Radiometric Metrology for Ocean Color

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Topics

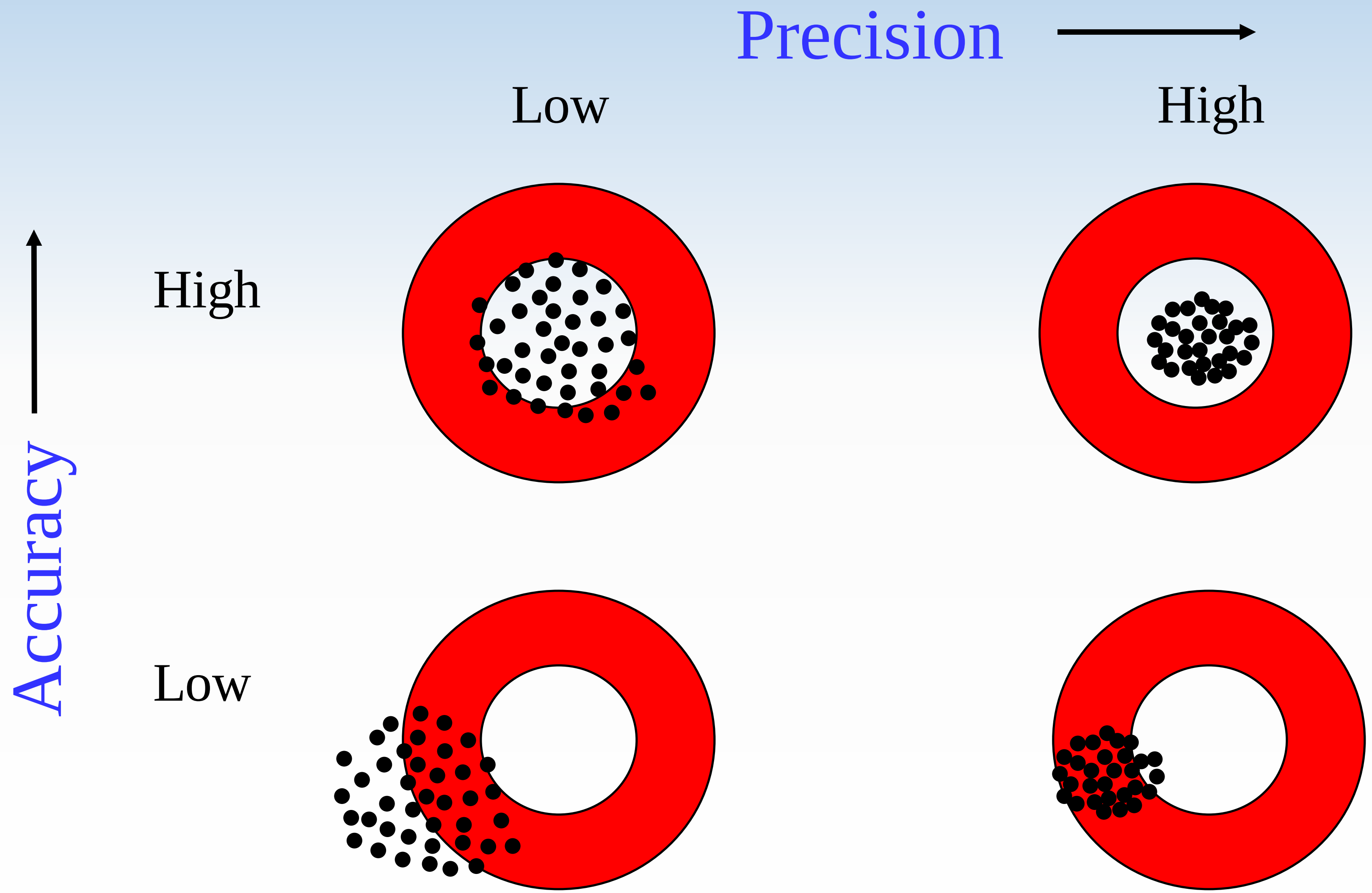
- Uncertainty Terminology (and Philosophy)
- A Word on Comparisons
- Lamp/Plaque Uncertainty Budget
- A Word on Vicarious Calibration

Results and Uncertainties are Data Products

- Traceability: "property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty." (International Vocabulary of Metrology - Basic and General concepts and Associated Terms (VIM), definition 2.41 http://www.bipm.org/en/publications/guides/vim.html

- Uncertainty: Quantitative, not qualitative; thus recommendations on, and introduction of, usage of terms (error, true value, Type A, Type B, bias, systematic, random, precision, accuracy, reproducibility, repeatability, …) see the VIM and the Guide to the Expression of Uncertainty in Measurement (GUM), http://www.bipm.org/en/publications/guides/gum.html

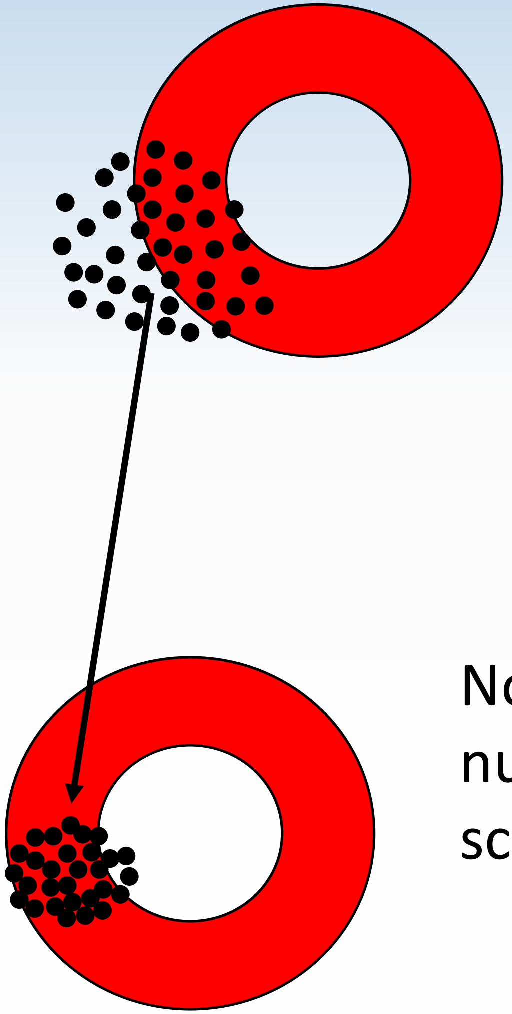
Terminology Example



Precision

Measurement Precision

"closeness of agreement between **indications** or **measured quantity values** obtained by replicate **measurements** on the same or similar objects under specified conditions", VIM 2.15

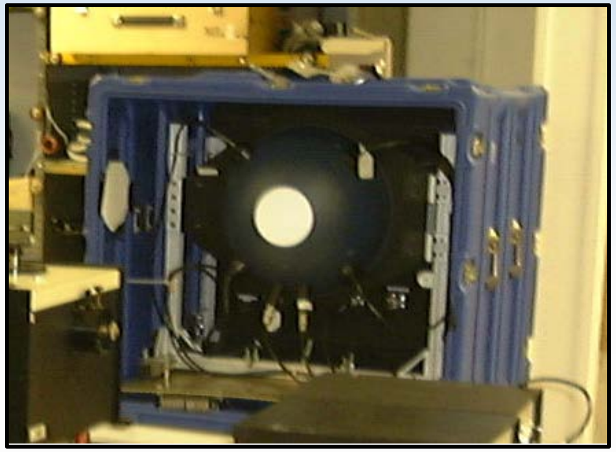


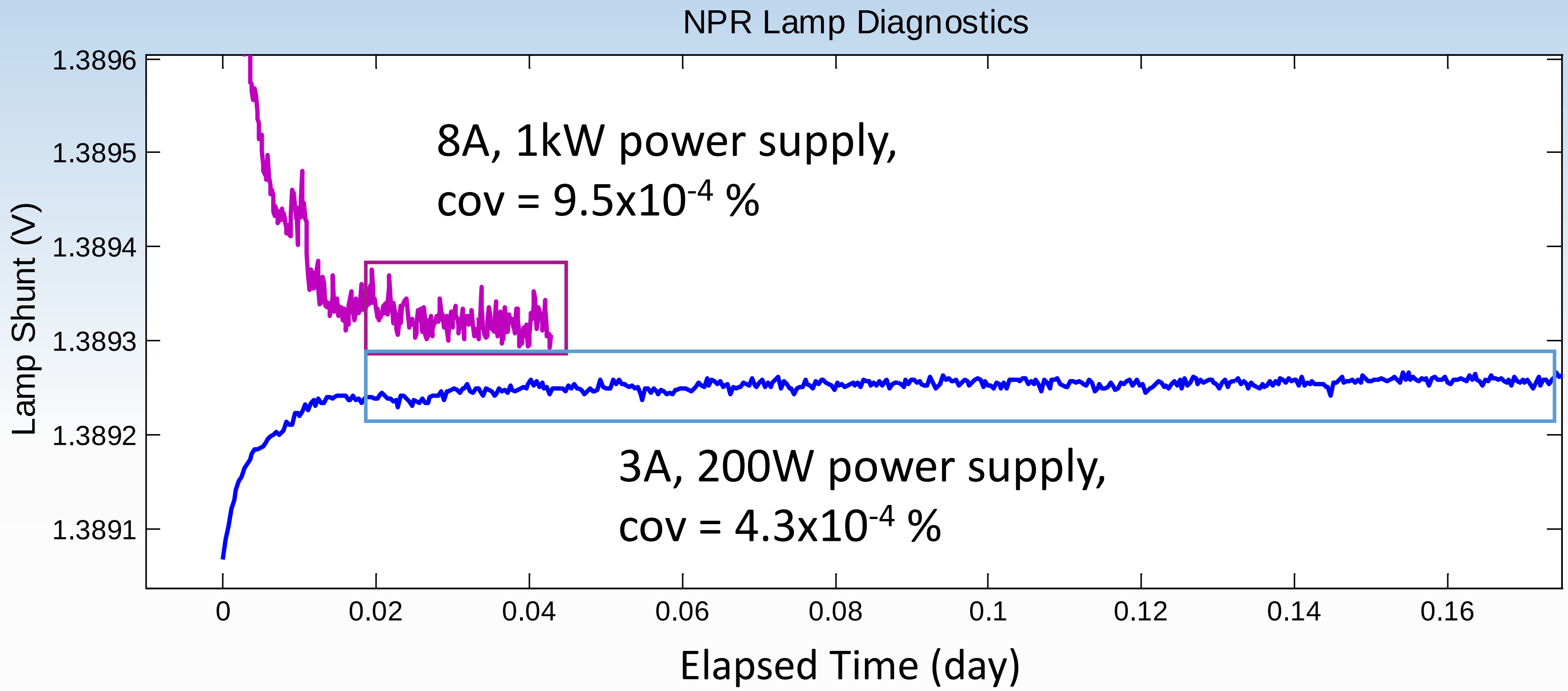
Archers learn to consistently have a tight pattern by training their bodies and gaining experience with influencing factors

Note: Archers can describe precision numerically, but also on a fit for purpose scale (e.g., defined target areas)

Precision

NPR source: Four 3A, 10W lamps in series



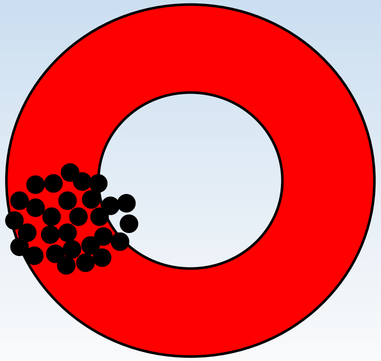


Metrologists specify equipment suited to the task and learn to minimize environmental influences

Note: Metrologists express this concept numerically, typically stated in terms of imprecision (e.g., cov = std/mean).

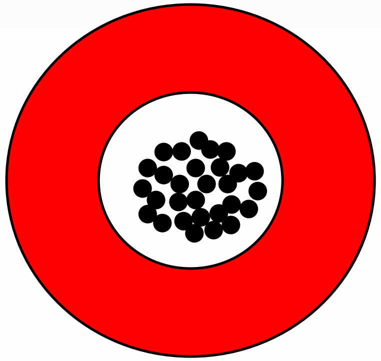
Accuracy

Measurement Accuracy
“closeness of agreement between a **measured quantity value** and a **true quantity value** of a **Measurand”**, VIM 2.13.

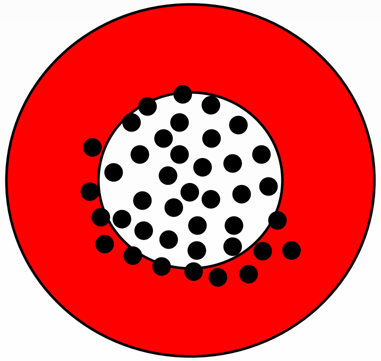


Once a good pattern is achieved, archers sight in the bow. They do this at different distances and under different environmental conditions in a continual process of training and calibration.

Calibration of bow/archer system



18.3 m (20 yds)



91.4 m (100 yds)

Archery is *not* for shoulder height measurements!

~~Accuracy~~ Uncertainty

Accuracy is a qualitative concept – in measurements, we don't know the true value. Numerical values cannot be assigned to "accuracy".

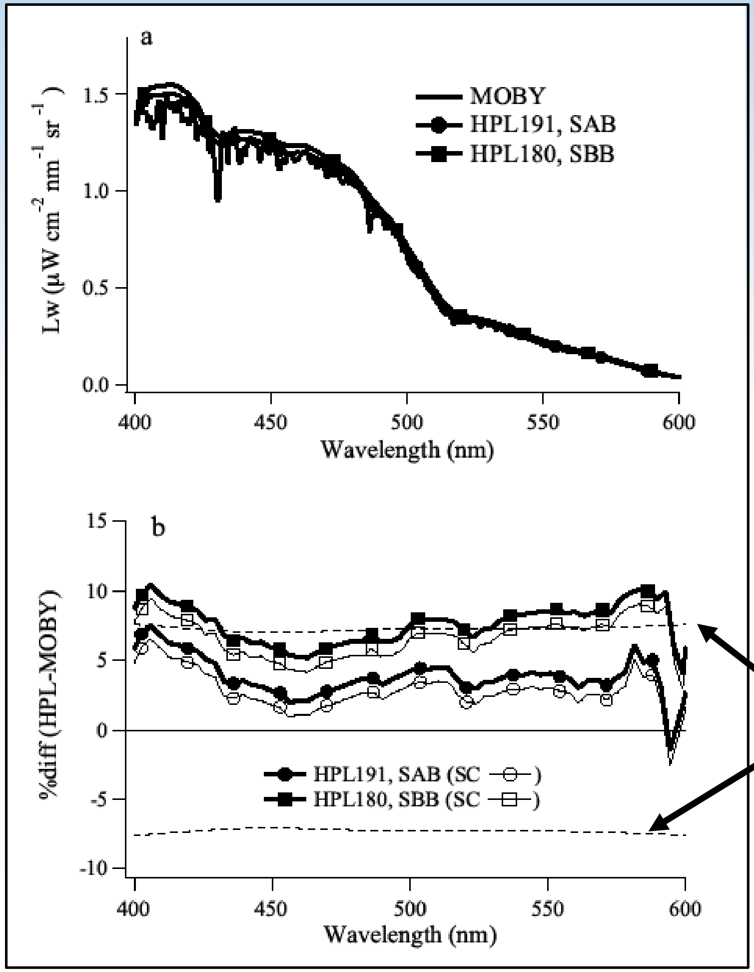
Measurements produce values for properties (the measurand) and comparison to a reference (calibration) gives meaningful physical results

Measurement Uncertainty is a "parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand" (GUM); a "non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used" (VIM).

Comparisons cannot be interpreted without first evaluating uncertainties

Comparison Example

SORTIE = Spectral Ocean Radiance Transfer Investigation Experiment

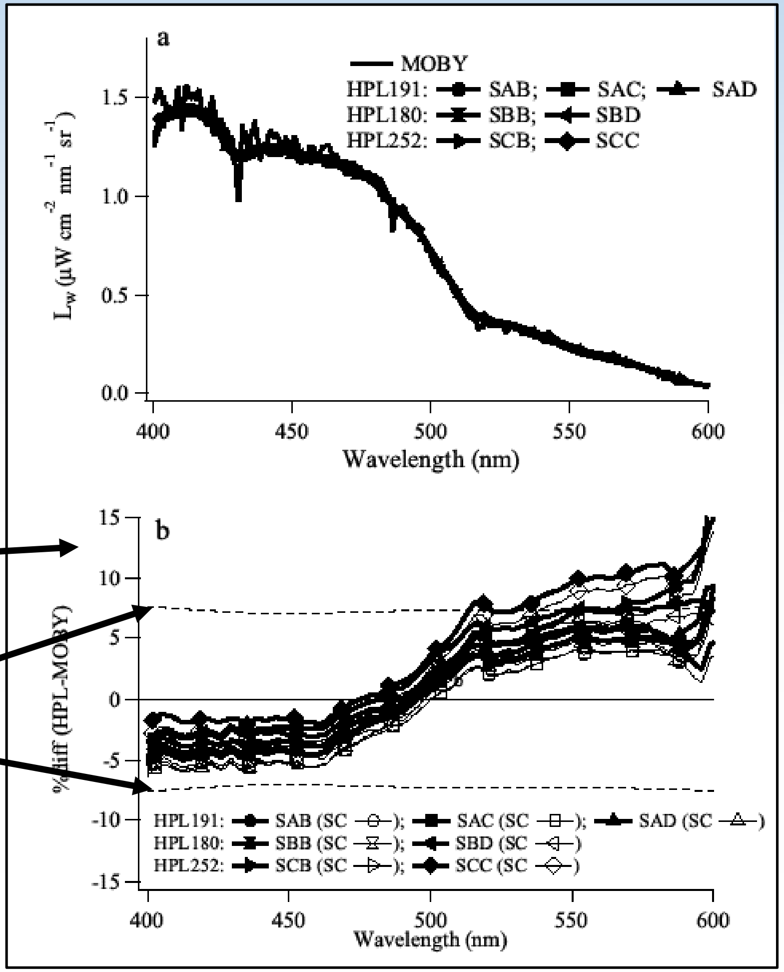


Calibrated hyperspectral radiometer in-water L_w comparison – MOBY and HPL HyperPRO II's (SORTIE).

$$y = 200\frac{HPL - MOBY}{HPL + MOBY}, \%$$

k = 2 uncertainties, %

Uncertainty ≠ difference in comparison results

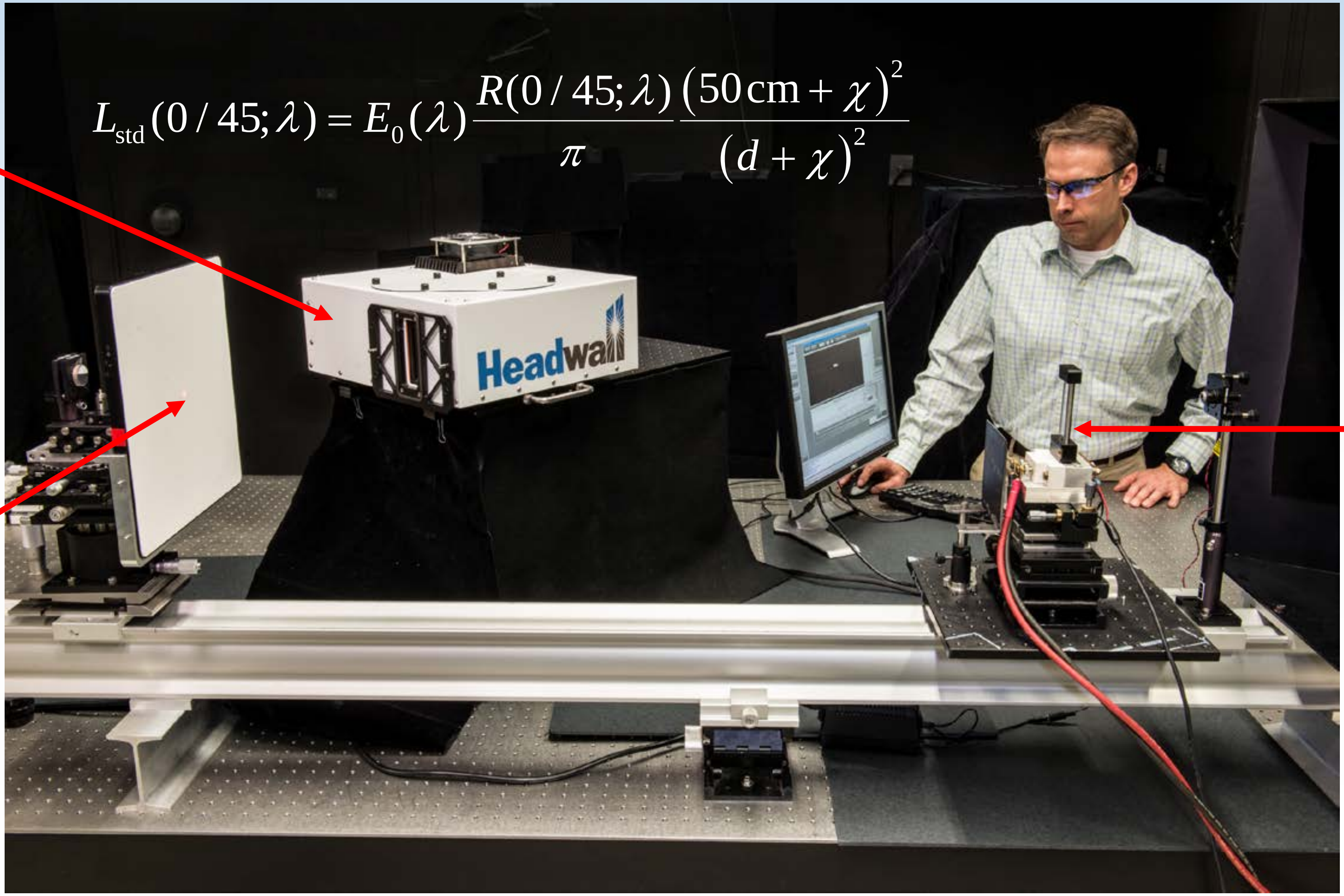


Voss et al., "An example crossover experiment for testing new vicarious calibration techniques for satellite ocean color radiometry," J. Atmos. Oceanic Technol. 21, 1059 – 1073 (2010).

Work through an example – lamp / plaque

Device Under Test (DUT)

Spectrally flat, diffuse reflectance target



Alignment jig for the Standard Lamp of spectral irradiance

Measurement Equation

$$L_{\text{std}}(0/45;\lambda) = E_0(\lambda)\frac{R(0/45;\lambda)}{\pi}\frac{(50\,\text{cm}+\chi)^2}{(d+\chi)^2}$$

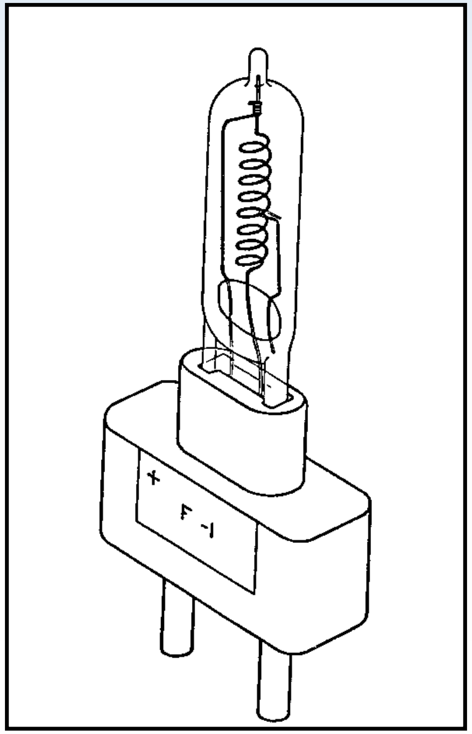
Allows for formal expression and evaluation of sensitivity coefficients

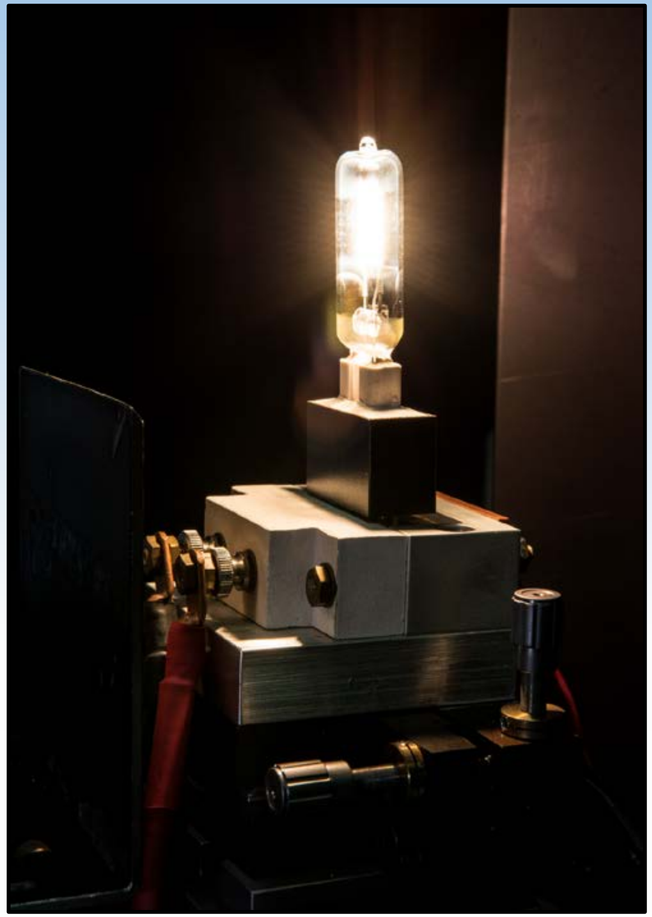
- L_{std} is spectral radiance of the illuminated reflectance standard (“plaque”)
- E_0 is the spectral irradiance of the FEL standard lamp at 50cm from the front of the bi-posts
- *R*(0/45) is the reflectance factor of the plaque (normal incidence, 45° view)
- *d* is the distance from the front of the plaque to the front of the bi-posts
- χ Is the displacement of the radiometric center of the lamp from the front of the bi-posts

Uncertainty Considerations (besides the obvious ones):
The lamp source behaves as an unpolarized point source
The plaque is Lambertian, uniform, and does not polarize radiant flux
The system is properly baffled for scattered radiant flux
d/*A* = 50; *A* = collection area in square centimeters
We can figure out χ and execute good alignment
All FEL lamps are similar

FEL Lamp Standards

- 1000 W output
- Coiled-coil structure
- Modified – bi-post base
- Calibrated by comparison to a high temperature blackbody
- 50 cm from front of post
- 1 cm^2 collecting area
- Selected and screened for undesirable features
- Operated at constant current, 8.2A





- Kinematic base
- Alignment jig
- Lamp voltage measured
- Front baffle placement
- Polarity matters

Example: $u(L_{std}(0/45;\lambda)$ in central 2.8 cm^2 area

At d = 140 cm, A = 2.8 cm^2 (r = 1.89 cm) for d/A = 50

k = 1 uncertainties in percent

Uncertainty Origin	Type	400 nm	500 nm	600 nm
FEL Calibration	B	0.545	0.422	0.367
Lamp Current	B	0.216	0.173	0.144
Stability	B	0.081	0.081	0.081
Plaque Calibration	B	0.500	0.500	0.500
Distance d	A	0.036	0.036	0.036
Offset χ	B	0.128	0.128	0.128
Scattered Light	B	0.318	0.318	0.318
RSS, k = 1		0.85	0.76	0.73
Expd, k = 2		1.70	1.53	1.46

FEL Calibration

Uncertainty is stated in the Calibration Report for the lamp

Uncertainty Origin	Type	400 nm	500 nm	600 nm
FEL Calibration	**B**	**0.545**	**0.422**	**0.367**
Lamp Current	B	0.216	0.173	0.144
Stability	B	0.081	0.081	0.081
Plaque Calibration	B	0.500	0.500	0.500
Distance *d*	A	0.036	0.036	0.036
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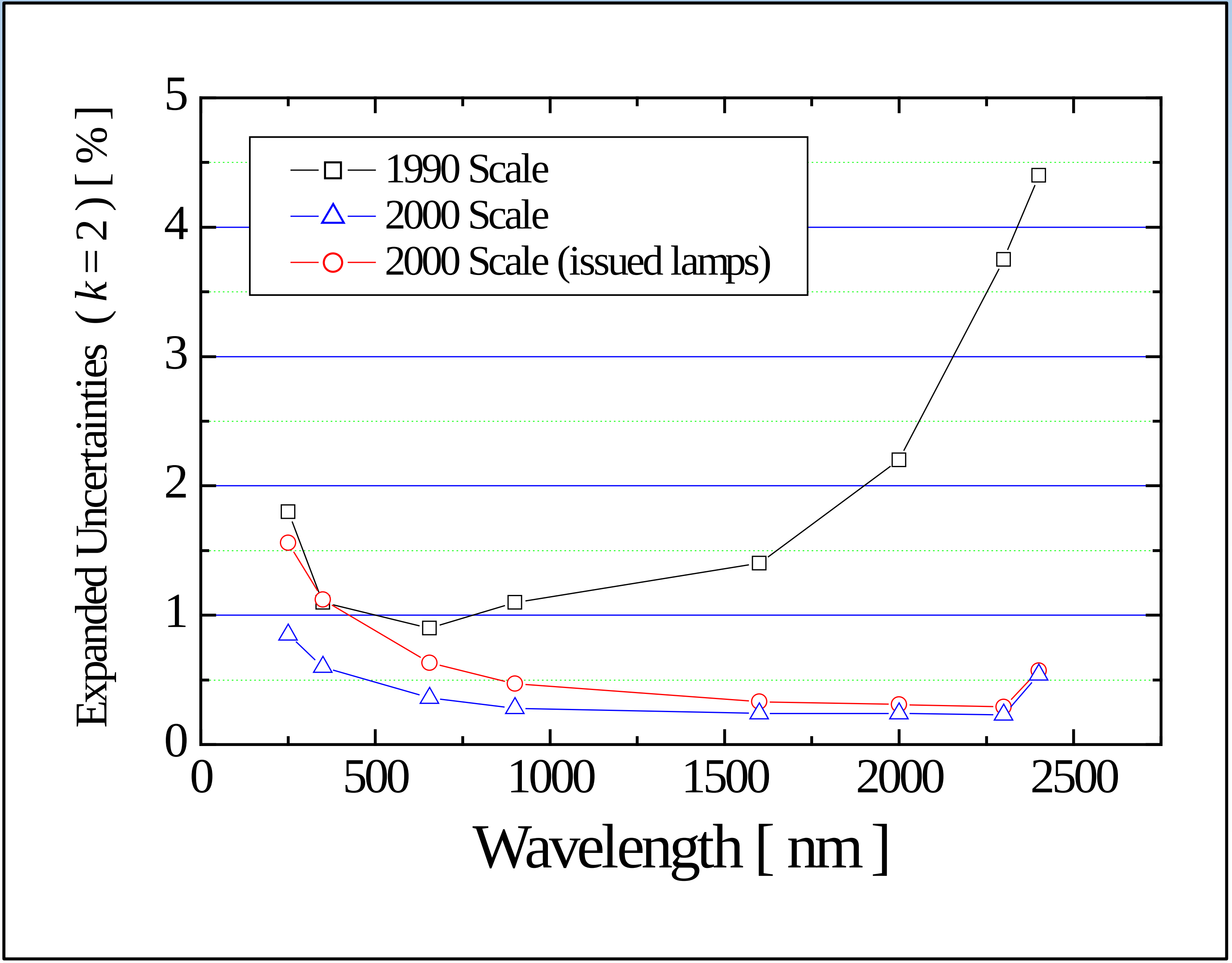
FEL Calibration



Lamp Current

The current uncertainty was estimated to be 2.2 mA in this example

Uncertainty Origin	Type	400 nm	500 nm	600 nm
FEL Calibration	B	0.545	0.422	0.367
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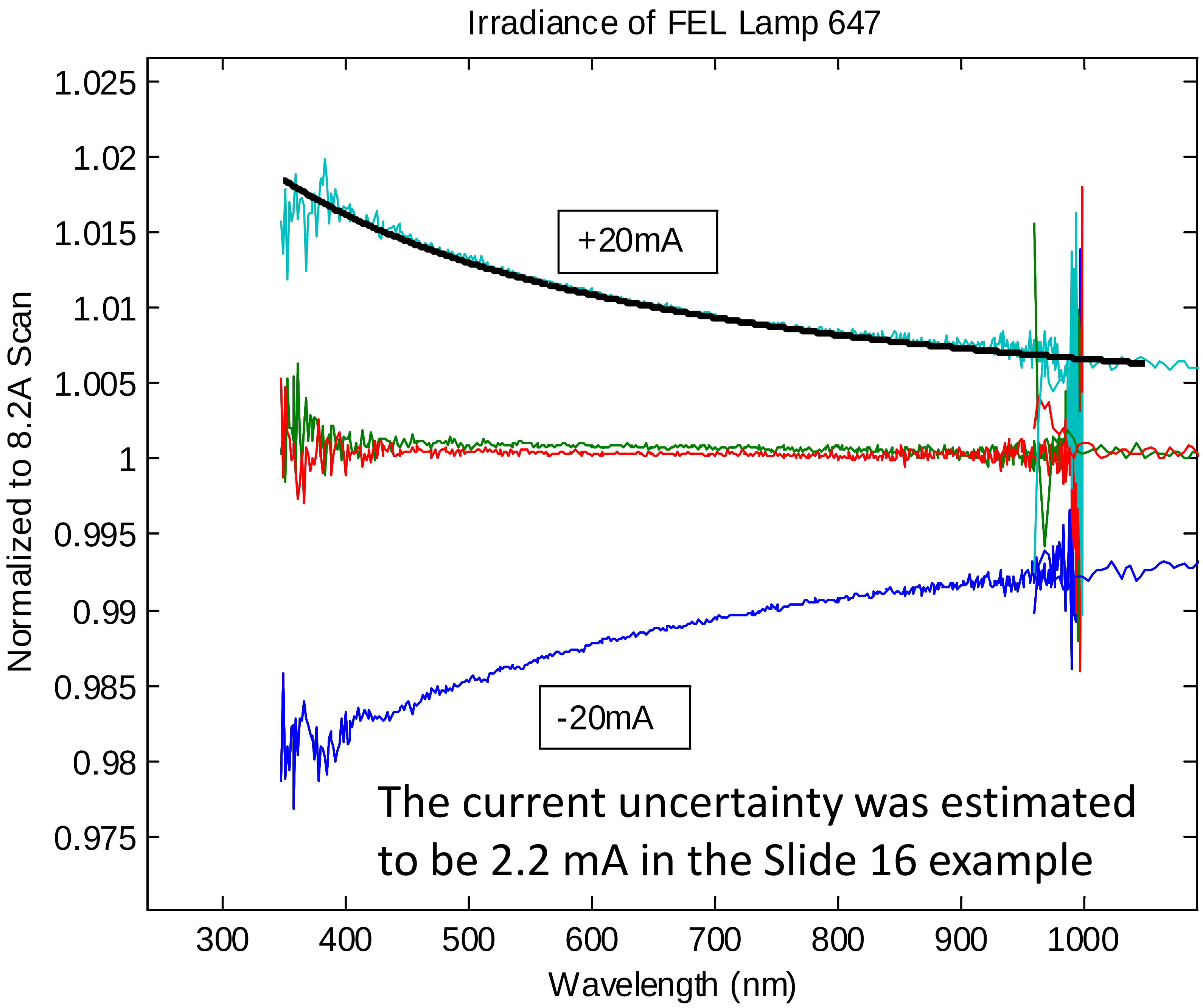


$$\frac{u(E_0)}{E_0} = \frac{654.6\text{ nm}}{\lambda}\frac{0.0006}{\text{mA}}u(I)$$

Early et al., *J Res NIST*, 1998

$$\frac{u(E_0)}{E_0} = \frac{654.6\text{ nm}}{\lambda}\frac{0.00049}{\text{mA}}u(I)$$

Fit to empirical data

Lamp Current

Offset χ for d = 140 cm

Uncertainty Origin1	Type	400 nm	500 nm	600 nm
FEL Calibration	B	0.545	0.422	0.367
Lamp Current	B	0.216	0.173	0.144
Stability	B	0.081	0.081	0.081
Plaque Calibration	B	0.500	0.500	0.500
Distance d	A	0.036	0.036	0.036
Offset χ	**B**	**0.128**	**0.128**	**0.128**
Scattered Light	B	0.318	0.318	0.318
RSS, k = 1		0.85	0.76	0.73
Expd, k = 2		1.70	1.53	1.46

The offset would be half the diameter of the bi-posts if the lamp filament coils were centered – so we expect χ = 3.175 mm.

Determine empirically: vary distance *d* (50 cm to 151 cm) for three lamps and measure irradiance (good cosine response; good control of scattered light), fit to $\frac{a}{(d+\chi)^2}$

Lamp	a (V cm^2)	χ (mm)
F-461	17321.62	1.8406
F-918	17045.37	2.1867
F-1051	17715.34	2.6652

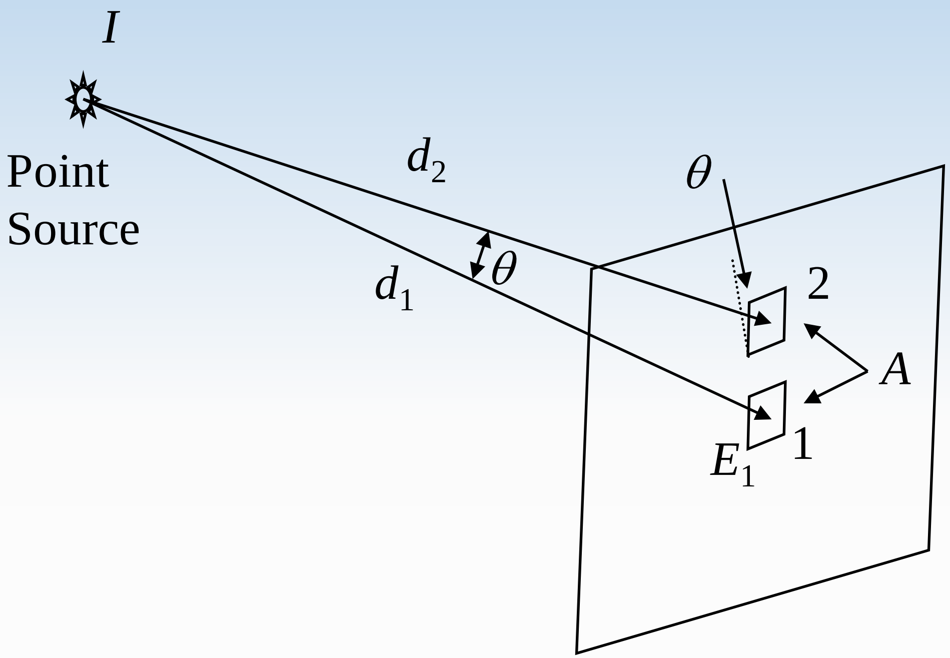
Yoon et al., Proc SPIE 8501 (2012)

The standard deviation of χ is 0.41 mm – we used 0.5 mm in the uncertainty budget

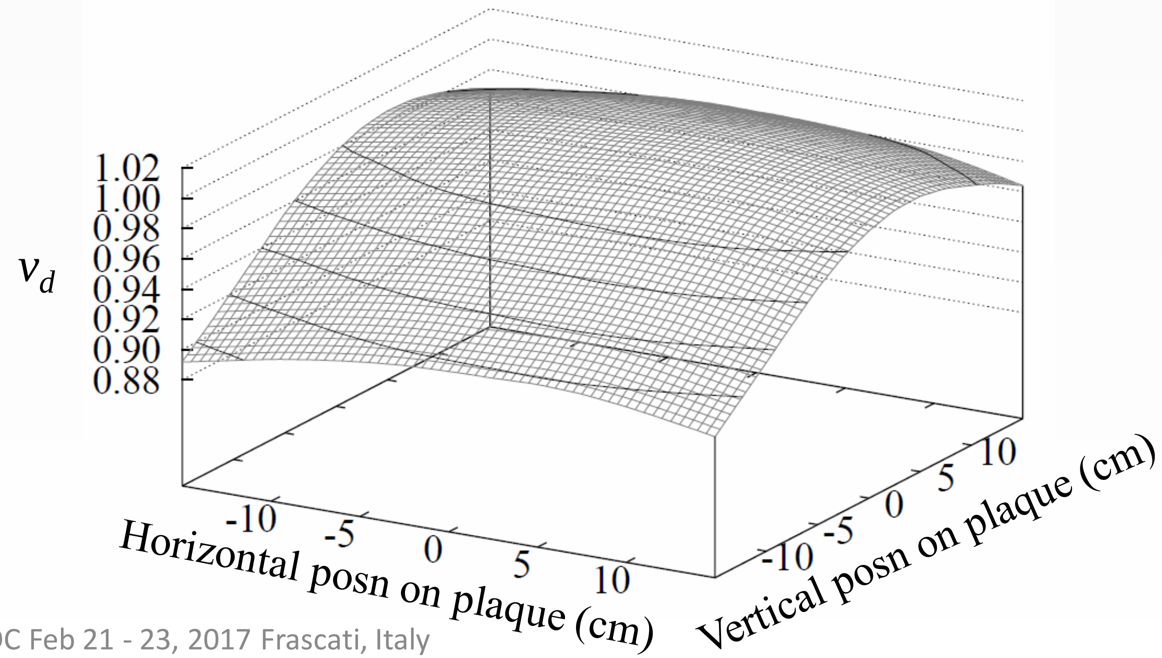
We use the GUM to find the sensitivity coefficient for χ: $\frac{\partial}{\partial\chi}\left(\frac{(50+\chi)^2}{(d+\chi)^2}\right)$

Off axis effects

The irradiance of a point source on a plane falls off as $\cos^3(\theta)$ – this is one reason we move the lamp to *d* > 50 cm for DUTs with large field-of-views. In addition, FEL lamps are not point sources.



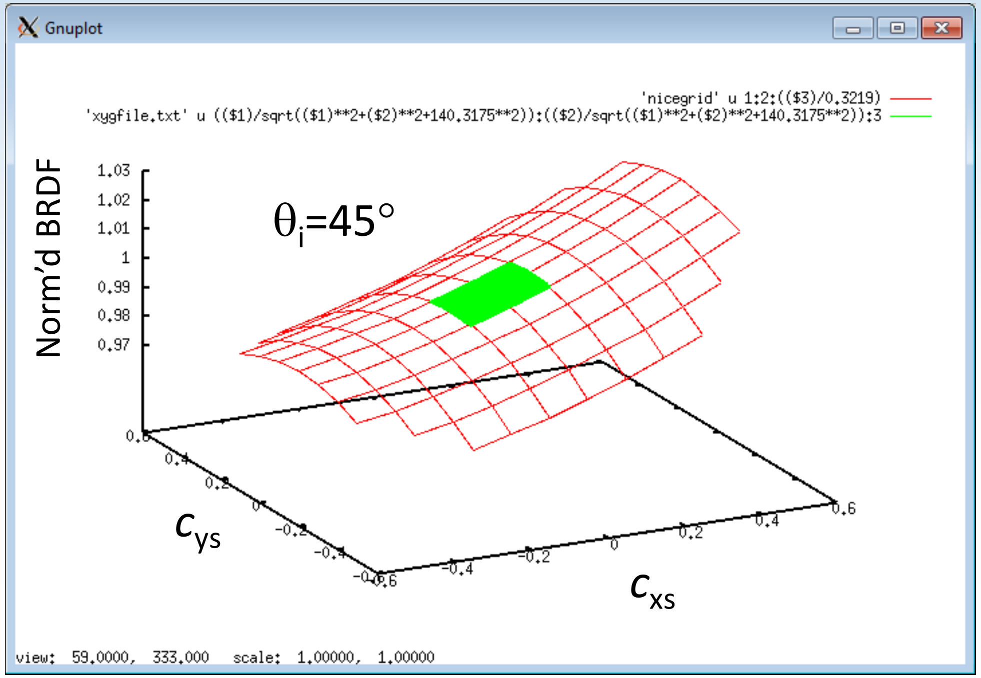
The measured intensity distribution for an FEL can be used to find correction factors $\nu_d(x,y)$

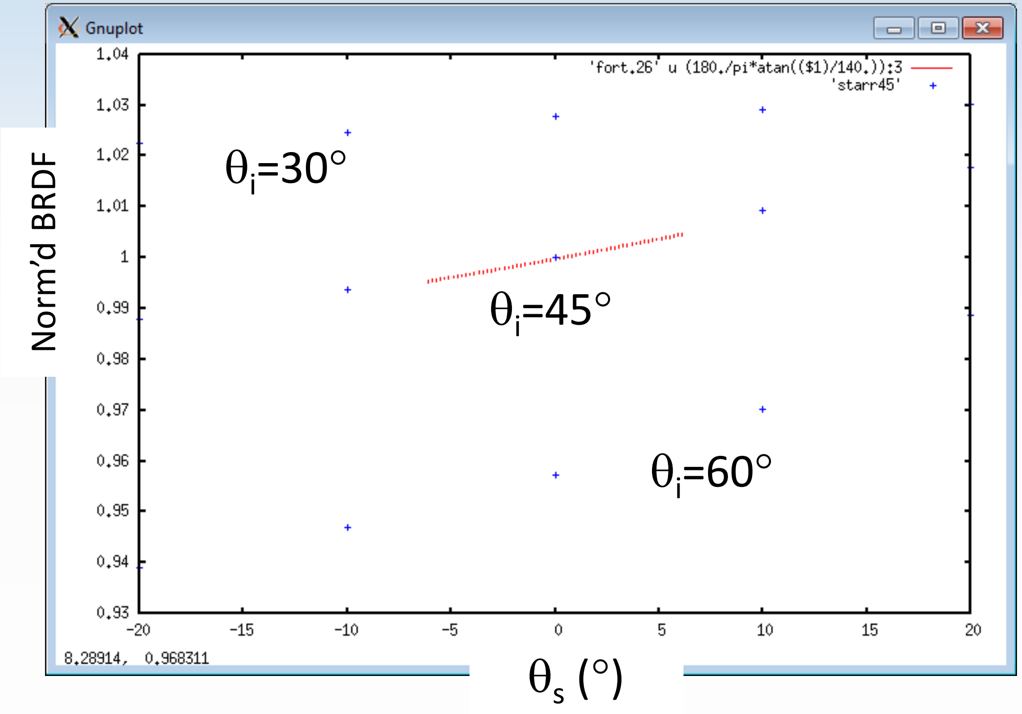


Example: Lamp F240 140 cm from a 30 cm square plaque

BRDF vs incident/view angles

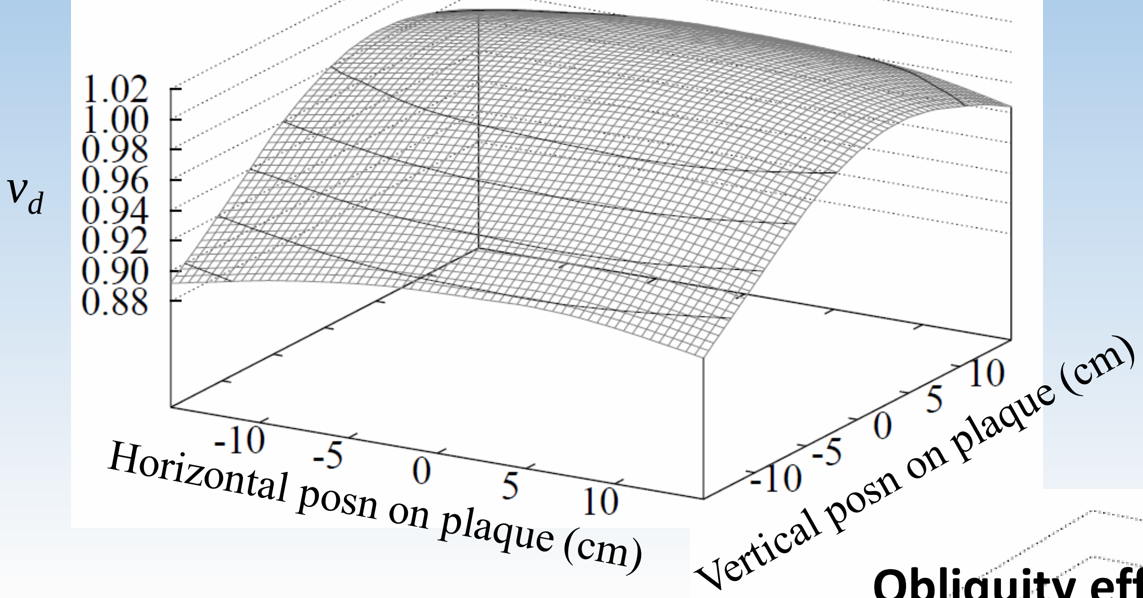
Ideal Lambertian reflectance targets do not exist

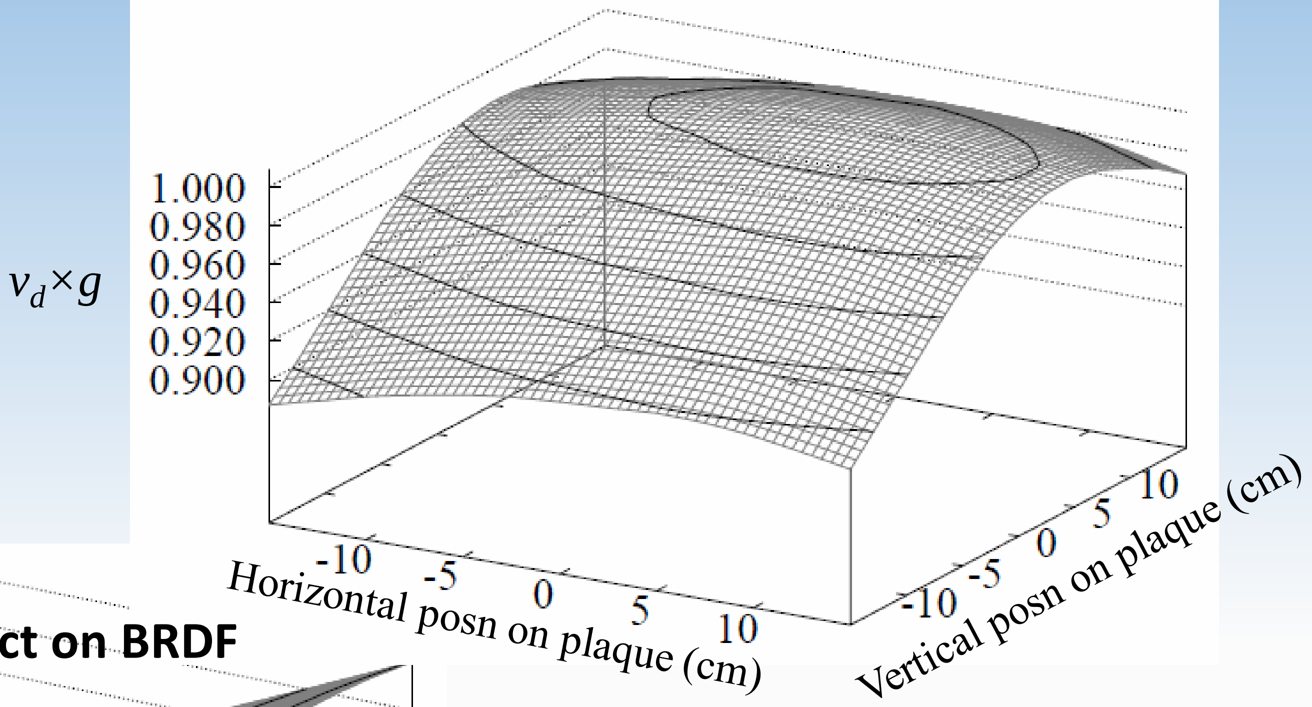




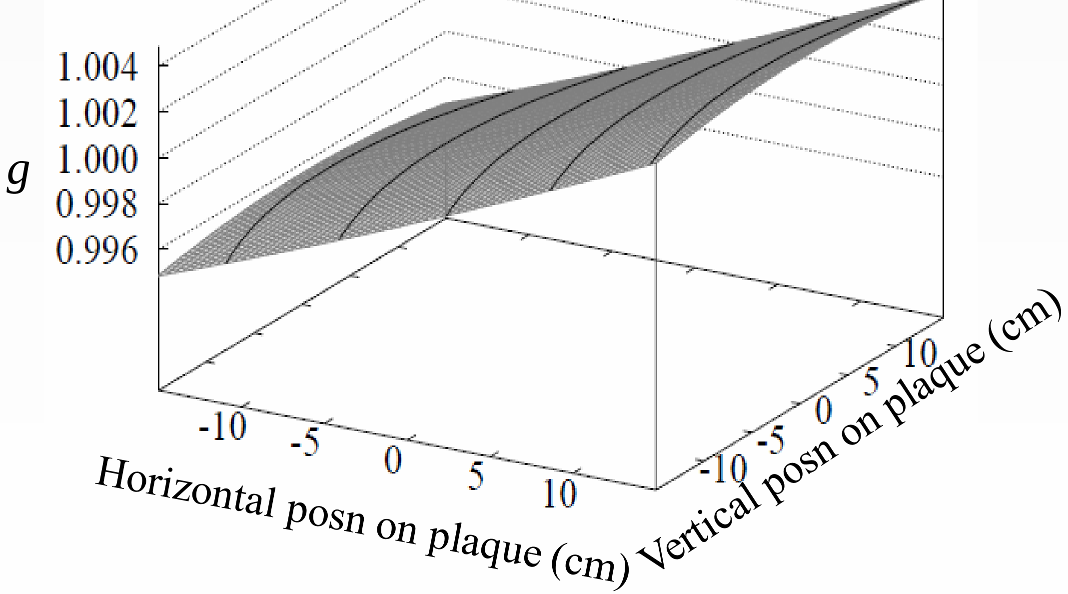
In- and out-of-plane measured BRDF for the plaque can be used to find correction factors $g(c_{xi}, c_{y1}, c_{xs}, c_{ys})$, which are a function of incident and view direction cosines *c*.

FEL / distance / obliquity effect on irradiance





Obliquity effect on BRDF



30 cm x 30 cm plaque
140 cm from FEL bi-post

0/45 radiances across the plaque are proportional to product

Plaque Uniformity and Polarization Effects

The plaque can be mapped spatially for variability in BRDF, and similar plaques can be compared for BRDF values – we estimate 0.05 % (k = 1)

FEL lamps are slightly polarized 2.9 % ± 0.25 %, along a direction 10° from horizontal (Voss and da Costa, Appl. Optics 2016). A sintered PTFE sample had 0/45 BRDF 1.1 % ± 0.4 % higher for s-polarized vs p-polarized. Therefore, polarization has a negligible effect on $L_{\text{std}}(\lambda)$.

The full measurement equation is:

$$L_{\text{std}}(x, y; c_{xs}, c_{ys}; \lambda) = L_{\text{std}}(0/45; \lambda)\upsilon_{\text{d}}(x, y)g(c_{xi}, c_{yi}, c_{xs}, c_{ys})\, f_{\text{unif}}\, f_{\text{pol}}$$

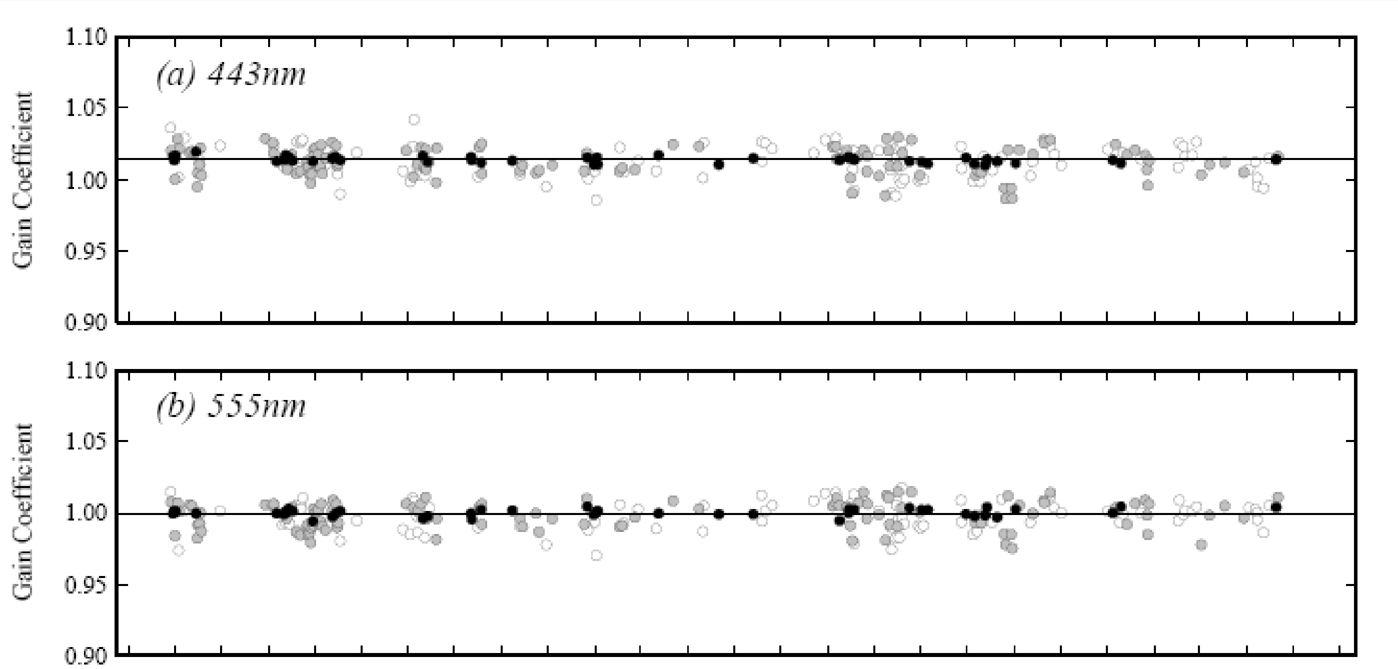
Note the complete uncertainty budget depends on the DUT’s entrance pupil diameter and field-of-view.

System Vicarious Calibration -- Match Ups

Global Observations: $L_t(\lambda) \rightarrow L_a(\lambda) \rightarrow L_w(\lambda) \rightarrow L_{wn}(\lambda) \rightarrow$ Bio-optical products

Vicarious Calibration (applied to start of mission):

$$L_w^r(\lambda) \rightarrow L_{wn}^r(\lambda) \rightarrow L_t^r(\lambda) \rightarrow \frac{L_t^r(\lambda)}{L_t(\lambda)} = \text{Gain correction factors}$$



Franz, et al., Applied Optics 46 (22), 5068- 5082 (2007)

Summary

Uncertainties must be estimated before comparisons

Uncertainties are reduced when the Like Rule is followed

Environmental sources of uncertainty – experienced in severity outside the laboratory – are critically important and probably under estimated

Comparisons may reveal unknown sources of bias

Thanks to my colleagues Eric Shirley, Howard Yoon, and Yuqin Zong in the Sensor Science Division for analysis and data

Radiometric Metrology for Ocean Color, Extended Abstract of Johnson's talk

Fiducial Reference Measurements for Satellite Ocean Colour (FRM4SOC) Workshop, Feb 21 – 23, 2017, Frascati, Italy

B. Carol Johnson, Sensor Science Division, National Institute of Standards and Technology

This talk covered the topics of uncertainty terminology (in brief), radiometric comparisons, gave an illustration of a spectral radiance scale realization, and concluded with a word on satellite system vicarious calibration (SVC).

It is important to review the uncertainty terminology and the philosophy behind the international consensus as one can easily get lost in the details. Though potentially tedious, one should always turn to the Guide to the Expression of Uncertainty in Measurement (GUM, [1]) and the associated International Vocabulary of Metrology – Basic and General Concepts and Associated Terms (VIM, [2]). These documents, and their supplements, are readily available from the web site of the Bureau International des Poids et Mesures (BIPM) and reflect international consensus on methodologies related to measurement uncertainties. The slides give an example using three common terms: accuracy, precision, and uncertainty. Recalling uncertainty is a data product that is evaluated numerically, we recognize that terms involving difference from the true value (e.g. as in the VIM definition of accuracy) cannot be assigned a numerical value because it is impossible to ever know the true value.

The archer's problem was used to illustrate the difference between accuracy and precision. The archer begins by improving their precision, e.g. getting a tight pattern that is fit for their purpose. For example, they may invest in a high quality bow or improve technique in order to achieve the desired result. In measurements, we select equipment and attempt to control influencing factors in order to improve the precision (e.g. 16 bit vs 8 bit, stable environmental temperature, etc.). If it is true we are performing "replicate measurements on the same or similar objects under specified conditions" (VIM, Sec. 2.15), then the differences in the results should be random and the uncertainty component for the mean value is reduced by $1/\sqrt{N}$ where N is the number of measurements. Accuracy is "closeness of agreement between a measured quantity value and a true quantity value of a measurand" (VIM, Sec. 2.13). At first glance, it seems we could assign a numerical value, at least for the archer, because we could measure the radial distance of the pattern mean from the bull's eye on the target. However, this is a calibration step, not a measurement. In other words, the archer is not making a dimensional measurement, but rather gauging and improving their performance in light of a different application (e.g., hunting or competition). All we can do as metrologists is design superb, fully characterized equipment, experiments that are least susceptible to influencing factors, and estimate the uncertainties so we can provide meaning to the results.

The concept of uncertainty and traceability recognize that measurements produce values for properties, termed the measurand, and a comparison to a reference gives meaningful physical results. So we design, characterize, calibrate, and measure the unknown in order to assign results. Uncertainty is a "parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be assigned to the measurand" (GUM, Sec. 2.2.3). Comparisons cannot be interpreted without prior evaluation of uncertainty.

I gave as an example the in-water comparison experiment the Spectral Ocean Radiance Transfer Investigation Experiment (SORTIE) [3]. We compared the radiometric responsivities of two types of instruments prior to a field deployment and they agreed very well. However, in the field we found that while the agreement was within the expanded uncertainty ($k = 2$), there were unaccounted biases present in the results that remained unexplained. This work illustrates the key components of a comparison and indicated that it is difficult to design the experiment in natural conditions so as to reveal and identify all sources of bias.

I continued with an example of a "scale realization" – the procedure by which one assigns radiometric values to an artifact. In this case, we realize spectral radiance using a 1000 W lamp standard of spectral irradiance, type FEL, and a white diffuse reflectance target made from sintered polytetrafluoroethylene (PTFE). The measurement equation was described, and uncertainties for the spectral radiance in the center of the target for normal incident and 45° view were presented. Significant terms in the uncertainty budget were the uncertainty in the spectral irradiance values of the lamp, and the 0°/45° reflectance factor for the target. Uncertainty in the lamp current and scattered light were important. In general, the distance is critical but here we measured with an uncertainty of 0.25 mm ($k = 1$) using an electronic ruler. A term that is often overlooked is the location of the radiometric center, e.g. the reference location for $1/d^2$ scaling. Ancillary data on the distance dependence resulted in an estimate for the offset of the radiometric center from the NIST mechanical reference, as the lamp was operated at non-standard distances of 100 cm and 140 cm. The intensity distribution of the lamp's spectral irradiance and the bi-directional reflectance distribution function of the sintered PTFE target were used to determine the uniformity of the irradiance across the target as well as a model accounting for the range of incident and view angles. The latter is dependent on the device under test (DUT). The complete uncertainty budget depends on the imaging and radiometric characteristics of the DUT – the location of its entrance pupil, field of view, focus setting, and other instrument parameters.

The last slide addressed System Vicarious Calibration, a topic which is well documented in the literature and familiar to the workshop participants. A couple of relevant references are Franz's documentation of the Sea-Viewing Wide Field-of-View Sensor (SeaWiFS) [4] and Zibordi's study of SVC requirements [5]. It is important to recognize the observed consistency of the time series of gain factors (see Fig. 3 in [4]) fails to identify bias in the MOBY values that apply to every measurement condition independent of all the possible variables (solar zenith angle, wavelength, arm to sun azimuth, arm depths, etc.) as well as the satellite variables (view angle, time difference with MOBY, etc.). In other words, the lack of time and geometric dependence in the gain factors for SeaWiFS confirms the consistency of the assignment of radiometric responsivities to MOBY, but does not offer protection from unidentified sources of invariant biases. It is worth emphasizing here a point made in the study of the uncertainties in the Lu MOBY product [6]: the standard deviation of the gain factor time series reported by Franz and co-workers was 0.9 % at 412 nm and 0.7 % at 670 nm. Taking the Lw to be 10 % of Lt means the standard deviation, or Type A uncertainty in the MOBY Lw values should be 9 % and 7 %, respectively. However, the Type A uncertainty for MOBY is much less, pointing to random sources of uncertainty, for example in the atmospheric correction, in the SVC analysis.

[1] JCGM/WG1, [Guide to the Expression of Uncertainty in Measurement] Bureau International des Poids et Mesures (BIPM), Sevres, France(2008).

[2] [International Vocabulary of Metrology -- Basic and General Concepts and Associated Terms (VIM)] International Organizaton for Standardization, Geneva, Switzerland(2012).

[3] K. J. Voss, S. McLean, M. Lewis, B. C. Johnson, S. J. Flora, M. E. Feinholz, M. A. Yarbrough, C. Trees, M. Twardowski, and D. K. Clark, "An example crossover experiment for testing new vicarious calibration techniques for satellite ocean color radiometry," J. Atmos. Oceanic Technol., 27, 1747 - 1759 (2010).

[4] B. A. Franz, S. W. Bailey, P. J. Wendell, and C. R. McClain, "Sensor-independent approach to the vicarious calibration of satellite ocean color radiometry," Appl. Opt., **46**, 5068 - 5082 (2007).

[5] G. Zibordi, F. Melin, K. Voss, B. C. Johnson, B. A. Franz, E. Kwiatkowska, J. P. Huot, W. Wang, and D. Antoine, "System vicarious calibration for ocean color climate change applications: requirements for in situ data," Remote Sens. Environ., **159**, 361 - 369 (2015).

[6] S. W. Brown, S. J. Flora, M. E. Feinholz, M. A. Yarbrough, T. Houlihan, D. Peters, Y. S. Kim, J. L. Mueller, B. C. Johnson, and D. K. Clark, "The Marine Optical Buoy (MOBY) radiometric calibration and uncertainty budget for ocean color satellite sensor vicarious calibration," Proc. SPIE, 6744, 67441M (2007).