Analysis of the NISTAR On-Orbit Absolute Radiometric Scale

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A long list of past contributors to NISTAR

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DSCOVR Spacecraft

Deep Space Climate Observatory (DSCOVR)
--- Enhanced Polychromatic Imaging Camera (EPIC)
--- NIST Advanced Radiometer (NISTAR)
NIST advanced radiometer measures the Earth solar-reflected and emitted irradiance from the Earth-Sun Lagrange 1 point in 4 bands

<table>
<thead>
<tr>
<th>Band</th>
<th>Wavelength Range</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photodiode</td>
<td>0.2 to 1.1 μm</td>
<td>UV-Vis-NIR</td>
</tr>
<tr>
<td>Band A</td>
<td>0.2 to 100 μm</td>
<td>Total Outgoing Radiation</td>
</tr>
<tr>
<td>Band B</td>
<td>0.2 to 4 μm</td>
<td>Solar-Reflected</td>
</tr>
<tr>
<td>Band C</td>
<td>0.7 to 4 μm</td>
<td>Near-IR Solar-Reflected</td>
</tr>
</tbody>
</table>

**NISTAR Science Requirement:** to provide measurements that could be used to determine the Earth outgoing irradiance in the wavelength range of 0.2 -100 microns with an accuracy of 1.5 percent or better.
NISTAR Hysterical Timeline

- 1996-1997: Rice and Lorentz start working on non-cryogenic electrical substitution radiometers using high-sensitivity thermistors and a “drop-floor” algorithm
- 1998: NIST/NRL Awarded 6-month NASA study for solar irradiance instrument
  - This was subsequently awarded to U. of Colorado and became SORCE
- March 1998: Gore instigates Triana (“GoreSat”): full Earth view from space.
- August 1998: Francisco Valero of Scripps calls Rice. Lorentz adds paragraph to Scripps/Lockheed Triana proposal: EPIC + NISTAR proposed. (1 out of 9 proposals)
- October 1998: Scripps wins Triana! **September 2000 launch date**
- December 1998: Lorentz begins discussions with Randy Abbott at Ball about NISTAR.
- 1999: Lorentz and Rice work with Ball to design NISTAR
- Congress suspends work on Triana program pending National Academy of Sciences review
- February 2000: NAS review passed. Ball back to work eventually
- October 2000: NISTAR delivered to NIST after fit test on satellite at NASA-GSFC
- February-March 2001: NISTAR at SIRCUS
- March 2001: Triana loses shuttle ride. (This shuttle eventually crashed in 2003)
- April 2001: NISTAR delivered to NASA for integration on spacecraft
- 2002: NISTAR back at NIST for re-calibration at SIRCUS
- 2003: Another re-calibration at NIST after improvements, then back in its box at NASA
- Triana changed to Deep Space Climate Observatory (DSCOVR)
- 2009/2010: Renewed interest in DSCOVR: NISTAR calibrated again at NIST SIRCUS
- 2012 Contamination Discovered at GSFC
- 2013 Sent to L-1 for refurbishment and calibration, Launched Feb 2015.
Scripps-NISTAR Instrument Overview

- **Actual Dimensions**
  - Instrument: 33.8 (l) x 25.9 (w) x 58.4 (h) cm
  - ICE: 33.8 (l) x 25.9 (w) x 25.4 (h) cm
  - Radiometer Assy: 85 (h) x 30 (dia) cm

- **Mass Budget Request**: 23.5kg Max
  - Radiometer Assy, ~8 kg
  - ICE Assy, ~14 kg
  - Cable Assy, ~1kg

- **Mechanical Interface to S/C**
  - Radiometer FOV 1.0 °
  - Radiometer FOR 7.0 °
  - Aligned to EPIC camera boresite w/i 0.1°

- **Thermal Interface to S/C**
  - ICE: 20 ± 10 °C
  - Heat transfer rate: 2-3 W conductive to S/C

- **Structural loads from GEVS**: 46g

- **Power Consumption**: ~43 watts @ 28vdc

- **Command/Data Interface**
  - Mil Std 1553
  - Average 2400 bits/s
L1 Where?

- L1 is the neutral gravity point between the sun and the Earth
- 1.6 million km away, orbit is ~200k km across
- Falcon 9 direct launch to L1 on February 16, 2015
- Six month trip
- Required to burn fuel for both insertion and maintenance
- Reached L1 orbit with a 25 year fuel reserves
Views from Typical LEO

- Usually polar orbiting, typically sun-synchronous
- Altitude typically 600 km to 700 km
- Orbit time typically about 90 minutes
- Takes 24 hours to scan entire sun-lit globe
Views from Geostationary Orbits

• Altitude 36,000 km, fixed over equator
• Each looks at the same region of Earth
• Typically scanned within that region
View of the Earth and Moon from L1

NISTAR: FOV 1°
FOR 7°

Stars from Hubble Guide Star Catalog shown to 16th magnitude
Estimated Spectral Radiance from Earth at L1

Source Radiance (mW/cm²·sr/µm)

Solar Reflected (30% albedo, Lambertian)

Earth Emitted (300 K Blackbody)
Optical Layout for 2010 NISTAR Calibration at NIST

Laser System
- Nd-Vanadate (532 nm)
- Ti:Sapphire (700 to 1000 nm)
- Wavelength Meter
- Intensity Stabilizer
- Ultrasonic Speckle Removal
- Shutter Controlled by NISTAR
- Fiber-Optic Output

Vacuum Chamber
- NISTAR
- Plane of NISTAR Primary Apertures

Trap Detector
- Precision Aperture

Fiber-Optic Cable (from tunable laser system)
- Monitor Photodiode (on bottom of sphere)
- Integrating Sphere

Baffle (on x-y stage)
- NISTAR Primary Apertures

Windows (2 of 4 shown)

Collimator

Precision Aperture

x-stage

y-stage
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.
Cavity/Heat Sink/Baffle Assembly within NISTAR
(This was the part of NISTAR developed by NIST)

Baffle Optical Properties:
• 1 degree Field of View (FOV)
• 7 degree Field of Regard (FOR)
• Nickel Phosphorus Black Coating
  >99% black in the visible

Receiver Cavity (RC) Properties:
• 30 degree silver cone
• Specular black paint (Z-302) coating
• Includes a 4-wire resistive heater
• Includes a thermistor

Receiver Cavity/Baffle Assembly
(Units: inches)
Example: NISTAR Receiver Cavity (RC) 2, Set 1
• Typically 20+ hours of data collected per set, 2 or 3 sets per RC
• 10 minute cycle, 600 data points sampled per cycle
• Laser wavelength: 532 nm, irradiance mode
• Monitor photodiode indicates laser intensity stability
• Instability typically was < 5 ppm
• RC responds to laser AND infrared background
• Irradiance measured using Trap Photodiode
Phase-Sensitive Detection Algorithm used for Demodulation

\[ r_J = \text{real} \left( \sum_{M=J-N+1}^{J} \sum_{L=M}^{M+N-1} \sum_{K=L-N+1}^{L} \sum_{I=K}^{K+N-1} e^{i \frac{2\pi I}{N} \phi_I} \right) \]

\[ \phi_I = \text{sequence of measured values} \]
\[ \psi_I = \text{sequence of shutter position values} \]
\[ I = \text{raw index} \]
\[ J = \text{processed index} \]
\[ N = \text{number of points per shutter cycle} \]
\[ r_J = \text{demodulated response} \]

Example: RC2 $\phi_I$ input

Example: RC2 $r_J$ output
Measurement Equation and Example Results for NISTAR at SIRCUS Absolute Calibration at Wavelength = 532 nm

\[ R_N = \frac{G_T R_T}{B \tau_w \left[ \frac{r_T}{r_M} \right]} \left\{ \frac{r'_N}{r'_M} \right\} \frac{dP_N}{dP'_N} \]

<table>
<thead>
<tr>
<th>Parameter Description</th>
<th>Parameter (Units)</th>
<th>Type of Parameter</th>
<th>Value</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain of SIRCUS Trap Pre-amplifier</td>
<td>( G_T ) (V/A)</td>
<td>B</td>
<td>1.000080E+07</td>
<td>0.001</td>
</tr>
<tr>
<td>Irradiance Responsivity of SIRCUS Trap Detector</td>
<td>( R_T ) (Amm(^2)/W)</td>
<td>B</td>
<td>4.270228E+00</td>
<td>0.100</td>
</tr>
<tr>
<td>Beam Non-Uniformity</td>
<td>( B )</td>
<td>A</td>
<td>1.000263E+00</td>
<td>0.033</td>
</tr>
<tr>
<td>Chamber Window Transmittance</td>
<td>( \tau_w )</td>
<td>A</td>
<td>9.901618E-01</td>
<td>0.018</td>
</tr>
<tr>
<td>Response of Trap / Response of Monitor</td>
<td>( r_T/r_M ) (V/V)</td>
<td>A</td>
<td>4.713248E+00</td>
<td>0.020</td>
</tr>
<tr>
<td>NISTAR Electrical Power Scale Correction Factor</td>
<td>( \Delta P_N/\Delta P'_N )</td>
<td>B</td>
<td>1.003523E+00</td>
<td>0.002</td>
</tr>
<tr>
<td>Response of NISTAR / Response of Monitor</td>
<td>( r'_N/r'_M ) (W/V)</td>
<td>A</td>
<td>5.493005E-06</td>
<td>0.043</td>
</tr>
<tr>
<td>Area of NISTAR Cavity Radiometer Primary Aperture</td>
<td>( A_N ) (mm(^2))</td>
<td>B</td>
<td>4.985580E+01</td>
<td>0.003</td>
</tr>
<tr>
<td>Irradiance Responsivity of NISTAR (in native scale units)</td>
<td>( R_N )</td>
<td>combined</td>
<td>1.011769</td>
<td>0.117</td>
</tr>
</tbody>
</table>
Transmittance of All Filters (2001 data) (Band A is without any filter)

Band B
(Bare Quartz)

Band C
(Interference Film on Quartz)
Band B Close Up (2001 data)

Transmittance vs. Wavelength (nm)

- FTIR
- SIRCUS
- Monochromator

Legend:
- F2 System Level
- F7 System Level
- F11 System Level
- F2 Piece Parts
- F7 Piece Parts
- F11 Piece Parts
Band C NISTAR System-level Filter Transmittance 2010

- Ti-Sapphire tunable laser used
- Each Band C filter measured at the silicon photodiode position relative to Band A (open)
Assessment of On-Orbit Performance

- Instability of the instrument since launch—evidence supports stability
  - Variability of offsets not captured by monthly measurements
  - Contamination of optical components
    - Filters (and PD) are very susceptible
    - (Cavities NOT sensitive to small contamination)
  - Changes in the ESR electronics
    - Radiation induced
    - Aging
  - Launch induced post calibration changes
    - e.g., paint loss in cavities

- Proper settling of instrument following shutter transitions
  - Unexpected transient was shown to be a removable background effect
  - A 1.8% settling error remains from improper servo feedforward settings—previously obscured by background transient and instrument noise

- Ground calibration errors—2013 calibration is inconsistent with on-orbit data, which is consistent with 2010 calibration (≈3% correction)
2010 vs 2013 Calibration

- Measurements during the 2010 and 2013 calibrations
  - Receiver responsivities (Band A – no filter in place)
  - System level measurements of the filter transmittances at discrete NIR wavelengths—used to scale more extensive component level spectral transmittances measured in the laboratory at an earlier time

- Receiver responsivities
  - All three receivers were similar in 2010 but not in 2013 (#3 was lower)
  - Responsibilities were lower in 2013 vs 2010 by a few percent

- Filter transmittances
  - Like-filters were similar in 2010 but not in 2013
  - Band B filter transmittances were higher in 2013 vs 2010 by several percent

- On-orbit receiver intercomparisons and filter transmittance measurements are consistent with minimal degradation and the 2010 calibration—but not that of 2013

- 2013 laboratory calibration results consistent with a calibration-source alignment error
Filter Inter-comparisons (Band-B and Band-C)

- Filter broad-band transmittance is measured using the photo-diode as a detector and the Earth as a source, which is stable of the 15 minute measurement time
- There are 3 nominally identical filters for each band—two are spares
- The ratio of transmittance between like filters is a measure of differential degradation
Filter Inter-comparisons (Band-B and Band-C)

- Pairwise filter transmission ratios stable to less than 0.1% in 1.5 years

→ Adds to evidence of stable, clean instrument
Band-B Filter Transmittance Measurements

- On-orbit filter transmittance measurements agree with 2010 calibration
  - The 3 filters of the same type are nearly the same both on-orbit and during the 2010 calibration—but not during the 2013 calibration
  - On-orbit transmittance measurements, which use the Earth as a source and the photo-diode as a detector, are consistent with the 2010 laboratory calibration

→ 2010 System level filter transmittance data is correct
Receiver (Band A) Inter-comparisons

- Three ESRs view the Earth in the Band A configuration (no filters) followed by a background measurement.
- Intercomparisons are consistent with the 2010—but not the 2013—laboratory calibration and with minimal degradation.
ESR Background: Offset Determination

- All ESRs have a large background as they measure the change in incident optical power.

- NISTAR removes the background in two steps:
  - A shutter modulates the source—removes most background but some remains.
  - Views of dark space remove the residual shutter-modulated background.

- The shutter modulated background is largest for the total channel (Band A) but is much smaller for the SW and NIR filtered channels (bands B and C).

  Filters block shutter modulated long wave IR—leaving only indirect heating effects.
**Laboratory:** calibration source modulated with external shutter—all background is un-modulated

**On-orbit:** Earth light and some background-IR are modulated with internal shutter

Square wave not observed but required in Earth signal for accurate demodulation
Coadded waveforms are fit to a square wave excluding data following the transitions and compared to the demodulated result

- Averaging of even more data—including special tests indicates a 1.8% demodulation error with and uncertainty of 0.3%.
- Cause identified as improperly set feedforward—correct settings would have reduce the error substantially
Total Channel Dark Offset Determination

- Total channel background changes in between monthly measurements driven by orbitally induced changes in spacecraft temperature
- Background tracks instrument temperature as sensed by the heatsink servo effort (heater power) and shutter motor temperature sensor
Filtered Channel Dark Offset Determination

- Filtered channel backgrounds are much more stable as drifts in the filter IR emissions from temperature are removed by the shutter.
- To reduce noise, three background measurements are smoothly averaged (blue curve below).

![SW Dark Space Offset (W)](image1)

![NIR Dark Space Offset (W)](image2)
### NISTAR Uncertainty Estimates

\[
\text{Earth Irradiance} = - \frac{D\{\text{Earth View}\} - D\{\text{Space View}\}}{R}
\]

\( D\{} \equiv \text{Demodulation Operation} \quad R \equiv \text{Responsivity (Calibration Constant)}

<table>
<thead>
<tr>
<th>Filter Channel</th>
<th>Instrument Noise(^1) (Precision)</th>
<th>Responsivity (Calibration)</th>
<th>NISTAR Total Uncertainty(^6)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Earth View(^3)</td>
<td>Total Noise</td>
<td>4 Hr Daily</td>
</tr>
<tr>
<td></td>
<td>4 Hr Daily</td>
<td></td>
<td>Daily</td>
</tr>
<tr>
<td>Total</td>
<td>1.0 %</td>
<td>1.2 %</td>
<td>&lt;0.2 %</td>
</tr>
<tr>
<td></td>
<td>0.7 %</td>
<td>1.2 %</td>
<td>0.3 %</td>
</tr>
<tr>
<td>SW</td>
<td>1.3 %</td>
<td>1.7 %</td>
<td>1 %</td>
</tr>
<tr>
<td></td>
<td>1.0 %</td>
<td>1.4 %</td>
<td>0.3 %</td>
</tr>
<tr>
<td>NIR</td>
<td>3.5 %</td>
<td>5.5 %</td>
<td>1 %</td>
</tr>
<tr>
<td></td>
<td>4.2 %</td>
<td>3.9 %</td>
<td>0.3 %</td>
</tr>
</tbody>
</table>

All uncertainties are calculated at \( k = 1 \)

1. Instrument noise is normalized to the Earth signal.
2. Noise reduced for the NIR and SW channels by averaging over 3 consecutive dark observations.
3. Averaged, separately over 4- and 24-hour time periods—source variability ignored.
4. Uncertainty components are from both the ESR receiver and the filter transmission. For the two filtered channels, SW and NIR, the uncertainty of the filter transmission dominates.
5. Estimate based from on-orbit inter-comparison between filters and receivers during Earth view.
6. Total uncertainties of daily averages is the quadrature sum of all listed components.
Comparison: CERES SW and NISTAR Band B

- Currently ≈5% difference between CERES SW SYN Flux and NISTAR Band B
- NISTAR uncertainty of ≈2% is, by itself, too low to explain the discrepancy
The NISTAR operating mode has remained stable since February 2017—no further changes anticipated.

Analysis of on-orbit data has led to two scale corrections to be applied to v2.1 level 1B release.
- Approximately a 5% reduction in the unfiltered shortwave radiance and 1.8% in the total channel
- Use of the 2010 calibration over that of 2013, which is believed to be in error. Affects both filter transmittance measurements and cavity responsivity.
- An error of approximately 1.8% due to a transient in the background subtracted Earth signal

A disagreement of \( \approx 5\% \) remains between the NISTAR Band B (SW) and the CERES 1 deg. Synoptic Model using LaRC anisotropy predictions.

Uncertainty budget updated to reflect latest measurements and corrections.

Ability to further resolve potential issues limited—no further scale adjustments anticipated.
Thank you.