Intelligent Solar Cell Carrier for Solar Cell Calibration Standards

Colin Mann, Don Walker, Justin H. Lee, John Nocerino, and Simon H. Liu
The Aerospace Corporation

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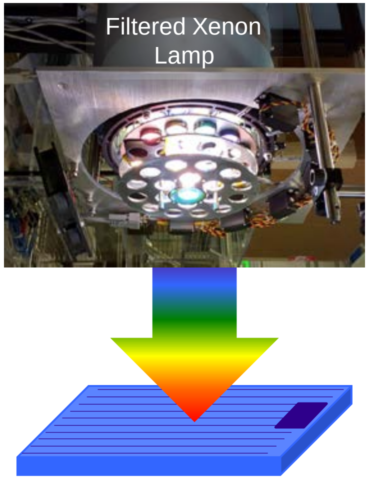
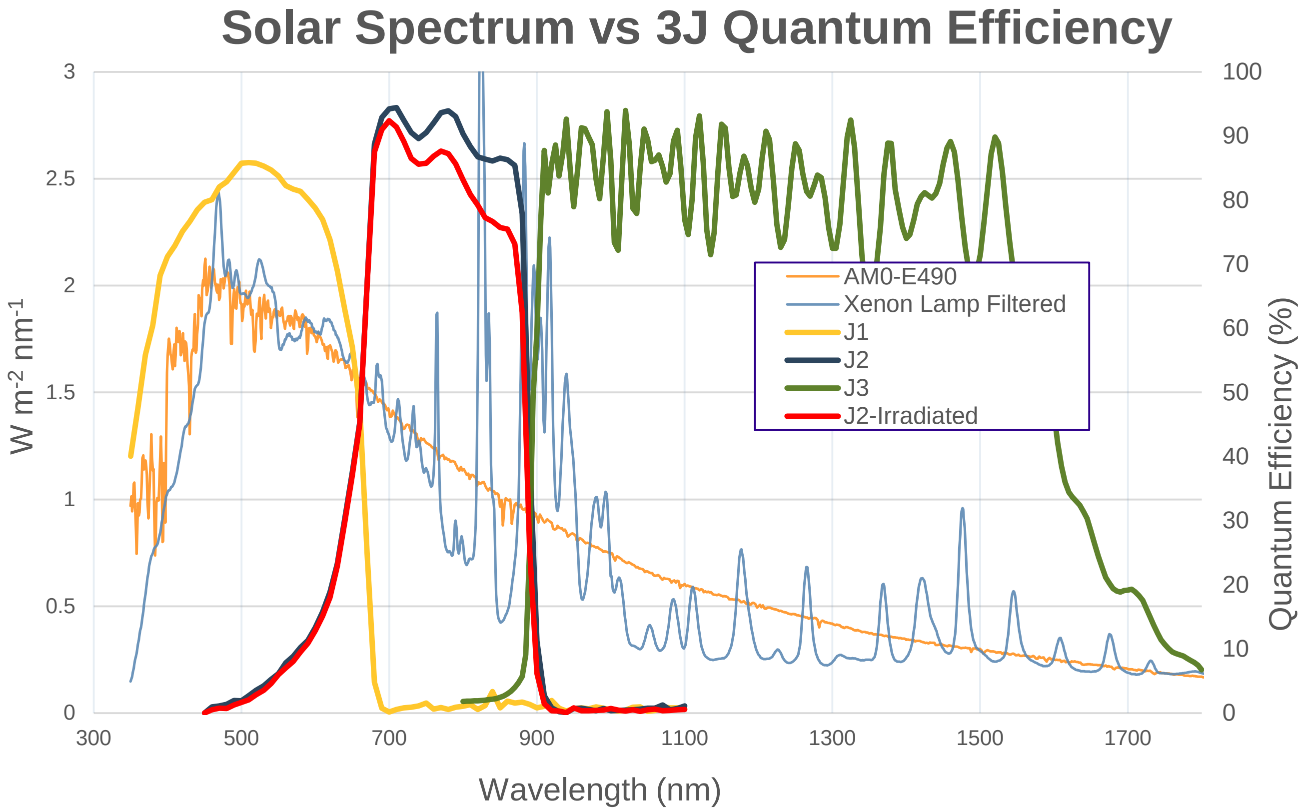
AM0 Solar Cell Measurements

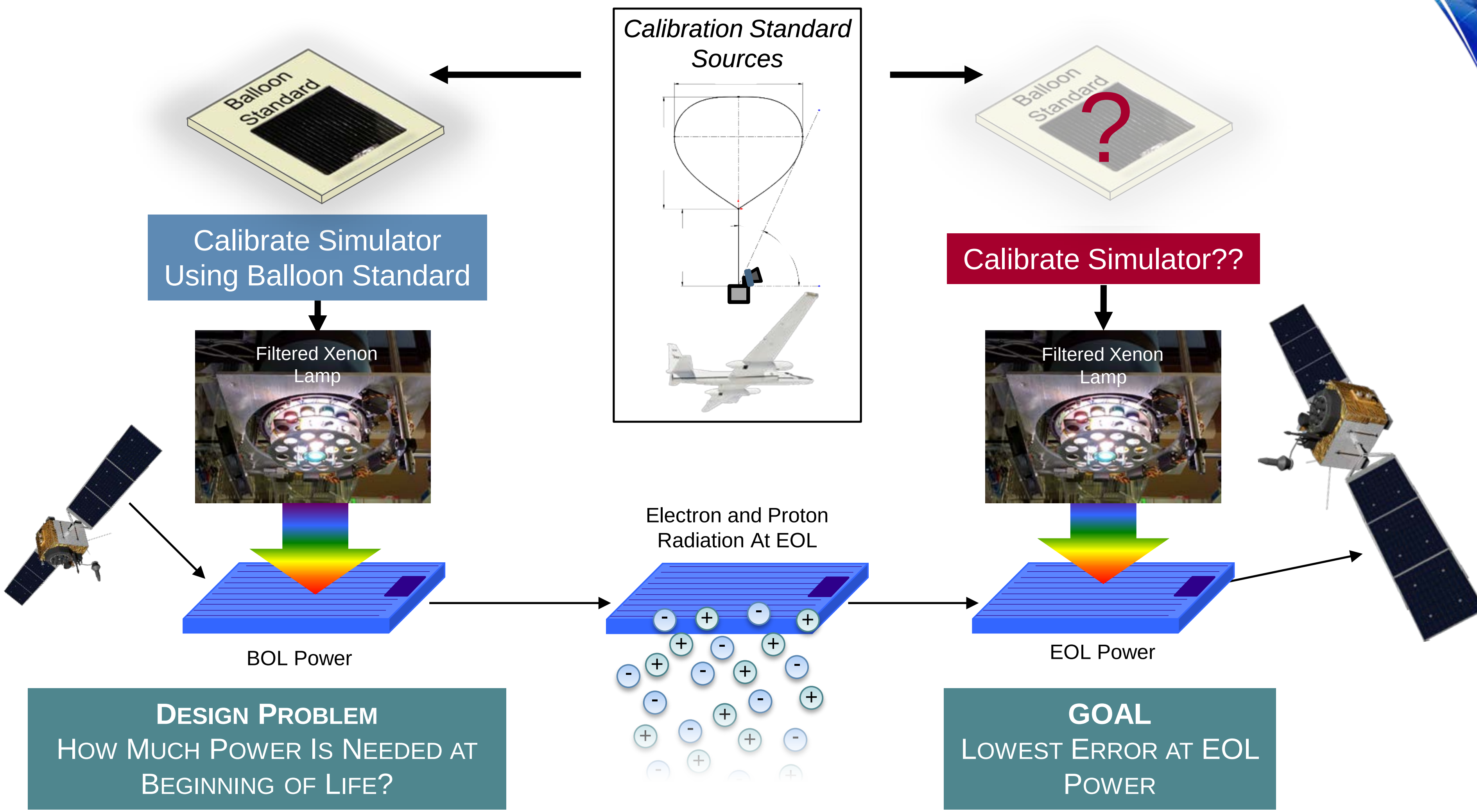
Reproducing AM0 on the Ground





AM0 Solar Cell Measurements

Why we need calibration standards



The challenges associated with predicting EOL performance of multijunction cells require new methods for obtaining calibration standards

Aerospace Solar Cell Carrier Development

- To increase flight availability and lower cost of flights, a smaller and lighter system is required.
  - *Recognizing the common need for high accuracy current-voltage (IV) and temperature measurements for high altitude and CubeSat flights, we developed the idea and prototypes to do onboard IV and temperature measurements*
  - *Solar Cell Carrier idea developed in response to future AeroCube missions as well as two potential solar cell calibration balloon flight opportunities (BlackSky and Angstrom Designs)*

- In May of 2016 we visited JPL's Electron Radiation facility and fortuitously found out that JPL still flies high altitude balloons for atmospheric research and they were open to the idea of us doing a solar cell experiment on board their instrument

JPL MkIV Balloon Experiment

Collaboration between JPL Atmospheric Research and Aerospace ETD

***MkIV** Gondola being prepared for launch at Ft. Sumner, New Mexico*

- We visited JPL in May 2016 and were introduced to the Upper Atmospheric Research Lab, which continues to do high altitude balloon experiments on a near annual basis.
  - *The primary balloon experiment uses the JPL MkIV Interferometer to measure atmospheric content (including ozone) throughout the atmosphere, from ground up to float (39km).*
  - *The MkIV instrument must be pointed at the sun throughout the entire flight*
    - *Gondola includes sun angle measurement and a mechanical rotator to maintain sun pointing within ±5°*
  - *Once at its maximum altitude, the gondola remains at float, pointing towards the sun for 12-24 hours depending on weather.*

Advantages of the JPL Remote Flight for Solar Cell Measurements

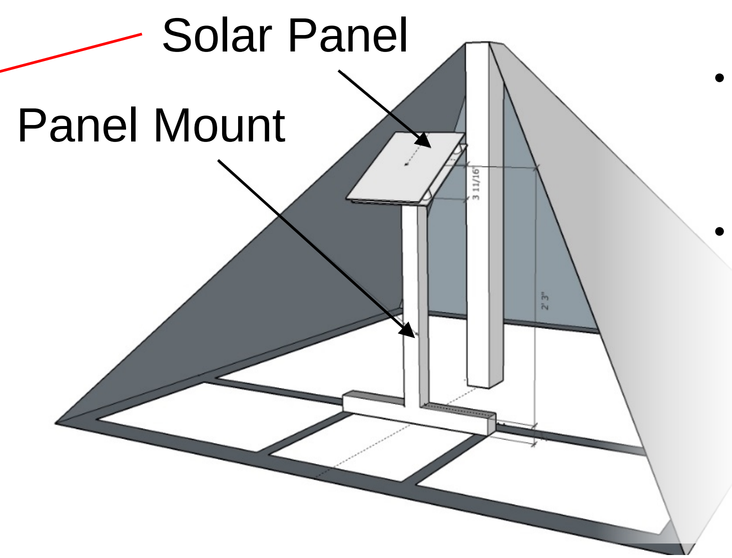
- At float majority of the day, including local noon
- Atmospheric content, including ozone, measured for entire flight duration
- Sun pointing within ±5° for entire flight
- GPS tracking and interferometer provide all necessary values for data correction
- High altitude provides near space conditions for photovoltaics

Photos courtesy JPL

JPL MkIV Balloon Experiment

Aerospace Solar Cell Experiment Additional Payload

- Within a 3 month window we designed, built, tested, and delivered our payload
  - *Solar panel was operated independently of JPL MkIV*
  - *Measurements were taken autonomously without ground communication*
- Our panel was mounted at a 34.5° angle to match the latitude of our launch site, and relied on the sun pointing required for the MkIV instrumentation measurements.



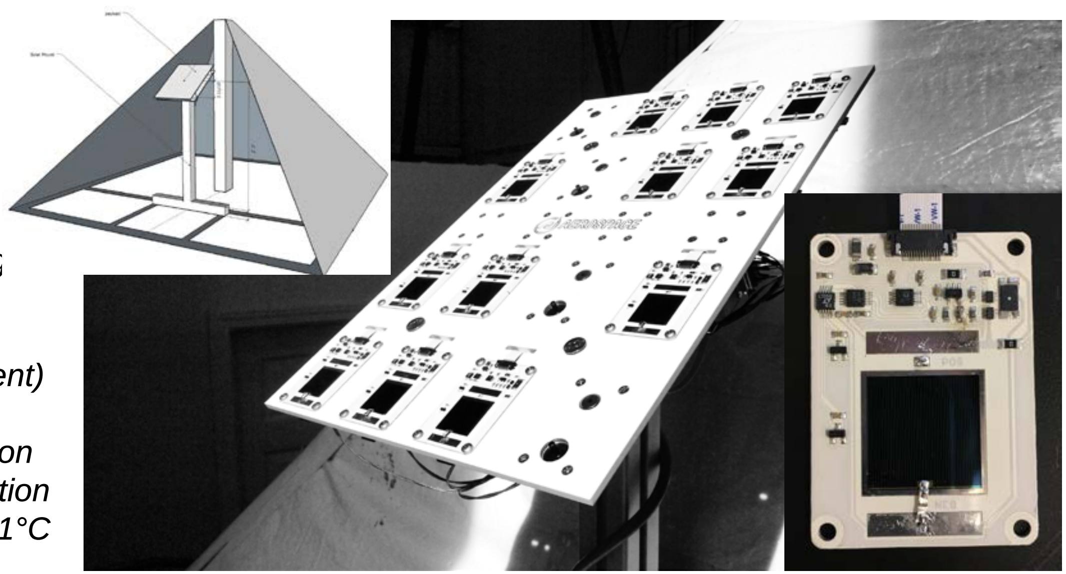
- The solar panel consisted of 12 solar cells
- Electronics powered by 4 independent battery packs of lithium primary batteries for redundancy
- Sun and pressure sensors recorded sun angle and flight altitude during measurements.
  - *Sun sensors and their calibration leveraged AeroCube heritage*

JPL MkIV Balloon Experiment

Aerospace Payload

- Goals:
  - Demonstrate ability to use small, lightweight electronics in a near space environment.
  - Develop I-V and temperature microelectronics that match the quality of laboratory source measurement units.

- Solar Cell I-V and temperature electronics were calibrated in lab
  - *Solar simulator was calibrated using JPL balloon primary standards and Learjet secondary standards*
  - *Temperature sensors were calibrated using calibrated sensor.*
  - *Able to obtain near short circuit values (approximately 7mV from short circuit current)*
  - *I-V Capabilities :*
    - *Current: 0 → 4A, up to 5 μA resolution*
    - *Voltage: 0 → 5V, up to 50 μV resolution*
    - *Temperature, ±0.5°C Accuracy, < 0.1°C resolution*
  - *4 quad-photodiode sun sensors*

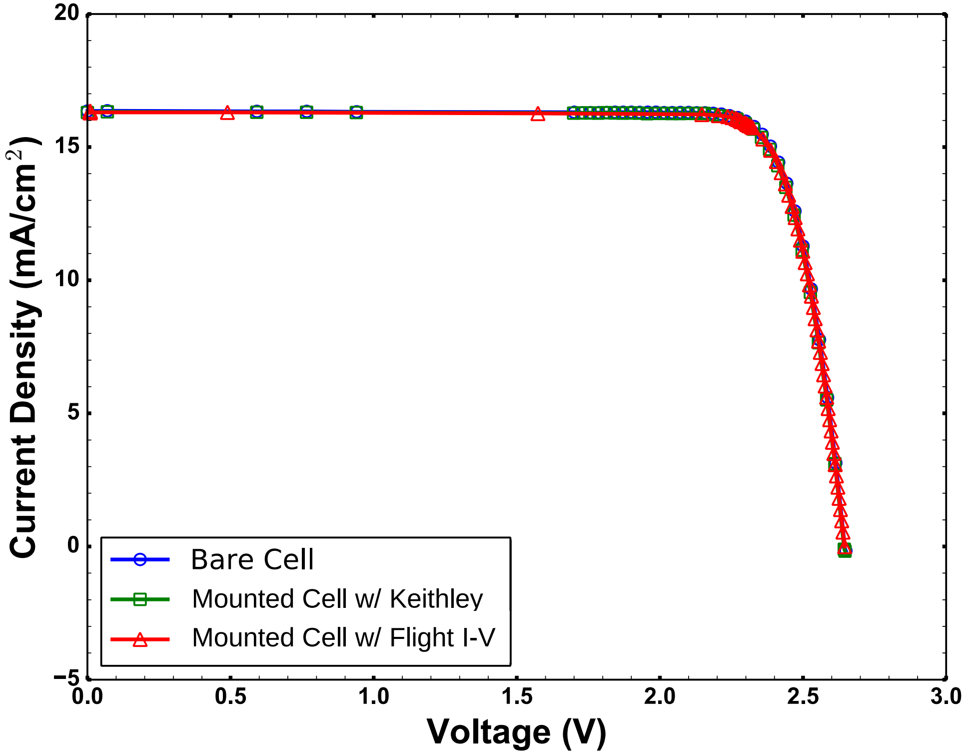


Panel installed onto JPL Gondola Pre-Flight

JPL MkIV Balloon Experiment

Solar Cell I-V Ground Validation Measurements

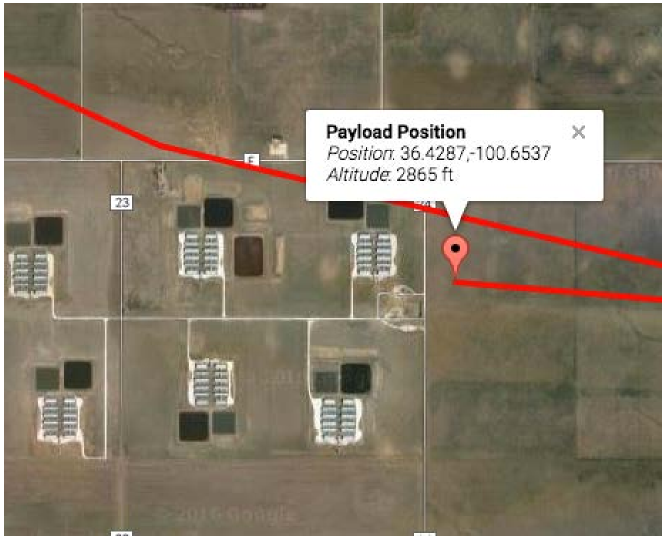
- Solar cell I-V performance was compared before and after integration using a Keithley 2425 SMU
  - *No change was observed*
- Performance of I-V electronics was compared to measurements conducted using Keithley 2425 SMU
  - *No differences were observed*



JPL MkIV Balloon Experiment

2016 Flight Results

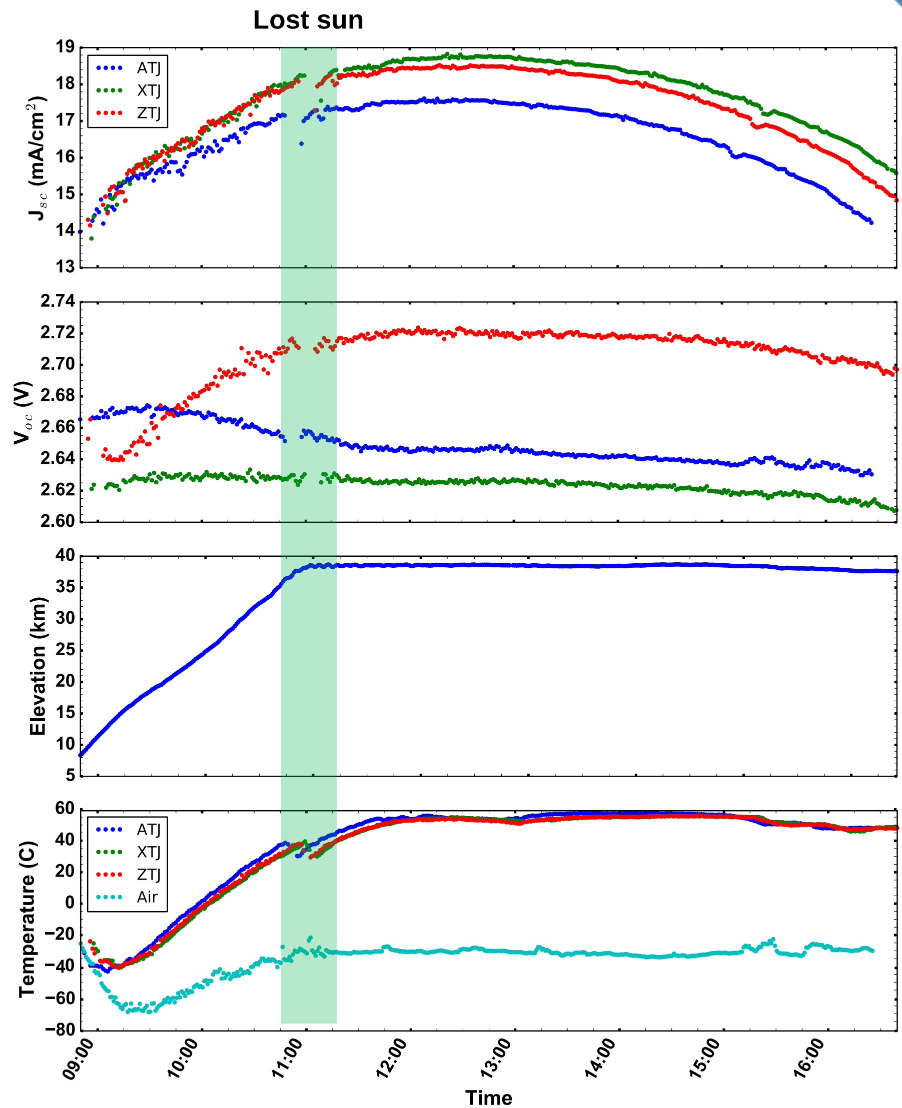
- Flight took off at 8am on 9/27/2016 and landed at 5am 9/28/2016
- Achieved float within 3 hours
- Obtained full I-V curves for duration of flight
  - *I-V sweeps were taken every minute for the entire duration of the flight experiment*
- Payload landed on the sun pointing side which damaged the bottom row of solar cells (1 in 4 chance)



JPL MkIV Balloon Experiment

2016 Flight Results

- Data has been filtered removing data from when the gondola lost contact with the sun and for sun angles greater than 20 degrees
- Data NOT corrected for air mass
  - *This can been seen in the "bow" of the current as the sun's zenith angle changed due to its rising and setting, which changes the path length of air the light passes through*
  - *AM = sec θ_z P*
    - Where θ_z is the solar zenith angle and P is the air pressure
- J_{sc} and V_{oc} are temperature corrected
  - *Temperature coefficients for V_{oc} below room temperature do not seem to be linear as indicated by the non-linearity after correction*
  - *Most temperature coefficients are measured between 28°C and 80°C*
- We did get reflection from the balloon which resulted in approximately 1mA of excess current in all cells
  - *Relative difference in current between the cells is similar*



Stray light baffles are needed for accurate cell characterization

JPL MkIV Balloon Experiment

2016 Flight Results

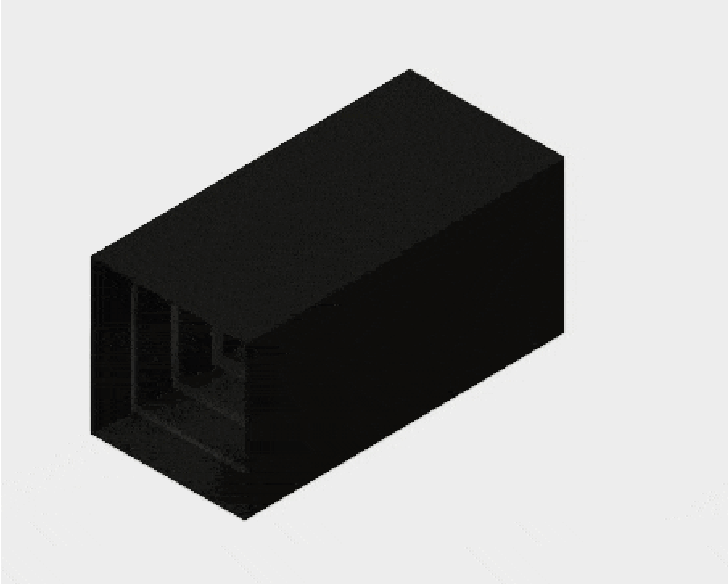
- Successes
  - *In 10 weeks went from concept to deliverable payload with no failures during flight*
  - *All 12 redundant systems produced hundreds of I-V curves throughout the flight including corresponding temperature and telemetry data*
  - *Successful I-V measurements confirmed that a more sophisticated light weight cell carrier is possible and reliable*
  - *Gained confidence in electronics with clear paths for improvement*

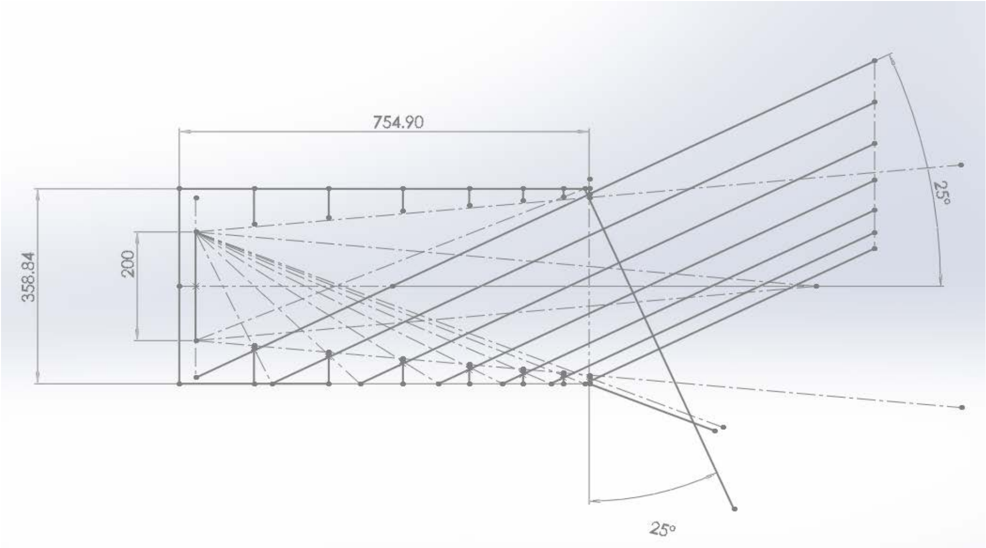
- Next steps
  - *Reflection*
    - With no baffle on the cell, too much light is reflected off the balloon and from the Earth albedo, a baffle would be needed going forward to get useable data
  - *Size*
    - Integrating all the electronics onto a single carrier would be save weight and reduce complexity, would require more engineering
  - *Ozone correction needed even at 39km for true AM0 conditions*
  - *I-V measurement resolution could be improved to match laboratory instruments*

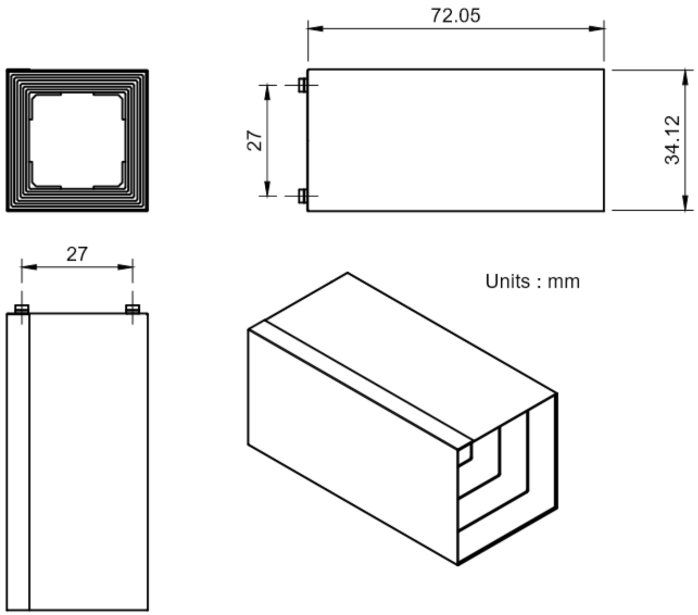
JPL MkIV 2017

Stray Light Baffle

- Photo etched aluminum baffles
  - *10° field of view*
  - *Lord Aeroglaze Z306 Flat Black Absorptive Polyurethane Coating*
    - Anti-reflective flat black
    - Low Outgassing



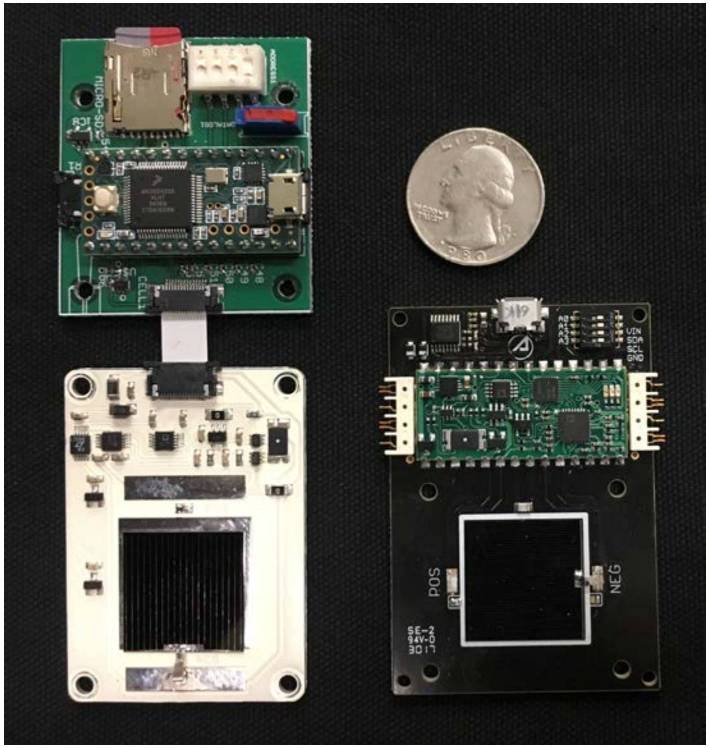




JPL MkIV 2017

Cell Carrier Version 2

- Photo etched aluminum baffles
- Cell Carrier Gen 2
  - *Improved IV electronics*
    - 4 wire measurements
    - Light and dark I-V measurements
  - *Improved temperature measurement (4 wire)*
  - *Integrated heater and heater PID in cell holder*
  - *Local µController*
    - I²C control for single 4 wire communication with all cell carriers
    - USB for laboratory control
    - On-board EEPROM stores all calibration data on device
  - *Power reduction to ~100 µA when idle*
  - *C++/LabVIEW Drivers using SCPI commands*
  - *Cell holder is made from aluminum clad PCB to minimize temperature differential between the sensor and the cell.*

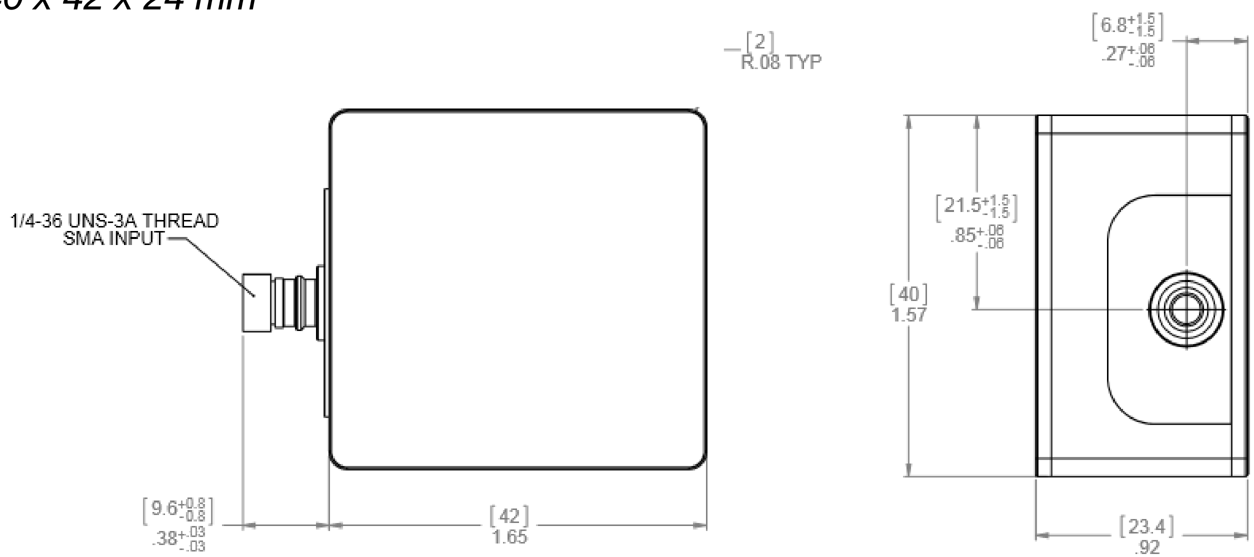


Patent Pending

JPL MkIV 2017

STS Mini Spectrometers

- Photo etched aluminum baffles
- Cell Carrier Gen 2
- Mini Spectrometers
  - *Calibrated using NIST primary FEL lamp*
  - *190 – 800 nm, 1.5nm steps*
  - *Cosine corrector input*
  - *Lightweight - ~65g*
  - *Compact size 40 x 42 x 24 mm*

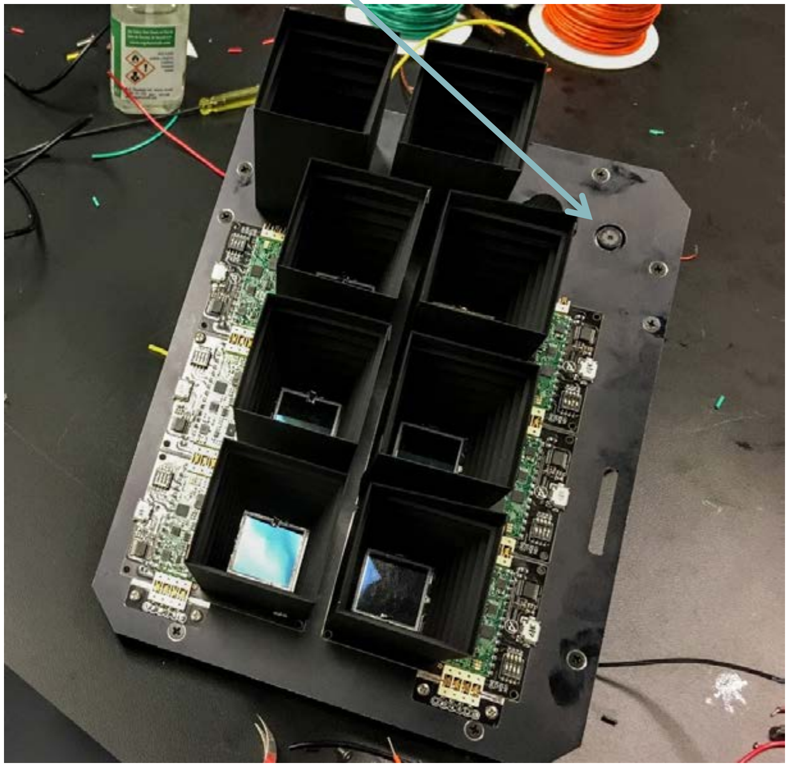


JPL MkIV 2017

JPL MkIV 2017 Flight

- Photo etched aluminum baffles
- Cell Carrier Gen 2
- Mini Spectrometers
- Quad Photodiode Sun Angle Sensors
    - Heritage sensor used on CubeSat flights
    - Calibrated in lab to 0.1°
    - Resolution to 1/1000th of a degree

Calibrated Quad Photodiode Sun Angle Sensor

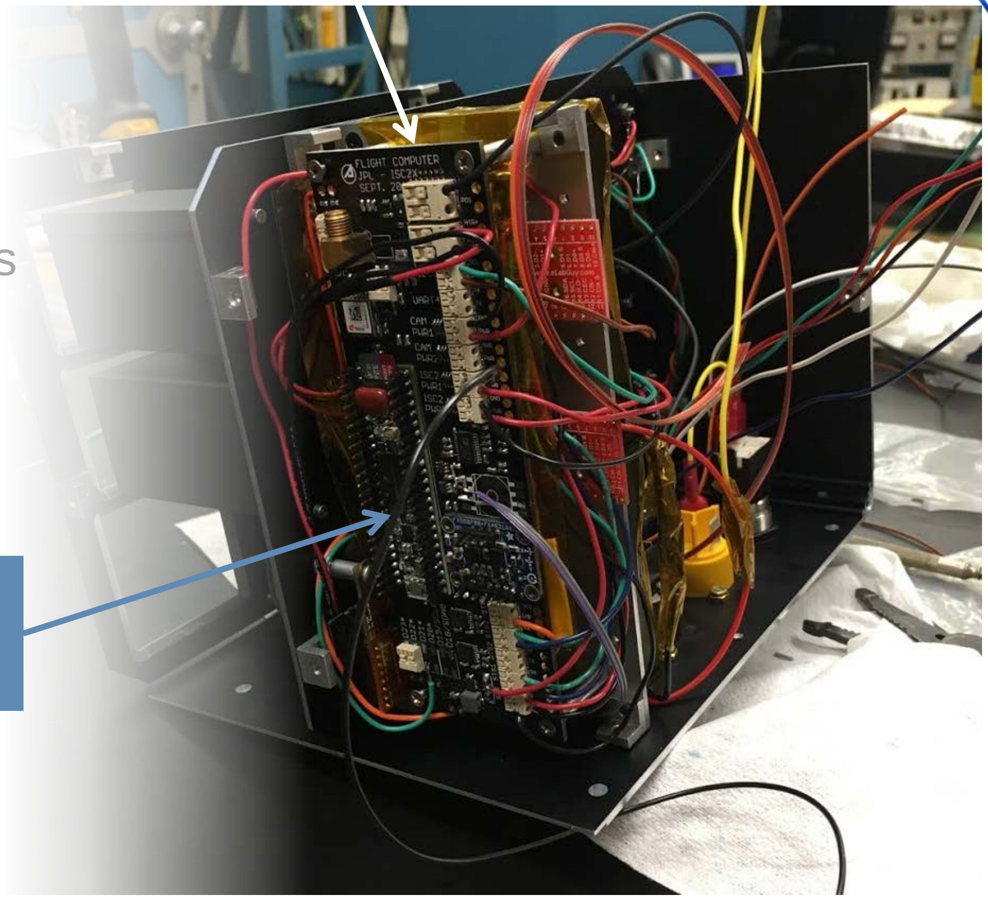


Selenium

JPL MkIV 2017 Flight

- Photo etched aluminum baffles
- Cell Carrier Gen 2
- Mini Spectrometers
- Quad Photodiode Sun Angle Sensors
- Onboard heaters for cell holders and spectrometers
- 15 Ah Lithium Ion Battery

Spectrometers (Under Flight Computer with Heater In Between)



Flight Computer + Data Storage (SD Card)

Selenium

JPL MkIV 2017 Flight

- Photo etched aluminum baffles
- Cell Carrier Gen 2
- Mini Spectrometers
- Quad Photodiode Sun Angle Sensors
- Onboard heaters for cell holders and spectrometers
- 15 Ah Lithium Ion Battery
- GPS Receiver
- 10 DoF IMU
  - *Gyroscope / Accelerometer / Magnetometer / Pressure Sensor on flight computer circuit board*
- 4 Cameras
  - *1 Telephoto*
  - *2 Standard at different viewing angles*
  - *1 Wide Angle 180° FOV*

Selenium

JPL MkIV 2017 Flight

- Photo etched aluminum baffles
- Cell Carrier Gen 2
- Mini Spectrometers
- Quad Photodiode Sun Angle Sensors
- Onboard heaters for cell holders and spectrometers
- GPS Receiver
- 15 Ah Lithium Ion Battery
- 10 DoF IMU
- 4 Cameras
- 32 GB Data Storage

Selenium

JPL MkIV 2017 Flight Postponed

- Successful re-design and delivery of second payload in 4 month window
- Flight postponed to 2018 due to weather conditions and initial balloon radio communication issue with ground station
  - *JPL team prepped the gondola, balloon, and communication link everyday for a possible flight*
  - *After ~6 weeks, the flight was postponed to 2018 due to heavy wind conditions*

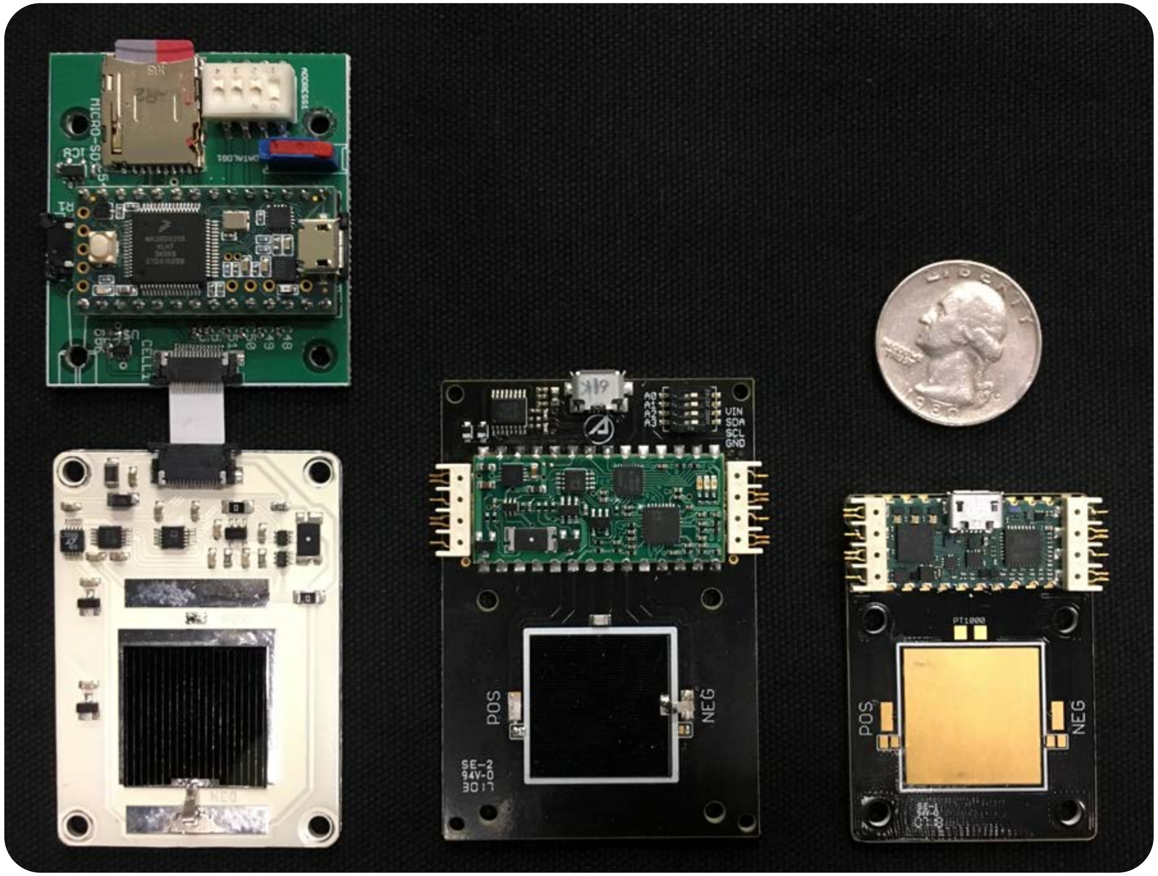
Selenium Payload Mounted at Ft. Sumner on JPL MkIV with protective cover. Power cable charges the battery before flight.

Next step : Reduce size and weight to meet FAA regulations on small balloon payloads to 6 lbs. (2.7kg)

Selenium Measurement Unit

Minimizing size of the cell holder

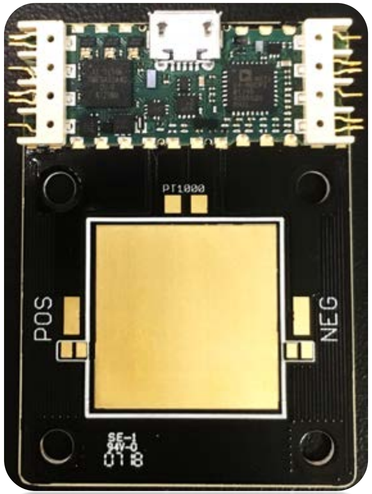
- Reducing the size of the cell holder is the clearest path towards total weight reduction. Smaller holder reduces baffle size and overall weight.

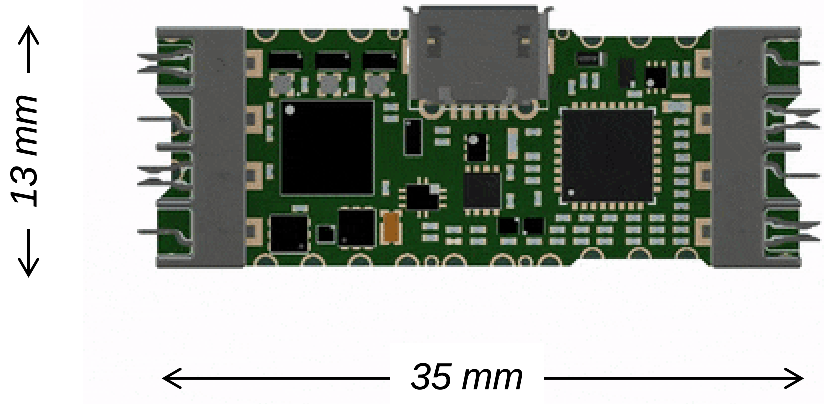


2016 **2017** **2018**

Selenium Measurement Unit

Modular measurement system





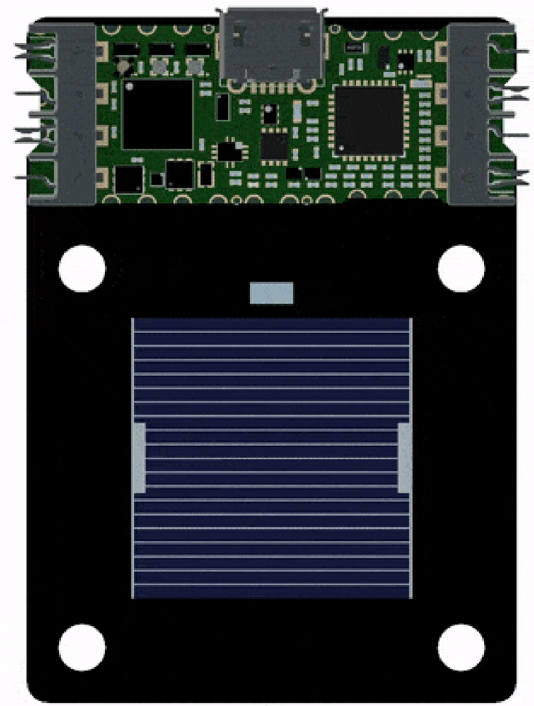
- Modular design can be incorporated onto any size cell holder, optimized for 2x2 cells, but could be used on large area cells as well
  - *Standard bread-board pinout spacing*
  - *Surface mounted or through hole using castellated edge vias*
- **Temperature compensated ADC**, 24-bit resolution
- 4 Wire Cell Measurement
- Light and Dark I-V up to 3A and 6.5V
  - *2.7 Watt continuous load, higher loads when pulsed*
- ~5 mV from Isc, ~2 µA from Voc
- Optimized 200 point I-V curve steps for max points at knee, ~50 points per second optimal
- 4 Wire RTD Measurement with 0.1°C accuracy
- 2 kB EEPROM stores all calibration data on device including full I-V curve
- 3 mA total current draw at 3.3V during measurement, idle state draws ~200 µA
- LabVIEW, Python, C++, Arduino, Raspberry Pi Compatible
- Class compliant USB, no drivers required

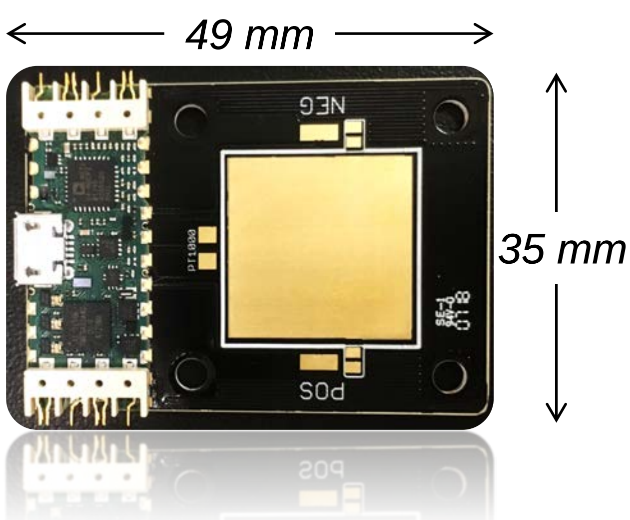
SMU – Configurable Source Measurement Unit in a 12 x 35 mm surface mount package with NIST traceable calibration of all measurements

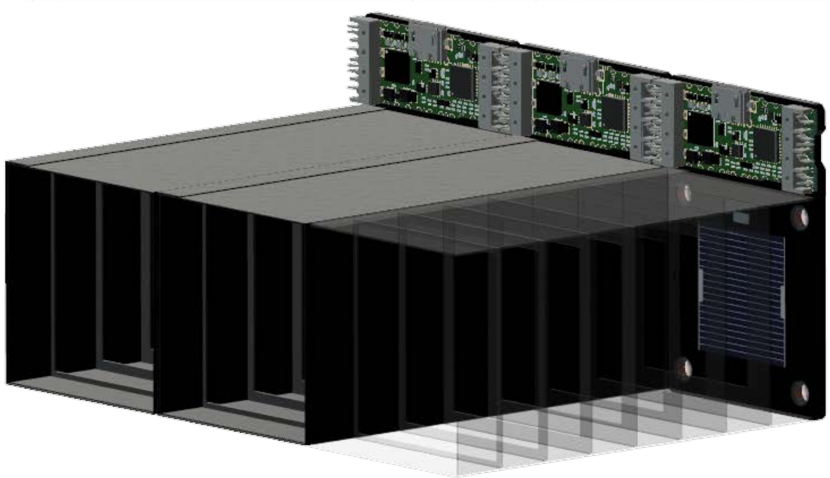
Selenium Measurement Unit

Cell Holder and Accessories

- Gold plated surface (ENIG, much flatter surface than tin plating on standard PCB)
- Cell is soldered down using low temperature solder Sn/Bi/Ag (Tin/Bismuth)
- Integrated heater (Up to 80°C using 5V USB power)
- Sun-Sensor attachment
  - *Silicon Quad Photo diode can be mounted above SMU utilizing same 24 bit ADC*
- External FET for loads greater than 3 Watts
- Bluetooth / coin cell attachment



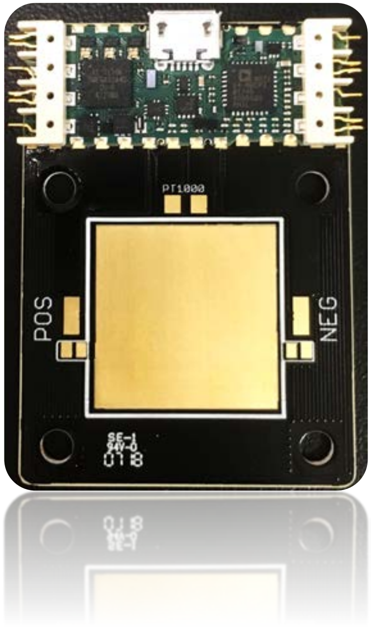




Selenium Measurement Platform

Advantages to Integrated Measurement Electronics

- Possible Errors of Balloon Standards
  - *Cell Temperature*
  - *Sun Angle*
  - *I-V Measurement*
  - *Systematic*
  - *Ozone*
  - *User error*



- Error remaining
  - *< .5° C error between cell and measurement*
  - *< .1° error when using photodiode attachment*
  - *Matches performance of Keithley SMU with temperature compensation*
  - *No systematic error. Same electronics used at altitude as on the ground*
  - *Using spectrometer measurements, can correct for spectrum seen during flight*
  - *Calibration data is stored locally on device, can reply with YES or NO for matching I-V response, no user comparison required*

Selenium Measurement Platform

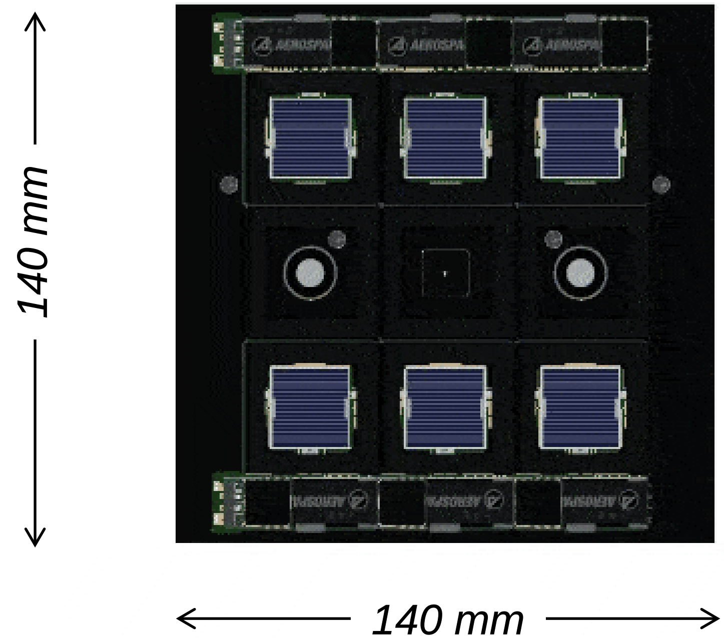
What it adds to the community

- The ability to use light weight balloon platforms rather than larger expensive delivery systems has the potential for:
  - *Increased flight availability (easier setup time, significantly lower cost)*
  - *Reduces error in balloon standards to near zero.*
  - *More frequent flight availability will result in quicker understanding of newer cell technologies.*
  - *If flight cost is reduced enough, testing a new cell technology on a balloon may become an alternative to ground testing using non-matching cell standards*

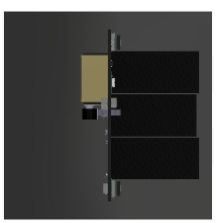
- Maintains backward compatibility with existing payload systems (near identical size to NASCAP holder with matching mounting hole pattern), reduces need to redesign current payload platforms

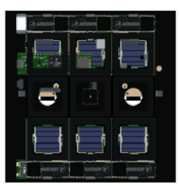
Selenium 2018 Flight Schedule

- NASA Flight Opportunities Program
  - *Angstrom Designs (2+ Flights beginning June through August)*
  - *Black Sky (2+ Flights beginning June through August)*
  - *NASA funding continues into 2019 with potential for more flight opportunities*
- JPL MkIV September 2019
- Other flight opportunities?



- 2018 Platform
  - *Incorporates all features of previous versions*
  - *Reduced power usage by 75%*
  - ***Reduced volume by > 50%***
  - ***Total weight < 500 grams***





Latest payload design meets all of the requirements for light weight balloon delivery systems.

Acknowledgments and Questions

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