The Establishment and Verification of Traceability for Remote Sensing Radiometry, with an Eye Towards Intercomparison of Results

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http://www.nist.gov

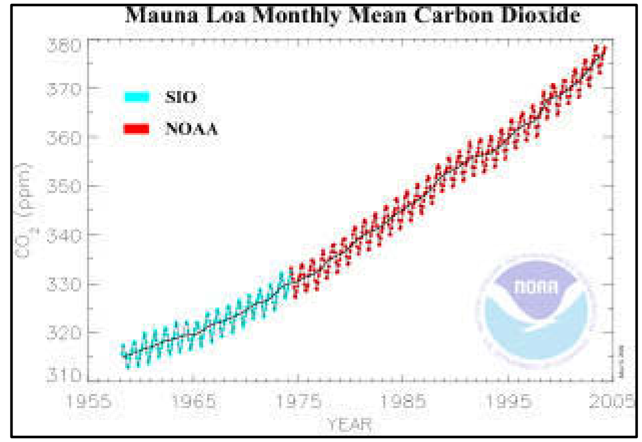
Overview

- Measurement uncertainty goals
- Traceability
- Realization of radiometric quantities
- Assessing claims of traceability
- Instrument characterization—lessons learned
- Recommendations for comparison of Level 2 products

Remote Sensing Uncertainties

- Climate change – one application
  - Observational evidence
  - Quantitative understanding

Business Week August 16, 2004



Credit: NOAA/CMDL

- Uncertainties: Derived products ? Radiometric measurements
  - Strategic Plan for US Climate Change Program, EOS Science Plan
  - NPP/NPOESS IORD II, GOES-R PORDs
  - Workshop on Satellite Inst. Calibration for Climate Change, NISTIR 7047
- Conclude
  - 2% to 5% (VNIR), 0.1 K to 1 K (TIR)

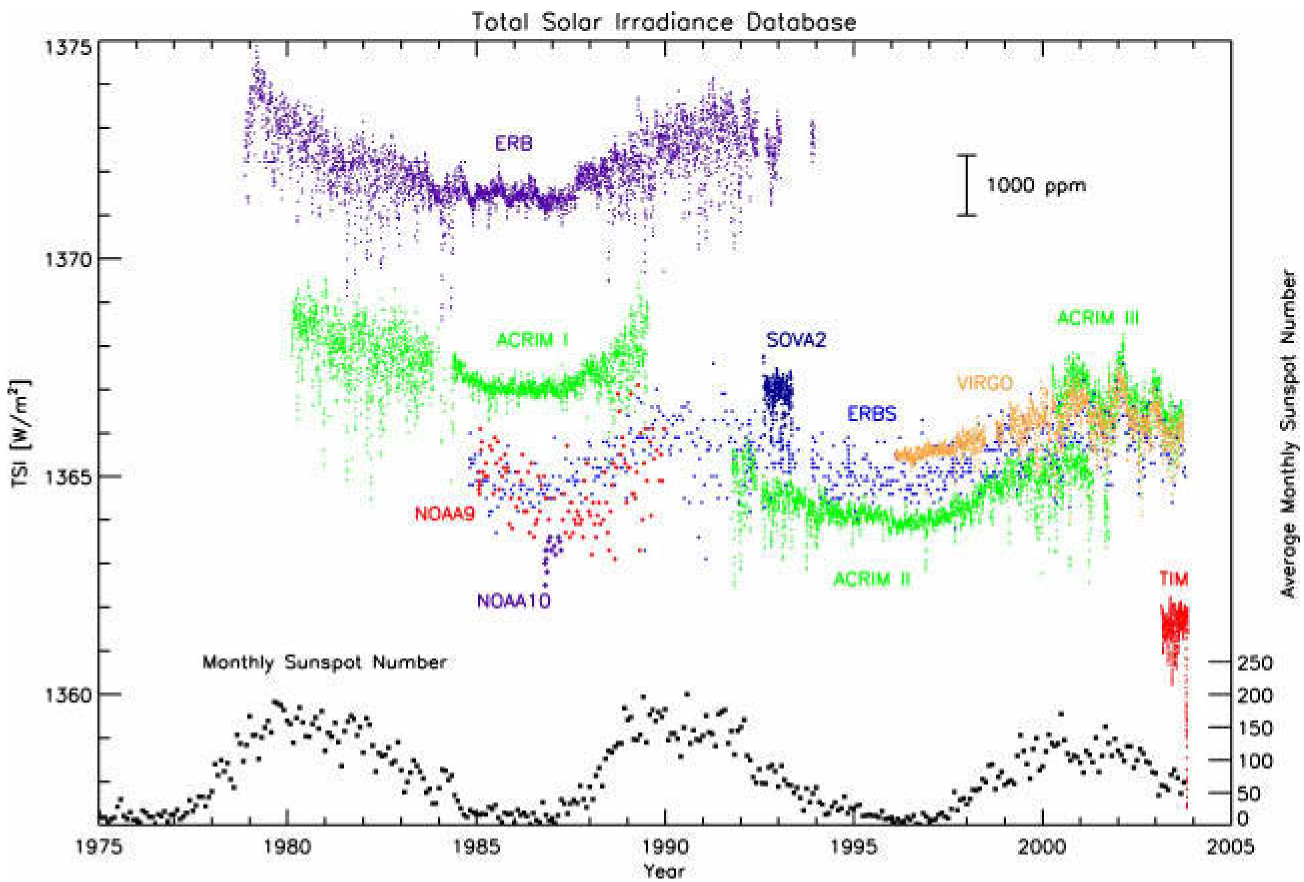
Traceability

Traceability – 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 (VIM, 6.10)

- Advantages
  - Uncertainties are determined and reported
  - Traceability chain is documented
  - Provenance of standards or artifacts is established
  - Results can be compared (a point of common reference)
- NIST Policy
  - The provider of the result of a measurement or value of a standard is responsible for supporting its claim of traceability of that result or value.
  - The user of the result of a measurement or value of a standard is responsible for assessing the validity of a claim of traceability.
  - See http://ts. nist.gov/traceability for more information

Why Traceability is Important

Measurements of Total Solar Irradiance



http://spot/colorado.edu/~koppg/TSI/

Additional Considerations

- "traceable to the" International System of Units
  - generally applies to *results of measurements*
  - may not apply to *values of standards*
- Instrument characterization functions (e.g., linearity)
  - affect the total uncertainty, even after applying algorithms to correct for known biases
- On-orbit measurement results
  - unexpected changes, degradation, unanticipated effects
  - procedures required to determine necessary corrections and the uncertainty in the correction
- Bottom line: don't neglect to consider all sources of uncertainty

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Technology Administration, U.S. Department of Commerce

Supporting Claims of Traceability (Provider)

- Clearly defined particular quantity that has been measured
- Complete description of the measurement system or working standard used to perform the measurement
- Stated measurement result or value, with documented uncertainty
- Complete specification of the stated reference at the time the measurement system or working standard was compared to it
- An "internal measurement assurance" program for establishing the status of the measurement system or working standard at all times pertinent to the claim of traceability
- An "internal measurement assurance" program for establishing the status of the stated reference at the time that the measurement system was compared to it

Realization of Radiometric Quantities

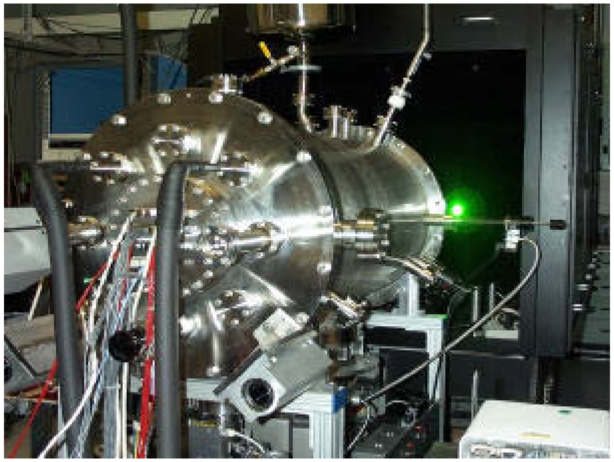
- Multiple methods to establish
  - Values for detector or source standards
    - Blackbody physics
    - Synchrotron radiation
    - Electrical substitution radiometry
    - Correlated photons
  - Values or results for reflectance and transmittance standards or samples
    - flux ratios that can be relative or absolute
- Ancillary information required
  - Data (e.g., area of limiting apertures)
  - Models (e.g., results of diffraction calculations)

Implementation of Radiometric Quantities

- Reflectance, emittance ($\varepsilon = 1-\rho$), transmittance, wavelength calibration
  - Standard Reference Materials (SRMs)
- Spectral irradiance
  - Source standards (e.g., FEL and D_2 lamps)
- Detector (radiometer) absolute (relative) spectral responsivity
  - Detector standards (e.g., Si photodiodes)

Irradiance standard lamp, calibrated for horizontal operation, for in situ calibration of downwelling solar irradiance instrument.

Laser-illuminated integrating sphere source (values traceable to detector standards) for irradiance responsivity calibration of flight sensor.



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Implementation of Radiometric Quantities

- Spectral radiance
  - Use lamp standards of spectral irradiance
    - "lamp/plaque" method
    - irradiance-to-radiance transfer (requires well defined apertures)
  - Use lamp standards of spectral radiance
  - Use temperature standards and blackbody physics

FEL-type standard lamp with diffuse reflectance standard to realize values of spectral radiance.

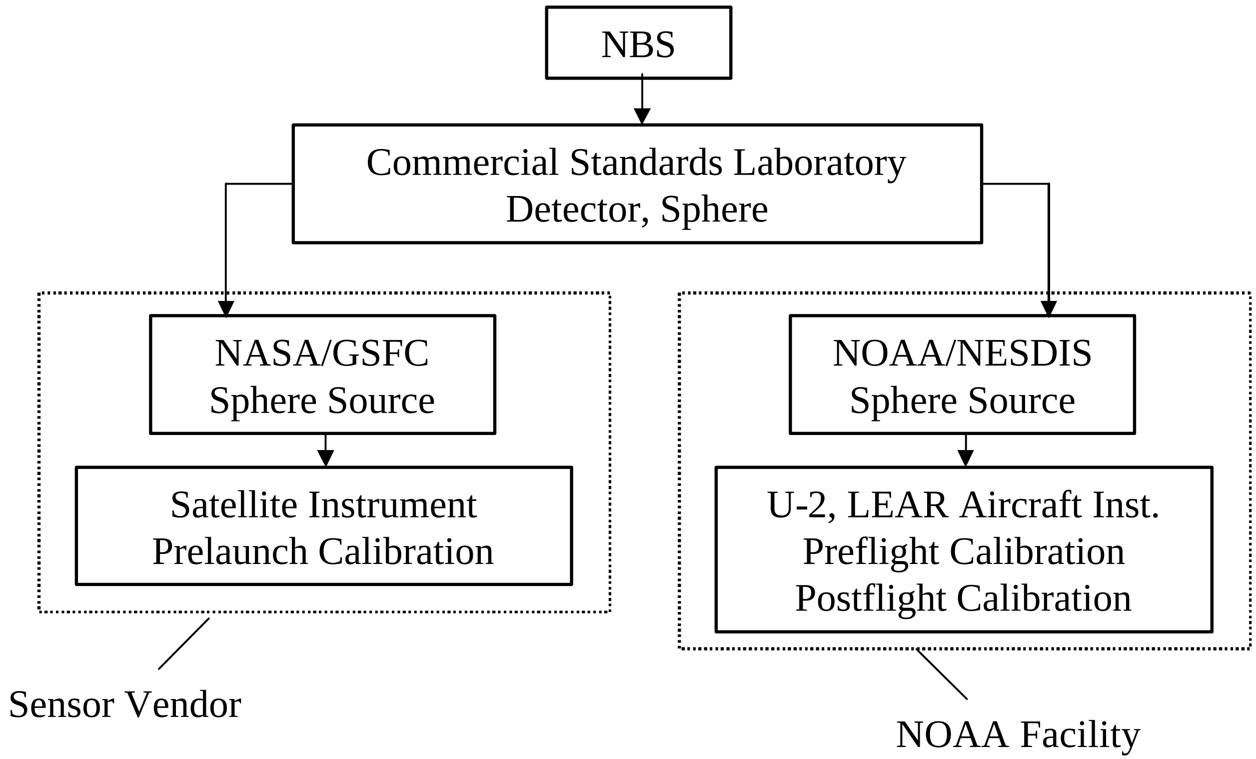
Highly absorbing cavity in stirred water bath with thermometry.

CASOTS Blackbody

Assessing Claims of Traceability (User)

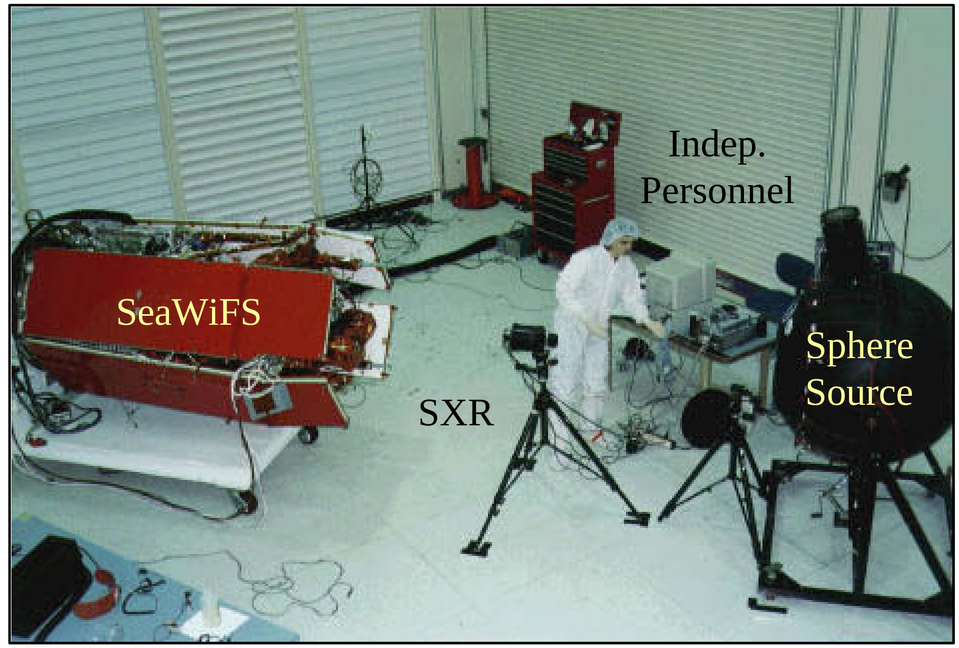
- Measurement (an External Measurement Assurance Program)
  - intercomparison activities
  - independent calibrations
- Analysis
  - Determine what is adequate to meet your requirements (e.g., in the level of rigor of the internal Measurement Assurance Programs)
  - Review provider's elements—they must all be present
  - Look for evidence of Quality Programs
- Guidelines
  - SRMs are tools for assessing measurement quality; purchase of an SRM does not automatically make the measurement results traceable to reference standards
  - CIPM MRA recognizes NMI signatories' measurement and calibration certificates; up to user to decide if sufficient evidence exists under the MRA to provide mutually acceptable traceability of results to the standards and measurements of two or more participating NMIs

Remote Sensing Example, Then



Adapted from Figure 1 in Smith et al. 1989. For AVHRR and VISSR, the source standards of spectral radiance were sent to a commercial laboratory for calibration. Comparisons between the operational satellite sensor and the aircraft sensor were used to correct the calibration coefficients.

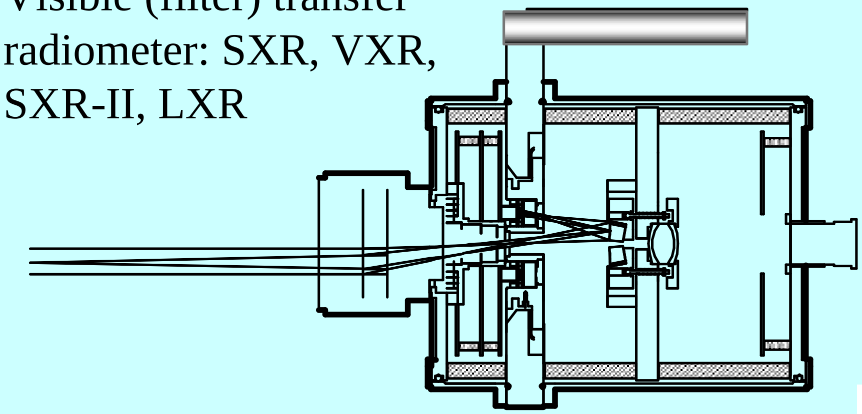
Remote Sensing Example, Now



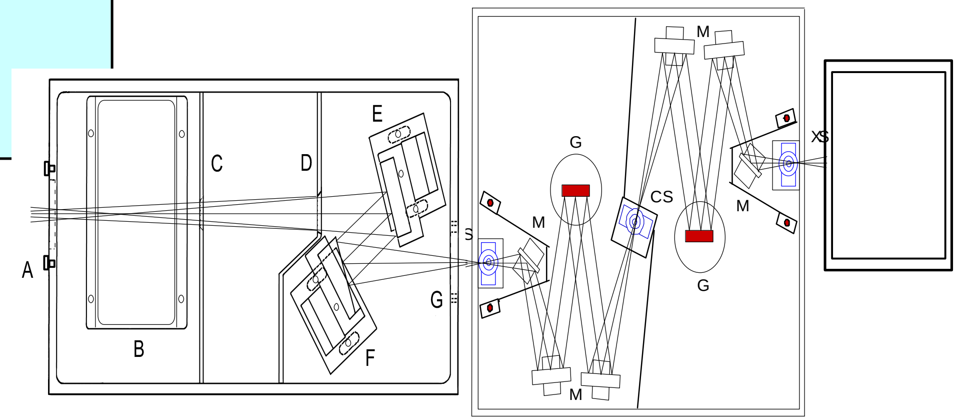
- Program elements
  - portable transfer radiometers
  - portable source standards for calibration and stability monitoring
  - artifact comparisons
  - specific characterization efforts
- Civilian sponsors & collaborators
  - NOAA, USDA, EPA, NSF, SERC, & AES (Canada)– Interagency network of UV monitoring spectrometers)
  - NASA: EOS Project Science Office, SeaWiFS Project Office; NOAA: Marine Optical Buoy (MOBY)
  - IPO (NPP/NPOESS)
  - NOAA: GOES-R

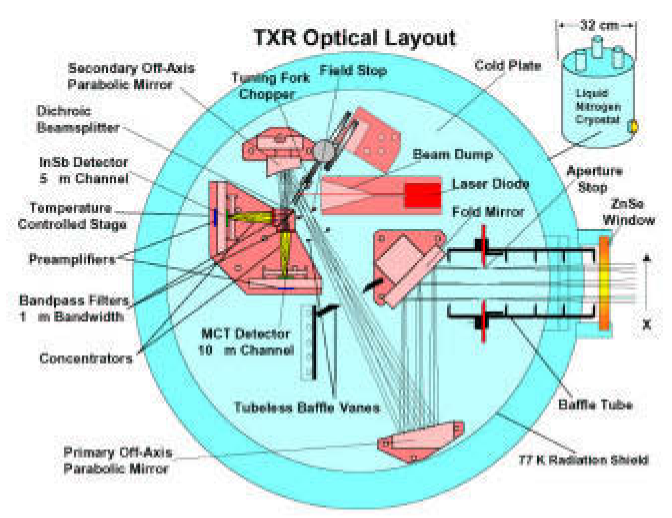
Transfer Radiometers

Visible (filter) transfer radiometer: SXR, VXR, SXR-II, LXR



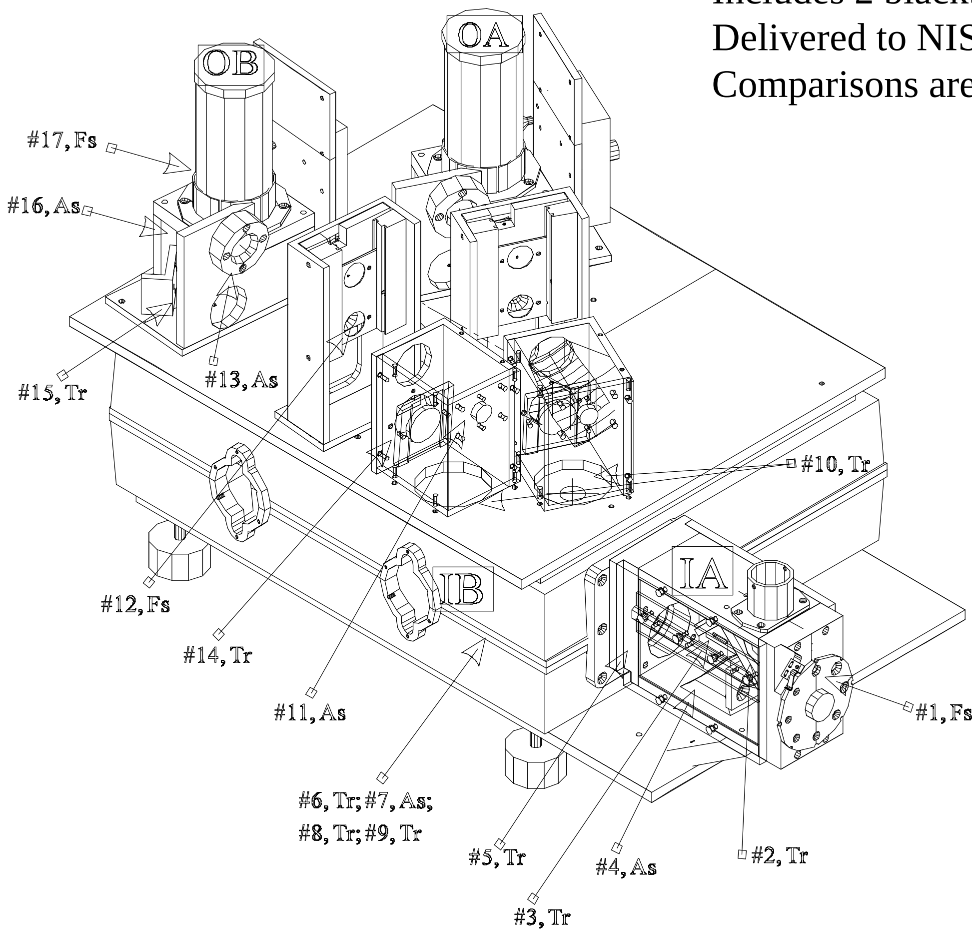
Short-wave Infrared Transfer Radiometer (SWIXR)





Thermal Infrared Transfer Radiometer (TXR)

Transfer Radiometers, Continued



FTXR (based on a Bomem MR-154)
Includes 2 blackbodies that hold the radiance scale; AERI heritage
Delivered to NIST December 2003
Comparisons are underway (WBBB and TXR)

Filter radiometer—trap detector and irradiance or radiance foreoptics for OMPS radiometric validation

NASA/SIO/EPIC Project

Transfer Sources

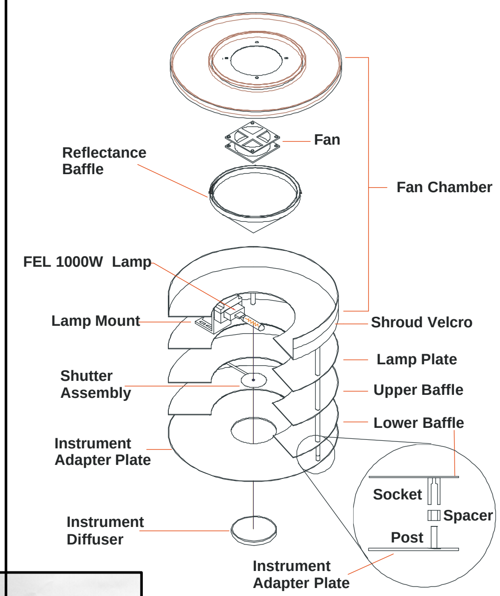
NIST Portable Radiance (NPR) Source

Blue LED Field Stability Source

SeaWiFS Quality Monitor (SQM)

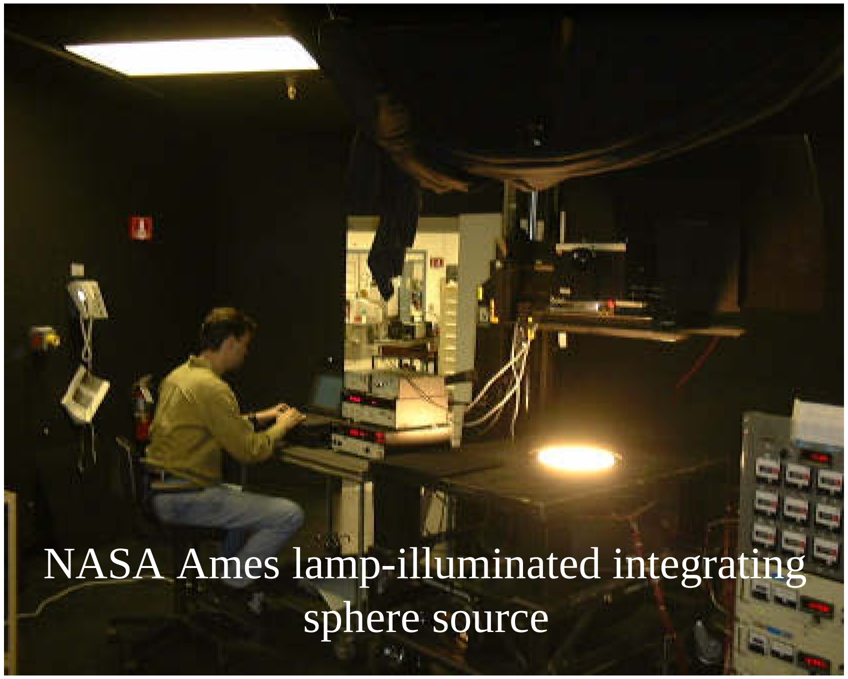
Water Bath Blackbody Source

UV Field Source Calibrator



Spectral Radiance, Vis-NIR

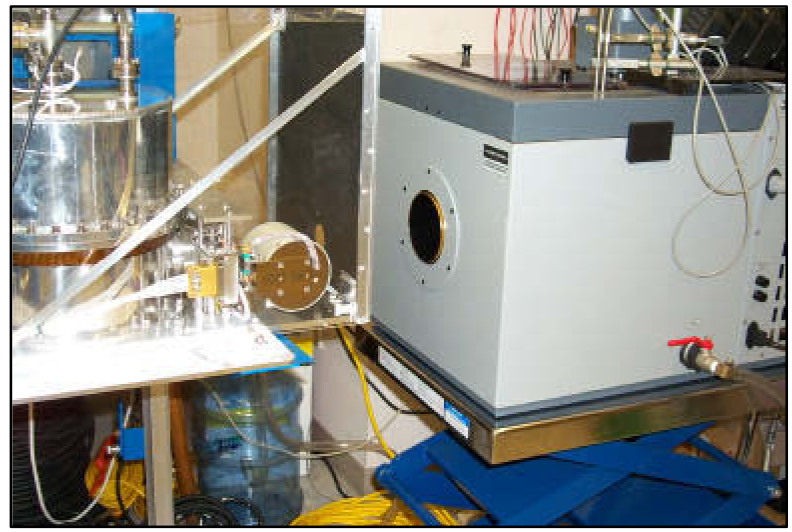
- Spectral range: 250 nm to 2500 nm
- Protocol: Assess accuracy of user calibration of working standard radiance sources using calibrated transfer radiometers
- Key Participants: NIST, UA, NASA/GSFC
- Comparisons held: Multiple, since 1993
- Characterizations: spatial and angular uniformity, temporal stability, repeatability
- Typical agreement: ~3% (visible), 4% to 10% (near infrared)



NASA Ames lamp-illuminated integrating sphere source

Spectral Radiance, TIR

- Spectral range: 5 µm and 10 µm
- Protocol: Assess accuracy of user calibration of working standard radiance sources using calibrated transfer radiometers
- Key Participants: NIST, NASA, NOAA, and affiliates UM, ITT, SBRS, LANL, CEOS/WGCV
- Comparisons held: Multiple, since 1999
- Typical agreement: 0.1 K
- VIIRS blackbody measured Jan/Feb 2004

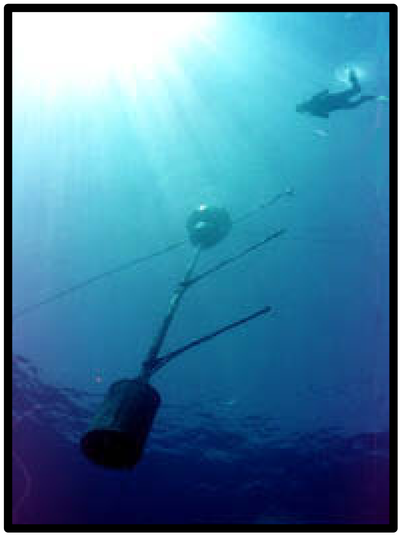


The TXR and the NIST WBBB at the Sea Surface Temperature Comparison in 2001 at the University of Miami.

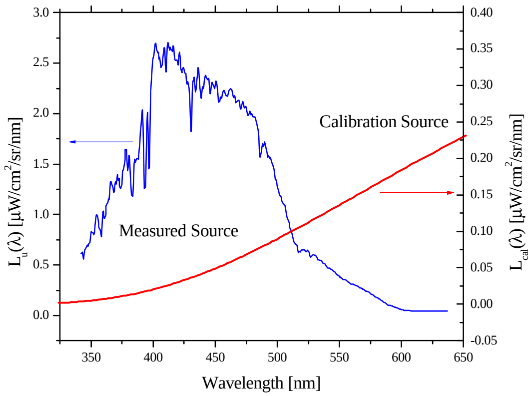
Instrument Characterization—Lessons Learned

Spectral Characterization

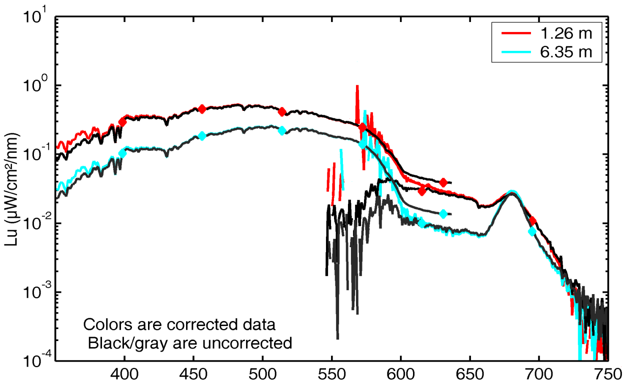
a) Stray Light Correction in Spectrographs



MOBY—for vicarious calibration of the sun-sensor-atmosphere-ocean measurement system (SeaWiFS, MODIS, etc.)



Spectral shapes of the known and the unknown sources are different!



Spectral shapes, in combination with stray light, resulted in unacceptable bias. Solution: SIRCUS characterization and SLC algorithm.

Impacts

Satellite Sensors: Gain coefficients for ocean color bands; fewer non-physical nLw's in the blue; on-orbit intercomparisons.

Bio-optical algorithm development: field radiometers subject to similar effects.

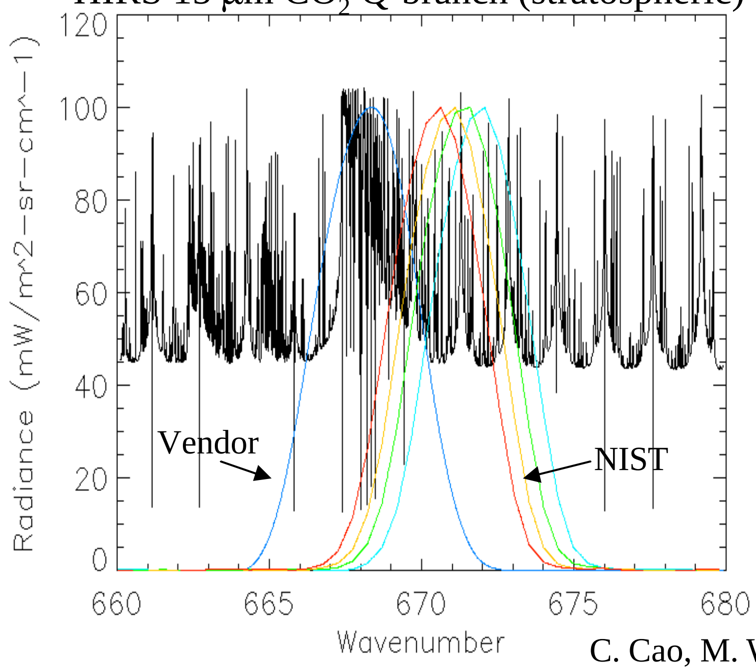
NOAA, MLML, NIST

Spectral Characterization

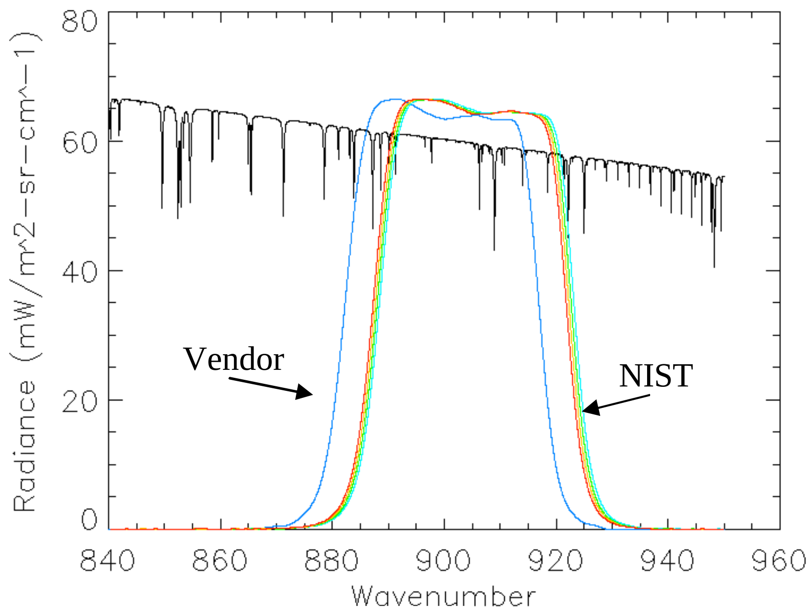
b) Spectral Transmittance

- NIST measurements (post launch) of witness samples using FTIR spectrophotometry (S. Kaplan and L. Hanssen)
- Vary sample temperature (15° C to 30° C); also possible to vary beam geometry (spot size, F/#, angle of incidence)
- **Impacts**: atmospheric temperature retrievals

HIRS 15 μm CO_2 Q-branch (stratospheric)



HIRS 11 μm window (surface)



C. Cao, M. Weinreb, S. Kaplan, CALCON 2004 Conf.

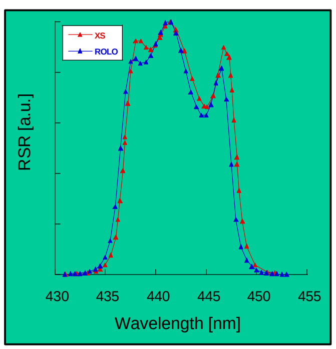
Spectral Characterization

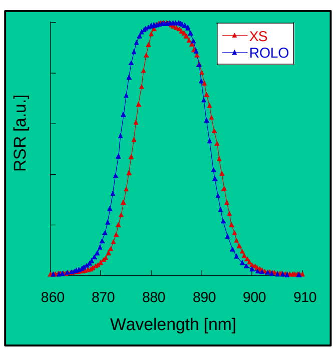
c) System Level Responsivity

Image: T. Stone & H. Kieffer

USGS Robotic Lunar Observatory (ROLO)—Dual Cassegrain telescopes with filter wheels. Sensor observes the moon from orbit; ROLO irradiance model allows for sensor intercomparisons and correction for in-flight degradation.

Issue: Filter transmittance data are from component measurements. Sensitivity to illumination geometry and other factors means system level relative spectral responsivity is necessary.





USGS, NASA, NIST

Solution: Fiber couple output of tunable laser system (Traveling SIRCUS) to a 0.5° collimator source assembly

Spatial Characterization
a) Scattered Light in Telescopes

The same USGS 0.5° collimator was designed as a standard source in order to establish traceability using laboratory standards, not values for Vega. Impact: Uncertainty in values assigned to this in-situ calibration standard (the Moon).

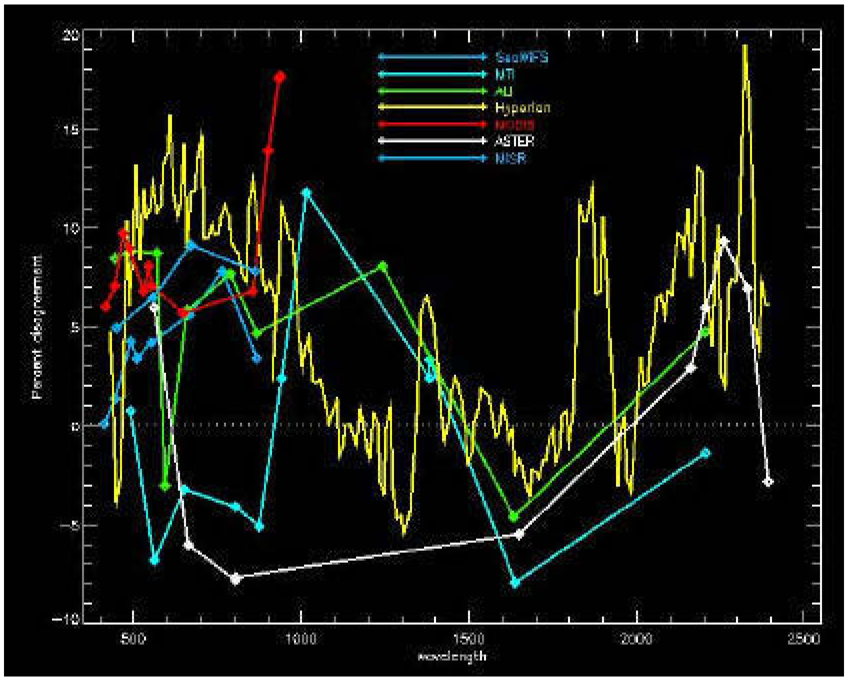
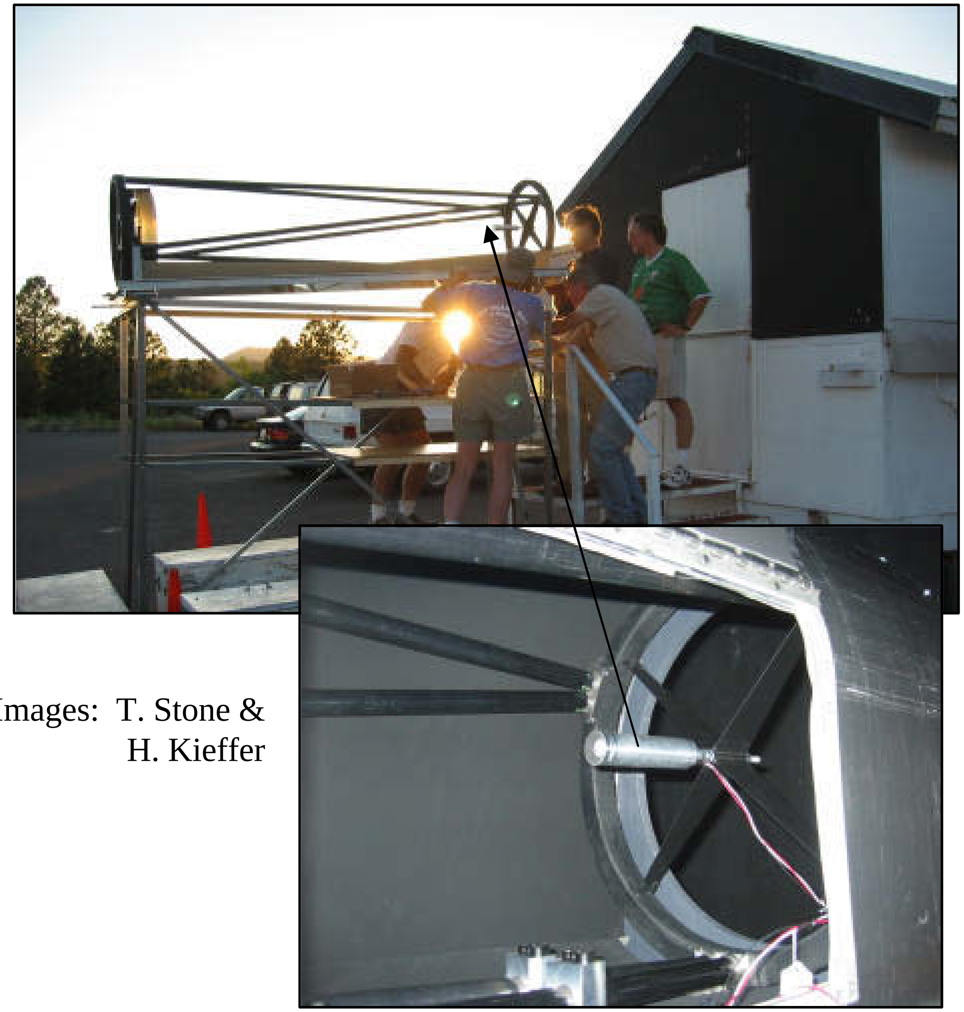


Image: T. Stone

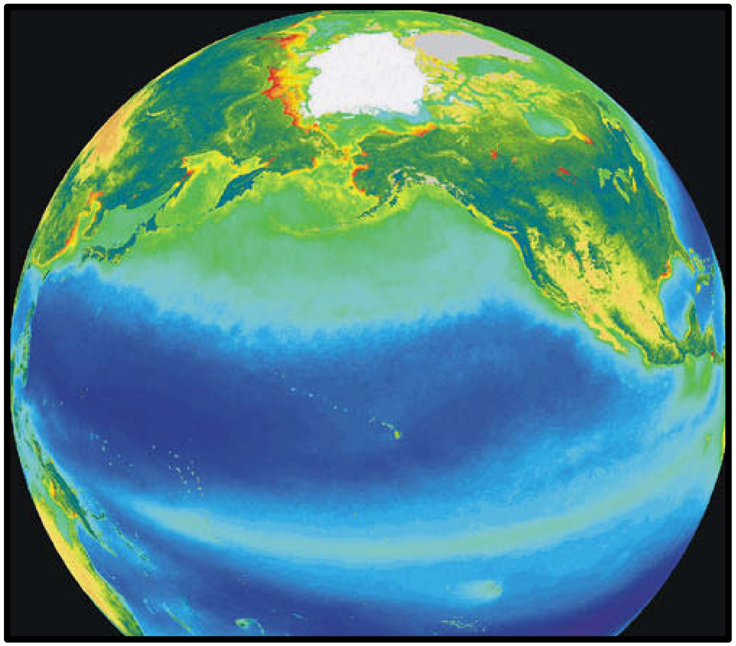


Images: T. Stone & H. Kieffer

Spatial Characterization
b) Response vs Scan Angle

Different sensors sample the solar illumination / sensor view parameter space differently, with different telescope designs. The BRDF of the oceans must be known to compare sensors and compute nLw. Angle dependent changes in throughput and polarization for the sensor must be known for accurate Level 2 products. Understanding of bright targets (clouds, coastline) recovery is essential.

SeaWiFS



MODIS

Images: http://oceancolor.gsfc.nasa.gov and ORBIMAGE

Recommendations for Level 2

- Measurements are the best way to assess claims of traceability
- Measurement system errors and insufficient instrument characterization are common problems and lead to misleading results for on-orbit sensor intercomparisons
- Essential program elements
  - Traceability for values assigned to all results (radiances, products, global averages).
  - Thorough pre-flight characterization in synergy with careful evaluation by end user (look at the data!)
  - Robust method to account for on-orbit degradation
  - This rigorous approach must be duplicated for in situ vicarious calibration and validation approaches
  - Research and development for fundamental measurement systems and associated standards (e.g., absolute lunar and solar radiometry, blue-rich calibration sources (LEDs), mechanisms responsible for degradation or drift, novel sources or radiometers, and so forth)
- Great benefit in long term collaborative relationships with calibration experts

NIST Participants

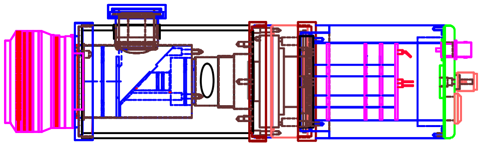
- David Allen
- Steve Brown
- Amanda Cox
- Ted Early
- George Eppeldauer
- Joel Fowler
- Charles Gibson
- Leonard Hanssen
- Carol Johnson
- Simon Kaplan
- Tom Larason
- Keith Lykke
- Jorge Neira
- Joe O'Connell
- Jim Randa
- Joe Rice
- Bob Saunders
- Ambler Thompson
- Toni Litorja
- Howard Yoon
- Jun Zhang

Backup Slides

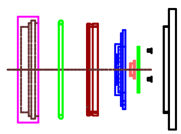
Transfer Radiometers, “EOS Era”

Standard Lamp Monitors (SLMs)—
radiance or irradiance foreoptics

Radiance (lens)

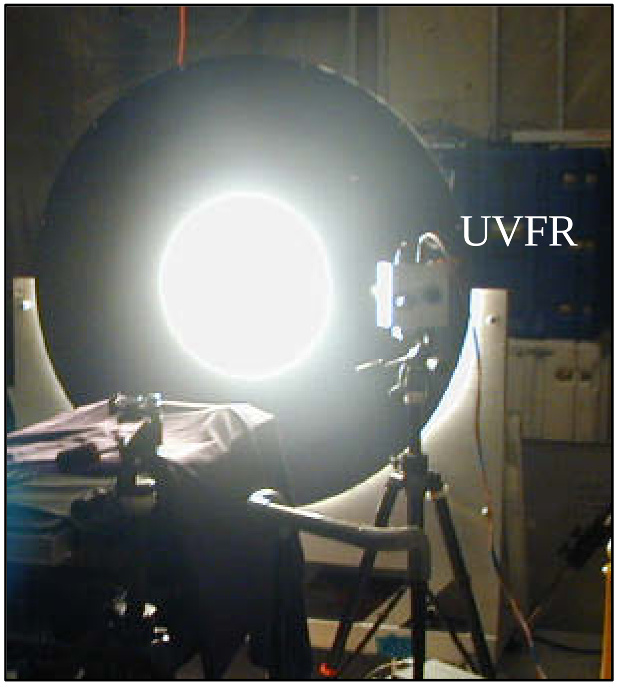


Irradiance (cosine collector)



NOAA/NESDIS MOBY Project

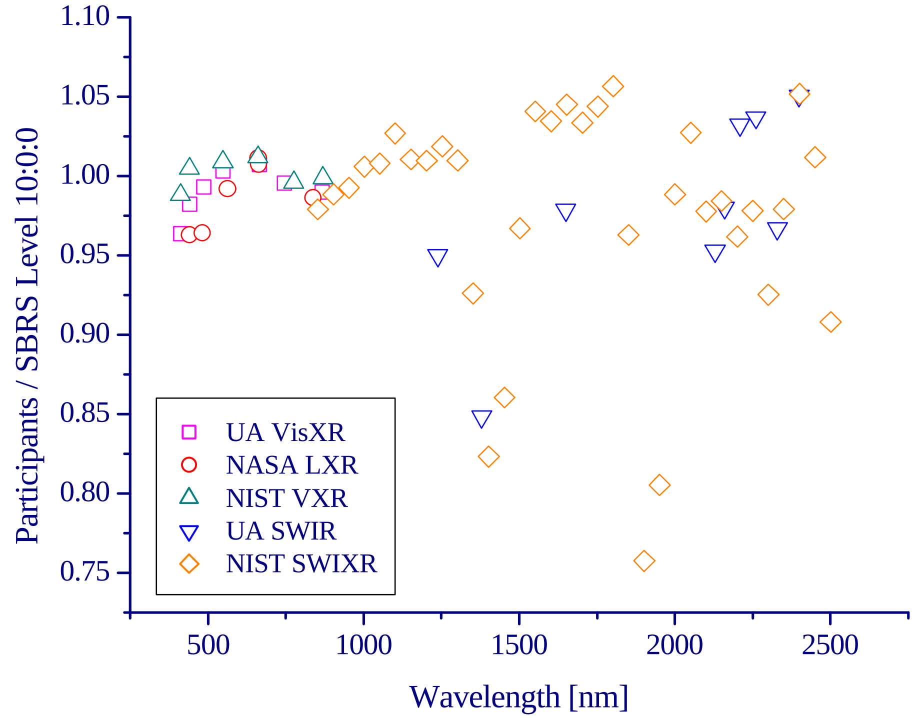
Filter radiometer—trap detector and irradiance or radiance foreoptics



NASA/SIO/EPIC Project

Example Results

- MODIS requirements: 5 %
- Sphere used for MODIS and ETM+ calibration
- NIST-traceable using spectral irradiance lamps and the “lamp/plaque” method
- Ignore results in regions of variable atmospheric absorption (water vapor and CO_2)—this results in large scatter
- Level of agreement assessed in terms of stated uncertainties for the source and transfer radiometers

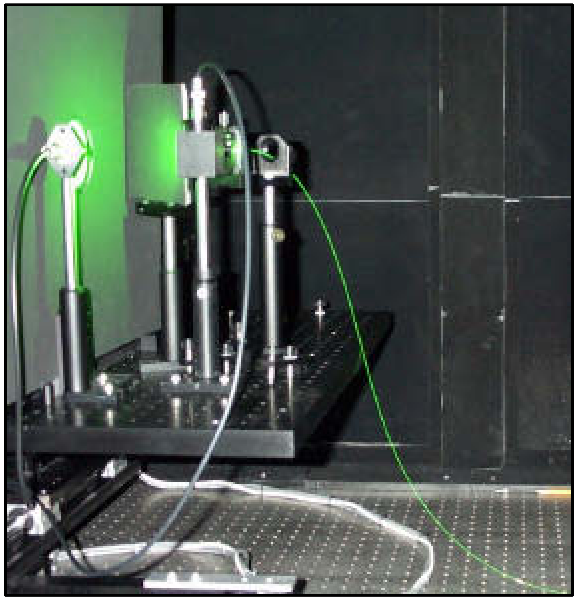


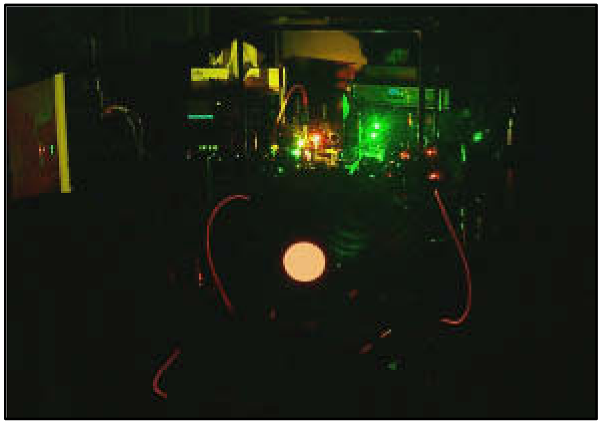
Spectral Characterization

Facility for Spectral Irradiance and Radiance Responsivity (SIRCUS)

Detector – based facility for determination of absolute spectral irradiance or radiance responsivity of optical sensors

Basic technique: Reference detectors calibrated using cryogenic electrical substitution radiometry; laser illuminated integrating sphere sources for monochromatic characterization and calibration of radiometers; variety of laser systems provide tunable coverage: UV, visible, near-IR, & IR

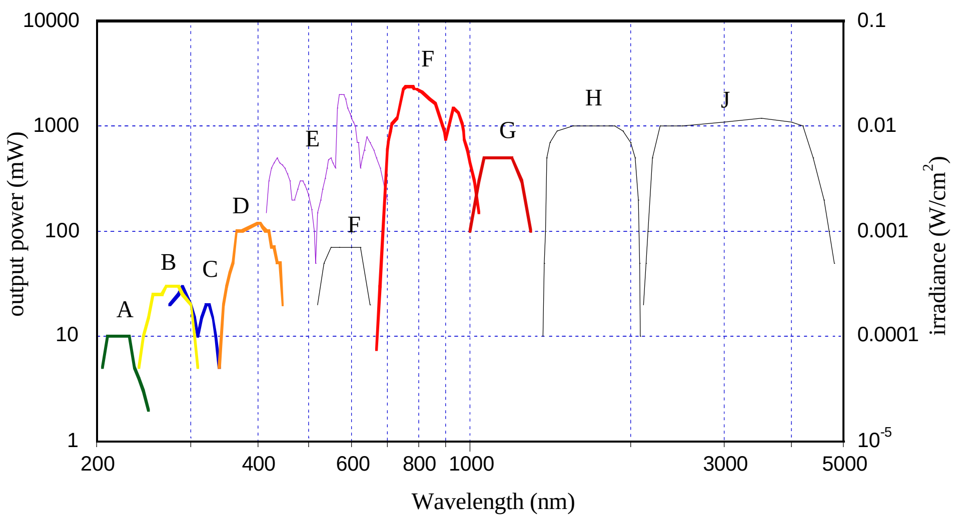


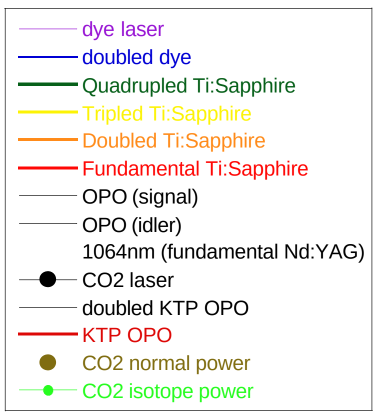


Low uncertainties: 0.1 % to 0.2 % (k = 2)

Validation methods: absolute determination of the freezing point of gold and silver; comparisons with the NIST Synchrotron Radiation User Facility (SURF III)

SIRCUS & Spectral Characterization





Accomplishments in Remote Sensing

- •Robotic Lunar Observatory (ROLO)
- •Marine Optical Buoy (MOBY)
- •Earth Polychromatic Imaging Camera (EPIC)
- •Goddard Space Flight Center Transfer Spectroradiometer (GSFC 746/ISIC)
- •Sun Photometers (SIMBIOS, AERONET)

Impacts

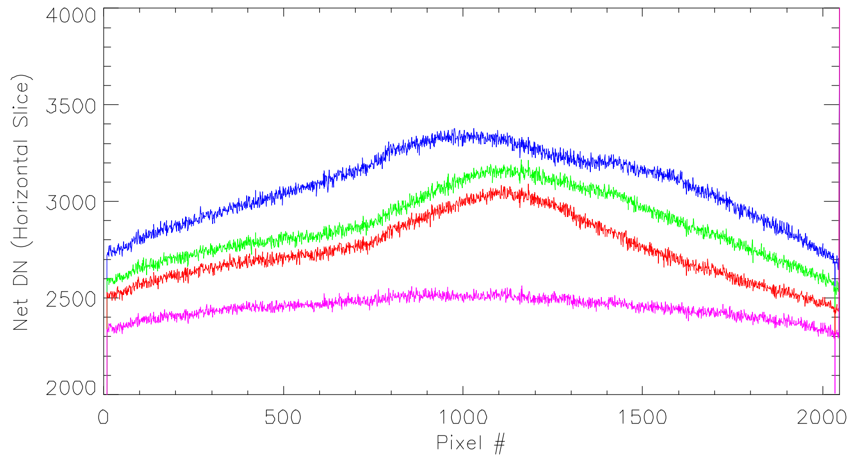
- •On-board calibration & degradation corrections
- •Accuracy of ocean color products (e.g. chl a)
- •Novel measurements (DSCOVR at L1)
- •Accuracy of aircraft validation sensors
- •Atmospheric correction procedures

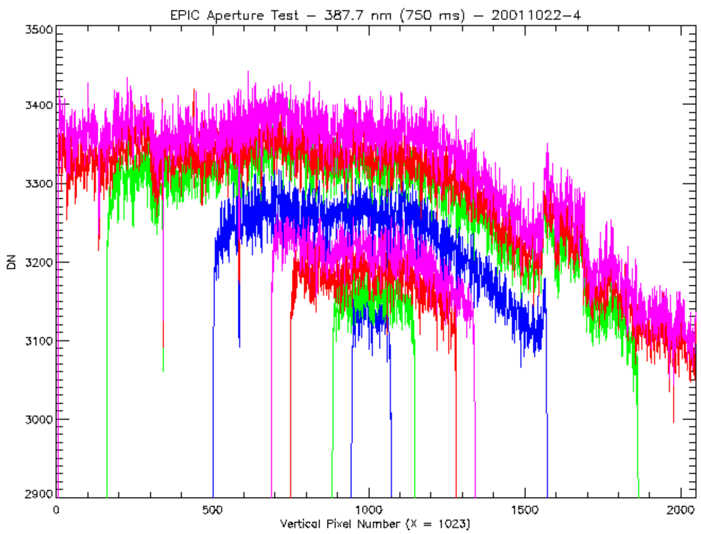
Traveling SIRCUS

Spatial Characterization (EPIC)

Issue: Radiance calibration of imaging systems with Cassegrain-type foreoptics

Near field source of constant radiance that overfilled the entrance pupil gave distance dependent results (this is non-physical, radiance is independent of distance!)





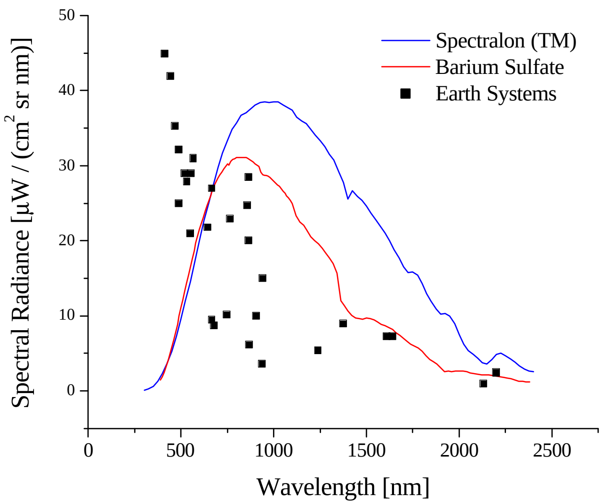
Use of a collimated source provided the required characterization as well as a more accurate radiance calibration

Novel Sources for Remote Sensing

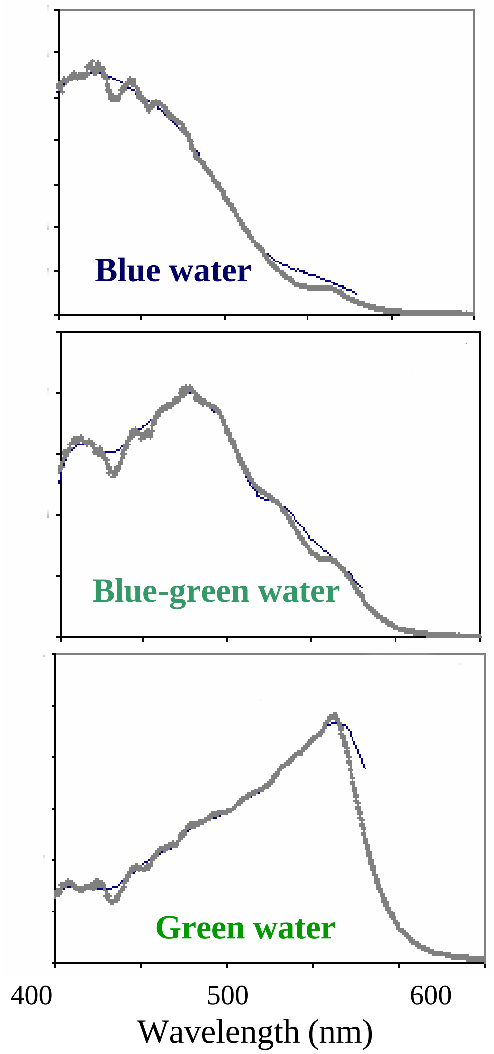
Solid-state LED Calibration Sources

Advantages:

- Controllable output 350 nm to >900 nm;
- Higher flux in UV and blue;
- Compact, light-weight, low power consumption;
- Good temporal stability;
- Shock resistant;
- Provides a great deal of flexibility in source design;
- Enables derivation of sources with unique spectral distributions.



Match target spectrum using multiple LEDs



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