Uncertainty of In-Situ Calibration and Commissioning of Uniform Source Systems in the Field

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1.0 ABSTRACT

Integration sphere based uniform sources are a primary tool for ground based calibration, characterization and testing of pre-flight and flight radiometric equipment. Periodic calibration of these devices traceable to a National Lab is required. This usually entails sending the device back to the original manufacturer or a qualified calibration lab if the capability does not exist in house. Sending commissioned equipment out of house is usually not easy or possible for most system users. Even if the in-house calibration capability does exist, need for accredited third party verification is usually desired to validate program performance. Labsphere has been investigating a radiometrically stable, NIST traceable and accreditable service for calibration at customer sites in the 0.3um to 2.4um wavelength range for spectral radiance and irradiance. Our instrumentation can be brought on site on-demand and at relatively low cost to provide traceable certification and measurement of existing sources and systems at customer sites around the world. In this poster, we will document our out-bound and in-bound calibration results and problems experienced over several campaigns. We will also discuss our initial traceability and characterization effort with basic commercial instrumentation, as well as in-house techniques (calibration station, stray light reduction characterization, wavelength registration problem and spectral anomalies) we have used to validate, inspect and improve on our results to provide under 2.5%, 2-sigma field-capable absolute uncertainty.

2.0 HARDWARE

2.1 OPTICAL CALIBRATION SYSTEM (OCS)

Spectral radiance measurement service of an integrating sphere source of uniform radiance ("uniform source") is performed by direct comparison of measurements carried out with equipment and methods traceable to the NIST. Measurement uncertainty is determined by best practices of expressions of uncertainties. The measurements are accomplished by referencing a calibrated Spectralon target of known diffuse reflectance factor that is irradiated by an FEL type tungsten halogen spectral irradiance lamp standard. The Spectralon target becomes the reference source of spectral radiance expressed as Equation 1:

$$L_\lambda = \frac{E_\lambda \rho_\lambda}{\pi} \qquad (mW/cm^2\ sr\ \mu m)$$

Where L is the spectral radiance of the target, E is the spectral irradiance of the FEL at its calibrated distance and ρ is the spectral reflectance factor of the Spectralon target.

Equation 1: Spectralon Target Spectral Radiance

The spectral radiance is then used to calibrate the field service spectroradiometer. The spectroradiometer spectral radiance responsivity is achieved by scanning and collecting the spectral radiance of the irradiated target and recording the responses. The spectral radiance responsivity calibration is performed on a full range UV-VIS-NIR dispersive spectroradiometer.

Reported sampling values from a typical scan are in 1nm intervals. The spectral measurements are performed with this FOV positioned at the center of the plane of the diffuse target. The radiance of the Spectralon target is transferred to the diffraction grating array spectrometer with a fixed mounted 1.2 meter metal clad fiber optic cable coupled to a 5 degree field of view foreoptic radiance detector head via an SMA-905 connector per Figure 1:

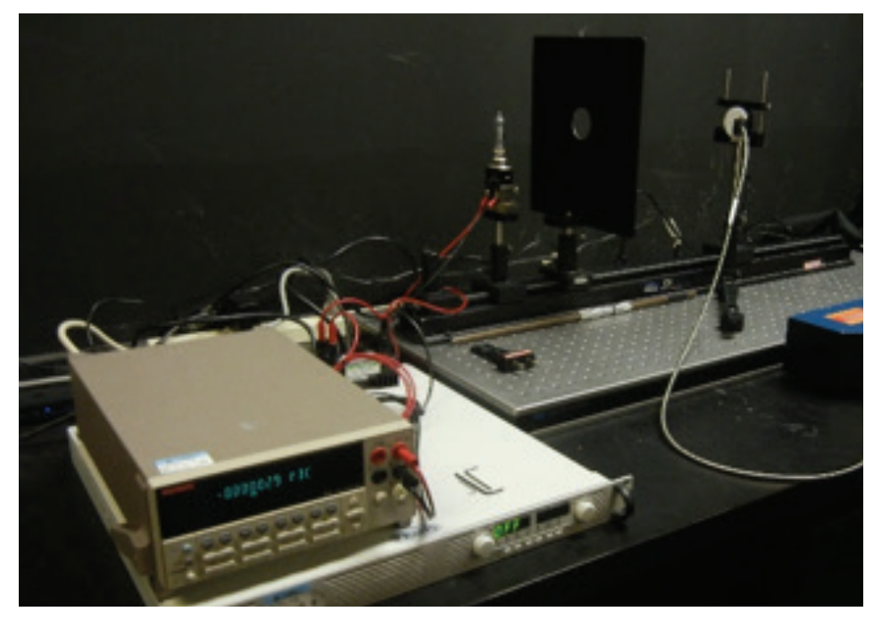


Figure 1:
Radiance Transfer Target Station

Long pass order sorting filters are used to reduce stray light and block higher orders. The complete spectral measurement range requires three array detectors and three diffraction gratings. A 512 element UV enhanced Si array is used for the 300 to 1000 nm spectral region. From 1000 to 1900 nm a 256 element extended InGaAs array is used and a second 256 extended InGaAs array is used from 1900 nm to 2400 nm.

2.2 ELECTRICAL VALIDATION KIT (EVK)

The electrical side of the system is also part of the fundamental calibration and uncertainty equation. Proper current, lamp operation and detector readings are essential to a fully commissioned system calibration. Labsphere provides a complete electrical evaluation of the system power supplies at site to ensure that lamp current is within our uncertainty tolerances (Figure 2). Since most of the power supplies are dedicated single current setting power supplies, each power supply is checked with its actual load (lamp and similar socket) in place. Additional current modifications may be required as part of the operational optical calibration of a system, so having this kit in place also allows our operators to dynamically evaluate current settings versus the measured (and targeted) radiometric goals of the system.

Figure 2:
Electrical Calibration Kit

New lamps are "pre-aged" and radiometrically screened to alleviate stability or infant mortality issues. Installing new lamps ensures that we will have a minimum chance of problems with the lamps after imparting a new calibration. Monitor detectors must also be inspected for stability if they are part of the system. Most settings of the monitor detector's electrical signal will be tied back to the absolute radiometric optical values (example: detector current vs. luminance), but it is important that the ammeter connected to the detector be checked for relative or absolute linearity and stability.

3.0 DEVELOPING A BASELINE CALIBRATION UNCERTAINTY:

The spectroradiometer spectral radiance responsivity calibration is performed in Labsphere's radiometric laboratories prior to performing the spectral radiance measurement field service. The uncertainty of the instrument calibration in the lab is expanded to determine the uncertainty of the measurements in the field. The uncertainty of the target radiance is defined in Equation 2:

$$L_e = \frac{\beta \rho_{45} E_{e0} \left(\frac{I_e}{I_{e0}} \right)^{M_I} (1 - \alpha \Delta t) 50^2}{\pi \sqrt{D^2 - x^2 - z^2}}$$

Where
β is angular dependency of the target reflectance factor
ρ is the Spectralon target spectral reflectance factor
E is the Spectral irradiance of the FEL reference standard
I is the FEL operating current
M is FEL irradiance relationship factor
(1 - αΔt) is the FEL tungsten halogen lamp aging factor
D is the calibration distance of the FEL
x is the lateral tilting offset of the distance measurement, and
z is the offset of the between the target and the center and the reference plane of the target

Equation 2: Expression of FEL-Target Uncertainty

Applied, the irradiated target spectral radiance expanded relative uncertainty in coverage factor k=2 is presented in Table 1. The values in Table 1 are used to determine the uncertainty of the field spectrometer responsivity calibration which in turn is used to determine the expended relative uncertainty of the on-site spectral radiance measurements in Section 4.0. Estimated uncertainties are available upon request.

Wavelength (nm)	Spectral Radiance Expanded Relative Uncertainty (k=2)
350	2.3%
450	2.0%
555	1.9%
654.6	1.8%
900	1.9%
1600	2.0%
2000	2.1%
2300	1.9%
2400	2.2%

Table 1:
Actual Uncertainty of FEL-Target Radiance

4.0 DEVELOPING A "REAL-TIME"CALIBRATION UNCERTAINTY:

In the previous section we outlined a laboratory-level calibration apparatus with very good levels of uncertainty. In a field situation, we have to establish the uncertainty of the measurement including the spectral radiometer and the given situation for measurement of the system to be calibrated. This expression is given in Equation 3:

$$L_{DUT} = \frac{S_{DUT} L_{ref}}{S_{ref}} = \frac{S_{DUT}}{S_{ref}} * \frac{\beta R_{45} E_{e0} \left(\frac{I_e}{I_{e0}} \right)^{M_I} (1 - \alpha \Delta t) * 50^2}{\pi * (\sqrt{D^2 - x^2} - z)^2}$$

Equation 3:
Expression of Radiance Uncertainty for Radiometric Transfer with Spectral Radiometer

As with any measurement, signal to noise ratio of the spectrometer values was a real concern and significant contributor to the total k-2 uncertainty. Two tables below are given to show the derivative effects of higher level (Table 2) and lower (Table 3) level radiance readings and corresponding effects on uncertainty of the reported spectral radiance.

Wavelength (nm)	Reference STD Expanded Relative Uncertainty (k=2)	Total Relative Uncertainty k=2 (%)
300	7.10%	10.03%
350	5.07%	5.40%
450	3.31%	3.44%
555	3.26%	3.90%
654.6	3.41%	3.70%
900	3.17%	3.60%
1600	3.45%	3.80%
2000	3.17%	3.61%
2300	5.73%	5.88%
2400	5.43%	5.91%

Table 2: High SNR Radiance Level Uncertainty Values 1.37e+1 mW/cm2-sr-um @ 0.6um

Wavelength (nm)	Reference STD Expanded Relative	Total Relative Uncertainty k=2 (%)
300	7.10%	41.27%
350	5.07%	14.94%
450	3.31%	2.71%
555	3.26%	2.95%
654.6	3.41%	3.34%
900	3.17%	2.57%
1600	3.45%	3.44%
2000	3.17%	3.63%
2300	5.73%	8.67%
2400	5.43%	17.30%

Table 3: Low SNR Radiance Level Uncertainty Values 3.92e-1 mW/cm2-sr-um @ 0.6um

There is an obvious direct relationship at the extreme wavelengths for low signals. This was expected and validates that the operator must use caution when calibrating a system in the field to make sure that the chosen transfer spectral radiometer and customer source must be above certain levels to ensure respectable values in calibration uncertainty. For the test case in this paper is was determined that values below 1.0 mW/cm2-sr-um @ 0.6um would be a recommended lowest level of calibrated spectral radiance. The system was now ready for real world testing, results and analysis of the developed process.

5.0 : CAMPAIGN RESULTS

5.1 INITIAL CAMPAIGN – FRANCE

Our first customer campaign was to validate spectral radiance of a uniform source that had arrived with some initial damage and to make sure that original calibrations were within tolerance. The system with calibrated with our station from Section 2.1 and sent out with a spreadsheet containing our uncertainty system of Section 3. A picture of the optical calibration kit is below in Figure 3. Packaging was in foam padded pelican case to minimize physical shock to the test devices. Since this first project was a validation of the optical values and the electrical components in the system had not sustained any damage, the electrical kit was not needed for this first effort.

Figure 3:
OCS Kit – Radiometer, Optics, Stages, Alignment Kit

Shipment of the system was from our headquarters in New Hampshire and the kit arrived at the customer site with no incident. Optical test results validated that the customer's system was still within the original calibration uncertainty. The optical kit was returned to our headquarters.

Our next task was to ensure that the spectral radiometer successfully maintained calibration during it trans-Atlantic travel. During the inbound shipment, the fiber optic cable on the spectral radiometer sustained minor damage.

The in-bound inspection was conducted using the aforementioned measurement techniques of the original FEL-Target. The in-bound results did indicate that something had changed on the receipt back at Labsphere.

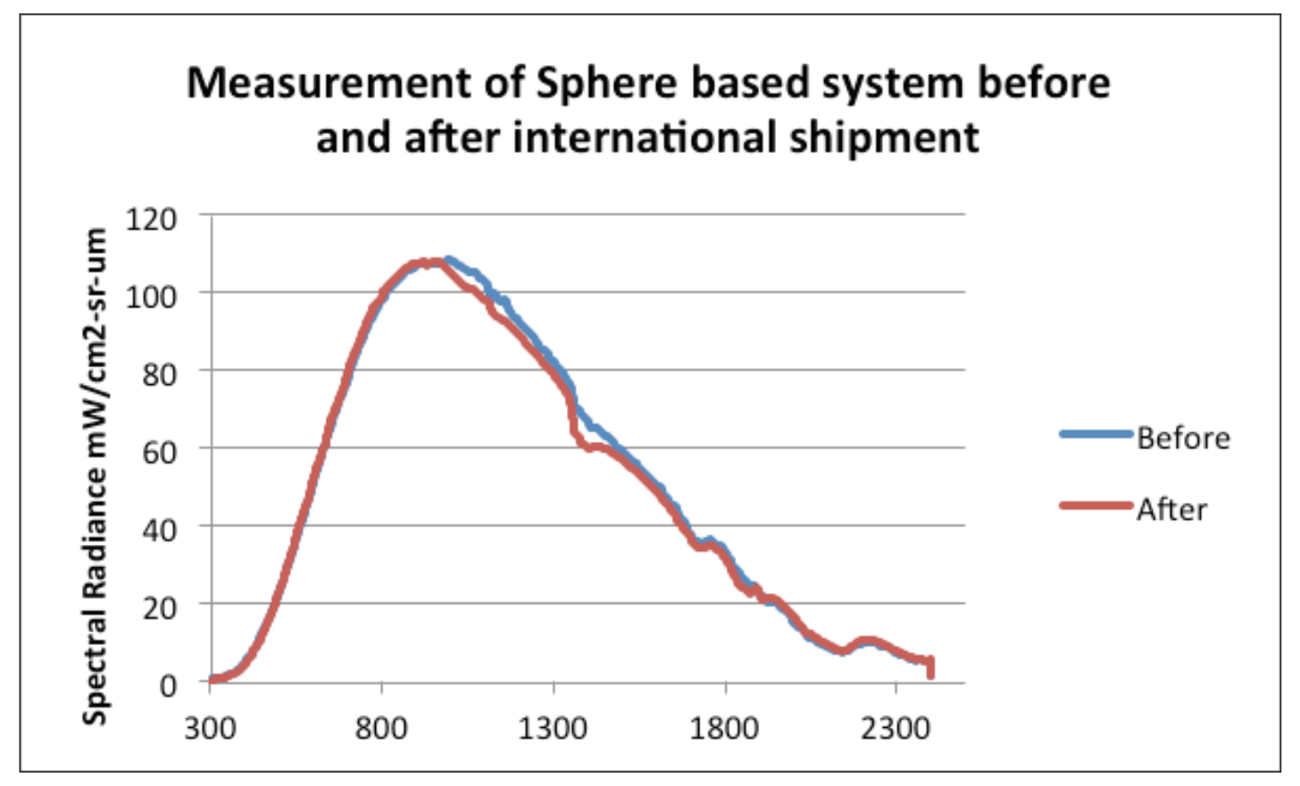


Figure 4:
In-bound Calibration Comparison Results from French Project

Baselines and the changed condition were confirmed with a monochromator scan. This result raised a new aspect of the project – despite the obvious culprit of the damaged fiber, how sure were we that the change had not happened in the first transit? How should we validate the condition of the instrument at arrival at the customer site? A portable validation system was needed to instill confidence that the system arrived in a calibrated state and, in the event of a mishap, that a re-calibration could be conducted at the customer site. This system could also be used to ensure customer confidence and give us a second line of assurance that our deployed assets (people, time and instrument) were not wasted due to logistic inevitabilities.

5.2 DEVELOPMENT OF AN OPTICAL VALIDATION KIT (OVK)

Discussion ensued on the proper type of portable validation system to send with the spectral radiance calibration kit. The FEL-Target constructed in the lab was deemed to be a good baseline system but its portability was questioned. A second suggestion of small sphere "Golden" standard system with monitor detector was proposed as an alternate to the FEL-Target. Labsphere had used such systems in past to send to customers as a secondary validation. This sphere is compact, robust, simple to operate (set lamp current and validate monitor detector current reading) with a good track record from our optical metrology team.

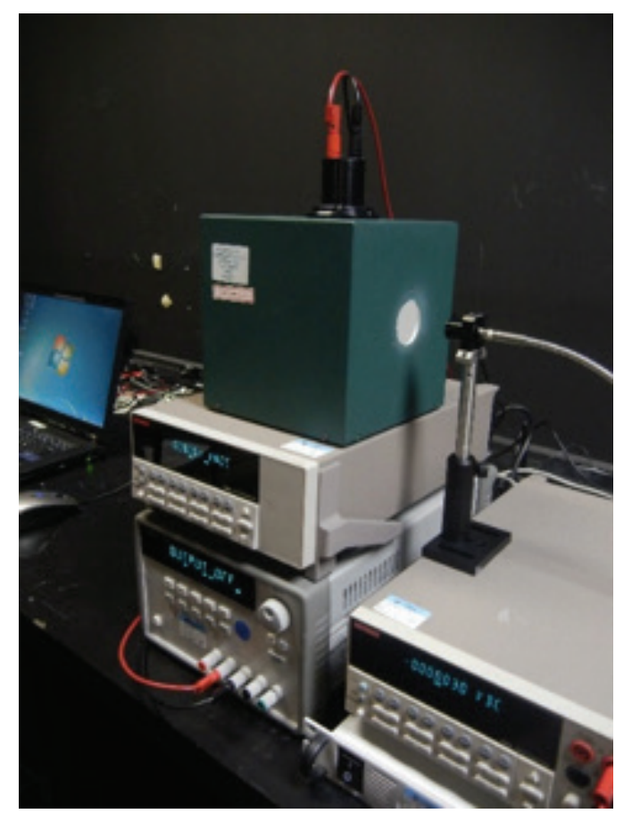


Figure 5:
"Golden Standard" Calibrated Sphere System

Objections to the sphere-based method were that it could be possibly unstable due to dust or other ambient contaminants during transit and that the M-factor of the sphere multiple-reflection integration effects might result in possible problems (vs. first surface of the target). Disassembly and reassembly of FEL-Target (and alignment), past success with the sphere method and possible uncontrolled conditions at the customer site ultimately deemed the sphere method to be the best choice for a secondary, portable validation system. The uncertainty method model from Section 3 was also updated for the new sphere-based OVK uncertainty values.

5.3 SECOND CUSTOMER CAMPAIGN

The next site was a domestic customer validation of a system with over a year of continuous use. The OCS of Section 2.1, the EVK of Section 2.2 and the new OVK of Section 5.2 were necessary items for this effort. The original lamps in the system would also need to be replaced with screened and seasoned lamps of similar make and model. The OCS and OVK were both calibrated for spectral radiance with our double monochromator and master FEL-Target system, packaged and sent to the customer site.

The first task at the customer site was to validate the existing customer system power supplies for proper current tolerances. We then set up our optical validation system with the optical calibration kit to verify the "as-received" instrument. We did observe small changes (~2%) in the "as-received" OCS using the sphere validation technique, and it was decided to re-baseline the OCS with the OVK at the customer site before performing the customer's system calibration. Lamps were replaced in the customer's original system and optical calibration was completed. Calibration certificates per Table were issued to the customer after a short interlude to validate the data and the uncertainty model. The customer was satisfied with the process and results of the at-site calibration.

Wavelength (nm)	Reference STD Expended Relative Uncertainty (k=2)	Total Relative Uncertainty k=2 (%)
300	7.1%	10.3%
350	5.1%	5.3%
450	3.3%	3.3%
555	3.3%	3.3%
654.6	3.4%	3.4%
900	3.2%	3.2%
1600	3.5%	3.5%
2000	3.2%	3.5%
2300	5.7%	6.2%
2400	5.4%	5.6%

Table 4:
Completed "Real-Time" At-Site Customer System Calibration Uncertainty

6.0 POST-MORTEM ON IN-BOUND OCS AND OVK

Labsphere decided to do a thorough in-bound assessment upon the return of the OCS and OVK to our headquarters. The returning optical units were to be validated against our original FEL-Target values and double monochromator. The results yielded several results which show we still have some development to do on the OVS and OVK as well as the FEL-Target. First we noticed an offset and spectral dependency in the original FEL-Target set-up of about 2-4% as noted in Figure 6.

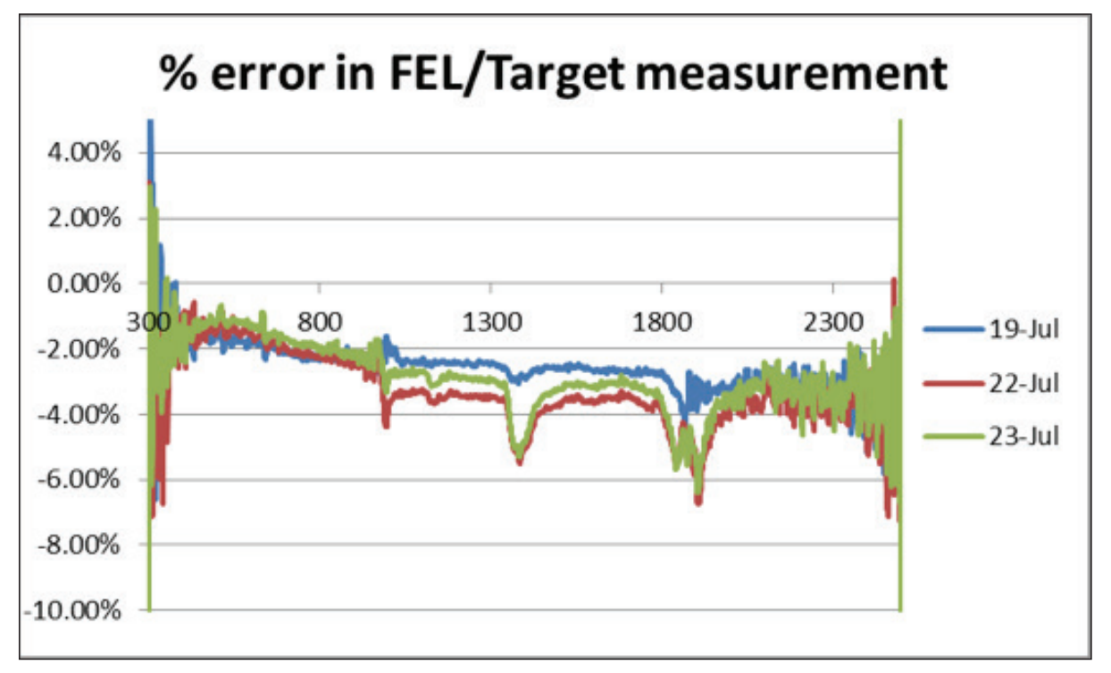


Figure 6:
Offset in FEL-Target Baseline

The spectral dependency is still under investigation as of the time of the publication of this paper, but the FEL-Target offset was determined to be due to the fact that a disassembly of the FEL-Target station had occurred by Labsphere laboratory staff. This result, while not intended, validated our concern that the FEL-Target disassembly error was substantial and that the sphere method may have been a better choice in our OVK.

Validation of the OVK was much closer match to expectations as shown in Figure 7, although spectral dependency and features are again lingering sources of investigation at the time of publication. These results, with exception of the spectral features are in line with our expressed uncertainty of the OCS in Table 4.

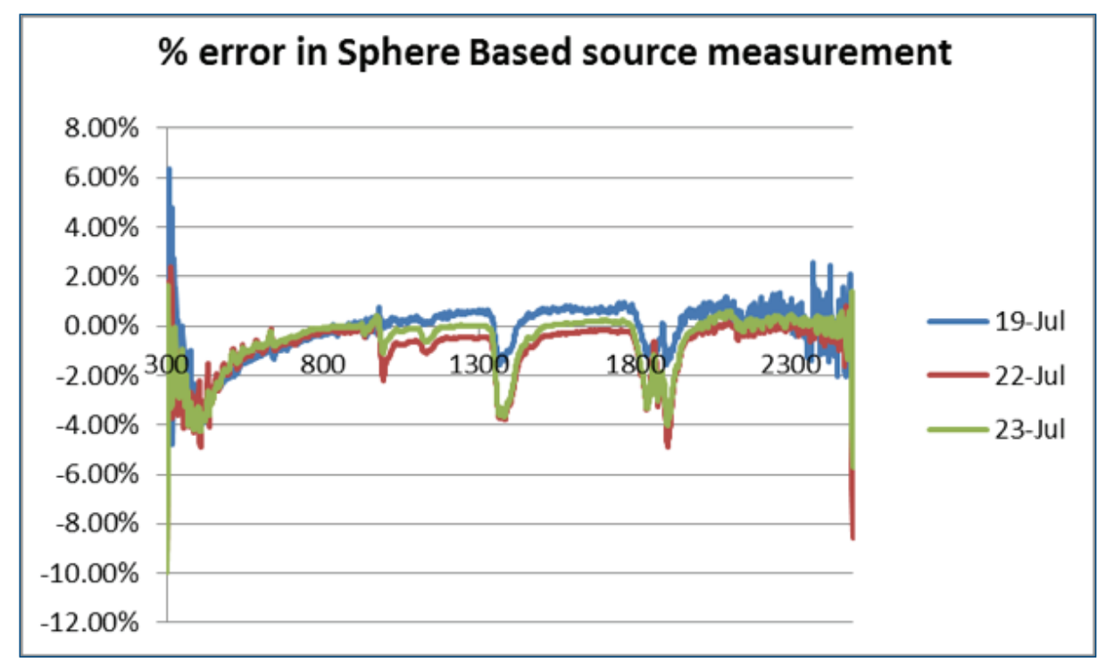


Figure 7:
OVK Uncertainty Results

More disturbing was a discovery that we had an additional potential problem with the dark back-ground offset of the FEL-Target measurement with the monochromator. Moving the FEL-Target between the OCS and the monochromator resulted in different ambient scalar contributions on the order of about 7-8% shown respectively in Figure 8 and Figure 9. This offset showed up in our sphere and FEL-Target incoming results. Further development on a static and shielded master system is necessary to eliminate this problem.

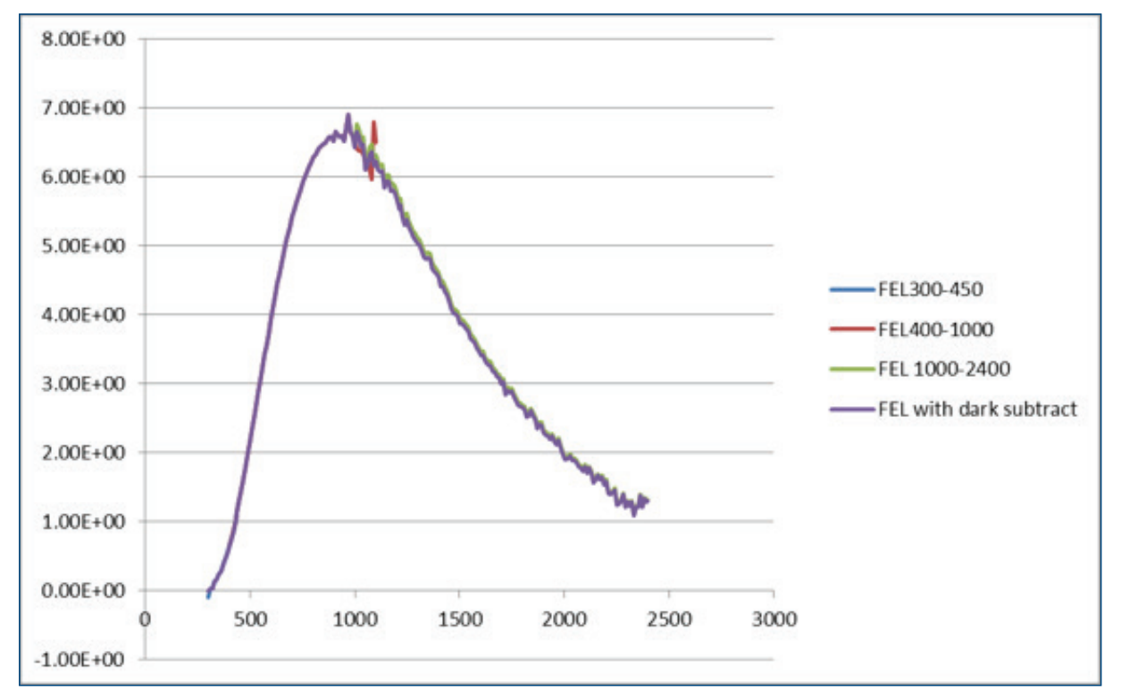


Figure 8:
FEL-Target Offset due to Dark Conditions

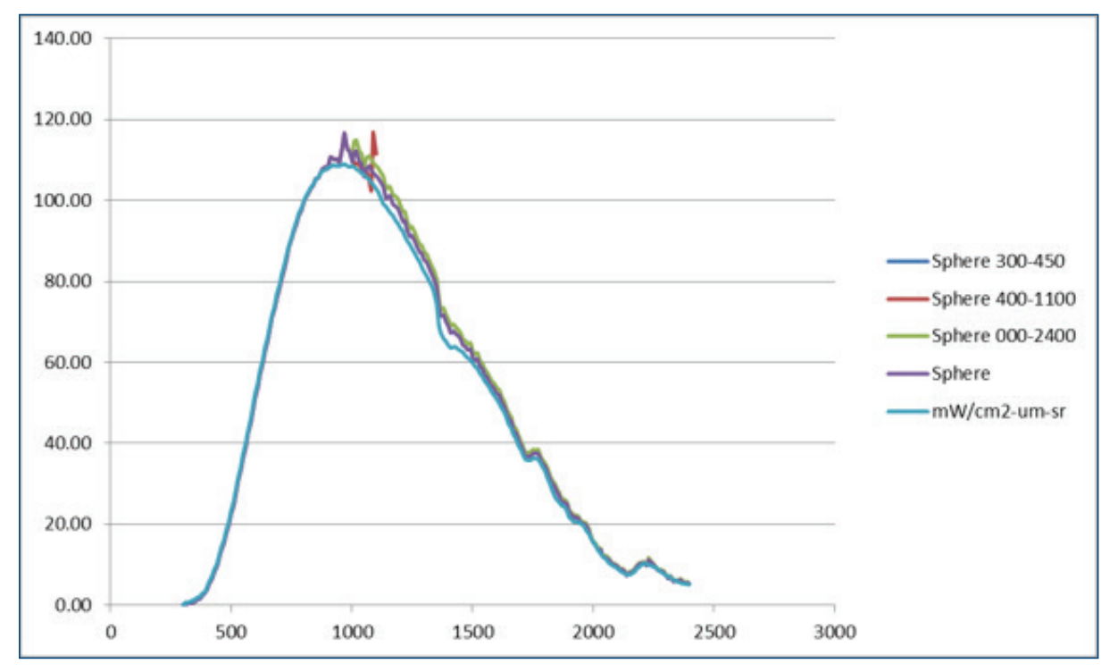
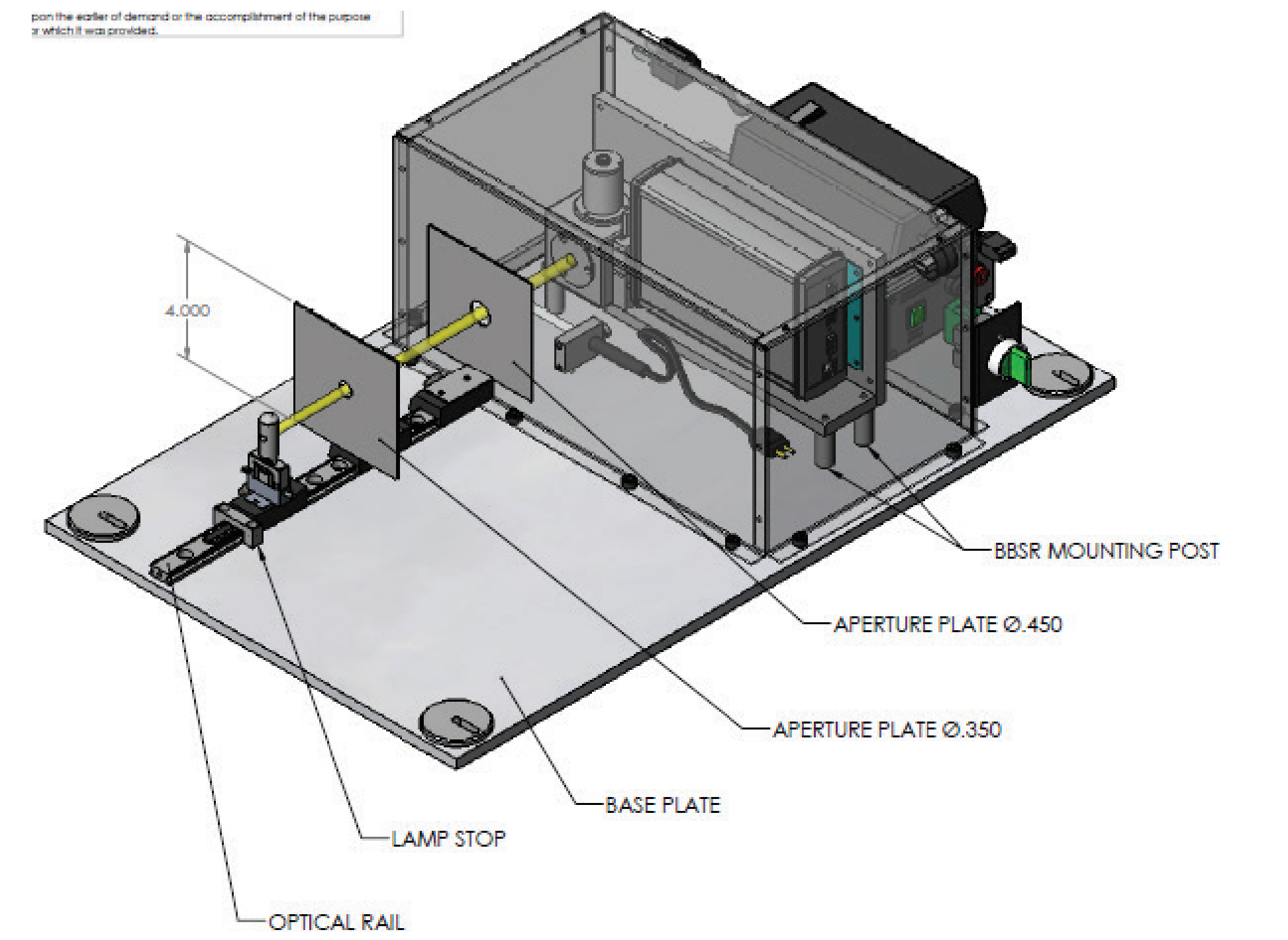


Figure 9:
Sphere OVK Offset due to Dark Conditions

One possible solution to alleviate this is a system previously developed for a customer as an on-site calibration static bench. This system outlined in Figure 10 includes optical shielding and rigid alignment jig which should help with the potential dark offset issues and may be a better master in-house and on-site system to lower our uncertainty.



6.0 CONCLUSIONS & ADDITIONAL DEVELOPMENT ITEMS

The OCS, OVK and EVK portable calibration system currently delivers an uncertainty of <3.5% for 0.45-2.0um spectral range which is above our targeted range of <2.5%. For UV and SWIR ranges we are fighting SNR and stability issues that lead to >5% uncertainty. We solved problems with shipment stability and at-site validation of the optical calibration. We have noted continuing investigation issues with spectral dependency, instrument stability, set-up variability and spectral features. TE-cooling on the Si channel of the spectral radiometer has also been suggested by the instrument manufacturer as a way to control some of the variability. Stray-light reduction techniques were not applied to the spectral radiometer and this will also assist blue band uncertainties when we can accomplish this testing. The sphere-based OVK appears to be a valid method to double check our calibration when at campaign sites. For future efforts, it has been determined that a better solution in a static FEL bench may be lead to lower uncertainty values.

7.0 REFERENCE CITATIONS

Barry N. Taylor and Chris E. Kuyatt (1994). Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results. NIST Technical Note 1297.