Characterization of a TS-Space Quad-Source Solar Simulator

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***Abstract* — We present a thorough evaluation of a first-of-its-kind quad-source AM 0 solar simulator developed by TS-Space Systems and installed at the AFRL Space Vehicles Directorate in Kirtland AFB, NM. With an underlying need to evaluate more complex and advanced space photovoltaics, the TS-Space Unisim 100 was chosen as replacement to the Spectrolab X-25. Several parameters of the Unisim were characterized including spectral irradiance, lamp stability (long-term and short-term), spatial uniformity, and repeatability. In addition, the impact of test plane translation due to variable cell holders was studied. The potential impact of AC input voltage to lamp ballast was also investigated. Further, comparisons are made to the X-25. Finally, operational considerations for the use of a multi-source simulator are discussed.**

***Index Terms* — photovoltaic cells, light sources, current-voltage characteristics, gallium compounds, indium gallium arsenide.**

I. INTRODUCTION

Over the past decade, significant advances in multijunction solar cell architecture [1,2] have led to an added level of complexity in standard cell characterization techniques, including quantum efficiency (QE) and current-voltage (IV) under illuminated conditions. Accurate QE measurements of subcells require an understanding of the shunting behavior of the device [3], but can otherwise be carried out using typical QE measurement equipment along with appropriate bias lamps and/or DC bias supply. However, for light IV measurements, one is inherently limited by the lamp source, which can only simulate the desired solar spectrum (e.g. AM 1.5, AM 0) to a finite degree. Standard multijunction cell architecture is such that subcells are electrically and optically in series. Therefore, the total current through the cell is limited by that of the lowest performing subcell, in terms of current generation. Coupling this with the fact that the adding of subcells serves to further split the incoming spectrum, special attention must be given to the ability to tune the incoming spectrum in a manner that is consistent with the expected cell output at short circuit (as determined by external QE measurements). Therefore, having more isolated control over segments of the solar spectrum is desired to provide a more accurate measure of the illuminated IV characteristic.

The majority of solar simulators consist of a single lamp source (typically a xenon-based arc lamp) that is filtered to give a best-fit to the desired air mass spectrum. However, with the desire to have more control over various parts of the spectrum, researchers and vendors have done extensive work on designing multi-source simulators to allow such flexibility. In particular, TS-Space Systems has pioneered a quad-source simulator that uses a metal-halide (HMI) lamp for the UV-visible portion of the spectrum along with quartz tungsten halogen (QTH) lamps for longer wavelengths (>700 nm). It is designed to be an ultra-stable system given the smooth response from the HMI and, particularly, the QTH lamps. This system is particularly well suited, then, for four junction solar cells which are soon to be making their way into the commercial market. Herein, we discuss our work on characterizing this first-of-its-kind system.

II. EXPERIMENTAL

The multi-source simulator being characterized, hereby referred to as the Unisim, is a four-zone (each zone corresponds to a given lamp) Class AAA system with 100mm illumination diameter that is filtered for the AM 0 spectrum. The system (model: Unisim 100 AM 0) was built by TS-Space Systems in the UK and installed in the Advanced Space Power Generation Lab at AFRL Space Vehicles Directorate, Kirtland AFB, NM in November 2010. At the time of installation, this was the first four-zone simulator of its kind. Specs include 2% spatial uniformity as measured with a 2 cm x 2 cm cell, ≤ 1% temporal stability, and 4° half-angle divergence. Each of four lamps is rack-mounted horizontally and illumination is reflected downward at a 45° angle onto the test plane through a series of dichroic optics and filters. Each lamp corresponds with a given spectral "zone" of illumination, as follows:

- Zone 1: HMI source, 320 – 700nm
- Zone 2: QTH source, 700 – 900nm
- Zone 3: QTH source, 900 – 1200nm
- Zone 4: QTH source, 1200 – 2500nm.

In addition, pneumatic shutters in front of each lamp allows for isolated illumination from each zone.

The test plane consists of a gold-plated copper test chuck that is temperature controlled by water cooling. This allows for excellent thermal and electrical conductivity and maintains cell temperature at a fixed set point even under illumination. Feedback to the temperature control unit is provided by a 3-wire, probe-style RTD inserted in a hole in the chuck. For data presented here, temperature was held at 25°C (± 0.5°C).

Electrical characterization was performed using a Keithley 2400 Source Measure Unit (for I-V) and a Keithley 2750 data acquisition system (for temperature). Control of the simulator is entirely manual, while the electrical characterization system is controlled by a LabView-based program, developed in-house, named "HELIOS" (High-Efficiency Light IV

Operating Station). In addition to typical light I-V characterization, HELIOS was designed for monitoring performance over time. For the SMU, unless otherwise noted, an integration time of 1 PLC (at 60 Hz) was used and filtering was turned off. The settling delay was set to automatic, as no difference was found with this feature being on or off. The “auto-zero” setting was set to “once” to recalibrate just before each sweep, but not in between successive data points. Four-wire connections from probe to instrument were used, as this can have a significant impact for cells with relatively low shunt resistance, as is typically seen in low band gap cells.

The cells under test are Spectrolab (GaInP and GaAs) and Emcore (1 eV InGaAs and 0.7 eV InGaAs) isotypes along with an Emcore four junction IMM cell. For notation purposes, GaInP is the “Top” subcell, GaAs the “Upper-Mid,” 1 eV InGaAs the “Lower-Mid,” and 0.7 eV InGaAs the “Bottom.” Each isotype cell is spectrally filtered such that the performance of the cell is limited to how it would perform in the full four junction device. Each cell was previously mounted onto a given cell holder. The upper two isotypes (GaInP and GaAs) are on legacy balloon holders with shunt resistor removed, while the lower two isotypes and the four junction are mounted on the new holder developed by the Near Space Characterization of Advanced Photovoltaics (NSCAP) Program. Each holder has a nominal difference in height, which was investigated. Four wire connection was maintained to at least the holder terminals.

Prior to testing on each day, the simulator was calibrated using similar isotypes as those discussed above, which were calibrated to the AM 0 spectrum either on previous balloon flights (GaInP and GaAs, with shunt resistor) or Learjet flights (remaining cells). Each zone was adjusted to within 0.3% of the calibrated value of I_{sc} from the cell. Adjustments were made to lamp current.

Additionally, measurements on the Unisim were compared with those from an in-house Spectrolab X-25. The X-25 is a mainstay for AM 0 measurements and consists of a single xenon arc lamp source that is appropriately filtered.

III. RESULTS

A. Lamp Start-Up Time

First, we monitored the start-up characteristics of each lamp to obtain a measure of how long we should wait prior to beginning measurements. Data shown as a function of shift relative to the steady-state I_{sc} is shown in Fig. 1a. From this, it is seen that a minimum of 30 minutes is needed, with 60 minutes being more optimal to ensure being within 0.5% of the steady-state value. Individual lamp stability after this warm-up period is shown as a function of relative shift in I_{sc} in Fig. 1b. While within spec of ±1%, this data illustrates the significant difference between an arc-based lamp source (Zone 1, HMI) and a halogen-based one (Zones 2-4, QTH).

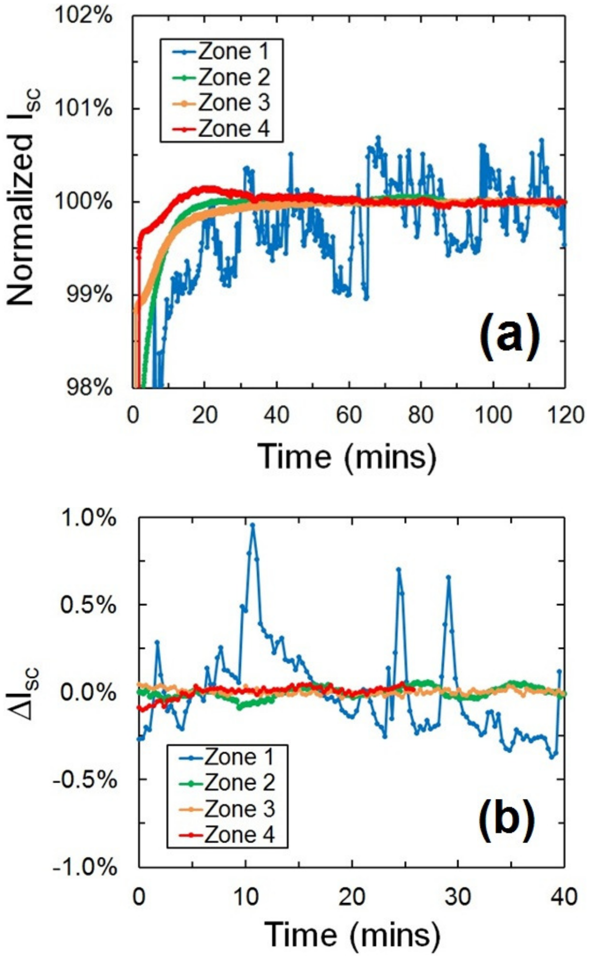


Fig. 1. Individual lamp performance on the Unisim. Zone 1 indicates response from HMI source, while Zones 2-4 are from QTH sources. (a) Start-up characteristics for each lamp indicating warm-up time of 30 minutes minimum. (b) Lamp stability after initial 60 min warm-up period, in relative I_{sc}, is shown as a function of time (data taken every 20s under continuous illumination).

B. Lamp Instability – Long-Term

Under full illumination after the initial warm-up period, we again find similar stability of ±1% on the Unisim (Fig. 2b). In comparing to data taken on the X-25 (Fig. 2a), we found a modest improvement in the long-term instability (LTI) of the Unisim. As noted in IEC 60904-9 [5], temporal instability is calculated as

$$Instability\ (\%) \equiv \frac{max-min}{max+min} \times 100\%, \qquad (1)$$

where the maximum and minimum values of I_{sc} were used. The Class A specification for LTI is 2%. The performance over 1 hour on the X-25 was 1.173%, whereas the Unisim was 0.83%. This is based on data from the GaInP “top” cell isotype, given that it is most sensitive to the stability of Zone 1 on the Unisim.

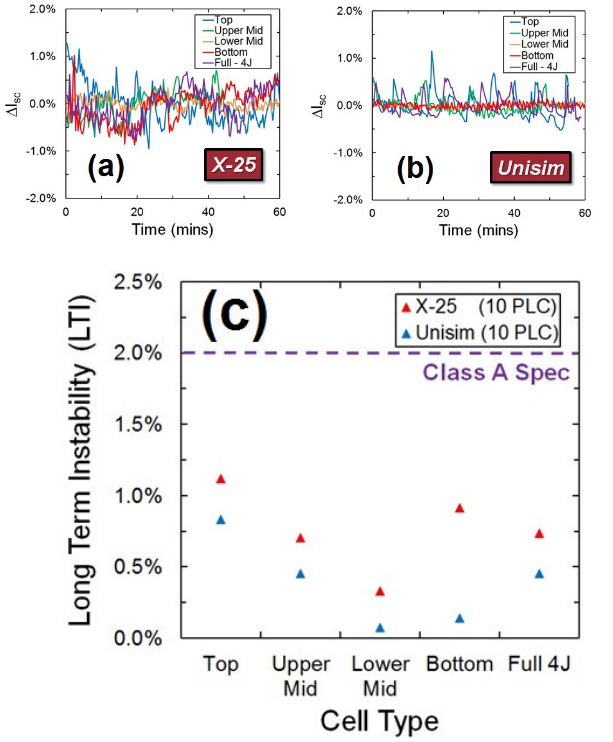


Fig. 2. Comparison between (a) Spectrolab X-25 and (b) TS-Space Unisim long-term stability on isotype and four-junction cells, in relatives I_{sc}, shown as a function of time (data taken every 20s under continuous illumination). Part (c) shows comparison to Class AAA solar simulator standard as defined by IEC 60904-9.

C. Lamp Instability – Short-Term

While a slight difference was seen in long-term instability, the more striking difference between the Unisim and X-25 was in short-term instability. This accounts more for lamp flicker, which can be seen in looking point-to-point in an I-V curve. A comparison of I-V curves on each isotype and the four junction was done between the X-25 (Fig. 3a) and the Unisim (Fig. 3b). These figures focus in on the flat portion of the I-V curve around I_{sc} and shows the X-25 to have fluctuations as much as 1% point-to-point, compared to <0.1% on the Unisim.

To accurately determine short-term instability (STI), 1000 data points (I_{sc}) were collected in rapid succession over a period of time that would encompass the typical scan time for an I-V sweep. Three different data acquisition times, 0.1, 1, and 10 PLC at 60 Hz, were used corresponding to acquisition times of around 3.45, 18.45, and 168.3 ms, respectively. Minor instrument and communication delays can account slightly longer acquisition times than may be expected (e.g. 18.45 ms vs. 16.67 ms for 1 PLC). In our lab, I-V sweeps are generally taken with acquisition times of 1 PLC, but other values were tested for this work to further articulate a benefit of the Unisim compared to the X-25. Results from these scans on the Unisim, X-25, as well as, for comparison, an ultra-stable Hg-Xe lamp are shown in Fig. 3c. As shown, the Unisim outperforms the X-25 in every category. Further, on the Unisim, aside from the top cell isotype measured at 0.1 PLC, all cells under all testing conditions performed below 0.2% STI, far below the Class A standard of 0.5%. The acquisition time relevant for the standard is usually around 50 ms, or 3 PLC.

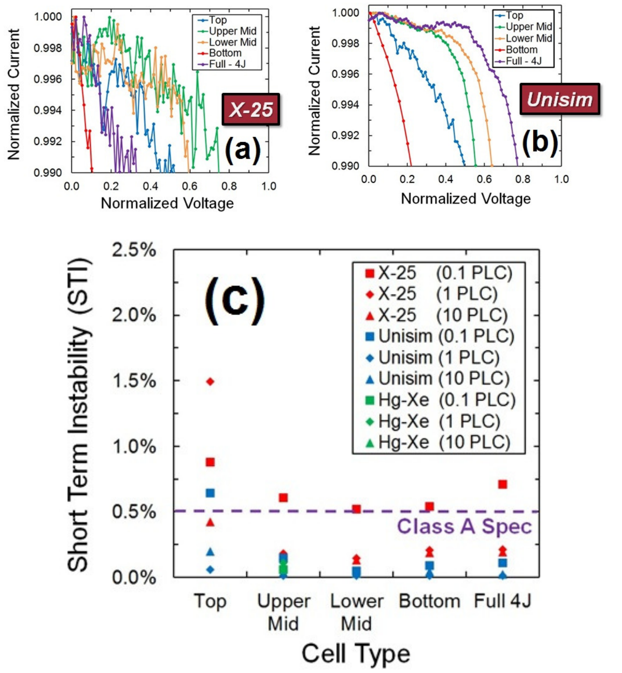


Fig. 3. Comparison between (a) Spectrolab X-25 and (b) TS-Space Unisim normalized I-V curves on isotype and four-junction cells. Part (c) shows comparison to Class AAA solar simulator standard as defined by IEC 60904-9, including comparison of acquisition times (0.1, 1, and 10 PLC) as well as to a Hg-Xe ultra-stable arc source.

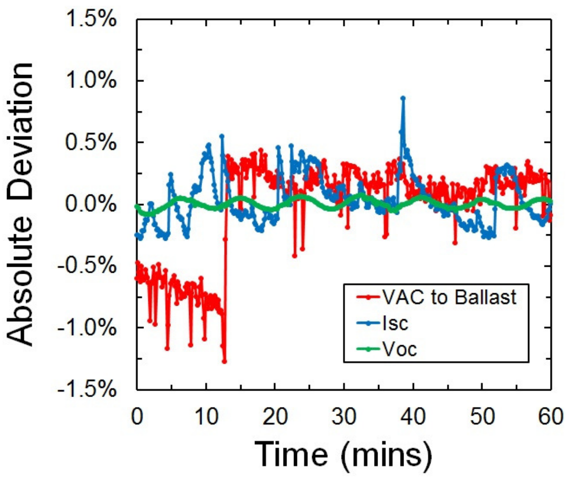


Fig. 4. Synchronous recording of AC line voltage going to Zone 1 ballast supply and I_{sc} / V_{oc} of “Top” cell under Zone 1 illumination.

In an effort to try and further improve stability of Zone 1, we also probed the AC input voltage to the lamp ballast in sync with cell performance (Fig. 4). Doing so allowed us to see if any noise or fluctuations on the power line led to significant shifts in cell output. While we did find some long-term trending, it was not significant enough to warrant the use of costly power stabilization hardware. Note that even a jump in the line voltage around 12 minutes, due to off-loading on the circuit, did not produce a significant disturbance to lamp output.

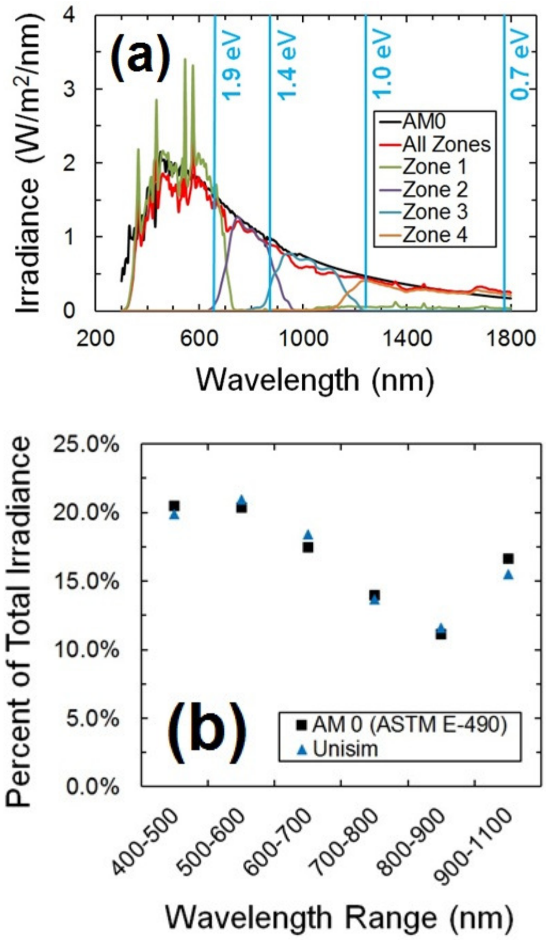


Fig. 5. Spectral irradiance comparison between AM 0 standard (ASTM E-490) and TS-Space Unisim: (a) irradiance from each of four lamps indicated by "zone" numbers and vertical blue markers indicate band gaps of typical IMM four junction solar cell; (b) percent of total irradiance for each of six wavelength regions as specified by IEC 60904-9.

D. Spectral Irradiance

The Unisim, at install, was calibrated to the AM 0 spectrum, per ASTM E-490 [4] with integrated intensity of 1366.1 W/m^2. Results from a spectroradiometer after calibration of the system with standard isotype cells are shown in Fig. 5a. Spectra under full illumination along with that from each of the isolated four zones are shown. Also, markers are included to indicate the approximate cut-off in spectral response for each of the four isotype cells. The correlation between each given isotype and its respective zone is easily seen. As seen in Fig. 5b, the Unisim provides a close match to AM 0 in each of the six wavelength ranges called out in the IEC 60904-9 standard. The requirement for Class A is to be ±25% relative to the AM 0 standard in each range. The Unisim is less than ±6% in each case.

E. Uniformity

Next, we examined the spatial uniformity of the beam as a function of individual zones and full beam. It was found that rather than having a circular uniform area, the beam is actually skewed to be more elliptical (Fig. 6). This deformation has been tied to the optics used internally to the system. Analysis of 13 data points taken from a 2 cm x 2 cm cell around the illumination area is shown in Table 1. With only accounting for the data points that fell within the skewed region (red ellipse in Fig. 6), we found all zones to be within the Class A specification of 2%, as calculated by (1). Uniformity across the full area (black circle in Fig. 6) ranged from 2-4%.

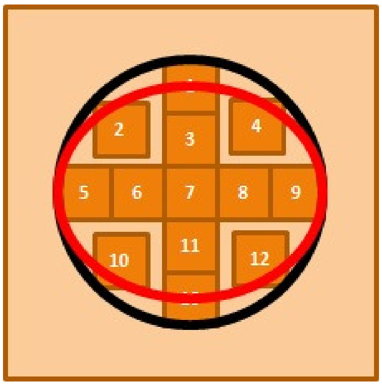


Fig. 6. Schematic representation of uniform illumination area (black circle is as-specified 100mm diameter "total area", red ellipse is area found to be the most uniform, "measure area").

TABLE I

SUMMARY OF BEAM UNIFORMITY. "TOTAL AREA" ENCOMPASSES ALL 13 MEASURED AREAS. "MEASURE AREA" ENCOMPASSES ONLY 11 MOST CENTRAL AREAS. SEE FIG. 6.

Zone	**Uniformity Analysis**	
	Total Area	Measure Area
1	2.7%	1.3%
2	3.5%	1.8%
3	3.2%	1.9%
4	3.7%	2.0%
All Zones	2.2%	1.5%

F. Repeatability

We then sought to examine whether measurements that we took day-to-day after re-doing calibrations would be repeatable. Given that a multi-source simulator requires greater care in calibrating each zone, there is always additional room for user error. However, as Fig. 7 shows, we were able to get very good repeatability on a four junction cell, with differences in I_{sc} and V_{oc} of only ±0.5%. And, the difference in V_{oc} is actually coupled to slight changes in cell temperature during each day of measurement due to lab conditions at time of measurement.

G. Sample Height

Finally, given the different thickness of samples we measure (bare cell, legacy balloon holder, new NSCAP holder, see Fig. 8), we performed careful measurements to quantify this impact of effectively shortening the working distance to the lamps. Fig. 9 summarizes these results from a four junction cell at heights that correlate, nominally, with a bare cell (0 mm), cell mounted to legacy balloon holder (3.55 mm), and cell mounted to NSCAP holder (4.9 mm). Despite the very narrow beam divergence for this system, we found variations of intensity up to 1.5%. This led us to augment our system with a vertical translation stage which allows us to keep the plane of the cell under test in the same active test plane from sample to sample, or from calibration cell to test cell.

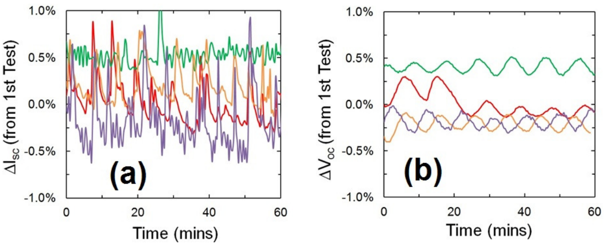
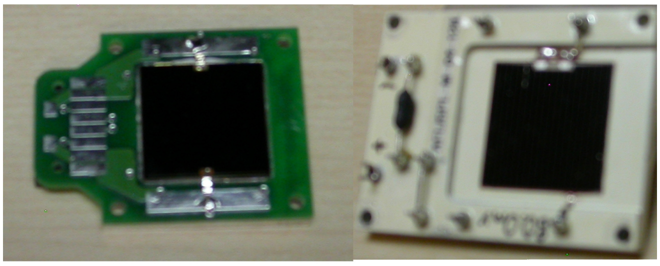


Fig. 7. Repeatability tests performed on TS-Space Unisim, considering both (a) I_{sc} and (b) V_{oc} on the same four junction cell with tests shown from four different days over the course of two weeks. Oscillations in V_{oc} directly coupled with oscillation of cell temperature due to water-cooled copper chuck.



(a) (b)

Fig. 8. Sample holders for 2 cm x 2 cm standards: (a) NSCAP holder and (b) legacy balloon holder.

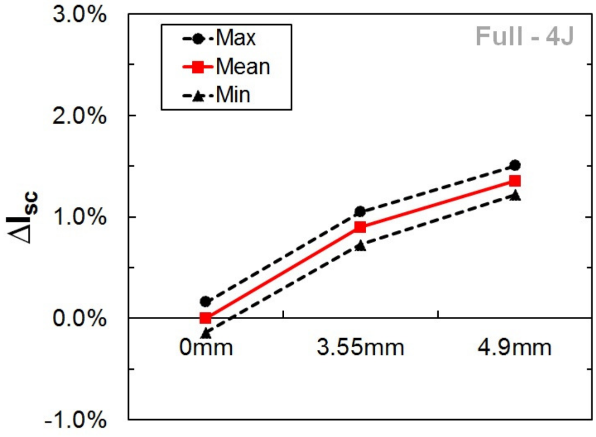


Fig. 9. Impact of sample height, relative to working distance of the lamp, is shown for a four junction solar cell at heights respective to nominal (0 mm), legacy balloon standard holder (3.55 mm), and NSCAP standard holder (4.9 mm).

IV. DISCUSSION

The array of tests shown in the previous section clearly demonstrates the enhanced capability of the Unisim solar simulator. Despite the added complexity of a multi-source system, it seems to have been well-engineered by the designers at TS-Space. For our purposes at AFRL, a calibration routine has been set in place that is not overly burdensome, yet still provides for highly accurate and reproducible results. The routine generally consists of iterating through each of the four lamp power supplies with the corresponding isotype standard until a match, within 0.3%, is made to the calibrated standard value (typically based on I_{sc}). The in-house HELIOS software assists the user in this process.

V. CONCLUSION

We have completed a thorough evaluation of the TS-Space quad-source Unisim simulator, including comparison to the Spectrolab X-25. It was shown that long-term instability between systems is comparable, but short-term instability is quite different. This is believed to be due to the use of the HMI lamp source on Zone 1, which TS-Space has specifically developed for use in solar simulators. We considered the AC input voltage to the HMI lamp ballast as a potential source of decreased stability, but did not find a strong correlation. In addition, we have looked at repeatability and spatial uniformity and found each to be within expectations. Finally, impacts from using different cell holders without proper adjustment in working distance was investigated and led to a system modification for internal control.

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