### Session 1: Role of the Sun in Climate Change During the SORCE Mission

*Panel Discussion: Current & Future Plans for Sun-Climate Research*

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<td>2. New SSI Record for 115-2400 nm range</td>
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<td>Tue. S2</td>
<td>3. New SSI Reference Spectra</td>
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<td>Tue. S1 &amp; Wed. S3</td>
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<td>5. Next-generation, highly-accurate Radiometers</td>
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<td>Tue. S2</td>
<td>7. Large Flare Measurements in SSI and TSI</td>
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<td>Wed. S4 &amp; Thur. S5</td>
<td>8. Advanced Models of the TSI and SSI</td>
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<td>9. Venus and Mercury Transit Observations</td>
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<td>10. Improved Calibrations for Stars and Lunar Reflectance</td>
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</table>

*Wednesday Poster Session includes most of these topics.*
After 11 years with SORCE – What’s new? What’s next?

Robert F. Cahalan
Climate & Radiation Laboratory, NASA-Goddard
SORCE, TCTE & Free Flyer-TSIS Project Scientist

Peter Pilewskie, TSIS PI
Tom Woods, SORCE PI
University of Colorado - LASP

Thanks also to Greg Kopp, Jerry Harder, and other LASP colleagues & to others at GSFC and NIST

– Changes in estimates of the Total Solar Irradiance (TSI), Earth’s albedo, and Earth’s outgoing longwave radiation
– Historic closing of calibration gap between the suite of TSI instruments, with Transfer Radiometer Facility (TRF)
– Climate models sensitive not only to TSI, but to variations in the Spectral Solar Irradiance (SSI)
  & vertical profiles of temperature and ozone are especially sensitive to SSI.
– SIM indicates multiyear changes at visible and near-infrared wavelengths out of phase with TSI,
– Out-of-phase SSI forcing can lead to larger temperature variations in the upper stratosphere,
  but smaller variations in troposphere and upper ocean.
– Variations in SSI need further study before they may be considered firmly established.
– TSIS SIM has recently undergone comprehensive end-to-end calibration in the LASP SSI Radiometry Facility (SRF)
  utilizing the NIST SIRCUS system covering 210 – 2400 nm for SSI, not yet available when SORCE launched.
– SORCE follow-on mission Total and Spectral Solar Irradiance Sensor (TSIS), could reduce uncertainty in SSI variability
– Long-term goal of improving the ability to monitor Earth’s energy balance, and energy imbalance that drives
global warming, requires improved measurements of both shortwave and longwave earth-emitted radiation.
– Lunar Borehole Experiment has potential to recover changes in TSI over past 400 years; could clarify “Little Ice Age.”
SORCE has logged more than 1.6 billion miles!

\[
2\pi \times 4344 \text{ miles} \times 59716
\]

Input interpretation:
\[2 \pi \times 4344 \text{ miles} \times 59716\]

Result:
1.63 billion miles

Unit conversions:
\[2.623 \times 10^9 \text{ km} \text{ (kilometers)}\]
\[2.623 \times 10^{12} \text{ meters}\]
\[2.43 \text{ light hours}\]

Comparison as length:
\[\approx 4.6 \times \text{ length of the longest observed comet tail (Hyakutake 1996)} (\approx 5.7 \times 10^{11} \text{ m})\]

Comparison as diameter:
\[\approx 3 \times \text{ optical diameter of Betelgeuse} (\approx 900 \text{ Gm})\]

Comparisons as distance:
\[\approx 0.2 \times \text{ smallest distance from the Sun to the heliosheath} (79 \text{ to } 100 \text{ au})\]
\[\approx 0.35 \times \text{ distance from the Sun to the Kuiper cliff} (\approx 7.48 \times 10^{12} \text{ m})\]
\[\approx 0.44 \times \text{ semimajor axis of Pluto's orbit} (5.906376272 \times 10^{12} \text{ m})\]
Total solar irradiance (shown in color) over the past three solar cycles since 1978 adjusted to a ground-based cryogenic instrument funded by NASA in collaboration with the National Institute of Standards and Technology (NIST).

Image Credit: Greg Kopp, LASP, University of Colorado / NASA
“We’re at Cocoa Beach FL this week to celebrate 11th birthday of SORCE, launched from Kennedy Jan 25 2003 & still after 60,000 Earth orbits is measuring our Sun's total energy & energy spectrum for wavelengths from 1 to 2400 nanometers.”
TCTE & TSIS to continue solar irradiance needed by IPCC

Radiative forcing of climate between 1980 and 2011

Forcing agent

- Well Mixed Greenhouse Gases
  - CO₂
  - Other WMGHG
  - NO₂
  - Halocarbons
- Ozone
  - Stratospheric
  - Tropospheric
- Stratospheric water vapour from CH₄
- Surface Albedo
  - BC on snow + Land Use
- Contrails
  - Contrail induced cirrus
- Aero.-Rad. Interac.
- Aero.-Cloud Interac.
- Total anthropogenic
- Solar irradiance

Radiative Forcing [W m⁻²]

Figure 8.20: Bar chart for RF (hatched) and ERF (solid) for the period 1980–2011, where the total anthropogenic ERF are derived from Monte-Carlo simulations similar to Figure 8.16. Uncertainties (5–95% confidence range) are given for RF (dotted lines) and ERF (solid lines).
**TSI Record**: Total Irradiance Monitor (TIM) (daily)

The Climate “Gold Standard” →

20°C estimates varied from 1340 to 1420, i.e. ± 3%. Today we know TSI to ~0.03%.

1360.8 ± 0.5 W/m²


TSI data@ http://spot.colorado.edu/~koppg/TSI/
None of these instruments have been validated end-to-end for irradiance to desired accuracies.
What have we learned during solar cycle 23?

- **TSI = 1360.8 ± 0.5 W/m², ~ 4.5 W/m² (0.33%) lower than previously accepted**
  - 1360.8/4 ~ 340; Reflected ~ 100 W/m², and Emitted ~ 240 W/m²
  - Net Imbalance ~ 0.5 W/m² – based on ocean heat storage estimate. (Estimates vary.)
  - Imbalance implies continued warming – Greenhouse dominates, Sun a player.
  - Cycle 23 Minimum TSI slightly lower than Cycle 22 Minimum, offsets some warming

- **Albedo smaller, ~29% (vs ~31%) – more solar absorbed than previously accepted**

- **Atmospheric Absorption larger ~23% (vs ~20%) due to Aerosol & H2O Continuum**

- **Sun’s Spectral shape may change, as does Earth’s (Controversial.)**
  - Near-Ultraviolet changes may be large enough to give 1.0 K variations at ~40 km
  - Visible and Near-Infrared changes may be out-of-phase with TSI.
  - TSI, integral of spectrum, may consist of spectral regions with compensating effects.
  - Surface solar forcing very small, direct surface response < 0.1 K in 11-year cycle

---

**Between 2000 & 2012, during cycle 23, Earth’s human population increased from 6 billion to 7 billion.**

**In 2013, atmospheric CO₂ reached 400 ppm, 43% above a pre-industrial 280 ppm, constant to 10% for 10,000 years.**
Temperatures are rising

Earth’s surface temperature has risen 0.6°C~1.1°F since 1950. The three major surface temperature data sets (NCDC, GISS, and HadCRU) all show global temperatures have warmed by 0.16 – 0.17°C (0.28 – 0.30°F) per decade since satellite measurements began in 1979.
Arctic Ice is melting

Warming and Melting are both raising sea level.
• Future TCTE-TSIS overlap could plug TSI time gap.
Continuity of 35+ year TSI Record

Loss of Glory-TIM at launch on March 4, 2011

- Delay of TSIS Flight Opportunity to 2016+

**SORCE/TIM**

- SORCE : 2003 – 2015 ??

**Glory/TIM**

- 2011 - 2014 (failed)

**JPSS Free Flyer/TSIS**

- TSIS : July, 2016 LRD

**Gap Risk**

- TCTE : 2013-2016 (expected)


TSI record continued since 1978

- To bridge continuity gap in 35 year TSI record continuity, SORCE-TIM Calibration Transfer Exp’t (TCTE) is selected - Air Force STPSat3 — Dec 2013.
TSIS FM-1 delivered Dec 2013!

TSIS TIM Assembly:
TSIS TIM & SIM now in storage

- Mass = 14.5 kg
- Size: 10.9” wide
- 10.1” tall
- 24.3” long

- Motor/Tach Assy.
- Optical Cavity (SIM Case)
- Focal Plane Assy.
- External Flex Harness Enclosure
- Fine Sun Sensor Location
- Thermal Straps (4)
- MLI Blanket Interface
- Channel C
- Channel B
- Channel A
- CCD Encoder
- Operational Heater
- Vent Valve Assy.
- Traditional External Harness
- Inputs
- Fevre Prism Drive
- External Flex Harness
- Vacuum Door Mechanism
- Kinematic Mounts (6)
- Operational Heater
- TSIS TIM & SIM now in storage

Robert F. Cahalan
SORCE Science, Cocoa Beach FL, Jan 28-31, 2014
# TSIS Top Level Requirements

<table>
<thead>
<tr>
<th>Level 1 Performance Requirement Parameter</th>
<th>TIM Requirement</th>
<th>SIM Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured Spectrum</td>
<td>Total solar spectrum</td>
<td>200-2400 nm</td>
</tr>
<tr>
<td>Measurement Accuracy</td>
<td>0.01% with noise ≤ 0.001%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Measurement Stability (long term)</td>
<td>0.001% per year</td>
<td>0.05%/yr (&lt;400 nm) 0.01%/yr (&gt;400 nm)</td>
</tr>
<tr>
<td>Spectral Resolution</td>
<td>n/a</td>
<td>1 nm: (&lt; 280 nm) 5 nm: (280 to 400 nm) 35nm: (&gt;400 nm)</td>
</tr>
<tr>
<td>Reporting Frequency</td>
<td>4 six hourly averages per day</td>
<td>2 spectra per day</td>
</tr>
<tr>
<td>Data processing approach</td>
<td>Consistent with SORCE approach for continuity</td>
<td>Consistent with SORCE approach for continuity</td>
</tr>
</tbody>
</table>
Summary – TSI / SSI Continuity

• TCTE launch June 2013 intended to maintain TSI Data Record Continuity
  – Glory loss threatened gap in solar irradiance record, but …
  – TCTE overlapped SORCE by 7 days; hope for overlap with TSIS by 50+ days

• TCTE lacks the Spectral Irradiance Monitor (SIM), but TSIS will include SIM
  – SORCE age means likely gap in 10+ year record of SORCE-SIM Solar Spectral Irradiance

• TSIS Free Flyer launch expected 2017, but 2014 budget allocated $00M
  – “NOAA received no funding of the $62M requested for the Polar Free Flyer program. The budget language indicates that NOAA should work with the FY 2015 budget and develop a strategy to address short- and long-term challenges associated with the possible gap in polar data, including reexamining the Polar Free Flyer program.” –Mary E. Kicza
Sun-Climate Questions

What is the solar forcing at decadal and longer time scales?

- Solar Irradiance Climate Data Record (CDR): time series of measurements of sufficient length, consistency, and continuity to determine climate variability and change.

How does the climate system respond?

- What are the mechanisms of climate response? Requires measurement of wavelength-dependent irradiance variability.
- Can a solar climate signal be attributed to unique mechanisms?
- How does the climate response to solar forcing differ from other forcings, for example, greenhouse gas forcing?

Attribution

- How much of the 20th-century warming trend was due to anthropogenic forcing?
  - Requires rigorous probabilistic analysis and highly accurate forcings.
- What are the expected climate changes for the 21st century?
Solar Influences on Climate

SIM and SOLSPEC Irradiance Spectra

![Graph showing irradiance spectra and resolution in relation to wavelength for SIM and ATLAS 3 Composite. The graph includes SIM detector ranges: 200-308 nm (n-p Silicon), 310-950 nm (n-p Silicon), 950-1620 nm (InGaAs), and 258-2423 nm (ESR).]

Solar Irradiance: how is it dispersed spectrally and where is it deposited into the atmosphere and ocean?

- How does the solar spectral irradiance vary in time?
Solar Rotational Variability

The image shows a graph with the x-axis representing wavelength in nanometers (nm) and the y-axis representing rms variability in W/m²/nm. The graph compares observed SOLSTICE data and model predictions labeled as "Lean (Model)". Two distinct wavelength ranges are highlighted, one from 200 to 255 nm and another from 255 to 300 nm.
(near) Solar Cycle Variability

Lean, SIM, SOLSTICE, 2004–2007

Difference in spectral irradiance (mW/m^2/nm) [<242 nm]

Difference in spectral irradiance (mW/m^2/nm) [>242 nm]

Wavelength (nm)

Lean

SIM

SOLSTICE
What impact does this have on the atmosphere?

Cahalan R., G. Wen, J. Harder & P. Pilewskie, GRL, 2010

Solar Variations (Lean 2000) And RCM Response

Solar Variations (Harder et al 2009) And RCM Response

Identical TSI

Increased 11-yr in Stratosphere
Decreased 11-yr At Surface & Oceans

“…consistent with contemporaneous measurements of ozone from the Aura-MLS satellite…”
UV Variability: Direct Heating vs. Photolysis

Responses from $\lambda < 242$, $> 242$ nm compete

**NRL SSI**

$\lambda > 242$

$\lambda < 242$

Total

**SORCE SSI**

$\lambda > 242$

$\lambda < 242$

Total

Swartz et al. 2010 – GEOS-5 CCM
SIM Degradation Trending Challenges

What is the reference with only two SIM channels and both are degrading?

- SIM previous results are derived with assumption that both channels degrade at same rate as a function of exposure time

\[ Degrade_A = 1 - k t_A \]
\[ Degrade_B = 1 - k t_B \]

Key result from SSI Validation Workshop at NIST in Feb. 2012: degradation scales with dose
New SIM analysis in progress

\[ Dose = \int \int_E (\lambda, t) R_A(\lambda, t) \sigma(\lambda) d\lambda dt \]
If \( E & R \neq f(t) \), \( Dose = kt \)
Hope: SRF to replicate TRF success for SSI at key wavelengths

2005
Result: TRF

2012
Result: degradation
Scales with dose

Instrument-level calibration complete (all in vacuum; all channels):
- SIRCUS laser wavelength calibration
- Spectral instrument function measurements
  - ESR and Photodiodes
- Channel to channel boresight alignment calibration
- Pointing and FOV mapping
- Absolute spectral irradiance calibration tied to NIST L1 Cryo
  - ESR (all channels)
SIM and SOLSPEC agree to within 1% over most of spectrum.

- Models can adequately reproduce rotational SSI variability.
- Solar-cycle variability in some SIM spectral bands exhibits out-of-phase trends with TSI.
  - Climate implications? Observations require further validation.
  - Continued validation efforts underway
  - New dose models of SORCE SIM degradation
  - New measurement-based degradation studies
  - SORCE SIM in the present solar cycle? SORCE/TSIS SIM overlap?

- TSIS SIM will have enhanced degradation tracking capability, lower noise ESR, ultra-clean optical environment to mitigate contamination, first end-to-end cal/val using cryogenic radiometer and SIRCUS sources.
What is the recent history of our Sun’s TSI?

Sun’s TSI highly uncertain due to unknown faculae!

Johannes Hevelius: 1647
www.sr.bham.ac.uk

SOHO (L1): launched 1995
sohowww.estec.esa.nl

Modern
Maximum
1843: Schwabe
discovered 11-year cycle

Maunder
Minimum

Is the Sun Darkening?

2000/02/29 09:12 UT

Sunspot Cycles

Figure 1: Sports on a Frozen River, by Aert van der Neer (courtesy The Metropolitan Museum of Art).

Robert F. Cahalan
Energy Budgets of Lunar Surface Climate

1. Daytime absorption of solar radiation is the driving force.

2. Daytime absorbed solar (542W/m²) is not balanced by emitted infrared (536W/m²).

3. Daytime net flux at the surface is stored as heat (6W/m²). This energy storage is released during lunar night.

4. Terrestrial radiation from the Earth (0.09W/m²) is about two orders of magnitude less than the heat storage (6W/m²), and can be ignored at Apollo sites.

Model Results vs Observations at the surface @ Apollo 15 latitude
Figure 1. Using two scenarios of reconstructed TSI in IPCC [2007] (left panel) as driving forces, lunar borehole temperature anomalies (right panel) distinguish between historical TSI scenarios of Lean (2000) and that of Wang, Lean, and Sheeley (2005). For latitudes from 0-80°, the anomaly peaks at a depth about 10 m [From Miyahara et al, 2008, Fig 3].
Figure 2. Left: sketch shows schematic of drilling operation. Right: shows the thermometer side branch (dark blue wire in vertical) that supports the PRT probes (orange round heads) that are inserted horizontally into lunar regolith at depth intervals of 10 cm, down to a total depth of 10 m. The thermometry control system (TCS) is used to control, acquire and store temperature measurements.
Lunar Borehole Summary

1. Two scenarios of the Sun’s luminosity (TSI) differing by \( \approx 2 \) W/m\(^2\) over 300 years can be distinguished by the lunar regolith temperature profiles that they produce, with peak difference \( \approx 10 \) mK at depth \( \approx 10 \) m. Paper in GRL, available at: *GRL* 35, L02716, doi:10.1029/2007GL032171, online at: [http://climate.gsfc.nasa.gov/viewPaperAbstract.php?id=1098](http://climate.gsfc.nasa.gov/viewPaperAbstract.php?id=1098)

2. The Moon’s surface is NOT in radiative thermodynamic equilibrium during day or night. ”Turning off” the Sun in a time dependent thermal model demonstrates that it would take \( \approx 1000 \) years to reach a nearly constant equilibrium temperature of about 24-38 K. However, equilibrium *may* be a good first-order approximation to surface temperature in a permanently shadowed region.
After 11 years with SORCE – What’s new? What’s next?

Robert F. Cahalan
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– Long-term goal of improving the ability to monitor Earth’s energy balance, and energy imbalance that drives
  global warming, requires improved measurements of both shortwave and longwave earth-emitted radiation.
– **Lunar Borehole Experiment** has potential to recover changes in TSI over past 400 years; could clarify “Little Ice Age.”
Backup Slides
Need SORCE follow-On TSIS launched in time to overlap with TCTE

Since 2005 we’ve closed the solar irradiance _calibration_ gap, and...

... now NASA & NOAA are planning “operational” solar irradiance mission, TSIS, but

- **IPCC** AR5 WG1 summary report, now in draft, shows that solar forcing changes are believed to have partly _offset_ greenhouse gas global warming during 1980-2011, a result that depends critically on continuity of the Total Solar Irradiance (TSI) record. This result is _opposite_ to the longer time change, as solar forcing is thought to have added to the warming since pre-industrial times, but with less confidence since solar irradiance was not measured with enough accuracy prior to the satellite era.

- SORCE and TCTE had a successful 2013 Christmas Campaign to ensure continuity of the Total Solar Irradiance Climate Data Record. All instruments collected science data for 7 days, 22-28 Dec inclusive. This will allow the new improved calibration of the Total Irradiance Monitor (TIM) onboard TCTE to be transferred to the SORCE TIM, and subsequently to the whole TSI record back to 1980.

- TCTE will carry forward the TSI record, and SORCE will attempt to continue the Spectral Solar Irradiance (SSI) record with the Spectral Irradiance Monitor (SIM). While TIM is needed to know the total “energy income” for Earth’s energy budget, SIM is needed to know where this energy is deposited, at what altitude for various seasons, and thus how it impacts ozone, temperature, sea ice, etc.

- TSIS instruments were built, tested, and in 2013 stored in preparation for launch. **TSIS needs to be launched in time to overlap with TCTE’s TIM, and preferably also with the SORCE SIM.**

- SORCE & TSIS teams, and the climate community, await news from NOAA about the 2014 budget “passback” and future plans.
Diffraction & Scatter Erroneously Increase Signal

All instruments except the TIM put primary aperture close to the cavity.

Expanding TRF beam from filling precision aperture while underfilling view-limiting aperture to overfilling view-limiting aperture causes increase in signal due to scatter and diffraction from front and interior sections of instrument.

Measured increases due to uncorrected scatter/diffraction are surprisingly large:

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Increase</th>
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<tbody>
<tr>
<td>PREMOS-1</td>
<td>0.10%</td>
</tr>
<tr>
<td>PREMOS-3</td>
<td>0.04%</td>
</tr>
<tr>
<td>VIRGO</td>
<td>0.15%</td>
</tr>
<tr>
<td>ACRIM-3</td>
<td>0.69%</td>
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## TSIS SIM Calibration Error Budget

Instrument uncertainties determined at the component level --> characterization of error budget

<table>
<thead>
<tr>
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<th>Origin</th>
<th>Value (ppm)</th>
<th>1σ (ppm)</th>
<th>Status</th>
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</thead>
<tbody>
<tr>
<td>Distance to Sun, Earth &amp; S/C</td>
<td>Analysis</td>
<td>33,537</td>
<td>0.1</td>
<td></td>
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<tr>
<td>Doppler Velocity</td>
<td>Analysis</td>
<td>43</td>
<td>1</td>
<td></td>
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<tr>
<td>Pointing</td>
<td>Analysis</td>
<td>0</td>
<td>100</td>
<td></td>
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<tr>
<td>Shutter Waveform</td>
<td>Component</td>
<td>100</td>
<td>10</td>
<td></td>
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<tr>
<td>Slit Area</td>
<td>Component</td>
<td>1,000,000</td>
<td>300</td>
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<td>Diffraction</td>
<td>Component</td>
<td>5,000-62,000</td>
<td>500</td>
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<td>Prism Transmittance</td>
<td>Component</td>
<td>230,000-450,000</td>
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<td>Standard Volt + DAC</td>
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<td>Standard Ohm + Leads</td>
<td>Component</td>
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<td>50</td>
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<td>Wavelength ($\Delta \lambda/\lambda = 150$ ppm)</td>
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<td>750</td>
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<td>Non-Equivalence, $Z_H/Z_R^{-1}$</td>
<td>Instrument</td>
<td>2,000</td>
<td>100</td>
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<td>Servo Gain</td>
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<td>Dark Signal</td>
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<td>Scattered Light</td>
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<tr>
<td>Noise</td>
<td>Instrument</td>
<td>-</td>
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<tr>
<td>Combined Rel. Std. Uncertainty</td>
<td></td>
<td></td>
<td></td>
<td>2000</td>
</tr>
</tbody>
</table>
Calibration and Verification

- SIM traces its calibrations to the standard Watt.
- All elements of SIM instrument equations are calibrated at either the component or instrument level.
- Analog to the TSI Radiometer Facility: end-to-end verification of SIM with NIST Spectral Irradiance and Radiance Responsivity Calibrations using Uniform Sources (SIRCUS) and a new LASP SSI Radiation Facility.
... And PREMOS Data Are Recently Available
Lunar Borehole Model
(Keihm 1984)

Paper in press in GRL & available at:

\[
\rho C_p \frac{\partial T(z,t)}{\partial t} = \frac{\partial}{\partial z} \left( k \frac{\partial T(z,t)}{\partial z} \right)
\]

with boundary conditions

\[
k \frac{\partial T(z,t)}{\partial z} \bigg|_{z=0} = \varepsilon \sigma T(z,t)^4 - (1 - \alpha) \cos(\theta_0) F(t)
\]

\[
k \frac{\partial T(z,t)}{\partial z} \bigg|_{z=z_b} = H
\]

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Formula</th>
</tr>
</thead>
</table>
| \( \rho(z) : \text{density (kg/m}^3) \) | \( \rho(z) = 1250 \) \( (z < 0.02 \text{m}) \) 
| | \( = 1900 - 650 \exp \left[ \frac{-200 - z}{400} \right] \) \( (z > 0.02 \text{m}) \) |
| \( k(z,T) : \text{thermal conductivity (W/m \cdot K)} \) | \( k(z,t) = k_1(z) + k_2 \cdot T^3 \) |
| | \( k_1(z) = k_d \) \( (z < 0.02 \text{m}) \) 
| | \( = k_d - (k_d - k_e) \cdot \exp \left( \frac{0.2 - z}{0.4} \right) \) |
| | \( k_d = 6 \times 10^{-4} \text{W/m} \cdot \text{K} \) 
| | \( k_e = 8.25 \times 10^{-3} \text{W/m} \cdot \text{K} \) 
| | \( k_s = 3.78 \times 10^{-11} \text{W/m} \cdot \text{K}^4 \) |
| \( C(T) : \text{specific heat (J/kg \cdot K)} \) | \( C(T) = 670 + (T - 250) \cdot 10^{-3} - \left( \frac{T - 250}{498.7} \right)^3 \cdot 10^3 \) |
| \( \varepsilon(T_s) : \text{emissivity} \) | \( \varepsilon(T_s) = a + b T_s + c T_s^2 + d T_s^3 \) 
| | \( a = 0.9696, b = 0.9664 \times 10^{-4} \) 
| | \( c = -0.31674 \times 10^{-6}, d = -0.9664 \times 10^{-9} \) |
| \( \alpha(\theta_0) : \text{albedo} \) | \( \alpha(\theta_0) = a + b (\theta_0/45)^3 + c (\theta_0/90)^8 \) 
| | \( a = 0.12, b = 0.03, c = 0.14 \) |

Solar zenith angle (\( \theta_0 \)) is computed from JPL ephemerides.

\( H \) : internal heat flux (W/m\(^2\))

\( H = 0.018 \text{W/m}^2 \)

\( d(t) \) : distance (AU)

Moon-Sun distance in astronomical unit (AU) computed from JPL ephemerides

\( TSI(t) \) : Total Solar Irradiance (W/m\(^2\))

Total solar irradiance at 1 AU
1. ”Turning off” the Sun in the time dependent model shows that it would take \( \approx 1000 \) years to reach a nearly constant equilibrium surface temperature in the range 24-38 K.

2. Simple radiative equilibrium (e.g. Huang 2007) is inappropriate to relate Apollo-observed nighttime temperature to Earth’s radiation budget.

3. Thermal equilibrium is a good first-order approximation for temperature in permanently shadowed regions where terrestrial radiation from the Earth does become important.