



Radiometric Solar Simulator Calibration for Space Photovoltaics

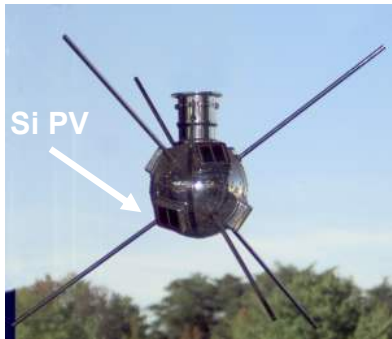
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4/21/26

Calibrating Solar Simulators for Space Photovoltaics

- Critical capability

- High altitude measurements of solar cells have been carried out on a yearly basis since 1962, 4 years after the launch of the first US solar power satellite Vanguard 1 on March 17, 1958

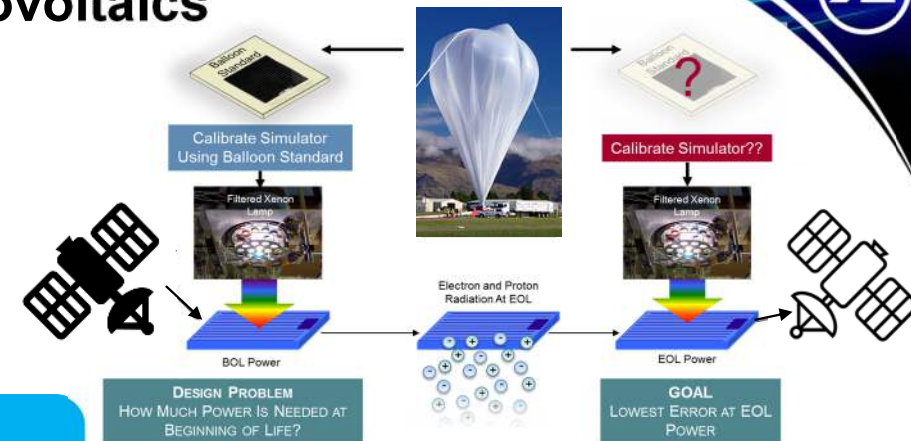


Vanguard-1

<http://nssdc.gsfc.nasa.gov/image/spacecraft/vanguard1.jpg> (NASA Public Domain)

- Accurate Prediction of On-Orbit Power

- *Duplicating the AM0 solar spectrum both spatially over an area and in intensity has yet to be achieved*
- Supercontinuum lasers can match the solar spectrum, but lack UV and the area for larger devices



Solar simulator photos are Aerospace, and weather balloon photo is from NASA (NASA Public Domain)

- Solution

- *Obtaining short circuit current of solar cells near AM0 and using those calibrated solar cells to calibrate ground based solar simulators*





Radiometric Solar Simulator Calibration

- What is it?

- A **calibrated spectroradiometer** is used to adjust/tune the solar simulator instead of calibrated isotype solar cells
- The solar simulator is tuned by adjusting its spectrum so that, when combined with the solar cell's quantum efficiency, the simulated current matches the current under standard sunlight (AM0), aiming for a ratio close to 1.

- $$F = \frac{I_{rad}}{I_{AM0}} = \frac{\int_{\lambda_1}^{\lambda_2} E_{sim}(\lambda) Q_e(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} E_{AM0}(\lambda) Q_e(\lambda) d\lambda} = 1$$

- Why do it?

- **Enables Accurate Measurement Without Calibrated Isotypes:** Not all subcells have calibrated isotypes available at every irradiance level.
- **Accounts for Changes in Quantum Efficiency (QE):** Solar cells, especially after irradiation, can have altered QE—calibration ensures accurate pre- and post-irradiation comparisons.
- **Enables continuous monitoring of simulator calibration:** Using a spectroradiometer allows you to easily check if the solar simulator drifts out of calibration over time.
- **Allows straightforward recalibration:** Unlike calibrated isotypes, spectroradiometers can be routinely and independently recalibrated, ensuring ongoing measurement accuracy.

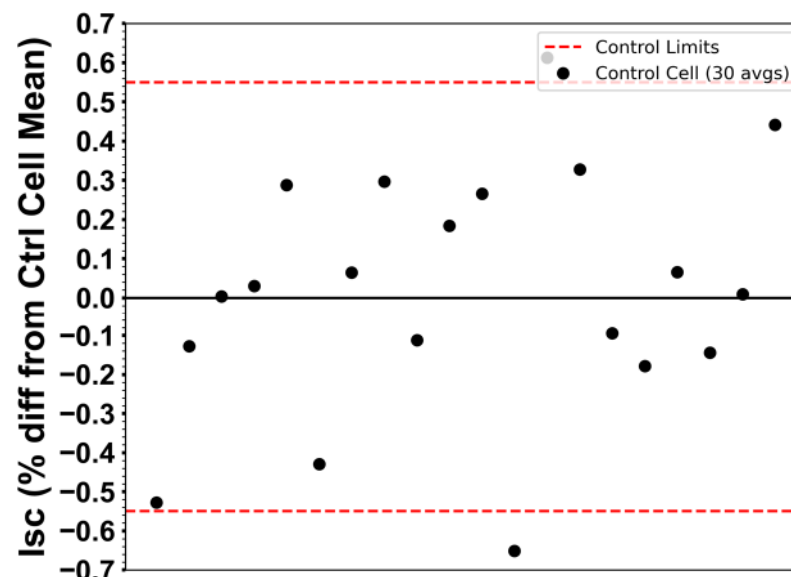


Validating Radiometric Solar Simulator Calibration

Uncertainty Estimation and Statistical Quality Control SQC

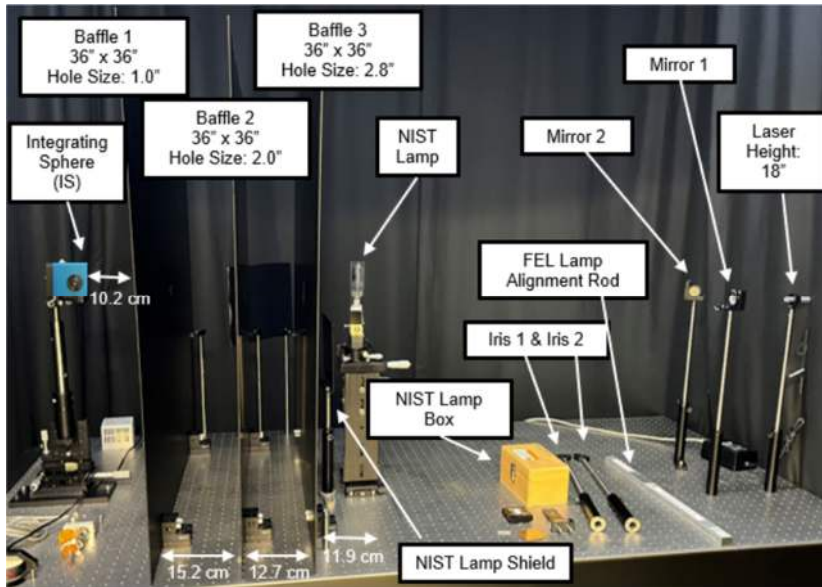
- **Goal**
 - Determine how well this calibration method compares to Balloon isotope calibration, determine an estimate of uncertainty, and control limits for statistical quality control
- **Uncertainty Estimation Analysis**
 - Purpose: Quantifies the degree of confidence in a single measurement or calibration (e.g., “the measured X is 1.01 ± 0.03 with 95% confidence”).
 - Outcome: Provides an estimate of the possible error or variability in a measurement, often reported as standard deviation, confidence interval, or expanded uncertainty.
 - Approach: Considers all sources of measurement error and combines them to express how much the measured value might differ from the ‘true’ value.
- **Statistical Quality Control (SQC)**
 - Purpose: Monitors a process or measurement system over time, ensuring it remains within predefined tolerance limits.
 - Outcome: Provides actionable thresholds for accepting/rejecting measurements or calibrations (e.g., “as long as F remains within 0.98–1.02, the simulator is considered calibrated”).
 - Approach: Uses control charts, process capability analyses, or similar tools to detect when a process drifts or is out of control.

SQC Chart for RadioCal



Identifying sources of uncertainty

Spectroradiometer Calibration Stage



Aerospace Authored Photo

System Component	Uncertainty Factor	Evaluation Technique
Spectroradiometer	Light measurement noise	Average of 60 measurements
	Dark measurement noise	Subsumed with light measurement
	External straylight	Measurement with entrance optic blocked and light source on
	Internal Straylight	Datasheet
	Spectral Bandwidth	Datasheet
	Wavelength Accuracy	Datasheet
	Wavelength Reproducibility	Datasheet
	Temperature	Recorded during average of 60 measurements
	Temporal Stability	Recorded during average of 60 measurements
Integrating Sphere	Orientation	Alignment repetition
	Fiber optic connection	Alignment repetition
Reference Lamp	Irradiance uncertainty	Datasheet
	Distance	Alignment repetition
	Orientation	Alignment repetition
	Current	Aerospace Metrology of current shunt and meter
Solar Simulator	Lamp Stability	Irradiance and Solar cell measurement over time
	Uniformity	Datasheet
	Temporal Stability	Datasheet / Lab measurement
	Orientation	Alignment in yaw and pitch
IV Electronics	Distance	Datasheet
	Current	Averaging LIV data
	Voltage	Averaging LIV data



Margin of Error Analysis to determine the number of spectra to average



- Problem: How do we know when we have taken enough data?
 - Balance time required to take a measurement with a given accuracy and precision
- Gauge variability using descriptive statistics like mean and standard deviation.
- Employ inferential statistics (standard error, confidence intervals) to assess sample size (n) representation of the true mean..

– **Standard Error** $\frac{\sigma}{\sqrt{n}}$

- Use sample standard deviation (σ) as the standard error of the mean when true mean standard deviation is unknown.

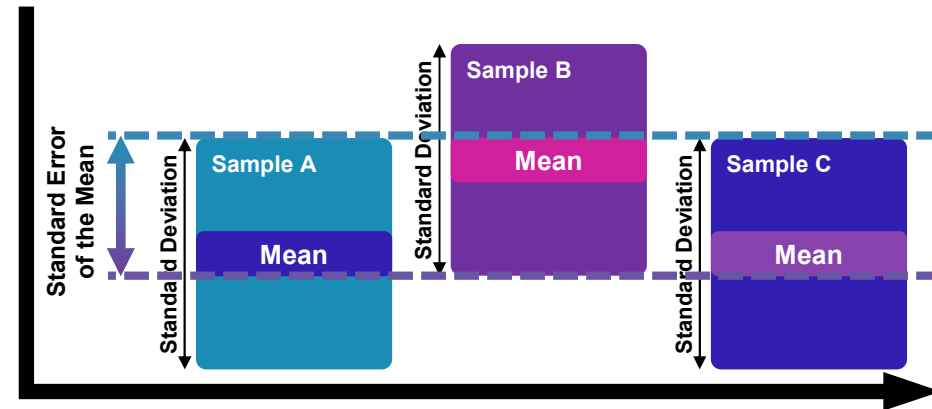
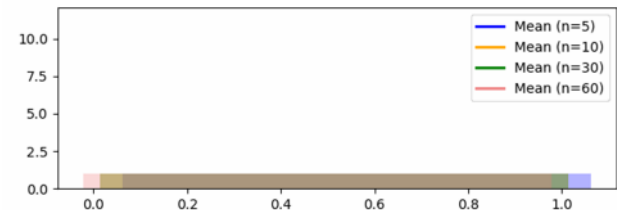
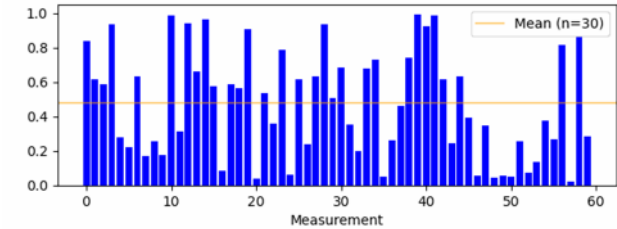
– **Margin of Error(MOE)** $t \times \frac{\sigma}{\sqrt{n}}$

- generates confidence intervals, providing uncertainty measures, plausible mean value ranges, and control limits.
- Utilize t-scores instead of z-scores for smaller sample sizes, as is often the case in our work.

- Determine Tolerances

Leverage Central Limit Theorem

Central Limit Theorem In Action

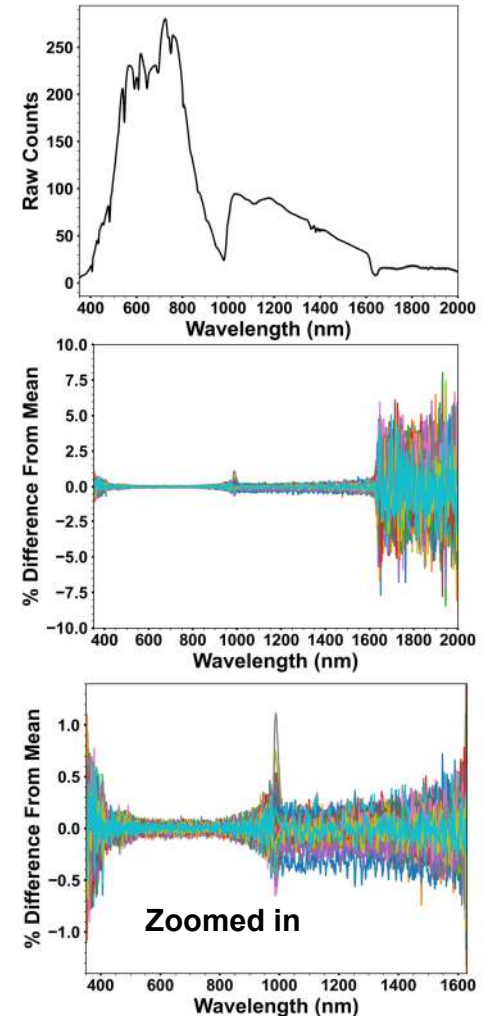


Spectroradiometer Uncertainty

Determining uncertainty in spectroradiometer calibration

- Purpose: Determine the variability of the spectroradiometer and the number of spectra to average when calibrating
- 60 spectra of a FEL lamp were taken at rate of 1 spectrum every 10s
- The data was averaged to determine the relative standard deviation at each wavelength
- By determining the confidence interval on the mean using the standard error of the mean and a 95% confidence level, as a function of the number of samples, we can determine the optimal number of spectra to average.
 - It's a balancing act between the time required to take each spectrum and the reduction in error achieved by averaging multiple spectra.

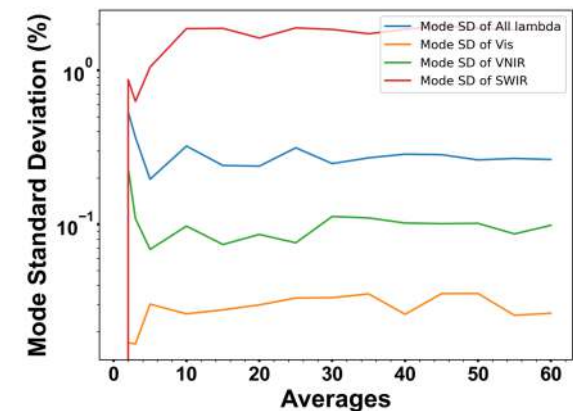
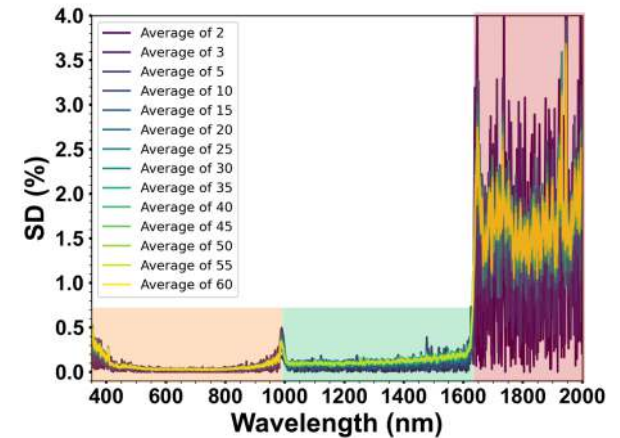
60 FEL Lamp Spectra





Determining the Spectroradiometer Standard Deviation

- Measured the spectrum of a NIST calibrated FEL lamp over the course of 60s.
- A raw counts spectrum was measured once every 10 seconds
 - The integration and gain settings of the spectrometer were constant
 - Resulted in 60 spectra taken
- The spectra standard deviation was derived from averages of 2 spectra -> 60 spectra
- The relative standard deviation was determined by normalizing the standard deviation to the mean of all 60 spectra
- The relative standard deviation was reduced to the mode of of histogram of the standard deviation for each detector where:
 - Vis is 350nm to 1000nm
 - VNIR is 1000nm to 1630nm
 - SWIR is >1630nm



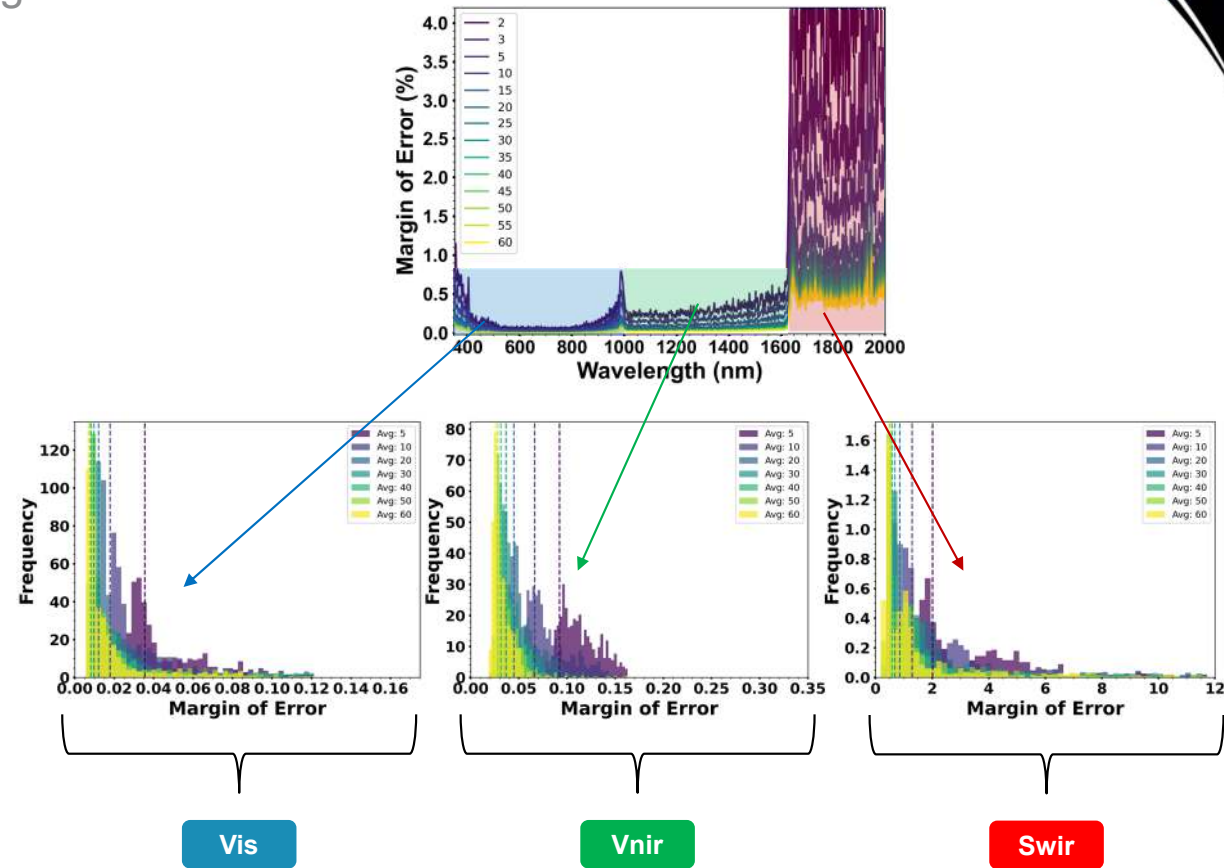
Standard deviation tops out at >10 averages. Which means that we have a good idea of the spectrometer standard deviation.



Aggregate Uncertainty using Mode of Histogram

Method to reduce 2d Uncertainty to a single value

- Problem: We need a quantitative measure of the dissimilarity between two spectra.
- Options to reduce differences in spectra to a single dimension
 - Averaging:
 - Pros: simple to implement and can yield some comparisons.
 - Cons: Variations in y-values across wavelengths can weight the average unfairly
 - Divide spectrum by QE ranges and average:
 - Pros: More realistic to what we would be using the spectroradiometer data for
 - Cons: We would have to have a metric for every known solar cell and it would be difficult to infer how the metrics impact solar cells we don't have QE for
 - Mode of histograms of margin of error (MOE) for each detector:
 - Pros: Outliers do not skew the MOE, Captures the most frequently occurring MOE across the detector population. Also, as the number of averages increases, the histogram sharpens and the mode converges toward the true MOE, better capturing this asymptotic behavior than the mean.
 - Cons: Hard to find any



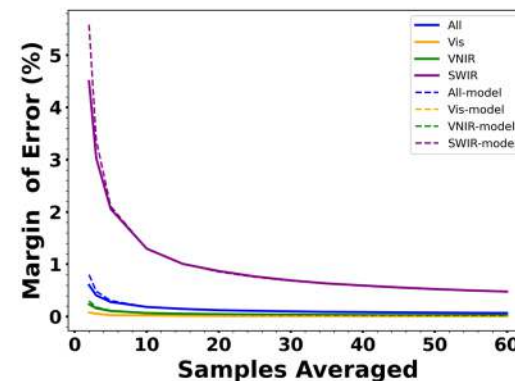
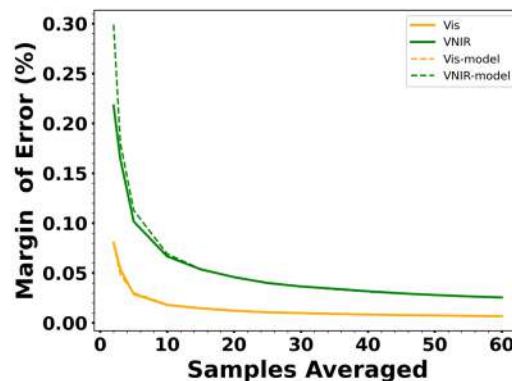
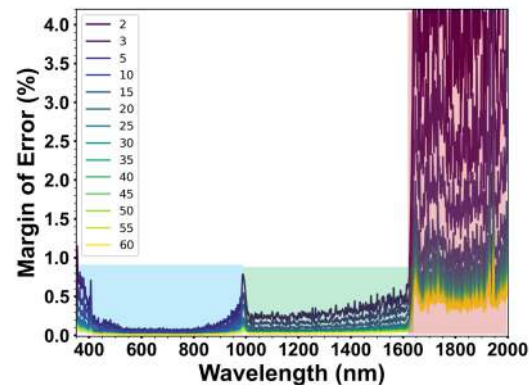
Using the mode of the histogram reduce the dimensionality of the spectra to 3 detectors..



Determining Aggregate Margin of Error

Determining how many spectra to average when calibrating spectroradiometer

- Calculated the margin of error for each y-point in the spectra, considering the number of spectra averaged (sample count).
- Aggregated the margin of error by constructing histograms for each detector range.
 - Vis < 1000nm
 - 1000nm < VNIR < 1630nm
 - SWIR > 1630nm
- Computed a mode to obtain a single representative number for the margin of error across each detector and the entire spectra.
- Compared measured and modeled margin of error.
 - Model just uses the population standard deviation as opposed to the standard deviation from each set of averages
 - Determines if central limit theorem applies

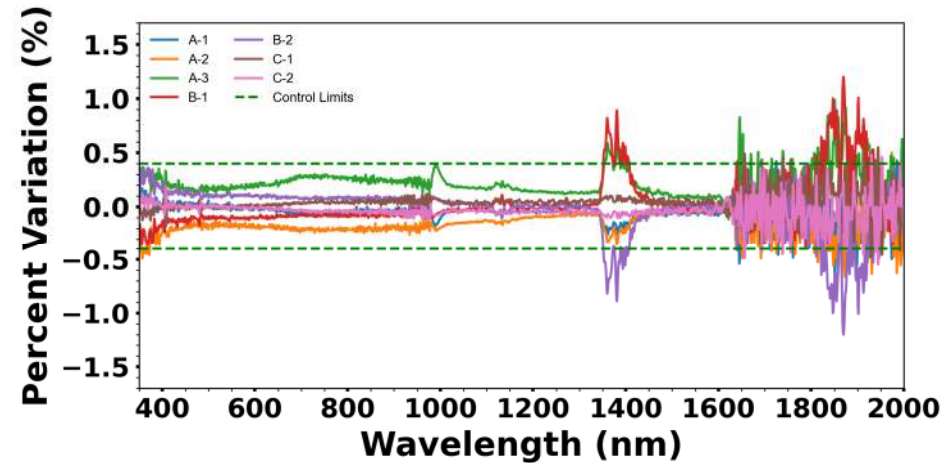


When calibrating the Spec Evo Spectroradiometer it is recommended to do 30 or more averages.

Alignment Repetition

Identify errors/uncertainty for spectroradiometer calibration alignment with FEL lamp

- Procedure
 - User A intentionally perturbs alignment.
 - User B performs Full Alignment Procedure while User A observes, provides double checks, and asks for verification.
 - Calibrate the spectroradiometer using a NIST 748 FEL lamp that is in calibration.
 - Update the spectroradiometer with the new system calibration (Syscal).
 - Repeat steps 1-4.
- Obtaining a statistical characterization is challenging due to the time-intensive nature of the process.
 - Only a few repetitions were performed due to time constraints.
- Statistical methods alone may not sufficiently address systematic offsets from the procedure.
- However, tolerances can be estimated and track out-of-process conditions.
- Accumulating more data through additional repetitions will contribute to a larger dataset for setting tolerance levels
- Currently on any given day, for an alignment, we can expect a 0.4% difference in calibration of the spectroradiometer



Alignment of the FEL lamp to the spectroradiometer was performed several times on three separate occasions (A, B, C). The difference between the mean of each group is plotted above.

Control limits of 0.4% are derived and set by this experiment as it was identified to have the highest variation

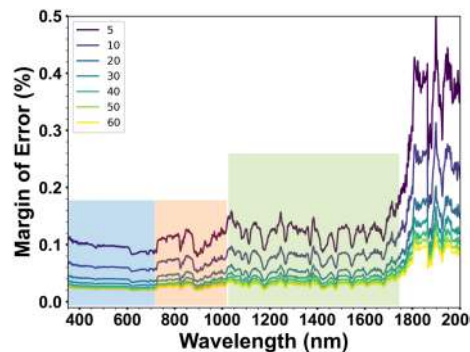




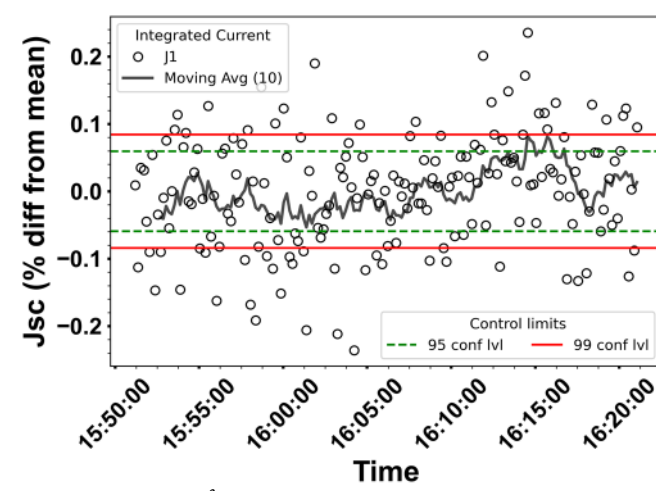
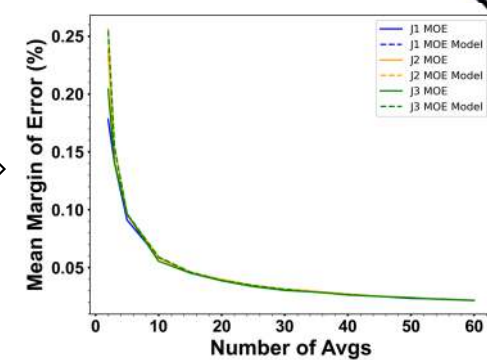
Solar Simulator Uncertainty and Calibration

Neonsee Solar Simulator

- We performed a similar analysis to what we did with FEL lamp to determine how many spectra to average tuning for radiocal and measuring LIV
- Using the quantum efficiency of a ZTJ solar cell we can derive the margin of error for a confidence level of 95% for each junction to determine how many samples to average to know how far we are from the true mean
 - Previously we used the mode.
- Solar Simulator spectrum is taken with the calibrated spectroradiometer and convolved with the QE of each junction of a solar cell
 - Integrating the QE with the Solar Simulator spectrum helps reduce the error
- Using an average of >10 samples minimizes the margin of error without excess averaging.
- On any given day, for a given syscal, we can expect the mean, QE integrated Isc of a solar cell be within 0.06%
 - Highly dependent on lamp flicker, but this can be measured and the confidence intervals adjusted



Qe



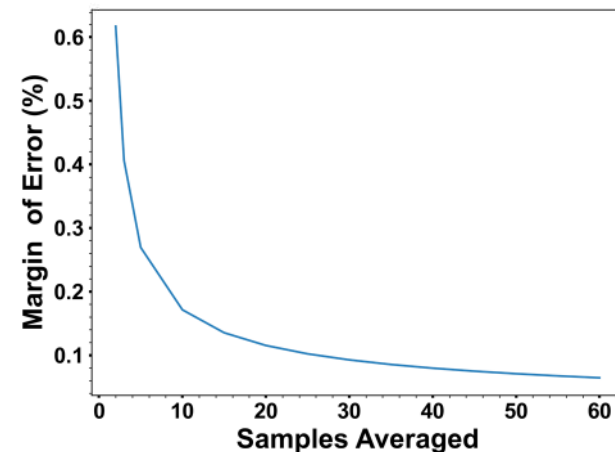
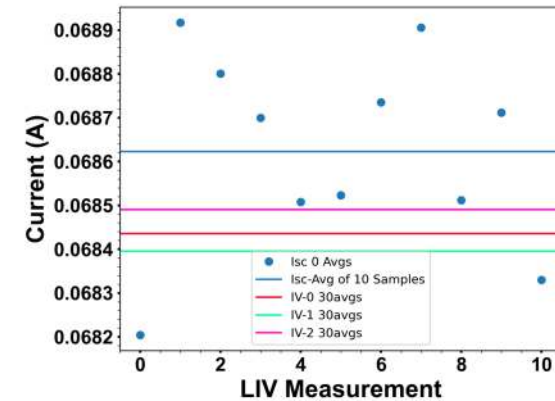
$$\frac{I_{rad}}{I_{AM0}} = \frac{\int_{\lambda_1}^{\lambda_2} E_{sim}(\lambda) Q_e(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} E_{AM0}(\lambda) Q_e(\lambda) d\lambda} = \frac{F}{1} \times 100 = I\% \text{ diff from mean}$$



Determining Number of Light IVs (LIVs) to Average

IV Electronic Uncertainty

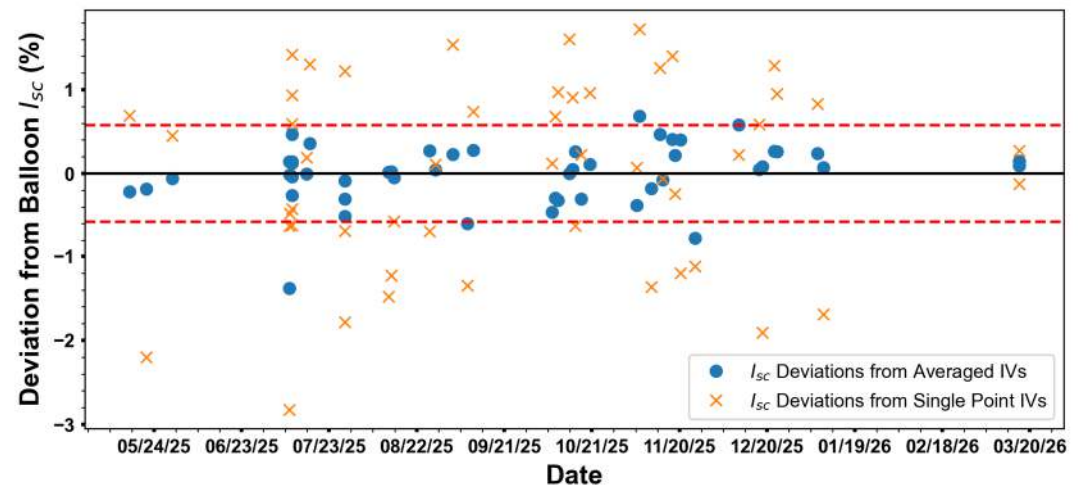
- Measured 10 LIVs without any averaging (I_{sc} s plotted as blue dots)
 - I_{sc} average of the 10 LIVs are plotted as horizontal line
- Separately, the LIV of same cell was measured three times, with the data reflecting the I_{sc} as the average of 30 measurements per trial
 - All data are within expected margin of error
- Averaging the LIV measurements helps reduce variability in the LIV I_{sc} (short-circuit current) readings by mitigating variations in the solar simulator and instrument electronics.
- The LIV file records the standard deviation of the current.
- We used the standard deviation from the I_{sc} point as the population standard deviation.
- We calculate the margin of error, which is influenced by the number of LIVs averaged.
- On any given day, if the calibration of the spectroradiometer has not changed, one can expect the mean value of the average of 30 LIV curves to be within 0.1% of each other



LIV Statistical Quality Control (SQC)

- Accepting an spectroradiometer calibration alignment error of +/- 0.4%.
- LIV margin of error 0.1% for an average of 30 LIVs accounts for variability in the LIV measurement
- The tuning margin of error is 0.06%
- Combining the alignment error, LIV margin of error, and tuning error (0.4% + 0.1% + 0.06%) gives a total tolerance of 0.56% for control limits.
- Control limits of 0.56% ensure acceptable variability by comparing control cell measurements to the average of all control cells.
- Exceeding control limits triggers an investigation, as it indicates potential issues.
- Control limits also represent the uncertainty of the mean value.
- Setting limits based on alignment error, tuning margin, and desired acceptability supports systematic measurement evaluation and control in solar simulator processes

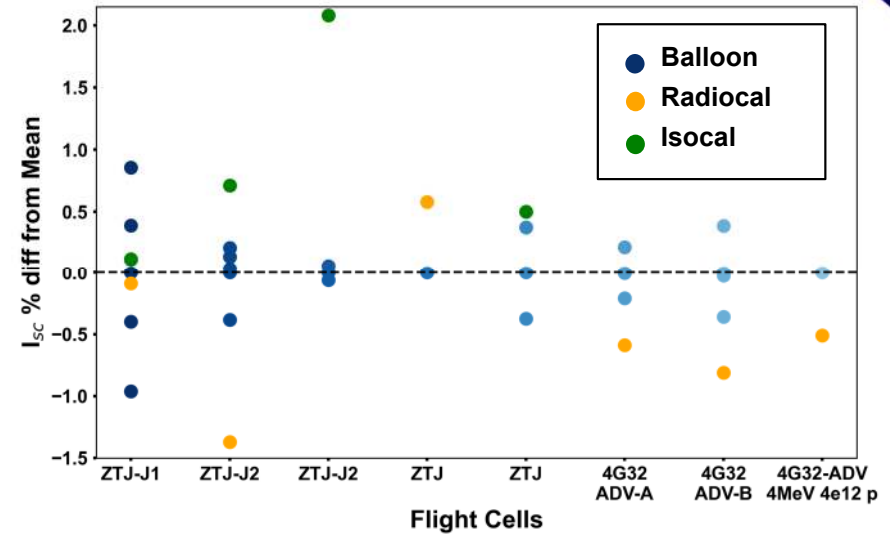
SQC Chart of J1 Isotype





Validating Radiocal with Balloon Flights

- Determining our control limits has enabled us to determine the uncertainty of our Radiocal measurements to be $\pm 0.55\%$ if all parts of the process are within SQC limits
- We measured the LIV I_{sc} of several balloon flown solar cells
- The balloon flown cells were flown multiple times
 - Some cells had more flights than others
- When comparing the means of the I_{sc} from Radiocal and Balloon the differences are under 1% except in the case of the ZTJ-J2
- Is this good enough?



Manufacturer	Model	Cell ID	Radiocal	Balloon	Radiocal / Balloon%
SolAero	ZTJ-J1	222741-0903	68.506	68.564	-0.09
SolAero	ZTJ-J2	222333-1104	67.446	68.380	-1.37
SolAero	ZTJ	256910-1404	69.960	69.558	0.58
Azur	4G32-Adv	81942-1271-0110	60.513	60.875	-0.59
Azur	4G32-Adv	81942-1271-0819	60.497	60.990	-0.81
Azur	4G32-Adv 4MeV 4e12 p ⁺	1238-0114	49.131	49.385	-0.51



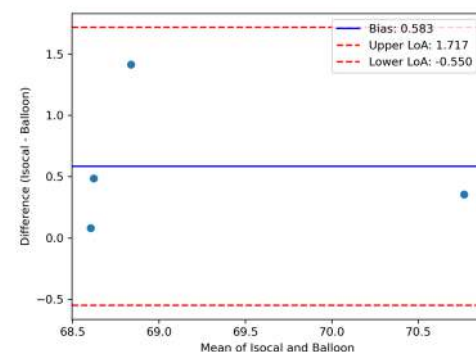
Comparing Radiocal and Isocal to Balloon

- Qualitatively the Radiocal method compares closely with the Balloon Data
- Paired t-test:
 - Tests how different each method
 - Each method is not statistically different than balloon
 - Isocal
 - Positive t-stat indicates Isocal values are higher than the balloon
 - Radiocal
 - Negative t-stat indicates Radiocal values are lower than the balloon
- Bland-Altman Analysis
 - Analyzes the agreement between two methods
 - Bias: average difference between Radiocal or Isocal vs Balloon
 - Limits of Agreement (LoA): Narrow indicates both methods agree closely and wide suggests methods are inconsistent with each other
 - Would this range of disagreement matter in practice?
 - How big is too big?
 - Isocal
 - Bias of approximately 0.51 indicates the Isocal values are higher, similar to paired t-test. Because the bias is close to zero this would indicate the isocal and balloon methods are similar
 - The LoA spans approximately $\pm 1.1\%$ which also indicates the methods agree
 - Radiocal
 - A negative bias of -0.25 indicates the radiocal values are lower than the balloon. The bias is still close to zero which indicate the methods are similar
 - The LoA spans approximately $\pm 0.8\%$ which also indicates the methods agree

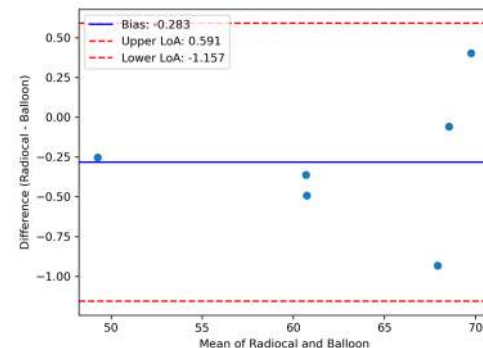
Radiocal and Isocal are equal in performance?

Paired t-test		
Cal Method	t-statistic	p
Radiocal	-1.555	0.18
Isocal	2.016	0.14

Bland-Altman Isocal vs Balloon



Bland-Altman Radiocal vs Balloon



Conclusions

- Developed SQC processes and charts for spectroradiometer, solar simulator tuning, and LIV measurements
- Determined control limits and uncertainties of the spectroradiometer and LIV measurements
- Validated radiometric solar simulator calibration as valid solar simulator tuning process using balloon flow data and a statistical approach



Backup



Approach

Identifying variations

- 1) Identify and prioritize sources of variation
- 2) Quantitate and validate variations
- 3) Verify variation with modeling
- 4) Perform uncertainty analysis
- 5) Apply uncertainty to final data product
- 6) Define Tolerances
- 7) Implement continuous monitoring

