Over Thirty Years Reporting on NASA's Earth Science Program

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The Editor's Corner

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It is with deep sorrow that we report the passing of Michael ("Mike") Freilich, Former Director of NASA's Earth Science Division (ESD) from 2006 to 2019, on August 5, 2020. Mike was instrumental in moving forward the mission of the ESD during his tenure, with contributions ranging from programmatic advances to fostering the growth and development of many researchers and engineers and their respective scientific research and technology activities. His activities covered all the best parts of leadership, partnership, and mentorship. Mike's energies covered a broad range of activities beyond the professional, to the benefit of all with whom he came into contact.[1]

Mike had great passion for NASA Earth Science, which was evident whenever he spoke about it. Whether he was in front of NASA's Hyperwall at a conference (see photo below and on page 20), speaking before a Senate sub-committee, meeting with international partners to discuss a new mission, or at the many other venues he found himself interacting with others as Director of ESD, Mike's energy and enthusiasm for what he did was always evident—and often made a lasting impression on his colleagues. His enthusiasm and passion for our planet was evident in the remarks he made for the fiftieth anniversary of Earth Day just a few months before his passing (*https://www.youtube.com/watch?v=QdSCkLrC4Fg*).

The ongoing successes of NASA's Earth Science program, which *The Earth Observer* has been chronicling for over three decades, are part of Mike's legacy. Our team here at the Science Support Office specifically wishes to recognize Mike's encouragement for the communication activities of the office—including *The Earth Observer*. His passing is a tremendous professional and personal loss to many—and he will be missed.

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[1] To learn more about Mike Freilich's life and legacy, see "Symposium on Earth Science and Applications from Space with Special Guest Michael Freilich," in the March–April 2020 issue of *The Earth Observer* [**Volume 32**, **Issue 2**, pp.4–18—*https://go.nasa.gov/3lsbsDG*].

continued on page 2

Michael ("Mike") Freilich, Former Director of NASA's Earth Science Division (ESD) from 2006 to 2019, passed away on August 5, 2020. Mike loved NASA Earth Science, which was evident whenever and wherever he spoke about it. He loved to tell the stories of NASA Earth Science and was extremely supportive of the division's communication activities. This photo of Mike was taken during NASA's Earth Day 2018 celebration at Union Station in Washington, DC, while he was waiting to give opening remarks in front of the Hyperwall. **Photo credit:** NASA

In This Issue

Reminder: To view newsletter images in color, visit *eospso.nasa.gov/earth-observer-archive.*

This sad news for NASA comes as the pandemic resulting from novel coronavirus disease COVID-19 continues. As of this writing, all NASA Centers are now at Stage 3 in the agency's four-stage framework.[2] Mandatory telework continues into its sixth month for most employees, although mission-essential, some mission-critical, and a few other health and safety-related activities are permitted to resume on site.

The Earth Observer reported in our last issue on NASA's efforts to document the impacts of COVID-19 via remote sensing with the funding of the first several Rapid Response and Novel Research in Earth Science (RRNES) science investigations.[3] NASA has also entered into a partnership with the European Space Agency (ESA) and the Japan Aerospace Exploration Agency (JAXA) to create a COVID-19 dashboard (*eodashboard.org*) that brings the collective Earth-observing capabilities of the three space agencies together to document planet-wide changes in the environment and human society resulting from COVID-19. The wealth of these agencies' combined information now is available at the touch of a finger. To learn more, see the News story on page 28 of this issue.

Despite the ongoing challenges posed by the pandemic, current and upcoming Earth Science missions continue to make progress.

The Copernicus Sentinel-6 Michael Freilich satellite remains on schedule for a November 10 launch. And while the altimeter community awaits this joint U.S.–European satellite, it simultaneously mourns the loss of its namesake.

"We miss him," said **Josh Willis** [NASA/JPL—*Sentinel-6 Michael Freilich Project Scientist*]. "We wish he could have been here for the launch. But each time we make a new discovery or unravel a new mystery with data from this satellite, we'll remember Mike."

Sentinel-6 Michael Freilich (followed by Sentinel-6B, planned to launch in 2025) will add another decade to the nearly 30-year sea-level time series that began in 1992 with the launch of the TOPEX/Poseidon mission and has continued with three more missions over the years: Jason-1, the Ocean Surface Topography Mission (OSTM)/Jason-2 (Jason-2 hereinafter), and Jason-3. In January, at the ceremony formally changing the name of Sentinel-6A to Sentinel-6 Michael Freilich, Mike described this sea-level time series as "the longest—and most successful—multinational and intercontinental, collaborative Earth remote sensing endeavor that our species has achieved." Turn to the News story on page 30 of this issue to learn more about the status of Sentinel-6.

Meanwhile, the Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission has cleared several major mission milestones within its critical design phase in late 2019 and early 2020, along its path to a planned spring 2023 launch. PACE represents NASA's next

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[2] View the framework at *https://go.nasa.gov/31hUJe9*.
[3] See "The Editor's Corner" of the May–June 2020 issue of *The Earth Observer* [**Volume 32**, **Issue 3**, p. 1—*https://go.nasa.gov/2QcDTH0*].

advance in the combined study of Earth's ocean–atmosphere–land system. The mission passed its mission-level Critical Design Review (CDR) in February 2020; it also awarded its launch vehicle contract to SpaceX. Its primary instrument—the Ocean Color Instrument (OCI)—passed its CDR in December 2019 and completed a system-level engineering test unit (ETU) thermal vacuum campaign in March 2020. OCI is a hyperspectral scanning radiometer that will measure reflected light from the near ultraviolet through near infrared, coupled with a multiband filter spectrograph to extend coverage into the shortwave infrared. It will be used to study phytoplankton as well as atmospheric aerosols and clouds. OCI is being built at GSFC.

PACE will also carry two multiangle polarimeters dedicated to aerosol and cloud science. The Spectropolarimeter for Planetary Exploration (SPEXone) will be built and overseen by the SRON Netherlands Institute for Space Research and Airbus Defence and Space Netherlands. The Hyper-Angular Rainbow Polarimeter (HARP2) will be built by the Earth and Space Institute at the University of Maryland, Baltimore County (UMBC). The SPEXone flight unit is currently undergoing environmental testing and will be delivered to the mission in early 2021. The HARP2 ETU continues to be developed and tested.[4] HARP—a CubeSat version of HARP2—continues to perform well, following its November 2019 launch from the International Space Station (ISS).[5]

In a previous issue, we reported on the passivation of the Solar Radiation and Climate Experiment (SORCE) in February 2020 after more than 17 years of observations of the total solar irradiance (TSI) and spectral solar irradiance (SSI).[6] The Total and Spectral Solar Irradiance Sensor (TSIS) now claims stewardship of the solar irradiance climate data record. Launched to the ISS in December 2017, TSIS-1 has now completed over two years of science observations—a significant portion of which overlapped with SORCE and the TSI Calibration Transfer Experiment (TCTE), which completed its science mission on July 1, 2019. The TSIS-1 total and spectral solar irradiance measurements continue to meet the high accuracy and stability requirements of a *climate data record*, a time series of measurements of sufficient length, consistency, and continuity to quantify climate variability and climate change. LASP at the University of Colorado, where TSIS-1 was built and is operated, is also flying a technology demonstration mission called the Compact Spectral Irradiance Monitor (CSIM). This CubeSat mission was launched in December 2018 and is still flying. Data from the initial operations of CSIM were released in March 2019, showing exceptional agreement with the Spectral Irradiance Monitor (SIM) on TSIS-1.

We are happy to report that TSIS-1 operations have continued with minimal impact from the COVID-19 pandemic since mission and science operations and data processing are largely automated for routine public access. Meanwhile, in January 2020, TSIS-2 completed an important milestone by passing its CDR as it prepares for a 2023 launch date. Unlike TSIS-1 on ISS, TSIS-2 will be a free-flyer mission much like its predecessor, SORCE. In early July the contract to build the TSIS-2 spacecraft was awarded to General Atomics Electromagnetic Systems Group of San Diego, CA.[7]

Related to these missions, the lead article in this issue is a summary of the Sun–Climate Symposium meeting that took place in January 2020 in Tucson, AZ. Sessions highlighted the achievements of the SORCE mission and covered current and future observations (e.g., TSIS-1 and TSIS-2), models, solar variability, as well as discussions of the expectations for the upcoming solar cycle 25. Turn to page 4 to read more about this meeting. ■

List of Undefined Acronyms Used in The Editor's Corner and Table of Contents

AOGS	Asia Oceania Geosciences Society
CALIPSO	Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Operations
COVID-19	2019 Novel Coronavirus Disease
CERES	Clouds and the Earth's Radiant Energy System
GSFC	NASA's Goddard Space Flight Center
JPL	NASA/Jet Propulsion Laboratory
LASP	Laboratory for Atmospheric and Space Physics

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[4] To learn more about PACE, visit *http://pace.gsfc.nasa.gov*.

[5] To learn more about HARP's achievements, see "The Editor's Corner" of the May–June 2020 issue of *The Earth Observer* [**Volume 32**, **Issue 3**, p. 2].

[6] See "The Editor's Corner" of the March–April 2020 issue of *The Earth Observer* [**Volume 32**, **Issue 2**, p. 3].

[7] To learn more about the status of TSIS-2, see *https://go.nasa.gov/2QkE4A5*.

Summary of the 2020 Sun–Climate Symposium

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Tom Woods, LASP/CU, tom.woods@lasp.colorado.edu
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Introduction

Observations of the Sun and Earth from space have revolutionized our view and understanding of how solar variability and other natural and anthropogenic forcings impact Earth's atmosphere and climate. For more than four decades (spanning four 11-year solar cycles and now beginning a fifth), the total and spectral solar irradiance and global terrestrial atmosphere and surface have been observed continuously, providing an unprecedented, high-quality time series of data for Sun–climate studies—see **Figure 1** on the next page.

The unique theme of the symposium was: "What Is the Quiet Sun and What Are the Subsequent Climate Implications?"

Sun–Climate Symposia, originally called SOlar Radiation and Climate Experiment (SORCE) Science Team Meetings, have been held at a regular cadence since 1999—even before the launch of SORCE in 2003. The 2020 Sun–Climate Symposium was held at the University Park Marriott in Tucson, AZ, January 27-31, 2020. (This sixteenth meeting in the series occurred one month prior to the decommissioning of SORCE.) The Sun–Climate Research Center—established as a collaboration between NASA's Goddard Space Flight Center (GSFC) and the Laboratory for Atmospheric and Space Physics at the University of Colorado (LASP/CU Boulder, hereinafter referred to as LASP)—organized the symposium. The unique theme of the symposium was: *What Is the Quiet Sun*[1] *and What Are the Subsequent Climate Implications?*

The symposium convened experts from across the solar–terrestrial community, including the disciplines of climate research, atmospheric physics and chemistry, heliophysics, and metrology, to discuss solar and climate observations and models over both spacecraft-era and historical timescales. Altogether, 89 scientists and students from around the world gathered to present their findings and to engage in spirited discussions—see photo below. One presentation was presented remotely.

Attendees at the 2020 Sun–Climate Symposium in Tucson, AZ. **Photo credit**: Kelly Hepburn [LASP]

The meeting consisted of seven oral sessions, a poster session, and an optional tour of two world-class laboratories at the University of Arizona—see *Sun–Climate Symposium Attendees Visit Prestigious University of Arizona Labs* on page 11. The first of the

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[1] Quiet Sun refers to the Sun at the minimum of solar activity during its 11-year cycle.

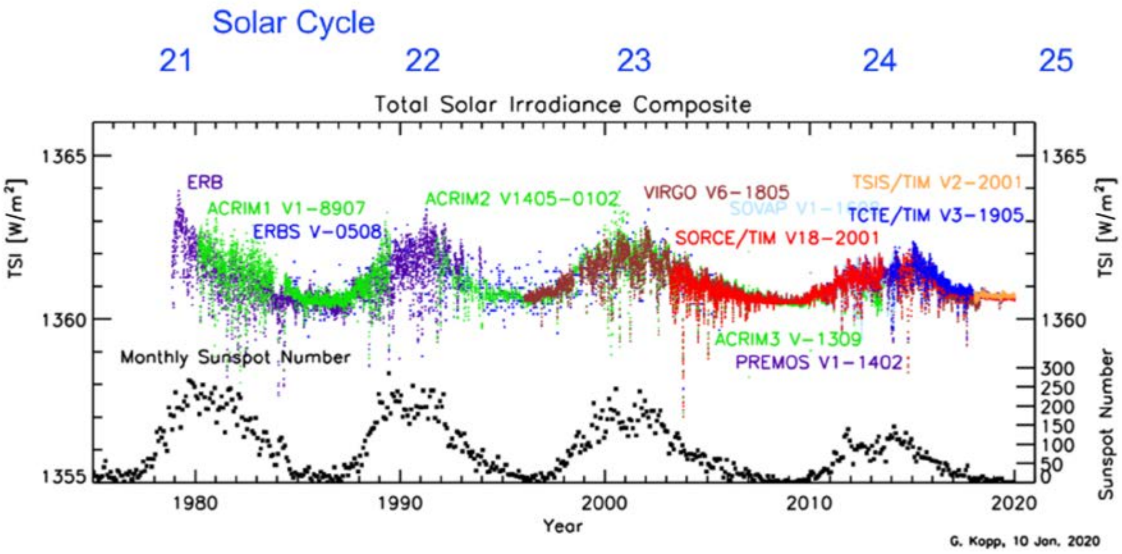

Figure 1. This graph shows the measurements that make up the record of total solar irradiance from space, adjusted to a common calibration scale. The SORCE mission added 17 years to earlier data to produce what is now a 42-year record. **Image credit:** Tom Woods [LASP]

List of Acronyms Used in Figure 1: *ERB*—Earth Radiation Budget (onboard Nimbus 7); *ACRIM*—Active Cavity Radiometer Irradiance Monitor (onboard ACRIM); *ERBS*—Earth Radiation Budget Satellite; *VIRGO*—Variability of solar IRradiance and Gravity Oscillations [onboard the SOlar and Heliospheric Observatory (SOHO)]; *SORCE/TIM*—Total Irradiance Monitor onboard SORCE; *SOVAP*—SOlar VAriability Picard (onboard the Picard satellite); *TSIS/TIM*—Total Irradiance Monitor [onboard TSIS]; *TCTE/TIM*—Total Irradiance Monitor (part of the Total Solar Irradiance Calibration Transfer Experiment onboard the STPSat-3 satellite); *PREMOS*—PREcision Monitoring Of Solar Variability (onboard the Picard satellite).

oral sessions highlighted SORCE achievements. The remaining sessions (including the posters) covered current solar variability, future solar and climate observations, models, as well as discussions of the expectations for the next solar cycle. Most of the 2020 Sun–Climate Symposium presentations are available online at *https://tinyurl.com/yahd2yz3*.

Meeting Overview

The 2020 Sun–Climate Symposium coincided with the transitional phase between the end of solar cycle 24 and the onset of cycle 25, a period known as *solar minimum*, when the Sun is relatively "quiet." As a result, the meeting's content was organized around these guiding questions:

The 2020 Sun–Climate Symposium coincided with the transitional phase between the end of solar cycle 24 and the onset of cycle 25, a period known as solar minimum, when the Sun is relatively "quiet."

- What exactly is the *quiet Sun*? Is it a time-invariant base level or is there variability in the Sun's radiative output over centennial-to-millennial time scales?
- What do those alternate scenarios imply for Earth's climate responses?

The meeting also coincided with a transitional period in the availability of observational tools to monitor the solar radiative input to the Earth system. The SORCE science mission ended just four weeks after the start of the symposium—on February 25, 2020. And last summer, on June 30, 2019, the Total Solar Irradiance Calibration Transfer Experiment (TCTE) mission ended.[2] Therefore, stewardship of the solar irradiance climate data record is now fully in the domain of the

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[2] TCTE launched in 2013 on the U.S. Air Force Space Test Program spacecraft known as Space Test Program (STPSat)-3, a mission designed to assess sensors for military needs.

Total and Spectral Solar Irradiance Sensor (TSIS). TSIS-1 launched in 2017 and is currently mounted on ExPRESS Logistics Carrier 3 (ELC 3)[3] on the International Space Station (ISS). TSIS-2 is in development and is currently scheduled for a 2023 launch on a still-to-be-determined, free-flying satellite[4] with a planned three-year mission lifetime. The two instruments on TSIS-2, the Total Irradiance Monitor (TIM) and Spectral Irradiance Monitor (SIM), will be identical to those on TSIS-1 and are being developed at LASP.

Opening Remarks

During the 2018 Sun–Climate Symposium, **Peter Pilewskie** [LASP—*TSIS-1 Principal Investigator (PI)*] and **Tom Woods** [LASP—*SORCE PI*] symbolized the connection between SORCE and TSIS with a relay baton being passed from SORCE to TSIS.[5] In the nearly two years since that meeting, SORCE has steadfastly refused to relinquish its grip on the baton: Despite a recurrence of battery problems that had plagued SORCE for years, initially triggering an acceleration of the SORCE decommissioning plan, NASA decided to extend SORCE operations first into January and then February 2020. In their opening remarks, Pilewskie summarized highlights from the first two years of TSIS-1, while Woods recapped the achievements from SORCE during its remarkable 17 years in orbit.

> *The 2020 Symposium kicked off with a special session to highlight many of the SORCE mission accomplishments, discoveries, and lessons learned during its 17-yearlong mission.*

Session 1: The Sunset of SORCE

The 2020 Symposium kicked off with a special session to highlight many of the SORCE mission accomplishments, discoveries, and lessons learned during its 17-yearlong mission.[6] Among the key SORCE results are the improved climate records of the total solar irradiance (TSI) and solar spectral irradiance (SSI), with measurements from the SORCE TIM, SIM, SOLar-STellar Irradiance Comparison Experiment (SOLSTICE), and Extreme Ultraviolet (XUV) Photometer System [XPS] instruments.

Gary Rottman [LASP—*Original Principal Investigator for SORCE from 1999–2006]* started the session with a history of the mission beginning in 1988 with LASP's original proposal to NASA's Earth Observing System (EOS) to provide a SOLSTICE instrument to measure the solar UV irradiance. Over the intervening years before the SORCE launch in 2003, the mission evolved to include two additional spectral instruments that measured almost all wavelengths from the shortest X-rays through a good portion of the shortwave infrared (IR) and a new instrument concept to revolutionize the measurement of TSI. Rottman discussed the many twists and turns of fate, some planned and some not, that expanded SORCE to its full capability. He was followed by **Bob Cahalan** [GSFC, *retired—SORCE Project Scientist from 1999 to 2015*], who provided his personal and professional reflections on the build and launch of SORCE.

> *SORCE can only be regarded as a highly, highly successful mission. It has achieved great scientific results, it has far outlived its intended mission life, and it has stayed well below all cost guidelines. Small free-flying spacecraft are the ideal and very best way of making solar irradiance observations as illustrated first by the Solar Mesosphere Explorer [1981–1989] and now by SORCE [2003–2020]. For both of these missions LASP and the University of Colorado excelled in managing the programs put in place by the PI and keeping the science objectives as the guiding principle—all the while training students, young scientists, and engineers, and returning exceptional value to NASA. TSIS-1 continues the observations of SORCE, with similar great instruments, albeit with restricted observations from ISS. TSIS-2 [will carry] on the "free-flying" tradition, although it will have a very different mission and management structure.*
>
> — **Gary Rottman**, Original SORCE PI [1999–2006]

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[3] ExPRESS stands for Expedite the Processing of Experiments to the Space Station; ExPRESS Logistics Carriers (ELCs) are unpressurized attached payload platforms for the International Space Station.

[4] **UPDATE:** In July 2020, NASA announced that General Atomics Electromagnetics Group of San Diego, CA, has been chosen to build the TSIS-2 spacecraft.

[5] To learn more about the previous meeting, read the "Summary of the 2018 Sun–Climate Symposium" in the May–June 2018 issue of *The Earth Observer* [**Volume 30**, **Issue 3**, pp. 21–26—*https://go.nasa.gov/3fRUOdm*]. The "baton" is pictured on page 22 of that issue.

[6] The significant accomplishments from the first 10 years of SORCE were summarized in "The SORCE Mission Celebrates Ten Years" in the January–February 2013 issue of *The Earth Observer* [**Volume 25**, **Issue 1**, pp. 3–13—*https://go.nasa.gov/3kGaqTQ*].

Greg Kopp [LASP—*SORCE, TCTE,* and *TSIS TIM Instrument Scientist*] described the TIM instrument, noting the many innovations in its design that led to improved accuracy and precision over previous instruments. He presented a long list of TIM accomplishments and how its measurements compared to those from other past and current instruments.

Jerry Harder [LASP—*SORCE SIM Instrument Scientist*] followed with highlights from the SORCE SIM instrument, the first to provide an uninterrupted record of daily solar variability at visible and IR wavelengths. Along with the ultraviolet (UV) part of the spectrum acquired by SIM, this represents 97% of the total solar output. Harder discussed the importance of SIM measurements to solar activity and climate modeling, and the technological advances incorporated into the design of SIM that have been passed on to the next generation of solar-spectral radiometers.

> *It is indeed a pleasure to recall being SORCE project scientist, through the build, the January 2003 launch, the 2003 Halloween X-rays, the 2008 "Great Minimum" during the "Great Recession," the TSI evolution from "Outlier" to "Gold Standard," the 2004 and 2012 dual Venus transits, the 2013 "gap year," the 2013-2014 double-peaked solar maximum, the flip-flop "DO-Op" mode, witnessing the fitful winding down of cycle 24, the beautiful 17-year record of the TSI, and the first-ever ultraviolet–visible–near infrared record of daily SSI variations. Though I retired as project scientist in 2015, I continue to enjoy and applaud successes such as the December 2017 TSIS-1 launch that enabled a full two-year SORCE–TSIS-1 overlap, which ended with the bittersweet moment of SORCE's "sunset" or "passivation" in February 2020. And now, as solar cycle 25 begins, TSIS-1 takes the baton and Sol begins cycle 25, I want to thank all who have been involved, as mission success has relied in essential ways on many varied contributions by all.*
>
> — **Bob Cahalan**, SORCE Project Scientist [1999–2015]

Marty Snow [LASP] reported on 17 years of SOLSTICE measurements of SSI from 115 to 300 nm. In addition to providing a new understanding of short- and long-term variability in the UV, SORCE SOLSTICE observations have been used to derive a Magnesium II Core-to-Wing Index. The so-called Mg II index is an important proxy for solar activity since it is highly correlated with solar extreme UV radiation (10–124 nm), which makes it important for understanding physical processes in Earth's upper atmosphere. Snow noted that SOLSTICE measurements have also been used to calibrate solar irradiance models, to calibrate other solar measurements, and to construct reference solar spectra.

Tom Woods summarized SORCE XPS observations of X-ray UV (1–34 nm) and the neutral hydrogen HI Lyman-α (121.6 nm) solar irradiance. One key finding showed that irradiance at the shortest wavelengths varies over the solar cycle by more than a factor of 10 and it varies by a factor of 1.7 for HI Lyman-α. Additionally, XPS observed more than 3000 flares during the SORCE mission, with the largest occurring in October-November 2003, during solar cycle 23, and in September 2017, during solar cycle 24.

> *The SORCE mission has provided an excellent dataset of total solar irradiance and solar spectral irradiance for the past 17 years, and this exceeds all of my expectations for the planned five-year mission. The last seven years have been particularly remarkable as SORCE has operated with a very unhealthy battery and still was able to have normal solar observations, thanks to the dedication and creative solutions by the SORCE operations team.*
>
> — **Tom Woods**, SORCE PI [2006–present]

Sean Ryan [LASP—*SORCE Mission Operations*] described the many challenges in managing SORCE flight operations. Perhaps the most notable was the extreme degradation in battery capacity that required redesigning the way the spacecraft was operated in 2014. As the capacity of the battery decreased, instruments were phased out of operations in *eclipse* (i.e., when Earth blocks SORCE from viewing the Sun) while strategies were tested to improve battery performance and longevity. By 2014 SORCE began to operate in daylight-only mode, and cleverly designed automation sequences allowed the mission to continue despite greatly reduced battery capacity.

The session closed with **Tom Sparn** [LASP—*Original SORCE Program Manager*] giving a retrospective view of the highly collaborative relationship between GSFC SORCE management, LASP, and Orbital Sciences Corporation (OSC), which built and integrated the spacecraft. Sparn discussed how management processes brought the implementation of the SORCE mission to its successful conclusion, on schedule and within budget. It was the outstanding relationship between the academic, government, and industry partners that enabled the success of SORCE.

> *The tremendous success of the SORCE program management started with establishing a true partnership with the three principal participants: LASP, NASA, and Orbital Sciences, [representing] academia, government, and industry. This partnership was the cornerstone on which a relationship of trust was formalized with clear, well-defined contracts that acknowledged the acceptance of shared risk by all partners. This successful relationship leveraged trust, mutual support, leadership, focused goals, defined requirements, science buy-in, and consistent financial support throughout the mission, from the start of Phase A to the conclusion of Phase E. The free and open communication fostered by this relationship allowed for optimal solutions to be accomplished and brought the mission success.*
>
> —**Tom Sparn,** LASP SORCE Program Manager [1999–2009]

Session 2: Recent and Spacecraft-Era Solar-Cycle Timescales

This session, beginning with the start of the "spacecraft era" for Sun and Earth observations in the late 1970s, was devoted to solar measurements and models covering the last few solar cycles. Particular emphasis was placed on current understanding of the quiet Sun. There were several presentations on SSI and spectral variability. New data from the TSIS-1 SIM were presented, along with comparisons of TSIS-1 data to other measurements and modeled spectral irradiance, and a quantitative analysis with SORCE SIM during the SORCE/TSIS-1 overlap period.

Serena Criscuoli [National Solar Observatory] gave an invited presentation on "Modern and Historical Reconstructions of Solar Ultraviolet (UV) Irradiance Variability." The hybrid reconstruction method she described combines semi-empirical and proxy models with data assimilation of sunspot number, full-disk observations, and modern UV-irradiance measurements by SORCE.

> *It was the outstanding relationship between the academic (LASP), government (GSFC), and industry (OSC) partners that enabled the success of SORCE.*

After the invited presentation, the focus of the session shifted from UV to TSI measurements. One presentation featured new results from the Compact Lightweight Absolute Radiometer (CLARA),[7] along with comparisons between CLARA data and contemporaneous TSI observations. Other TSI-focused presentations considered a three-point differencing technique to quantify the precision in VIRGO,[8] SORCE, TCTE, and TSIS-1 measurements, and the quantitative comparison between SORCE and TSIS-1 TSI data.

Understanding how TSI measurements have varied in the past relies on sophisticated solar *proxy models* that connect modern measurements of solar irradiance to features on the Sun that have been measured for centuries. Some presentations during this session detailed the progress that has been made with the development of new methods to construct coherent time series that are tied to the latest calibration scales. Additional improvements in solar irradiance reconstructions from solar proxy models may be achieved by the use of linear transfer functions that assume convolutional rather than instantaneous relationships between the proxy and solar irradiance.

Bo Andersen [Norwegian Space Agency] gave an invited presentation, during which he delivered a moving homage to Claus Fröhlich, who is one of the modern giants in the measurement of solar irradiance, former director of Physikalisch-Meteorologisches Observatorium Davos (PMOD), and an original member of the SORCE Science Team—see *In Memoriam: Claus Fröhlich [1936–2019]* on page 9.

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[7] CLARA flies on the Norwegian satellite NORSAT-1, a nanosatellite launched in 2017.

[8] VIRGO stands for Variability of solar IRradiance and Gravity Oscillations; it flies on the European Space Agency–NASA SOlar and Heliospheric Observatory (SOHO) that launched in 1998. The instrument is the result of an international collaboration by several European countries.

In Memoriam: Claus Fröhlich [1936–2019]

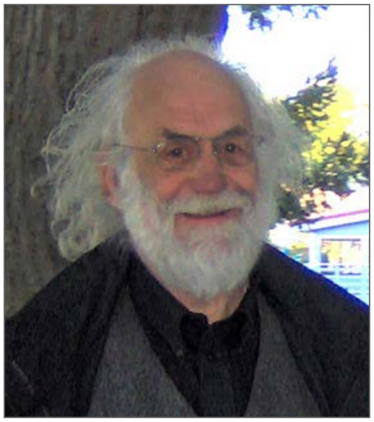

Photo credit: Vanessa George [LASP]

Claus Fröhlich passed away on February 22, 2019. He put his heart and soul into his solar research and was one of the original co-investigators on SORCE. He led several key solar missions in Europe and was very important in contributing to the continuation of the long-term solar irradiance data record. To view his full In Memoriam, see *https://www.sps.ch/en/archive/nachrufe/in-memoriam-claus-froehlich*.

Session 3: Solar Variability and Climate Trends on Secular Timescales

This session focused on the following questions:

- What have we learned about the ranges of total and spectral solar irradiance variability?
- What are the trends in proxies of solar activity and paleoclimate records, such as tree rings and cosmogenic isotopes, on multidecadal-to-millennial timescales?
- What are the potential secular trends in the Sun, based on trends observed in other stars?
- What are the associated impacts on Earth's climate that are estimated from these records?

A key physical phenomenon that underlies much solar behavior of interest is the *solar dynamo,* which generates a magnetic field in the interior of the Sun that travels through the convective zone and emerges on the solar surface, leading to various manifestations of solar magnetic activity, including variations in solar brightness. Much progress has been made in understanding solar variability on timescales ranging from hours to millennia, and recent observations of Sun-like stars younger than the Sun have been used successfully to reconstruct solar activity and brightness variability over the last four billion years.

Creating a composite sunspot record by merging the many hundreds of observations that contribute to the record requires corrections for offsets, trends, and nonlinearities in the individual time series.

Considering only the last four centuries, the sunspot record is the longest continuous, directly observed solar record in existence. Creating a composite sunspot record by merging the many hundreds of observations that contribute to the record requires corrections for offsets, trends, and nonlinearities in the individual time series. Sunspot numbers are collated by the World Data Center (WDC) Sunspot Index and Long-term Solar Observations (SILSO) Version 2.0 at the Royal Observatory of Belgium. But a new group sunspot number composite is the result of testing several new composite-creation methods and recovering and updating many historical sunspot records. These revisions produce a sunspot record that differs from prior versions with expected impacts on several solar phenomena and historical TSI reconstructions.

In addition to looking at the Sun's activity over time, we also look to other stars to gain insight into the behavior of our own Sun. Missions like Kepler and the Transiting Exoplanet Survey Satellite (TESS) have enabled *asteroseismology* (study of the internal structure of stars by the interpretation of their frequency spectra as they correlate with oscillation modes at different depths) and measurement of star-spot modulation for a multitude of stars. These datasets have enabled examination of the link between stellar rotation and magnetism observed in the Sun, facilitating the study of stars in various phases of their evolution. There is evidence that middle-aged stars undergo a transition in their magnetic properties, manifested by changes in their rotational behavior and magnetic activity. The question remains: *What are the implications for our own middle-aged star, the Sun?*

Stars also provide a means to judge the state of the quiet Sun. By collecting large samples of stellar observations, it is possible to determine a lower activity level among solar-type stars. This facilitates the extrapolation of observed solar activity to even "quieter" levels, to examine consequences of the Sun in its quietest possible state.

Valerie Trouet [Laboratory of Tree-Ring Research, University of Arizona] focused on a very different dataset in her presentation titled "Reduced Caribbean Hurricane Activity During the Maunder Solar Minimum." Trouet combined a time series documenting Spanish shipwrecks in the Caribbean (1495–1825 CE) with a tree-growth suppression chronology from the Florida Keys (1707–2010 CE) to find a 75% reduction in decadal-scale North Atlantic tropical cyclone (NATC) activity during the *Maunder Minimum.*[9] These results emphasize the need to enhance our understanding of the responses of oceanic and atmospheric circulation patterns to radiative forcing and climate change in order to improve the skill of future NATC projections.

There is evidence that middle-aged stars undergo a transition in their magnetic properties, manifested by changes in their rotational behavior and magnetic activity. "The question remains: What are the implications for our own middle-aged star, the Sun?"

Session 4: Solar Influence on the Atmosphere and Climate

This session was devoted to the measured and modeled responses of Earth's atmosphere and climate to solar variability over the last few solar cycles. **Judith Lean** [Naval Research Laboratory, *retired*] gave a keynote presentation on "Navigating the Causes of Modern Climate Change." One challenge she addressed was the so-called "global warming hiatus" from 2000 to 2015, when global surface temperatures increased less rapidly than during the last half of the twentieth century, despite the continued increase in greenhouse gas concentrations. The suggestion that "missing" mechanisms are influencing climate exacerbated confusion among policy makers, the public, and other stakeholders about the causes and reality of modern climate change. Lean presented a statistical analysis of surface-temperature observations for a quantitative interpretation of modern climate change as a mix of both anthropogenic and natural influences, including the Sun's irradiance cycle.

Perhaps the most easily detectible solar influence on Earth's atmosphere is the response of ozone concentration in the middle atmosphere to solar UV variability, as changes in ozone concentrations can influence dynamical processes in both the troposphere and the stratosphere. Decreases in stratospheric ozone have been linked to stratospheric cooling trends and increases in the strength of the *Brewer–Dobson* (ozone) *circulation*[10] in the lower stratosphere, while—at the surface—the largest climate impacts are in the Southern Hemisphere summer. These climate impacts are expected to reverse over the coming decades as stratospheric ozone recovers due to the actions taken to dramatically reduce ozone-depleting chemicals as a result of the 1987 Montreal Protocol. The relative importance of ozone recovery for future Southern Hemisphere climate will depend on the evolution of atmospheric greenhouse gas concentrations.

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[9] The Maunder Minimum, a.k.a., the prolonged sunspot minimum, is the name given to a period of extremely slow solar activity (e.g., sunspots) that lasted from 1645 to 1710. The term Maunder Minimum was first used in a 1976 landmark paper by John C. Eddy to honor the work of Annie Russell Maunder [1868–1947] and her husband, Edward Walter Maunder [1851–1928], who studied how sunspot latitudes changed with time.

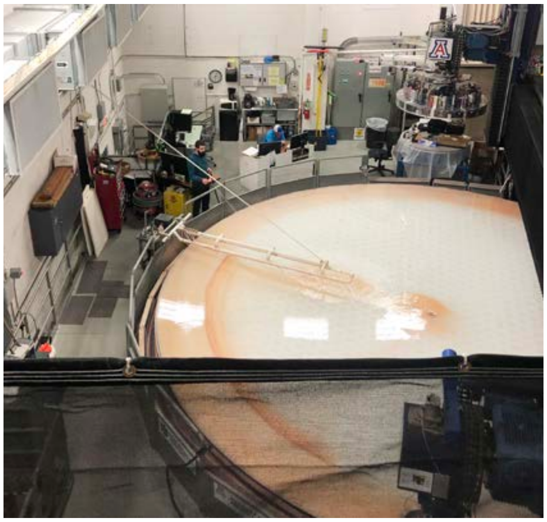
[10] The Brewer–Dobson circulation is an atmospheric circulation that explains why there is less ozone in the tropics than at the poles—even though more ozone is produced in the tropical stratosphere. The model posits the existence of a slow current in the winter hemisphere that redistributes air from tropics to extratropics. It is named after Alan Brewer and Gordon Dobson who proposed the theory in 1949 and 1956, respectively.

Sun–Climate Symposium Attendees Visit Prestigious University of Arizona Labs

On the afternoon of the second day, symposium attendees had the opportunity to tour the Richard F. Caris Mirror Laboratory and the Laboratory of Tree-Ring Research at the University of Arizona.

Richard F. Caris Mirror Laboratory

Participants were privileged to listen to a lecture on the history of the Richard F. Caris Mirror Laboratory and to view the facilities where the complex fabrication occurs, where a team of scientists and engineers are making giant, lightweight mirrors of unprecedented power for a new generation of optical telescopes. During the tour, the participants learned that—unlike conventional solid-glass mirrors—the mirrors produced at the Laboratory have an internal honeycomb structure, so they can be made significantly larger and dramatically lighter than other mirrors. The mirrors are made out of Ohara E6-type borosilicate glass that is melted, molded, and spun cast into the shape of a paraboloid in a custom-designed rotating oven. The Laboratory continues its impressive history of successful, groundbreaking mirror castings with its work on the Giant Magellan Telescope being built by an international consortium at its location in the Las Campanas Observatory in Chile. When completed, this telescope will be the largest and most advanced Earth-based telescope in the world. Currently, five of the seven 8.4-m (27.6-ft) segmented mirrors have been cast. The first mirror is complete and the other four are in various stages of production.



During the tour of the University of Arizona's Richard F. Caris Mirror Laboratory, participants got to see one of the massive mirrors being built for the Giant Magellan Telescope, which will be the largest Earth-based telescope in the world. **Photo credit**: Marty Snow [LASP]

Laboratory of Tree-Ring Research

The other tour was of the Laboratory of Tree-Ring Research (LTRR), which was created in 1937 by Andrew Ellicott Douglass to study tree rings in America. Since its founding, LTRR has helped establish many *dendrochronology* labs to date and conducted studies of annual rings in trees around the world. During the tour, participants learned that scientists use tree rings to answer questions about the natural world in order to put the present in proper historical context; to better understand current environmental processes and conditions; and to improve understanding of possible future environmental issues. Ring counting alone does not ensure the accurate dating of each individual ring, which can lead to incorrect conclusions. One of the techniques used by the LTRR is *cross-dating** to match ring growth characteristics across many samples. Through their work, LTRR is making significant contributions to understanding natural variability in climate including hydrologic, geomorphic, and ecological systems.

*Cross-dating is a basic technique used in dendrochronology that ensures each individual tree ring is assigned its exact year of formation by matching patterns of wide and narrow rings between cores from the same tree, and between trees from different locations.

During the tour of the University of Arizona's Laboratory of Tree-Ring Research, participants got a chance to get a close-up view of the tree rings on this cross section from a giant sequoia. **Photo credit**: Marty Snow [LASP]

Solar UV variability may also play an influential role in the *Madden–Julian Oscillation*.[11] In addition, a new model study shows that sustained low solar forcing leads to complex changes in both atmospheric and oceanic circulations. The expected surface cooling under such conditions occurs at different rates between the two hemispheres, the result of which is to generate atmospheric waves. The results provide further evidence of the importance of atmosphere–ocean coupling in Sun–climate connections.

Christopher Castro [University of Arizona, Tucson] wrapped up the session with a local flair as he discussed a topic relevant to Arizona: the "North American Monsoon in a Changing Climate." He showed that North American monsoon precipitation associated with organized convection is becoming less frequent and more extreme. Such changes are broadly consistent with how extreme precipitation is changing globally during the current warming world.

Session 5: A New Reference Spectrum for Remote Sensing

Solar spectra are widely used by the modeling and remote sensing communities as the solar input constraint.

Solar spectra are widely used by the modeling and remote sensing communities as the solar input constraint. Uncertainties associated with solar spectral measurements can have significant impacts on theoretical and experimental topics ranging from upper atmospheric photochemistry to the full system radiation budget. They also have an impact on techniques that use the Moon as a solar-reflectance calibration standard. Improved accuracy in solar spectral irradiance measurements has opened the possibility of achieving Système Internationale d'Unités-traceable lunar radiometry. However, as with many applications in remote sensing and global energy budget assessments, this technique requires higher resolution than the directly measured solar-irradiance spectra. Some presenters during this session discussed implications of the improved accuracy of solar-irradiance spectra from TSIS-1 SIM. Others highlighted the need for new solar-reference spectra and current progress toward that goal.

The Global Space-based Inter-Calibration System (GSICS), an international organization designed to promote calibration best practices across satellite dataset providers, has long recognized the need for a common solar reference spectrum to maintain consistency in band radiances among the many sensors used in Earth remote sensing from space. GSICS is working to promote a recommended solar spectrum used by all dataset providers. **Dave Doelling** [NASA's Langley Research Center] provided background on community needs and requirements for a common reference spectrum by looking at sensor band radiance differences based on several widely used solar spectra.

One example of the sensitivity of satellite remote sensing applications to solar spectral irradiance input came from the Orbiting Carbon Observatory–2 (OCO-2), which measures reflected shortwave-IR solar radiation carbon dioxide (CO_2) and methane (CH_4) concentrations. For OCO-2, the solar spectrum provides an in-orbit radiometric and spectroscopic calibration standard that is used in retrieval algorithms for estimating the column-averaged mole fractions of CO_2 and CH_4, denoted as X_{CO2} and X_{CH4}, respectively. Although the newly implemented TSIS-1 solar spectrum showed significant differences from the previously used ATLAS 3 SOLSPEC[12] spectrum, the associated changes in retrieved X_{CO2} were less than 0.3%, but were positive over land and negative over water. Consequently, these changes may still be important for source–sink inversion studies due to their spatial distribution.

From the realm of ground-based remote sensing, the AErosol RObotic NETwork (AERONET) is also being used to examine potential changes in its remotely sensed products as a result of a new, higher-accuracy reference spectrum from TSIS-1 SIM. AERONET is a global ground-based sunphotometer network for characterizing

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[11] The Madden-Julian Oscillation (MJO) is the major source of fluctuation in tropical weather on weekly to monthly timescales. The MJO can be characterized as an eastward moving "pulse" of clouds and rainfall near the Equator that typically recurs every 30 to 60 days.

[12] SOLSPEC stands for Solar Spectrum spectrometer, which flew with the Atmospheric Laboratory for Applications and Science (ATLAS) on the Space Shuttle.

aerosol optical, microphysical, and radiative properties at approximately 600 sites supporting satellite aerosol retrieval assessments and global aerosol model validation research; the top-of-atmosphere solar spectra play a key role in the creation of the AERONET database.

In addition to these applications of the new TSIS-1 solar spectrum, work is underway to combine high-resolution solar transmittance spectra with the high-accuracy but low-resolution measured spectra to maintain the irradiance calibration scale at high resolution. The promising results from these studies will broaden the impact of high-accuracy TSIS-1 spectra to a myriad of remote sensing and radiative transfer applications.

Session 6: Observational Predictions

This session addressed these questions:

- What are expectations for the next solar cycle and what are climate-change scenarios for the upcoming decades?
- What future measurements are expected to improve knowledge of Sun–climate connections?

Dean Pesnell [GSFC] asked, "How Well Can We Predict Solar Cycle 35?" This symposium takes place during the transition period between the fading solar cycle 24 and the start of solar cycle 25, the signs of which are beginning to appear at the solar surface. Data from NASA's Solar Dynamics Observatory (SDO) and the Solar Terrestrial Relations Observatory (STEREO) had improved predictions of solar activity during solar cycle 24 on time scales ranging from days to more than a year. But predictions made long before the next cycle begins still rely on precursors. Longer-term predictions—say, ten cycles out, as the title suggests—are limited by the growth of the forecast error, which increases until a simpler forecast becomes more accurate. The climatological average is the only long-term prediction whose error grows slowly. The consensus among participants was that accurate, long-term forecasting should adopt an ensemble format.

Philip Judge [National Center for Atmospheric Research, High Altitude Observatory] attempted to predict the future, as his presentation considered the "Next Five Decades Under the Sun." At decadal-to-millennial time scales, solar variations that are induced by hydromagnetic effects can be constrained by solar and stellar data in the absence of credible models based upon first principles. New solar and stellar observatories combined with machine learning methods may enable the present generation of scientists to predict with a higher degree of confidence the solar–terrestrial effects that are of concern to modern society.

New solar and stellar observatories combined with machine learning methods may enable the present generation of scientists to predict with a higher degree of confidence the solar-terrestrial effects that are of concern to modern society.

Session 7: Looking Ahead—Future Observations of the Sun and Earth

Presentations in this session addressed plans for the next generation of solar and terrestrial observations, missions, and implementation strategies to allow new observing systems to meet current and future challenges facing climate-change studies. One such mission is the Climate Absolute Radiance and Refractivity Observatory (CLARREO) Pathfinder mission. CLARREO Pathfinder will fly an imaging spectrometer on the ISS in 2023 to demonstrate high-accuracy measurements of the solar radiation scattered from Earth for climate-change studies and to intercalibrate other orbiting instruments.

The Sun–earth IMBAlance (SIMBA)[13] satellite is another Earth-climate demonstration mission, this one a 3U CubeSat.[14] The long-term objective of SIMBA and follow-on missions is a direct measurement of Earth radiation imbalance, as SIMBA will

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[13] SIMBA is a mission developed by Belgium's Royal Meteorological Institute (RMI) for the European Space Agency; it is scheduled for launch in 2020.

[14] CubeSats (a.k.a., nanosatellites) are a class of research satellites; they are typically built to standard dimensions (Units or "U") of 10 cm x 10 cm x 10 cm. They can be 1U, 2U, 3U, 6U, or more, in size, and typically weigh less than 1.33 kg (3 lbs) per U.

use one instrument—a cavity radiometer—to measure incoming solar radiation and outgoing Earth radiation.

Plans are well underway for future solar irradiance measurements. The next TSIS mission, TSIS-2, will fly heritage SIM and TIM instruments, and is currently in the instrument build phase, with a scheduled launch in February 2023 on a free-flyer satellite. A Compact TIM, or CTIM, is an eight-channel, 6U, CubeSat instrument currently being built for a flight in 2021 to demonstrate next-generation technology to monitor total solar irradiance. Its cousin, the Compact SIM (CSIM), is already in orbit (since December 2018), collecting solar spectral irradiance from a 6U CubeSat. Measurements from CSIM match very well with those of TSIS SIM—see **Figure 2**.

FURST will obtain the first high-resolution, radiometrically calibrated, vacuum UV (120-180 nm) spectra of the Sun, with applications in climate science, solar and stellar physics, and the interaction of solar UV radiation with comets, moons, and planets.

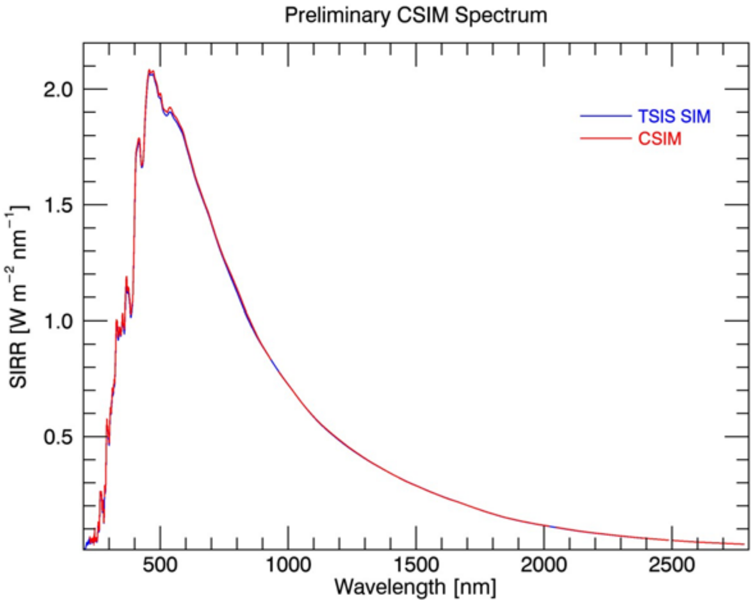


Figure 2. Comparison of solar spectral irradiance measured by TSIS SIM and CSIM. The spectra agree to better than 0.4% over the spectral range. **Image credit**: Erik Richard [LASP]

A new sounding-rocket mission, the Full-disk Ultraviolet Rocket SpecTrograph (FURST), is planned for launch in 2022. FURST will obtain the first high-resolution, radiometrically calibrated, vacuum UV (120-180 nm) spectra of the Sun, with applications in climate science, solar and stellar physics, and the interaction of solar UV radiation with comets, moons, and planets.

Conclusion

We bid you farewell, SORCE—you won't be soon forgotten.
— SORCE Science Team

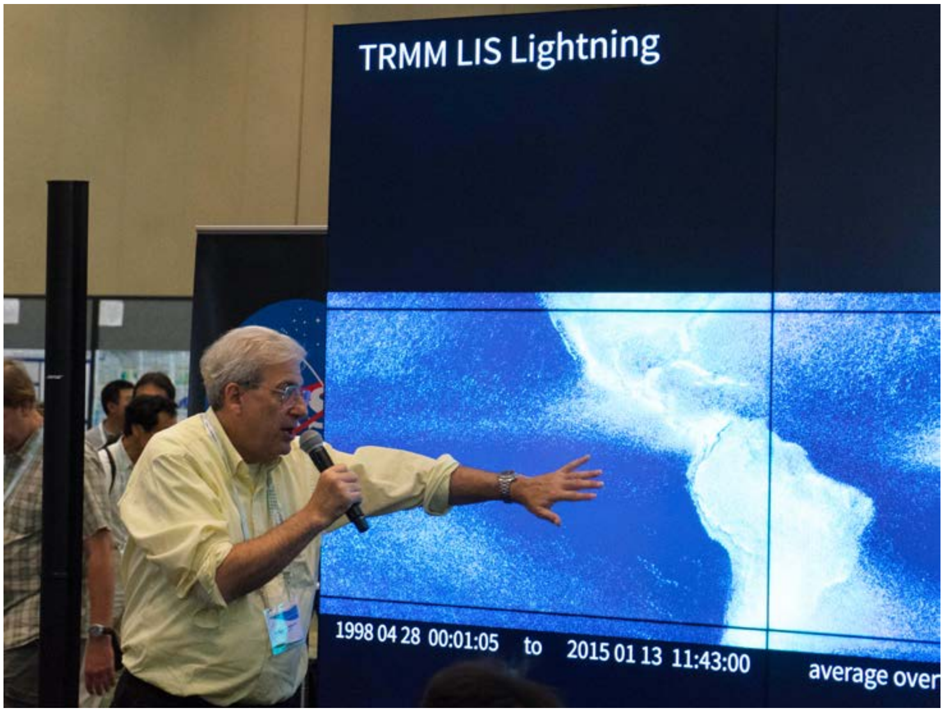
This meeting marked the sixteenth in the series of symposia that started as SORCE Science Team Meetings in 1999. It also marked the end of an era, as it was the final meeting held while SORCE was operational and still providing science data. The melancholy tone from that realization was lessened by considering that the achievements ushered in by SORCE will continue by the people who have followed in the footsteps of those who developed the SORCE mission and in the hardware (e.g., TSIS) that owes its legacy to the groundbreaking instruments developed for SORCE.

The 2020 Sun–Climate Symposium addressed the quiet Sun in the context of present-day climate change and anthropogenic and natural drivers. The multidisciplinary nature of the meeting brought together specialists in measuring and modeling the Sun's output and Earth's radiation budget, climate and atmospheric modelers (who interpret those and other forcings to quantify Earth's changing environment), solar physicists (who study how the Sun varies), and other specialists developing new instruments and missions to address some of the questions raised during the meeting. The team looks forward to the next meeting, when updates on some of the most vexing issues in Sun–Earth connections will be discussed, and new challenges are sure to be identified.

To stay up to date on the latest TSIS and SORCE news and meeting announcements, read the TSIS/SORCE newsletter at *http://lasp.colorado.edu/home/sorce/news-events/newsletter*. ■

Michael Freilich Receives 2020 Wing Ip Medal from AOGS

As reported in "The Editor's Corner" of this issue, **Michael** (**"Mike"**) **Freilich** [Former Director of NASA's Earth Science Division (ESD)] passed away on August 5, 2020. Prior to his passing, the Asia Oceania Geophysical Society (AOGS) announced that Mike is one of the recipients of its *Wing Ip Medal* for 2020.



Michael Freilich [Former Director of NASA's Earth Science Division (ESD)] in front of the Hyperwall at the 2018 AOGS Annual Meeting in Honolulu, HI. **Photo credit:** NASA

Freilich was chosen because of his tireless efforts to make NASA's Hyperwall (a nine-screen video wall) an integral part of the AOGS Annual Meeting. Since 2012 the Hyperwall has been the centerpiece of not just the NASA exhibit, but the entire conference experience, with a steady stream of eye-catching presentations to entertain and inform conference participants. The contributions of NASA scientists to the paper sessions have steadily increased over time, making a significant impact on the quality of the AOGS conferences, which in turn has helped the Society to grow in size and reputation. Freilich has been a key figure, championing the link between NASA and AOGS. His support, ambition, and charisma have been vital in developing AOGS. It is therefore most appropriate that he be awarded this prestigious medal.

The Wing Ip award was established to honor Professor Wing Huen Ip, a world-renowned astronomer. The award is given to individuals who display unselfish cooperation and leadership in geoscience in the Asia Oceania region.

The Earth Observer is pleased that Mike could receive this honor before his passing.

Summary of the Joint CALIPSO/CloudSat Science Program Annual Review

Deborah Vane, NASA/Jet Propulsion Laboratory, deborah.g.vane@jpl.nasa.gov

Introduction

The joint Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO)/CloudSat Science Program Annual Review was held March 3–5, 2020—one of the last in-person NASA meetings to happen before COVID-19 shutdowns began. Ball Aerospace hosted the event at their facility in Boulder, CO. Nearly 100 scientists attended in person, with a few more participating remotely. The review was held as the fourteenth anniversary of the joint CloudSat–CALIPSO launch (April 26, 2006) was approaching—an awesome milestone for two missions built during NASA's "faster-better-cheaper" era.[1]

This report summarizes the annual review, which was broken into the following thematic sessions: Programmatic Updates, Instruments and Algorithms, Science Highlights (including presentations related to Polar Regions, Radiation and Climate, Clouds, Aerosols, and Storms and Precipitation), and Future Missions. A few highlights from each of the sessions are discussed here. The full agenda and presentations can be downloaded from *https://sites.google.com/view/ccstm-2020*.

Programmatic Updates

David Considine [NASA Headquarters (HQ)—*Program Scientist for CALIPSO and CloudSat*] welcomed the attendees and talked about the results of the 2018 Research Opportunities in Space and Earth Science (ROSES 18) CALIPSO and CloudSat Science Team (CCST) recompetition. Altogether, 101 proposals were evaluated and 21 were selected. Of those, 11 are new principal investigators (PIs) and 10 are continuing PIs. The ROSES 2021 solicitation will be released in February 2021, and funding for that ROSES call will be independent of the operational status of the CALIPSO and CloudSat satellites.

Considine then gave an overview of the President's NASA Earth Science budget and, in that context, discussed the Aerosol and Cloud, Convection and Precipitation (ACCP) mission study and the Earth Venture Continuity (EVC) Program, both of which are elements of the 2017 Earth Science Decadal Survey.[2] ACCP combines two of the five priority Designated Observable missions called out as high-priority missions by the Decadal Survey: the Aerosol (A) mission and the Clouds, Convection and Precipitation (CCP) mission. The nominal cost limit for the ACCP observing system is $1.6B, possibly in two staggered funding wedges. The observing system will likely include both orbital and suborbital observations—see expanded discussion below.

Considine also discussed the EVC Program, the goal of which is to implement means to maintain the measurement continuity of scientifically and/or societally important observations, without undue impact on the NASA Earth Science Division (ESD) budget. The EVC-1 measurement goal is Earth radiation budget continuity, and the selected mission was Libera.[3] In Roman mythology, Libera was the daughter of Ceres, so the name is an acknowledgment of the heritage of the new mission. Libera will continue the radiation balance measurements that the Clouds and the Earth's Radiant Energy System (CERES) instruments have made for more than 20 years.[4]

Chip Trepte [NASA's Langley Research Center (LaRC)—*CALIPSO Project Scientist*] discussed the status of the CALIPSO spacecraft. CALIPSO and CloudSat left the A-Train[5] in 2018 and formed the C-Train—see **Figure 1** on page 17—at a lower altitude (currently ~680 km, or ~422 mi).[6] The CALIPSO spacecraft is healthy and is satisfying all operational

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[1] "Faster, better, cheaper" was the slogan NASA used during the 1990s, when Dan Goldin was NASA Administrator. To learn more about some of the remarkable achievements of CloudSat and CALIPSO, see "A Useful Pursuit of Shadows: CloudSat and CALIPSO Celebrate Ten Years of Observing Clouds and Aerosols," in the July–August 2016 issue of *The Earth Observer* [**Volume 28**, **Issue 4**, pp. 4–15—*https://go.nasa.gov/2WM2HcM*].

[2] The report is called "Thriving on a Changing Planet: A Decadal Strategy for Earth Observations from Space" and is available for download at *https://www.nap.edu/catalog/24938/thriving-on-our-changing-planet-a-decadal-strategy-for-earth*.

[3] Libera will fly on the National Oceanic and Atmospheric Administration's (NOAA) operational Joint Polar Satellite System-3 (JPSS-3) satellite, which is scheduled to launch by December 2027. More information on Libera can be found in the "CERES Science Team Update Report" on page 24 of this issue.

[4] Six CERES instruments are currently collecting data on NASA and NOAA satellites. A seventh flew and operated briefly on the Tropical Rainfall Measuring Mission (TRMM), which launched in 1997 and was decommissioned in 2015.

[5] NASA and its international partners operate several Earth-observing satellites that closely follow one another along the same (or very similar) orbital "track," called the Afternoon Constellation, or A-Train (*https://atrain.nasa.gov*).

[6] The C-Train currently flies 16.5 km (~10 mi) below the A-Train and therefore follows a slightly different ground track, though it intersects the A-Train ground track about every 20 days, allowing for regular simultaneity between A-Train and C-Train instrument observations. Over time, the C-Train orbit is drifting eastward to later mean local times of the ascending node (i.e., it is no longer Sun synchronous).

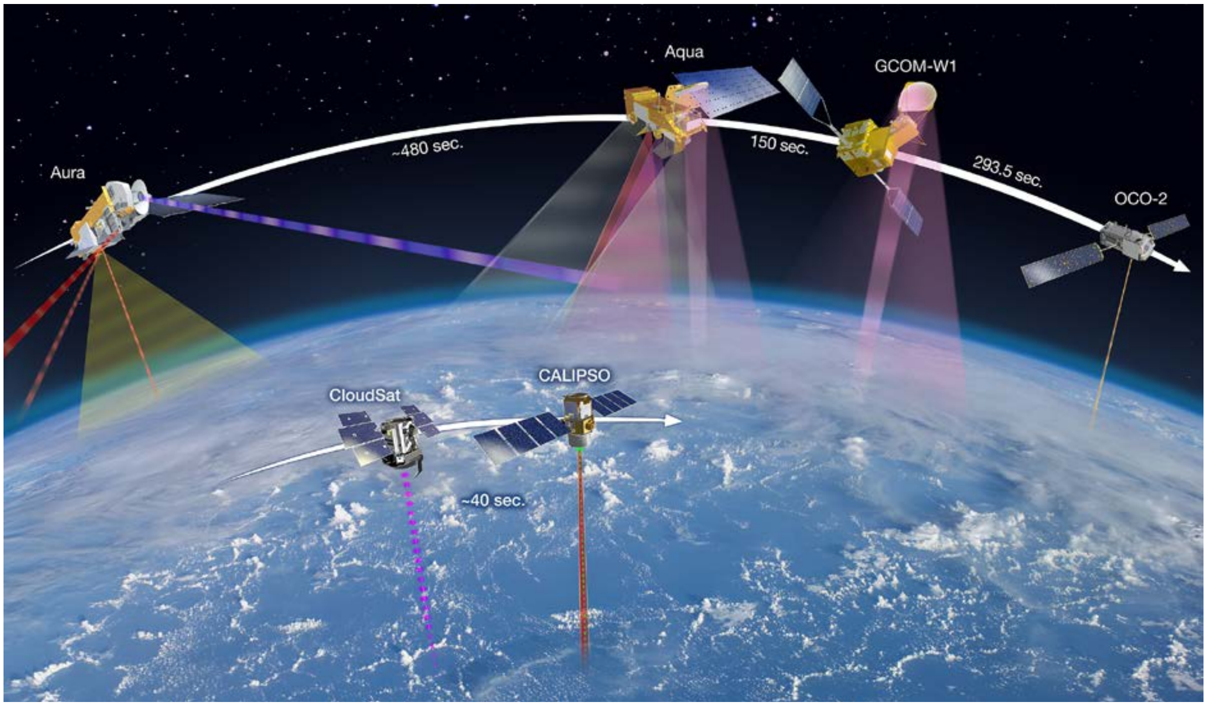

Figure 1. This diagram shows the international A-Train satellites (OCO-2, GCOM-W1, Aqua, and Aura) as well as the C-Train satellites (CALIPSO and CloudSat) at a slightly lower orbit than that of the A-Train. (GCOM-W1 stands for Global Change Observation Mission—Water, which is a Japan Aerospace Exploration Agency mission launched in 2012.) **Image credit:** NASA

requirements. Fuel reserves, however, are mostly depleted; it is possible that CALIPSO may only be able to make one additional collision avoidance maneuver.[7] As the C-Train orbit drifts eastward, the Sun angle on the solar panels will change and, by September 2023, CALIPSO will have insufficient power to continue the mission and will begin decommissioning. The currently operating laser is still functional, despite being at pressures where corona discharges are expected for the laser Q-switch. Low-energy laser shots have been observed since mid-June 2016, mostly occurring within the South Atlantic Anomaly, but their frequency elsewhere is increasing rapidly. It is likely that the primary laser (currently not operating) will be restarted within the next year. CALIPSO has had 2853 peer-reviewed publications since launch. In 2019 alone, there was nearly the equivalent of one publication per day (363 publications).

Deborah Vane [NASA/Jet Propulsion Laboratory (JPL)—*CloudSat Project Manager*] discussed the status of the CloudSat spacecraft. CloudSat has been successfully operating in Daylight-Only Operations (DO-Op) mode since 2011. CloudSat left the A-Train in 2017, following the failure of one reaction wheel in June 2017 and followed by the unreliable behavior of a second wheel beginning in December 2017. CloudSat is operating successfully on three wheels, including formation-flying and collision-avoidance burns. For emergencies and end-of-life de-orbit, burns can be conducted without the wheels, so the loss of an additional reaction wheel—although science-mission ending—would not pose a risk to decommissioning.

CloudSat is proposing to the 2020 Earth Science Senior Review process to extend the mission through 2023 and beyond. CloudSat has ample remaining fuel through 2026 to formation fly with CALIPSO through 2023 and still comply with NASA's 25-year rule for low Earth orbit (defined in this context as below 2000 km, or ~1243 mi).[8] Significant redundancy on the spacecraft and on the Cloud Profiling Radar (CPR) provides confidence for continued mission operations. CloudSat would continue to operate after CALIPSO is decommissioned in FY23. The CloudSat project reports nearly 3000 peer-reviewed publications using CloudSat data.

Updates on Instruments and Algorithms

There were presentations on the status of the CPR and several CloudSat data products, as well as the status of the CALIPSO Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) and several CALIOP data products. Topics included the CALIOP Level 1 and 2 data

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[7] Although CloudSat and CALIPSO fly in close formation in the C-Train, they are sufficiently far apart that CALIPSO's inability to maneuver would not immediately threaten CloudSat's safety; it would be able to use its own fuel to maneuver to a different altitude.

[8] This rule stipulates that the object will be left in an orbit in which natural forces will lead to atmospheric reentry within 25 years after the completion of the mission but no more than 30 years after launch. This rule is Requirement 56876 of NASA Procedural Requirements *8715.6A*.