Solar Simulation Performance Metrics: Real-time ~~Zone~~ *All-Junctions/Cells* Isc Mismatch Measurement Offers Improvement over AIAA/ ASTM Class AAA

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Why Ask More From Illuminated Ground Testing?

- Illuminated ground testing of solar panels happens many times during R&D and manufacturing so we can “test as we fly”

- An honest assessment of solar simulation error analysis gives large errors:
  - Balloon-Flown Calibration Standard: 0.5% for balloons, higher for other methods
  - Solar Simulator Spectral Match: 1% (ASTM is 25%!)
  - Solar Simulator Spatial Uniformity: 3% or higher
  - Solar Simulator Temporal Stability: 2%

Better Ground Testing Gives Lighter, More Efficient Satellites

- This error stack up can lead to substantially oversizing circuits… for every array we fly
  - Larger circuits mean larger wings and rotary joints… which mean larger satellites and bigger, more expensive rockets

Terrestrial Solar Simulator Metrics

- A logical place to start is to ask, “what do the terrestrial simulators do?”

- ASTM space standard is derived from the standard for terrestrial solar simulators, E927-10:
  - Spectral Class A: Divide spectrum into 8 bins (6 bins for terrestrial). Irradiance in each bin must be within ±25% of AM0.
    - This is inadequate for multi-junction cells
  - Spatial: sample at least 25% of the area with at least 36 samples with a sensor equal to or smaller than the cells. Get all samples within 3%.
  - Temporal: Keep drift below 2% over 100ms, 1s, 1min and 1hr

- Spatial and Temporal percentage specs are (max-min)/(max+min)
  - Which is the same as ±. So 2% (max-min)/(max+min) = ±2%
- IEC and JIS standards are similar

AIAA Standards Are For Space

- The AIAA S111A and S112A are built for space applications
  - But they are also built for the short-comings of pulsed, Xenon-lamp simulators
- AIAA standards use ASTM E927-10 for spatial nonuniformity (3%) and temporal stability (2%), but rejects the spectral binning in favor of a requirement of ±1% for current match for Isc for each junction in multijunction cells
  - Spectral match requirement is relaxed to +30%/ -1% for Germanium junctions
  - ±1% AIAA = 1% ASTM
    - Because ASTM is (max-min)/(max+min)
- AIAA recognizes that spectral binning isn't good enough for space
- AIAA allows the E927-10 stacking of errors: 1% current match + 3% spatial nonuniformity + 2% temporal stability
  - We should do better than this

Even AIAA standard allows for large 1%+3%+2% error stack

Current Matching Isotypes and Generating Calibration Standards

- We need to adjust power into each junction for best accuracy
  - So, we need solar simulator spectral adjustability and calibrated isotypes
  - AIAA supports this method, but allows significant error margins
- Round robin studies inform our pick of calibration methods
  - Lab methods, give worst errors of all: ±3.63%[1]
  - Old, large balloons gave the best performance: ±0.5%[1]
  - Aerospace Corp. small balloons study shows the Aerospace AMU has even more accuracy, balloons using the AMU may have improved even further
    - A fresh error analysis is needed

Method/Lab	Total Estimated Uncertainty (U_{95})
Balloon/JPL	±0.5%
Balloon/CNES	±0.5-0.7%
Aircraft/NASA[3]	±2%
Global Sunlight/ SPASOLAB[2]	±1.3%
Solar Simulator method/NASDA[4]	±3.63%

Table 1) Estimated total uncertainty for each of the calibration methods.[5]

Barrier: ASTM Spectral Binning Isn't Accurate Enough For Space. We use isotypes.

1: "Results from the 1st international AM0 calibration round robin of silicon and GaAs solar cells" by Brinker et al.

ASTM Spatial Non-Uniformity Sub-Sampling

- For spatial non-uniformity, ASTM says: sample at least 25% of the area with at least 36 samples with a sensor equal to or smaller than the cells. Get all samples within 3%.
  - ASTM makes no allowance for spatial uniformity differences for different parts of the spectrum

- So, ASTM is basically 6x6
  - This doesn't give the best resolution, unless your circuit is exactly 6x6 cells and then you can still under-sample to 25% of the area

- We really care that the current production of each cell is correct, which means we care about every junction of every cell
  - ASTM sub-samples our illimitation beam

Barrier: ASTM Sub-Samples Our Beam

Temporal Stability

- ASTM allows for drift over time, up to 2% for “Class A”
- This is very straight forward: drift over time
- 2% is a pretty good drift spec of a lamp…
- But LEDs can do far, far better
  – We’ve measured drift of less than 0.1% on some of our LED simulator tests

Barrier: ASTM Temporal Stability Adds Further Error

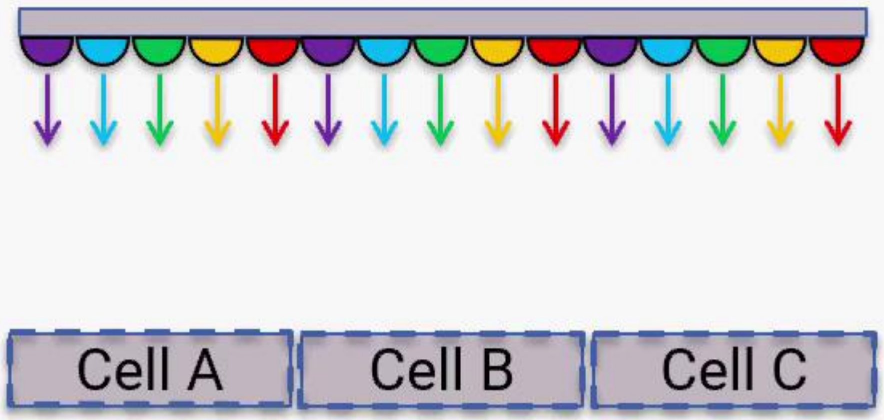
We Have Lots of Barriers to Overcome to Reduce Error Sources

- Our barriers so far:
  - ASTM Spectral Binning Isn't Accurate Enough For Space
    - AIAA acknowledges this, but leaves 1% error margin in place
  - ASTM Spatially Sub-Samples Our Illumination Beam
    - For large areas Xenon bulbs often don't meet the large 3% error bounds
  - ASTM Temporal Stability Adds Even More Error: 2%
- An AIAA/ ASTM Class AAA simulator gives 1% + 3% + 2% error
  - Spectral and spatial ambiguities mean these could add to 6% (or more) in practice

We Need Better Methods

What Is An All-Junctions/Cells Isc Mismatch Measurement?

- All-Junctions, All-Cells Isc Mismatch = JCM
  - JCM is a table, but can be summarized as a single number: JCMmax - JCMmin
  - Formerly called “Zone Errors”, but JCM is far less ambiguous
- JCM uses isotypes to measure the short-circuit current for every junction in every cell location in the circuit
  - Every isotype must visit the location in the beam of every cell
  - Compare the measured value to the expected value from AM0 calibration
  - Automate this measurement to make it fast and easy
- JCM captures all the aspects of spectral binning/ matching and spatial non-uniformity at the resolution of the present test

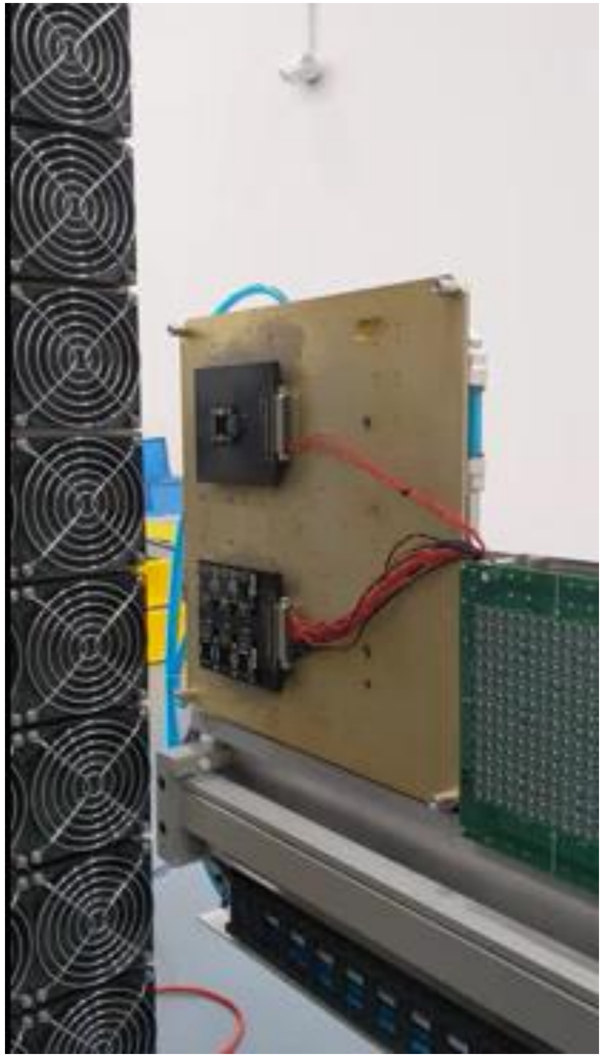


	Cell A	Cell B	Cell C
J1			
J2			
J3			
J4			
J5			

JCM = Measured Isotype Isc Mismatch for All Junctions of All Cells

All-Junction/Cells Isc Mismatch versus AIAA on a 5J, 60 cell panel

- Using a *partially-calibrated* 5J pLEDss, we calibrated to a circuit of 5J cells 3 cells wide and 20 cells high
  - JCM measurements are in percent error from isotype expected Isc
- JCM is fully automated
  - JCM measurement duration is pulse duty cycle * # of cells * # of junctions
    - Duty cycle typically 1-2 second pulses and 2-10 seconds off, depending on panel heating



	J1			J2			J3			J4			J5	
-0.40	2.56	-0.15	-1.06	2.15	-1.09	0.08	1.60	0.43	-0.13	2.61	0.05	-0.06	3.59	0.31
-0.13	2.79	-0.15	-0.80	2.37	-1.06	0.16	1.67	0.32	-0.05	2.41	-0.02	-0.06	3.57	0.35
-0.20	2.89	-0.19	-0.80	2.52	-0.90	0.28	1.80	0.09	-0.37	2.12	-0.30	-0.21	3.30	0.35
-0.57	2.56	-0.46	-0.89	2.41	-0.99	0.08	1.30	-0.25	-0.64	1.89	-0.50	-0.19	3.19	0.09
-0.80	2.35	-0.66	-0.72	2.52	-1.00	-0.16	1.11	-0.29	-0.73	1.63	-0.64	-0.05	3.22	0.03
-1.08	2.31	-0.87	-0.80	2.66	-0.74	-0.60	0.54	-0.48	-0.88	1.50	-0.83	0.00	3.15	0.01
-1.20	2.22	-0.82	-0.83	2.53	-0.87	-1.17	0.35	-0.61	-0.90	1.64	-0.83	-0.03	3.20	0.05
-1.04	2.56	-0.61	-0.71	2.72	-0.84	-1.46	0.00	-0.85	-0.86	1.37	-1.25	-0.01	2.99	-0.17
-1.09	2.52	-0.53	-0.82	2.57	-0.85	-1.53	0.01	-1.09	-0.61	1.64	-1.03	0.10	3.26	-0.21
-0.80	2.75	-0.51	-0.78	2.70	-0.76	-1.31	0.15	-1.11	-0.65	1.68	-0.80	0.11	3.17	-0.27
-0.76	2.71	-0.48	-1.04	2.62	-0.73	-0.50	1.03	-0.73	-0.75	1.63	-0.64	-0.15	3.20	-0.28
-0.55	2.84	-0.24	-1.25	2.35	-0.99	-0.64	1.45	-0.04	-0.76	1.93	-0.68	-0.28	3.08	-0.39
-0.67	2.72	-0.38	-1.43	2.29	-1.08	-0.78	1.33	0.27	-0.84	1.86	-0.74	-0.10	3.27	-0.27
-0.78	2.42	-0.63	-1.42	2.16	-1.20	-0.47	1.58	0.23	-1.02	1.73	-0.61	-0.03	3.38	-0.06
-1.21	2.23	-0.73	-1.24	2.23	-1.21	-0.84	1.15	0.21	-0.65	1.93	-0.99	0.31	3.58	-0.02
-1.17	2.37	-0.93	-1.17	2.37	-1.10	-1.22	0.51	-0.43	-0.65	1.76	-0.73	0.56	3.89	0.17
-1.16	2.50	-0.85	-0.87	2.61	-0.86	-1.03	0.30	-0.97	-0.67	1.95	-0.92	0.55	3.97	0.27
-1.17	2.38	-0.91	-0.64	2.89	-0.79	-0.99	0.75	-0.55	-0.62	2.01	-0.72	0.39	3.81	0.03
-1.26	2.42	-0.87	-0.78	2.80	-0.71	-1.19	0.62	-0.67	-0.61	1.94	-0.99	0.00	3.54	-0.24
-1.77	1.85	-1.55	-1.46	2.27	-1.23	-1.15	0.91	-0.92	-1.18	1.65	-1.02	-0.98	2.56	-1.04

Ambiguity in the Existing Specifications ???

- The AIAA current matching spec says we need to match current in all isotypes, but it doesn't say where (in XY) in the beam
- The ASTM spatial non-uniformity spec says we need to use 36 spatial zones, but it doesn't say how, and it doesn't tell us which junction to use
- So, which of these specifications is correct?

Case	JCM Max	JCM Min	Max-Min/Max+Min	SNU small (2%)	SNU large (3%)	Current match (1%)
Worst-case, all junctions	3.97	-1.77	2.87	Fail	Pass	Fail
Best-case, all junctions	1.80	-0.28	1.04	Pass	Pass	Fail
Worst-case, best junction	3.81	-1.31	2.56	Fail	Pass	Fail
Best-case, best junction	1.60	-0.28	0.94	Pass	Pass	Pass
Worst-case, J1	2.89	-1.77	2.33	Fail	Pass	Fail

Because J1 is the BOL current limiter, and the non-limiting JCM errors are within the J1 current margin

Advantages Of All-Junctions/Cells Isc Mismatch Measurements

- JCM provides measured data instead of spectral assumptions
  - Columns of JCM table are the current production matching of each cell
- JCM provides measured data instead of spatial under-sampling
  - Rows of JCM table are the spatial non-uniformity of each junction
- Measuring JCM before and after a test (or a shift) provides measured data instead of temporal assumptions

- JCM is fully automated in pLEDss
- JCM allows tight specifications where needed (BOL and EOL current limiting junctions) and looser specifications elsewhere

- A test with JCM measurements before and after the test removes any solar simulator calibrations/ assumptions and replaces them with measured data

JCM is measured data, not calibration assumptions

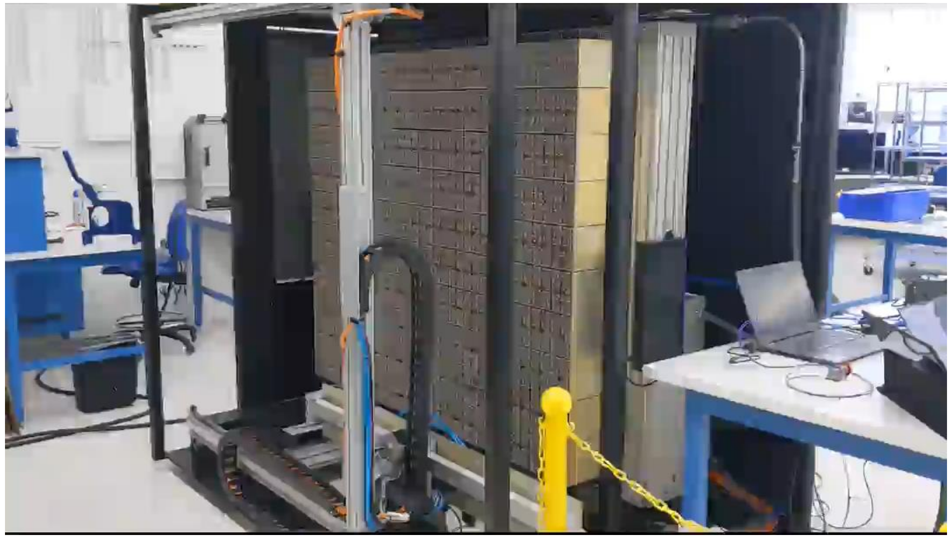
JCM For Small Tabletop Simulators

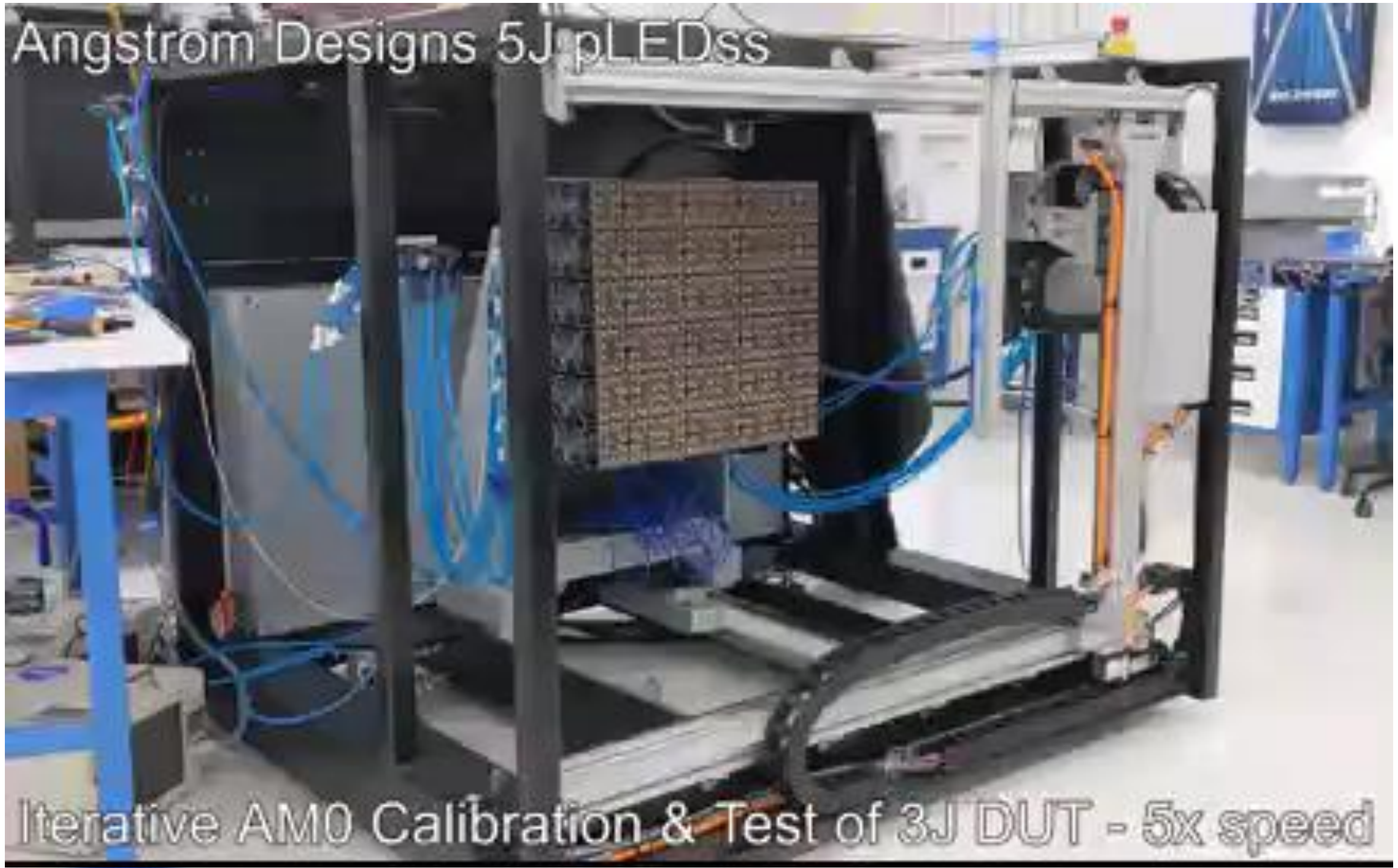
- Many ASTM-based tabletop simulators target 5% total error
  - The X-25 can do much better for a small area
- pLEDss has recently demonstrated JCM of 0.3% for small coupons
  - JCM taken before and after testing
  - Development of improved calibration is in progress, so more improvements are possible

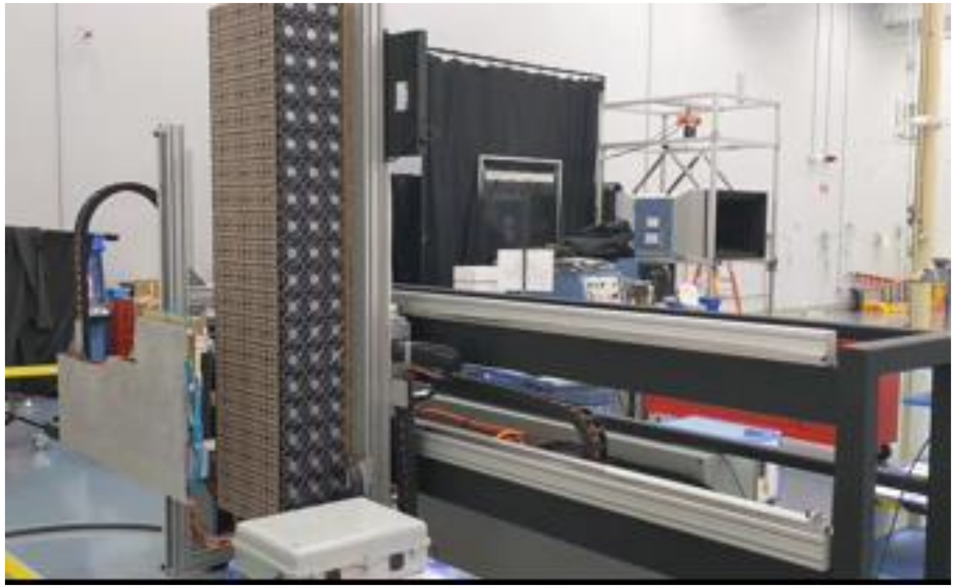
JCM of 0.3% are possible for small coupons

JCM For Large Panel Simulators

- Large-area Xenon lamp simulators can stack ASTM errors to over 6%
- pLEDss has recently demonstrated JCM of 1.0% - 2.2% for large panel circuits
  - Development of improved calibration is in progress, so more improvements are expected







Conclusion: All-Junctions/Cells Isc Mismatch Measurement is a Big Step Forward

- ASTM/ AIAA and Xenon Lamps gives errors of 6% (or more) for large panels
  - Larger error while under-sampling spatial non-uniformity

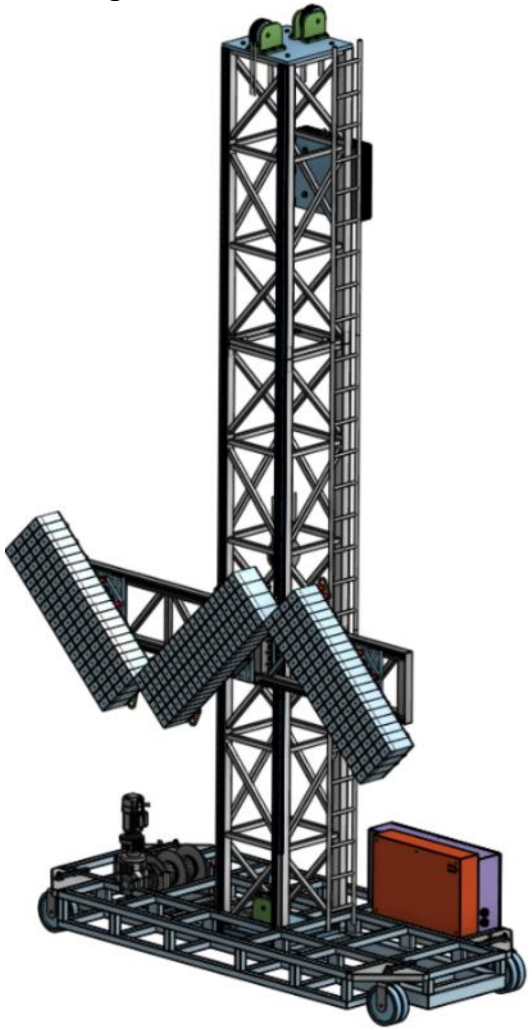
- JCM and LEDs gives errors of 2.2% (or less) for large panels
  - pLEDss has demonstrated JCM <0.3% for small coupons
  - JCM is measured data rather than calibration assumptions

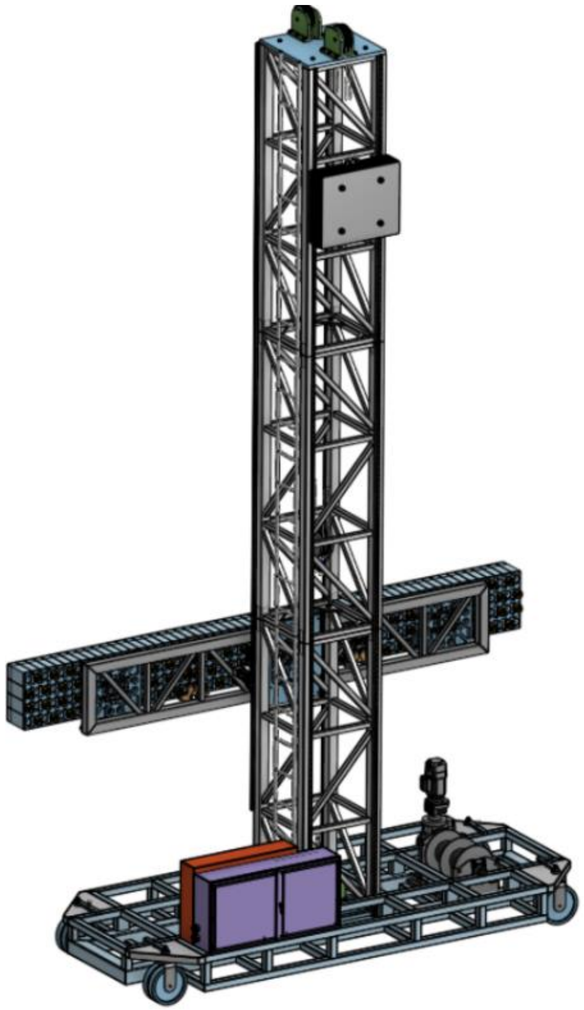
- Why should programs want a 4% (or more) improvement?
  - Use Fewer Solar Cells: shorter or fewer strings and/or circuits
  - Higher confidence in on-orbit power
  - Lower mass and lower cost
  - Lower mass gives many other benefits, including low spacecraft moment of inertia, smaller wings, smaller rotary joints, smaller rockets or more spacecraft per launch, …
  - … For every panel we fly

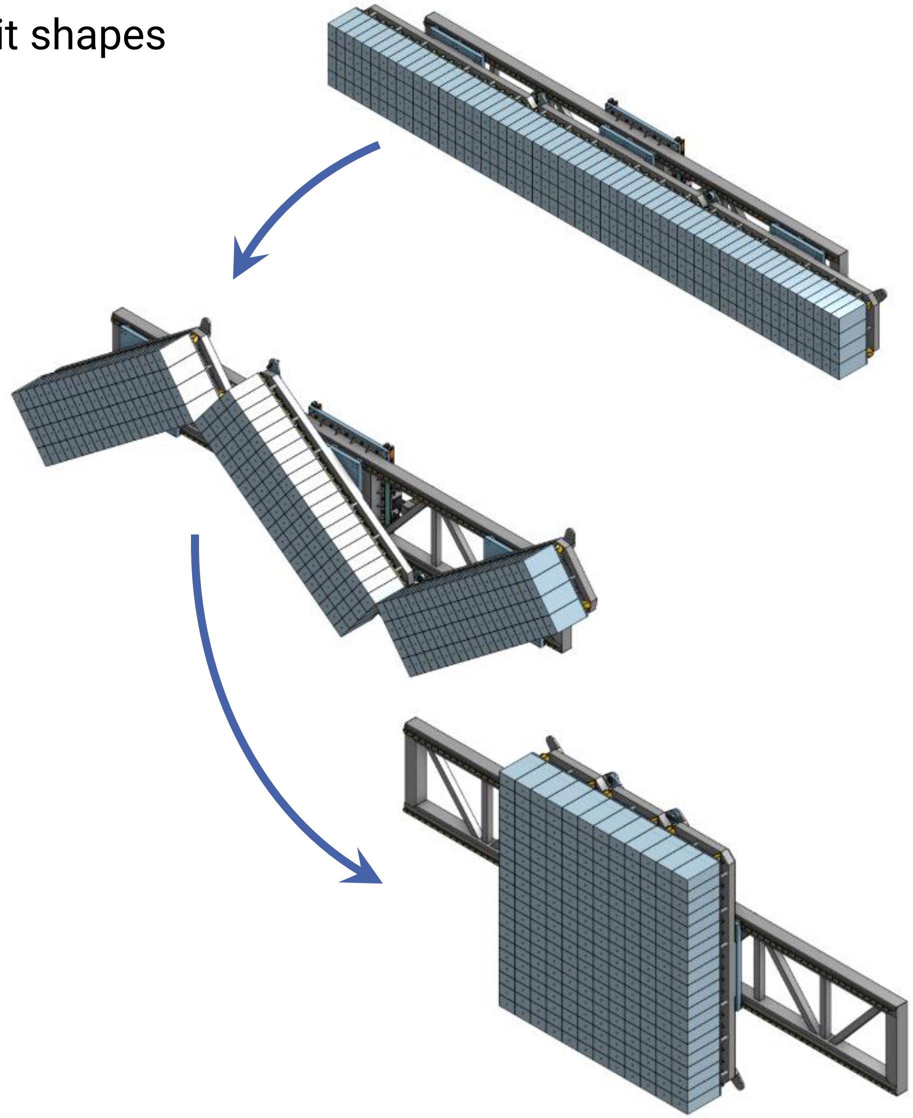
JCM is stricter and measures error sources directly

pLEDss for Artemis Power Propulsion Element

- We are building the biggest pLEDss yet, to test the wings for NASA’s Artemis Power Propulsion Element solar arrays
  - Large Illumination Beam changes aspect ratios to test 2 different circuit shapes

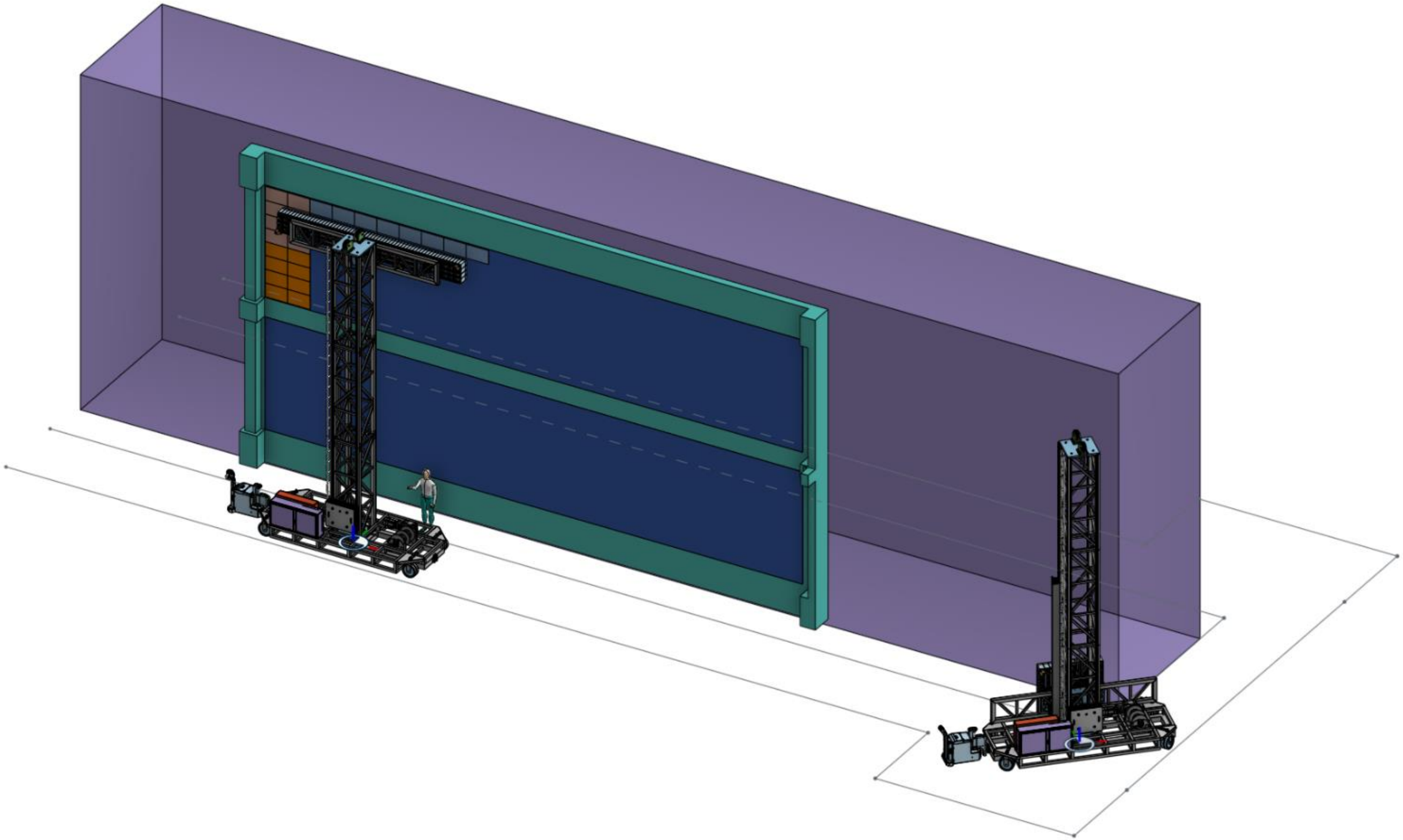






pLEDss for Artemis Power Propulsion Element

- Human for scale
- pLEDss R&D was originally co-invented and SBIR funded by NASA GRC
  - When we started no one knew if LEDs could make a valid IV curve
- Having pLEDss come full circle to Artemis is thrilling



Questions?

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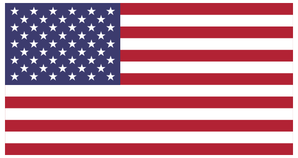

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