Annual Progress Report for award number: NASA NNX14AC83G
R&A Program Name: NASA Heliophysics Senior Review (MO&DS Extended Missions)
Dates covered by this report: January 1, 2016 to December 31, 2016 (Year 15)

Proposal Title: TIMED Solar EUV Experiment (SEE) Extended Mission

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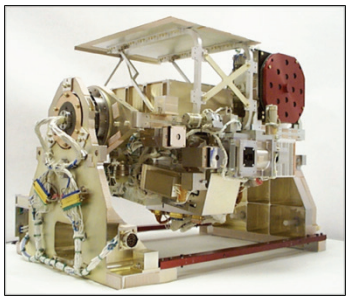
I) Summary of research originally proposed



The NASA Thermosphere-Ionosphere-Mesosphere-Energetics-Dynamics mission was launched on December 7, 2001, and normal science operations began in January 2002. The Solar Extreme ultraviolet Experiment (SEE) is one of the four instruments aboard the TIMED spacecraft. The SEE instrument is designed to daily observe the solar extreme ultraviolet (EUV) and soft X-ray (XUV) irradiance. The SEE channels include the EUV Grating Spectrograph (EGS) that measures the solar EUV spectrum from 27 nm to 195 nm with about 0.4 nm spectral resolution and the XUV Photometer System (XPS) that measures the solar XUV radiation in broadbands below 40 nm. Woods *et al.* [2015] provide detailed overviews of the SEE science goals, instrument design, pre-flight calibrations, data processing algorithms, and first results. An example of the solar spectrum from TIMED SEE is shown in Figure 1.

The original objectives for SEE are:

(1) Accurately and precisely determine the time-dependent solar vacuum ultraviolet (VUV) spectral irradiance
(2) Study the solar-terrestrial relationships utilizing atmospheric models
(3) Determine the thermospheric neutral densities from solar occultations
(4) Study solar VUV variability and its sources
(5) Improve proxy models of the solar VUV irradiance

During the TIMED extended mission, the SEE science team has not been supported, and we depend on ROSES, other opportunities, and international collaborators to provide TIMED-related science analysis and modeling. During the extended mission the TIMED SEE grant to the University of Colorado primarily supports only original objective #1 (measure the solar VUV spectral irradiance).

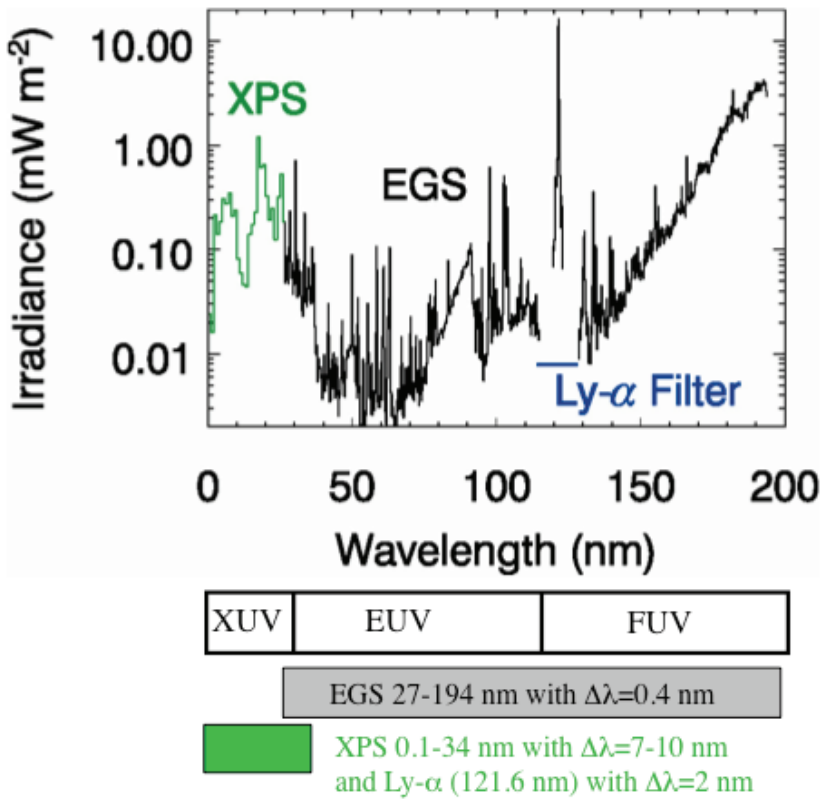


Figure 1. Example Solar Spectrum from TIMED SEE.

There are very few observation gaps in the daily record of the solar UV irradiance from TIMED SEE, and there has only been one instrument anomaly that has limited SEE's observations. This anomaly is the XPS filter wheel mechanism became stuck in position 6 on day 2002/205; consequently, the XPS solar observations are limited to 3 XUV channels instead of its 9 channels. Nonetheless, these 3 XPS channels have been adequate to provide the solar XUV irradiance below 27 nm throughout the TIMED full mission.

II) Summary of accomplishments made during this grant period

The primary activities for the SEE extended mission include generating the weekly operational plans which includes sending uplink commands to the TIMED MOC in JHU APL and the daily production of the SEE solar irradiance data products (currently Version 11). There have been no data gaps for SEE this past year. Example time series plot of some solar emission lines are shown over the TIMED mission in Figure 2.

The primary science study for SEE during this past year has been studying the solar irradiance variability with emphasis on solar cycle variability and improvements of the Flare Irradiance Spectral Model (FISM) using TIMED SEE and SDO EVE data. These are discussed more in the Science Highlights section below.

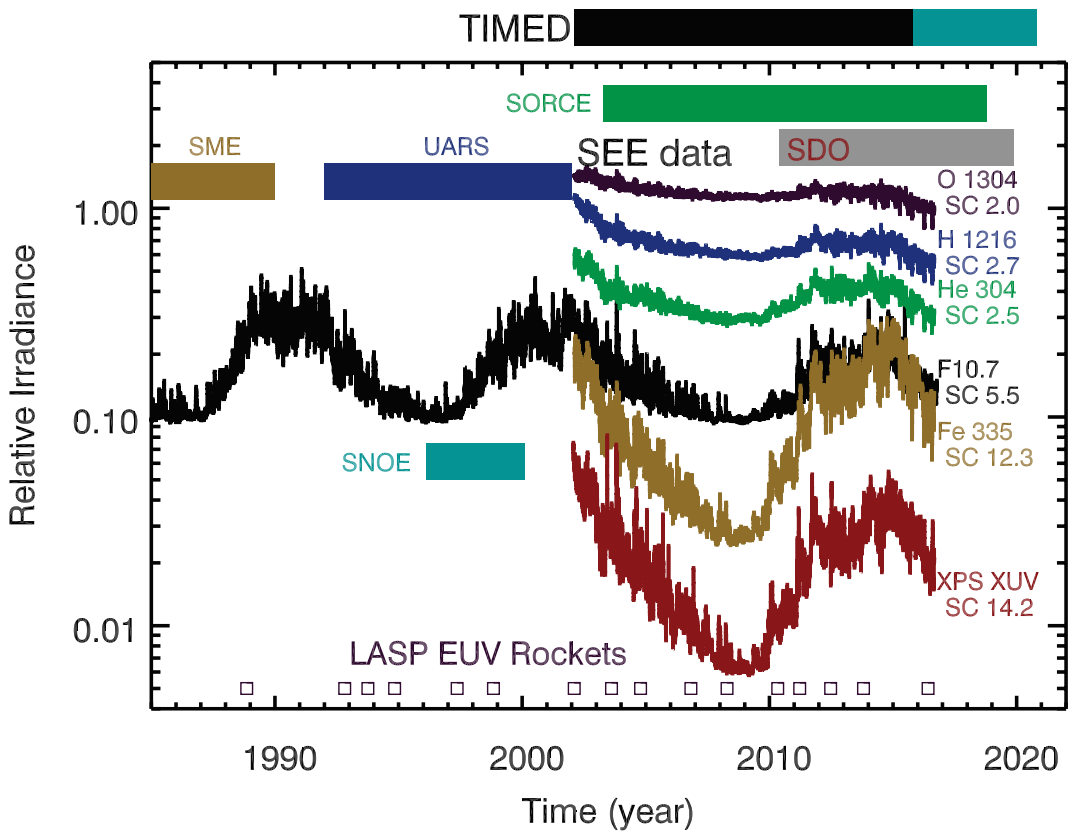


Figure 2. Solar variations during the TIMED mission as observed by SEE. The "SC" values are the solar cycle variations. The F10.7 is the 10.7 cm radio flux and is not measured by SEE. The TIMED measurements overlap with other solar EUV-FUV irradiance measurements from SORCE and SDO. The SEE version 11 data are shown here. These data have degradation trend corrections only through 2011, and improved degradation corrections are being incorporated for the new SEE version 12 data products.

III) Summary of risks or obstacles, plus mitigation strategies

There have been no new anomalies for the SEE instrument this year.

The SEE data processing computer, that has been used for about 10 years, has been replaced and all of the data processing jobs have been transferred to this replacement computer. The SEE data products are now produced daily on this replacement computer and the data products are then transferred to the SEE public web page at http://lasp.colorado.edu/home/see/.

The SEE instrument operations computer, which sends weekly command loads to the TIMED MOC at JHU APL, is also a very old computer, and it will need to be replaced as funds are available in next year's budget.

Both data processing and weekly operation plans are fully automated, being a necessity of very low funding for SEE operations. There are risks for extended down time for SEE because the ground system computers are single string and because there are limited funds to support the SEE operations team at a small fraction of their time. Fortunately, there were no instrument anomalies and only minor ground system anomalies during this past year; consequently, there are no gaps in SEE daily data products during the past year.

IV) Summary of plans for the coming year

The new version 12 data products for SEE are expected to be released in the next few months, and a paper describing the SEE solar irradiance version 12 products and recent solar modeling results will be prepared.

The SEE instrument operations computer will be replaced.

V) Publications produced during the past year

The TIMED SEE grant supports mission operations and data processing but very little science analysis. Although this grant did not directly support the following publications, this list provides SEE-related papers published in 2016.

Peer-reviewed Articles

Jacobi, C., N. Jakowski, G. Schmidtke, and T. N. Woods, Delayed response of global total electron content to solar EUV variations, *Adv. Radio Science*, **14,** 175-180, doi: 10.5194/ars-14-175-2016, 2016.

Lee, J. N., R. F. Cahalan, and D. L. Wu, Solar rotational modulations of spectral irradiance and correlations with the variability of total solar irradiance, *J. Space Weather & Space Climate*, **6,** 27, A33, doi: 10.1051/swsc/2016028, Sept. 2016.

Lin, C. Y., S. M. Bailey, A. Jones, D. Woodraska, A. Caspi, T. N. Woods, F. G. Eparvier, S. R. Wieman, and L. V. Didkovsky, Soft X-ray irradiance measured by the Solar Aspect Monitor on the Solar Dynamic Observatory Extreme ultraviolet Variability Experiment, *J. Geophys. Res.: Space Physics,* **121,** 3648-3664, doi: 10.1002/2015JA021726, April 2016.

Suess, K., M. Snow, R. Viereck, and J. Machol, Solar Spectral Proxy Irradiance from GOES (SSPRING): a model for solar EUV irradiance, *J. Space Weather & Space Climate,* **6**, 27, A10, doi: 10.1051/swsc/2016003, Feb. 2016.

Wieman, S., L. Didkovsky, T. Woods, A. Jones, and C. Moore, Sounding Rocket Observations of Active Region Soft X-Ray Spectra between 0.5 and 2.5 nm using a Modified SDO/EVE Instrument, *Solar Physics,* Open Access, doi: 10.1007/s11207-016-0999-6, Oct. 2016.

Presentation Abstracts

Didkovsky, L. V., S. Wieman, T. N. Woods, A. Jones, and W. Chao, Imaging Grating SpectroPhotometer (I-GRASP) for Solar Soft X-Ray Spectra and Images from a Cube Sat Mission, *American Astronomical Society's Solar Physics Division (AAS/SPD) Meeting #47*, Boulder, CO, May 31 – June 1, 2016.

Didkovsky, L. V., S. Wieman, and T. N. Woods, How Calibration and Reference Spectra Affect the Accuracy of Absolute Soft X-ray Solar Irradiance Measured by the SDO/EVE/ESP during High Solar Activity, *Solar Dynamics Observatory (SDO) Workshop*, Burlington, VT, Oct. 2016.

Didkovsky, L. V., S. Wieman, W. Chao, T. N. Woods, A. R. Jones, E. Thiemann, and J. P. Mason, Imaging Grating Spectrometer (I-GRASP) for Solar Soft X-Ray Spectral Measurements in Critically Under-Observed ~0.5 – 7 nm Spectral Range, *AGU Fall Meeting*, San Francisco, CA, Dec. 2016.

Royer, E. M., J. Ajello, G. Holsclaw, R. West, L. W. Esposito, and E. T. Bradley, Chapman Solar Zenith Angle variations at Titan, *American Astronomical Society /Division for Planetary Sciences (AAS/DPS) Meeting #48*, id #515.11, Pasadena, CA, Oct. 2016.

References used in this report but not included above

Thiemann, E. M. B., *Multi-Spectral Sensor Driven Solar EUV Irradiance Models with Improved Spectro-Temporal Resolution for Space Weather Applications at Earth and Mars*, PhD dissertation, University of Colorado, Boulder, April 2016.

Woods, T. N., F. G. Eparvier, S. M. Bailey, P. C. Chamberlin, J. Lean, G. J. Rottman, S. C. Solomon, W. K. Tobiska, and D. L. Woodraska, The Solar EUV Experiment (SEE): Mission overview and first results, *J. Geophys. Res.,* **110,** A01312, doi: 10.1029/2004JA010765, 2005.

Woods, T. N., M. Snow, J. Harder, G. Chapman, and A. Cookson, A different view of solar spectral irradiance variations: Modeling total energy of six-month intervals, *Solar Physics*, **290,** 10, 2649-2676, doi: 10.1007/s11207-015-0766-0, 2015.

VI) Science highlights

Solar Cycle Variability

Precisely understanding solar cycle variability requires accurate measurements of the solar irradiance over many years and also understanding and correcting for instrument degradation trends accurately. A new modeling technique of examining six-month intervals of solar variability has been able to separate out any uncorrected instrument trends from solar variability as discussed by Woods *et al.* (2015). This technique involves modeling the variability over several six-month intervals using the San Fernando Observatory (SFO) facular excess proxy derived from the SFO solar Ca II K images. These new solar cycle variability results are illustrated in Figure 3 for the TIMED SEE data.

Figure 3a shows the solar variability results at 1 nm resolution and up to 250 nm from TIMED SEE, SORCE SOLSTICE, and UARS SUSIM measurements. A scaling factor is needed for this comparison because different missions covered different levels of the solar cycle. The TIMED SEE results are plotted without any scaling. The UARS mission included the peaks of solar cycle maximum and thus cover higher levels of solar activity than TIMED, so the UARS SUSIM results have a lower scaling factor of 0.7 relative to TIMED. Conversely, the SORCE mission started after the TIMED mission and did not cover any high solar activity in cycle 23, so the SORCE results have a higher scaling factor of 1.3 relative to TIMED. ***Because these are over three different solar cycles, an important conclusion is that solar variability appears to have the same spectral behavior independent of solar activity level.***

The combination of the results from multiple missions and multiple solar cycles in Figure 3a is referred to as the model average in the other three panels in Figure 3. The relative variability generally increases with shorter wavelengths. The upper photosphere and lower chromosphere emissions have less variability, and these dominate primarily in the 150 nm to 250 nm range. The transition region and coronal emission lines, with several of them labeled in Figure 3b, have enhanced variability with one to two orders of magnitude more than the chromosphere variability. Some of the ionization edges (IE) are also labeled in Figure 3b. The comparison shown in Figure 3b suggests that one needs to use caution in scaling 27-day solar rotation variability for estimating solar cycle variability for wavelengths longer than 180 nm and for some coronal lines in the EUV.

The TIMED mission started near the maximum of solar cycle 23 and has observed all of solar cycle 24. The differences from the scaled variability from specific mission measurements to the model average as shown in Figure 3 panels (c) and (d) are indications of uncorrected instrument degradation. The TIMED SEE deviation at longer than 140 nm for the solar cycle 24 measurement is a known problem in SEE version 11 data and will be corrected in SEE version

12 product. The solar cycle variability during the decline of solar cycle 23 and during the rise of solar cycle 24 are shown in Figure 3c. ***A key result for this comparison is that solar cycle 24 variability is 1.8 times less than that for solar cycle 23***. This has important implications on how the solar influence on Earth's atmosphere energetics and dynamics will be different from solar cycle 23 (1996-2008) to cycle 24 (2008-2019).

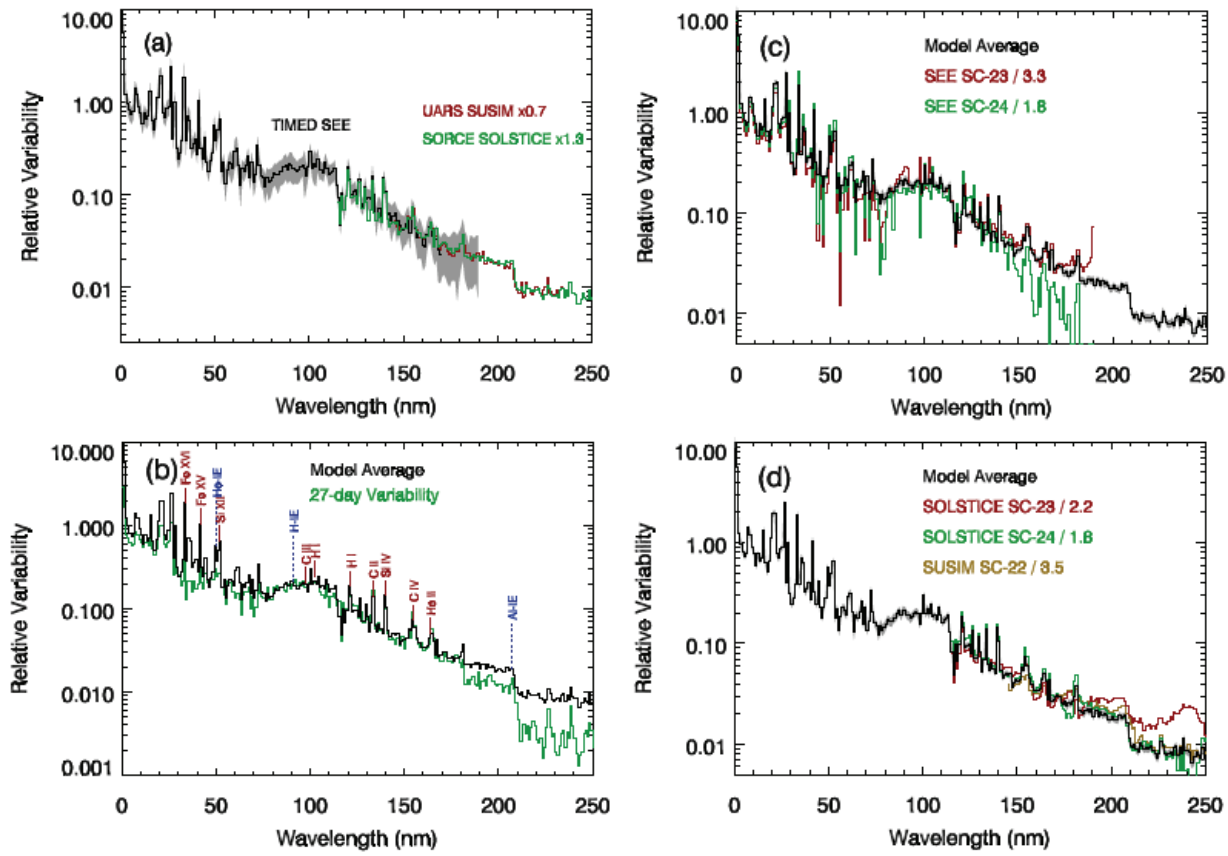


Figure 3. The solar cycle variability is consistent for TIMED SEE, SORCE SOLSTICE, and UARS SUSIM in the UV range as shown in panel (a), and these are combined into a reference variability spectrum referred to as Model Average. Panels (b), (c), and (d) compare this reference variability to the 27-day solar rotation variability from 2005, TIMED SEE solar cycle variability measurements, and SORCE SOLSTICE / UARS SUSIM solar cycle variability measurements, respectively. The variability uncertainty is included as the grey region in panel (a) for SEE data. This figure is adopted from Figure 4 in Woods *et al*. (2015).

<u>Extending Solar Irradiance Model to Mars</u>

One of the solar irradiance models developed with TIMED SEE data is the Flare Irradiance Model (FISM), originally developed by Phil Chamberlin as his PhD research at the University of Colorado. With the NASA MAVEN mission to Mars, it has been important to provide solar spectral irradiance results for the MAVEN mission studies about the escape processes for the Martian atmosphere. The MAVEN mission includes a few broadband EUV photometers for measurements at Mars. These Mars-based solar EUV monitors are fed into a modified version of FISM to provide the solar irradiances over the full EUV range for the MAVEN research. The modification to FISM, called FISM-Mars, includes improved proxy relationships based on

TIMED SEE, SDO EVE, and SORCE SOLSTICE latest observations and also scaling of Earth-based measurements to Mars via $1/R^2$ distance scaling and time shifting based on the 27-day solar rotation. This research was done by Edward Thiemann as part of his PhD research at University of Colorado (Thiemann, 2016).

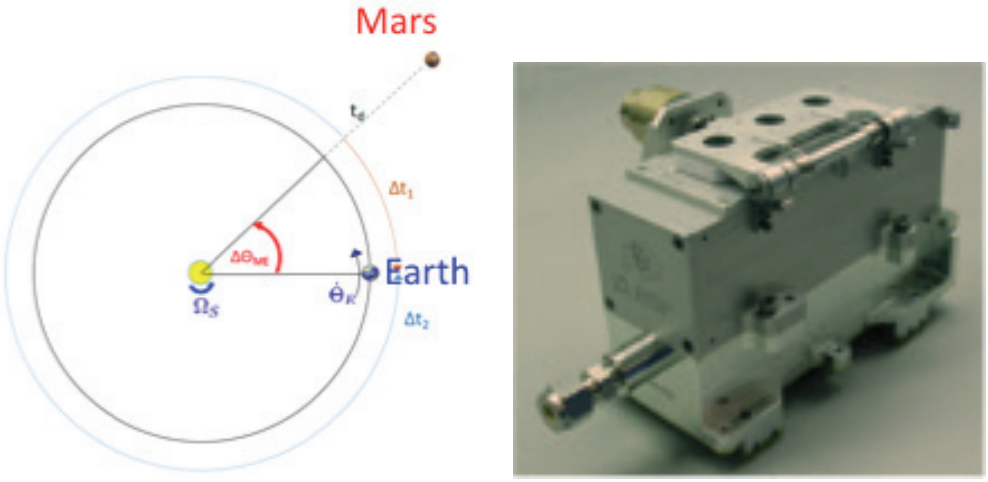


Figure 4. The TIMED SEE based solar irradiance model called Flare Irradiance Spectral Model (FISM) has been modified by the NASA MAVEN project to predict the solar irradiance at Mars. The left panel illustrates that the Earth-based measurements need to be scaled to Mars via $1/R^2$ distance scaling and time shifting (rotating) based on the 27-day solar rotation. The right picture is the MAVEN EUV instrument that measures the solar irradiance at Mars in broadbands at 0.1-7 nm, 17-22 nm, and the bright H I 121.6 nm emission line. The MAVEN EUV measurements serve as the proxies in the Mars version of the FISM model.