The SORCE Mission Celebrates Fifteen Years
Speakers: Tom Woods, Marty Snow, Jerry Harder, and Emily Pilinski

OSC
Pegasus XL
Launch

January 25, 2003
Dedicated Team = Successful Mission

- **CU / LASP**
  - PI institution
  - instruments
  - mission operations
  - science data processing

- **Orbital Science Corporation**
  - spacecraft
  - launch

- **NASA GSFC**
  - NASA oversight
  - Project Scientist (Bob Cahalan, Dong Wu)

- **NRLTSI and NRLSSI Solar Models**
  - Co-I Judith Lean
Dedicated Team = Successful Mission

- **CU / LASP**
  - PI institution
  - instruments
  - mission operations
  - science data

- **Orbital Science**
  - spacecraft
  - launch

- **NASA GSFC**
  - NASA oversight
  - Project Scientist (Bob Cahalan, Dong Wu)

- **NRLTSI and NRLSSI Solar Models**
  - Co-I Judith Lean

---

Juan Fontenla
October 28, 1948 - January 11, 2018
... walk down memory lane

Solar Radiation and Climate Experiment (SORCE)

Gary Rottman
SME & UARS SSI
then SORCE PI
1989-2005


1988 EOS AO issued
1989 EOS SOLSTICE selected
1991 UARS launched (with 1st SOLSTICE)
1996 New SIM - SOLSTICE re-design with ESR technology
1997 TSIM AO issued
1998 TIM designed for TSIM Concept Study
1999 LASP selected for TSIM / SOLSTICE; renamed SORCE
2001 TIMED SEE (XPS) launched
2003 SORCE launched
2008 SORCE Mission
2010 2012 2014 2016 2018

2008 SORCE Mission Extended

2008 SORCE Mission Extended

Mar. 4, 2011 Glory Launch Failure
Nov. 19, 2013 TCTE TIM launch
Dec. 15, 2016 TSIS-1 TIM and SIM launch

SORCE Book
Solar Physics
Vol. 230, 2005
Motivation for SORCE Mission
How much of global warming is due to natural solar variability?

- **Solar forcing is 1 of 4 primary contributions to climate change over the past decade** [Lean, *Solar Phys.*, 2005]
  - Solar forcing and greenhouse gases (GHGs) contribute to warming
  - El Nino (ENSO) and volcanoes (aerosols) contribute to short-term changes

### 11-year Solar Cycle Forcing Results

- **Global** temperature change is 0.1 K for 1996-2002 (solar cycle min to max)
- But **regional** temperature changes are much larger
  - some hotter
  - some cooler

[figure from Woods and Lean, *EOS*, 2007]
Solar Irradiance Measurements

Total Solar Irradiance (TSI)

SORCE Celebrates 15 Years

SOLar STellar Irradiance Comparison Experiment (SOLSTICE)

115 – 320 nm

Spectral Irradiance Monitor (SIM)

200 – 2400 nm

XUV Photometer System (XPS)

1 – 34 nm

SORCE TSI and SSI Data Products
http://lasp.colorado.edu/home/sorce/
Total Irradiance Monitor (TIM)

- Measures the Total Solar Irradiance (TSI)
  - Has 4 Electrical Substitution Radiometers (ESRs)
    - 1 used daily, others used for calibration
    - 350 ppm absolute accuracy
    - 10 ppm/year long-term accuracy

![Sorce TIM TSI Daily Average](chart)

<table>
<thead>
<tr>
<th>Solar Cycle 23</th>
<th>Solar Cycle 24</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004-2018</td>
<td></td>
</tr>
</tbody>
</table>

Data Gap (battery)

Day Only Ops (DO-Op)

SORCE Data Sites
http://lasp.colorado.edu/home/sorce/
http://lasp.colorado.edu/home/lisird/
NASA GSFC GES DISC
Spectral Irradiance Monitor (SIM)

- Measures the Solar Spectral Irradiance (SSI)
  - NUV-Visible-NIR range: 200 – 2400 nm
  - Has micro-ESR, photodiodes, and Fery prism
  - SIM-A is used daily, SIM-B is for calibration
  - 2% absolute accuracy
  - 200 ppm/year long-term accuracy
Solar and Stellar Irradiance Comparison Experiment (SOLSTICE)

- Measures the Solar Spectral Irradiance (SSI)
  - FUV-MUV range: 115 – 320 nm
  - Has photomultiplier tube (PMT) and grating
    - SOLSTICE-A & -B use stars for calibration
  - 2% absolute accuracy
  - 0.2%/year long-term accuracy

SORCE SOLSTICE is 2nd generation from UARS SOLSTICE
X-ray ultraviolet Photometer System (XPS)

- Measures the Solar Spectral Irradiance (SSI)
  - XUV range: 1 – 34 nm
  - Has photodiodes and thin-film XUV filters
    - Rocket underflights for calibration
  - 20% absolute accuracy
  - 1%/year long-term accuracy

XPS was first developed for SORCE and variations flew on other missions:
- SNOE SXP
- TIMED SEE XPS
- SDO EVE MEGS-P
- 13 sounding rockets

SORCE Celebrates 15 Years
Annual Sun-Climate Workshops highlight many of SORCE’s Accomplishments

2002  Steamboat Springs, CO
2003  Sonoma, CA
2004  Meredith, NH
2005  Durango, CO
2006  San Juan Islands, WA
2008  Santa Fe, NM
2009  Montreal, Canada
2010  Keystone, CO
2011  Sedona, AZ
2012  Annapolis, MD
2014  Cocoa Beach, FL
2015  Savannah, GA
2018  Lake Arrowhead, CA
(March 19-23, 2018)
SORCE Redefines the TSI Level
Establish More Accurate TSI

1360.8±0.5 W/m² (Kopp & Lean, GRL 2011)
Establish More Accurate TSI

TSI Radiometer Facility (TRF) Measures **Irradiance**

1. Improves the calibration accuracy of future TSI instruments,
2. Establishes a new ground-based radiometric irradiance reference standard,
3. Provides a means of comparing existing ground-based TSI instruments against this standard under flight-like operating conditions.

- Glory/TIM, PICARD/PREMOS, TSIS-1/TIM have had TSI instrument end-to-end calibrations in LASP’s TRF.
- First facility to measure *irradiance*
  - at solar power levels
  - in vacuum
  - at desired accuracies

*Kopp et al., SPIE 2007*
Establish More Accurate TSI

SORCE TSI Lower Values

LASP TSI Calibration Facility

Validates TIM Level and New Climate Record

New Models of TSI Variability
SORCE Provides New Results on Flare Energetics
First solar flare measurements in TSI
“Halloween Storm” in October-November 2003

- Woods et al. [GRL, 31, L10802, 2004] highlight the flare variations from the largest flares observed during the SORCE mission
First solar flare measurements in TSI

- TIM detected first solar flare in the TSI record
  - Hudson & Willson (1983) had searched but had not found any flares in earlier TSI data sets

X17 Flare on Oct. 28, 2003
First solar flare measurements in TSI

- TIM TSI flare and white light flare results indicate that flares near solar disk center are more geoeffective (more energy)
  - from Woods, Kopp, & Chamberlin [JGR, 111, A10S14, 2006]

* TIM TSI
\* WLF (Hudson, 2005)
\* XPS XUV (0.1-27 nm)
  [22%-85% of TSI]

Surprise Result
Total flare energy is 10 times more than expected from prior estimates
(Hudson & Willson, 1983)
FIRST CONTINUOUS SOLAR SPECTRAL IRRADIANCE (SSI) RECORD
First continuous SSI Record

- LASP’s contributions to solar irradiance studies
  - All missions currently operable + recently launch TSIS
    - SORCE Senior allocated funds for ~1year SORCE/TSIS overlap
  - Find the data at: http://lasp.colorado.edu/lisird/

Still Working!
First continuous SSI Record

Whole Heliospheric Interval Reference Spectrum

Integrated SORCE 200-2423nm = 1324.49 Wm\(^{-2}\)
~ 97.3% of TSI

Infrared portion >2423nm ~ 36.32 Wm\(^{-2}\)
Solar Variability from SIM

- Brightness temperature change SC23 descending phase
- Changes relative to solar minimum in late 2008
- Both in-phase and out of phase contributions

- Integrated SIM from 240-1600nm matches TSI to about the 225 ppm level
SORCE Provides SSI & TSI Input to Climate Models
4: Provide SSI & TSI input to Climate Models

- The Earth’s atmosphere responds to changes in SSI
  - Energy is re-distributed through photochemical, light scattering, & dynamical mechanisms

- Altitude dependent atmospheric response is strong function of wavelength

- Climate models now require accurate absolute irradiance scale and spectral variability to resolve the mechanisms
Continuous SSI record needed for Earth climate models.

Tropical Atm over Grass

Cooling Spectrum at 1013.00 hPa

Integrated Cooling Rate

Cooling Rate (K day\(^{-1}\)/cm\(^{-1}\))

Courtesy of Gail Anderson, MODTRAN®5.2i.e. Berk et al., Proc. SPIE, 2006
Mechanisms of Solar Influence

**Mechanisms: top-down**

**Solar Maximum:**
- More UV radiation -> higher temps
- More ozone -> higher temps

2 'top-down' routes:
- Polar route: planetary waves
  (only during winter)
- Equatorial route: synoptic-scale waves
  (all year round)

**Polar Route**
- +ve temp anomaly at stratopause
- -ve temp anomaly lower stratosphere
  => increased horizontal temp grad.
  => altered synoptic wave propagation
- Altered planetary wave propagation
  => fewer sudden stratospheric warmings (SSWs)
- +ve NAO at surface in Smax

**Equatorial Route**
- Increased Solar
  (~0.2 Wm² Global Average)
- Increased Energy Input at Surface
  in Cloud Free Areas
  (~2 Wm² Locally)

**Bottom-up**

Meehl et al., J. Clim, 2008

Courtesy of Lesley Gray, Oxford Univ.
SORCE irradiance data revitalized the irradiance and atmospheric modeling communities. Lots of recent modeling activity!

<table>
<thead>
<tr>
<th>Author</th>
<th>Reference</th>
<th>Model/Topic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Haigh et al.</td>
<td>Nature, 2010</td>
<td>IC2D model/SC Ozone</td>
</tr>
<tr>
<td>Merkel et al.</td>
<td>GRL, 2011</td>
<td>WACCM/SC ozone &amp; TIMED SABER</td>
</tr>
<tr>
<td>Oberländer et al.</td>
<td>GRL, 2012</td>
<td>EMAC-FUB/Strat. temp</td>
</tr>
<tr>
<td>Swartz et al.</td>
<td>ACP, 2012</td>
<td>GEOS CCM/ Strat. Ozone &amp; temp</td>
</tr>
<tr>
<td>Wang et al.</td>
<td>PNAS, 2013</td>
<td>WACCM/MLS &amp; grnd based OH</td>
</tr>
<tr>
<td>Shapiro et al.</td>
<td>JGR, 2013</td>
<td>SOCOL/SC response</td>
</tr>
<tr>
<td>Wen et al.</td>
<td>JGR, 2013</td>
<td>GISS ModelE/Temp. response</td>
</tr>
<tr>
<td>Maycock et al.</td>
<td>JGR, 2105</td>
<td>Impacts of grand minima on future climate</td>
</tr>
<tr>
<td>Matthes et al.</td>
<td>Geosci. Model Dev., 2017</td>
<td>Solar forcing for CMIP6</td>
</tr>
</tbody>
</table>

**Modeling studies focusing on SSI implications:**

- Photochemistry
- Radiative response
- Circulation - NAO
- “Top down” vs “Bottom up”
SORCE Provide SSI & TSI Input to Models of Solar Variability
Two types of modeling:

- **Proxies**: irradiance results from the linear combination of activity indicators, typically MgII index, Ca II K index, F10.7, and Photometric Sunspot Index (PSI). Coefficients are derived by regression with irradiance measurements on rotational time scales, under the assumptions that major instrumental effects occur at longer temporal scales.

- **Semi-empirical**: irradiance variations are determined from the spectra of solar magnetic features driven by the temporal variations of their area coverage.

No strict definitions, some models are hybrid!

Details depend on the spectral and temporal ranges that the technique aims to reproduce. None of them is universal!
**PROXY MODELS**

**SAN FERNANDO** (e.g. Chapman et al. 1996, 2012, 2013)  
**Morrill et al.** 2011  
**MGNM** (Thuiller et al. 2012)  
**Tapping et al.,** 2007, 2013  
**MOCASSIM** (Bolduc et al. 2012)  
**NRL-TSI/SSI -1/2** (e.g. Lean 2000, Coddington 2016)  
**EMPIRE** (Yeo, Krivova, Solanki 2017)

**SEMI-EMPIRICAL MODELS**

**SATIRE-S/T** (e.g. Krivova2003, Yeo2014);  
**NESSY** (Shapiro et al. 2010; 2011);  
**OAR** (e.g. Ermolli et al. 2011; Ermolli et al. 2013);  
**SRPM** (e.g. Fontenla 2011; Fontenla 2015)
Still discrepancies with SORCE-SSI
• VIS is in-phase everywhere
• UV variability smaller than SOLSTICE/SIM
• UV variability smaller than other models

INPUTS:
• MgII index Bremen composite
• RGO and SOON sunspot area
• SIM/SOLSTICE measurements
• TIM measurements
• Explains 92% of TSI / TIM variability
SRPM Spectral Synthesis

- SRPM combines solar feature areas with physics-based solar atmospheric spectral models at high spectral resolution to compute the emergent intensity spectrum.
- SRPM uses a broad variety of solar images (PSPT, AIA, Meudon, Coimbria, etc.) as input to the model.
- Solar line structure is well produced throughout the entire spectrum.
- In Fontenla et al. (2015) integrated spectrum shows better agreement with TSI than in earlier versions.
SORCE Advances the Mg II core-to-wing Index for Proxy Modeling
Some regions of the solar spectrum vary more than other regions. In particular, near 280nm, the cores of the Magnesium II h & k are formed in the solar chromosphere while the wings of the lines are formed in the more stable photosphere. The ratio of these adjacent features is known as the MgII Index.
Long Term Data Record

Magnesium II Index Composite

Index


SORCE Celebrates 15 Years
The SORCE Mission MgII
Measurements in 2017

![Diagram showing solar and space weather data over the year 2017. The graph plots the MgII index with data from SORCE SOLSTICE and GOES-16 EXIS.]
Fifteen years is a long time for a spacecraft
Observations over 15 years

Lyman alpha Composite

Irradiance (1e11 ph/s/cm²/nm)

- Prime Mission
- Extended Mission
- RTS
- DOOp

Dates:
- 26-Dec 2003
- 21-Sep 2006
- 17-Jun 2009
- 13-Mar 2012
- 08-Dec 2014
- 03-Sep 2017
Controversy in the Ultraviolet

Fig. 8 from Ermolli et al. 2013

SIM V20 includes only 240 nm. SOLSTICE and models show integrated 220-240 nm band.
Operations Team Reconfigures SORCE to Run With Weak Battery Pack
Battery Challenges

In 2013, SORCE faced an uncertain future
- Minimum bus voltage was approaching the brownout threshold where the S/C could no longer support the primary computer in eclipse

July 2013 - Emergency Mode:
- Manual care of the spacecraft, commanding heaters each orbit and ensuring safe by sunset
- Approximately 30 days of 24/7 operations
- Momentum bias installed to prevent backflips

Led to the development of new automated ops concept...
Daylight-Only Operations (DO-OP) made possible with new Flight Software to both the primary and backup computers.

Added 4+ years (and counting) of life to the SORCE mission and enabling the cross-calibration with TCTE and TSIS.
Daylight-Only Operations (DO-OP)

- New ops concept of automated Daylight-Only Operations was activated in April 2014. This complete redesign of how the primary and backup computers were used on SORCE led to an entirely new ops concept that eliminated the need for a computer in eclipse. Many teams stepped up to make this happen including Orbital ATK, White Sands TDRS schedulers, SORCE scientists and the student operations team. Below are examples of work that went in to DO-OP:

  - **Flight Autonomy**
    - New FSW to configure the spacecraft for science every sunrise, make safe each sunset

  - **Ground Autonomy**
    - Load products redesigned and process for developing and installing products reworked, new processes in place for ground system receipt of science data

  - **Fault Protection**
    - Onboard telemetry monitoring system and ground fault monitoring and interaction completely reworked

  - **Time**
    - Computer loses time each sunset, requiring jam commands to be sent each orbit

  - **Science**
    - Relatively timed sequences designed and burned to spacecraft FSW that trigger science observations

  - **Communication**
    - No information stored in SSR at sunset, motivated creative use of unused TDRS time to fill in orbits without ground contacts
Orbit in the Life: Eclipse

- All non-critical loads off in eclipse:
  - Primary Computer (OBC)
  - Instruments, MU
  - RWAs, MTBs, Star Tracker
  - Heaters
  - Transmitter

- Spinning about Z-axis to maintain pointing
  - 0.5 deg/min

- No Science Collection

- No Data Stored beyond the low voltage watermark

- No communication with the spacecraft
Orbit in the Life: Sunrise

- Solar Arrays and Coarse Sun Sensors detect the Sun and begin to turn loads
- Spacecraft stops spinning and transfers momentum to RWAs
- Communication with ground reestablished ~2 min after sunrise
- Primary computer boots and checks configuration of the S/C, restoring flight software to the backup computer if necessary via “Boot to Bank 2”
- Once S/C is fully configured and stable exits Safehold and is ready to be configured for Science Mode
Orbit in the Life: Day

- Ground autonomy loads ATS with commands to science attitude
- Once science attitude achieved, S/C detects and enables science sequences
- ATS commands prime science and special calibrations
- Science data are captured by TDRS satellites and recorded by the ground
Orbit in the Life: Sunset

- **ATS commands spacecraft to safe state 5 minutes prior to sunset**
  - Loads off
  - Backup computer (APE) control
  - Enter Safehold

- **Ground Automation confirms safe configuration, prepared to send commands to make spacecraft safe if necessary**

- **As solar array current begins to fall, momentum transfers from RWAs to the S/C body initiating a slow roll to maintain pointing throughout eclipse**

- **Communication blackout at sunset**
### Science Success Statistics (2016)

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Experiment/Calibration</th>
<th>Requirement</th>
<th>Success Rate</th>
<th>Total %</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIM A</td>
<td>Quick Scan 24</td>
<td>1 full scan per day</td>
<td>See next slides for discussion</td>
<td>94</td>
</tr>
<tr>
<td></td>
<td>ESR Scan</td>
<td>1 complete scan per month</td>
<td>See next slides for discussion</td>
<td>95</td>
</tr>
<tr>
<td></td>
<td>Servo Calibration</td>
<td>4 per month (2 Gain, 2 Gain50)</td>
<td>Successfully achieved at least 2 of each scan every month</td>
<td>100</td>
</tr>
<tr>
<td>SIM B</td>
<td>Quick Scan 24</td>
<td>1 full scan per month</td>
<td>See next slides for discussion</td>
<td>95</td>
</tr>
<tr>
<td></td>
<td>ESR Scan</td>
<td>1 complete scan per month</td>
<td>See next slides for discussion</td>
<td>95</td>
</tr>
<tr>
<td></td>
<td>Servo Calibration</td>
<td>2 per month (1 Gain, 1 Gain50)</td>
<td>Successfully achieved at least 1 of each scan every month</td>
<td>100</td>
</tr>
<tr>
<td>SOL A/B</td>
<td>FUV Scan</td>
<td>1 full scan per day</td>
<td>Successfully achieved at least 1 orbit each day</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>MUV Scan</td>
<td>1 full scan per day</td>
<td>Successfully achieved at least 1 orbit each day</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>Filter Calibration Scan</td>
<td>2 scans per month</td>
<td>Successfully achieved at least 2 scans each month</td>
<td>100</td>
</tr>
<tr>
<td>TIM</td>
<td>Normal Solar</td>
<td>1 orbit per day (7.1%)</td>
<td>Successfully achieved at least 1 orbit each day</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>Degradation A,C &amp;</td>
<td>50% of scheduled calibrations are successful</td>
<td>A: 100%, C: 100, D: 100%</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>Aliveness D</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>XPS</td>
<td>65s Integration</td>
<td>1 integration per day</td>
<td>Average 385 integrations per day</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>Calibration</td>
<td>1 every 30 days</td>
<td>17/19 See next slides for discussion</td>
<td>95</td>
</tr>
</tbody>
</table>

- **High success rate for achieving Science Mode (98.0% of orbits)**
- **Large majority of orbits with at least 25 minutes in Science Mode (93.0%)**
- **Majority of orbits show at least 35 minutes spent in Science Mode (63.9%)**
- **Only 200 out of 10014 orbits failed to reach Science Mode (1.9%)**
A new mode of operations is on the horizon…

SORCE has successfully survived the backup computer brownout in eclipse and continued to achieve science requirements. In this mode, SORCE does not need a battery in eclipse and could potentially continue for many more years allowing for a complete cross-calibration with TSIS.
The Future After SORCE
Solar Irradiance Future after SORCE

**TSIS**

- Total and Spectral Irradiance Sensor (TSIS)
  - TCTE with TIM instrument was launched Nov. 2013
  - TIM & SIM instruments launched to ISS in Dec 2017 and are in commissioning now

**GOES-R**

- GOES-R four EUV X-ray Irradiance Sensors (EXIS)
  - EUVS-C also continues the Mg II index
  - GOES-16: Nov 2016
  - Next up is GOES-S (17): Mar 1, 2018 launch

**CubeSats**

- 3U & 6U CubeSats
  - XPS-like mission MinXSS flew in 2016
  - Compact SIM (CSIM) launch is in 2018
  - Compact TIM (CTIM) launch is in 2020
  - Compact SOLSTICE rocket cal is 6/2018
Children of SORCE

- Compact TIM
- TSIS-1 TIM
- TCTE TIM
- Glory TIM
- SORCE TIM
- Compact SIM
- TSIS-1 SIM
- SORCE SIM
- Compact SOLSTICE
- GOES-R EUVS-C
- SORCE SOLSTICE
- MinXSS CubeSat
- GOES-R XRS
- SORCE XPS
Thanks to all who have contributed to the SORCE mission and its many successes !!!!