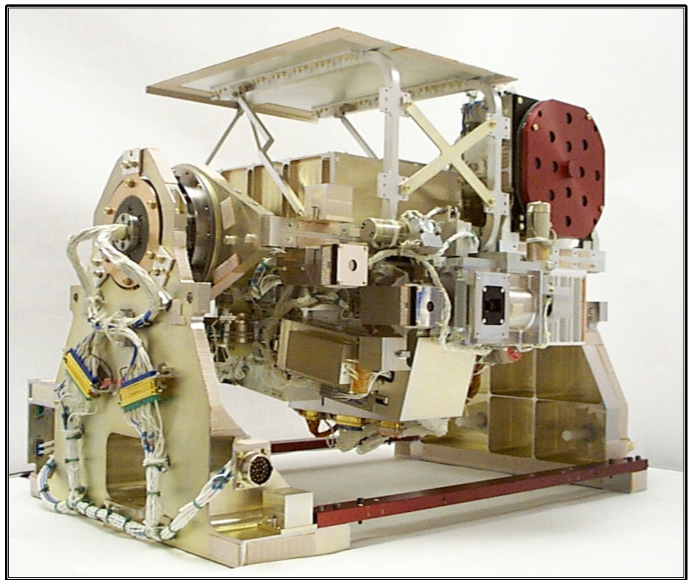
Progress Report for
TIMED Solar EUV Experiment (SEE)
November 2014 - October 2015



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Report Outline:

1. Solar EUV Experiment (SEE) Science Results

1a. SEE Overview

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. The Woods *et al.* [2005] 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.

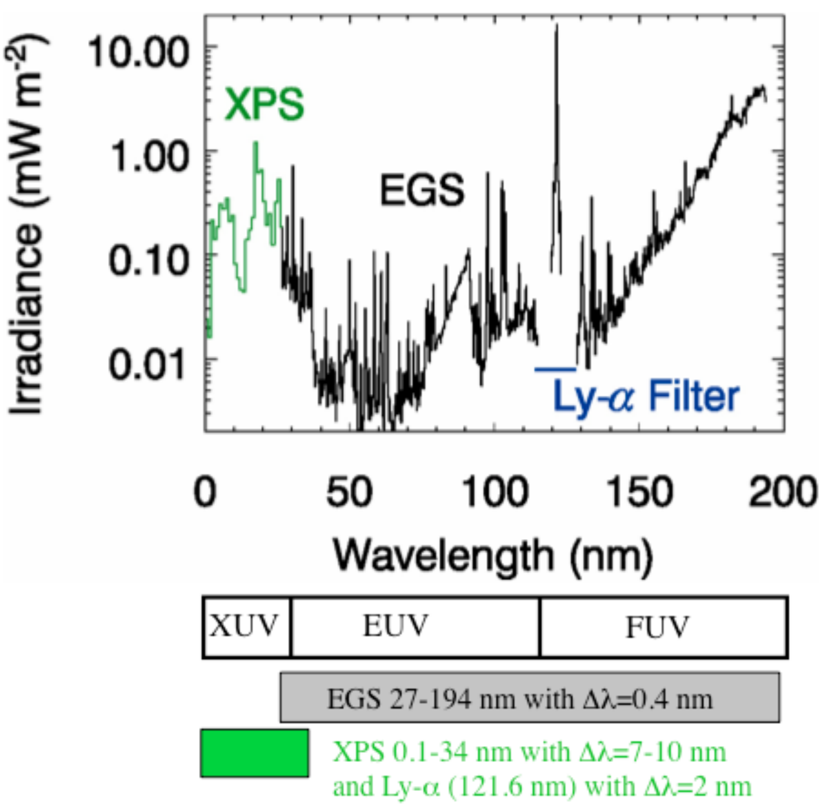

Figure 1. Example Solar Spectrum from TIMED SEE.

There are very few observation gaps in the daily record of the solar UV irradiance from TIMED SEE (more details given in Section 2), 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.

The primary objective for SEE science analysis during this past year has been studying the solar irradiance variability during solar cycle 24 (2008-present) and comparison of that variability to solar cycle 23 (1996-2008). Figure 2 shows the variation of some of the solar EUV emission lines during the TIMED mission and in context with solar variability from the previous solar cycle. Another important aspect of the SEE solar EUV-FUV irradiance record is to combine the TIMED record with earlier data to make an even longer term solar irradiance climate record. This study is important because long-term (years) changes of the ionosphere, thermosphere, and mesosphere (ITM) are heavily modulated by the solar cycle (11-year) irradiance variations and also by anthropogenic forcing from below. For example, a reduced solar energy input will lower the ionosphere density and peak altitude, and the thermosphere will be cooler.

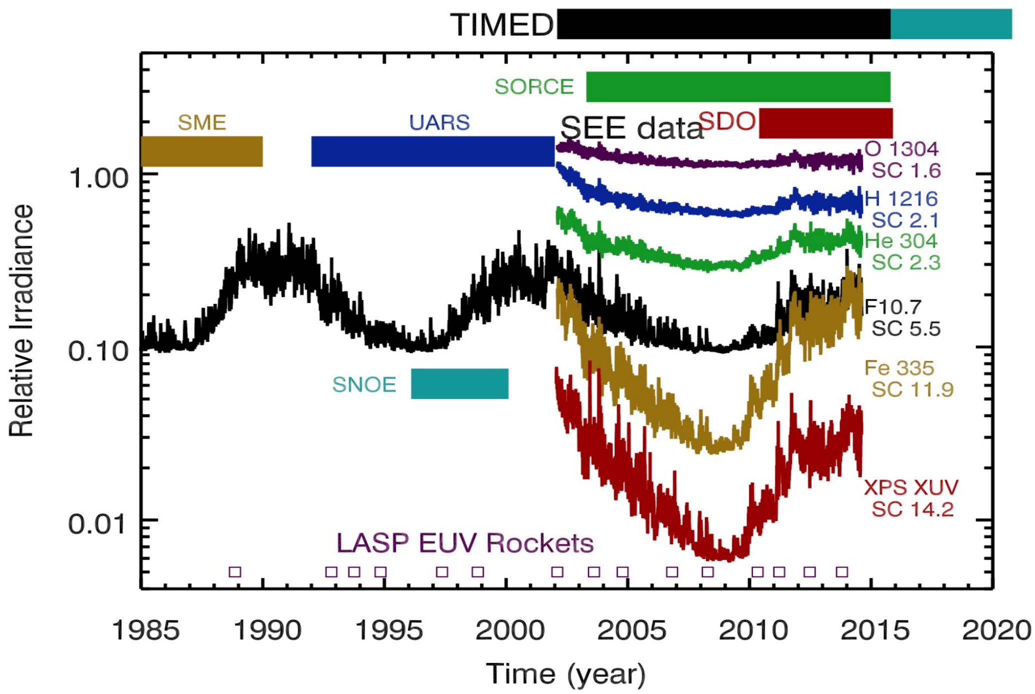

Figure 2. Solar variations during the TIMED mission as observed by SEE. The "SC" values are the solar cycle variations. The F10.7 is the 10.7 cm radio flux and is not measured by SEE. The TIMED measurements overlap with other solar EVU-FUV irradiance measurements from SORCE and SDO.

1b. Solar Cycle 24 Variability

Solar EUV and particle input to Earth's environment is lower in solar cycle 24 (SC-24: 2008-present) than in SC-23 (1996-2008), so ITM response is expected to be much lower during SC-24 maximum (2011-2015) than during SC-23 maximum (2002) in the TIMED data set. Figure 3 shows that the solar EUV irradiance variation (maximum minus minimum) is half as much in 2012 than it was in 2002. A cooler thermosphere has already been observed by TIMED SABER [Mlynczak *et al.*, 2014] and other satellites, and the primary contribution is from the reduction of the solar EUV irradiance [Solomon *et al.*, 2011]. There is still much to study concerning the solar cycle variations, both in the solar EUV irradiance and in the solar forcing (response) in Earth's upper atmosphere, and we will continue to study these with the TIMED science team and the broader ITM community.

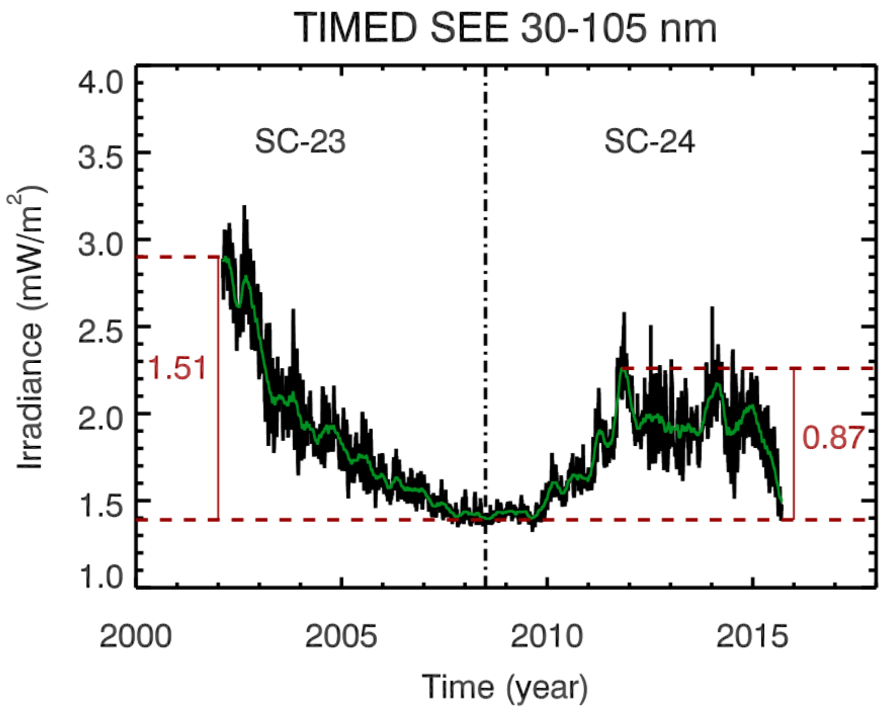

Figure 3. The solar cycle variations for the integrated solar EUV irradiance (30-105 nm). The black line is the daily measurements, and the green line is the 81-day smoothed time series. The solar EUV variations (maximum- minimum) is about half as much for solar cycle 24 (2008-present) as compared to solar cycle 23 (1996-2008). There have been three peaks during solar cycle 24: November 2011, November 2013, and March 2015.

1c. Additional Results about Solar Variability with TIMED SEE Measurements

Woods *et al.* (2015) explored a different approach for studying solar spectral irradiance (SSI) variations through examining the total energy of the irradiance variation during six-month periods. This duration is selected because a solar active region typically appears suddenly and then takes about six months to decay and disperse back into the quiet Sun network. The solar outburst energy, which is defined as the irradiance integrated over the six-month period and thus includes the energy from all phases of active region evolution, could be considered the primary cause for irradiance variations. Because solar cycle variation is the consequence of multiple active region outbursts, understanding the energy spectral variation may provide a reasonable estimate of the variations for the 11-year solar activity cycle. This new method was used to study the moderate-term (6-month) variations from the TIMED Solar EUV Experiment (SEE) and Solar Radiation and Climate Experiment (SORCE) instruments by modeling the variations using the San Fernando Observatory (SFO) facular excess and sunspot deficit proxies. This analysis reveal that the TIMED SEE far ultraviolet (FUV: 120-200 nm) variability is consistent with SORCE SOLSTICE and UARS SUSIM measurements of the FUV variability as illustrated in Figure 4a and that solar cycle 24 (2008-present) has about half as much variability as solar cycle 23 (1996-2008) as shown with scaled values of solar cycle variability in Figure 4c.

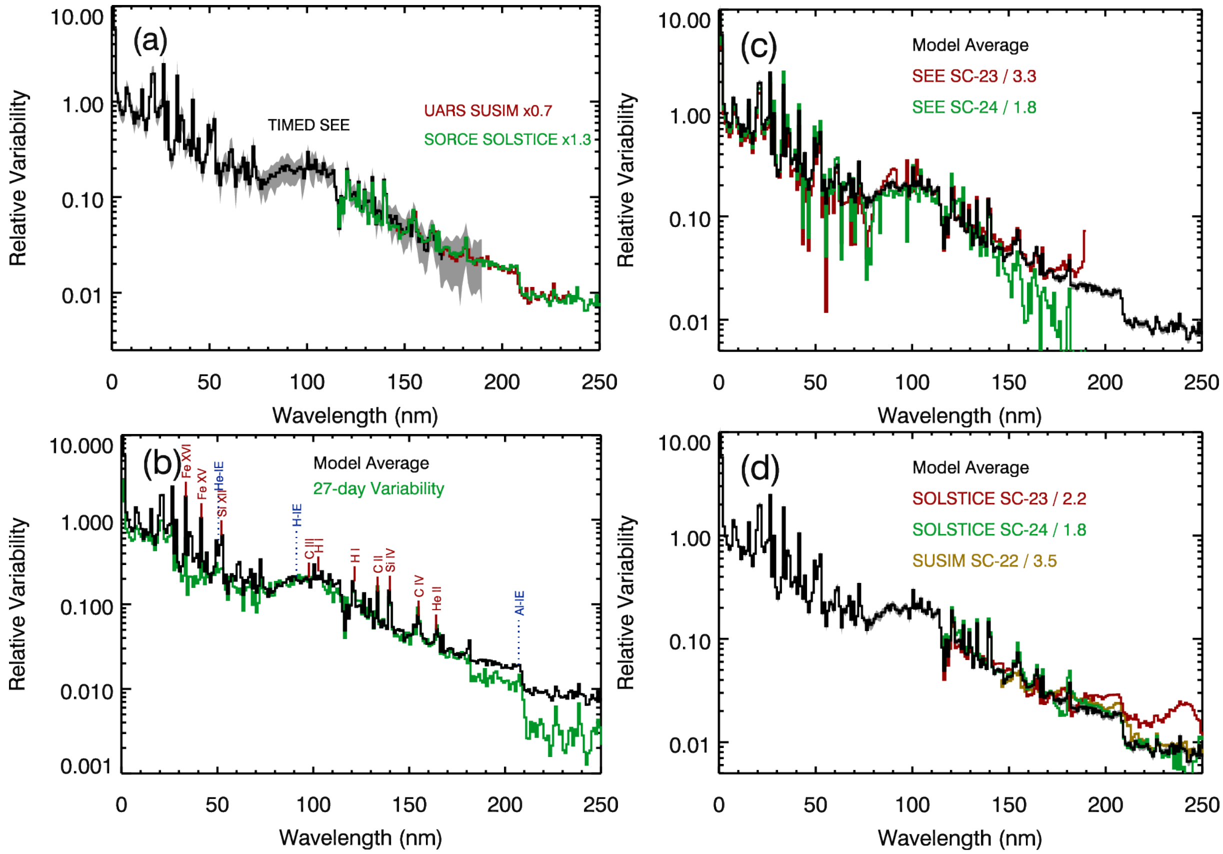

Figure 4. The average energy relative variability is consistent for TIMED SEE, SORCE SOLSTICE, and UARS SUSIM in the UV range as shown in panel (a). The composite of energy variability shown in panels b, c, and d includes TIMED SEE at wavelengths shorter than 115 nm and SORCE SOLSTICE at wavelengths longer than 115 nm. Panels (b), (c), and (d) compare these energy variability results to the 27-day solar rotation variability, TIMED SEE solar cycle variability, and SORCE SOLSTICE / UARS SUSIM solar cycle variability, respectively. The energy variability uncertainty (RMS of standard deviation of fitted parameters) is included as the grey region in panel (a) for SEE data.

1d. New Reference Spectra for the Soft X-ray (SXR) and Extreme Ultraviolet (EUV) Irradiance

Recent measurements of the soft X-ray (SXR) spectrum from sounding rockets in 2012 and 2013 indicate that the SEE XPS model spectra (SEE Level 4 data product) is too high in the 0.1-2 nm range [Caspi, Woods, & Warren, 2015]. The XPS model spectra is also noted to be too low as compared to the Solar Dynamics Observatory (SDO) extreme ultraviolet (EUV) measurements in the 6-10 nm range. While the integrated irradiance as measured by SEE XPS is accurate to about 20%, the Woods *et al.* [2008] model that has previously been used for modeling the broadband measurements of the SEE XPS needs to be updated with better reference spectra from these rocket SXR measurements and SDO EUV measurements. The following describes these new reference spectra that will eventually be incorporated into the SEE Level 4 data processing algorithm.

The equation for the irradiance (E) model is:

$$E = QS + f_{AR} AR' + f_{FL} FL'$$
$$AR' = AR - QS$$
$$FL' = FL - QS$$

The quiet sun (QS) and active region (AR) reference spectra are determined through linear fits with SDO EVE MEGS and TIMED SEE EGS daily measurements of the EUV irradiance and the fraction of AR area (f_{AR}) derived from the EVE 6-10 nm time series (see Figure 5). The CHIANTI isothermal spectral model is compared to the rocket SXR spectra, and it was determined that the CHIANTI log(T)=6.0 is best fit for QS and log(T)=6.4 is best fit for active sun (but not flaring). These CHIANTI spectra are used shortward of 6 nm to provide SXR spectra for the QS and AR reference.

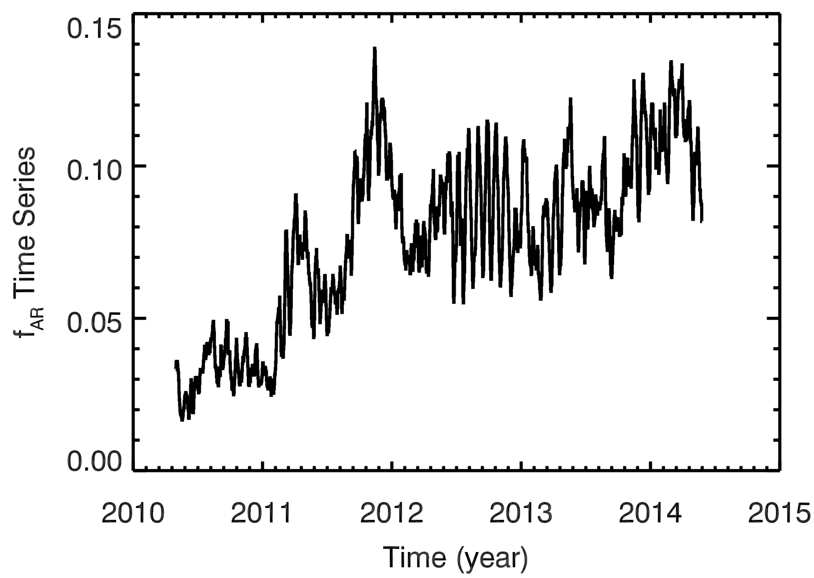

Figure 5. The Active Region (AR) fractional area (f_{AR}) is derived using the SDO EVE 6-10nm integrated variability and so it is limited to the 2010-2014 period.

The MEGS reference spectra (black lines in Figure 6) are at higher 0.1-nm spectral resolution than the EGS 0.4-nm resolution (red lines in Figure 6). The MEGS EUV reference spectra and CHIANTI (rocket) SXR reference spectra are the ones recommended for modeling the daily variations. The ratio of the AR to QS spectra provides insight to the source of the variability with coronal emissions having a AR/QS ratio of about 30 or higher, chromospheric emissions having a AR/QS ratio of about 3 or lower, and transition region emissions having a AR/QS ratio between 3 and 30.

The QS and AR reference spectra were fit up to 2013 for the SDO mission and between 2010 and 2012 for the TIMED mission. The extrapolation of the mission past the fit period is shown in Figure 7. The TIMED SEE Version 11 data product was only calibrated up to 2012, and it is obvious that most wavelengths need new corrections for EGS degradation trending starting in 2012.

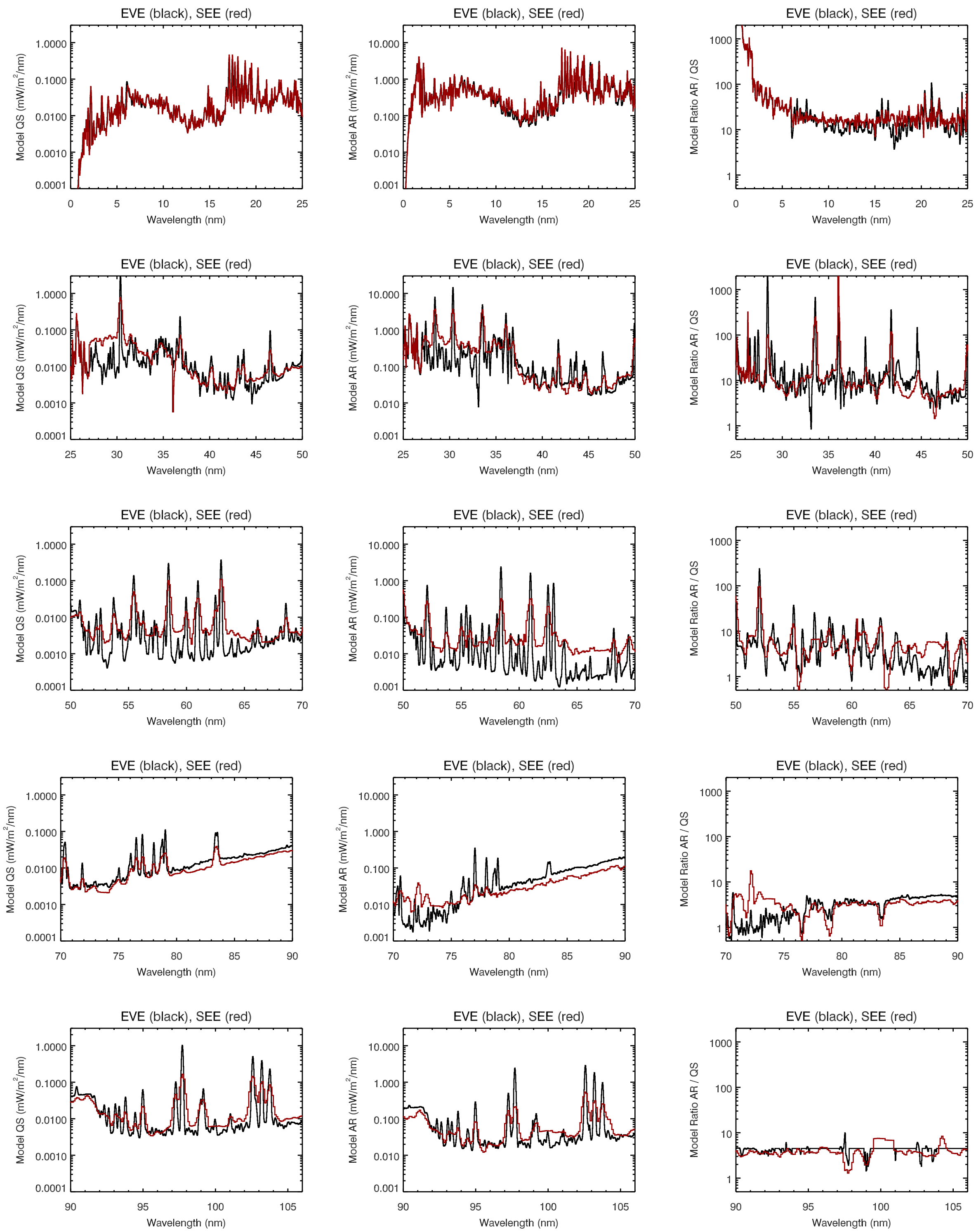

Figure 6. Comparison of Quiet Sun (QS) [left side] and Active Region (AR) [middle] reference spectra derived for SDO EVE MEGS (black lines, 0.1-nm resolution, 6-106nm) and TIMED SEE EGS (red lines, 0.4-nm resolution, 27-106nm). CHIANTI spectra are used in the 0-6nm range. The AR / QS ratio [right side] indicates source of the variability: corona above 30, transition region between 3 and 30, and chromosphere below 3.

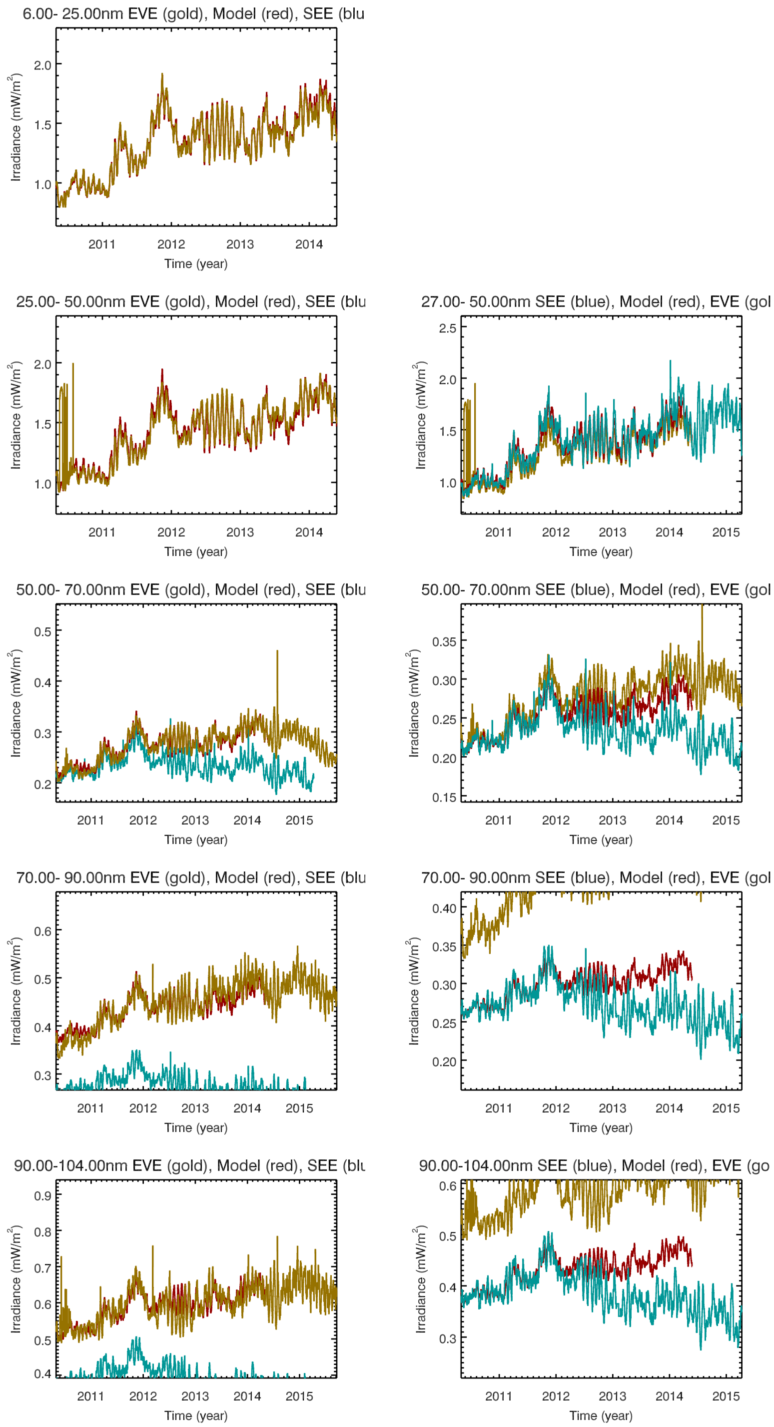

Figure 7. The model variability results (red lines) are compared to the SDO EVE MEGS (left side) and TIMED SEE EGS (right side) time series. The EVE-derived model is used in the left plots, and the SEE-derived model is used in the right plots. The EGS degradation trends need to be updated for 2012 and forward as discussed more in Section 3b.

1e. Development of New Irradiance Proxy Models

The Extreme UltraViolet Monitor (EUVM) on board the Mars Atmosphere and Volatile EvolutioN (MAVEN) probe at Mars uses measurements from three bands in the Soft X-ray (SXR) and EUV range to produce its Level 3 (L3) data product. The L3 product is a modeled spectrum from 0.5-190.5 nm range at 1 nm resolution based on the Flare Irradiance Spectral Model (FISM) developed by Chamberlin *et al.* (2007, 2008) which is an empirical model that estimates irradiance based on pre-determined correlations with available measurements. In the case of the MAVEN-EUVM L3 product, TIMED-SEE spectra have been used as a training set to determine the model coefficients for the 0.5-5.5 nm range and the 106.5-117.5 nm range. TIMED-SEE spectra have also been used to validate the MAVEN-EUVM L3 product in the 0.5-5.5 nm range. Furthermore, TIMED-SEE measurements of an X2.2 flare on October 19, 2014 are being used to study the resulting energetic photoelectrons observed by the Solar Wind Electron Analyzer (SWEA) instrument; and results are anticipated to be published in an appropriate peer-reviewed journal in spring of 2016.

TIMED-SEE data have also been used to develop model coefficients for the GOES-R EUV and X-ray Irradiance Sensors (EXIS) irradiance model. This model is similar in principle to the MAVEN-EUVM L3 data product, but differs in the number of available input measurements (10), and the model output spectral range and resolution (5 nm resolution from 5-115 nm plus a single bin spanning the 117-127). SEE data have been used as a training data set to determine model coefficients for the bins spanning 40-115 nm. These model coefficients have been delivered to NOAA and are expected to be used for the first year of GOES-R instrument operations following the spring 2017 launch.

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2. SEE Mission Operations Summary

Through October 20, 2015, SEE successfully completed 69,912 normal solar experiments out of the 71,172 experiments planned. This success rate is 98%, which meets the minimum NASA mission criteria. Throughout the entire mission SEE has consistently been well above the acceptable levels. As shown in Table 1, there have been very few observational gaps since TIMED normal operations began in January 2002. The SEE normal operations ended in April 2011, but SEE has remained on for overlapping measurements with the Solar Dynamics Observatory (SDO) EUV Variability Experiment (EVE) in 2010-2015. This extension is being operated with automatic operations and data processing (minimal funding).

Table 1. List of TIMED SEE Data Gaps. SEE Sensors are EGS and XPS.

Date	State	Sensor(s)	Science Data Affected
March 1, 2002	Safe Mode	Both	Part Day
March 2, 2002	Safe Mode	Both	All Day
March 4, 2002	Ground SW Anomaly	EGS	All Day
March 5, 2002	Ground SW Anomaly	EGS	Part Day
March 19, 2002	Safe Mode	Both	Part Day
March 29, 2002	Safe Mode	Both	Part Day
July 24 – 30, 2002	XPS Filter Wheel Anomaly	XPS	All Days
Nov. 18 – 19, 2002	Leonid Safing	Both	Part Day
Sept. 16 – 21, 2004	TIMED Flight Software Load	Both	Sept. 16, 21: Part Day Sept. 17 – 20: All Day
Sept. 29 – Oct. 1, 2004	TIMED Flight Software Load	Both	Sept. 29, Oct. 1: Part Day Sept. 30: All Day
May 4, 2005	Lost data due to HK rate being at 5 sec (nominally at 15 sec)	Both	Part Day (after SSR allocation reached)
Aug. 16 – 18, 2006	Safe Mode	Both	Aug. 16, 18: Part Day Aug. 17: All Day
July 25 – 26, 2007	Safe Mode	Both	Part Day
Nov. 19, 2007	Safe Mode	Both	Part Day
Jan. 8 – 15, 2008	Safe Mode	Both	Jan. 8: Part Day Jan. 9 – 15: All Day
May 24 – 25, 2008	Safe Mode	Both	May 24: Part Day May 25: All Day
July 7, 2008	Planning Anomaly	Both	Part Day
June 14 – 23, 2009	Safe Mode	Both	June 14 - 22: All Day June 23: Part Day
Dec. 2 – 3, 2009	Safe Mode	Both	Dec. 2: All Day Dec. 3: Part Day
Nov. 27 – 28, 2011	Safe Mode	Both	Part Day
Jan. 28 – Feb. 17, 2013	Default ODC due to planning computer anomaly	Both	All Day
July 8, 2014	SEE Power Off	Both	Part Day

3. SEE Data Processing and Data Products Summary

3a. Current SEE Data Products

The TIMED SEE data products are currently at Version 11, and the products through 2012 have been archived at SPDF. The SEE data processing is automated and produces new products each day.

All SEE data products are available from the SEE web site (http://lasp.colorado.edu/see), but the TIMED archive site will be the long-term residence for the SEE data products. LASP currently provides access to all data products through FTP (ftp://laspftp.colorado.edu/pub/SEE_Data) and also http (http://lasp.colorado.edu/data/timed_see). VITMO contains links that point to the LASP FTP site directories, but there does not appear to be any SEE data accessible through public SPDF interfaces.

The SEE data product types are listed in Table 2. Most research papers have used the SEE L3 and L3A products. The SEE Version 12 products are expected to be released in early 2016 and will include updated corrections for the instrument degradation trends as discussed more in the next section.

The SEE Level 3 data product and Composite Lyman-alpha time series is also available on the LASP Interactive Solar Irradiance Datacenter (LISIRD) website – http://lasp.colorado.edu/LISIRD.

Table 2. List of TIMED SEE Data Products

Data Product	Period	Description
SEE L2A SpWx	Orbit	8 solar indices (emissions/bands) for SpWx Ops
SEE L3	Day	1-nm spectrum from 0.5 nm to 194.5 nm, 38 emission lines, XPS 9 bands
SEE L3A	Orbit	Same as L3 but for orbit average (3-min avg)
EGS L2, L2A	D & O	0.1-nm spectrum from 27 nm to 195 nm
XPS L2, L2A	D & O	XPS 9 bands
XPS L4, L4A	D & O	0.1-nm spectral model from 0 to 40 nm
EGS L2B (Occ)	Orbit	Atmospheric transmission (single altitude)
Composite Ly-α	Day	H I Lyman-α irradiance from 1947 to present

3b. Future Update for SEE Data Products

The primary update needed for the TIMED SEE data products is revision of the degradation trend since 2012. The current Version 11 of the TIMED SEE data products includes degradation trend through 2012 and only extrapolation of those degradation functions between 2012 and 2015. The next SEE data product Version 12 needs to include updated degradation functions but this has been challenged by having the EVE underflight rocket calibration in 2015 being a failure due to a launch vehicle failure. ***Until the SEE products are updated, we caution the use of SEE Version 11 data for solar variability studies between 2012 and present time.***

An example of the consequence of extrapolating degradation functions for several years is shown in Figure 8 in a comparison between TIMED SEE and SDO EVE for the H I Lyman-alpha (121.6 nm) emission. In this figure, the SEE and EVE irradiance values begin to drift apart, soon after the last SEE calibration experiment was applied in mid 2011.

The drift of the SEE / EVE Lyman-alpha ratio is about 4% per year, as shown in Figure 8. We need additional information to understand which trend might be true solar cycle variability versus instrument degradation trend. SORCE SOLSTICE has previously been useful for validating the SEE trends in the far ultraviolet (FUV: 120-200 nm) as it has a robust in-flight calibration with early-type stars. However, the last stellar calibration for SOLSTICE was in June 2011; SOLSTICE star calibrations had to end then due to SORCE satellite battery performance degrading and requiring SOLSTICE to be off during the orbit eclipse (night). The NOAA GOES-15 EUVS and ESA PROBA2 LYRA are also making Lyman-alpha measurements, but neither has on-board calibrations or their own underflight calibration program to help with SEE cross-calibration. In fact, both GOES EUVS and LYRA have relied on EVE calibration rocket measurements for their long-term trending.

We don't currently have the information to determine which, if either, is the correct solar cycle trend shown in Figure 8. Fortunately, this Lyman-alpha trend (drift), and the trends at all the other EUV wavelengths, will be settled with the next EVE calibration rocket measurement in 2016.

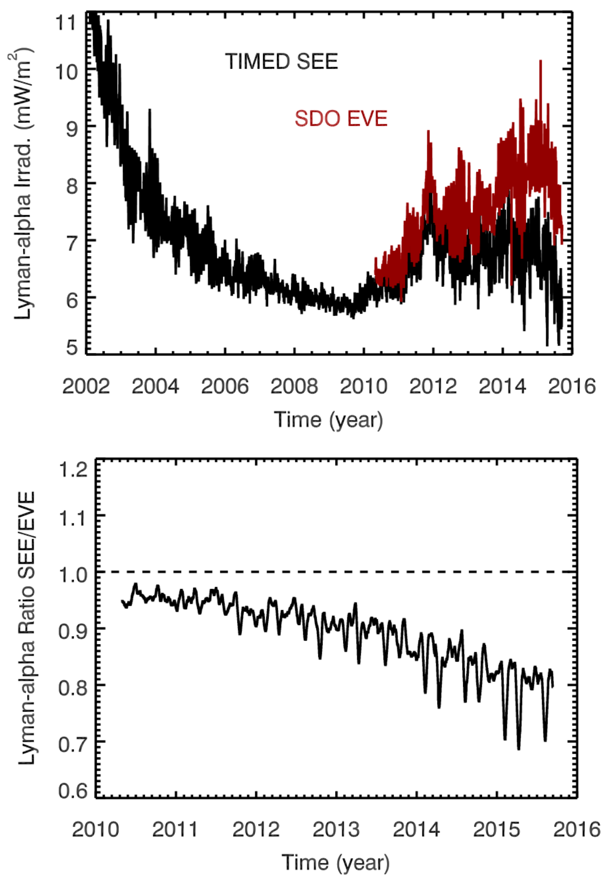

Figure 8. Comparison of the SDO EVE and TIMED SEE Lyman-alpha (H I 121.6 nm) irradiance measurements. The top plot shows the measurements in irradiance units, and the bottom plot shows the ratio of TIMED SEE to SDO EVE irradiance. The two measurements are in good agreement while we have regular underflight calibration rocket measurements for EVE in 2010-2012, but the ratio drifts apart by about 4% per year after about mid 2011.

4. Plans for Next Year

The plans for the next year include updating the degradation trends for the SEE EGS for Version 12 data products, incorporating improved reference spectra for the XPS model spectra for SEE Level 4 data products, and continue study of the solar cycle 24 variability as the sun heads toward its next cycle minimum, perhaps in 2018-2020.