexpected issues preclude calibration of sun-angle sensors

Vehicle assembly: RBF cover removed @ KSC Florida

Feb 13: First photo from host



Charles gets first partial IV file! More packets are returned over following several days

First Alba telem!

Nov | Dec | 2023 | Feb | Mar

23 days w/RBF | **43 days unsealed in Florida** | **42 days in space**

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

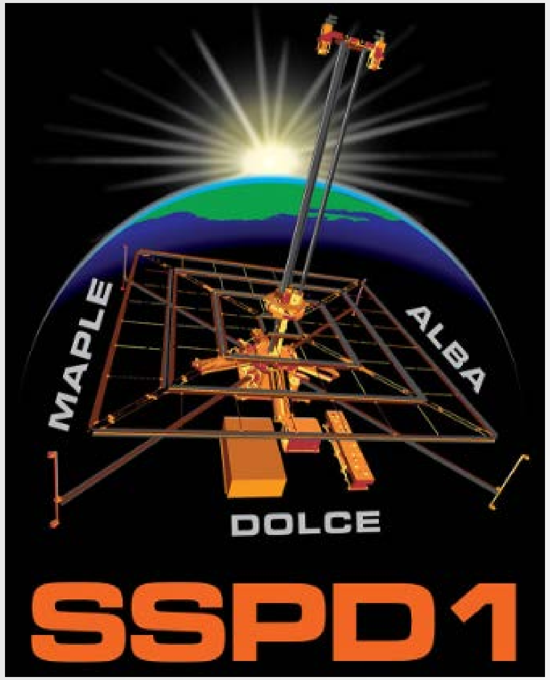
Oct 31 – Nov 2: Caltech team integrates Alba onto Vigoride @ Momentus HQ.

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
- Alba on, downlinking telemetry data
- Efforts to downlink I-V file data



SUMMARY

Caltech
Space Solar Power Project

- Numerous PV cell technologies are being evaluated for potential utility in space-based solar power systems
- We are currently measuring on-orbit performance of experimental solar cells
- Future work will seek to integrate and test new PV technologies with ultralight deployable structures and integrated RF power converters.

Acknowledgements

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