Calibration of Earth-Viewing Satellite Sensors

Steve Brown, Leonard Hanssen, Carol Johnson, Keith Lykke,
Steve Maxwell, Joe Rice, Ping-Shine Shaw,
John Woodward, and Yuqin Zong

Presented by Joe Rice

Outline

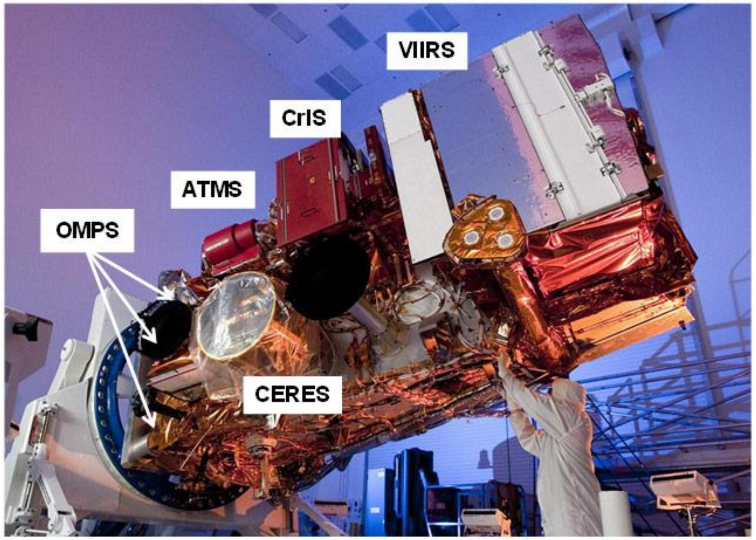
- Overview of Earth-viewing satellite sensors
- Overview of NIST sensor calibration capabilities
- Examples, with results and impacts
- Future directions

Overview of Satellite Programs & Sensors

Example Operational Satellites and Sensors (ongoing)

- Geostationary Operational Satellite System (GOES-R)
  - Advanced Baseline Imager (ABI)
  - Space weather sensors
- Joint Polar Satellite System (JPSS)
  - Advanced Technology Microwave Sounder (ATMS)
  - Cross-Track Infrared Sounder (CrIS)
  - **Visible Infrared Imaging Radiometer Suite (VIIRS)**
  - Ozone Mapping and Profiler Suite (OMPS)
  - Cloud and Earth Radiant Energy System (CERES)
- Landsat Data Continuity Mission (LCDM)
  - Operational Land Imager (OLI)

Suomi National Polar-orbiting Partnership (NPP)



Example Current NASA Scientific Satellites (sensors exist)

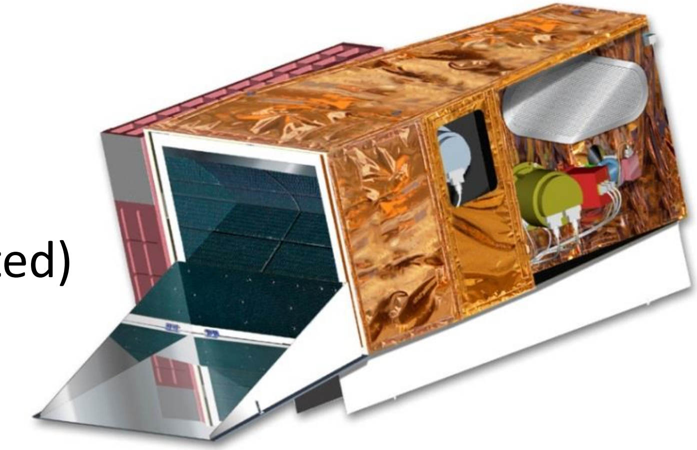
- Earth Observing System (all flying and near end of life – some similar sensors on JPSS)
- Orbiting Carbon Observatory-2 (OCO-2) (Launched in July 2, 2014)
- Stratospheric Aerosol and Gas Experiment (SAGE-III) (Planned launch 2015)
- NIST Advanced Radiometer (NISTAR) and EPIC (On DSCOVR Planned launch in 2015 to L-1 orbit)

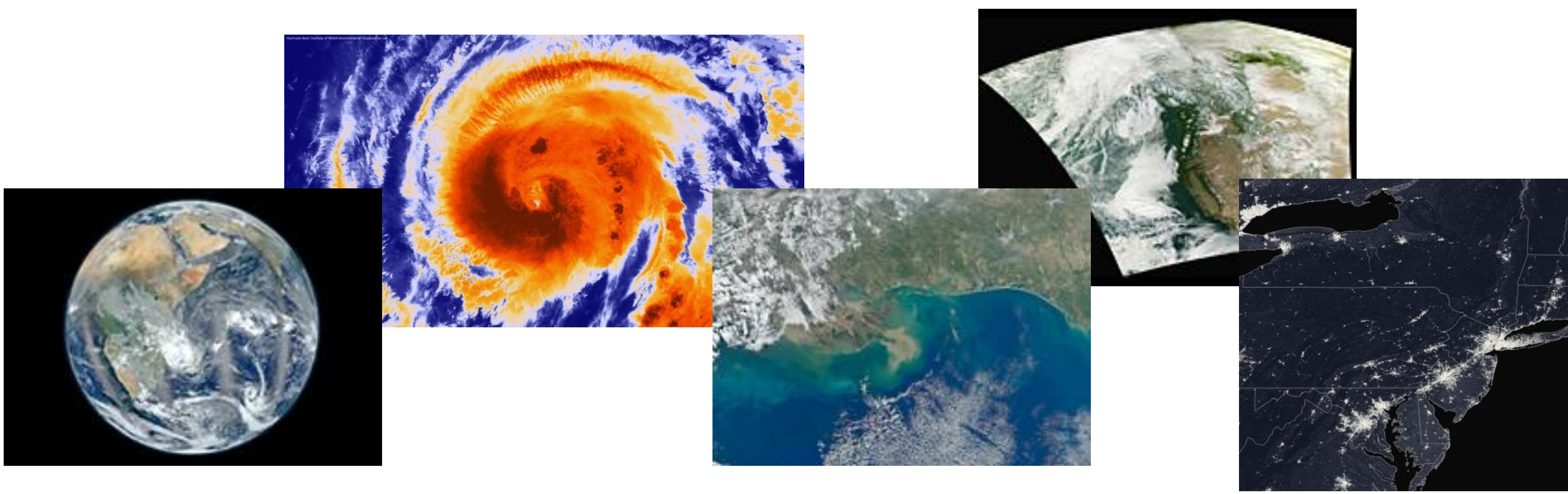
Example Future NASA Satellite Missions (still in formation stage)

- Ocean Radiometer for Carbon Assessment (ORCA) for PACE and/or ACE missions
- Climate Absolute Radiance and Refractory Observatory (CLARREO)
- Hyperspectral and InfraRed Imager (HyspIRI)

Example: VIIRS Sensor
(Visible Infrared Imaging Radiometer Suite)

- Ocean color (Carbon/Biomass-related)
- Sea surface temperature
- Aerosol characteristics
- Vegetation index (Carbon/Biomass-related)
- Land and Ice temperature
- Fire detection and monitoring

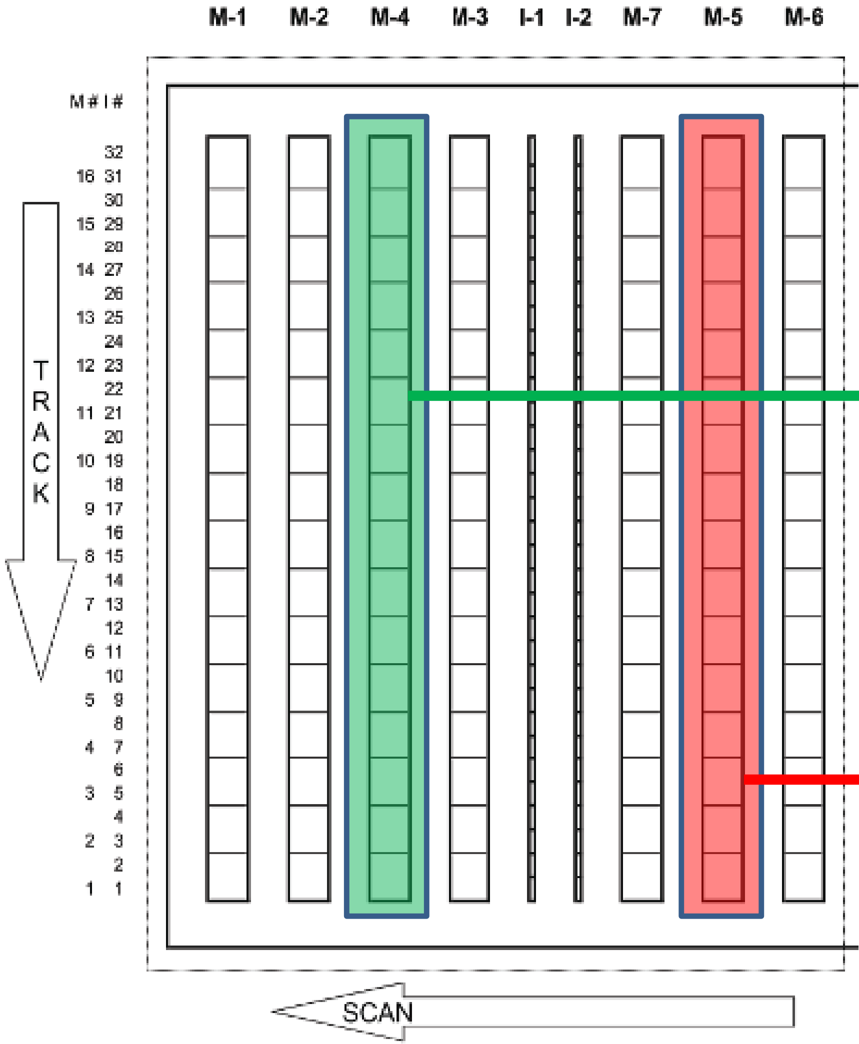




Imagery Weather Ocean Color Clouds Low light Imaging

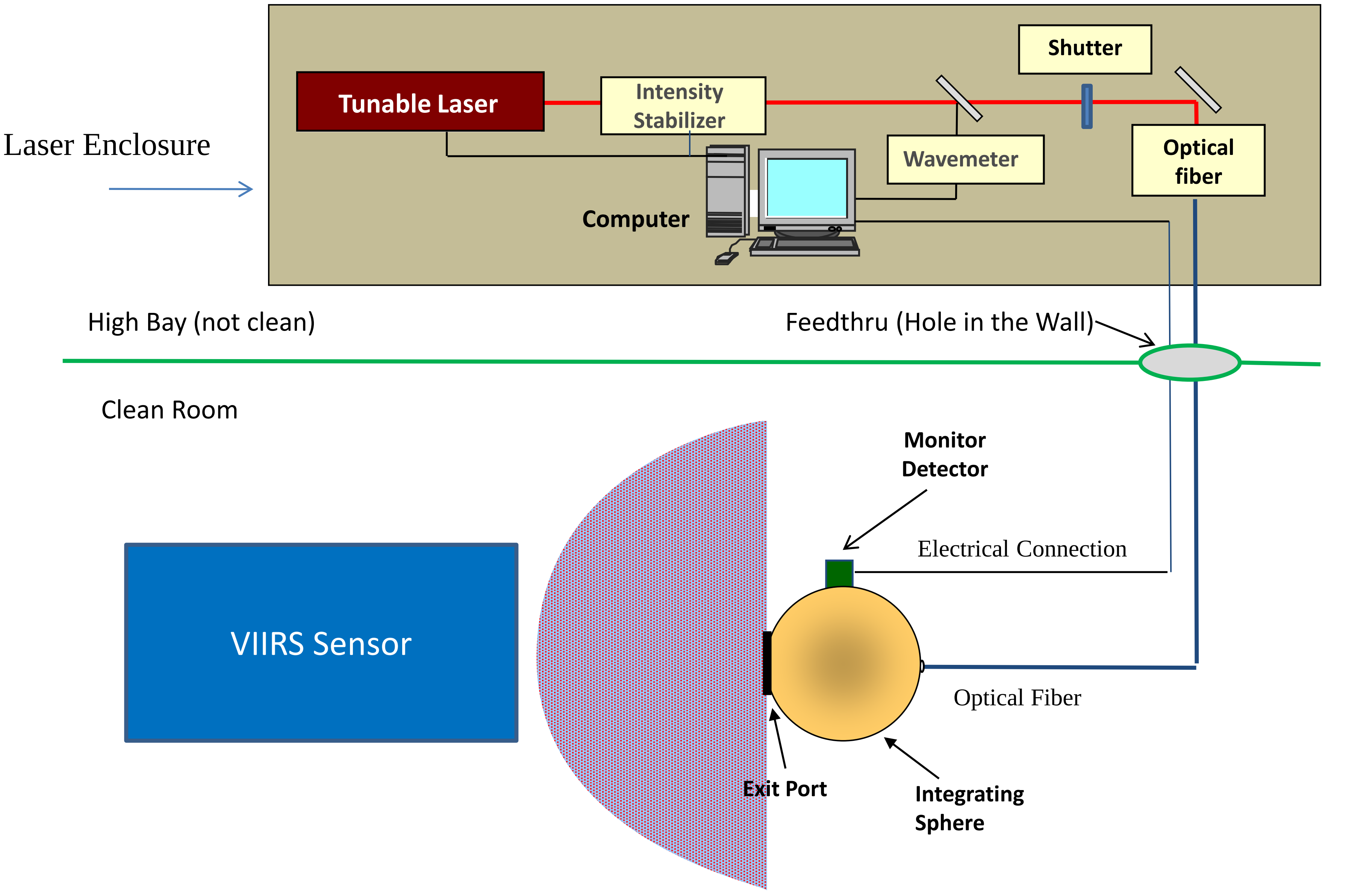
VIIRS has Detector Arrays with Filters

- 16 detectors in a column along satellite track direction
- Each column at a different wavelength band
- Calibration: Determine the responsivity of each detector



Band	Wavelength [nm]
M1	412
M2	445
M4	555
M3	488
I1	640
I2	865
M7	865
M5	672
M6	746

Traveling Spectral Irradiance and Radiance Responsivity with Uniform Sources (T-SIRCUS)

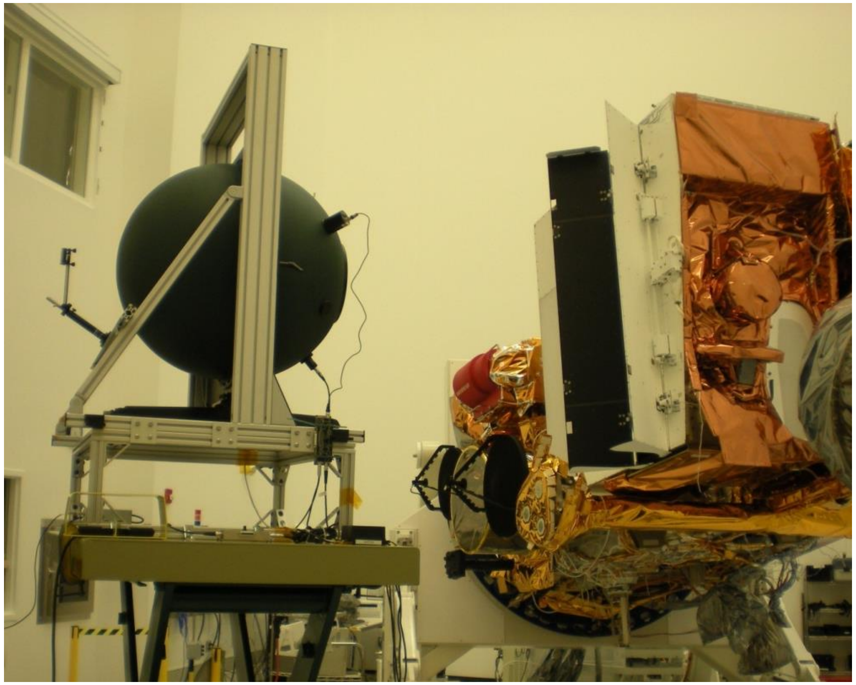


T-SIRCUS used for Suomi NPP VIIRS

Radiance responsivity illuminating VIIRS Earth Port with an integrating sphere
Irradiance responsivity illuminating VIIRS solar port with a collimator

SpIS in front of VIIRS Earth Port

Nadir doors are open

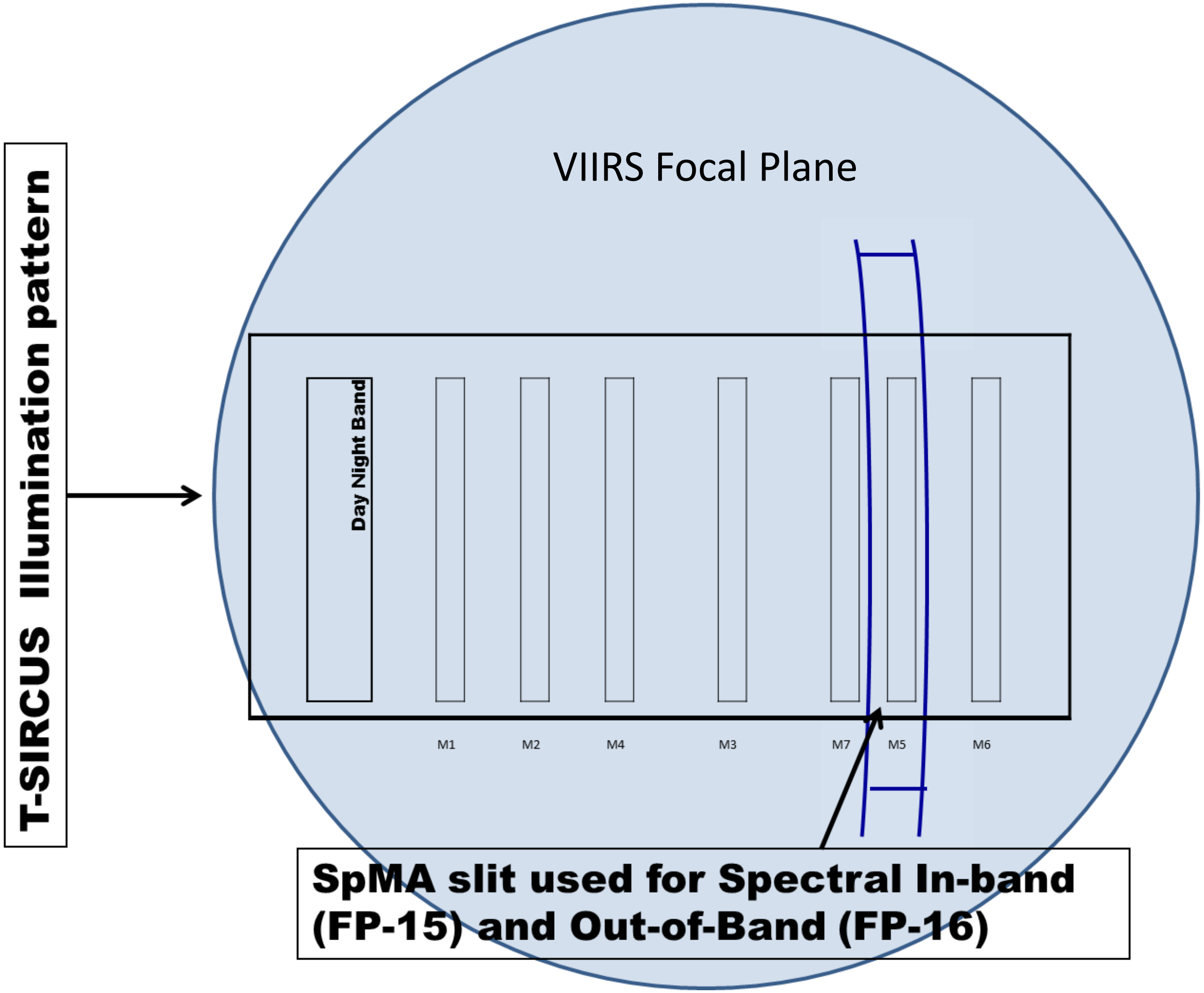


Can achieve ~0.1 % uncertainties in the sphere radiance

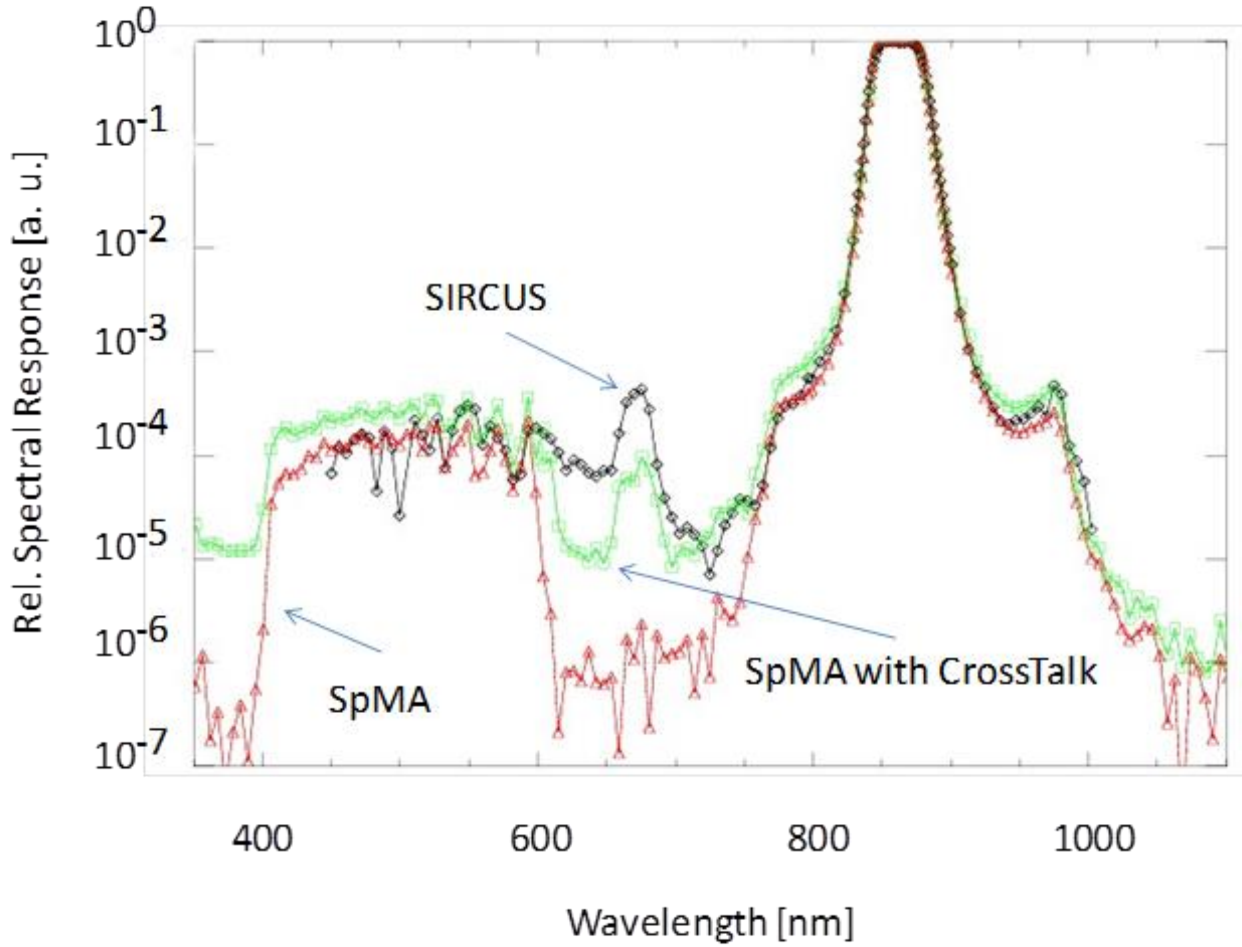
Collimator illuminating VIIRS solar port

Collimator irradiance uncertainty depends on beam uniformity

- T-SIRCUS provides full-aperture system-level calibration
- Traditional monochromator (called the SpMA here) is not full-aperture



Example Result: VIIRS Band M7, Detector 8
Optical Cross-talk



*resolved questions about the magnitude of the optical cross-talk and showed that it was small relative to the IB signal

David Moyer, Aerospace Corp.

T-SIRCUS value added to the calibration of NPP VIIRS

- T-SIRCUS provides a significant improvement in the radiance responsivity and the spectral registration calibration (smile) compared to what was done for EOS-MODIS. *Both improvements were by "more than a factor of 10".*
  - Wavelength uncertainty lower (< 0.1 nm v. 0.5 nm)
- Validated optical cross-talk coefficients
  - Established the magnitude of the optical cross-talk (small)
  - Relieved community concerns about the validity of the ocean color data products

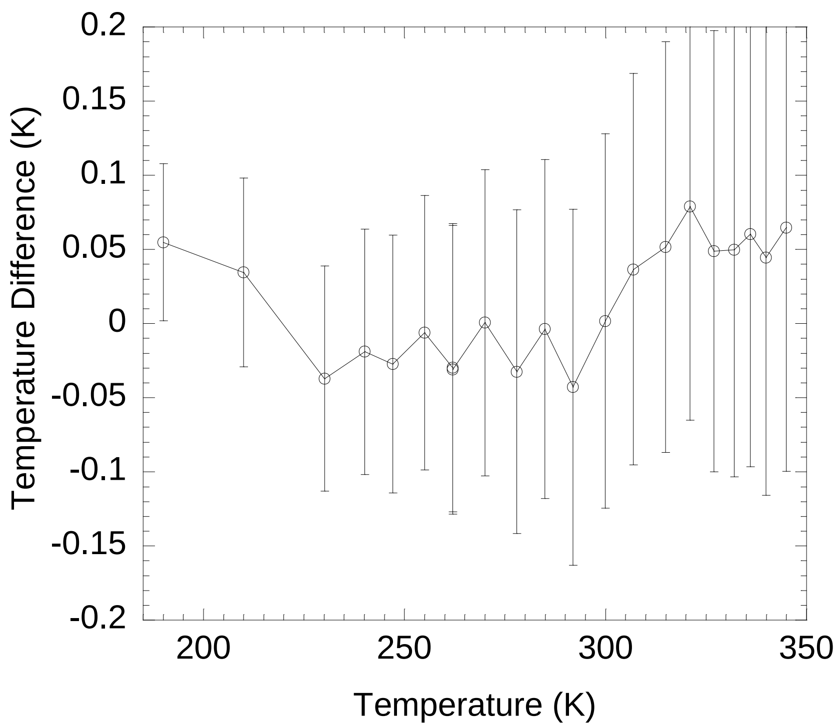
- As a result of the successful NPP VIIRS testing, JPSS-1 VIIRS calibration using T-SIRCUS is scheduled for Fall 2014

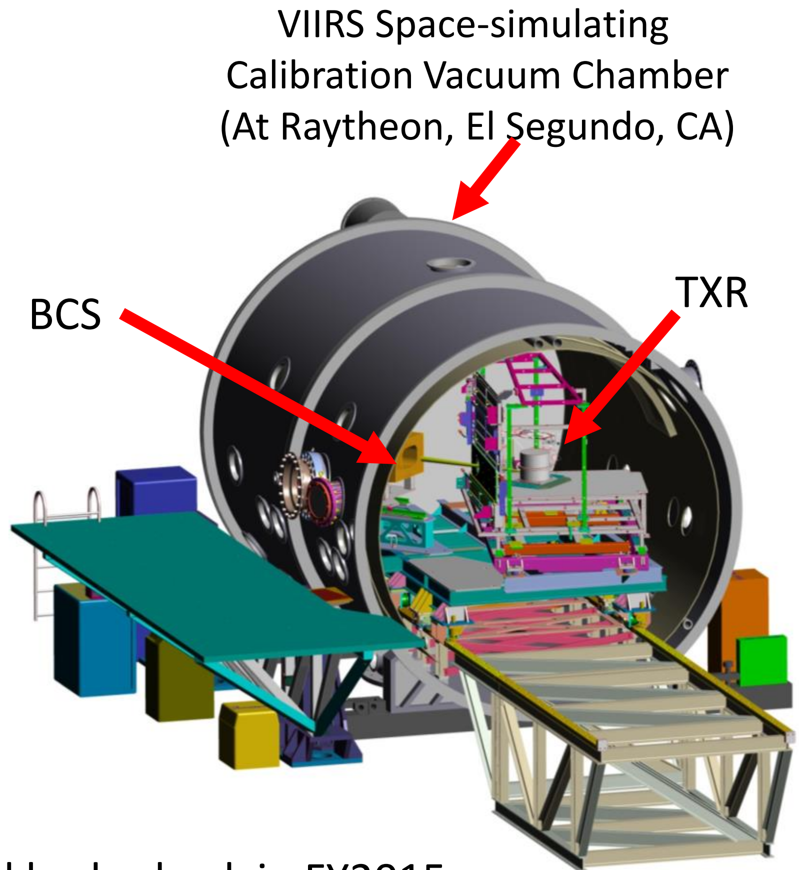
- Refinements to the T-SIRCUS system
  - Improved lasers
  - Improved Sources
    - A 1-m Spectralon sphere replaces the 30 inch diameter barium sulfate sphere
    - Fiber-optic-based source called the FPI
      - Greater dynamic range
      - Operates in-vacuum; may be used to provide a calibration of the VIIRS SWIR bands during Thermal Vacuum (TVAC) testing

T-SIRCUS measurements took about half the time as the SpMA measurements.
*cost and schedule savings with T-SIRCUS

Verification of JPSS VIIRS Blackbody Calibration Source (BCS) Radiance Temperature Using the NIST Thermal-infrared Transfer Radiometer (TXR)

- The difference between TXR Radiance Temperature at 10 um and BCS Effective Temperature
- Error bars are current k=1 uncertainty estimates for TXR-measured Radiance Temperature
- Work is in progress to reduce these uncertainties
- Verifies that standard used for VIIRS Thermal-Emissive Bands calibration agrees with NIST
- Impacts VIIRS sea-surface and land-surface temperature calibration





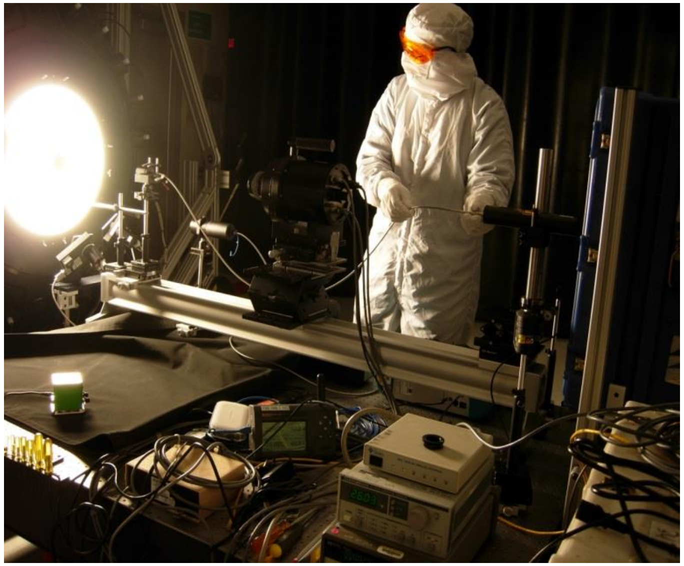
Currently upgrading TXR to use for JPSS CrIS blackbody check in FY2015

GOES-R Advanced Baseline Imager (ABI)

ABI is a multi-spectral filter radiometer in Geostationary Orbit

What NIST Did:

- Validated the radiance from the large lamp-illuminated integrating sphere used for ABI calibration at Exelis
  - ➢ Used the NIST transfer standards below
- Validated the radiance from the large vacuum-chamber blackbody used for ABI calibration at Exelis (the ABI vendor)
  - ➢ Use the NIST TXR
- Measured the ABI filter transmittance functions from witness filters, which served to validate the spectral responsivity functions used for all of the ABI bands



NIST Transfer Standard	Sub-systems	Spectral coverage [nm]	Bandpass (sampling) [nm]
Spectral radiance standard (NPR)	4 lamps, 2 internal filtered photodiodes	250 to 2500	10
Filter radiometer (VXR)	6 channels	412 to 870	10
SR-3500 spectroradiometer	VNIR SWIR1 SWIR2	342 to 1000 980 to 1894 1860 to 2505	3.5 (0.8 – 1.5) 10 @ 1500 (3.3 – 4) 7 @ 2100 (2.1 – 2.9)
FieldSpec 3 spectroradiometer	VNIR SWIR1 SWIR2	350 to 1000 1001 to 1800 1801 to 2500	3 @ 700 (1.3) 10 @ 1400 (2) 10 @ 2100 (2)

Orbiting Carbon Observatory (OCO-2)

OCO-2 will map CO_2 globally using the 1.6 micron band

What NIST Did:

- Assisted with integrating sphere and spectrometer operation and analysis
    - Sphere loading issues investigated

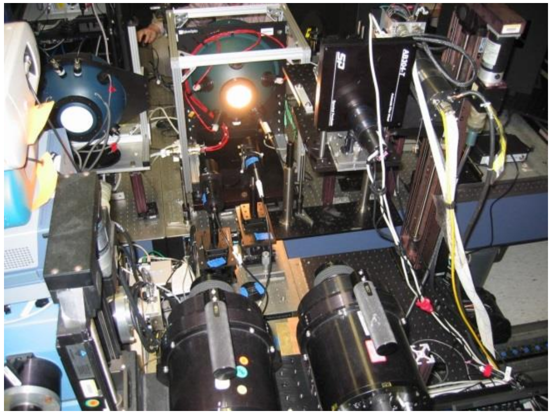
- Calibrated the integrating sphere on site at JPL
    - Used NIST transfer standards

- Aided in development of background subtraction methods for flight instrument

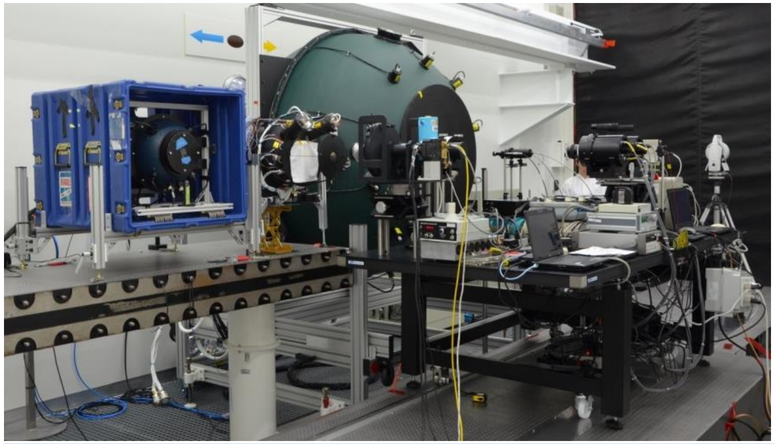
Operational Land Imager (OLI)

What NIST Did:

- Multi-year spectrometer and sphere weekly tracking and intercomparison/validation
- With NASA and OLI-calibration collaborators



OLI-Related: ESA Sentinel-2 Lamp-illuminated Integrating Sphere Radiance Scale Comparison

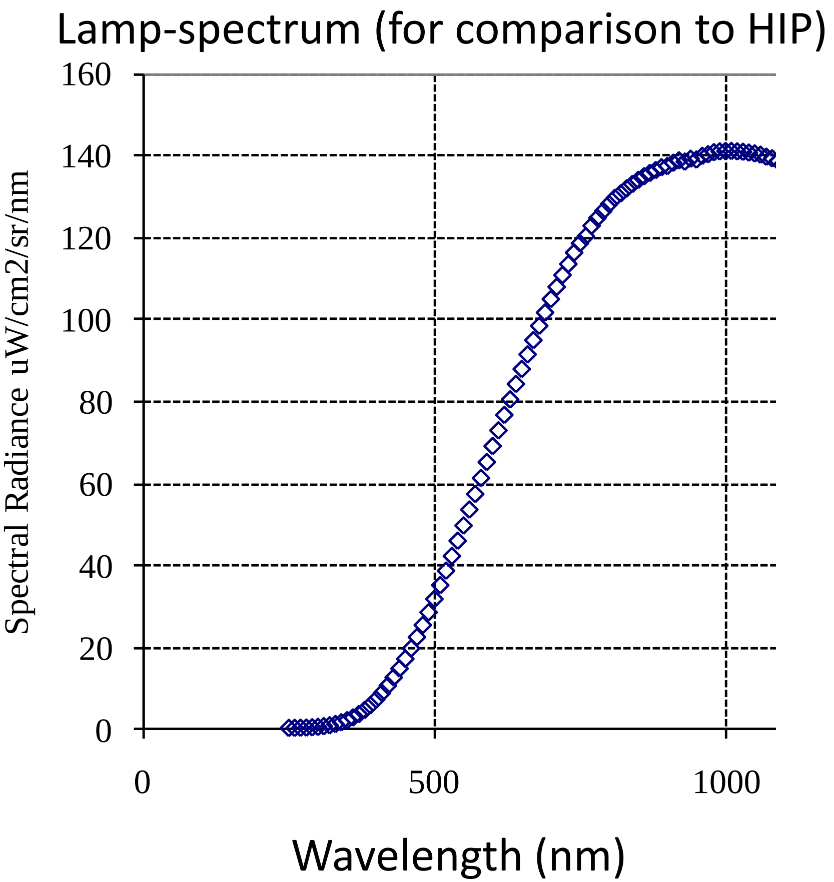


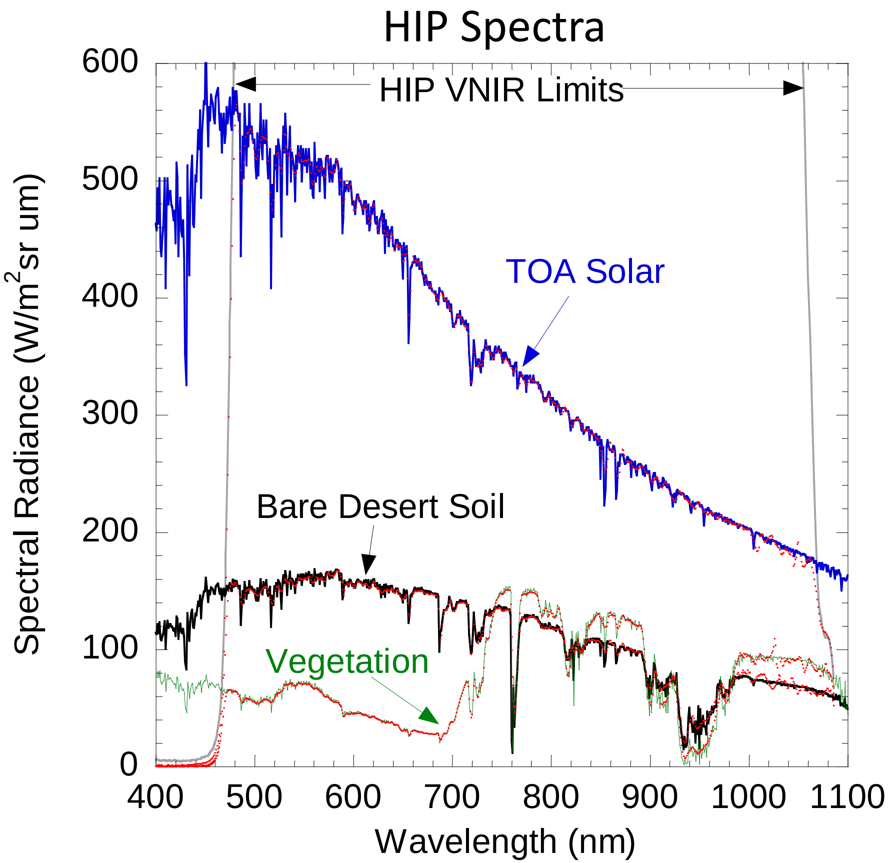
From left to right, the sphere sources (NPR, the SWIR and VNIR) were mounted next to the back wall of the cleanroom. In front there was a low table that supported a moving table that held the radiometers. From left to right are the UAVNIR, the UASWIR, the LXR, the VXR, the fiber coupled spectroradiometers, and the OL770.

- Assisted with validation and debugging of calibration procedure

Future: Hyperspectral Image Projector (HIP)

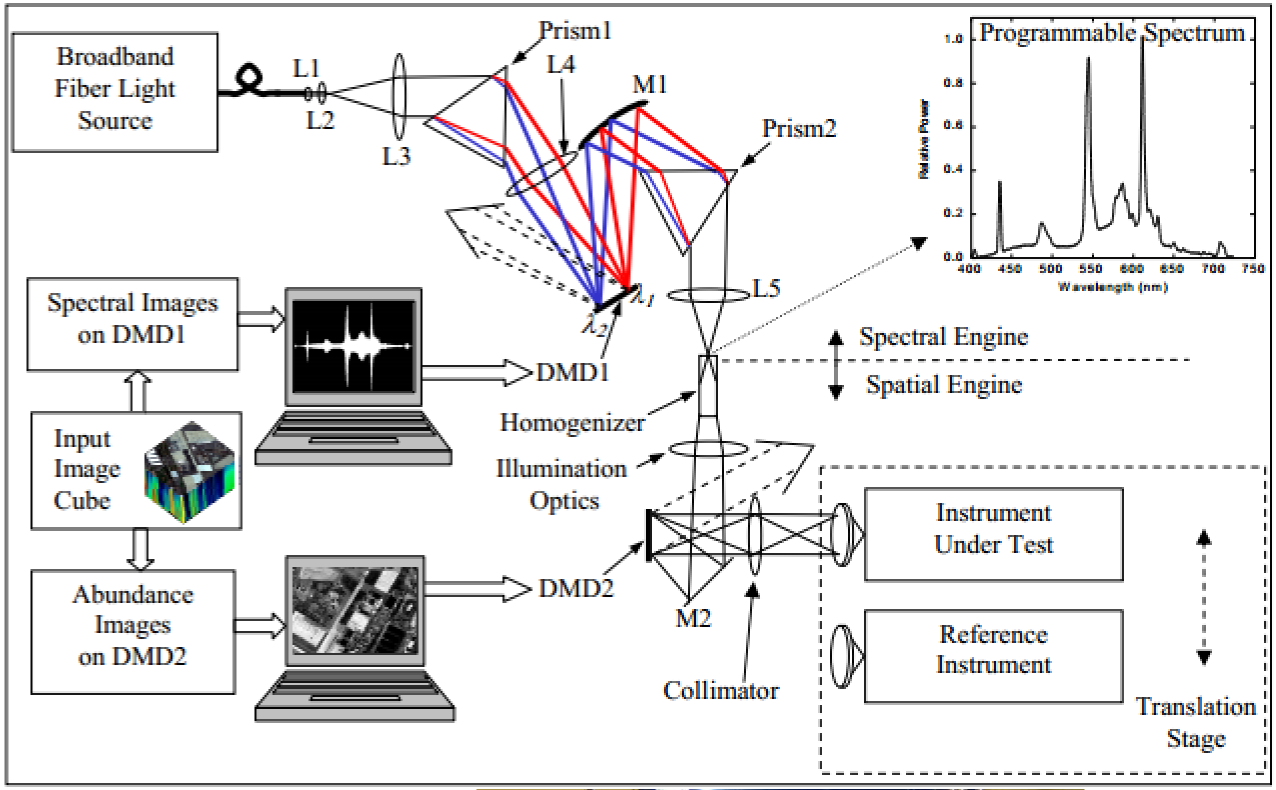
- The HIP is a NIST scene projector providing high resolution spectra at each spatial pixel.
- Using this for sensor testing prior to flight could validate designs and avoid future problems.
- **Red** data below right shows actual HIP output spectra matched to some typical Earth-reflected spectra, shown in other colors, including Top-of-Atmosphere (TOA).
- This demonstrates that the HIP can simulate the scene from a bright sunny day outside.





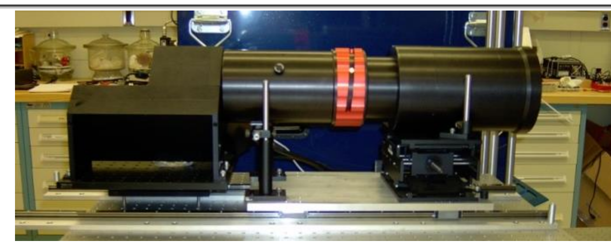
NIST Hyperspectral Image Projector (HIP)

Spectral Engine



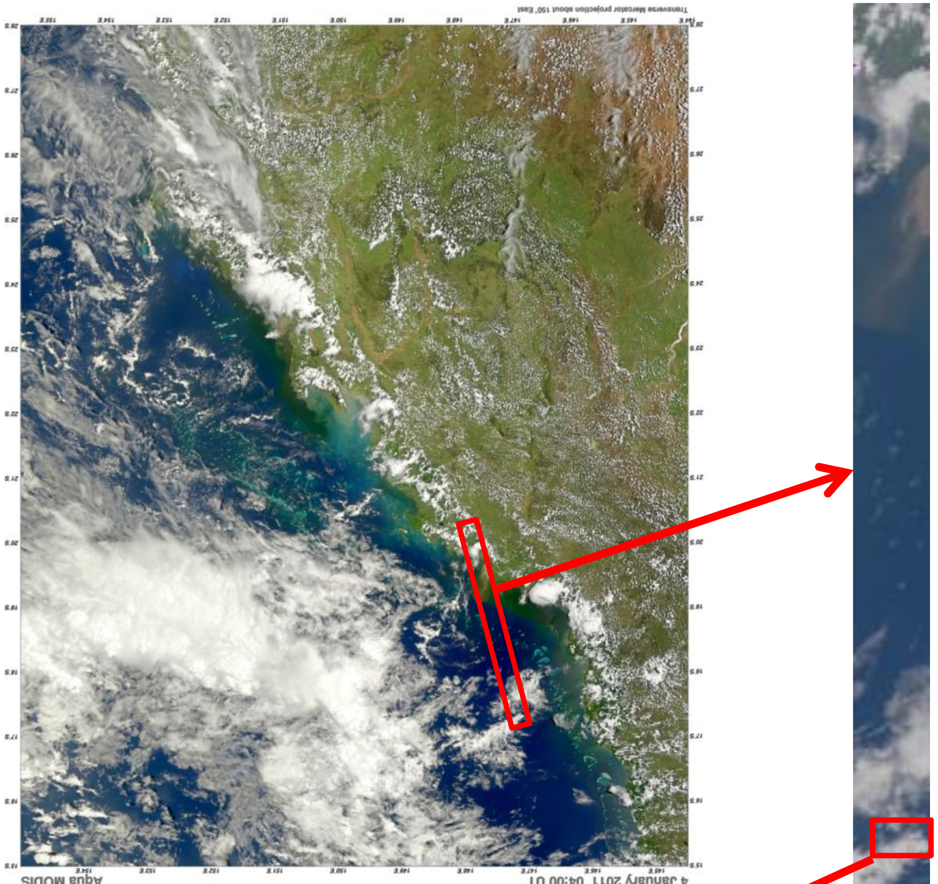
DMD

Spatial Engine



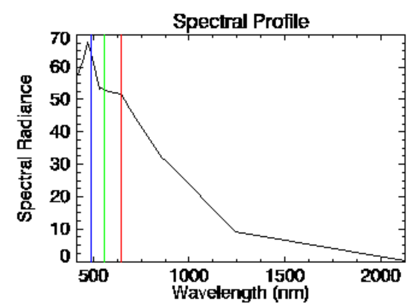
- Spectral and spatial image control using Digital Micromirror Devices (DMD)
- DMD1 controls spectrum, while DMD2 generates the spatial information
- Instrument Under Test is customer’s multispectral or hyperspectral imager

HIP Projection of Satellite Imagery Into ORCA Prototype in the Lab

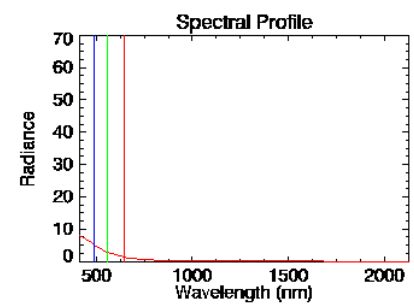


- NASA ORCA is a proposed future satellite (Ocean Radiometer for Carbon Assessment).
- Clouds provide stray light that interferes with the ability to measure ocean color and bio-chemistry to quantify carbon processes.
- HIP difference images (below) enable measurement of stray light effects with realistic scenes before ORCA flies.

Typical Cloud Pixel



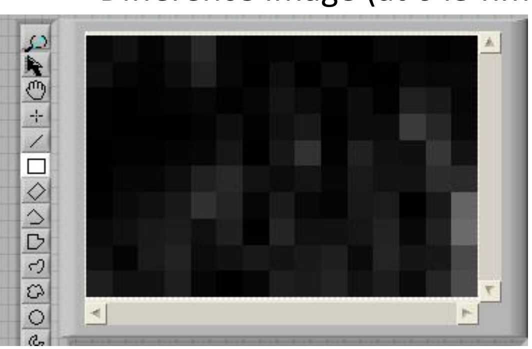
Typical Ocean Pixel



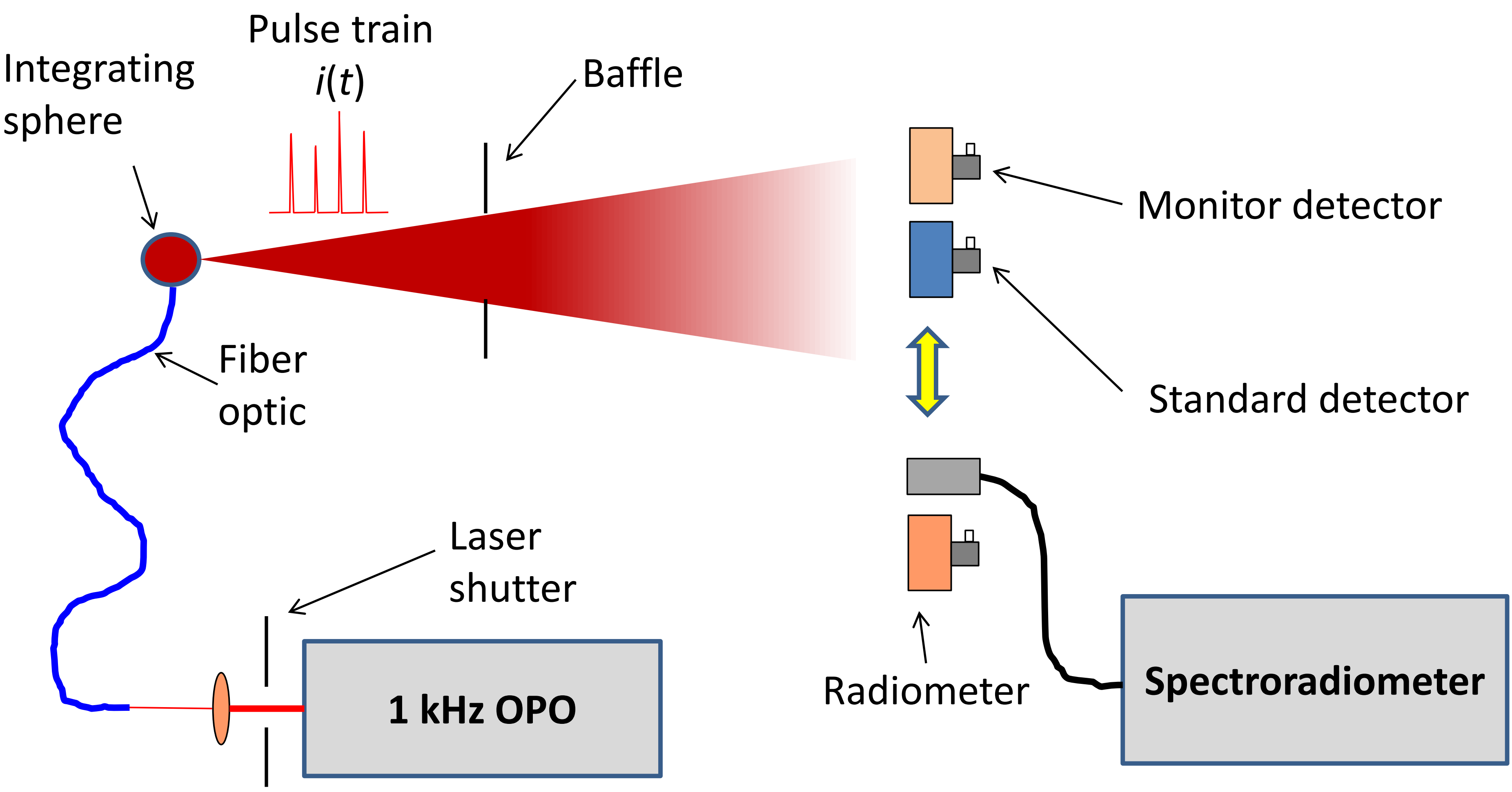
Original Image

HIP Image Measured by ORCA

Difference Image (at 645 nm)



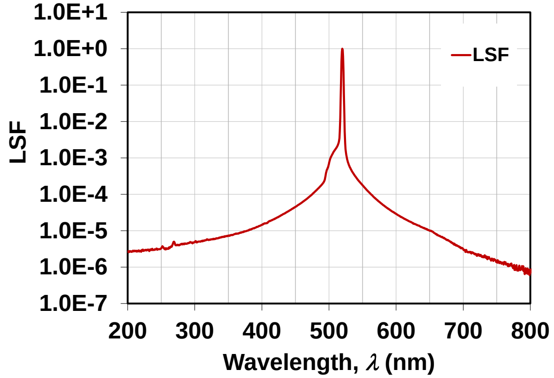
Future: SIRCUS-type calibration of sensors using 1kHz OPO



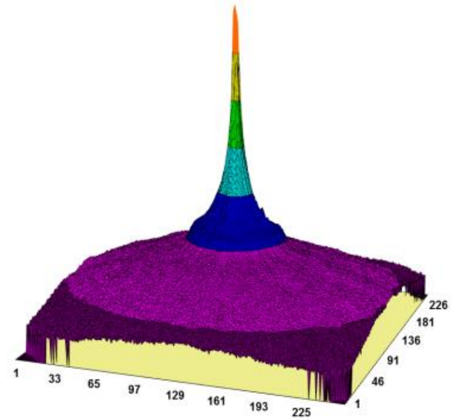
- Use energy mode (dose) instead of power mode
- Use charge amplifiers instead of trans-impedance amplifiers
- This method more easily enables tuning automation

Future: Stray-light correction for spectrometers & imagers

Spectrometer's Line Spread Function (LSF)



Imager's Point Spread Function (PSF)



$$\boxed{\mathbf{Y}_{\text{true, }n\times 1}} = \boxed{\mathbf{C}_{n\times n}}\,\boxed{\mathbf{Y}_{\text{meas, }n\times 1}}$$

True signals **Correction matrix** **Raw signals**

- Simply, fast matrix methods; reduced stray-light errors by > 1 order of magnitude.
- Wide applications in SSL lighting, optical remote-sensing, UV radiometry, display metrology, and medical imaging.

[1] Yuqin Zong, Steve Brown, Carol Johnson, Keith Lykke, and Yoshi Ohno, "Simple spectral stray light correction method for array spectroradiometers," *Applied Optics*, Vol. **45**, No. 6, 1111-1119. (2006)
[2] Yuqin Zong, Steven W. Brown, Keith R. Lykke, and Yoshihiro Ohno, "Simple matrix method for stray-light correction in imaging instruments," US 8,554,009, Oct. 8, 2013.

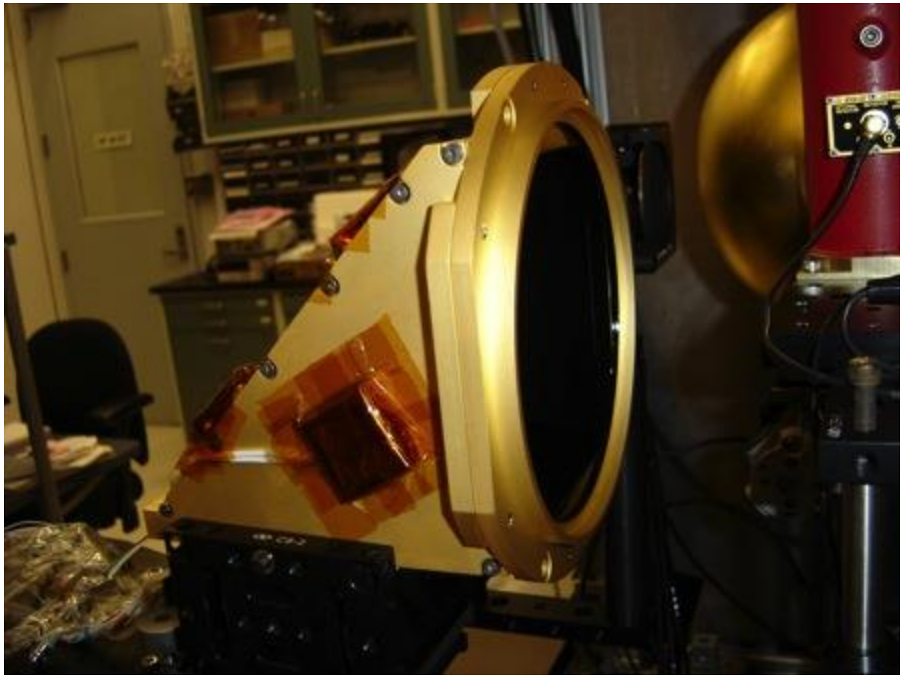
Blackbody Cavity Reflectance Measurements for JPSS CrIS and for CLARREO

CrIS Internal Calibration Target (ICT)

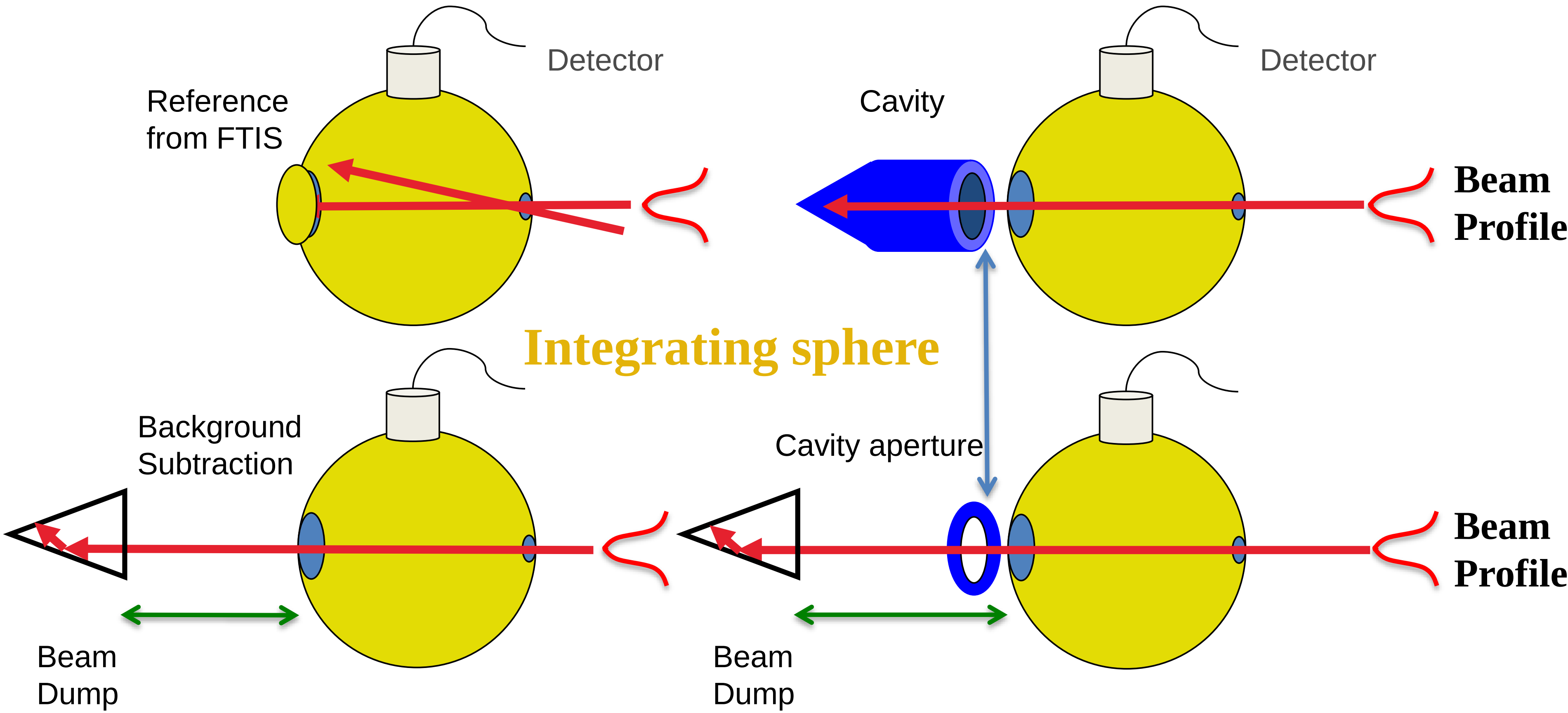
- CrIS is the Cross-track Infrared Sounder instrument on NPP
  - Will measure vertical distribution of temperature, moisture and pressure
  - Fourier Transform Spectrometer
  - CrIS bands are 3.9 to 4.7 μm, 5.7 to 8.3 μm, 9.1 to 15.4 μm

    (4 μm, 7.3 μm, 10.6 μm)

- The ICT is the Internal Calibration Target for CrIS
  - specular trap blackbody
  - Aperture 5” (rounded square)
  - No heaters
  - Emissivity requirement 0.995
  - Models show design meets emissivity requirements



Schematic of CHILR Measurement Setup



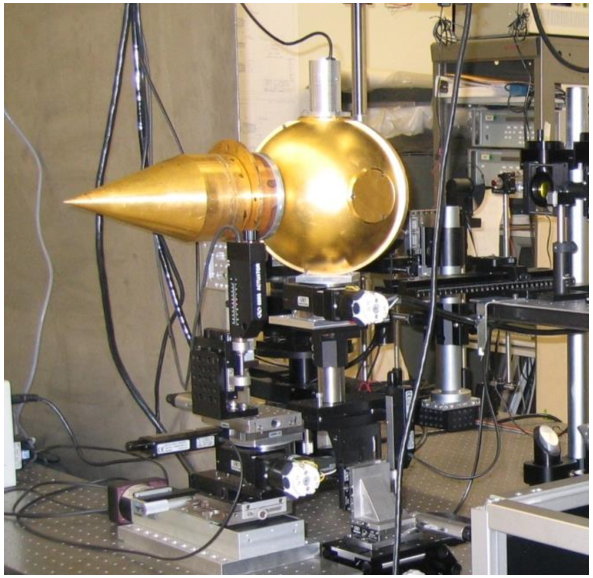
$$R = \frac{V_{sc} - V_{ap}}{V_r - V_{back}} R_r$$

Light trap with specular black coating

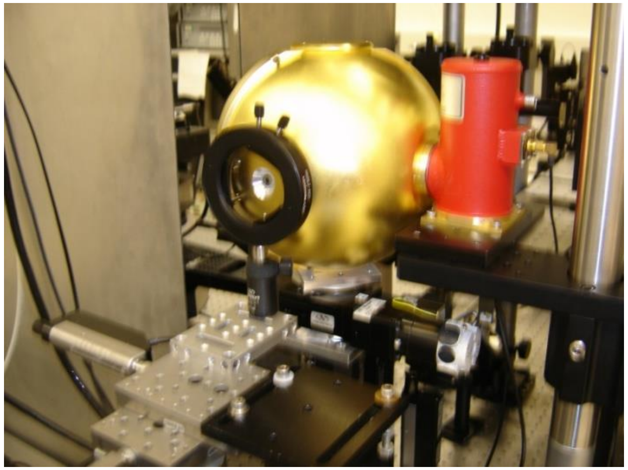
Light trap with diffuse black coating (distance needed)

Complete Hemispherical Infrared Laser-based Reflectometer

Rear View w/ Water Bath Cavity



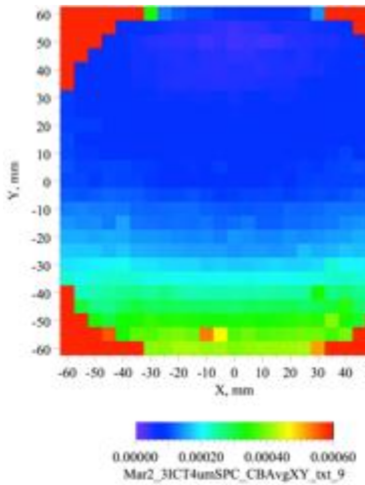
Front View of Sphere



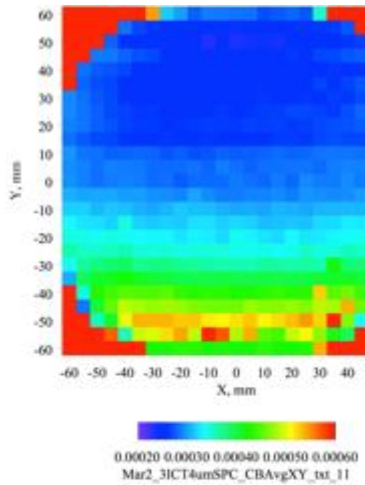
- Can measure reflectance down to approx. 10^{-5} (equivalent to emissivity 0.99999)
- Reflectance expanded uncertainties currently 15 - 20% for 10^{-3} to 10^{-5} range

Results for CrIS ICT @ 4 µm and 10.6 µm

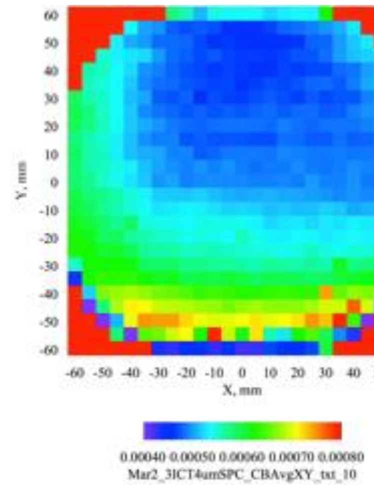
Vertical Polarization



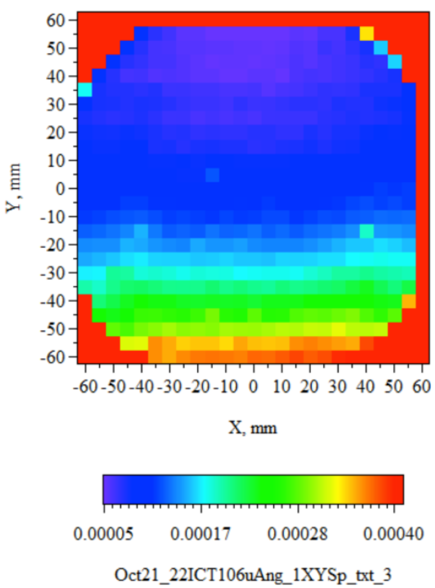
45° Polarization



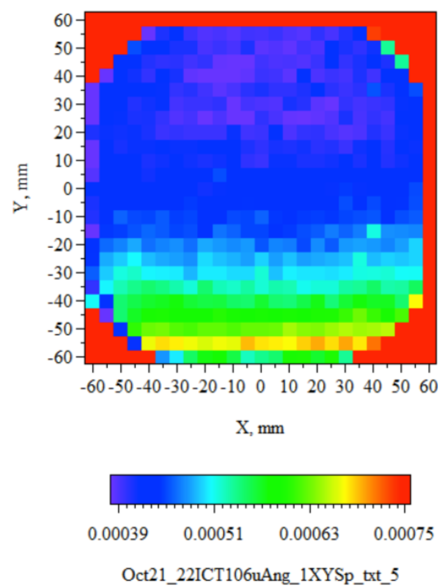
Horizontal Polarization



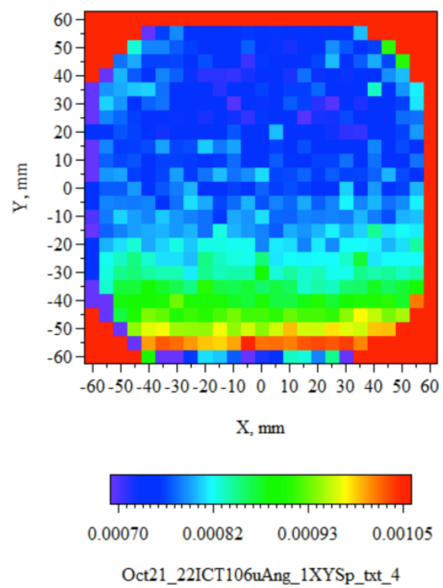
Vertical Polarization



Circular Polarization



Horizontal Polarization



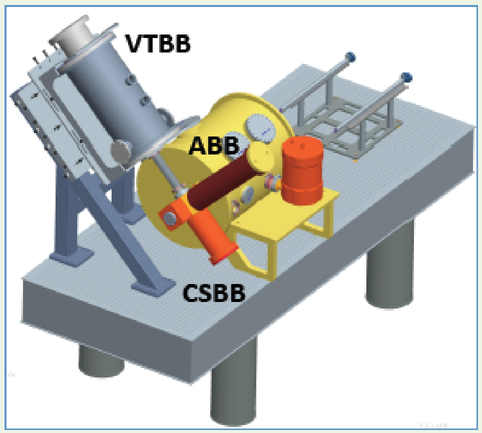
NIST support of NASA CLARREO Calibration Demonstration Systems (CDS)

- For solar-reflected band, long-term loaned NASA Goddard a T-SIRCUS and trained on use
- For infrared emissive bands, performed research on blackbodies as shown below

NASA LaRC Blackbody Sources

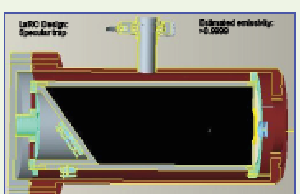
- NASA's Langley Research Center (LaRC) has produced an IR **Calibration Demonstration System** (CDS) as a prototype for a potential CLARREO instrument.
- The CDS contains 3 sources:
  - **Ambient Temperature Blackbody** (ABB)
  - **Variable Temperature Blackbody** (VTBB)
  - **Cold Source Blackbody** (CSBB)
- LaRC needs to know effective emissivity - uncertainty goal < 50 ppm in the IR
- NIST measurements to support emissivity determination

LaRC CLARREO IR Calibration Demonstration System*

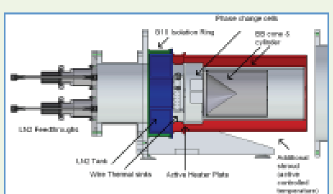


LaRC Blackbody Cavity Designs*

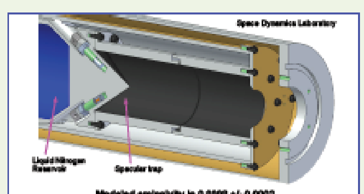
ABB Blackbody†



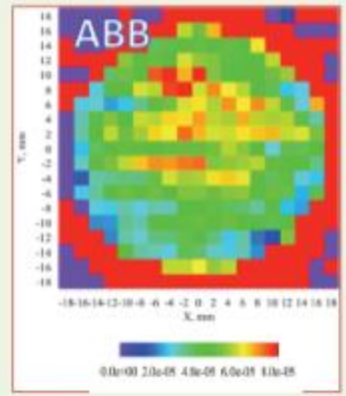
VTBB Blackbody‡

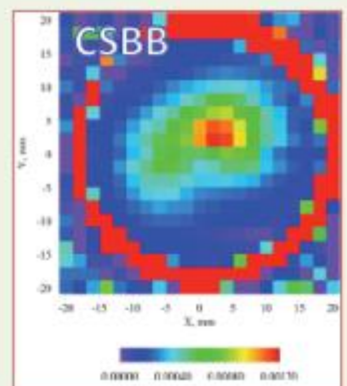


CSBB Blackbody‡

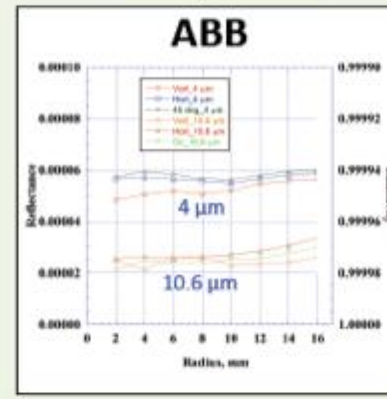


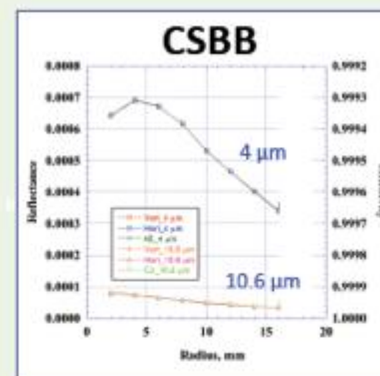
Spatial Reflectance Scans





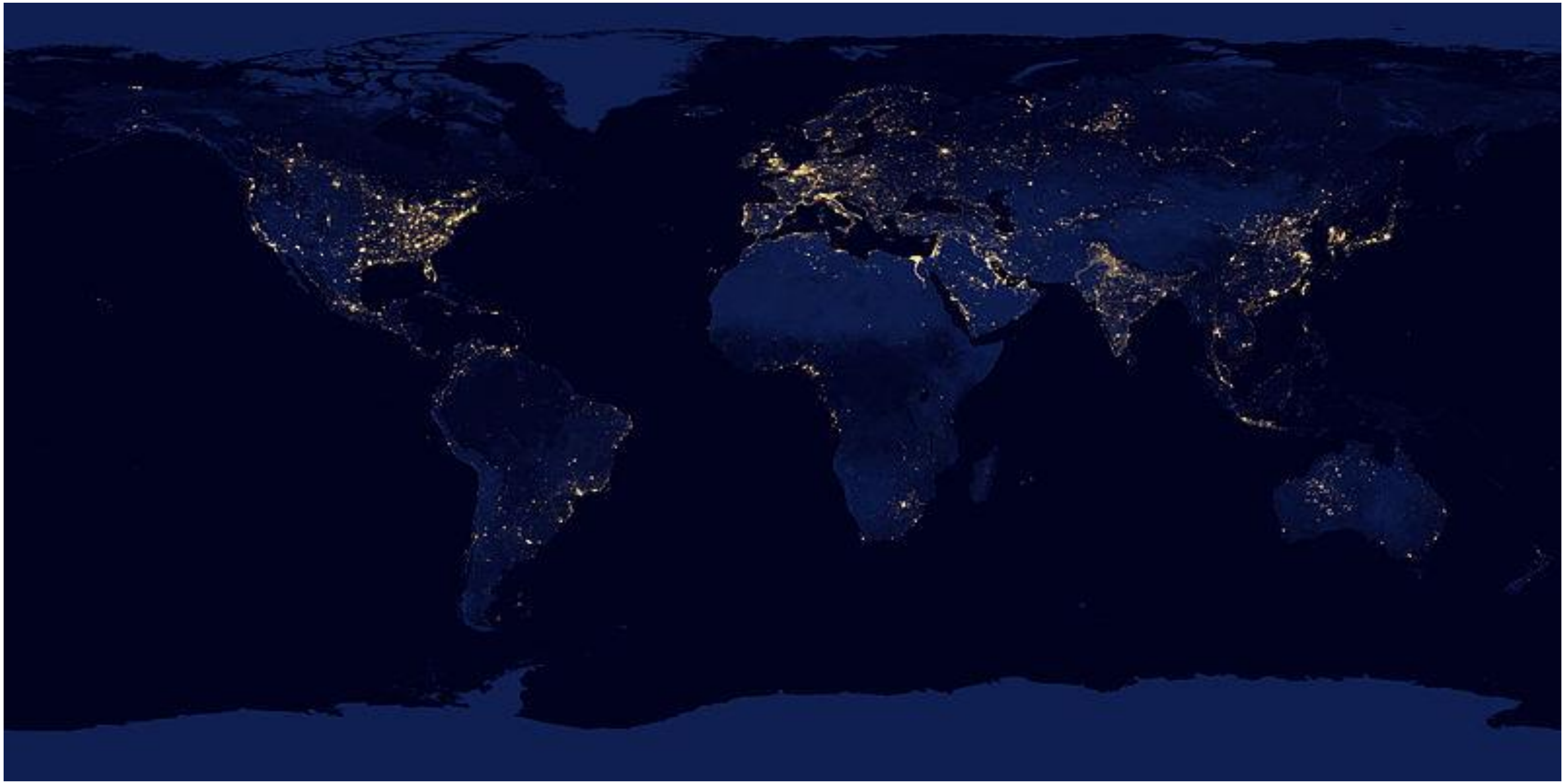
Reflectance / Emissivity vs. Viewed Spot Radius





Questions?

The Earth at Night as seen by VIIRS



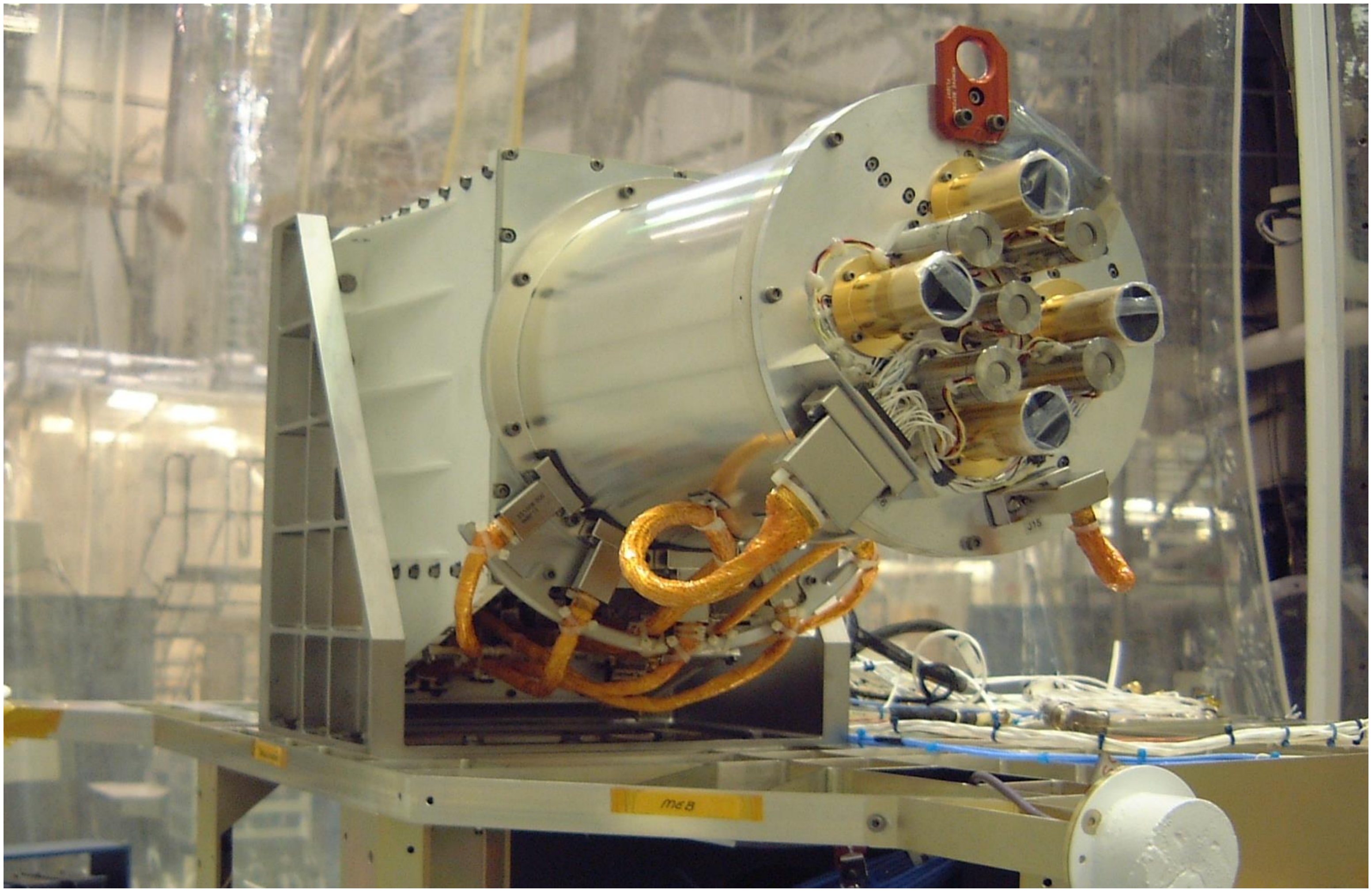
Wikimedia Commons

Backup Slides

NIST Primary Target (proposal)

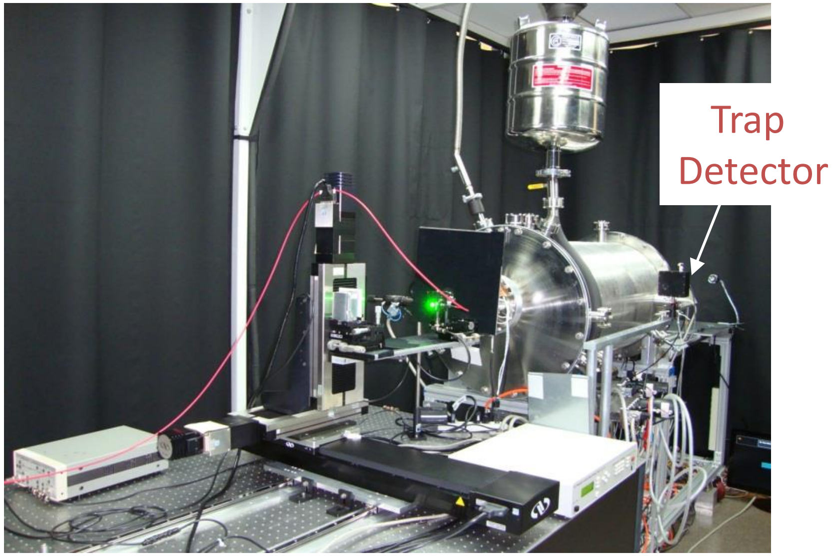
- A kilowatts power sea/land-based radiant intensity light source (a man-made NIST traceable star on the earth)
- For monitoring/calibrating Earth-Viewing Satellite Sensors for short and long term changes and fluctuation of atmosphere.
- Use high-power LEDs and/or incandescent lamps for produce kilowatts level of radiant flux.
- Source is calibrated/monitored using reference detectors and spectroradiometers.

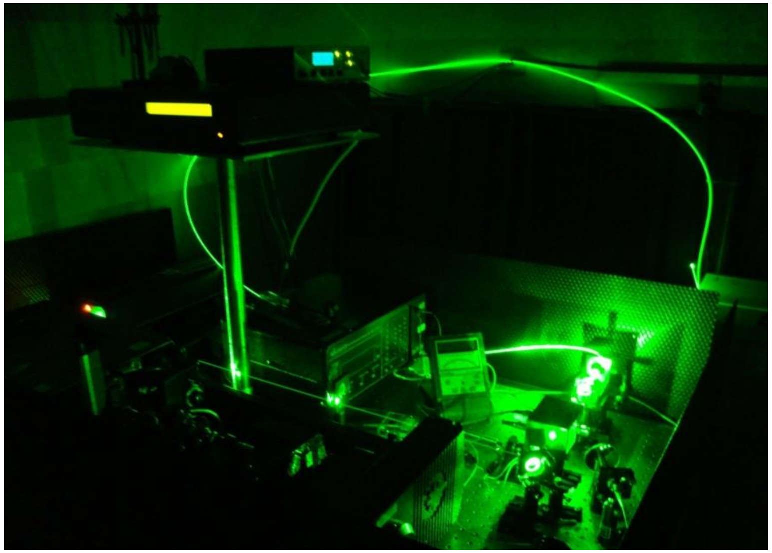
NIST Advanced Radiometer (NISTAR) during fit check to DSCOVR spacecraft at NASA Goddard Space Flight Center



Optical Layout for 2010 NISTAR Calibration at NIST using Portable SIRCUS

•During the 2010 calibration of NISTAR using a portable SIRCUS facility, the instrument was in a thermal-vacuum chamber to simulate the space environment.
•It viewed the output of a laser-illuminated integrating sphere coupled to an off-axis parabolic mirror collimator, simulating the geometry of the view of Earth from L1.



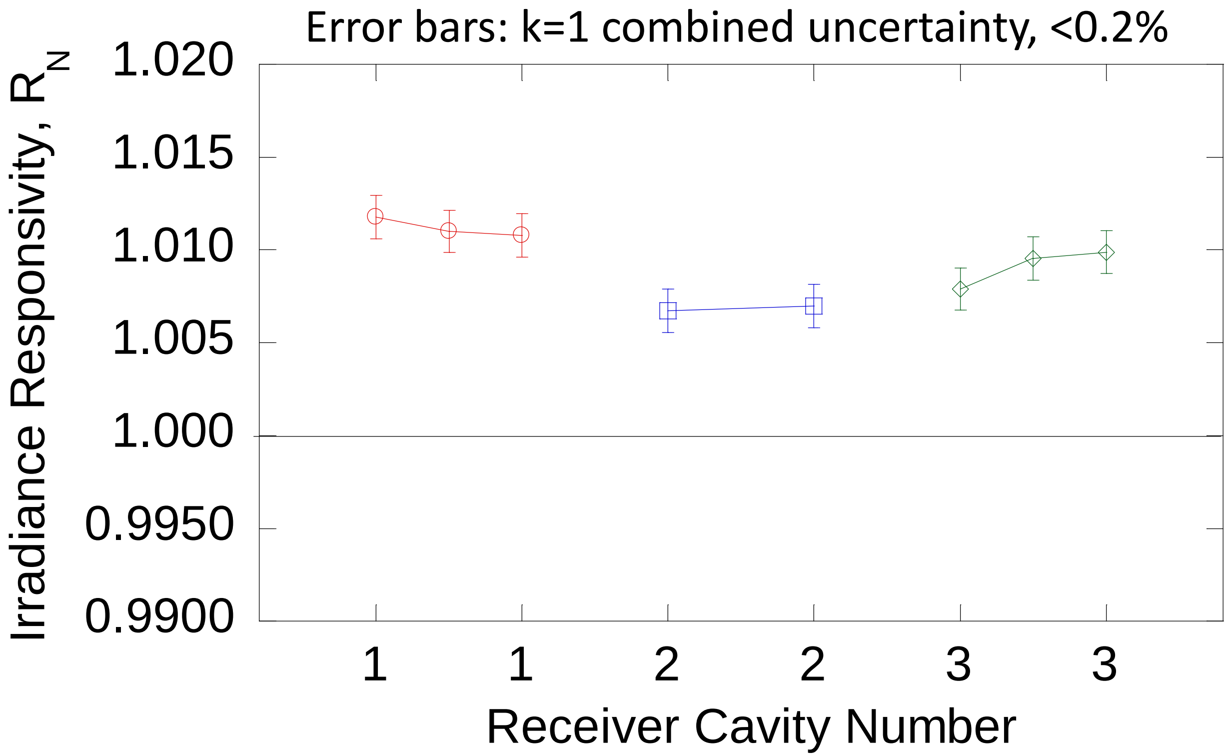


•The integrating sphere and collimator were on a translation stage, and the laser was fiber-optically fed.
•This enabled the source to be moved relative to the large, fixed vacuum chamber that contained NISTAR
•A silicon photodiode trap detector served as the irradiance responsivity standard

NISTAR at SIRCUS: Summary of Absolute Calibration at 532 nm

- Ideally responsivity would be 1, in units of a fully-developed native scale, but it is not necessary to be 1 since we calibrated it against the SIRCUS (NIST detector-based) scale
- Value > 1 means that NISTAR responsivity as measured at SIRCUS is greater than that determined by (crude) NISTAR native scale
- Difference from 1 here believed to be drift of NISTAR native electrical power scale, but it could include effects from stray light, Joule heating, diffraction, nonequivalence

➢ The result of this work is that the irradiance responsivity of NISTAR is now known to within an uncertainty of <0.2% (k=1) because we calibrated against SIRCUS



Community Letter to NASA and NOAA regarding concerns over NPOESS Preparatory Project VIIRS Sensor

“Recent summaries of VIIRS performance from the IPO and NASA, presented at the NPP Science Team Meeting in August 2007, clearly show that the present configuration of the VIIRS sensor will not come close to meeting the VIIRS design specifications and required spectral radiometric accuracies - …The so-called "cherry-picked" configuration of the VIIRS's filter array will just meet these standards but only if the rest of pre-flight testing is completely error free (which is unrealistic as VIIRS just entered its testing phase).   Hence, we have little confidence that VIIRS on NPP will ever provide well- calibrated ocean color imagery. “

Signed by over 50 prominent U.S. ocean researchers

Posted on SpaceRef, October 2, 2007

EARTH OBSERVING

U.S. Prepares to Launch Flawed Satellite

The U.S. government is planning to fly an Earth-observing satellite that will be essentially colorblind, at least as far as the oceans are concerned.

The NPP satellite is a prototype for the $12 billion National Polar-orbiting Operational Environmental Satellite System (NPOESS), a series of satellites to be launched between 2013 and 2022. In 2006, scientists learned that there was a problem with the filter on one of NPP's instruments, VIIRS, which will prevent it from accurately measuring ocean color, a window into how sea life responds and contributes to fluctuating atmospheric and ocean carbon. But officials with NASA and the National Oceanic and Atmospheric Administration (NOAA) rebuffed a request last fall from scientists to correct the problem out of concern that working on the filter could jeopardize the other 21 parameters that VIIRS measures, including clouds, the extent of ice sheets, and forest cover. Last month, NOAA announced that a glitch in the system to regulate the satellite's temperature would push back the mission by 8 months, to 2010, prompting scientists to ask the government to use the delay to at least conduct a risk-benefit analysis of correcting the filter problem.

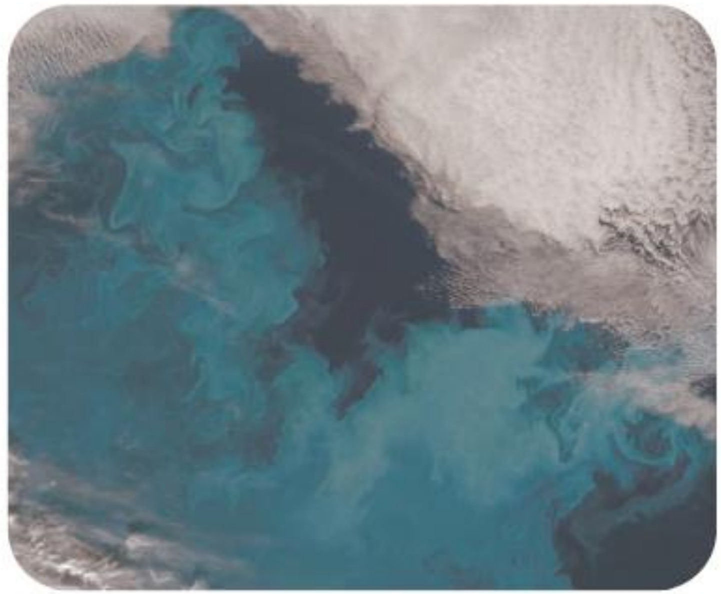
Last week, NOAA officials told *Science* that they have no plans to do such an analysis or to alter the timetable to accommodate any changes to VIIRS's filters. Instead, says NPOESS manager Dan Stockton, the agency will try to fix the ocean-color problem "for the first NPOESS" mission set to launch in 2013.

Scientists fear that the flaws in NPP will disrupt the longitudinal record on ocean color, because two experimental NASA craft now providing good data are near or beyond their 5-year design life. Color data from a European satellite have been difficult to use, and an Indian sensor has yet to be launched, they add.

"Are we going to [make it] to NPOESS [in 2012]? I don't think so," says David Siegel, a marine scientist at the University of California, Santa Barbara.

But Art Charo, who follows the issue for the U.S. National Academies' National Research Council, points out that the ocean-color community is at least better off than other climate specialties that had instruments removed from NPOESS in 2006 and don't know whether they will be restored (*Science*, 31 August 2007, p. 1167). "With such a tight budget environment, it's a question of triage," he says.

–ELI KINTISCH



Bloomin' brilliant. NASA's 9-year-old Terra is living on borrowed time but still provides good data for studies of plankton blooms.

CREDITS (TOP TO BOTTOM): COURTESY OF E. HAMMOND; GSFC/NASA

"In 2006, scientists learned that there was a problem with the filter on one of NPP's instruments, VIIRS, which will prevent it from accurately measuring ocean color, …"

Thoughts About the Future of Satellite Ocean Color Observations

by David A. Siegel (UCSB), James A. Yoder (WHOI), Charles R. McClain (NASA/GSFC)

"Unfortunately, the VIIRS instrument to fly on NPP is unlikely to maintain the climate data record of the ocean's biosphere started by SeaWiFS...

In particular, the integrated filter array (IFA), the component that disperses light spectrally onto the focal plane detectors, on the VIIRS flight instrument has known flaws that make it highly unlikely for VIIRS to meet the climate community's measurement requirements."

OCB News October 2008

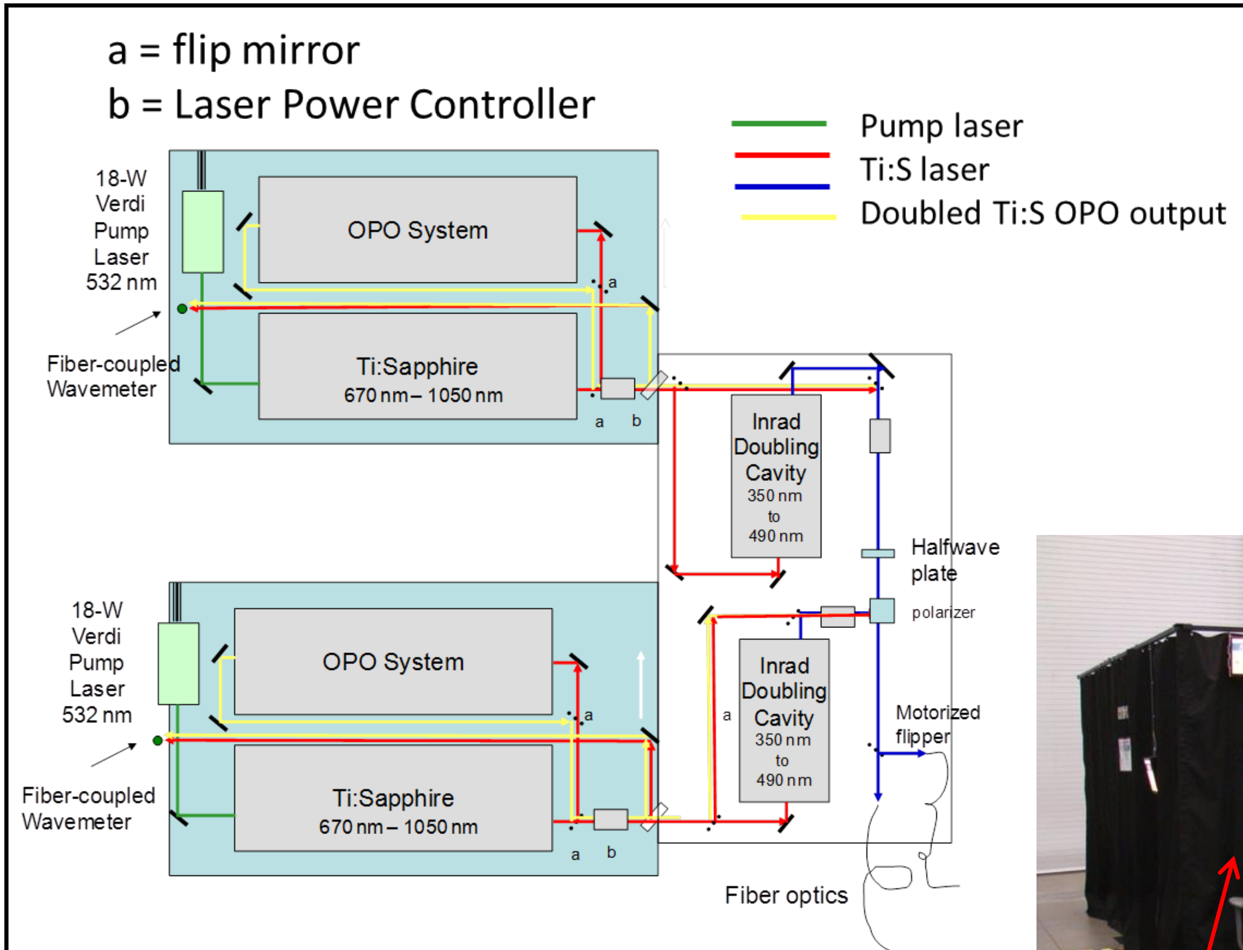
http://oceancolor.gsfc.nasa.gov/DOCS/OCB_OceanColorLetter.pdf

NPP Launched from Vandenberg Air Force Base, CA,

United Launch Alliance Delta II rocket, 28 October 2011

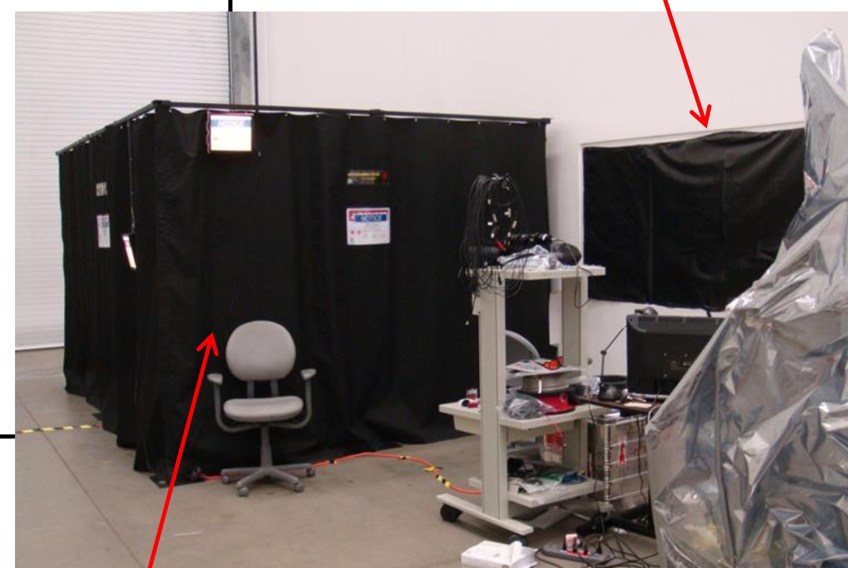
T-SIRCUS Laser Setup at BATC for NPP VIIRS

Schematic Diagram



Kentek laser containment curtains

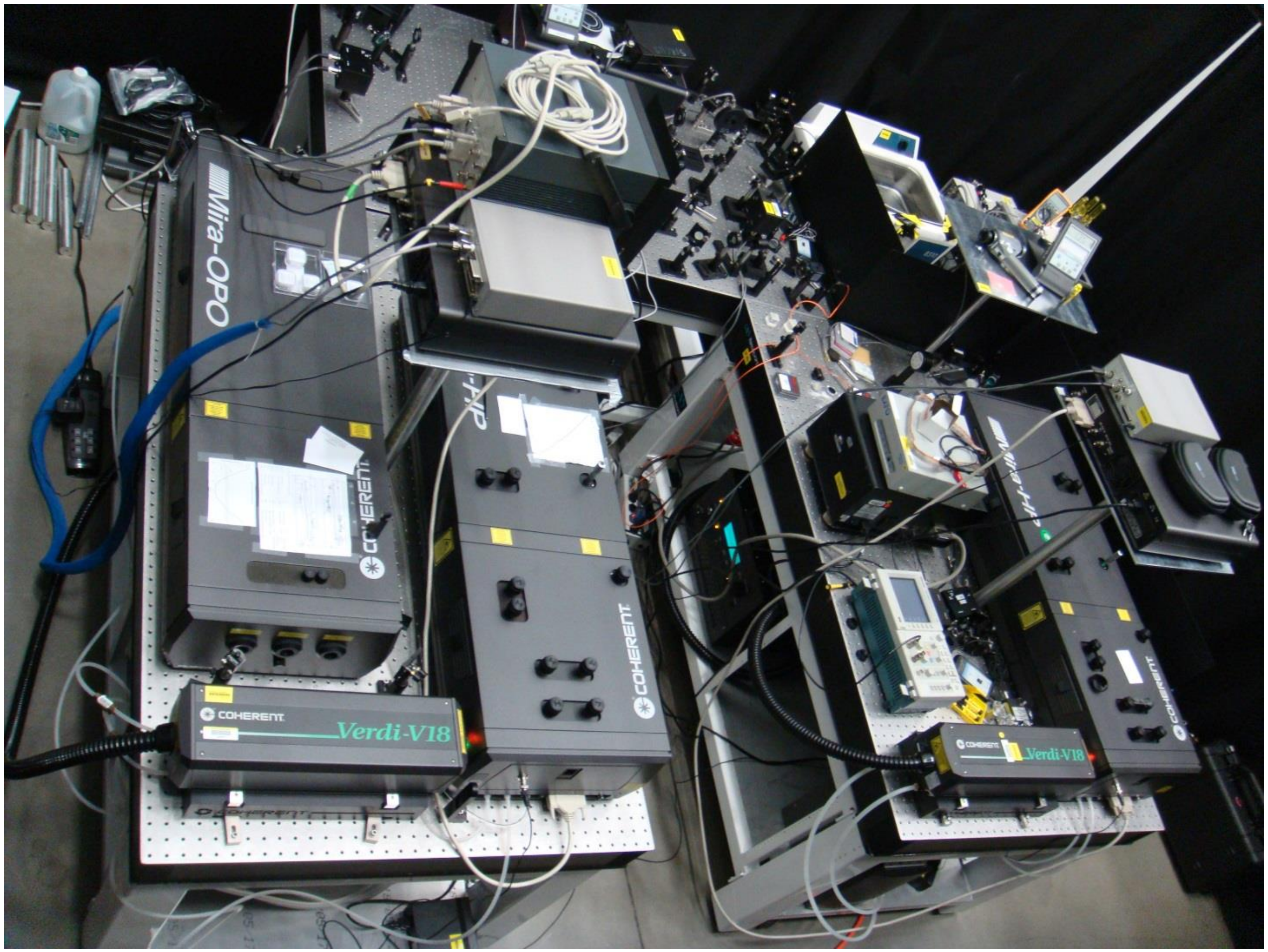
Window to Clean Room



Laser Containment Curtains

T-SIRCUS Laser Setup for Calibration of Suomi NPP VIIRS Vis/NIR Bands

(MIRA plus doubling plus doubled OPO)



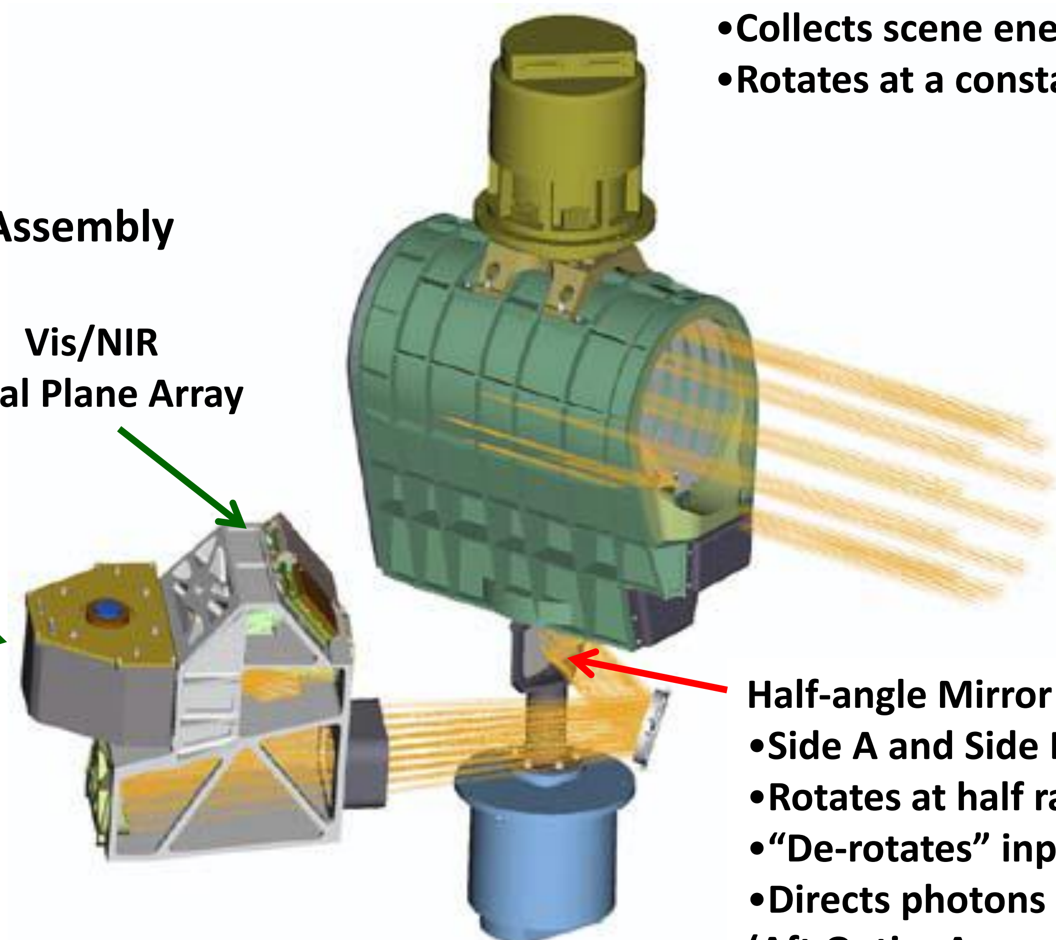
VIIRS Optical Design

Rotating Telescope Assembly (RTA)
- **Collects scene energy**
- **Rotates at a constant**

Aft Optics Assembly

Vis/NIR
Focal Plane Array

SWIR/MWIR&
LWIR Dewar



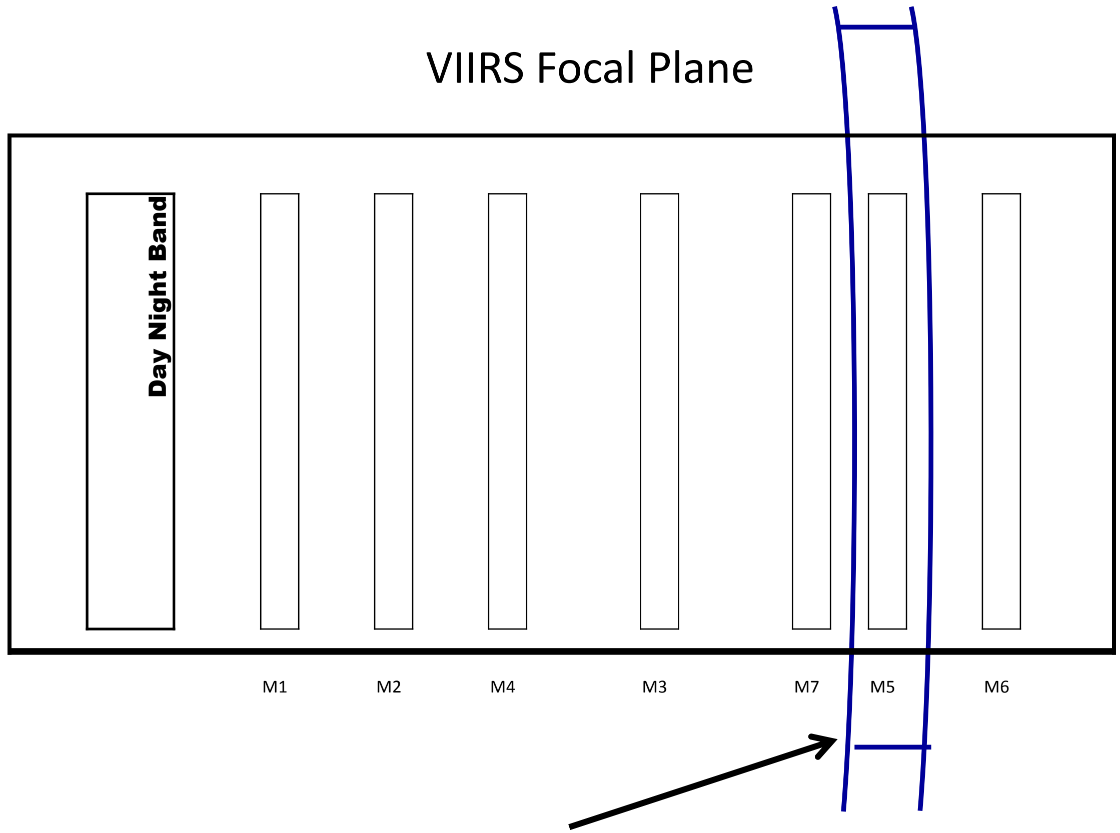
Half-angle Mirror (HAM)
- **Side A and Side B work alternatively**
- **Rotates at half rate of RTA**
- **“De-rotates” input beam**
- **Directs photons into the fixed AOA (Aft Optics Assembly**

Potential Problem with VIIRS Filters

- Filters placed on top of the detectors for spectral selection.
  - The properties of the filters were measured and it was discovered that they scattered a great deal of light – much more than expected.
- Great concern in the community about
  - Optical Crosstalk
    - Scattering from one band to another
    - Means that the bands to not measure the radiation at the focal plane accurately.
  - and whether or not VIIRS could provide Climate Quality Ocean Color Data Records

Spectral Measurements

Raytheon used a lamp-monochromator system
Spectral Measurement Assembly (SpMa)



SpMA slit imaged on the VIIRS focal plane.

Difficult to measure optical cross-talk