

Spectral Solar Irradiance Requirements for Earth Observing Sensors Operating in the Ultraviolet to Shortwave Infrared

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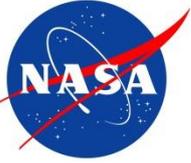
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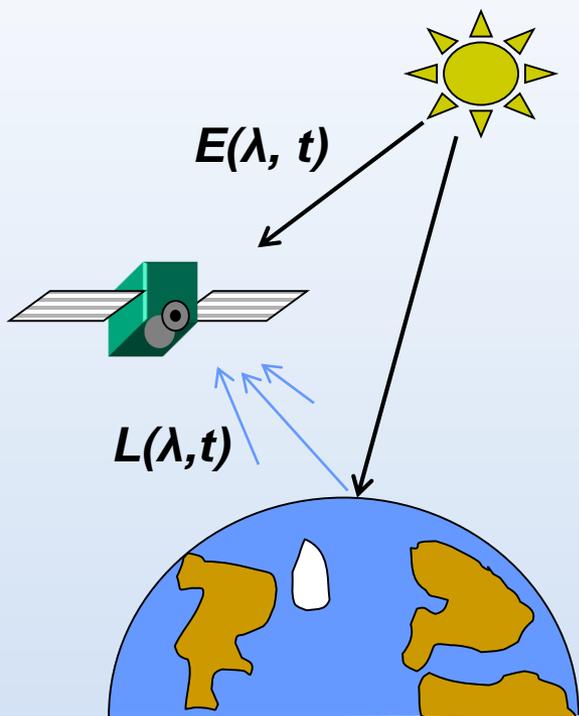
Presentation Outline

- Reflectance and radiance products from satellite instruments operating from the uv through swir (i.e. the reflected solar wavelength region)
 - UV: BUV instruments (e.g. TOMS, SBUV/2, OMI, GOME-2)
 - Vis/NIR/SWIR: MODIS/VIIRS
- Challenges in the solar diffuser-based on-orbit calibration of reflected solar instruments
- Spectral Solar irradiance in instrument intercomparisons, vicarious calibration, and production of long-term consistent datasets
- Reflectance and radiance products: SI and traceability
- Developing climate benchmark instruments and Spectral Solar irradiance
- *Brief summary of discussions and recommendations from the 2014 SORCE Spectral Solar Irradiance Review*



Reflectance and radiance products from satellite instruments operating in the UV: UV instruments

• The UV technique measures the Earth's directional reflectance (top of the atmosphere) through comparison to a solar reflector with known directional reflectance



$$L(\lambda, t) = k_r(\lambda) \cdot C_r(\lambda, t)$$

$$E(\lambda, t) = k_i(\lambda) \cdot C_i(\lambda, t)$$

$$\frac{L(t, \lambda)}{E(t, \lambda)} = \frac{k_r(\lambda)}{k_i(\lambda)} \cdot \frac{C_r(t)}{C_i(t)} = A(\lambda) \cdot \frac{C_r(t)}{C_i(t)}$$

$$A \cong BRF_{SD} \cos \Theta_i$$

$L(\lambda, t)$: Backscattered Earth radiance
 $E(\lambda, t)$: Solar irradiance
 $k_r(\lambda)$: Radiance calibration constant
 $k_i(\lambda)$: Irradiance calibration constant
 $C_r(t)$: Earth view signal
 $C_i(t)$: Solar view signal
SD: Solar diffuser
 BRF_{SD} : Bidirectional Reflectance Factor of SD
 Θ_i : Solar incident angle
A: Albedo calibration

Goal: Detect column O_3 changes to within 1%/decade



Reflectance and radiance products from satellite instruments operating in the Vis through SWIR: MODIS

•MODIS (primary) Level 1 SDR reflectance product:

$$\rho_{EV} \cdot \cos(\theta_{EV}) = m_1 \cdot dn_{EV}^* \cdot d_{Earth-Sun}^2$$

$$m_1 = \frac{BRF_{SD} \cdot \cos(\theta_{SD})}{\langle dn_{SD}^* \rangle \cdot d_{Earth-Sun}^2} \cdot \Gamma_{SDS} \cdot \Delta_{SD}$$

$$\Delta_{SD} = \frac{dc_{SD}}{dc_{Sun}}$$



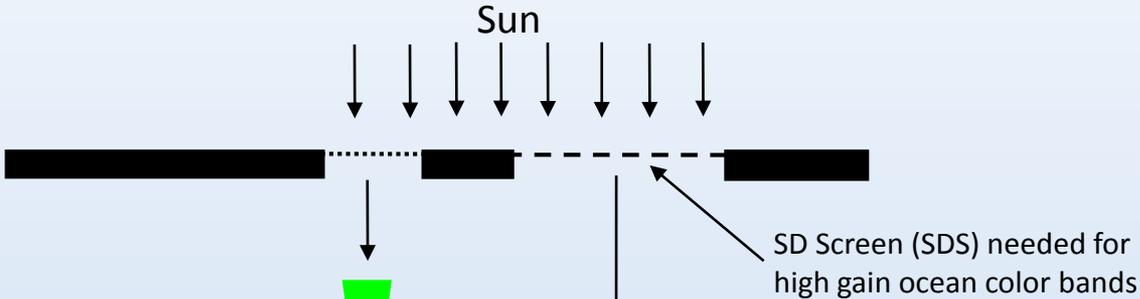
•MODIS Level 1 SDR radiance product:

$$L_{EV} = \frac{E_{Sun} \cdot \rho_{EV} \cdot \cos(\theta_{EV})}{\pi \cdot d_{Earth-Sun}^2}$$

$$= \frac{E_{Sun}}{\pi} m_1 \cdot dn_{EV}$$

where E_{SUN} is the spectral solar irradiance

E_{SUN} for MODIS:
 -0.4-0.8 μm Thuillier et al., 1998;
 -0.8-1.1 μm Neckel and Labs, 1984;
 -above 1.1 μm Smith and Gottlieb, 1974



SD Screen (SDS) needed for high gain ocean color bands

Scan Mirror

SD

- SD: Solar Diffuser
- SDSM: Solar Diffuser Stability Monitor
- SDS: Solar Diffuser Screen
- EV: Earth View
- M_1 : SD calibration coefficient
- BRF_{SD} : Bidirectional Reflectance Factor of SD
- Δ_{SD} : SD degradation factor;
- Γ_{SDS} : SDS vignetting function
- $d_{Earth-Sun}$: Earth-Sun distance
- dn^* : Corrected digital number (SD or EV)
- dc: Digital counts from SDSM (SD or Sun)
- θ_{EV} : Solar zenith angle
- θ_{SD} : Solar incident angle on SD



Reflectance and radiance products from satellite instruments operating in the Vis through SWIR: VIIRS

•VIIRS (primary) Level 1 SDR radiance product:

$$L_{EV} = F \cdot (c_0 + c_1 \cdot dn_{EV} + c_2 \cdot dn_{EV}^2)$$

$$F = \left(\frac{1}{d_{Earth-Sun}} \right)^2 \cdot \frac{L_{SD} \cdot \cos(\theta_{SD})}{c_0 + c_1 \cdot dn_{SD} + c_2 \cdot dn_{SD}^2}$$

$$L_{SD} = \frac{E_{Sun} \cdot BRF_{SD} \cdot \Gamma_{SDS} \cdot \Delta_{SD}}{\pi}$$

$$L_{EV} = \frac{E_{Sun} \cdot BRF_{SD} \cdot \cos(\theta_{SD}) \cdot \Gamma_{SD} \cdot \Delta_{SD}}{\pi \cdot d_{Earth-Sun}^2 \cdot (c_0 + c_1 \cdot dn_{SD} + c_2 \cdot dn_{SD}^2)} \cdot (c_0 + c_1 \cdot dn_{EV} + c_2 \cdot dn_{EV}^2)$$

•VIIRS Level 1 SDR reflectance product:

$$\rho_{EV} = \frac{\pi \cdot F \cdot (c_0 + c_1 \cdot dn_{EV} + c_2 \cdot dn_{EV}^2)}{\cos \theta_{EV} \cdot E_{Sun}}$$

where E_{SUN} is the spectral solar irradiance

E_{SUN} for VIIRS:
-MODTRAN 4.3

SD: Solar Diffuser
SDSM: Solar Diffuser Stability Monitor
SDS: Solar Diffuser Screen
EV: Earth View
BRF_{SD}: Bidirectional Reflectance Factor of SD
Δ_{SD}: SD degradation factor;
Γ_{SDS}: SDS vignetting function
d_{Earth-Sun}: Earth-Sun distance
c₀, c₁, c₂: Non-linearity coefficients
F: Radiance calibration coefficient
L_{SD}: SD spectral radiance
θ_{EV}: Solar zenith angle
θ_{SD}: Solar incident angle on SD
dn: Corrected digital number (SD or EV)

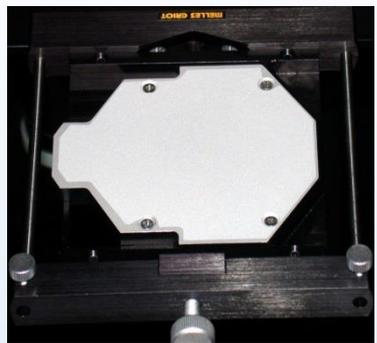


Challenges in On-orbit Calibration of Reflected Solar Satellite Instruments (1 of 2)

•Current challenges in the on-orbit calibration of satellite instruments operating in the reflected solar wavelength regions are largely identical to those experienced in the EOS era

1. Evolution of solar diffuser materials:

Instrument Operating Wavelength Range	Instrument: SD material
250-425nm	<ul style="list-style-type: none"> -BUV & SBUV: roughened aluminum -TOMS Meteor-3/ADEOS/EP/QuikTOMS: roughened aluminum -OMI: quartz volume diffuser -SNPP OMPS: roughened aluminum -JPSS OMPS: quartz volume diffuser -TEMPO & GEMS: roughened transmissive quartz
400-2500nm	<ul style="list-style-type: none"> -SeaWiFS: YB-71 IITRI thermal control paint -MODIS Terra & Aqua: spacegrade Spectralon -MISR: spacegrade Spectralon -MERIS: spacegrade Spectralon -SNPP & JPSS VIIRS: spacegrade Spectralon -Landsat-7: YB-71 IITRI paint -Landsat-8: spacegrade Spectralon



Roughened Al → Quartz Volume Diffuser



Mie Diffuser (exptl.)



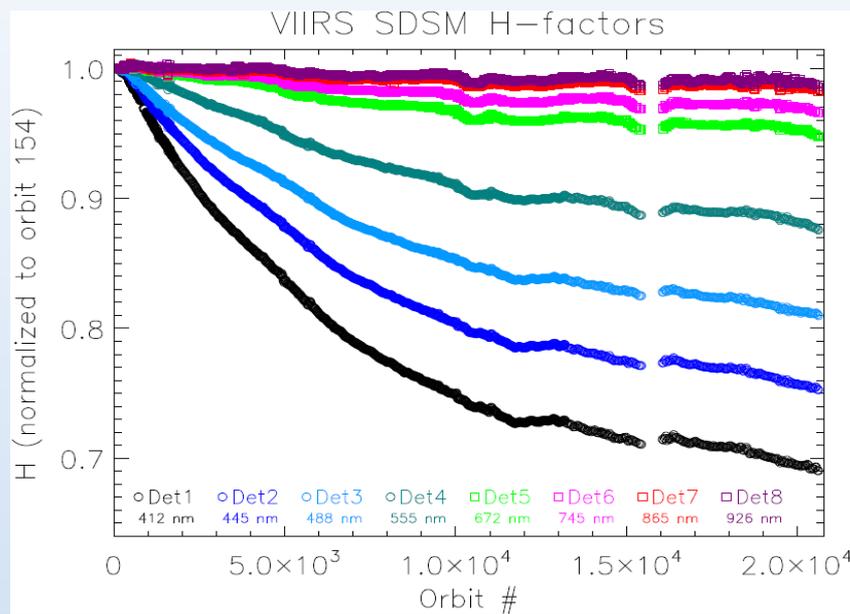
Spacegrade Spectralon



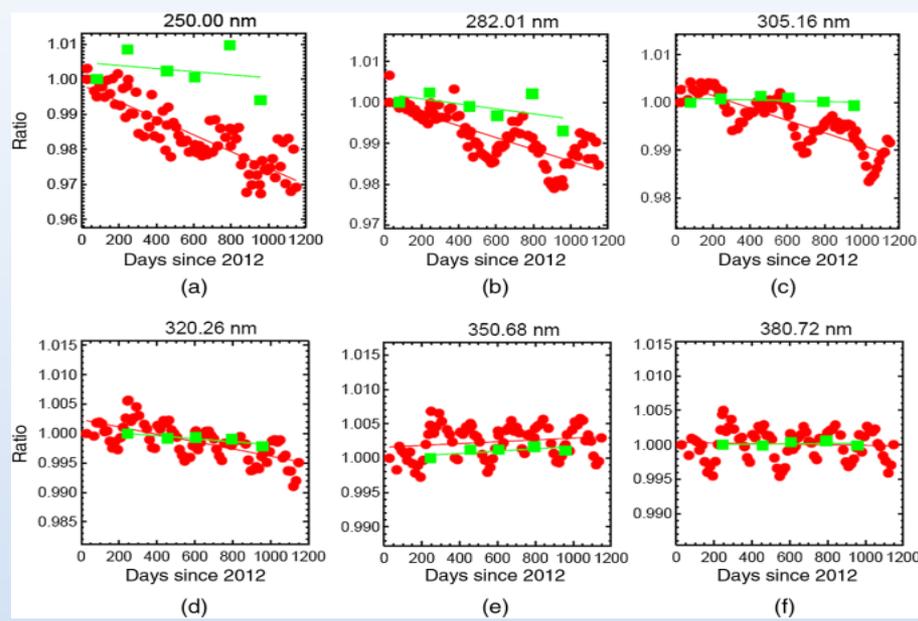
Challenges in On-orbit Calibration of Reflected Solar Satellite Instruments (2 of 2)

2. Monitoring solar diffuser (and by inference, instrument) degradation:

a. On-orbit monitoring hardware
(e.g. SDSM on MODIS & VIIRS)



b. Multiple diffusers with varying solar exposure times (e.g. SNPP OMPS)

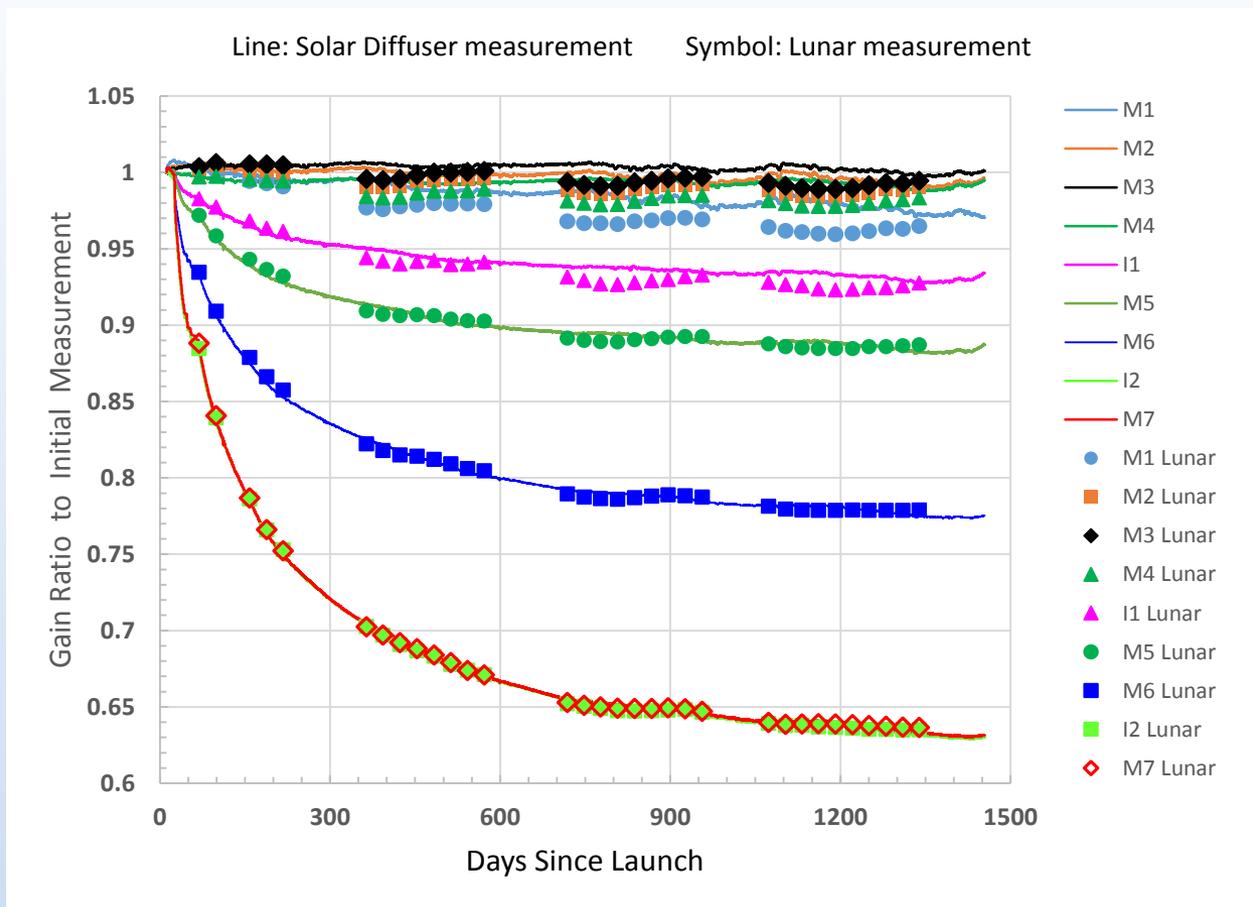


OMPS diffuser measurement trends:
Working diffuser
Reference diffuser



Challenges in On-orbit Calibration of Reflected Solar Satellite Instruments (3 of 3)

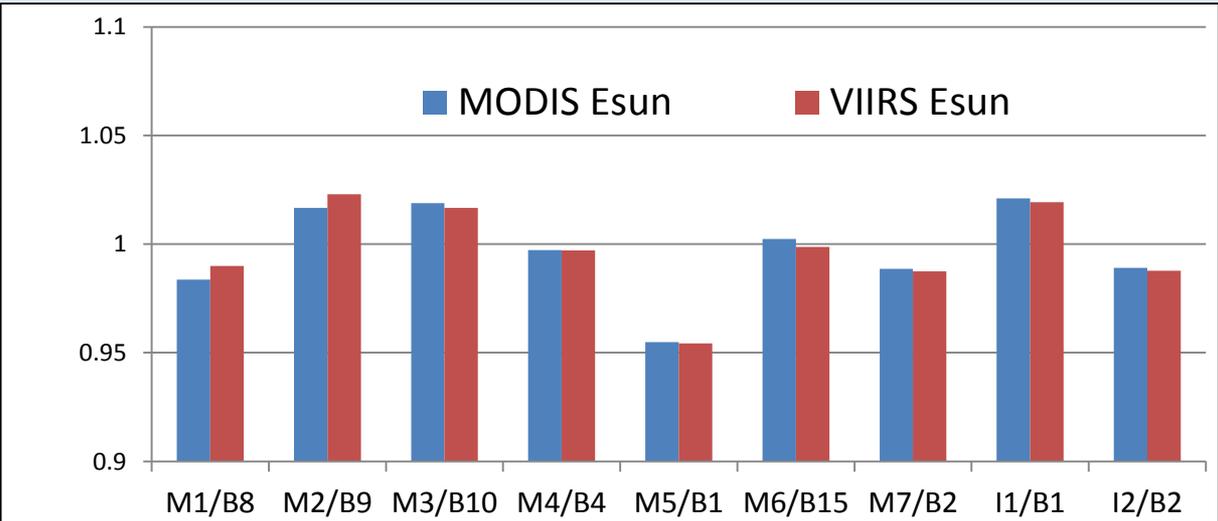
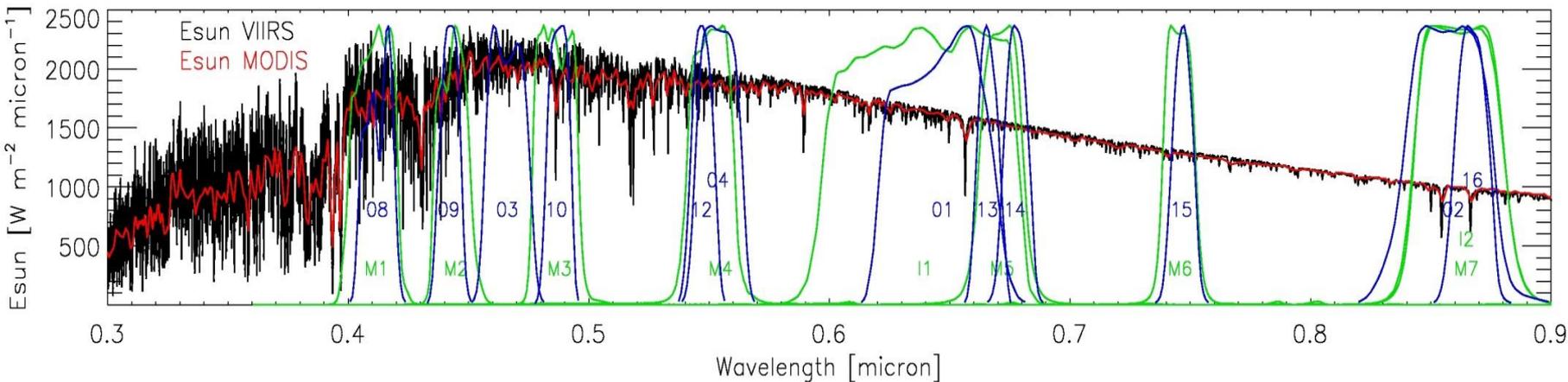
3. Comparison of SD-based and lunar-based instrument degradation predictions (e.g. SNPP VIIRS)





Effect of Solar Spectral Irradiance on Reflected Solar Instrument Inter-comparisons: MODIS and VIIRS

- Instrument inter-comparisons are critical to the production of long-term satellite data records
 - Differences in comparison results can be due to spatial registration effects, spectral differences, temporal changes in atmosphere and surface between sensor data collects



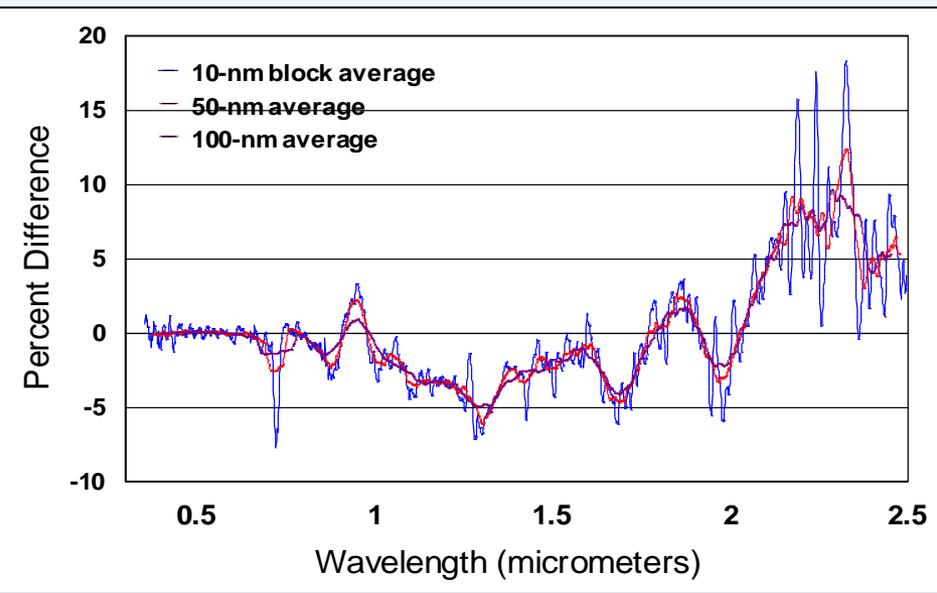
VIIRS to MODIS radiance ratios determined using sensor-based Esun models (MODIS and VIIRS) and RSR for their spectrally matched bands



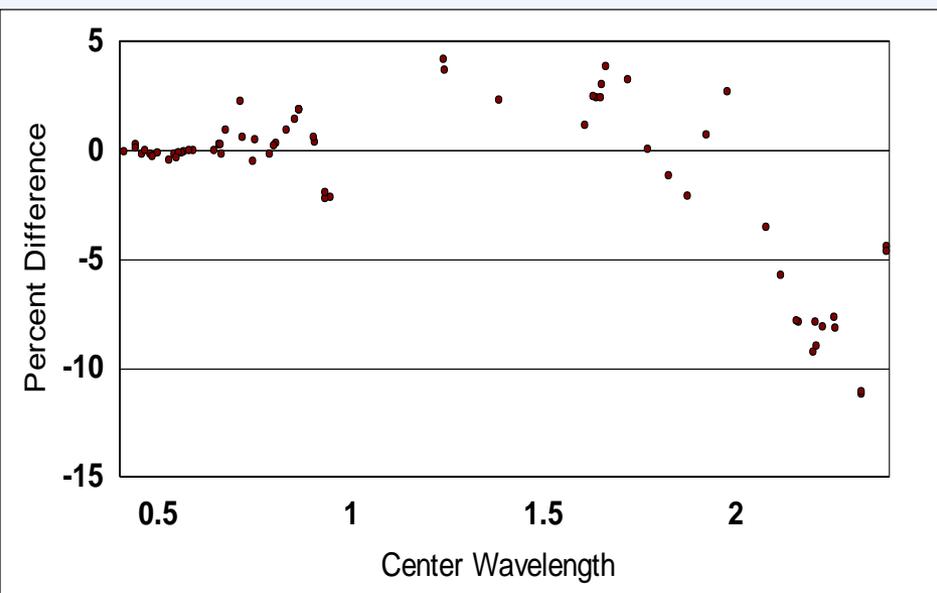
Effect of Solar Spectral Irradiance on Reflected Solar Instrument Inter-comparisons: MODIS, ALI, ASTER, ETM+, and MASTER

• In addition to the satellite instrument requirement on the use of a solar irradiance spectrum to derive a radiance product in the on-board solar diffuser approach, vicarious calibration methods of instrument inter-comparison all require the use of a solar irradiance spectrum.

-EOS era comparison of the WRC and MODTRAN-4 spectral solar irradiance models:



Percent difference between the WRC model originally chosen as the EOS standard and the Chance-Kurucz model embedded in MODTRAN



Percent difference between the WRC model originally chosen as the EOS standard and the Chance-Kurucz model embedded in MODTRAN for the ALI, ASTER, ETM+, MASTER, and Terra MODIS spectral bands

-K. Thome, et al., Proc. SPIE, 4540, 260-269 (2001)



Reflectance and radiance products: SI and traceability, (1 of 3)

-NIST: *the U.S. National Metrology Institute (NMI) responsible for developing, maintaining, and disseminating national standards used to realize the SI.*

-SI: *an internationally accepted coherent system of physical units, derived from the MKSA (meter-kilogram-second-ampere) system, using the meter, kilogram, second, ampere, kelvin, mole, and candela as the basic units (SI units) respectively of the fundamental quantities of length, mass, time, electric current, temperature, amount of substance, and luminous intensity.*

-Traceability: *The property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties. International Vocabulary of Basic and General Terms in Metrology, VIM 2nd ed., Geneva: International Organization for Standardization, Sec. 6.10 (1993).*

Traceability:

- (1) establishes a common reference base for measurements
- (2) provides a quantitative measure of assessing the agreement of results from different sensors at different times.

Note: *It is the responsibility of the instrument calibrator to establish and support their claim of traceability and the responsibility of instrument data users to assess the validity of that claim*



Reflectance and radiance products: SI and traceability (2 of 3)

-In late 1995 at the request of the EOS MODIS Science Team, the decision was made that the MODIS primary Level 1 project would be **reflectance** not radiance.

-This decision initially led to a discussion on whether reflectance (i.e. a unitless quantity) was traceable to the SI.

-The BIPM's 20th Conference Generale des Poids et Mesures, held October 9-12, 1995 adopted the resolution recommending "that those responsible for studies of Earth resources, the environment, human well-being, and related issues **ensure that measurements made within their programmes are in terms of well-characterized SI units** so that they are reliable in the long term, are comparable world-wide and are linked to other areas of science and technology through the world's measurement system established and maintained under the Convention du Metre."

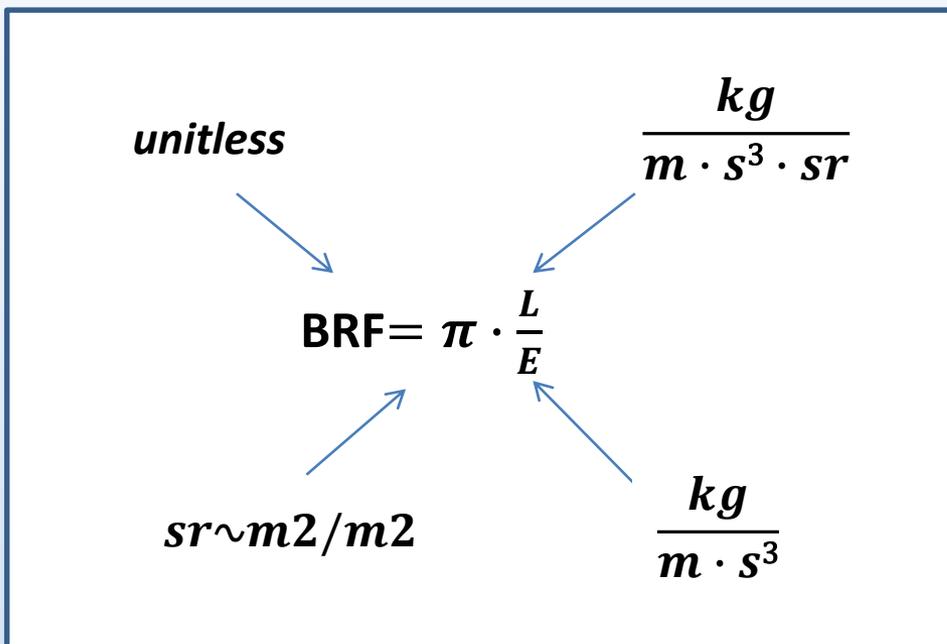
-NML perspective: **Reflectance measurements are considered a valid type of SI unit if the (spectral) radiant flux of the reference source (the Sun in this case) is measured simultaneously using absolute detectors.** Assuming the Sun stays constant is not acceptable in the view of the CCPR/BIPM.

-At the **October 12-14, 2004 CEOS/IVOS Calibration Workshop at ESA/ESTEC, NIST stated "the results of measurements or values of standards do not have to be part of the SI to be "NIST traceable." In the assignment of values of transmittance, reflectance, or absorptance to filter, windows, mirrors, or other optical components, the underlying measurements of radiance flux can be absolute or relative, since ratios determine the final values."**



Reflectance and radiance products: SI and traceability (3 of 3)

-BRF is a derived product which can be described in terms of SI basic units:



-However, the debate on the traceability of unitless SI quantities continues:

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Dimensionless units in the SI

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Abstract
The International System of Units (SI) is supposed to be coherent. That is, when a combination of units is replaced by an equivalent unit, there is no additional numerical factor. Here we consider dimensionless units as defined in the SI, e.g. angular units like radians or steradians and counting units like radioactive decays or molecules. We show that an incoherence may arise when different units of this type are replaced by a single dimensionless unit, the unit ‘one’, and suggest how to properly include such units into the SI in order to remove the incoherence. In particular, we argue that the radian is the appropriate coherent unit for angles and that hertz is not a coherent unit in the SI. We also discuss how including angular and counting units affects the fundamental constants.

Keywords: SI, international system of units, dimensionless units, radian, hertz

A parable of dimensionless units
Bert has a turntable operating at a rotation frequency of 333 revolutions per minute. His friend, Ernie, asks Bert, ‘At what frequency is your turntable rotating?’ If Bert were to answer ‘0.555 Hz’, Ernie would know the rotation frequency. Similarly, if Bert were to answer ‘3.49 radians per second’, Ernie would know the rotation frequency. And, if Bert were to say ‘200 degrees per second’, Ernie would be well informed. On the other hand, if Bert were to respond ‘the rotation frequency is 3.49’, we would all agree that Ernie would not know the rotation frequency. Nor would a response of ‘3.49 per second’ be useful to Ernie, any more than a response of ‘200 per second’. In order to convey useful information, Bert must tell Ernie the units in which he is reporting the rotation frequency, including the so-called dimensionless units of cycles or radians or degrees. The current formulation of the SI specifically allows the units ‘radian’ or ‘cycle’ to be replaced by the dimensionless unit ‘one’, and it allows both radians per second and cycles per second (Hz) to be replaced with inverse seconds. Clearly, if Bert had followed this prescription, allowed by the current SI, he would have left Ernie in the dark about the rotation frequency.

If Bert had given an uninformative response about the rotation rate, Ernie might have asked ‘what is the concentration of oxygen in the air you’re breathing?’ Bert could respond ‘about 10²³ atoms m⁻³’ or ‘5 × 10²³ molecules m⁻³’. These are clear answers. A factor-of-two ambiguity would arise if he had not specified the entity being counted; in fact, the current SI says that ‘atoms’ or ‘molecules’ are dimensionless units that should be set equal to ‘one’. If Bert had said ‘5 × 10²³ m⁻³’, Ernie might have interpreted that as being the atomic density and wonder if oxygen deprivation had compromised his friend’s mental acuity.

Such situations allowed by ambiguous units are untenable, which is one of the main points of this paper. Fixing the problem is not going to be easy, as evidenced by the fact that it has persisted for so many years after the institution of the SI in 1960. This situation has led to such problematic pronouncements as ‘the radian and steradian are special names for the number one ...’ [1]. One starting point is to recognize that replacing radians or cycles or similar dimensionless units by ‘one’ leads to trouble, and replacing molecules by ‘one’ in expressions for molecular concentration may also lead to trouble. These and similar arguments are made explicit below, as are our suggestions for a revision to the SI that goes a long way toward solving the problem’.

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¹ The hypothetical conversation in this section is not meant to suggest that there actually was such a conversation between Albert Einstein and Ernest Rutherford.

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Developing climate benchmark instruments and Spectral Solar Irradiance (1 of 2)

MODIS/VIIRS type instruments carry 2% (k=1) reflectance and 5% (k=1) radiance measurement requirements

Climate benchmark instruments such as CLARREO and TRUTHS drive the calibration of reflected solar Earth observing instruments to state-of-the art levels

MODIS reflectance uncertainty budget

MCST
2004

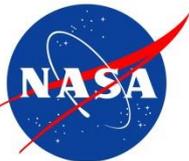
1 NIST reference:	0.50%
2 Characterization of SBRS scattering goniometer:	0.70%
3 Transfer of NIST BRFS scale to MODIS SD reference:	0.50%
4 MODIS SD characterization:	0.50%
5 SD spatial non-uniformities:	0.70%
6 Interpolation angular / spectrally:	0.10%
7 Pre-launch to on-orbit SD BRDF change:	0.50%
8 SD screen:	0.50%
9 SDSM solar 2% attenuation and SDS impact:	0.50%
10 Solar illumination of the SD surrounds (stray light)	0.30%
11 Earthshine through the SD door	0.50%
12 Earthshine through nadir aperture door	0.10%
	RSS 1.69%
	RSS (non-ocean without SDS) 1.61%

1. CLARREO Radiometric Specifications:

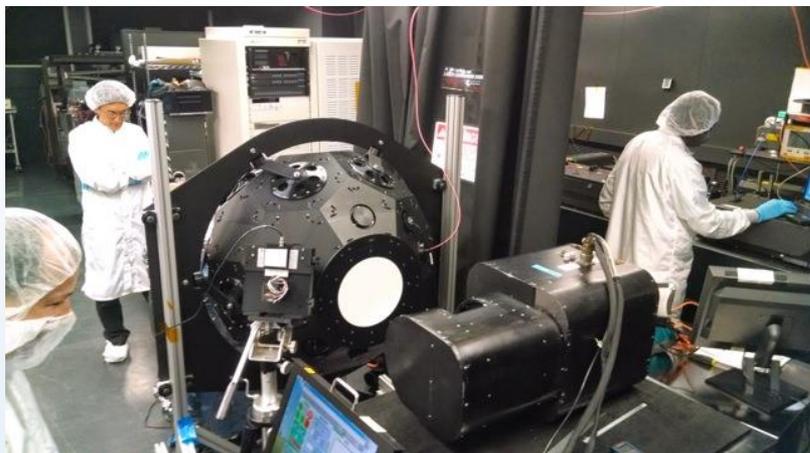
- Spectral range: 320-2300 nm
- Radiometric calibration uncertainty $\leq 0.3\%$ in **reflectance** (k=2)
- Radiance calculated from reflectance using SSI spectrum with uncertainty 0.2% (k=1)

2. TRUTHS Radiometric Specifications:

- Spectral range: 320-2450 nm
- Earth spectral **radiance** measurement accuracy of $<0.3\%$
- SSI measurement accuracy of $\leq 0.1\%$



Developing climate benchmark instruments and Spectral Solar Irradiance (2 of 2)



Comparison of two methodologies for calibrating satellite instruments in the visible and near-infrared

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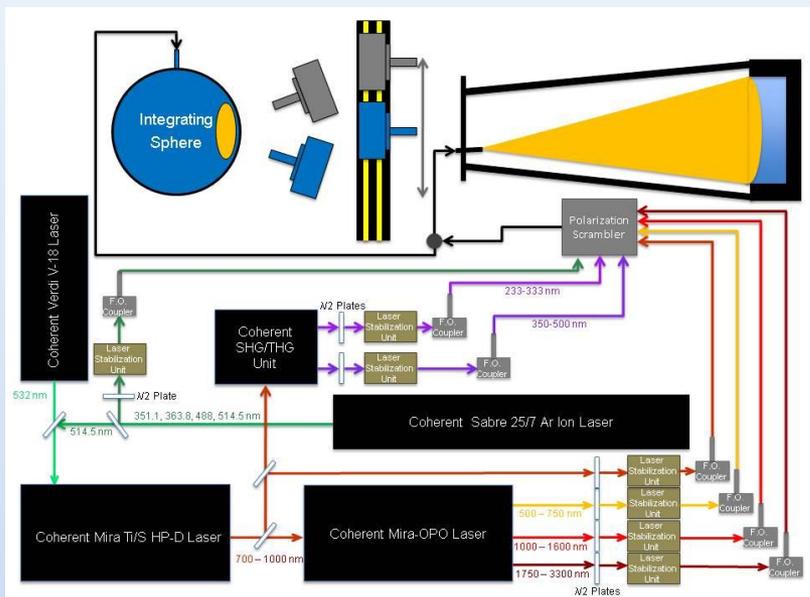
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⁸University of Wisconsin, Madison, WI 53706

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From the abstract:

“More recently, a full-aperture absolute calibration approach using widely tunable monochromatic lasers has been developed. Using these sources, the ASR of an instrument can be determined in a single step on a wavelength-by-wavelength basis. From these monochromatic ASRs, the responses of the instrument bands to broadband radiance sources can be calculated directly, **eliminating the need for calibrated broadband light sources such as lamp-illuminated integrating spheres.** In this work, the traditional broadband source-based calibration of the Suomi National Preparatory Project (SNPP) Visible Infrared Imaging Radiometer Suite (VIIRS) sensor is compared with the laser-based calibration of the sensor. Finally, the impact of the new full-aperture laser-based calibration approach on the on-orbit performance of the sensor is considered.”



**Quasi-cw tunable laser systems in the US:
NIST, NASA GSFC (2), U. of Colorado LASP**

Accepted for publication in Applied Optics

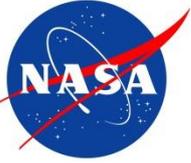


In Conclusion:

- **Consistency in satellite instrument remote sensing data sets and products, requires a standard, high quality solar irradiance spectrum**

Applications include:

- **Production of radiance products from satellite instruments (i.e. radiance based calibration methods)**
 - **Production of satellite instrument radiance products from reflectance products**
 - **Ground-based and airborne vicarious calibration methods**
 - **Inter-comparisons of satellite instrument radiance measurements**
 - **Production of long-term remote sensing data sets from multiple instruments**
-
- **The adoption of the Thullier spectrum (G. Thuillier, et al. Solar Physics 214(1): 1-22 (2003)) by the 17th CEOS Plenary in November 2003 as the standard solar spectrum was a necessary and important first step in establishing inter-instrument product consistency**
 - **Improvements in the accuracy and consistency (i.e. full validation) of solar irradiance spectra and new instrument calibration/characterization approaches are being strongly driven by climate science requirements**



The 2014 SORCE Spectral Solar Irradiance Review

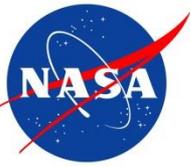
-The 2013 Senior Review of Earth Science Operating Missions provided programmatic direction for the SORCE mission for FY 2014-2017

- For SORCE, the review panel recommended an independent review of the SSI methods and results to ensure data quality and to resolve discrepancies with other observations and model results.**

-In response to the above recommendation, a SORCE SSI review was held at LASP from September 16 to 18, 2014

- Review panel members included**
 - Jim Butler (NASA/GSFC) panel co-chair**
 - Joe Rice (NIST) panel co-chair**
 - Kurt Thome (NASA/GSFC)**
 - Carol Johnson (NIST)**
 - Jeff Morrill (NRL)**
 - George Mount (Washington State U.)**

-The review focused on SOLSTICE and SIM SSI measurements and their long-term inter-solar cycle variability, instrument calibration approaches, algorithms, techniques for determining instrument performance degradation and resulting impacts on measurement uncertainty.



2014 SORCE Spectral Solar Irradiance Review panel recommendations

-General recommendations were made by the panel in 4 areas:

1) Exploitation of SSI data sets from other instruments and models

- Pursue obtaining additional SSI data sets for comparison purposes (eg.OMI on NASA Aura, SOLSPEC on ISS, OMPS on SNPP)

2) On-orbit instrument hardware/performance degradation

- Perform a ray trace study invoking free parameters to examine the effect of on-orbit degradation on SOLSTICE optics while examining impacts on the instrument's FOV profiles
- Evaluate the applicability/assumptions of the SIM instrument physical model in the determination of on-orbit instrument degradation (eg. prism opacity as a function of λ , deposition thickness vs. t , and solar exposure t)

3) Measurement uncertainty analyses

- Perform rigorous error analyses (i.e. all error sources clearly identified and quantified) for both SIM and SOLSTICE

-Panel recommended a Monte Carlo analysis approach

4) Conduct a independent review of the TSIS SIM ISS on-orbit instrument operational plan

-A total of 20 additional (detailed) recommendations (with recommendees) were identified



Questions?