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

Space Power Workshop – Torrance CA
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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


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# 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


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# 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


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# 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.


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# 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


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# 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


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# We Have Lots of Barriers to Overcome to Reduce Error Sources

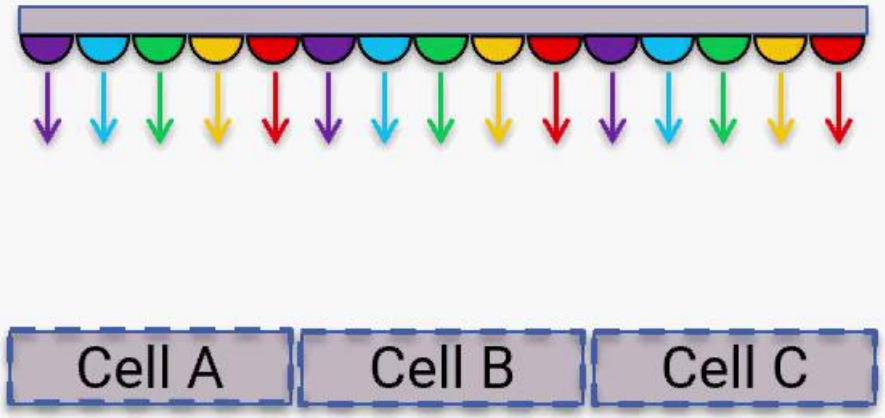
- Our barriers so far:
  - ASTM Spectral Binning Isn't Accurate Enough For Space
    - AIAA acknowledges this, but leaves 1% error margin in place
  - ASTM Spatially Sub-Samples Our Illumination Beam
    - For large areas Xenon bulbs often don't meet the large 3% error bounds
  - ASTM Temporal Stability 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


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# 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



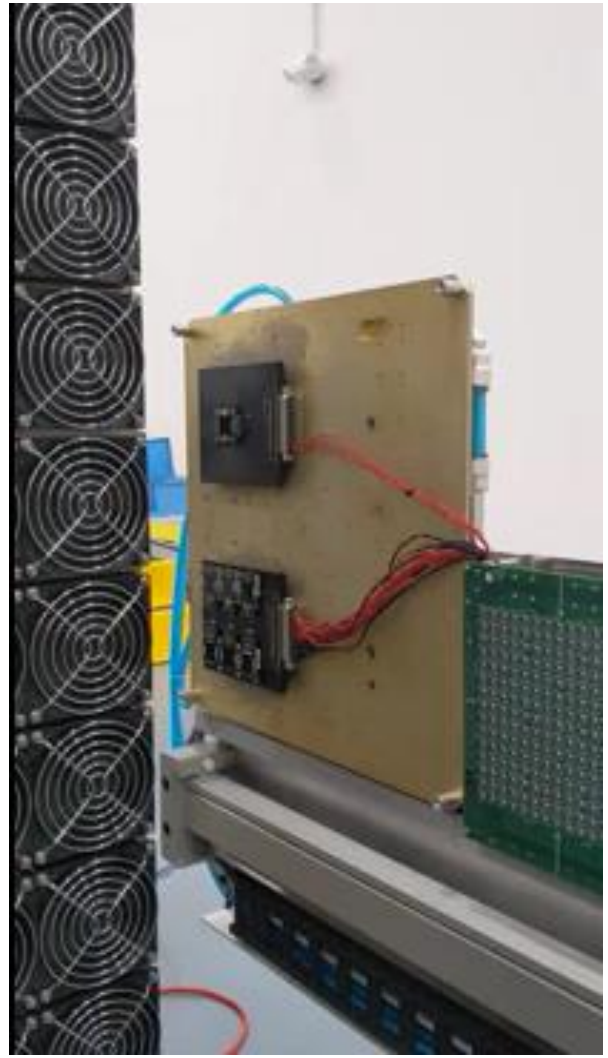

| | Cell A | Cell B | Cell C |
|---|---|---|---|
| J1 | | | |
| J2 | | | |
| J3 | | | |
| J4 | | | |
| J5 | | | |

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


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# 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 |


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# 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


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# 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


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# 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

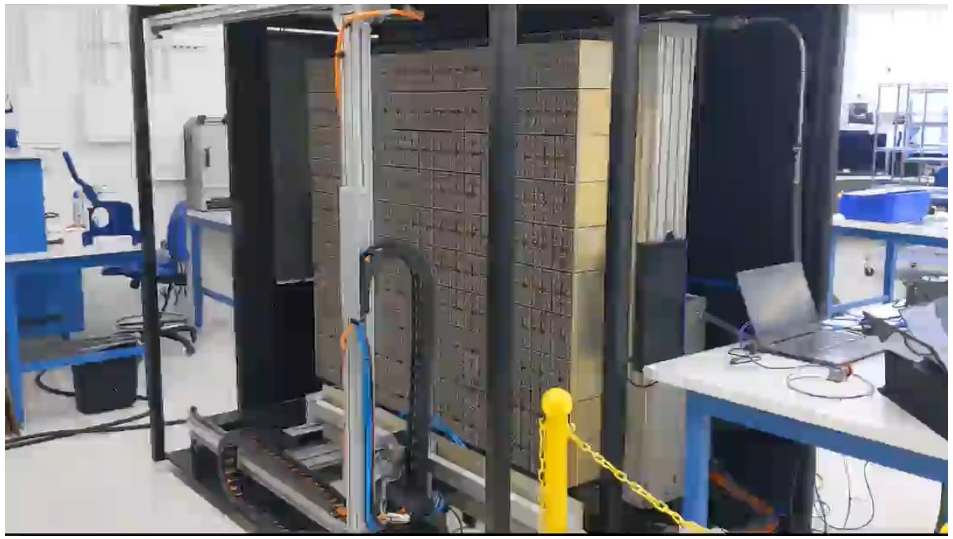


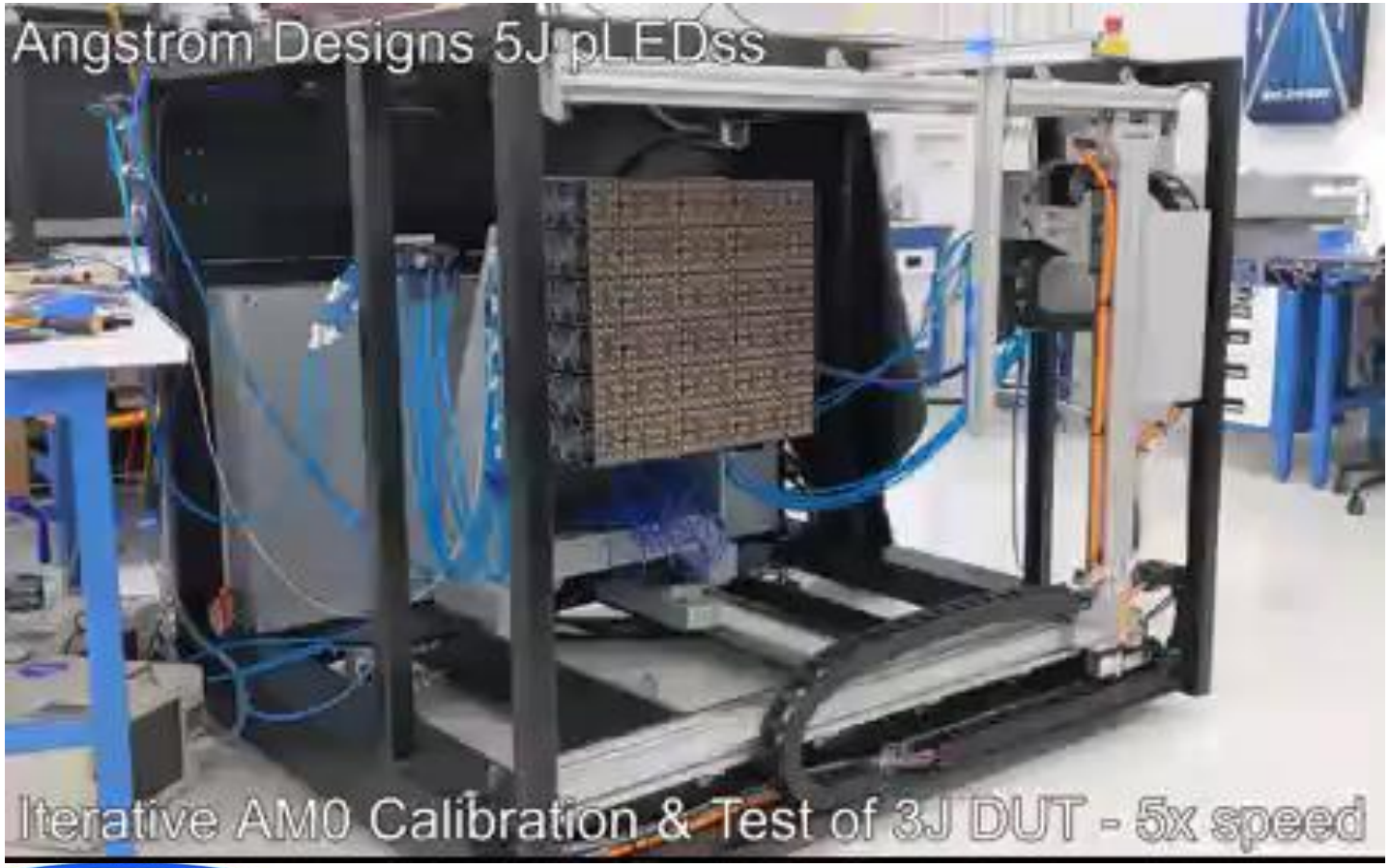

JCM of 0.3% are possible for small coupons

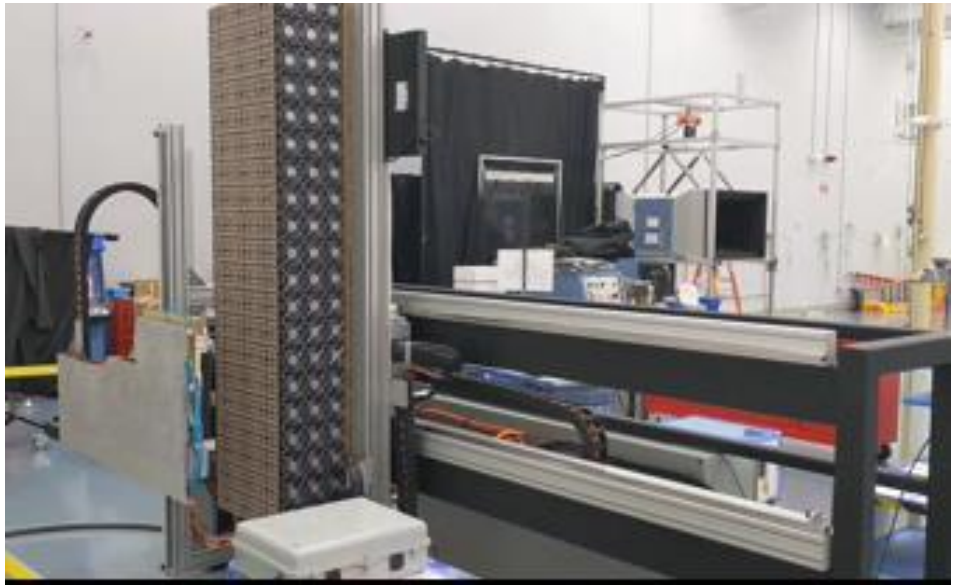

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# JCM For Large Panel Simulators

- 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






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

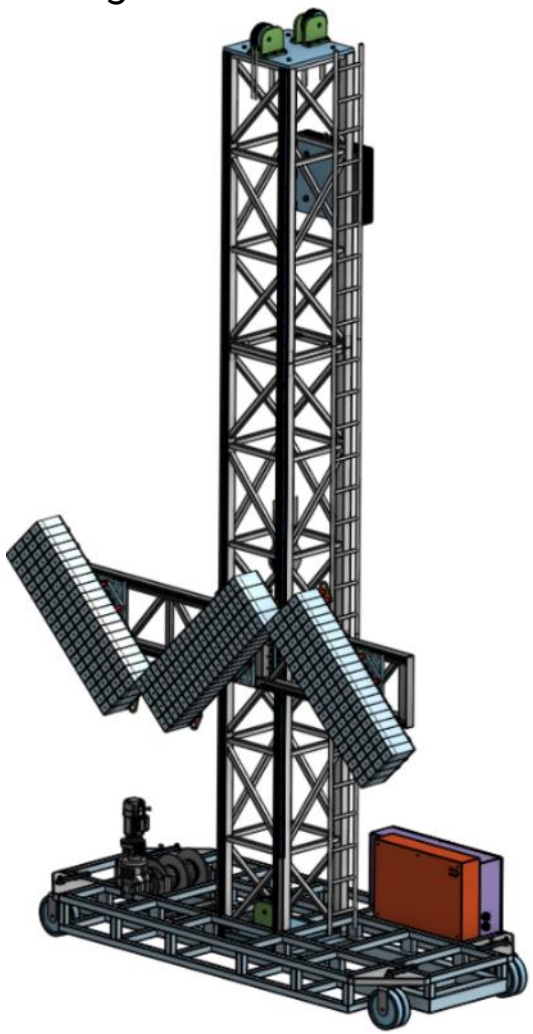
- ASTM/ AIAA and Xenon Lamps gives errors of 6% (or more) for large panels
  - Larger error while under-sampling spatial non-uniformity
- JCM and LEDs gives errors of 2.2% (or less) for large panels
  - pLEDss has demonstrated JCM <0.3% for small coupons
  - JCM is measured data rather than calibration 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

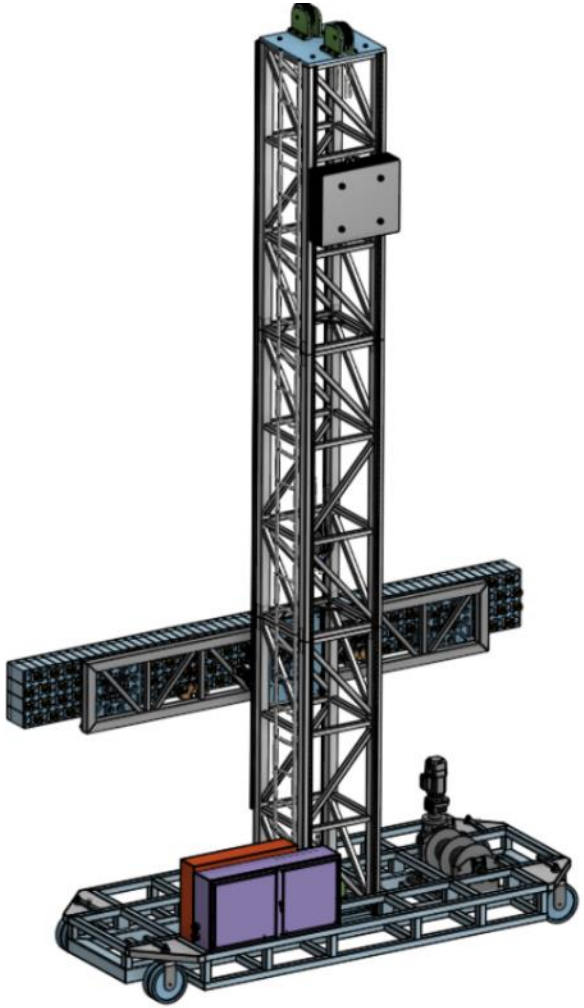
JCM is stricter and measures error sources directly

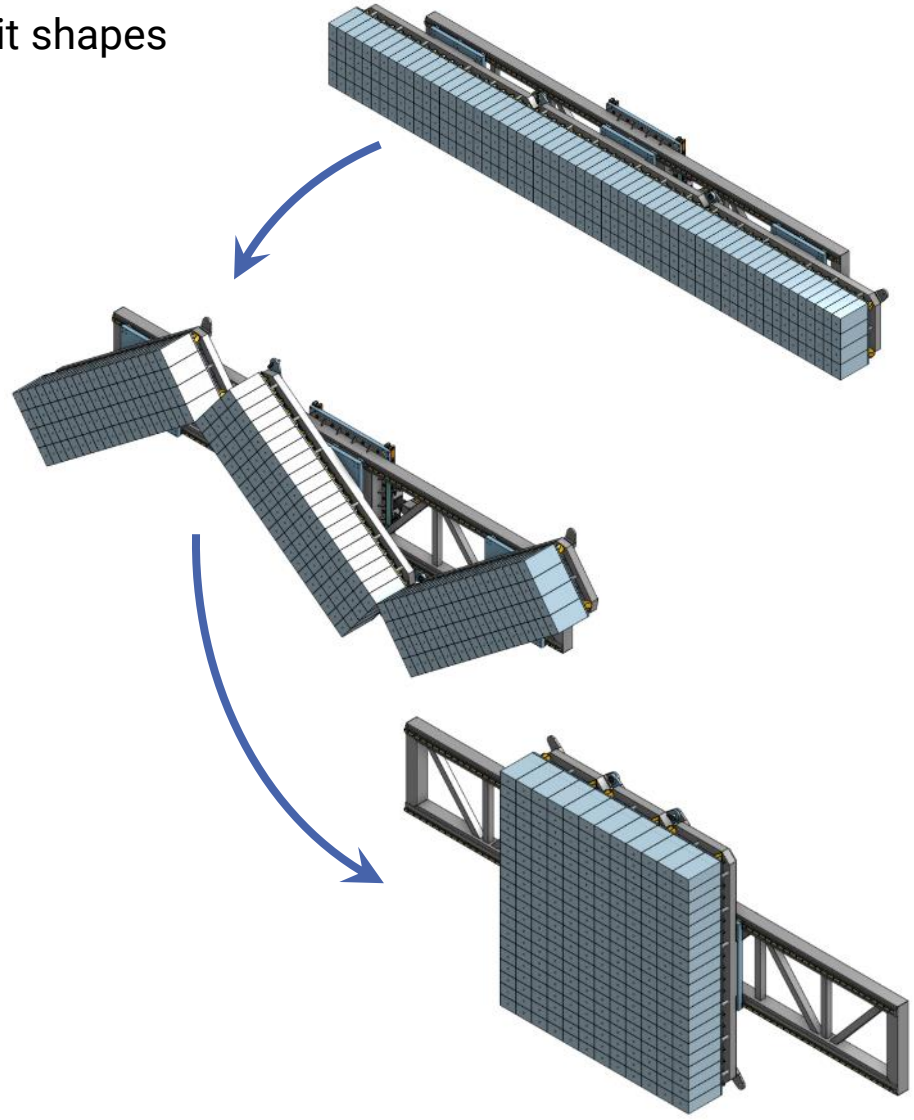

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# pLEDss for Artemis Power Propulsion Element

- 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



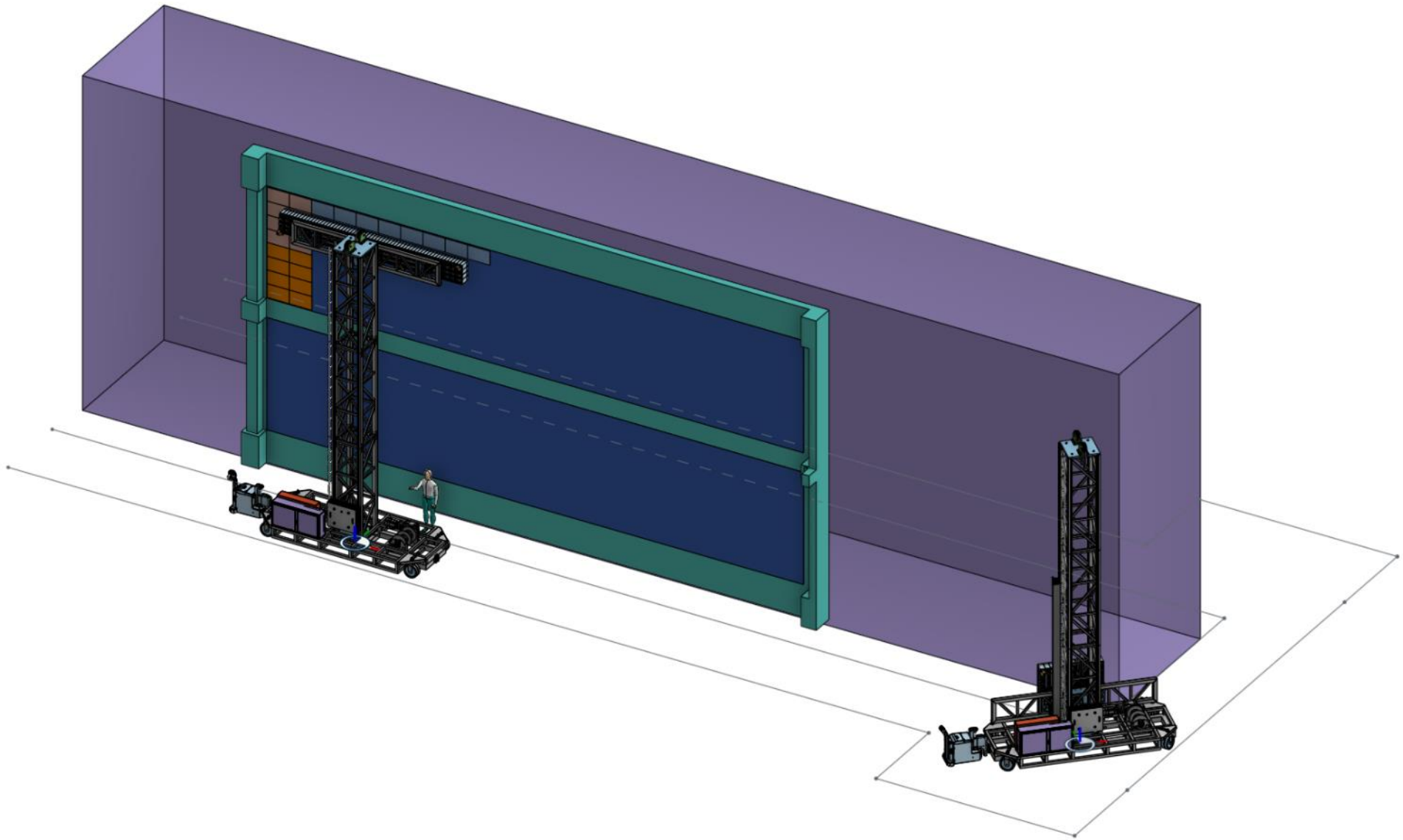





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# pLEDss for Artemis Power Propulsion Element

- 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




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# Questions?

For More Information:

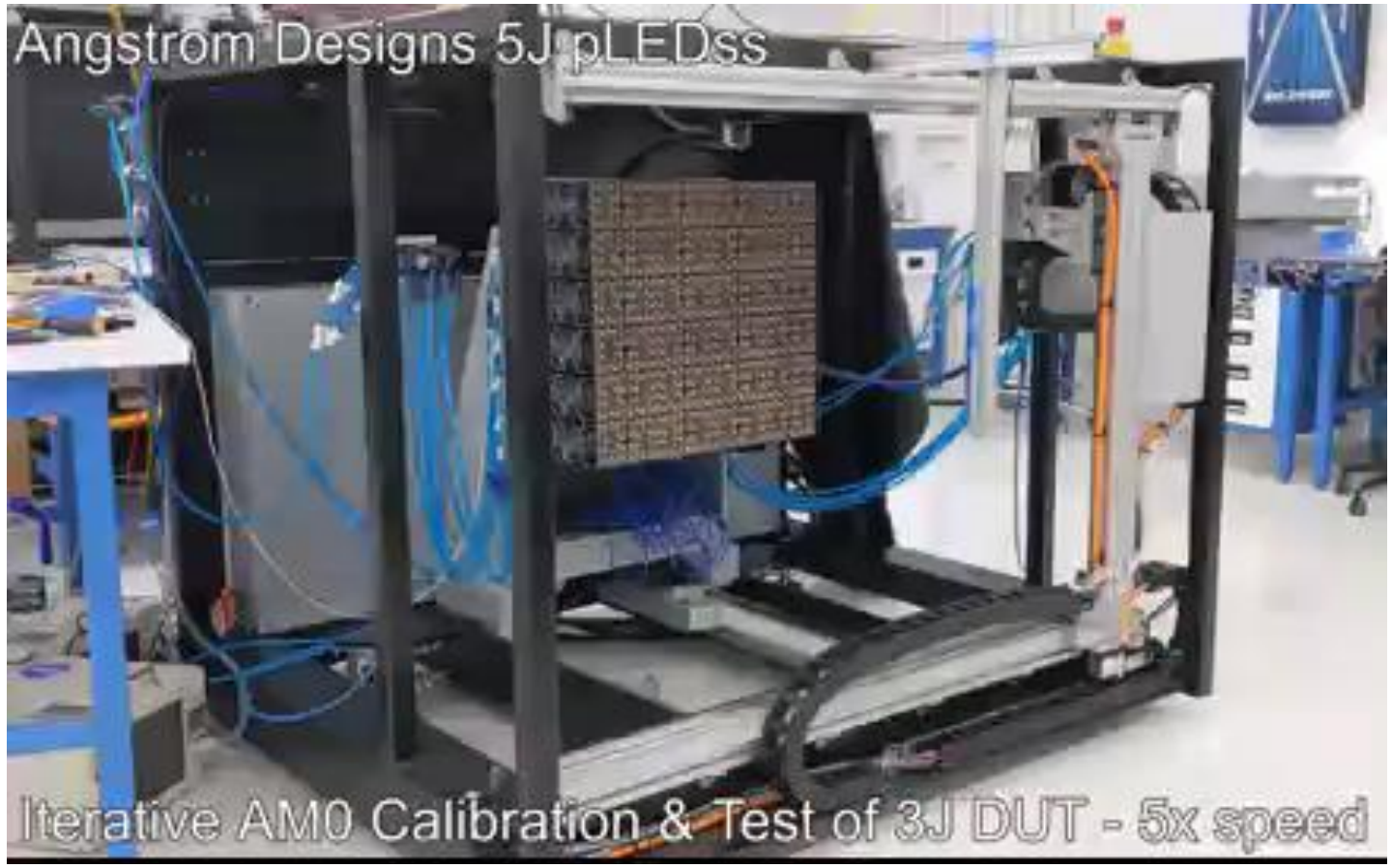
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