Review of NOAA Working Group Report on Maintaining the Continuation of Long-Term Satellite Total Irradiance Observations

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Committee on Evaluating NOAA's Plan to Mitigate the
Loss of Total Solar Irradiance Measurements from Space

Board on Atmospheric Sciences and Climate

Division on Earth and Life Studies

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COMMITTEE ON EVALUATING NOAA'S PLAN TO MITIGATE THE LOSS OF TOTAL SOLAR IRRADIANCE MEASUREMENTS FROM SPACE

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This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their participation in their review of this report:

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Jeffrey Hall, Lowell Observatory
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Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions nor did they see the final draft of the report before its release. The review of this report was overseen by Thomas Vonder Haar, of Colorado State University, appointed by the Division on Earth and Life Studies, who was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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Summary

Solar irradiance provides the only significant source of energy input to the climate system and its variability has the potential to either mitigate or exacerbate anthropogenic change. Maintaining an unbroken record of Total Solar Irradiance (TSI) is critical in resolving ongoing debates regarding the potential role of solar variability in influencing Earth's climate.

Space-borne instruments have acquired TSI data since 1978. Currently, the best calibrated and lowest noise source of TSI measurements is the Total Irradiance Monitor (TIM) onboard NASA's SOlar Radiation and Climate Experiment (SORCE). These TIM-era data are of higher quality than the older data in the full record. Thus, the TSI climate data record (CDR) has two components. There is the shorter, but more accurate record of the TIM era and the full (33+ year) space-based TSI measurement record. Both are important and require preservation.

SORCE is well past its design life and is encountering significant battery degradation. The Total Solar Irradiance Sensor (TSIS), a dual-instrument package that will be flown on the Joint Polar Satellite System (JPSS) Free Flyer 1 (FF-1) mission to continue the TSI record, is not scheduled to launch until late 2016 or early 2017, creating the potential for a data gap. Unfortunately, NASA's Glory spacecraft, which carried a TIM that would have provided a gap filler, failed to reach orbit on March 4, 2011. Without a mitigation plan, the continuity of both data records (the TIM-era and full record) is threatened.

In examining options to avoid a gap in the record between SORCE and JPSS TSIS measurements, scientists at the Laboratory for Atmospheric and Space Physics (LASP), working with NASA and NOAA officials, identified an opportunity to include a TSI Calibration Transfer Experiment (TCTE) module, which includes a TIM sensor and electronics box, on an upcoming Air Force STPSat-3 launch. In early 2013, a NOAA Working Group developed a plan that describes how the agency anticipates mitigating the measurement gap through the TCTE mission.

The Committee found that the plan faithfully followed the scientific content of two studies conducted by Greg Kopp and Judith Lean for NOAA. The solution presented was a creative, rapid, and low-cost response that exploited the availability of an existing engineering instrument model, and heritage in engineering, mission architecture, and data analysis.

The CDR requirements can only be met when TCTE data overlap occurs at both ends of the gap (with both SORCE/TIM and JPSS FF-1/TSIS). The focus of the NOAA plan was on the shorter, more accurate TIM-era record, and the Committee concluded that the plan is unable to ensure the integrity of the TIM-era data record because as presented it is a 1.5 year plan to fill a 3+ year gap. The launch of the TCTE is currently scheduled for October 30, 2013, which will likely ensure overlap with SORCE. A 1.5 year collection of data on orbit however leaves a gap of more than a year between the stated end of TCTE and beginning of the TSIS on JPSS FF-1. Based on data furnished by the spacecraft provider and LASP, the Committee found the likelihood of achieving overlap with the JPSS/TSIS is 0.56, or slightly better than 50 percent. If the launch of the JPSS FF-1 is delayed, the probability of overlap will decrease. Although the TCTE mission will not ensure continuity of the TIM-era data record, it is more likely to ensure continuity of the full, lower quality data record. The Committee does note that NOAA would be wise to utilize all available data resources (e.g., TCTE, other instruments, proxy models) to fill the gap.

Taken together, the NOAA Plan and the Kopp and Lean studies provided a balanced discussion of strengths and weakness of the proposed method to fill the TSI gap and recognized fully the limitations of TCTE. The Committee was not initially convinced that the CDR requirements as posed represent requirements that were derived from those relevant to understanding climate change. The Committee's research on the source of the requirements given suggests they derive from empirical knowledge of solar variability and instrumental capability and are less related to the energetics of the Earth system. To determine the implications of these requirements on the understanding of the Earth's climate system, the Committee considered two different pathways for setting these requirements based on climate sensitivity, rather than on solar variability or instrumental capability. Coincidentally, the outcome of the calculations made by the Committee agrees with the pre-defined CDR requirements. Hence, given that the recommendations were based on these requirements, the Committee considers that the plan, to an appreciable extent, explored the implications of loss of, or changes in, TSI measurements on the understanding of Earth's climate system and processes.

1

Introduction

Solar irradiance provides the only significant source of energy input to the Earth's climate system and its variability has the potential to either mitigate or exacerbate anthropogenic change. Because intrinsic atmospheric variability precludes solar irradiance measurement with sufficient accuracy and precision from Earth's surface, a space-based record is essential for specifying solar forcing of climate. The current record of total solar irradiance, comprising reasonable overlapping time series of measurements from different space-borne instruments, extends uninterrupted since 1978 and, although it is one of the longest continuous space-based climate records, it covers less than three 11-year solar activity cycles. To understand the Sun's role in climate change, scientists need an uninterrupted irradiance record that extends over many, not just a few, solar activity cycles with sufficient precision to resolve long-term solar changes that may manifest from one activity cycle to the next. Additionally, this record is important to understanding the creation of magnetic fields on the Sun (Judge et al., 2012) and determining if the Sun is anomalous among similar stars (Shapiro et al., 2013). The magnitude of long-term solar irradiance change is highly uncertain because the observational record is, thus far, too short to reliably detect possible centennial-scale variations that may underlie the activity cycle. A reliable, uninterrupted, long-term solar irradiance record can also guide policy by constraining external climate forcing to plausible limits.

The Total Solar Irradiance Sensor (TSIS) is a dual-instrument package that was originally designed to measure solar irradiance on the National Polar-orbiting Operational Environmental Satellite System (NPOESS). It was de-manifested during the 2006 NPOESS restructuring, but was restored in 2008 to the first NPOESS satellite, because of its critical role in determining the natural forcing of the climate system and because of the high priority given by the 2007 National Research Council (NRC) Decadal Survey, *Earth Science and Applications from Space*. TSIS is comprised of the Total Irradiance Monitor (TIM), which measures the total solar irradiance (TSI) that is incident at the top of the atmosphere; and the Spectral Irradiance Monitor (SIM), which measures solar spectral irradiance (SSI) from 200 nm to 2400 nm (96 percent of the TSI). The TSIS TIM and SIM are successor instruments to those currently flying on NASA's SOlar Radiation and Climate Experiment (SORCE).

In 2008, the NRC Committee on a Strategy to Mitigate the Impact of Sensor Descopes and Demanifests on the NPOESS and GOES-R Spacecraft provided recommendations for continuing the total solar irradiance record in its report, *Ensuring the Climate Record from the NPOESS and GOES-R Spacecraft: Elements of a Strategy to Recover Measurement*

Capabilities Lost in Program Restructuring. Ranking TSI measurements in the second highest of four tiers, the committee recommended that the "agencies should consider use of an appropriate combination of small, low-cost satellites and flights of opportunity to fly TSIS (or at least TIM) as needed to ensure overlap and continuity of the measurement of total solar irradiance." A subsequent NPOESS restructuring assigned TSIS flight responsibility to the Joint Polar Satellite System (JPSS).

On March 4, 2011, NASA's Glory spacecraft, which carried a TIM, failed to reach orbit after liftoff aboard a Taurus XL rocket. The best calibrated and lowest noise source of solar irradiance measurements used to support climate research and applications therefore remains the instruments onboard SORCE (Kopp and Lean, 2011), which is well past its design life and is encountering significant battery degradation. Without a mitigation plan, a gap in the record of TSI will occur, causing a serious obstruction to the creation of a consistent data record.

In examining options to avoid a gap in the record between SORCE and JPSS TSIS measurements, scientists at the Laboratory for Atmospheric and Space Physics (LASP), working with NASA and NOAA officials, recently identified an opportunity to include a TSI Calibration Transfer Experiment (TCTE) module, which includes a TIM sensor and electronics box, on an upcoming Air Force STPSat-3 launch. However, once on orbit, the TCTE module would be the only solar-looking instrument among the payloads (the others are Earth-viewing) and would require re-orientation of the spacecraft. As a result, TSI measurements would not be made continuously.

To ensure effective transfer calibration between SORCE and TCTE, a daily observation with both instruments is necessary for 50 days, which corresponds to two solar rotation periods; a similar calibration period would be required to transfer calibration from TCTE to the TSIS that will be on the JPSS Free Flyer 1 (FF-1) mission. In the interim, weekly measurements may be used to maintain a measurement record. This option represents a feasible, current solution to maintaining a well-calibrated TSI record from space, although it relies on a less than ideal platform and will substantially decrease the number of solar observations that are made. In addition, neither the TCTE module nor the spacecraft bus on STPSat-3 are anticipated to have a long lifespan, with the likelihood of insufficient overlap with SORCE and/or FF-1, thus leaving the community with the prospect of a gap in TSI measurements in the event that both SORCE and TCTE end before the start of JPSS TSIS data collection.

STUDY CONTEXT AND CHARGE TO THE COMMITTEE

Maintaining an unbroken record of TSI is critical in resolving ongoing debates regarding the potential role of solar variability in influencing Earth's climate. Available evidence indicates that solar irradiance variations are responsible for only a small part of overall climate forcing over the past 150 years but the magnitude is controversial and the record is not long enough to discern longer time scale processes that may play an important role in Earth's climate. A gap in the record would also make the contribution of solar

BOX 1.1
Committee on Evaluating NOAA's Plan to Mitigate the Loss of Total Solar Irradiance Measurements from Space
Statement of Task

Measurement of total solar irradiance is an important long-term climate record. An ad hoc committee appointed by the National Research Council will evaluate NOAA's plan for mitigating the loss of total solar irradiance measurements from space, given the likelihood of losing this capacity from instruments currently on the SORCE satellite in coming years and the short-term/experimental nature of the currently identified method of filling the data gap (interim observations from TCTE).

The committee will evaluate NOAA's plan for mitigating the gap in total solar irradiance data (including consideration of two commissioned papers upon which NOAA is basing its plan). The committee's evaluation will include consideration of:

- Whether the plan appropriately reflects the scientific content of the commissioned papers,
- Whether the potential alternate method in the plan maintains the integrity of the data record,
- Whether the plan adequately summarizes the strengths and weaknesses of the proposed approach, and
- Whether the background documents and plan together fully explore the implications of loss of or changes in measurement on the understanding of Earth's climate system and processes.

variability to any observed changes to the climate system difficult to characterize. One of the most important roles of the TSI record has been as a null argument, providing evidence that it is not the Sun driving observed global warming. Without a reliable mechanism in place to measure/model TSI, it will be difficult for scientists to accurately assess the natural components of the Earth's primary climate forcing agents. Finally, successive TSI instruments are calibrated in part against overlapping TSI measurements provided from reliable heritage instruments. Thus, if the TCTE mission proves to be unsuccessful, or short-lived, the resulting gap could introduce additional uncertainties in the calibration of future TSI instruments.

Based on two background papers, a NOAA Working Group developed a plan that describes how the agency anticipates mitigating the measurement gap. These two background papers and other relevant information from validated references are the basis for this NRC Committee's independent evaluation of the NOAA plan (Box 1.1).

STUDY APPROACH AND METHODOLOGY

To carry out its charge, the committee held one in-person meeting during which they heard input from NOAA staff and the authors of the background papers upon which NOAA based its plan. The committee reviewed the literature and other relevant documents, which are listed in the References section. During the rest of the review process and preparation of this report, interaction among the committee members was maintained via email and teleconference.

2

Plan Review

The NOAA Working Group Report (Appendix B) outlines the TCTE mission. This mission is the NOAA approach to address the impending gap in TSI measurements that is expected to occur with the imminent end of SORCE and the late 2016 to early 2017 launch of TSIS on the JPSS FF-1 mission. This approach evolved from two studies conducted by Greg Kopp and Judith Lean for NOAA.[1] In its review of the TCTE proposal, the Committee considered the information contained in all three documents (the NOAA Working Group Report, Study A, and Study B). Studies A and B arose from the involvement of Kopp and Lean in a LASP/NRL/NIST team that successfully competed for a 3-year award from the NOAA Climate Data Record (CDR) Program in 2009. Following the GLORY launch failure, Kopp and Lean offered to conduct the two studies as part of their contribution to that project. The NOAA Working Group Report reviewed by the Committee was an abbreviated summary of these two reports plus a very brief description of the TCTE mission and even briefer description of the accommodation of the TIM on the STPsat-3. Much of the analysis that frames the rationale for TCTE concerned the impact of a gap in the TIM data record that started with the TIM launched on SORCE in 2003 (January 25). The NOAA data record as perceived, however, extends back to earlier satellite measurements as summarized below. The perspective of the impending gap on this longer record was not quantitatively addressed in the studies.

TOTAL SOLAR IRRADIANCE DATA RECORD

An approximate two-year gap occurred between ACRIM I and ACRIM II (see upper panel of Figure 2.1).[2] This hiatus in the ACRIM data record offers an ideal test case to gain some understanding of the influence of a gap on the construction of a TSI climate data record. Over the past several years, different procedures have been developed by three different groups to address this issue and to construct a composite time series (see lower panels of Figure 2.1) using ERBE data or the Nimbus HF data (sometimes augmented by TSI models based on proxy data) to fill the gap. Clearly the details of how the data are combined matter. Comparison between the composites of the change of levels of irradiance during solar

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[1] The two Kopp and Lean studies, *Uncertainties Spanning Potential SORCE/TIM to JPSS/TIM Gap* (2011) and *The Solar Climate Data Record: Scientific Assessment of Strategies to Mitigate an Impending Gap in Total Solar Irradiance Observations between the NASA SORCE and NOAA TSIS Missions* (2013), will be referred to as Study A and Study B, respectively. Both are provided in Appendix C.

[2] ACRIM is the Active Cavity Radiometer Irradiance Monitor instrument and is part of NASA's Earth Observing System program.

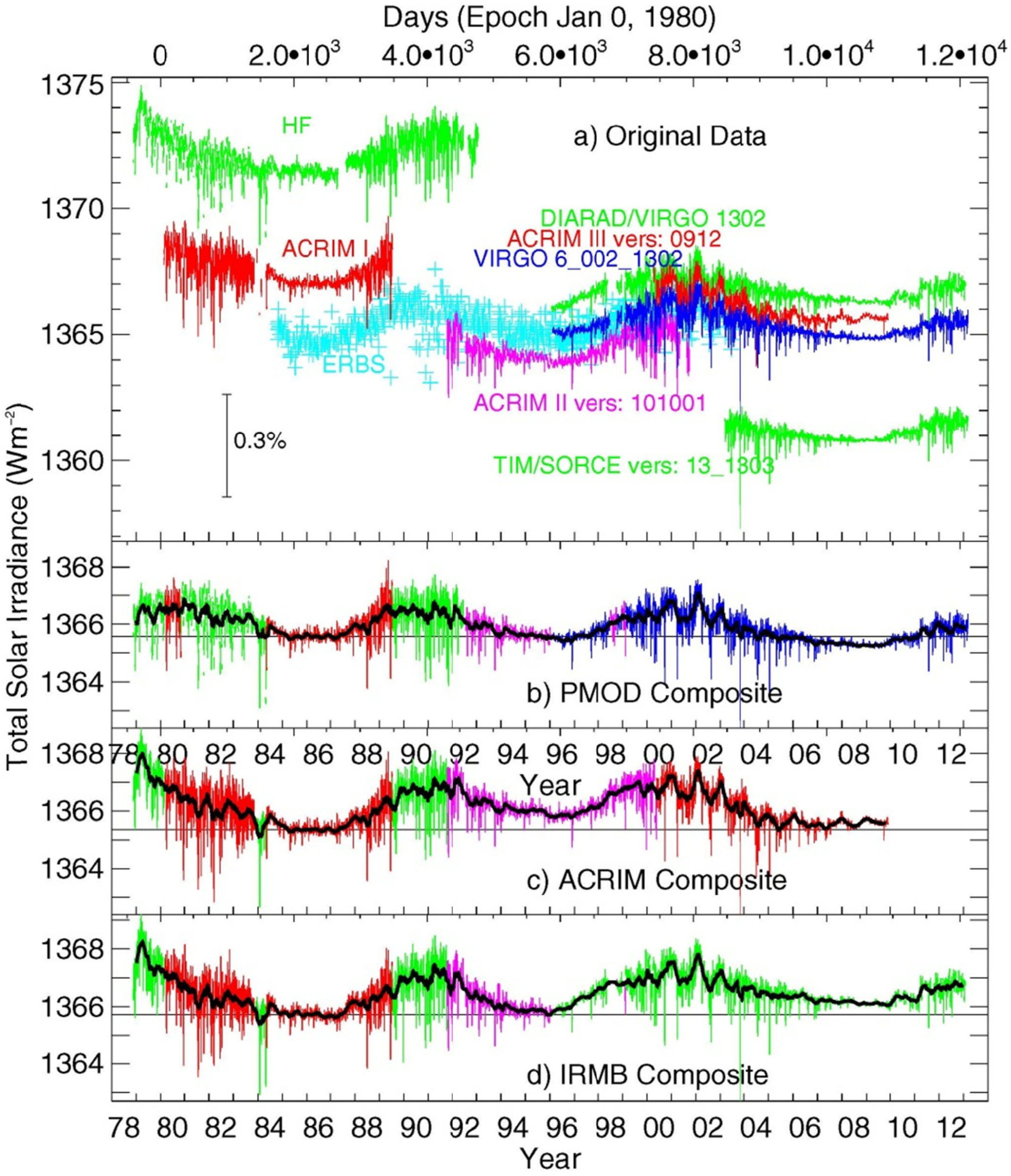

FIGURE 2.1 Upper Panel The daily averaged values of TSI from radiometers on different space platforms since November 1978: HF on Nimbus7, ACRIM I, ERBE, ACRIM II, VIRGO, ACRIM III, and TIM on SORCE. The data are plotted as published by the corresponding instrument teams. **Lower Panels** The PMOD, ACRIM and IRMB composite TSI as daily values plotted in different colors to indicate the data sources used in the composite. SOURCE: PMOD. (ACRIM is the Active Cavity Radiometer Irradiance Monitor, ERBE **i**s the Earth Radiation Budget Experiment, VIRGO is the Variability of solar Irradiance and Gravity Oscillations).

TABLE 2.1 Climate Data Record Requirements for the JPSS/TIM. SOURCE: NOAA Working Group Report.

Parameter	**CDR Requirement**
Absolute Accuracy	0.01% (100 ppm; 0.14 Wm^{-2})
Stability (long-term precision)	0.001%/yr (10 ppm/yr; 0.014 Wm^{-2}/yr)
Noise (short-term precision)	0.001% (10 ppm; 0.014 Wm^{-2})

Note: 1 ppm ~ 0.0014 Wm^{-2}

minimum periods can be taken as a measure of overall precision of the record. The differences between the three reconstructions alone are greater than the 10 ppm/yr precision specified in Table 2.1 and have resulted in considerable debate as to the Sun's role in warming over the decade 1986 to 1996 and misinterpretation of the influence of the Sun on recent global warming.

Because the stringency of the CDR requirements (Table 2.1) severely limit solutions for filling a gap, the Committee determined that it was important to take a step back and revisit these CDR requirements themselves. The traceability of the TSI requirements appears to arise out of an understanding of the variability of the Sun rather than from an understanding of Earth climate system variability and change (Kopp, 2011). The climate-driven requirements first began to emerge in *Solar Influences on Global Change* (NRC, 1994) and can be traced through a series of documents (Box 2.1). Since then much more has been learned about the variability of Earth's energy imbalance (Loeb et al., 2012) and about how to define requirements tailored for climate change detection (Wielicki et al., 2013). Box 2.2 later in this chapter revisits the TSI CDR requirements formulated within the context of this new understanding.

COMMITTEE FINDINGS AND CONCLUSIONS

Question 1: Does the plan appropriately reflect the scientific content of the commissioned papers?

Findings

1. The Committee found that the plan faithfully followed the Kopp and Lean studies. The plan also displayed an admirable degree of nimbleness in reacting to a pressing need to fill an impending CDR gap. The solution presented was a creative, rapid, and low-cost response that exploited the availability of an existing engineering instrument model, and heritage in engineering, mission architecture, and data analysis. Studies A and B themselves also provide a useful analysis that furthers our understanding of the performance of existing space-borne TSI measurements.

Given published information on instrument accuracy and stability available as of the dates of the Kopp and Lean studies and the NOAA working group report, the Committee considers the review of gap-filling alternatives to be fair. While the plan did reflect the scientific content of Studies A

BOX 2.1
Traceability of Total Solar Irradiance Measurement Requirements

Requirements for climatically useful TSI measurements can be traced to discussions in *Solar Influences on Global Change* (NRC, 1994). The National Polar-Orbiting Operational Environmental Satellite System (NPOESS) Integrated Operational Requirements Document (IORD-I; NPOESS, 1996) specified threshold (minimum success) and objective (goal) accuracies of 0.1% and 0.035% and precisions of 0.002% yr^{-1} and 0.0005% yr^{-1}, respectively. An NRC workshop (NRC, 2000) changed the accuracy objective to 0.01%, restated precision threshold and objective as 0.002% and 0.001% respectively, and added stability threshold and objective values of 0.002% yr^{-1} and 0.0005% yr^{-1}, respectively. These values were formalized in IORD-II (NPOESS 2001). A multiagency workshop (Ohring, 2007) confirmed the accuracy objective of <0.01% and recommended a stability objective of <0.001% yr^{-1}. A report by Datla et al. (2009) quoted the less stringent threshold values in IORD-I for accuracy and stability. Given the inconsistency of the values, transition from research to operational requirements, unclear justifications for the values, and the emergence of a Climate Data Record Project at NOAA, a workshop was held in 2011 to sort out these issues (LASP, 2011). When NPOESS was restructured in 2010, NOAA became responsible for JPSS. The original Level 1 requirements for the TSI-measuring part of the TSIS package selected to fly on JPSS-1 stated minimum success accuracy and stability of 0.35% and 0.035% yr^{-1} and goals of 0.01% and 0.001% yr^{-1}, respectively (Viereck and Denig, 2011). The present Level 1 threshold requirement values are listed in Table 2.1; objective values are one-half of the values in Table 2.1 (Viereck and Denig, 2011). Justification for the values was originally driven by instrument capability but is now primarily based on present understanding of long-term solar variability and a need to detect <0.1% long-term TSI changes in a century (Kopp, 2011).

and B, as presented it lacked certain essential information needed to determine the strength of the proposal. No reliability information (probability of TCTE surviving until the launch of JPSS FF-1) for the key mission elements was provided. There was no budget and no clear timeline of the funding or continued support from the Air Force was offered. These aspects of the Committee's review are discussed in greater detail in response to Question 2 below.

Question 2: Does the potential alternate method in the plan maintain the integrity of the data record?

Findings:

2.a Study B clearly argues that the CDR requirements can only be met when data overlap occurs at both ends of the gap. Because no reliability estimates of mission components or information about mission funding or Air Force support were provided, it was not possible to assess the real likelihood of the gap being filled. The Committee concluded that the plan is unable to ensure the integrity of the data record because as presented it is a 1.5 year plan to fill a 3+ year gap.

2.b The launch of TCTE is currently scheduled for October 30, 2013, which will likely ensure overlap with SORCE. Although not presented to the Committee, it appears the probability is high of SORCE operating beyond the launch of TCTE, thus providing critical overlap at the front end of the gap. This determination was based on information provided by the Spring 2013 SORCE senior review proposal made available to the Committee by NASA (Woods, 2013). A 1.5 year collection of data on orbit however leaves a gap of more than a year between the stated end of TCTE and beginning of the TSIS on JPSS FF-1.

2.c Although the Committee was not briefed on what elements of the mission limit the lifetime of TCTE, it was able to determine that there is high probability that the single-string spacecraft could operate beyond 3 years. Independent information provided to the Committee by the spacecraft provider indicated that the single string baseline STPSat-3 type bus reliability for 3 years on-orbit is above 0.80 and drops to 0.75 for 4 years on orbit (personal communication to Committee Chair). Estimates provided to the Committee by LASP indicate that the TIM instrument reliability is 0.80 at 3 years and 0.74 at 4 years. Thus the likelihood of achieving 4 years of data on orbit and thus overlap with the JPSS/TSIS (scheduled to launch in late 2016 to early 2017) is 0.56, or slightly better than 50%. In the reliability data provided to the Committee by LASP, the drop in probability of TCTE survival from one to two years, two to three years, and three to four years are all the same: about 0.86 times the previous year's value. This is typical of spacecraft and instrument reliability estimates. Thus, the Committee can estimate the probability of overlap if the launch of JPSS/TSIS is delayed beyond 2017. If the launch slips to 2018, the probability of overlap drops to 0.48. If it slips to 2019, the probability of overlap drops further to 0.41.[3]

2.d The NOAA Working Group report did not provide information on funding support for the TCTE mission and stated that NOAA is working with the Air Force to ensure operation of the STPSat-3/TCTE mission for as long as possible. Continued funding and cooperation from the Air Force will be necessary for continued data collection and maintaining the integrity of the data record.

Question3: Does the plan adequately summarize the strengths and weaknesses of the proposed approach?

Finding:

3 Taken together, the three documents provided a balanced discussion of strengths and weakness of the proposed method to fill the TSI gap and

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[3] The probability of TCTE maintaining data collection for four years is 0.56. The probability of survival drops by a factor of about 0.86 each year. Thus the probability of TCTE surviving five years (until 2018) is 0.56 × 0.86 = 0.48. The probability of TCTE surviving six years (until 2019) is 0.48 × 0.86 = 0.41.

recognized fully the limitations of the proposed TCTE gap filler. In developing the plan, the analysis of the stability uncertainty estimates for ACRIM3, VIRGO, and PREMOS in comparison to SORCE/TIM was essential in the formulation of TCTE. The comparative stability of different instruments and empirical models summarized in Table 2.2 are based on comparisons of the instrument data records relative to those of the SORCE/TIM and from changes between each instrument's successive data versions. The Committee was however aware that it was only being presented a TIM-based gap-filling concept and then only the TCTE concept. The Committee considered material from the NOAA Working Group Report, Kopp and Lean Studies A and B, the SORCE and ACRIM-3 NASA Senior Review proposals, existing literature on TSI observations, and past changes in TSI records needed to correct instrument artifacts. Overall, the arguments in favor of TIM as the current best reference were the most compelling. The TIM instruments for example show one-third the on-orbit degradation of that for ACRIM, and reduced systematic noise during quiet sun periods. The use of TIM as the reference leads directly to the results in Table 2.2 and Figure 2.2.

Figure 2.2 illustrates how the uncertainty in TSI introduced by the presence of a gap is influenced by a number of parameters. Based only on the absolute accuracy of the instruments, shown in Figure 2.2 as the dashed line at ~360 ppm representing the accuracy of SORCE/TIM, the uncertainty does not depend on gap length. With overlaps, provided by intervening measurements or models, the drift between the two TIM measurements can be estimated and the uncertainty reduced. Figure 2.2 illustrates how longer overlaps and shorter gaps enhance this effect; for example with a gap of 3 year duration an overlap of more than 0.5 years will improve uncertainty over that which would be obtained by relying on absolute accuracy alone. The improvement is limited for short (< ~10 days) overlaps by noise in the measurements. Figure 2.3 provides analogous illustrations of alternative gap-filling methods.

Because filling the TSI data gap with the TCTE is not assured, it was prudent to examine other options.[4] In particular, models of TSI based on proxy data (e.g., sunspot darkening and facular brightening) can, in principle, be used to fill a gap depending on the demonstrated performance of the model, duration of the gap, and availability of high-quality proxy data. In Study B several models were constructed based on linear regression of various combinations of proxy data to the TIM TSI observations (2003-2012). The best agreement was an NRL model based on a sunspot blocking index derived from ground-based white light images and a Mg II spectral line ratio index derived from SORCE/SOLSTICE observations. This model had a correlation coefficient of 0.961 and thus fits 92.4% of the observed TSI measurement variance (Study B). The

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[4] It is beyond this Committee's charge to prioritize other options (e.g., proxy data models versus other space instruments). However, the Committee does note that NOAA would be wise to utilize all available data resources to fill the gap.

TABLE 2.2 Instrument and Model Performance Estimates. SOURCE: Kopp and Lean Study B.

Instrument	Stated Accuracy (ppm)	Stability (ppm/yr)	Noise (ppm)
SORCE/TIM	350	10	4
ACRIMSat/ACRIM3[b]	1000	71	34
SoHO/VIRGO	2500	29	28
PICARD/PREMOS	300	79	<52
JPSS/TCTE/TIM	350	10	50[a]
JPSS/TSIS/TIM	100	10	10
NRL Model	-NA-	48	38
SFO Model	-NA-	88	19

[a] Effective noise due to orbital sampling at times of high solar activity. Instrument noise is less than 10 ppm.

[b] The ACRIM Senior Review Proposal (Willson, 2013) states that ACRIM3 results have demonstrated a traceability uncertainty of < 5 ppm/yr and that LASP/TRF calibration will result in accuracy improvement. If these performance improvements prove to be true, ACRIM could be a viable alternative for filling the data gap.

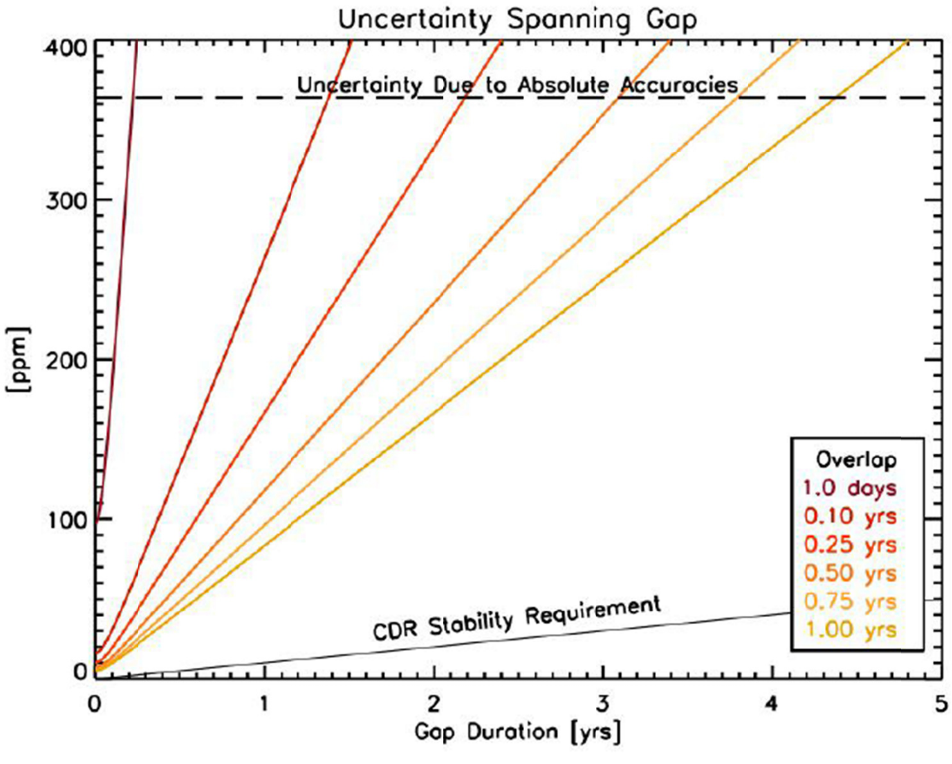

FIGURE 2.2 General effects contributing to uncertainties in filling a TSI data gap. Stability uncertainties increase with gap duration, limiting accuracy; measurement noise limits the uncertainties at short gap durations. Longer overlap durations with prior (SORCE/TIM) and following (JPSS/TIM) instruments improve knowledge of stability of, and agreement with, intervening gap-filling instrument or model, decreasing uncertainties. **SOURCE**: NOAA Working Group Report. (This figure, with accompanying explanation is in Appendix B.)

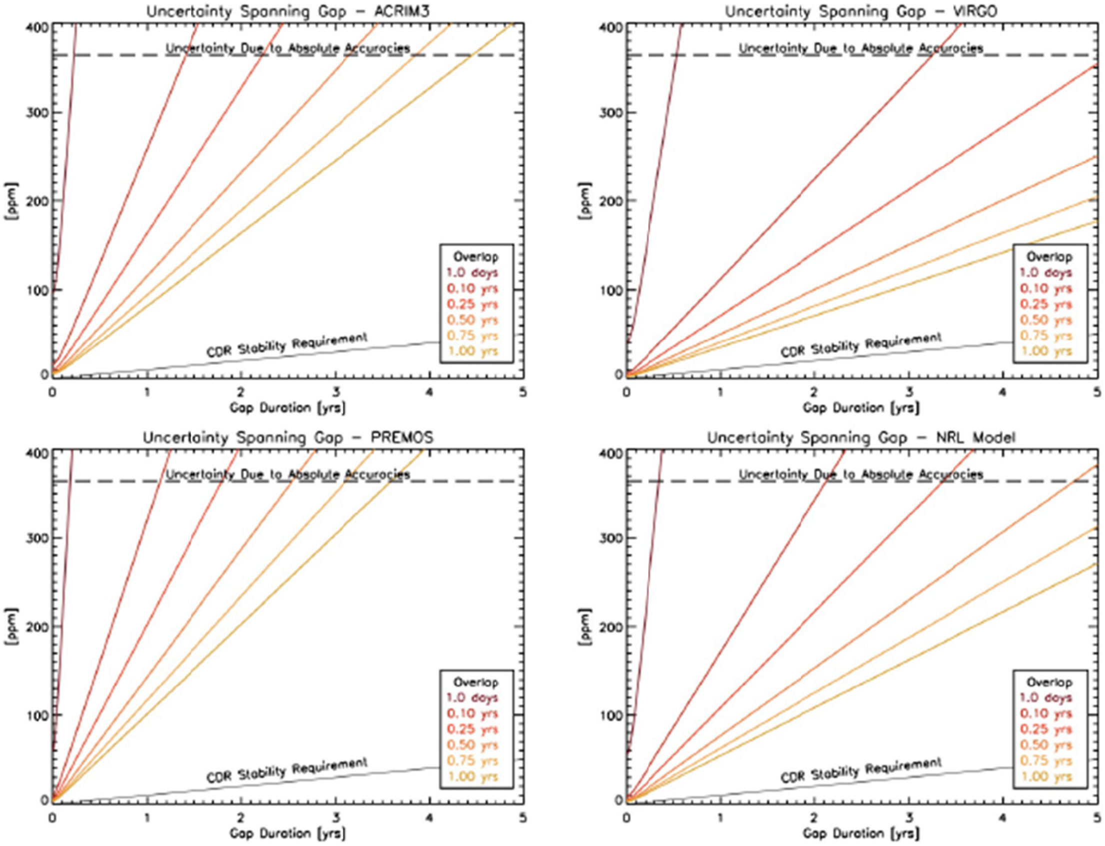

FIGURE 2.3 Estimated uncertainties as a function of gap and overlap duration for gap-filling alternatives: ACRIM3 (top left), VIRGO (top right), PREMOS (bottom left), and NRL model (bottom right). In all four cases, longer gap durations and shorter overlap times increase uncertainties. **SOURCE**: Kopp and Lean Study A. (This figure, with accompanying explanation is in Appendix C.)

SOLSTICE data will not outlive data from TIM so models based on non-SORCE data are relevant. The best correlation reported in Study B for such a model was 0.942, which fits 88.7%[5] of the TIM variance.

The Committee considered two published comparisons not included in Study B. Ball et al. (2011) compared TSI modeled with SATIRE-S (based on sunspot images and magnetic field measurements) with observed TIM data. For the period 2003-2009 they found a correlation of 0.984 (97% of variance fitted). Chapman et al. (2012), using a different set of ground-based proxy observations for the period 2003-2010, found a slightly smaller correlation of 0.974 (95% of variance fitted) with TIM data. These two empirical models have recently been compared with the PMOD composite TSI index. Ball et al. (2012) for the period 1996-2008 obtained a correlation

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[5] This value was calculated by the committee. It is simply the square of the correlation coefficient reported in Study B. This value, the coefficient of determination, gives the percentage of the total variation that is explained by the model (Wackerly et al., 2008).

of 0.981 and Chapman et al. (2013) found 0.96 for 2003-2010.

It appears that by using different proxy data sources than those of Study B, the agreement between empirical models of TSI and observations may be improved so that ≥95% of the TSI variance can be fit with a model. Combining such models with the instrumental approaches suggested in the Working Group Report would greatly improve the chances of successfully bridging a TSI gap. However, as noted in Study B, there is no certainty that the sources of proxy data for the models will be available during the TSI gap. Declining funding, age, and looming closures threaten both ground- and space-based sources of synoptic solar observations. Nor are resources readily available to improve the quality of or add new sources of solar data useful for TSI modeling.

A hypothetical alternative method for future gap filling not explicitly discussed adequately by the plan is reliance on absolute accuracy. Now that LASP has the TSI Radiometric Calibration (TRF) facility whereby it can provide a reported pre-flight absolute calibration of the TIM instruments to about the 200 ppm to 300 ppm level (personal communication from G. Kopp to the Committee), it seems that not only the TSIS TIM, but also the TCTE TIM and all subsequent TIMs (assuming maintenance of the TRF scale), should be calibrate-able to this level. The Committee notes that these results have not been peer reviewed, but if this uncertainty can in fact be achieved and could be improved in the future to 100 ppm, we could be more tolerant of gaps, because comparison of any pair of sufficiently long (to overcome short-term random effects) segments of non-overlapping data, each with absolute uncertainty at this level, would approach the CDR values required for detecting solar variability. The TCTE provides an early test of this. It will be the first TIM to fly that was calibrated against the TRF (the PREMOS-A active cavity radiometer instrument was calibrated to 280 ppm in 2010), and thereby potentially one of the most absolute accurate measurements of TSI to date. The comparison of the TCTE TIM TSI value with all the others will provide a highly accurate tie point, and will validate the SORCE TIM and PREMOS values. This provides additional incentive to fly the mission, even if it does not fill the gap.

Question 4: Do the background documents and plan together fully explore the implications of loss of, or changes in, measurement on the understanding of Earth's climate system and processes?

Finding:

4 The Committee was not initially convinced that the requirements as posed (Table 2.1) represent requirements that were derived from those relevant to understanding climate change. The Committee's research on the source of the requirements given suggests they derive from empirical knowledge of solar variability and instrumental capability and are less related to the energetics of the Earth system (Box 2.1). To determine the implications of these requirements on the understanding of the Earth's climate system, the Committee considered two different pathways for setting these requirements based on climate sensitivity, rather than on solar variability or instrumental capability. These are summarized in Box 2.2.

Box 2.2

TSI Accuracy Requirements for Understanding Anthropogenic Climate Change

Approach I: The analysis below is based on the arguments for the measurement requirements of the CLARREO mission (Wielicki et al., 2013) and revolves around certain assumptions of future climate change. Dangerous climate change is internationally agreed to be ~ 2 °C over the long term (Copenhagen Accord, 2009). Best current estimate of equilibrium (long term) climate sensitivity is approximately 3 °C for an anthropogenic forcing of ~ 4 Wm^{-2} associated with a nominal doubling of carbon dioxide (Andrews et al., 2012). Thus a 2 °C warming corresponds to a radiative forcing of roughly 2.7 Wm^{-2} [(2 °C/3 °C)*4 Wm^{-2}]. Because separation of natural from anthropogenic radiative forcing is required for adequate scientific understanding of the Earth's climate system and processes, long term radiative forcing due to changing TSI should be known to at least 10 percent of the level of dangerous climate change with 95 percent confidence (2σ) in order to clearly separate anthropogenic signal from natural variability (e.g. Wielicki et al., 2013).[a] This suggests a knowledge of TSI changes to levels that can cause less than or equal to 0.13 Wm^{-2} (1σ) in radiative forcing of the climate system. Changes in TSI relate to changes in climate radiative forcing by $\Delta F = 0.7\ \Delta S/4$, where ΔS is the change in TSI. The factor of 4 is the ratio of the Earth's cross-sectional area to its surface area and the factor of 0.7 is the global average solar absorption of Earth (1 - albedo). Or equivalently, $\Delta S = 5.7\ \Delta F$. This implies that the long term change in TSI should be known to $5.7 * 0.13 = 0.74$ Wm^{-2} or less. The time interval for this long term trend in TSI should be roughly that over which current anticipated anthropogenic radiative forcing would reach the 2 °C warming level. Climate model simulations of doubled CO_2 radiative

Coincidentally, the outcome of the calculations made by the Committee agrees with the pre-defined requirements in Table 2.1. Hence, given that the plan and the background documents together made their recommendations based on these requirements, the Committee considers that these documents, to an appreciable extent, explored the implications of loss of, or changes in, TSI measurements on the understanding of Earth's climate system and processes.

This Committee was charged to address how the loss of TSI data specifically would affect understanding of Earth's climate because TSI, and its variations, play a fundamental role in determining global average temperature. However, there is increasing evidence that variations in solar ultraviolet (UV) radiation contribute to regional and seasonal climate (Gray et al., 2010). In fractional terms UV changes are much larger than those in TSI and these directly affect the temperature and composition of the stratosphere, where UV is predominantly absorbed. To fully appreciate the potential of the Sun in regional climate change it is therefore essential that measurements of spectrally-resolved radiance are maintained in parallel forcing typically use a roughly 1 percent increase in CO_2 per year for a 70 year doubling time (Cubasch et al., 2001). This suggests that the rough time scale for the 2 °C warming for our metric is then (2 °C/3 °C)*70 years or ~ 50 years. A long term trend in TSI to be discernable above anthropogenic climate forcing is then 0.74 Wm^{-2} / 50 years = 0.015 Wm^{-2}/yr. Since TSI ~ 1361 Wm^{-2} (Kopp and Lean, 2011), then a 1000 ppm/yr (0.1 percent) trend is 1.4 Wm^{-2}/yr, and the 0.015 Wm^{-2}/yr trend corresponds to an 11 ppm/yr trend in TSI. This value of 11 ppm/yr is similar to the current JPSS requirement of 10 ppm/ yr stability for TSI observations.

Another way to look at the above requirement is that the 50 year change in TSI should be uncertain to less than 0.75 Wm^{-2} (1σ) which is equivalent to ~500 ppm. For the JPSS 100 ppm absolute accuracy requirement (1σ), the absolute accuracy requirement is ~ 1/5th the total trend uncertainty desired over 50 years. This level of accuracy would also provide a climate record that is robust to data gaps, unlike our current record.

Approach II: A second approach for setting the requirement relevant to climate change studies is to place the TSI change within the context of the global net radiation. Current estimates of ocean heat storage indicate that the global net radiation is ~ 0.5 Wm^{-2} (Loeb et al., 2012). TSI is one component of global net radiation, and its absolute accuracy should be no worse than 10 percent of global net radiation (2σ), or 0.025 Wm^{-2} (1σ). Using the same relationship between TSI and radiative forcing of the Earth's climate, this results in a TSI absolute accuracy requirement for global net radiation of (0.025)(5.7) = 0.15 Wm^{-2}, or ~100 ppm (0.01 percent) in TSI. The JPSS requirement is 100 ppm for absolute accuracy and thus is consistent with a requirement based on energy imbalance and long term ocean heat storage.

[a] 2σ represents two standard deviations from the mean of a Gaussian normal distribution. Approximately 95% of the distribution is contained within two standard deviations of the mean. This is a commonly used confidence boundary in statistics (Wackerly et al., 2008).

with those of TSI.

The TSI CDR has two components. There is the shorter, but more accurate record of the TIM era with SORCE/TIM-level data quality. There is also the full (33+ year) space-based TSI measurement record. This longer record, although not of the quality of the TIM era record, is still important to preserve. The NOAA Working Group Report focused on the impending TSI gap that is to occur because of end of life of SORCE and the failure of the GLORY mission. Much of the working group report emphasized the importance of maintaining an unbroken record of TSI to inform ongoing debates regarding the potential role of solar variability in influencing Earth's climate. Thus the focus was directed to the shorter, more accurate TIM era record and no real discussion of the full TSI CDR and its stewardship was offered. Although this existing satellite data record, dating back to 1978, currently fails to meet the stability requirements of Table 2.1, the Committee believes it is also important to maintain the stewardship of the entire record and place the current TIM era data and impending gaps within the context of the longer data record. NOAA's plan does not ensure continuity for the TIM-era record, but is more likely to ensure continuity of the full 33 year record.

ADDITIONAL THOUGHTS

While the Committee was charged with evaluation of NOAA's response to an impending gap in TSI observations for climate research, NOAA's response and its appropriateness can only be understood in light of how it fits into the larger context of climate observations. Unlike for weather observations, there is no U.S. or international climate observing system. As a result, monitoring of climate change including TSI is a necessarily ad hoc, high risk, and loosely coordinated activity across the 13 U.S. agencies of the U.S. Global Change Research Program (USGCRP). The USGCRP has the responsibility for climate change research, but has no authority over agency actions, nor budget to deal with observing system issues like those that arose for TSI when the NASA Glory mission launch vehicle failed March 3, 2011. Glory was to be the end of NASA leading TSI observations from space, with the NOAA JPSS weather satellite system beginning the next set of observations in 2016. As a result of the launch failure, the solution that NOAA found was severely constrained by cost, schedule, and programmatic challenges. The TCTE solution is not optimal in a scientific sense given roughly 50 percent likelihood of successful overlapping observations in the best case scenario of an on-time JPSS FF-1 launch combined with an absence of any programmatic issues in NOAA and Air Force collaboration on extending the TCTE mission life from 2 to 4 years. Yet in the context of the lack of a climate observing system, the TCTE solution can be considered optimal within the constraints present. We should expect similar issues in the future with many of the approximately 50 essential climate variables. There have been some recent reports that show a recognition of this challenge, in particular the U.S. NSTC "National Strategy for Civil Earth Observations" (April, 2013), and the international "Strategy Towards an Architecture for Climate Monitoring from Space" (January, 2013). Development of a national and international climate observing system could be the long term solution to climate monitoring challenges like TSI.

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Appendixes

A

Acronyms and Abbreviations

ACRIM	Active Cavity Radiometer Irradiance Monitor
CDR	Climate Data Record
CLARREO	CLimate Absolute Radiance and REfractivity Observatory
ERBE	Earth Radiation Budget Experiment
FF-1	Free Flyer-1
GOES-R	Geostationary Operational Environmental Satellite, R-Series
IRMB	Royal Meteorological Institute of Belgium (L'*I*nstitut *r*oyal *m*étéorologique de *B*elgique)
JPSS	Joint Polar Satellite System
LASP	Laboratory for Atmospheric and Space Physics
NASA	National Aeronautics and Space Administration
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NRC	National Research Council
NRL	Naval Research Laboratory
PMOD	Physikalisch-Meteorologisches Observatorium Davos
PREMOS	PREcision MOnitor Sensor
SATIRE-S	Spectral And Total Irradiance REconstruction model - Satellite era
SIM	Spectral Irradiance Monitor
SOHO	SOlar and Heliospheric Observatory satellite
SOLSTICE	SOlar Stellar Irradiance Comparison Experiment
SORCE	SOlar Radiation and Climate Experiment
SSI	Solar Spectral Irradiance
TCTE	TSI Calibration Transfer Experiment
TIM	Total Irradiance Monitor
TRF	TSI Radiometer Facility
TSI	Total Solar Irradiance
TSIS	Total Solar Irradiance Sensor
USGCRP	U.S. Global Change Research Program
VIRGO	Variability of solar IRradiance and Gravity Oscillations

B

NOAA Working Group Report

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION (NOAA)/
NATIONAL ENVIRONMENTAL SATELLITE, DATA, AND INFORMATION SERVICE (NESDIS)/
NATIONAL CLIMATE DATA CENTER (NCDC)
& NOAA JOINT POLAR SATELLITE SYATEM OFFICE (NJO)

Maintaining the Continuation of Long-term Satellite Total Solar Irradiance Observation

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(NOAA Working Group Report)

02/27/2013

Executive Summary

The Sun is the only significant external source of energy to the Earth system. Thus, total solar irradiance (TSI) has a major impact on Earth's average temperature. Furthermore, solar radiation is the dominant, direct energy input into terrestrial ecosystems and, consequently, it affects all physical, chemical, and biological processes – many of which impact human health and well-being. Precise and continuous observation of the total solar output is therefore essential for climate change understanding and attribution. Accurate TSI observation is deemed to be obtained from satellites since atmosphere interference can be avoided from the TSI observation above the top of atmosphere (TOA). There are currently about 35-year continuous TSI spacecraft record acquired from several different satellite missions started from 1978. Although the absolute accuracy of this TSI data record has been limited, measurement overlap will eventually allow us to construct high quality long-term TSI climate data record (CDR) through retrospective inter-satellite calibration from future advanced NOAA and NASA Joint Polar Satellite System (JPSS)/Total and Spectral Solar Irradiance Sensor (TSIS) measurement.

Due to the launch failure of NASA/Glory mission satellite in March of 2011, there will be highly likely a gap of at least one year of TSI data record between the measurement from the NASA/Solar Radiation and Climate Experiment (SORCE) Total Irradiance Monitor (TIM) instrument (launched in 2003) and JPSS free-flyer 1 TIM instrument (to be launched in 2016). The opportunity of extending the SORCE mission until the launch of JPSS free-flyer 1 satellite to fully fill the data gap is also vanishing due to evident battery degradation of the SORCE satellite since its operation time (~ 10 years) has greatly exceeded its design lifetime (5 years). Thus, continuous long-term TSI satellite measurement is in jeopardy and NOAA and NASA have the obligation to explore the gap filling mitigation options in order to maintain the continuity and quality of the long-term TSI measurement.

Two simple mitigation options, spanning the gap via the measurement from extant satellite instruments and spanning the gap via an empirical solar model were first investigated through the Phase-A study funded by NOAA climate data record (CDR) Program. Uncertainties in the TSI data record were estimated in the event of a gap in data between the TIM instrument currently on the SORCE mission and that being built for the upcoming JPSS. Three extant satellite TSI instruments (ACRIM3, VIRGO, PREMOS) and the Naval Research Laboratory (NRL) empirical solar model were considered as possible methods of filling a TIM data gap, and uncertainties were provided as a function of gap duration and TIM overlap observational time. Europe Space Agency's (ESA's) VIRGO was identified to provide the best means of filling a TIM data gap, with the NRL solar model offering limited capability for short duration gaps; but no gap filling method meets the JPSS TSI CDR requirements, since no other instrument or model has demonstrated the stability or low noise required for SORCE or JPSS TIM instrument.

Therefore, other gap filling mitigation options need to be sought to meet the TSI CDR requirements.

The TSI Calibration Transfer Experiment (TCTE) mission was proposed to help filling the data gap after an initial feasibility study. NOAA and NASA (who is the instrument procurement contractor for NOAA) accepted the TCTE propose due to its advantage of filling the measurement gap through direct calibration transfer. Moreover, the mission is cost effective since several major components of the TIM instrument are available from the spare parts of previous or current NASA and NOAA TSI missions. The spacecraft and launch vehicle are also available from the current US Air Force (USAF)/Space Test Program (STP) Satellite-3 (STPSat-3) mission.

The objective of the TCTE mission is to provide a National Institute of Standards and Technology (NIST) traceable (or absolute) calibration link between current SORCE/TIM instrument and future TSIS/TIM instrument and to provide a bridge for the continuation of the 35 year TSI climate data record. NOAA JPSS Office and NASA JPSS Free Flyer Project in collaboration with the Laboratory of Atmospheric and Space Physics (LASP) at the University of Colorado, Boulder and USAF/Ball Aerospace are responsible for implementing the TCTE mission. The LASP is responsible for building and delivering the TIM instrument and the data processing and production. The TCTE/TIM instrument will satisfy an accuracy requirement of better than 350ppm (or 0.035%; SORCE/TIM requirement) and stability of better than 10 ppm/year (or 0.001%; TSIS/TIM requirement). USAF/Ball Aerospace is responsible for integrating the TIM instrument to the STPSat-3 spacecraft, launching the satellite, operating the TIM with the LASP support, and relaying the observational data through its ground system to the LASP for data production. The final TSI data production, archiving, and dissemination will heavily leverage on the data processing, preserving, and distribution systems developed at the LASP and NASA Distributed Active Archive Center (DAAC) at the Goddard Space Flight Center (GSFC) for the SORCE mission to reduce cost.

The STPSat-3/TCTE satellite current planned Launch Readiness Date (LRD) is August 2013 and has a nominal 18-month mission design lifetime. NOAA is discussing with the Air Force operating the STPSat-3/TCTE mission as long as possible, hopefully to March 2017. Three-phase observational cadence will be performed for the gap mitigation: 1) SORCE-to-TCTE overlap calibration transfer phase (about 50 days or two solar rotations), 2) Periodic TSI measurements phase (TCTE observations between SORCE and TSIS), 3) TCTE-to-TSIS overlap calibration transfer phase (about 50 days or two solar rotations). Both comprehensive and minimum mission success criteria have been defined.

In consideration of the TCTE mission and improved data quality from extant satellite TSI instruments, NOAA further funded the Phase-B TSI data gap mitigation study through its CDR program. The best, intermediate, and worst mitigation scenarios have been explored by adding the TCTE in the study. The best scenario is TCTE observation overlaps with both SORCE and TSIS observations, which can maintain the stability of the long-term TSI record on the level of CDR requirements. The worst scenario is TCTE observation doesn't overlap with either SORCE or TSIS observation. As a result, TCTE mission brings no improvement on the gap filling compared to the case without TCTE mission. The intermediate scenario is TCTE observation overlaps only with SORCE observation and the TCTE-to-TSIS gap will be filled by VIRGO measurement. Even though, in this case, the limit of VIRGO gap filling conceals the advantage brought by the TCTE in the gap filling, TCTE observation does prolong the stability of the TSI record until the end of the TCTE mission, which may allow time to implement alternate measurement approaches.

Through the comprehensive gap mitigation studies and planned TCTE mission funded by NOAA with contributed NASA instruments, the impact of the undesirable TIM data gap, due to the failure of Glory launch, battery degradation of SORCE satellite, and the delay of TSIS launch caused by restructuring the JPSS Program from the NPOESS Program, can be minimized. It will greatly benefit the continuation of 35-years satellite TSI observations as well as preserve its climate quality.

1. Background

The exchange of radiant energy between the Sun, Earth, and space is fundamental to our climate. The net Earth radiation budget at the top of atmosphere (TOA) is determined by solar radiation absorbed by Earth and thermal infrared radiation emitted back to space. Energy from the Sun establishes the basic structure of the Earth's surface and atmosphere and defines its external environment. Solar radiation powers the complex and tightly coupled circulation dynamics, chemistry, and interactions among the atmosphere, oceans, ice, and land that maintain the terrestrial environment as humanity's habitat. Natural variability on a wide range of temporal and spatial scales is ubiquitous in the Earth system, and this constant change combines with anthropogenic influences to define the net system state, in the past, present, and future (see **Figure. 1**). For this reason a reliable and continuous record of solar irradiance is essential for climate change understanding and attribution. This is also why a high priority was given to the TOA solar irradiance measurement in the 2007 National Research Council (NRC) Decadal Survey, *Earth Science and Applications from Space*.

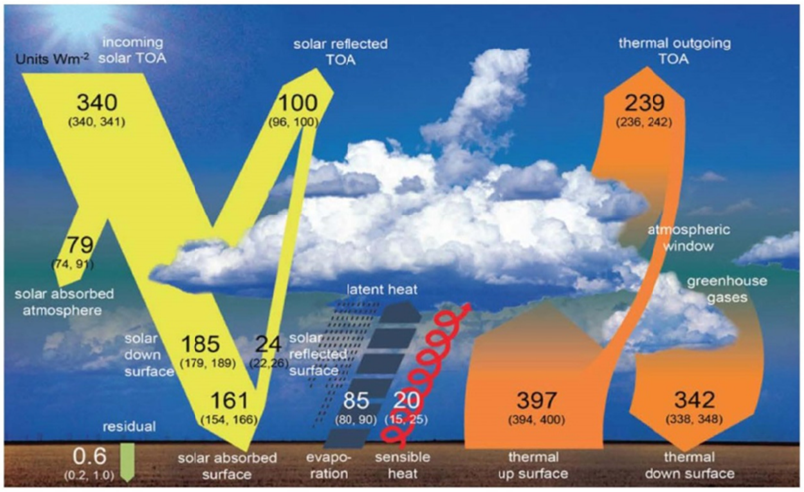

Figure 1. Schematic diagram of the global mean energy balance of the Earth. Numbers indicate best estimates for the magnitudes of the globally averaged energy balance components together with their uncertainty ranges, representing present day climate conditions at the beginning of the twenty first century. Units Wm^{-2}. (after Wild et al., 2012).

Accurate solar irradiance measurement is generally obtained from the top of atmosphere in order to avoid atmospheric interference. Observations of both total solar irradiance (TSI) (the sum over the entire spectrum of the Sun's irradiance at all wavelengths incident at TOA) and spectral solar irradiance (SSI) (the Sun's irradiance incident at TOA for a given wavelength interval) are used to monitor the changes of solar energy arriving the Earth. A solar irradiance monitoring satellite mission generally needs to perform both TSI and SSI measurements with TSI measurement as a minimum requirement. The Total Irradiance Monitor (TIM) instrument is used to measure TSI and the Spectral Irradiance Monitor (SIM) instrument is used to measure SSI. There is currently about 35-years uninterrupted TSI data record available due to the result of several overlapping instruments flown on different space missions (see **Figure 2**). Although the absolute accuracy of this 35-years TSI data record has been limited, continuity of TSI measurements allows successive instruments to be linked to the extant TSI data record and to eventually allow us to construct high quality long-term TSI climate data record (CDR) through retrospective inter-satellite calibration from future advanced TSI instruments.

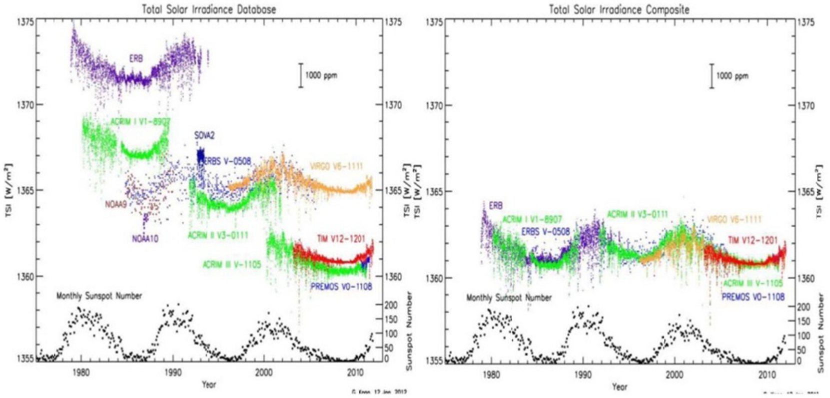

Figure 2. The spaceborne TSI data record has been continuous since 1978 (left plot). Offsets due to calibration differences are adjusted by overlap between successive instruments. The composite record (right plot) relies on measurement continuity and instrument stability (after Kopp and Lean, 2011).

To continue the 35-years TSI measurement constructed from previous space solar missions, NASA planned the Glory mission to carry on its TSI/SSI measurement started in 2003 from its SORCE mission to year 2017. Then, the measurements of TSI/SSI from the Total and Spectral Solar Irradiance Sensor (TSIS) of NOAA and NASA Joint Polar Satellite System (JPSS) free-flyer 1 (FF-1) mission (to be launched on 2016) will extend the continuous data record to 2021, which will be further extended beyond 2032 by TSIS measurement onboard JPSS FF-2, -3, and -4 satellites. Due to the launch failure of Glory satellite by using the Taurus XL rocket in March of 2011, there will likely be a data gap between the SORCE TIM measurement and JPSS

FF-1 TIM measurement. The mitigation opportunity of extending the SORCE mission until the launch of JPSS FF-1 satellite in 2016 to fully fill the data gap is vanishing due to recent fast battery degradation of SORCE satellite since its operation time (~ 10 years) has greatly exceed the design lifetime (5 years). Restructuring of the JPSS program from NPOESS has resulted in the delay of selecting a spacecraft to accommodate TSIS and exacerbated the gap issue. Thus, a TSI data gap of at least one year (see **Figure 3**) is expected so that other gap filling mitigation options have to be explored in order to maintain the continuity and quality of the long-term solar irradiance measurement.

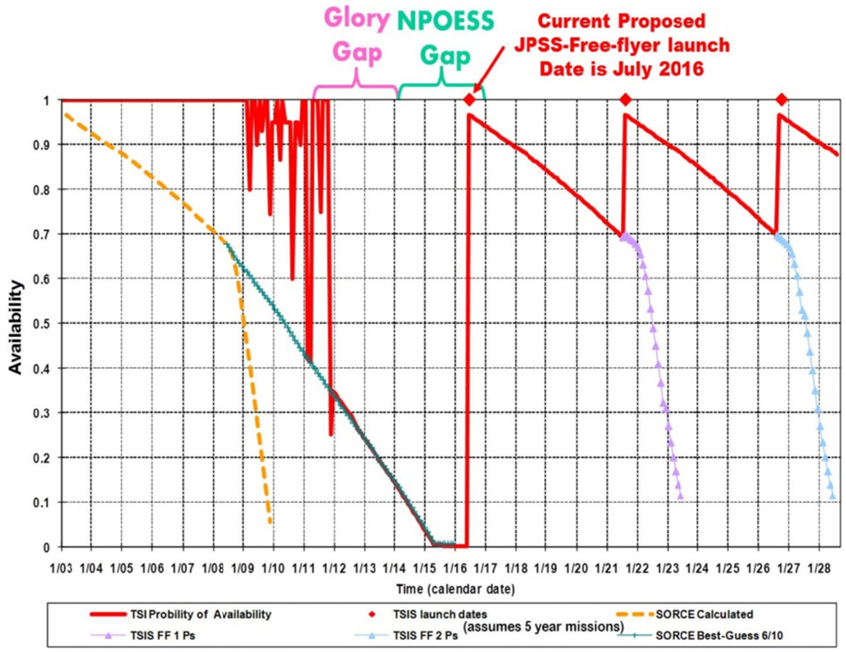

Figure 3. Schematic diagram of TSI data probability of availability.

2. Phase-A Gap Mitigation Study

The current SORCE/TIM measurement has demonstrated superior accuracy, noise, and stability to any other TSI instruments on orbit. The upcoming JPSS/TIM has yet more stringent climate driven accuracy requirements that are not met by any other flight instrument. Overlapping measurement with JPSS/TIM and retrospective inter-satellite calibration will increase previous TSI measurement quality to a level comparable to that to be achieved from JPSS/TIM measurement. As a result, the constructed long-term TSI CDR through composite will meet the CDR accuracy and stability requirements. Since the TSI climate data record currently relies on measurement continuity and instrument stability, a gap in TIM measurement due to the failure of Glory launch and battery degradation of SORCE satellite will jeopardize the continuation of the 35-year TSI data record. Therefore, gap filling mitigation that can meet the TSI CDR requirements has to be explored and implemented.

2.1. TSI Climate Data Record Requirements

The JPSS/TIM measurement requirements are driven by the need to detect any long-term solar variability which is critical for climate studies following the recommendations in the 2006 Achieving Satellite Instrument Calibration for Climate Change (ASIC3) report (Ohring et al., 2007) as well as the NIST publication "Best Practice Guidelines for Pre-Launch Characterization and Calibration of Instruments for Passive Optical Remote Sensing, NISTIR 7637" (Datla et al., 2009). The CDR requirements for JPSS/TIM are summarized in **Table 1**.

Table 1. CDR Requirements for the JPSS/TIM

Parameter	CDR Requirement
Absolute Accuracy	0.01% (100ppm; 0.14Wm^{-2})
Stability (long-term precision)	0.001%/yr (10 ppm/yr; 0.014Wm^{-2}/yr)
Noise (short-term precision)	0.001% (10 ppm; 0.014Wm^{-2})

Note: 1ppm ~ 0.0014Wm^{-2}

Any gap filling approaches should be evaluated to meet the CDR requirements. Based on this guideline, NOAA through its national climatic data center (NCDC)/CDR program funded the Laboratory for Atmospheric and Space Physics (LASP), University of Colorado at Boulder and the Naval Research Laboratory (NRL) to perform a gap mitigation study for TSI CDR, which is named as Phase-A study (see Kopp and Lean, 2011). The mitigation options were investigated through sensitivity studies on gap duration and TIM overlap time by spanning the gap via the measurement from extant satellite instruments or by spanning the gap via NRL empirical solar model. The results of Phase-A study are summarized below.

2.2. Sensitivity Studies on Gap Duration and TIM Overlap Time

Spanning a gap relying on absolute accuracy is limited by the uncertainties of the prior and subsequent instruments. For example, if the SORCE/TIM (with uncertainty of ~360ppm) measurement could be extended to JPSS/TIM era, then it could bridge a gap to ~360 ppm uncertainty independent of the gap duration. Uncertainties from noise and stability for short gap duration are small compared to accuracy limitation. Spanning a gap via either intervening measurements or models relies on the utilized instruments' or models' stabilities, which increase uncertainties with gap duration, and on measurement agreement (limited by noise) with the TIMs prior to and after the gap. Longer overlap durations improve knowledge of both stability and agreement, so gap uncertainties decrease with overlap duration. Examples of these effects are shown in **Figure 4**.

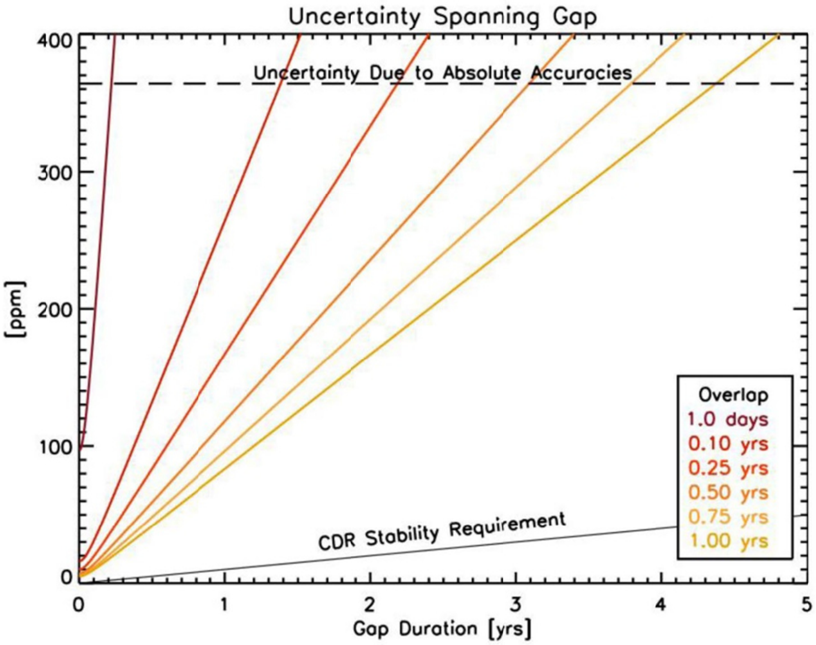

Figure 4. General effects contributing to uncertainties in spanning a TSI data gap. Stability uncertainties increase with gap duration, limiting accuracy; measurement noise limits the uncertainties at short gap durations. Longer overlap durations with prior (SORCE/TIM) and following (JPSS/TIM) instruments improve knowledge of stability and agreement with intervening gap-filling instrument or model, decreasing uncertainties (after Kopp and Lean, 2011).

2.3. Spanning the Gap Using the Measurement of Extant Satellite Instruments

TIM measurement from three extant satellites, ACRIMSat/ACRIM3 (launched in 1999), SoHO/VIRGO (launched in 1996), and PICARD/PREMOS (launched in 2010), were explored by PIs of LASP and NRL to fill the data gap in the phase-A study. In the reality, PREMOS is probably the only instrument that can be used to fill the measurement gap between SORCE/TIM and

TSIS/TIM if its operation could be extended to the TSIS era. However, studies of the dependence of filling uncertainty on instrumental absolute accuracy, noise, stability, and the duration of gap and overlap were performed for all three instruments for the comparison purpose. **Figure 5** provides an example of a TIM data gap filled by ACRIM3. TIM data prior to the gap are shown in red, with a fainter red curve indicating the "true" TSI values (i.e. in the absence of a gap). Another TIM instrument, offset from the first by one standard deviation (~360 ppm) of the absolute accuracies of both instruments, acquires data (shown in blue) after the 1.5 year gap. ACRIM3 data (green) are used to link the TIM data across this gap. Differences in slope between the TIM instruments and the ACRIM3 during the 1 year overlap periods prior to and after the gap are used to estimate and correct for the ACRIM3 drifts relative to the TIMs across the gap, when only the ACRIM3 provides any knowledge of solar variability. These slope corrections and the TIM-to-ACRIM3 offsets before and after the gap link the pre- and post-gap TIMs, correcting the TIM data after the gap downward (dark blue). In the example shown, this correction differs from the "true" TSI by 60 ppm, causing an erroneous drift in the TSI climate data record of 40 ppm/yr.

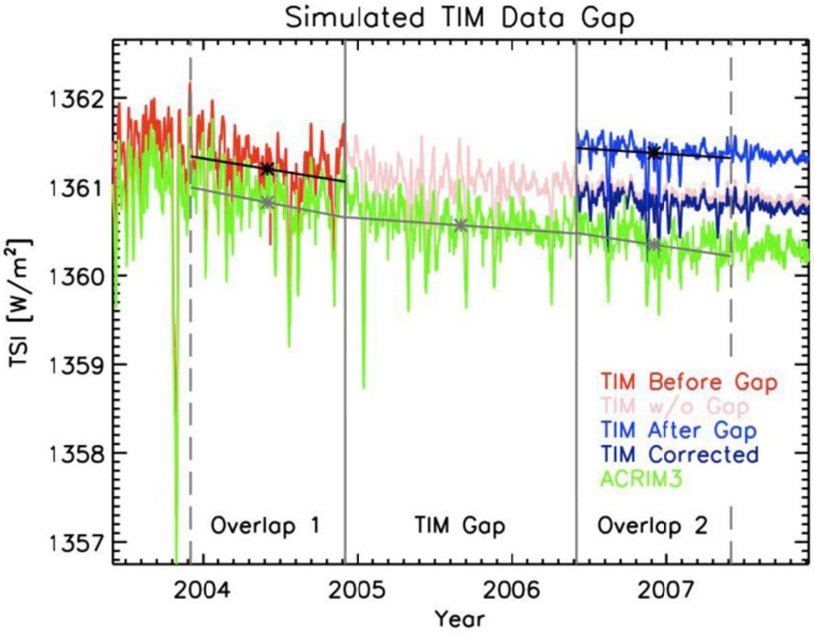

Figure 5. A simulated 1.5 year gap in TIM data filled by ACRIM3 demonstrates the effects of differences in instrument offsets and slopes leading to a 60 ppm error (after Kopp and Lean, 2011).

Actually, TSI variability models can also be constructed for individual extant TSI satellite observations and used for filling the TSI data gap. Since these variability models were developed (through regression) by correlating the TSI satellite observations with solar activity indices (including sunspots darkening and facular brightening) obtained from a variety of ground- and space-based observations of the Sun, the quality of the TSI data generated from these variability models cannot surpass the quality of the corresponding TSI satellite observations. As a result, their gap filling capability can be comparable at most to that of the corresponding satellite observations as indicated in the Phase-A gap mitigation study of Kopp and Lean (2011) so that it will not be further discussed here.

In summary, due to limited absolute accuracy of ACRIM3 (~0.1%) and VIRGO (~0.4%) and extremely high degradation of PREMOS, the phase-A study indicates *none of these instruments (and their variability models) can presently fill a potential TIM measurement gap while achieving the CDR stability requirement listed in* ***Table 1***.

2.4. Spanning the Gap Using Empirical Solar Models

Proxy-based solar models can estimate TSI in the absence of actual TSI measurements. Such models can then be used to span a TIM data gap. Empirical models utilize information about the primary solar sources of solar irradiance variability to calculate the relative changes that occur when these features are present on the Sun's disk. The Naval Research Laboratory TSI model, created by Dr. Judith Lean, is constructed from two time series, the sunspot blacking function and the facular brightening function. The model does not allow for long-term changes in the base level of the quiet Sun, but they can track solar variability on the short-term time scales to span a TIM data gap. Uncertainties introduced into the TSI climate data record by the NRL solar model were estimated as a function of gap duration and TIM overlap time.

For a gap of one year the values of the best-case TSI model for the subsequent 365-day averages differ from the "true" TSI (i.e. as measured directly by the TIM) by almost 0.05 Wm^{-2} (37 ppm), so using the NRL TSI model to span a TIM measurement gap introduces a 37ppm/yr drift uncertainty to the record. For the worst case scenario, the added imprecision can be up to 88 ppm/yr. Further improving empirical model by combing both space and surface measurements was also examined and the conclusion is that *proxy models may achieve comparable gap filling capabilities to the alternate extant TSI instruments for the best-case scenario but cannot achieve the CDR stability requirement listed in* ***Table 1.***

2.5. Conclusions from the Phase-A Gap Mitigation Study

The ACRIM3, VIRGO, PREMOS (including their variability models), and the NRL empirical solar model were evaluated for noise and stability and for their resulting capabilities in filling a potential gap in TIM measurements between the SORCE and JPSS missions. Uncertainties introduced into the TSI climate data record were estimated as a function of gap duration and TIM overlap time for each, which are summarized in **Table 2** for 1.5 year TIM data gap with 1 year overlap durations. The VIRGO provides the best method for filling a TIM data gap due to its stability and relatively low noise, both critical for spanning a TIM data gap. Nevertheless, a gap analysis with this instrument indicates the JPSS CDR stability requirement would be exceeded by 350%. Solar models are the next best option for spanning a gap of short duration, with ACRIM3 and PREMOS providing the least gap filling capability due to their higher noise and/or lower stabilities. *No instrument or model achieves the JPSS TSI CDR requirements in the undesirable event of a TIM data gap. Other gap filling mitigation options need to be sought to meet the TSI CDR requirements.*

Table 2. Errors from 1.5 year TIM data gap with 1 year overlap durations.

Instrument	ACRIM3	VIRGO	PREMOS	NRL Model
Error (ppm)	123	53	152	81

3. TCTE Mission

Following the above gap mitigation study, the LASP (who is the TIM and SIM instruments developer for the SORCE, Glory, and TSIS) proposed the concept of Total Solar Irradiance (TSI) Calibration Transfer Experiment (TCTE) to the NOAA/NASA JPSS Office for extending the TSI data record from SORCE to TSIS and mitigating the TSI data gap. The basic concept is to fly a SORCE/TIM-like instrument on the US Air Force (USAF) Space Test Program (STP) Satellite 3 (STPSat-3) which is already underway and planned August 2013 launch. The objective of the mission is to provide a National Institute of Standards and Technology (NIST) traceable (or absolute) calibration link between current SORCE/TIM instrument and future TSIS/TIM instrument and to provide a bridge for the continuation of the 35 year TSI climate data record.

The initial feasibility study performed by the SORCE science team found out that the TCTE/TIM instrument payload can be quickly built in cost effective by using some spare or extant parts. For examples, a spare ground-based SORCE/TIM witness sensor is available from the LASP, which was originally developed alongside the SORCE/TIM flight unit and has been used for inter-comparisons at NIST and at the 2010 International Pyrheliometer Comparison (IPC-XI); TSIS/TIM instrument Generic Channel Interface (GCI) flight electronics are also available; a spare Fine Sun Sensor (FSS) that was residual after completion of the Glory TIM instrument delivery can also be used. Ball Aerospace who is responsible for the integration and launch of STPSat-3 satellite confirmed TCTE compatibility and the launch manifest opportunity for STPSat-3 mission was also approved by USAF.

NOAA together with NASA (served as the instrument procurement contractor for NOAA) accepted the TCTE proposal for the TIM calibration transfer and TSI data gap filling mitigation in consideration of its merits compared to the other mitigation options discussed in the above Section 2. The TCTE mission is being implemented through the NOAA/NASA JPSS Program in collaboration with LASP, USAF, and Ball Aerospace. An overview of the TCTE mission is provided below.

3.1. TCTE/TIM Instrument

The LASP is responsible for building and delivering the TCTE/TIM instrument, which is shown schematically in **Figure 6**. The JPSS/Free-Flyer Project will provide a mass model of TCTE and any required technical support. The TCTE/TIM instrument will satisfy an accuracy requirement of better than 350ppm (0.035%; SORCE/TIM requirement) and stability of better than 10 ppm/year (0.001%; TSIS/TIM requirement) in order to transfer TSI data record from SORCE to TSIS. The instrument has been delivered on September 2012 in order to meet the STPSat-3 launch schedule.

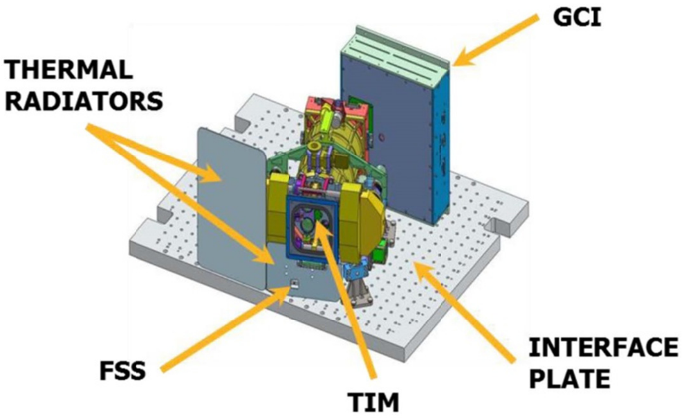

Figure 6. Schematic diagram of TCTE instrument.

3.2. Satellite Launch, Flight Configuration, and Observing Sequence

Ball Aerospace as the contractor of USAF STPSat-3 mission is responsible for the integration of spacecraft and the lunch of the STPSat-3 satellite. The satellite is scheduled being launched on August 3, 2013 from Wallops Flight Facility, VA using Minotaur-1 rocket. The target orbit altitude is ~500 km with an inclination angle of 40.5^{o} (or 48.2^{o}). The normal mission operational time is 12 months with an 18-months goal after one month commissioning period. A Memorandum of Agreement (MOA, 2012 April) has been developed between NASA and USAF for the integration, launch, and flight of TCTE on P10-1 (STPSat-3) satellite. **Figure 7** shows the flight configuration of the satellite. Solar-viewing TCTE instrument shares observational time with other four original STPSat-3 Earth-viewing instruments. Spacecraft is oriented and solar panel is rotated to track the sun so that TIM can point to the sun for ≥ 40 minutes for each measurement while the other 4 instruments will stay as non-producing mode during the solar viewing. TCTE science observation requires every solar observation being bracketed by periods of dark sky measurements for on-board calibration. Dark sky measurement is defined as no Sun or Earth limb within ±20° of TIM boresight (moon intrusion is permitted). Thus, the observing sequence includes pre-solar dark sky measurement (at least 20 minutes), solar observation (at least 40 minutes), and post-dark sky measurements (at least 40 minutes). Dark sky–Sun or Sun–dark sky pointing transition will be achieved in 100 seconds to guarantee the best observation results.

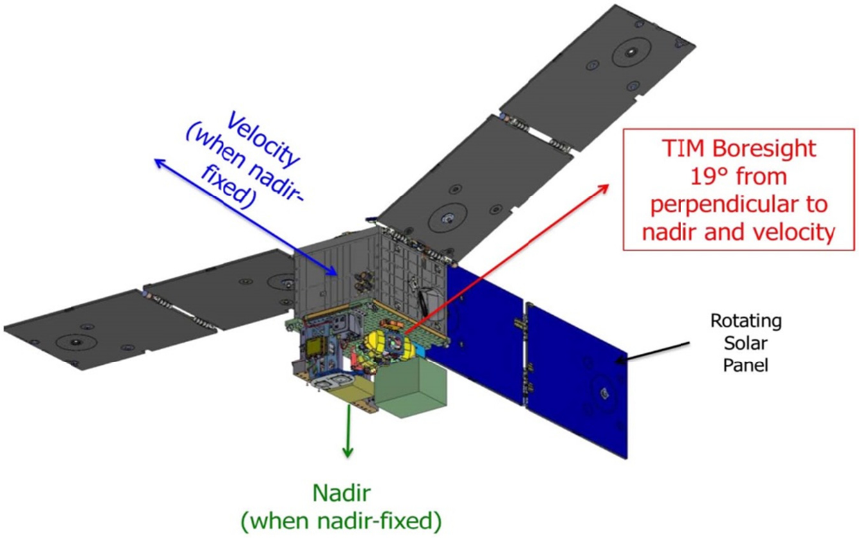

Figure 7. STPSat-3 flight configuration.

3.3. TCTE Success Criteria

Since TCTE mission is not intended to directly achieve the measurement requirements of **Table 1**, but to reduce the severity of a long-duration measurement gap between the SORCE and TSIS TIMs. So specific TCTE mission success criteria have been defined and are described below.

3.3.1. Comprehensive Success Criteria

Comprehensive success requires an overlap of 6 months with both SORCE and TSIS. During the overlap periods a measurement should be acquired at least every 2 days while weekly measurements should be acquired during the intervening period without overlap. The TCTE must meet its stability requirement of 10 ppm/yr and its accuracy requirement of 350 ppm. The stability requirement helps to maintain the TSI record from SORCE forward with needed long-term solar trend detection capability, while the accuracy requirement reduces the offsets between the SORCE and TSIS TIMS should overlap not be achieved.

3.3.2. Minimum Success Criteria

Two scenarios need to be considered for minimum success. The first scenario is assuming only overlap with SORCE is achieved. Then, minimum success criterion is two months of overlap with one measurement every 2 days while weekly measurements should be acquired for at least 1-year intervening period. In this way, the data record acquired is sufficient to improve the filling data record provided by other methods discussed in the above Section 2. The second scenario is no overlap with SORCE. Then, the minimum success criterion is 3-years duration of one measurement per day. This will provide a gap filling on either side of TCTE with an uncertainty lower than any other gap filling mitigation methods discussed in Section 2. In both scenarios, the TCTE must meet its stability requirement of 10 ppm/yr.

3.4. 3-Phases Observational Cadence

To meet the objective of TIM calibration transfer and TSI data gap filling mitigation, the following 3-phases observational cadence will be performed. Both threshold and objective time sampling criteria are defined so that a successful gap mitigation mission can be achieved at least on the threshold level.

1) SORCE-to-TCTE overlap calibration transfer phase: Overlap observations need to span at least two solar rotations (~50 days). Measurement of once per day is the objective and once of every other day is the threshold.

2) Periodic TSI measurements phase: TCTE observations between SORCE and TSIS. Measurement of once per day is the objective and once of every week is the threshold.

3) TCTE-to-TSIS overlap calibration transfer phase: Overlap observations need to span at least two solar rotations (~50 days). Measurement of once per day is the objective and once of every other day is the threshold.

3.5. Data Processing, Archive, and Dissemination

The raw data record (RDR) (or Level-0 data) from the TCTE/TIM observation will be transferred to the LASP through the USAF STPSat-3 ground system to producing sensor data record (SDR) (or Level-1 data), Climate Data Record (CDR) (or Level-2), and daily averaged CDR (or level-3 data). Only level-3 data will be released to public for the comparison to other TSI instruments and models. Lower level data are not intended for broad dissemination. This is because, due to anticipated temperature excursions and limited observing time, interpretation of lower level data requires instrument insight and will be improved with ongoing on-orbit calibration measurements (i.e. darks) throughout the mission. Security is another reason since STPSat-3 is a classified mission (see Section 3.6). To reduce the mission cost, TCTE data production, preservation, and dissemination will heavily leverage on the data processing, archiving, and distribution systems developed at the LASP and NASA Distributed Active Archive Center (DAAC) at the Goddard Space Flight Center (GSFC) from the SORCE mission.

3.6. Limits and Risk

One limit of the TCTE observation is caused by the time sharing measurements with the other four Earth-viewing instruments. Measurements of the four original STPSat-3 instruments have a high priority so that TCTE measurement time and sampling numbers will be greatly reduced comparing to normal TIM measurement of SORCE or TSIS. This precludes the low noise measurements needed to fully meet the CDR requirements (see **Table 1**). Thus, the TCTE mission is defined as a TSI calibration transfer mission rather than a standard TSI observation mission. More calibration/validation (cal/val) efforts and quality control procedures need to be involved in TCTE data processing compared to that of SORCE and TSIS. Both comprehensive and minimum mission success criteria are defined so that a successful gap mitigation mission can be achieved at least on the minimum success level.

Another limitation is related to the data transfer from classified STPSat-3 system to the civil LASP data production and distribution systems. All telemetered data from the STPSat-3 spacecraft are initially classified. USAF currently lacks any means of declassifying the TCTE data in a timely fashion. While intended for public release eventually, these data will likely remain classified until well after launch, precluding broad community assessments of the data quality and approval of operations scenarios initially. The TCTE TIM science and operation teams are acquiring security clearances to assess instrument state of health and acquisition of intended data for the planned initial mode of operation. How to transfer the data from STPSat-3 system to LASP data production and distribution systems after initial model of operation still needs to be worked out between NOAA/NASA JPSS Office and USAF STP program.

Since STPSat-3 mission was designed for 12 months with an 18-month goal limited by spacecraft bus, it poses a risk that the TCTE may not be able to overlap with the TSIS/TIM planned for launch no earlier than mid-2016. Thus, TCTE can postpone a pre-TSIS TSI measurement gap but highly likely cannot prevent this gap completely. Thus, new gap filling mitigation by combing the TCTE with extant TSI measurements or solar models should be explored, which is the task of phase-B gap mitigation study to be presented below in Section 4. This is another reason that both comprehensive and minimum mission success criteria were defined for the TCTE (see Section 3.3) so that success of the TCTE mission can be achieved at least on the minimum success level.

4. Phase-B Gap Mitigation Study

Phase-A gap mitigation study introduced in the above Section 2 was performed prior to planning for the TCTE mission. The calibration of PICARD/PREMOS launched in June 2010 has also been gradually improved after its launch and has achieved good agreement with the absolute calibration value of the SORCE/TIM. However, the PICARD is intended to be decommissioned in January 2013 so that it will likely not provide continued TSI measurements beyond those of the SORCE. The ACRIM3 data processing has also been updated to correct a previous thermal artifact causing high noise. In consideration of these new scenarios, NOAA believed it is necessary to perform a new round of (named Phase-B) gap mitigation study by including these new scenarios. NOAA/NCDC CDR program funded the same PIs of Phase-A study at the LASP and NRL to further carry out the Phase-B tasks. They repeated the previous gap mitigation studies in a more completed way by including the TCTE mission and improved data of extant instruments and adding a new San Fernando Observatory (SFO) empirical solar model.

First, the Phase-B study (Kopp and Lean, 2013) carefully evaluated the performance of the TSI instruments and solar models used in the study by using up-to-date information and the results are summarized in **Table 3** (or **Table 5** of Kopp and Lean, 2013).

Table 3. Instrument and Model Performance Estimates.

Instrument/Model	Accuracy (ppm)	Stability (ppm/yr)	Noise (ppm)
ACRIMSat/ACRIM3	1000	71	34
SoHO/VIRGO	2500	29	28
PICARD/PREMOS	300	79	<52
SORCE/TIM	350	10	4

TCTE/TIM	350	10	50*
TSIS/TIM	100	10	10
NRL Model	N/A	48	38
SFO Model	N/A	88	19

*This is effective noise which is much larger than the instrument noise (< 10 ppm) due to sparse orbital sampling of TCTE mission at the times of high solar activity (see Section 3.6).

Then, in-depth studies were performed for a variety of gap mitigation scenarios by combing the instruments and models listed in **Table 3**. The major results are summarized below.

4.1. SORCE-to-TSIS Gap without TCTE

This is the baseline scenario which had been studied in the Phase-A. The conclusion from the Phase-A study is still valid: The VIRGO provides the best method for filling a TIM data gap due to its stability and relatively low noise. The net uncertainty induced in the TSI record over the 4-year period between the present (early 2013) and the TSIS launch (end of 2016) is 97 ppm (24 ppm/yr), mainly due to the 3-year TIM measurement gap from late 2013 to late 2016 spanned by VIRGO having 1-year overlaps with both SORCE and TSIS; Solar models are the next best option for spanning the gap, which may induce a net uncertainty of 154 ppm; ACRIM3 and PREMOS provide the least gap filling capability due to their higher noise and/or lower stabilities. *No instrument or model achieves the JPSS TSI CDR requirements in the undesirable event of a TIM data gap.*

4.2. No TCTE Overlaps with Either SORCE or TSIS

If SORCE/TIM were fail imminently and STPSat-3/TCTE achieves its 1-year measurement requirement, there will be a 6-month gap between the SORCE and TCTE TIMs followed by 1-year stable TCTE measurements and then a 2.5-year gap between TCTE and TSIS TIMs. In this case, VIRGO measurement again provides the best gap filling result, assuming it remains operational to provide 1 year of overlap after the TSIS launch. The weekly TCTE observing cadence slightly increases the noise connecting the TCTE record to that of VIRGO. Spanning both the SORCE-to-TCTE and the TCTE-to-TSIS gaps with VIRGO induces a net uncertainty to the TSI record of 98 ppm (24 ppm/yr), with 15 ppm attributable to the SORCE-to-TCTE gap, 10 ppm to the TCTE stability during one year of operation, and 73 ppm to the 2.5-year TCTE-to-TSIS gap. Thus, *the TCTE brings no improvement on the gap filling compared to the above baseline (no TCTE mission) case.*

4.3. TCTE Overlaps with SORCE only

If SORCE lasts to provide a minimum of 2 months of overlap with TCTE, during which time TCTE acquires its minimum of one orbit of measurements every two days, the continuity of the TSI record in the near future can be greatly improved. This is because the SORCE/TIM's low measurement noise allows nearly cotemporaneous high cadence data comparisons between SORCE and the TCTE's orbital measurements so that offset uncertainties due to the TCTE's subsampling of solar variability can be reduced and the connection of the two data records can be improved. If VIRGO measurement is still chosen to fill the TCTE-to-TSIS gap of 2.5 years, the net uncertainty induced in the TSI record is 88 ppm (22 ppm/yr), with 5 ppm from the 6-month SORCE-to-TCTE period, 10 ppm for the TCTE's 1-year duration of measurements, and 73 ppm for the 2.5-year TCTE-to-TSIS gap. Similar to the case of Section 4.2, TCTE-to-TSIS gap filled by VIRGO measurement limits the gap filling capability for the current case. However, *TCTE measurement does prolong the stability of the TSI record until the end of the TCTE mission, which may allow time to implement alternate measurement approaches.*

4.4. TCTE Overlaps with Both SORCE and TSIS

If SORCE can last to provide 2-months overlap with the TCTE and the TCTE can last 4 years (despite the 18-months lifetime designing goal of STPSat-3 satellite) to provide 2-months overlap with the subsequent TSIS/TIM, expected uncertainties induced in the TSI record over these four years from the three stable and overlapping instruments are 40 ppm (10 ppm/yr), with 5 ppm from the 6-month SORCE-to-TCTE period, and 35 ppm for the following continuous TCTE operations. *For this most ideal scenario, the stability of the TSI record can be maintained on the level of CDR requirement.*

5. Summary

In order to find a better solution for filling the TSI measurement gap created from the failure of Glory mission between SORCE and TSIS missions and maintain the continuity of long-term TSI CDR, NOAA through its JPSS and CDR programs funded the LASP of University of Colorado at Boulder and the NRL to study possible gap filling mitigation options in the two phases (A and B). In phase-A, two simple mitigation options, spanning the gap via the measurement from extant satellite instruments and spanning the gap via NRL empirical solar model were first investigated through the studies on gap duration, TIM measurement overlap time, and meeting the CDR requirements. The results indicate these simple gap filling options cannot achieve the JPSS TSI CDR requirements in the undesirable event of a TIM data gap.

Then, TSI Calibration Transfer Experiment (TCTE) mission was proposed to help filling the data gap after an initial feasibility study. NOAA and NASA (who is the instrument procurement contractor for NOAA) accepted the TCTE propose due to its advantage on filling the TSI measurement gap and maintaining the continuation of long-term TSI CDR. Moreover, the mission is cost effective due to the usage of spare instrument parts from previous or current NASA and NOAA TSI missions. The spacecraft and launch vehicle are also available from the current USAF STPSat-3 mission.

The objective of the TCTE mission is to provide an absolute calibration link between current SORCE/TIM instrument and future TSIS/TIM instrument and to provide a bridge for the continuation of the 35 year TSI climate data record. NOAA JPSS Program and NASA JPSS Free Flyer Project in collaboration with the LASP and USAF/Ball Aerospace are responsible for implementing the TCTE mission. The LASP is responsible for building and delivering the TIM instrument and the data processing and production. The TCTE/TIM instrument will satisfy an accuracy requirement of better than 350ppm (or 0.035%; SORCE/TIM requirement) and stability of better than 10 ppm/year (or 0.001%; TSIS/TIM requirement). USAF/Ball Aerospace is responsible for integrating the TIM instrument to the STPSat-3 spacecraft, launching the satellite, operating the TIM with the LASP support, and relaying the observational data through its ground system to the LASP data production system. The final data production, archiving, and dissemination will heavily leverage on the data processing, preserving, and distribution systems developed at the LASP and NASA/GSFC DAAC for the NASA/SORCE mission to reduce cost.

The STPSat-3/TCTE satellite current planned Launch Readiness Date (LRD) is August 2013 and has a nominal 18-month mission design lifetime. NOAA is discussing with the Air Force operating the STPSat-3/TCTE mission as long as possible, hopefully to March 2017. Three-phase observational cadence will be performed for the gap mitigation: 1) SORCE-to-TCTE overlap calibration transfer phase (about 50 days or two solar rotates), 2) Periodic TSI measurements phase (TCTE observations between SORCE and TSIS), 3) TCTE-to-TSIS overlap calibration transfer phase (about 50 days or two solar rotates). Both comprehensive and minimum mission success criteria have been defined.

In consideration of the TCTE mission and improved data quality from extant satellite TSI instruments, NOAA further funded the Phase-B TSI data gap mitigation study. The best, intermediate, and worst mitigation scenarios have been explored by adding TCTE in the study. The best scenario is SORCE measurement can last to provide 2-months overlap with the TCTE measurement and the TCTE measurement can last 4 years to provide 2-months overlap with the subsequent TSIS/TIM measurement. Then, the stability of the long-term TSI record can be maintained on the level of CDR requirements. The worst scenario is TCTE measurement doesn't overlap with either SORCE or TSIS measurement, as a result, TCTE measurement brings no improvement on the gap filling compared to the case without the TCTE mission, which had been studied in Phase-A. The intermediate scenario is TCTE measurement overlaps only with SORCE measurement and TCTE-to-TSIS gap will be filled by VIRGO measurement. Even though, in this case, the limit of VIRGO gap filling conceals the advantage brought by the TCTE in gap filling, the TCTE does prolong the stability of the TSI record until the end of the TCTE mission, which may allow time to implement alternate measurement approaches.

Through above comprehensive gap mitigation studies and planned TCTE mission, NOAA and NASA will be able to minimize the impact of the undesirable TIM data gap due to the failure of Glory launch, battery degradation of SORCE satellite, and the delay of TSIS launch caused by restructuring the JPSS program from the NPOESS. It will greatly benefit the continuation of 35-years satellite TSI observations as well as preserve its climate quality.

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7. Acronyms

ACRIM3:	Active Cavity Radiometer Irradiance Monitor 3
ACRIMSat:	Active Cavity Radiometer Irradiance Monitor Satellite
ASIC3:	Achieving Satellite Instrument Calibration for Climate Change
CDR:	Climate Data Record
DAAC:	Distributed Active Archive Center
DoD:	Department of Defense
ESA:	European Space Agency
FF:	Free Flyer
FSS:	Fine Sun Sensor
GCI:	Generic Channel Interface
GSFC:	Goddard Space Flight Center
IPC:	International Pyrheliometer Comparison
JPSS:	Joint Polar Satellite System
LASP:	Laboratory of Atmospheric and Space Physics
LRD:	Launch Readiness Date

MOA:	Memorandum of Agreement
NAS:	National Academy of Science
NASA:	National Aeronautics and Space Administration
NCDC:	National Climate Data Center
NESDIS:	National Environmental Satellite, Data, and Information Service
NIST:	National Institute of Standards and Technology
NISTIR:	NIST Interagency Report
NJO:	NOAA JPSS Office
NOAA:	National Oceanic and Atmospheric Administration
NPOESS:	National Polar-orbiting Operational Environmental Satellite System
NPP:	NPOESS Preparatory Project
NRC:	National Research Council
NRL:	Naval Research Laboratory
PI:	Principal Investigator
PICARD:	Last name of the 17th century French astronomer Jean Picard
PREMOS:	PREcision MOnitor Sensor
RDR:	Raw Data Record
SDR:	Sensor Data Record
SFO:	San Fernando Observatory
SIM:	Spectral Irradiance Monitor
SoHO:	Solar and Heliospheric Observatory
SDTD:	Space Development and Test Directorate
SORCE:	Solar Radiation and Climate Experiment
SMSC:	Space and Missile Systems Center

SSI:	spectral solar irradiance
STP:	Space Test Program
STPSat-3:	STP Satellite 3
TCTE:	TSI Calibration Transfer Experiment
TIM:	Total Irradiance Monitor
TOA:	Top of Atmosphere
TSI:	Total Solar Irradiance
TSIS:	Total and Spectral Solar Irradiance Sensor
USAF:	US Air Force
VIRGO:	Virtual Geosatellite

8. NOAA Working Group

Drs. Xuepeng (Tom) Zhao and Jeff Privette (NESDIS/NCDC)

Drs. Mitch Goldberg and Stephen Walters (NOAA/JPSS)

9. External Review Panel

An *ad-hoc* external review committee will be organized by the National Research Council (NRC) of National Academy of Science (NAS).

C
Background Papers

Uncertainties Spanning Potential SORCE/TIM to JPSS/TIM Gap

Greg Kopp & Judith Lean

Sept. 2011

EXECUTIVE SUMMARY OF A TIM DATA GAP

Uncertainties in the TSI climate data record are estimated in the event of a gap in data between the TIM instrument currently on the SORCE mission and that being built for the upcoming JPSS. ACRIM3, VIRGO, PREMOS, and solar models are considered as possible methods of filling a TIM data gap, and uncertainties are provided as a function of gap duration and TIM overlap time for each. ESA's VIRGO currently provides the best means of filling a TIM data gap, with solar models offering limited capability for short duration gaps; but no gap filling method meets the JPSS TSI climate data record requirements, since no other instrument or model has demonstrated the stability or low noise of the TIM instrument.

1. STATEMENT OF PROBLEM

The 33 year long spacecraft record of total solar irradiance (TSI) has been acquired by several different instruments. Although absolute accuracy has been limited, measurement overlap enables the construction of TSI composites, such as that shown in Figure 1, that provide knowledge of the energy driving the Earth's climate system and a needed input for climate models.

The current SORCE/TIM has demonstrated superior accuracy, noise, and stability to any other TSI instrument on orbit. The upcoming JPSS/TIM has yet more stringent climate-driven accuracy requirements that are not met by any other flight instrument. Since the solar climate data record (CDR) currently relies on measurement continuity and instrument stability, a gap in TIM measurements will degrade the 33 year data record.

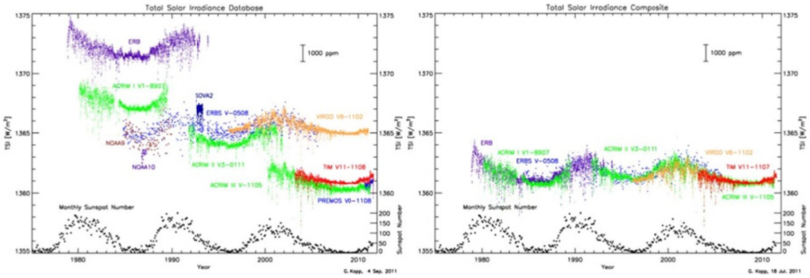

Figure 1: The spaceborne TSI data record has been continuous since 1978 (left plot). Offsets due to calibration differences are adjusted by overlap between successive instruments. The composite record (right plot) relies on measurement continuity and instrument stability.

In the undesirable event of a gap in measurements between the SORCE and JPSS TIM instruments, how well can other extant flight instruments measure or solar models estimate solar variability? What uncertainties will be induced in the 33-year TSI climate data record by such a gap?

2. APPROACH

1. Via comparisons to co-temporal TIM observations, estimate uncertainties in TSI measurement accuracy, stability, and noise from extant spaceborne radiometers, particularly ACRIM3, VIRGO, and PREMOS.
2. Use resulting TSI measurement uncertainties to estimate uncertainties in knowledge of solar variability as a function of TIM measurement gap duration, accounting for observed inter-instrument drifts (if constant).
3. Consider fits to TSI data via empirical solar proxy models, in particular sunspot- and faculae-based models and photometric indices from ground observations, and estimate uncertainties in spanning a TIM measurement gap via such models.
4. Simulate a gap in SORCE/TIM data and fill with data from other instruments or proxy-based models, estimating uncertainties in filled data.
5. Compare uncertainties in filled data with JPSS TSI CDR requirements and with uncertainties from purely relying the absolute accuracies of the SORCE and JPSS TIMs.
6. Deliver report describing potential instrument and model comparisons with associated uncertainty assessments.

3. CLIMATE DATA RECORD REQUIREMENTS

The JPSS/TIM climate data record (CDR) requirements are driven by the need to detect possible long-term solar variability critical for climate studies, and are summarized in Table 1.

Table 1: CDR Requirements for the JPSS/TIM

Parameter	CDR Requirement
Absolute Accuracy	0.01% (100 ppm)
Stability	0.001%/yr (10 ppm/yr)
Noise	0.001% (10 ppm)

4. EFFECTS CONTRIBUTING TO GAP UNCERTAINTIES

The effects contributing uncertainties in filling a gap in TIM measurements, similar for both instruments and models used to fill that gap, are:

1. **Absolute Accuracy:** Absolute accuracy allows measurements against an SI scale. Sufficient accuracy enables long-term solar trend detections without reliance on measurement continuity. Uncertainties filling a gap via absolute accuracy are independent of gap duration. While the JPSS/TIM promises improved accuracy over prior TSI instruments, existing instruments – the SORCE/TIM being the best at a low 350 ppm uncertainty – are more limited. Solar models cannot indicate absolute accuracy.
2. **Stability (Long-Term Precision):** Relative changes, or drifts, between instruments or models limit gap filling. If constant, such drifts may be estimated during times of instrument measurement overlap, so can be removed to the accuracy with which they are known. Uncertainties filling a gap increase with stability uncertainties and gap duration.
3. **Noise (Short-Term Precision):** Gap filling relies on overlap with measurements or models prior to and after the gap. Noise, or short-term variances, between the TIM and comparison instruments or models will limit the accuracy to which the SORCE/TIM and the JPSS/TIM can be connected. Noise effects are reduced statistically with longer overlap periods.

Spanning a gap relying on absolute accuracy is limited by the uncertainties of the prior and subsequent instruments; in this case, the SORCE/TIM and the JPSS/TIM, which could bridge a gap to ~360 ppm uncertainty independent of the gap duration. Uncertainties from noise and stability for a short gap duration are small compared to accuracy limitations. Spanning a gap via either intervening measurements or models relies on the utilized instruments' or models' stabilities (unaccounted for drifts), which increase uncertainties with gap duration, and on measurement agreement (limited by noise) with the TIMs prior to and after the gap. Longer overlap durations improve knowledge of both stability and agreement, so gap uncertainties decrease with overlap duration. Examples of these effects are shown in Figure 2.

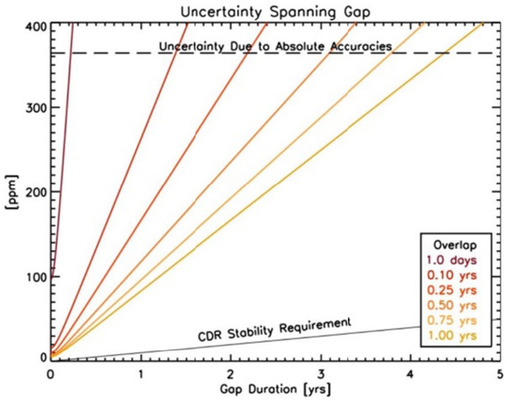

Figure 2: General effects contributing to uncertainties in spanning a TSI data gap. Stability uncertainties increase with gap duration, limiting accuracy; measurement noise limits the uncertainties at short gap durations. Longer overlap durations with prior (SORCE/TIM) and following (JPSS/TIM) instruments improve knowledge of stability of and agreement with intervening gap-filling instrument or model, decreasing uncertainties.

5. SPANNING A GAP VIA INSTRUMENTS: ACRIM3, VIRGO, PREMOS

The **ACRIMSat/ACRIM3** was launched in 1999. Recent comparisons of a ground-based model to the TSI Radiometer Facility (TRF) have improved the on-orbit ACRIM3 absolute accuracy significantly, reducing its uncertainty from a heretofore unrecognized ~0.4% to perhaps an optimistic 0.1%.[1] This accuracy is not sufficient to achieve the JPSS CDR requirements, so reliance on ACRIM3 will depend on this instrument's stability during a gap and its noise during periods of overlap with the SORCE/TIM and JPSS/TIM.

The **SoHO/VIRGO** was launched in 1996. Tests of a ground-based unit have demonstrated high scatter that has not been corrected and some uncertainty in power measurement accuracy, limiting the VIRGO's absolute accuracy to ~0.4%.[2] This instrument utilizes TIM measurements to some degree for correcting long-term degradation, so its stability may be degraded during a TIM gap.

The **PICARD/PREMOS** was launched in June 2010, so is the youngest TSI instrument on orbit and thus may overlap with both the SORCE and JPSS TIMs. This instrument is the most thoroughly characterized of those on-orbit, but is showing extremely high degradation that limits its stability critical for spanning a TIM gap. Data have recently been made available for this study and are preliminary – future degradation corrections are hoped to improve these data.

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[1] Updated uncertainties have not yet been reported by ACRIM instrument team.

[2] Author assessment based on recent laboratory findings.

The instrument data records and models utilized for this report are listed in Table 2. The instrument daily TSI time series are shown in Figure 3.

Table 2: TSI Data Records Studied

Instrument/Model	Data Set & Version	Time Range
SORCE/TIM	V.11	25 Feb. 2003 - 22 Aug. 2011
ACRIMSat/ACRIM3	acrim3_sdc_ts_1104	5 Apr. 2000 - 2 May 2011
SoHO/VIRGO	virgo_tsi_d_v6_002_1102	7 Feb. 1996 - 2 Feb. 2011
PICARD/PREMOS	preliminary (for study)	27 July 2010 - 17 Aug. 2011
NRL Model	tis_mod_mr2_11Mar11	6 Nov. 1978 - 26 Dec. 2010
SFO Model	sfo_Sigmas_F10_Mg	9 May 1988 - 31 May 2011

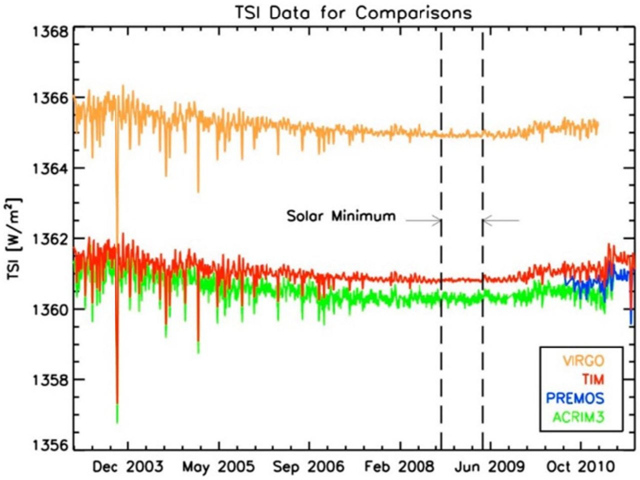

Figure 3: Time series of TSI data from TIM, ACRIM3, VIRGO, and PREMOS where instruments overlap. These are the data used for this analysis.

5.1. Instrumental Noise

The noise in the ACRIM and VIRGO measurements is estimated during solar minimum, shown in the expanded time scale of Figure 4. The reported standard deviations of the TSI values for each instrument, being the quadrature sum of the instrumental noise and the actual solar variability, are listed in this figure. For the TIM, independent calibration measurements give 4 ppm as the noise, implying that the solar activity during this plotted time range accounts for nearly all of the TIM's reported 17 ppm variability. The larger variations in the ACRIM and VIRGO data during this time period indicate they are limited by instrumental noise rather than solar variability, with estimates of their noise given in Table 4. The noise from two

TSI models, discussed later, is computed similarly over this solar minimum period and is included in Table 4. Higher noise values will require longer overlap periods with the SORCE and JPSS TIMs to reduce gap uncertainties.

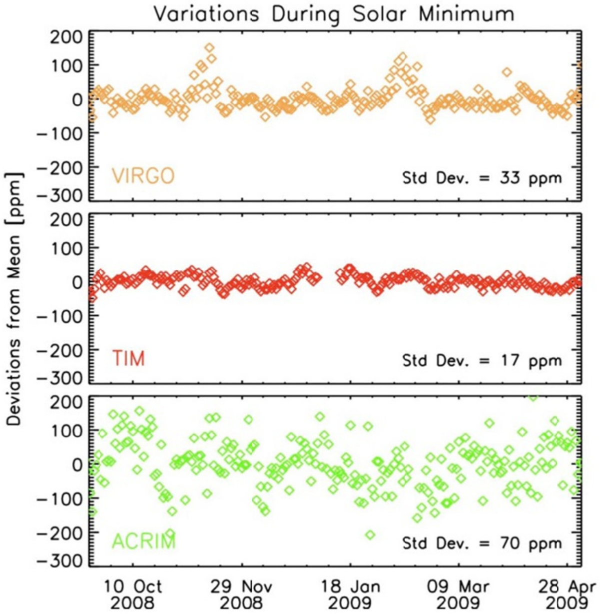

Figure 4: Instrument noise is estimated during low solar activity at solar minimum.

The PREMOS data, shown in Figure 5, began in mid-2010 and thus cannot be compared during solar minimum. This instrument agrees within uncertainties to the SORCE/TIM on an absolute scale. Relative variations, mainly due to uncorrected degradation (i.e. instrument stability), currently greatly exceed those from the ACRIM and the VIRGO, but may improve with future PREMOS degradation corrections.

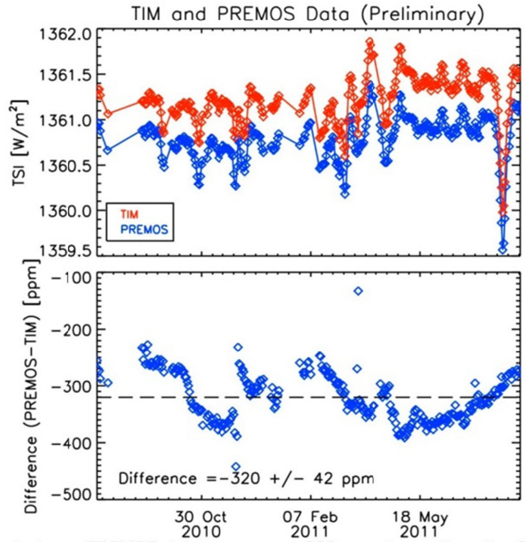

Figure 5: Preliminary PREMOS data are a mere 320 ppm lower than the SORCE/TIM TSI values. Relative variations are higher than the ACRIM and VIRGO vs. TIM, but may improve with future PREMOS degradation corrections.

5.2. Instrumental Stability

This study's stability estimates for the ACRIM3 and VIRGO come from comparisons of the instruments relative to the SORCE/TIM and from changes with reprocessing for different data versions. (For instance, the latest version of the ACRIM3 data differs in slope from the prior version by 11 ppm/yr, indicating the instrument's stated 3 ppm/yr stability – quoted at the time for the older version – is underestimated.) Relative comparisons of the TSI data from the instruments and the NRL empirical solar model (see §6) are shown in Figure 6 and indicate high drift rates that will contribute to increasing uncertainties with time if using these instruments to fill a TIM data gap.

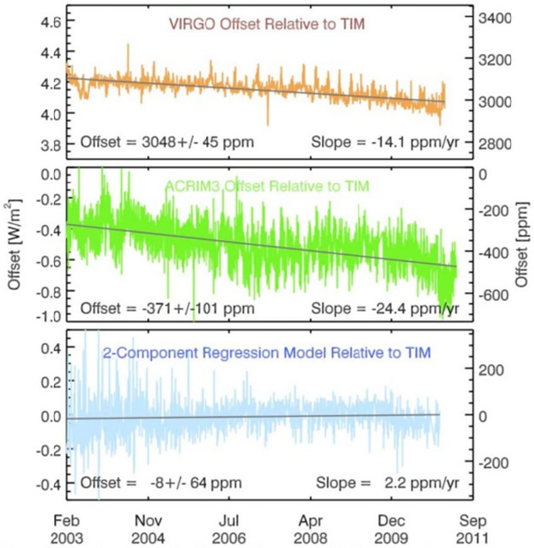

Figure 6: Relative comparisons of the ACRIM3 and VIRGO to TIM show measurement offsets and relative drifts that need to be assessed via overlap periods, but will even then introduce uncertainties in spanning a gap in TIM measurements. Lean's empirical NRL solar TSI model shows better trend agreement with the TIM data.

Where constant, the drifts in Figure 6 can be removed during a gap. Drift consistency (i.e. stability uncertainty) is estimated using residuals smoothed over different time scales. The residuals and smoothed residuals are plotted in Figure 7. The standard deviation of the varying slope of the smoothed residuals indicates the uncertainty in drift knowledge, which improves with smoothing duration (linked to overlap time) as shown in Table 3. The lower noise and better stability of the VIRGO make it the preferred instrument for filling a potential TIM data gap, although future improvements in the PREMOS degradation corrections may lower its stability uncertainties. *None of these instruments can presently fill a potential TIM measurement gap while achieving the CDR stability requirement in* Table 1.

Table 3: Stability Uncertainties Decrease With Smoothing Time

Smoothing Time [yr]	**ACRIM3 [ppm/yr]**	**VIRGO [ppm/yr]**	**PREMOS [ppm/yr]**
0.10	819	397	597
0.25	330	141	366
0.50	141	58	159
0.75	77	34	79
1.0	57	23	71

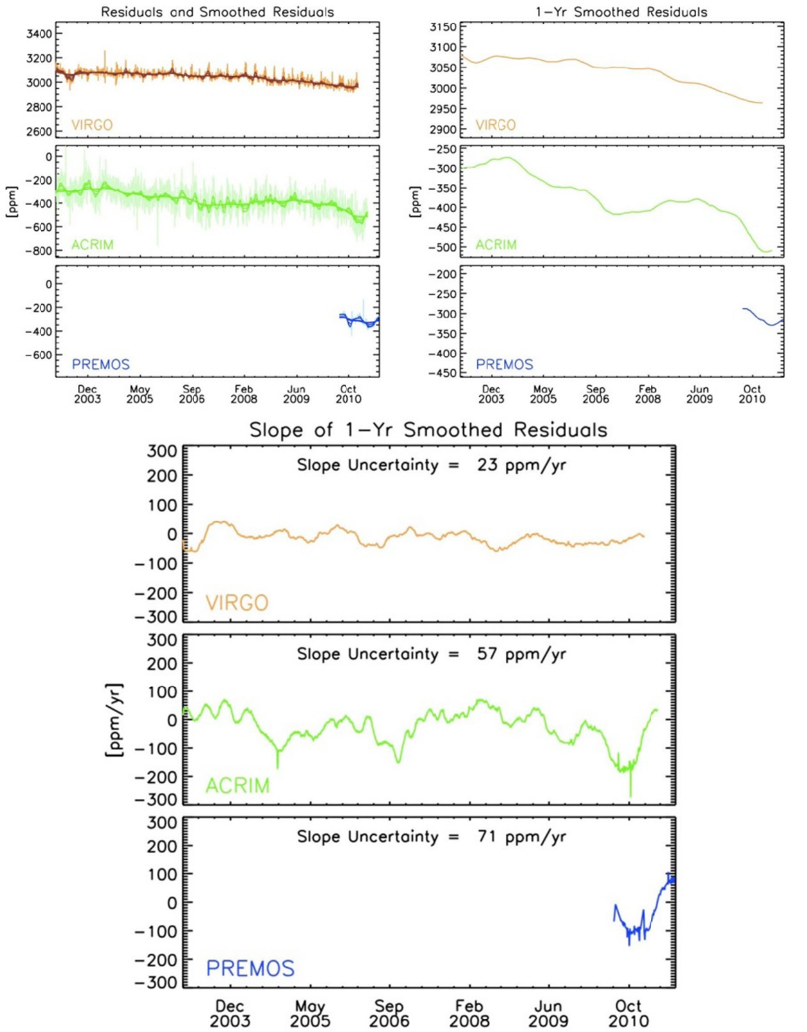

Figure 7: ACRIM, VIRGO, and PREMOS stability uncertainties are estimated by studying the variability of the residuals smoothed over various time scales expected for instrument overlap (upper left plot). The smoothed residuals from a 1-year running triangular weighting are shown individually in the upper right plot. The standard deviation of the slope of these smoothed residuals indicates the uncertainty in each instrument's drift consistency (lower plot).

5.3. Example TIM Data Gap Filled by ACRIM3

Figure 8 provides an example of a TIM data gap filled by ACRIM3. TIM data prior to the gap are shown in red, with a fainter red curve indicating the "true" TSI values (i.e. in the absence of a gap). Another TIM instrument, offset from the first by one standard deviation (~360 ppm) of the absolute accuracies of both instruments, acquires data (shown in blue) after the 1.5 year gap. ACRIM3 data (green) are used to link the TIM data across this gap. Differences in slope between the TIM instruments and the ACRIM3 during the 1 year overlap periods prior to and after the gap are used to estimate and correct for the ACRIM3 drifts relative to the TIMs across the gap, when only the ACRIM3 provides any knowledge of solar variability. These slope corrections and the TIM-to-ACRIM3 offsets before and after the gap link the pre- and post-gap TIMs, correcting the TIM data after the gap downward (dark blue). In the example shown, this correction differs from the "true" TSI by 60 ppm, causing an erroneous drift in the TSI climate data record of 40 ppm/yr.

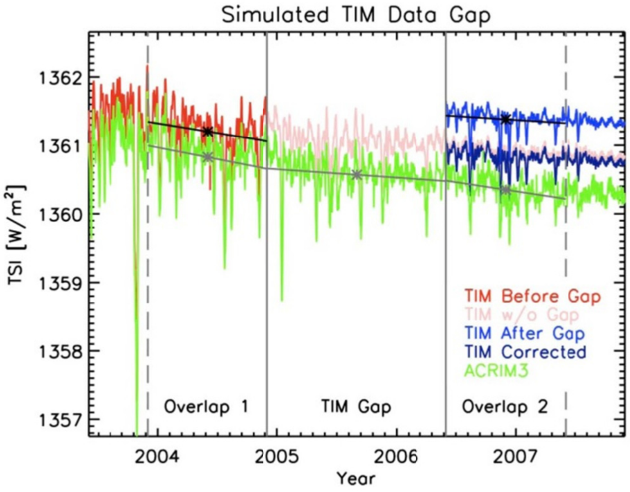

Figure 8: A simulated 1.5 year gap in TIM data filled by ACRIM3 demonstrates the effects of differences in instrument offsets and slopes leading to a 60 ppm error.

5.4. Summary of Accuracies, Stabilities, and Noise

Table 4: Instrument and Model Performance Estimates

Instrument	Accuracy [ppm]	Stability [ppm/yr]	Noise [ppm]
SORCE/TIM	350	10	4
ACRIMSat/ACRIM3	1000	57	68
SoHO/VIRGO	2500	23	28
PICARD/PREMOS	~350 (?)	71	<42
JPSS/TIM	100	10	10
NRL Model	NA	37	39
SFO Model	NA	?	18

6. SPANNING A GAP VIA EMPIRICAL SOLAR MODELS

Proxy-based solar models can estimate TSI in the absence of actual TSI measurements. Such models can then be used to span a TIM data gap.

Empirical models utilize information about the primary solar sources of solar irradiance variability to calculate the relative changes that occur when these features are present on the Sun's disk. The Naval Research Laboratory (NRL) TSI model, created by Dr. Lean, is constructed from two time series, the sunspot blocking function and the facular brightening function. The San Fernando Observatory (SFO) TSI model utilizes red and Ca K photometric sums from ground images representing sunspots and faculae, respectively, to create a similar model. Figure 9 shows results from these two models fitted to the TIM data, with both models estimating TSI based on their proxies prior to the SORCE launch. A SATIRE-based 4-component model fitted to TIM data was presented at the 2011 SORCE Science Meeting and shows even higher correlations (R=0.992). None of these proxy models allow for long-term changes in the base level of the quiet Sun, but they can track solar variability on the short-term time scales to span a TIM data gap. This paper focuses on the potential of the NRL model for spanning a gap in TIM measurements.

The bolometric sunspot blocking used in the NRL model is calculated from ground-based white-light images of the solar disk made by the Air Force Solar Optical Observatory Network (SOON) and available from the NOAA National Geophysical Data Center. A daily average sunspot blocking function is calculated as the mean of sunspot region observations made by multiple observatories spaced around the globe so as to sample different times of day. The facular brightening function is specified by the Mg II index of activity in the solar chromosphere. Being a relative measure of the ratio of the emission in the core of the Mg II 282 nm Fraunhofer line to that in the wings, this index achieves greater stability than an absolute flux measurement. Because it is obtained from UV observations, the Mg II index must be measured from space. For the duration of the SORCE mission, a Mg II index is available from the SORCE/SOLSTICE measurements. NOAA also produces a Mg II index from its SBUV instruments, which must be cross calibrated to the SORCE measurements because of differing instrument spectral resolutions.

Figure 9 shows the NRL and SFO TSI models compared with the SORCE TIM measurements, and the separate sunspot and facular influences. The relative contribution of the sunspot blocking and facular brightening components is determined from multiple regression of the two time series with the TIM measurements. The coefficients from this regression also provide the conversion of the input time series to energy units.

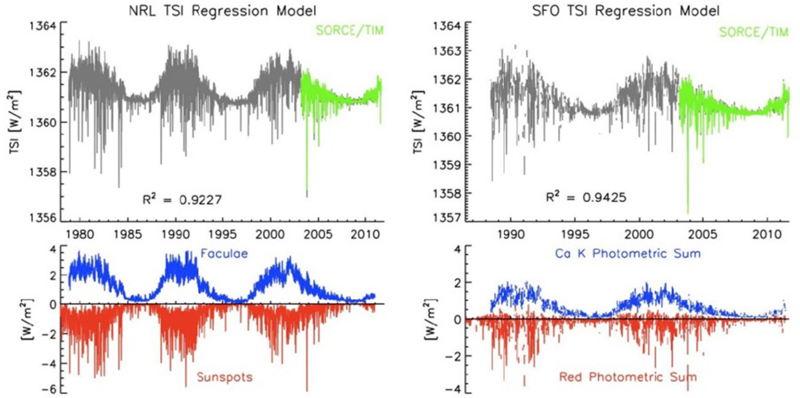

Figure 9: The NRL (left) and SFO (right) TSI models (grey) are matched to the TIM observations (green) by linearly regressing facular brightening (blue) and sunspot darkening (red) indices to the TSI measurements.

The correlation of the NRL TSI model with the TIM measurements is *R*=0.96; the model therefore explains a high fraction (92%) of the observed TSI variability. Differences occur between the measurements and the model on multiple time scales; in particular, the model has reduced short-term precision relative to TIM observations and small systematic drifts on longer time scales. Figure 6 shows the differences between the TIM measurements and the NRL TSI model for the duration of the SORCE mission. The magnitude of these differences and their temporal evolution with solar activity determines the utility of the NRL TSI model in filling a gap between the SORCE/TIM and JPSS/TIM, with the model's stability and noise parameters summarized in Table 4.

By simulating TIM data gaps during both 2003-2004 (representative of solar maximum) and 2009-2010 (for solar minimum) and extrapolating the NRL model through each of these time periods then comparing to the actual TIM data, estimates of the model's accuracy to span a data gap are acquired. Figure 10 shows the differences between the TIM measurements and the modeled TSI estimates averaged over subsequent 365-day and 80-day intervals starting in 2009. The top panel uses the best TSI model, which assumes the Mg II facular index is available, while the second plot shows a similar analysis but with a TSI model that instead uses a proxy based on the F10.7 cm flux. Figure 11 shows a similar gap analysis for times prior to 2005 and representative of solar maximum. There is little difference between the simulated gaps during solar maximum and solar minimum, with both comparisons showing drifts with gap duration between the model and the TIM observations.

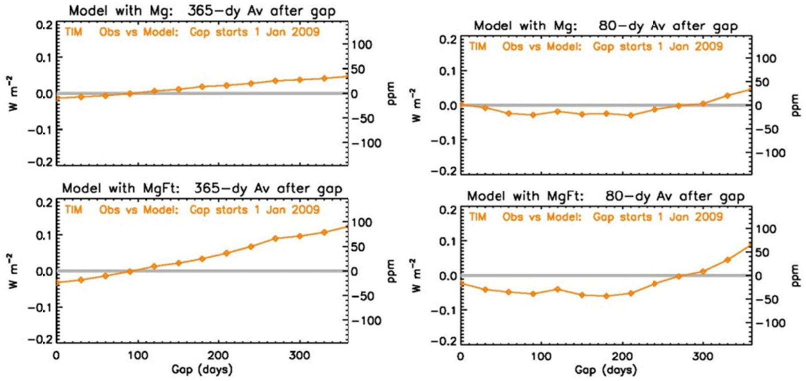

Figure 10: One-year (left) and 80-day (right) running mean differences between model and TIM measurements for a data gap starting in 2009 (representative of solar minimum) using Mg II (top) and F10.7 (bottom) facular proxies.

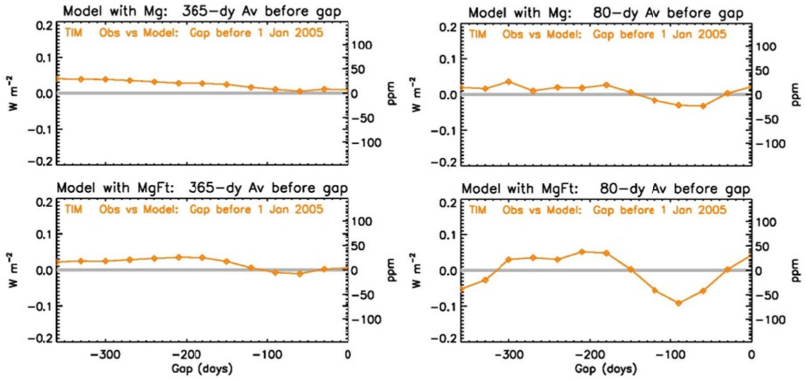

Figure 11: One-year (left) and 80-day (right) running mean differences between model and TIM measurements for a data gap prior to 2005 (representative of solar maximum) using Mg II (top) and F10.7 (bottom) facular proxies.

For a gap of one year (i.e. 365 days in the plots) the values of the best-case TSI model for the subsequent 365-day averages differ from the "true" TSI (i.e. as measured directly by the TIM) by almost 0.05 Wm^{-2} (37 ppm), so using the NRL TSI model to span a TIM measurement gap introduces a 37 ppm/yr drift uncertainty to the record. If the Mg II index is not available, forcing the use of a poorer facular index in the model, then the added imprecision can be up to 88 ppm/yr. This should be considered a worst case scenario since a variety of other solar data and models would be investigated in the absence of SORCE Mg II data to better substantiate the facular component than the F10.7 cm flux alone.

In either case, *proxy models may achieve comparable gap filling capabilities to the alternate TSI instruments for these best-case simulated gaps, but cannot achieve the CDR stability requirement in* Table 1.

7. Summary of Uncertainties Via Different Gap Filling Methods

The uncertainties in spanning a TIM data gap of different durations and different overlap periods are estimated from the derived noise and stability estimates summarized in Table 4. Using the graphical representation of Figure 2, these are plotted in Figure 12 for the ACRIM3, VIRGO, PREMOS, and NRL model.

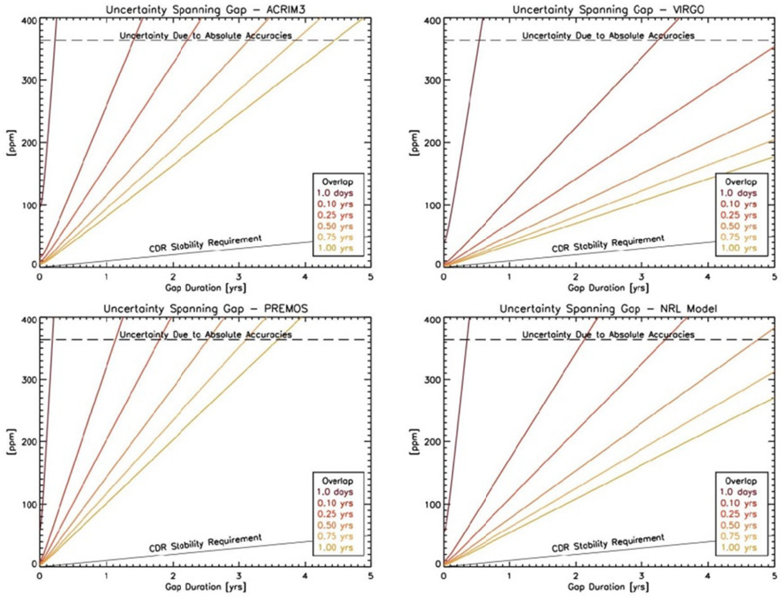

Figure 12: Estimated uncertainties as a function of gap and overlap durations are estimated for the ACRIM3 (top left), VIRGO (top right), PREMOS (lower left), and NRL model (lower right). All show similar trends: longer gap durations and shorter overlap times contribute to greater uncertainties. The VIRGO currently provides the best means of filling a TIM data gap, although no instrument or model used to fill a gap comes close to achieving the TSI CDR stability requirement (grey line).

The expected induced errors for a TIM data gap of 1.5 years with 1 year overlaps prior and following are summarized in Table 5 for each instrument or model. All exceed the JPSS TSI CDR stability requirement.

Table 5: Errors from 1.5 Year TIM Data Gap with 1 Year Overlap Durations

Instrument	ACRIM	VIRGO	PREMOS	NRL Model
Error [ppm]	123	53	152	81

8. CONCLUSIONS

The ACRIM3, VIRGO, PREMOS, and solar models are evaluated for noise and stability and for their resulting capabilities in filling a potential gap in TIM measurements between the SORCE and JPSS missions. Uncertainties introduced into the TSI climate data record are estimated as a function of gap duration and TIM overlap time for each.

The VIRGO currently provides the best method for filling a TIM data gap due to its stability and relatively low noise, both critical for spanning a TIM data gap. Nevertheless, a gap analysis with this instrument indicates the JPSS CDR stability requirement would be exceeded by 350%. Solar models are the next best option for spanning a gap of short duration, with ACRIM3 and PREMOS providing the least capability due to their higher noise and/or lower stabilities. No instrument or model achieves the JPSS TSI CDR requirements in the undesirable event of a TIM data gap.

The Solar Climate Data Record:

Scientific Assessment of Strategies to Mitigate an Impending Gap in Total Solar Irradiance Observations Between the NASA SORCE and NOAA TSIS Missions

(Study B)

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31 Jan. 2013

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1. Background

1.1. *Need for the Solar Climate Data Record*

The need for the solar climate data record is well documented in NRC, NASA, and NOAA reports. In the 1980's NASA designated solar irradiance as one of 21 key Earth Science observables needed to provide the scientific foundation of the Earth Observing System (EOS) envisioned in *Earth System Science: A Closer View* (1988). In the 1990's the NPOESS Integrated Operations Requirement Document (IORD) identified solar irradiance as an operational Climate Data Record and specified the requirements for the Total Solar Irradiance Instrument (TSIS); however, NPOESS's descope and Nunn-McCurdy recertification in 2006 eliminated the TSIS. NRC's *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond* (2007) recommended that "NOAA ensure the continuity of measurements of Earth's Radiation Budget (ERB) and total solar irradiance (TSI)." A subsequent NRC report, *Options to Ensure the Climate Record from the NPOESS and GOES-R Spacecraft: A Workshop* (2007), addressed the specific impacts of the descoped NPOESS on climate records and identified as the highest priority "Preservation of long-term climate records...including multi-decadal records of total solar irradiance." The TSIS was subsequently manifested under the JPSS Free Flyer program with expected launch no earlier than mid-2016.

1.2. *Requirements for TSI Climate Data Record*

The TSIS Climate Data Record (CDR) requirements are driven by the need to detect possible long-term solar variability critical for climate studies, and are summarized for the TSIS Total Irradiance Monitor (TIM) in Table 1.

Table 1: CDR Requirements Established for the TSIS/TIM

Parameter	CDR Requirement	
Absolute Accuracy	0.01%	(100 ppm, 0.14 Wm^{-2})
Stability	0.001%/yr	(10 ppm/yr, 0.014 $Wm^{-2}yr^{-1}$)
Noise	0.001%	(10 ppm, 0.014 Wm^{-2})

1.3. *Existing TSI Observational Record*

Multi-decadal solar irradiance records are obtained by cross calibrating space-based measurements made by individual solar radiometers since 1978. Figure 1 compares the PMOD and ACRIM composite records, constructed independently by combining respectively the SoHO/VIRGO (Dec. 1995 to present) and the SMM/ACRIM1 (Feb. 1980 to 1989), UARS/ACRIM2 (Sept. 1991 to 2001), and ACRIMSat/ACRIM3 (Dec. 1999 to present) datasets with select other TSI measurements. Evident between these two primary TSI composites are drifts ranging from -0.043 Wm^{-2} per year (in the 1980's) to +0.172 Wm^{-2} per year (in the 1990's). Comparisons of each composite record with the SORCE/TIM, as shown in Figure 2 and Table 2, indicate that relative to the TIM, the PMOD is drifting at -0.0242 Wm^{-2} per year and ACRIM at -0.0235 Wm^{-2}, both of which exceed the TIM's CDR-level of stability of 10 ppm per year (0.014 Wm^{-2} per year) by almost a factor of two. Thus, of the currently operating TSI instruments, only the TIM has the needed accuracy and stability to meet the TSIS requirements.

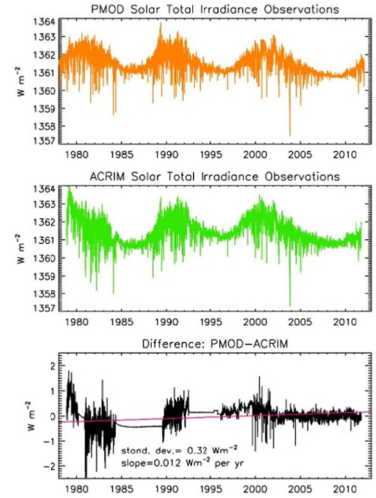

Figure 1: Compared are the PMOD-based TSI composite (upper panel) and ACRIM-based TSI composite (middle panel). Over the 34-year duration, differences between these two primary multi-decadal TSI records (lower panel) show a long-term drift of 0.012 Wm^{-2} per year, with significantly larger short-term drifts, for example, -0.043 Wm^{-2} per year in the 3-year period from 1981 to 1983 (inclusive) and +0.172 Wm^{-2} per year in the 2-year period from 1990 to 1991 (inclusive). These drifts exceed the needed solar CDR stability.

Table 2: Statistical Comparisons of SORCE/TIM with SoHO/VIRGO and ACRIMSat/ACRIM3 in the period 2003 to 2012.

Instrument	Mean Value Wm^{-2}	Standard Deviation of daily means Wm^{-2}	Slope of daily means Wm^{-2}yr^{-1}	Correlation with TIM	Standard Deviation of differences from TIM Wm^{-2}	Slope of differences from TIM Wm^{-2}yr^{-1}
TIM	1361.07	0.370	+0.0191	1.0	0	0
VIRGO	1365.50	0.350	-0.0226	0.9753	0.0777	-0.0242
ACRIM3	1360.54	0.362	-0.0389	0.9351	0.1280	-0.0235

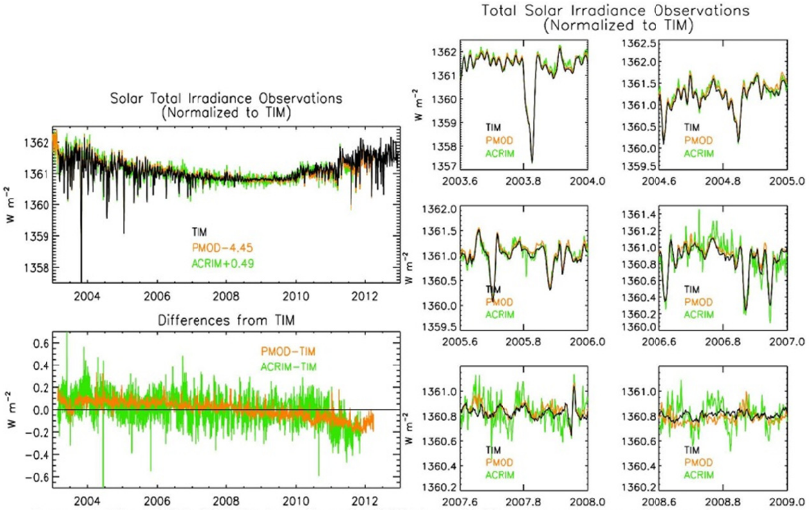

Figure 2: The PMOD (VIRGO-based) and ACRIM-based TSI composites are offset to the mean of and compared with the SORCE/TIM observations in the upper left panel. Their differences from TIM are shown in the lower left panel for the duration of the SORCE mission. Details of select short-term irradiance variations are shown at different epochs of the solar cycle in the panels on the right.

1.4. Future TSI Observations

To mitigate the loss of stable TSI measurements in the expected gap between the 5-yr SORCE mission launched in 2003 and the subsequent NPOESS/TSIS, NASA planned and developed the Glory mission, on which a next-generation TIM would provide the needed measurements.

The failure of the Glory launch in 2011 put the extant TSI record severely at risk.

The SORCE spacecraft on which the SORCE/TIM currently operates has been in orbit for ten years, well beyond its design lifetime, and is suffering severe battery problems that have recently started to limit the TIM calibration observations and degrade its thermal stability. Both SoHO/VIRGO and ACRIMSat/ACRIM3 have been operating in space even longer than SORCE (17 and 13 years, respectively). In addition to lacking the capability to meet the long term stability requirements for the solar climate data record, both are susceptible to budgetary and logistical limitations. The recently launched PICARD mission, which carries the PREMOS and SOVAP TSI instruments, will terminate in February 2013.

Launch of the TCTE/TIM is planned for mid- to late-2013 to provide crucial overlap of TSI measurements with the SORCE/TIM and reduce uncertainties in the TSI record prior to launch of the JPSS/TSIS.

1.5. Study of Uncertainties Spanning Potential SORCE/TIM to JPSS/TIM Gap

In an earlier report, delivered to NOAA in September 2011 and prior to plans for TCTE to help bridge the gap, uncertainties in the TSI climate data record were estimated for assumed scenarios of a measurement gap between the TIM instrument currently on the SORCE mission and that built for the upcoming JPSS/TSIS with an intended 2016 launch. Uncertainties were estimated as a function of gap duration and TIM overlap time for each of the ACRIM3, VIRGO, and PREMOS databases, and also using solar models. That "Study A" report determined that ESA's SoHO/VIRGO instrument provided the best means of filling a TIM data gap, with solar models offering limited capability for short duration gaps. Using VIRGO to fill a 1.5-year data gap (with 1 year overlap on both ends) was estimated to introduce an error of 53 ppm to the solar climate data record, far exceeding the CDR stability requirements. Subsequent delays in the expected launch of the TSIS have since extended that expected gap duration.

No gap-filling method was found to meet the JPSS TSI climate data record requirements, since no other instrument or model has demonstrated the stability or low noise of the TIM instrument.

2. Status of Present TSI Measurements

Spaceborne TSI measurements began in 1978 and have continued uninterrupted since (see Figure 3). Measurement overlap helps enable cross calibrations of the independent databases that have different absolute calibrations. The primary cause of offsets among the different TSI time series is uncorrected internal instrument scatter, which causes erroneously high readings. Since the needed levels of absolute accuracy (Table 1) have not yet been demonstrated on-orbit, this 34-year long solar climate data record relies on continuity from stable instruments.

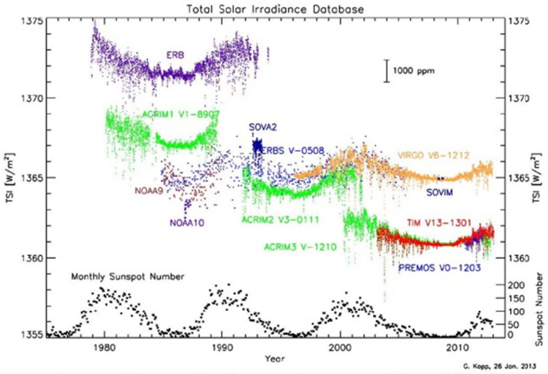

Figure 3: The spaceborne TSI record has been uninterrupted since 1978, helping account for offsets between different instruments due to calibration errors.

2.1. SORCE

The SOlar Radiation and Climate Experiment (SORCE) was launched in Jan. 2003 with a Total Irradiance Monitor (TIM) to continue the TSI record with improved accuracy and stability over prior instruments. The TIM has been successful in both regards, and has established a new, lower value of TSI due to improved calibrations and instrument design (Kopp and Lean, 2011). SORCE is currently ten years old and is having battery issues that limit the TIM's measurements and will at some point likely cause an abrupt end to the mission. The SORCE/TIM measurements were intended to be continued, with overlap, via the Glory mission's TIM, which was intended to continue the solar irradiance CDR until the launch of the TIM on JPSS/TSIS. The Glory launch failure in 2011 puts the quality of the TSI record at risk due to a likely gap in the TIM data, since no other instrument currently achieves the TSIS CDR requirements.

2.2. PREMOS

The CNES PICARD mission launched in June 2010 carrying two TSI instruments, the PREMOS and the SOVAP. The PREMOS, the first flight instrument to have successfully transferred state-of-the-art SI-traceable TSI Radiometer Facility (TRF) irradiance calibrations to orbit, shows good agreement with the absolute value of the SORCE/TIM. This instrument has now acquired 2.5 years of measurements, which are evaluated in §2.4. No data have been made publicly available from the SOVAP, so its quality is not evaluated in this report.

The PICARD is intended to be decommissioned in Jan. 2013, so will likely not provide continued TSI measurements beyond those of the SORCE.

2.3. VIRGO and ACRIM3

The SoHO/VIRGO and the ACRIMSat/ACRIM3 both currently provide TSI measurements. While neither achieves the CDR requirements in Table 1, they may provide some benefit for spanning a short-term TIM data gap. Study A showed that the VIRGO provided the best means of spanning a gap, but subsequent updates to the ACRIM3 data have reduced the signal noise that limited its usefulness at the time of that earlier report. The latest data from both instruments are reevaluated in §2.4 of this report. As with SORCE, VIRGO and ACRIM3 are both operating well beyond their intended mission lifetimes, so their dependability, particularly in the timeframe of the TSIS launch, is questionable.

2.4. Comparisons of Measurements from Current TSI Instruments

The instrument data records and models utilized for this report are listed in Table 3. The instrument daily TSI time series are shown in Figure 4.

Table 3: TSI Data Records Analyzed

Instrument/Model	Data Set & Version	Time Range
SORCE/TIM	V.13	25 Feb. 2003 – 19 Jan. 2013
ACRIMSat/ACRIM3	daya2sddeg_ts4_Nov_2012_hdr	5 Apr. 2000 – 21 Oct. 2012
SoHO/VIRGO	virgo_tsi_d_v6_002_1212	7 Feb. 1996 - 4 Dec. 2012
PICARD/PREMOS		27 July 2010 – 31 Mar. 2012
NRL Model	TIM_models_14Jan13	1 Jan. 2003 - 30 Oct. 2012
SFO Model	'SFO Indices' (13 Dec. 2012)	28 Apr. 1988 - 12 Dec. 2012

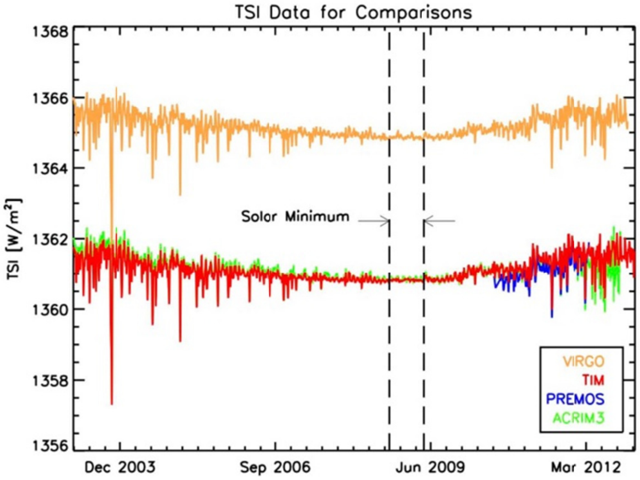

Figure 4: Time series of TSI data from TIM, ACRIM3, VIRGO, and PREMOS since the 2003 SORCE launch. These are the instrument data used for this report's analyses.

2.4.1. *Instrument Noise*

The solar minimum period indicated in Figure 4 allows estimates of instrument noise, as the Sun was relatively quiet during this time. This time range is expanded for the TIM, ACRIM3, and VIRGO in Figure 5. Common mode variations between instruments likely indicate true solar variations; differences are instrument artifacts. Two prominent such artifacts are: two positive spikes in the VIRGO data, which coincide with SoHO spacecraft Keyhole pointing maneuvers; and a varying periodicity (see also Figure 6) in the ACRIM3 data, the cause of which is currently unknown but suspected to be due to uncorrected instrument thermal variations.

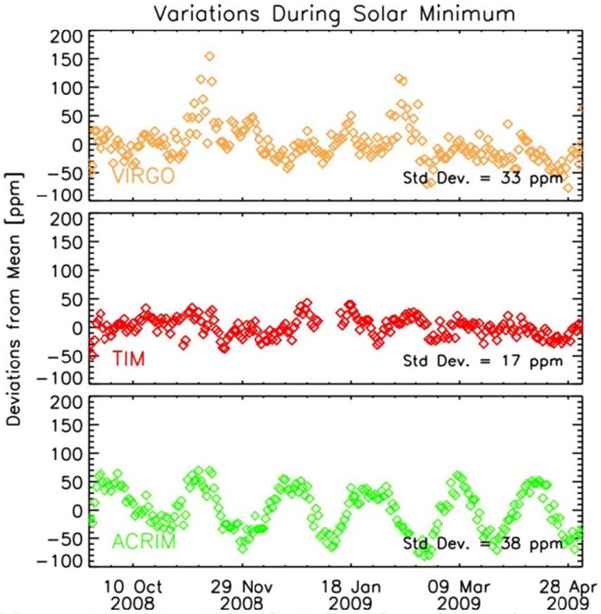

Figure 5: Instrument noise is estimated during low solar activity at solar minimum. Actual solar variability likely accounts for only 16 ppm of the computed standard deviations.

The standard deviations of the daily TSI values from each instrument, being the quadrature sum of the instrument noise and the actual solar variability, are listed with each plot in Figure 5. The TIM's noise is lower than that of any other flight instrument because it is the only instrument utilizing phase sensitive detection in either on-orbit thermal control or ground data processing. Independent calibration measurements give 4 ppm as the TIM instrument noise, implying that the solar activity during this solar minimum time range accounts for nearly all of its plotted 17 ppm variability. The larger variations in the ACRIM3 and VIRGO data during this time period indicate that their solar minimum measurements are dominated by instrument noise rather than solar variability. Estimates of the noise of each instrument are given in Table 5. Higher noise values necessitate longer measurement overlap periods to reduce gap uncertainties.

The PREMOS data, shown in Figure 6, began in mid-2010 and thus cannot be compared during solar minimum. This instrument agrees within uncertainties with the SORCE/TIM on an absolute scale. Relative variations, mainly due to uncorrected degradation (i.e. instrument stability), exceed the needed CDR stability. The PICARD mission is due to be decommissioned in Feb. 2013, so it is very unlikely that the PREMOS will overlap with TCTE or TSIS.

2.4.2. Instrument Stability

This study's stability uncertainty estimates for the ACRIM3, VIRGO, and PREMOS come from comparisons of the instrument data records relative to those of the SORCE/TIM and from changes between each instrument's successive data versions.

Relative comparisons of the TSI instrument data and the NRL empirical solar model (see §5.4) to the SORCE/TIM are shown in Figure 6. The drift rates, indicated by the slopes of linear fits to the differences, exemplify the lack of long-term stability of the different TSI instrument records. Filling a TIM measurement gap with any of these other instrument data could induce erroneous trends in the 34-year TSI record.

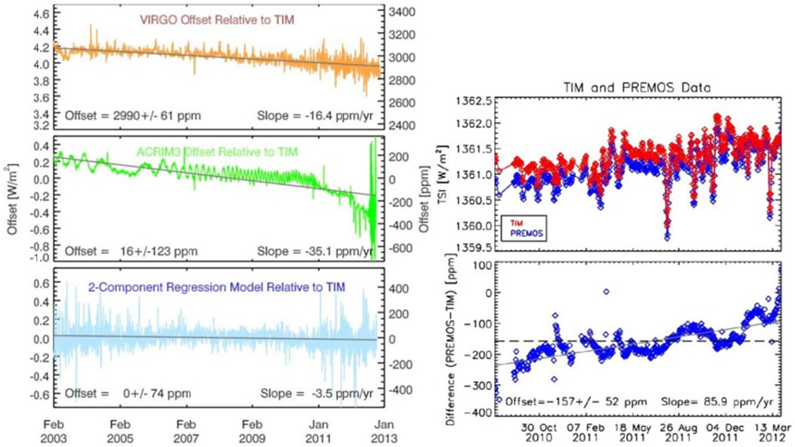

Figure 6: Relative comparisons of the ACRIM3 and VIRGO to TIM (left-hand plots) show measurement offsets and relative drifts that – even if corrected for the linear portion – will introduce uncertainties in spanning a gap in TIM measurements. The empirical NRL solar TSI model shows better trend agreement with the TIM data (bottom left). PREMOS data show good absolute agreement with the SORCE/TIM TSI values, but are drifting steeply upward relative to the TIM (right-hand plots), whereas the VIRGO and ACRIM3 show downward drifts of different rates.

If constant, the linear portion of the drifts in Figure 6 could be removed to help span a gap; however, even removing a linear drift leaves residual variations that would induce errors. Drift inconsistencies (i.e. instrument or model stability uncertainties) are estimated using such residuals smoothed over different time scales. The residuals and smoothed residuals are plotted in Figure 8 for comparisons of the SORCE/TIM to the VIRGO, ACRIM3, and PREMOS instruments as well as to the NRL and SFO models (shown in Figure 12). The standard deviation of the varying slope of each smoothed residual indicates an instrument's or model's stability uncertainty. These uncertainties improve with smoothing duration as shown in Table 4 and in Figure 7. These essentially give the uncertainties induced across a TIM data gap spanned by the listed instruments and models for different smoothing times. (Each smoothing time necessitates even longer measurement overlap duration with both a TIM and another instrument observing in order to estimate the trend differences.)

Table 4: Stability Uncertainties Decrease With Smoothing Time

Smoothing Time [yr]	ACRIM3 [ppm/yr]	VIRGO [ppm/yr]	PREMOS [ppm/yr]	NRL Model [ppm/yr]	SFO Model [ppm/yr]
0.10	711	421	508	623	1701
0.25	273	150	273	187	522
0.50	132	66	174	89	237
0.75	89	41	114	61	127
1.0	71	29	79	48	88

The comparative stability of the VIRGO and its relatively lower noise (both of which are summarized in Table 5) make it the preferred instrument for filling a potential TIM data gap. The NRL solar proxy model is the next best choice for filling this gap based on its stability; the SFO model's stability uncertainties are higher because it has data points on only about half the days due to limited ground-based solar sampling. As Table 4 indicates, *none of these instruments or models can fill a potential TIM measurement gap while achieving the CDR stability requirement* in Table 1.

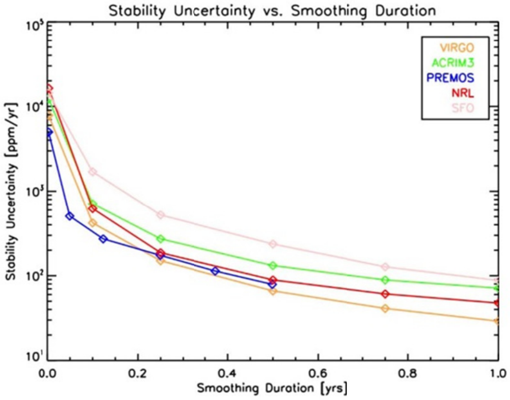

Figure 7: Stability uncertainties between two instruments or models decrease with longer smoothing durations, which require overlap between the two of at least this duration. These uncertainties provide estimates of the trending potentially induced in the TSI data record if using the shown instruments or models to span a potential SORCE-to-TSIS TIM data gap.

In addition to differences between data records indicating stability uncertainties, changes between successive instrument data versions as updated corrections are applied by the instrument teams indicate a likely lower bound to an instrument's stability uncertainty. For example, the latest version of the ACRIM3 data differs in slope from the prior version by 8 ppm/yr, indicating that the ACRIM instrument team feels the prior data were incorrect and needed adjusting by this amount. Differences between the most recent VIRGO data versions show similarly large changes.

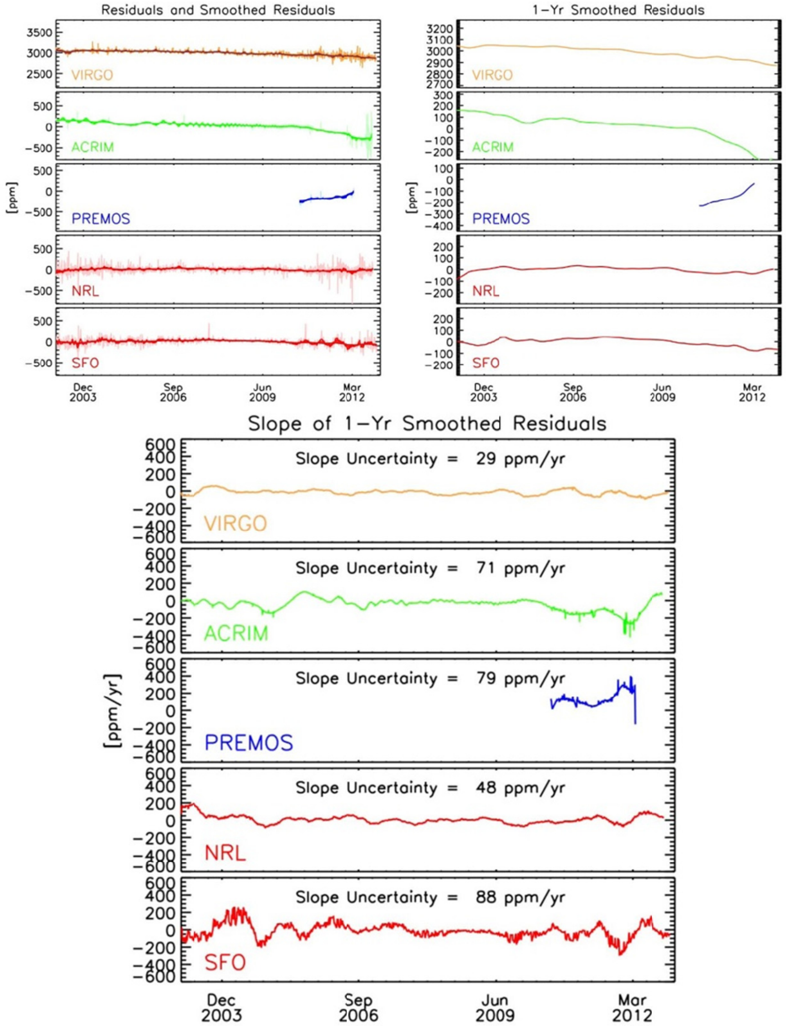

Figure 8: Stability uncertainties are estimated for the ACRIM, VIRGO, and PREMOS instrument and the NRL and SFO models by studying the variability of the residuals relative to the TIM TSI data smoothed over various time scales expected for instrument overlap (upper left plot). The smoothed residuals from a 1-year running triangular weighting are shown separately in the upper right plot. The variation in the slope of these smoothed residuals indicates the uncertainty in each instrument's stability uncertainty (lower plot).

2.4.3. Summary of Accuracies, Stabilities, and Noise

Table 5: Instrument and Model Performance Estimates

Instrument	Stated Accuracy [ppm]	Stability [ppm/yr]	Noise [ppm]
SORCE/TIM	350	10	4
ACRIMSat/ACRIM3	1000	71	34
SoHO/VIRGO	2500	29	28
PICARD/PREMOS	300	79	<52
JPSS/TCTE/TIM	350	10	50*
JPSS/TSIS/TIM	100	10	10
NRL Model	-NA-	48	38
SFO Model	-NA-	88	19

* Effective noise due to orbital sampling at times of high solar activity (see §4.3). Instrument noise is less than 10 ppm.

2.5. NOAA JPSS/TSIS

The NOAA JPSS/TSIS utilizes an advanced TIM instrument to achieve the CDR requirements in Table 1. Baselined as part of the JPSS Free Flyer program, this instrument is currently intended for launch no earlier than 2016 due to delays in spacecraft selection, making overlap with TCTE/TIM on the 1-year (18 month goal) duration STP-Sat3 mission unlikely. *Any extended duration of the TCTE or earlier launch of the JPSS/TSIS will greatly benefit the TSI data record* by reducing the TCTE-to-TSIS gap (see §4).

3. The TSI Calibration Transfer Experiment (TCTE) Motivation and Need

3.1. TCTE Mission Background and Approach

The Glory launch failure left a gap between the planned SORCE and TSIS TIM measurements intended to achieve the TSI CDR requirements. Restructuring of the JPSS program has resulted in delays selecting a spacecraft to accommodate TSIS, which exacerbated this problem.

TCTE, the TSI Calibration Transfer Experiment, is JPSS's approach to mitigating risk of a TSI measurement gap in a timely manner. This mission utilizes the ground-based SORCE/TIM Witness instrument, which was built alongside the SORCE/TIM Flight unit and has been used for inter-comparisons at NIST and at the 2010 International Pyrheliometer Comparison (IPC-XI). The already underway Air Force program STP-Sat3 with planned August 2013 launch was identified to carry the TIM as part of its payload. Accommodation modifications to the SORCE/TIM Witness unit (now called the TCTE/TIM) and updated calibrations have been completed, and the instrument has been integrated on the STP-Sat3, which is currently finishing environmental testing.

The STP-Sat3 payloads are primarily nadir-viewing, so solar measurements with the TCTE are made only intermittently. This mission is not intended to directly achieve the measurement requirements of Table 1, but to reduce the severity of a long-duration measurement gap between the SORCE and TSIS TIMs. As such, the TCTE must meet the stability requirement given in Table 1 and have measurement overlap with both the SORCE and TSIS in order to transfer the improved TSIS/TIM's absolute calibration between the two. Although the TCTE should meet or exceed the SORCE/TIM absolute accuracy given in Table 5, its primary benefit is in providing stable knowledge of solar irradiance fluctuations between the two surrounding TIM instruments on solar-dedicated missions. The TCTE success criteria are described below.

3.1.1. Comprehensive Success Criteria

Comprehensive Success requires 6 months of *overlap with both SORCE and TSIS*. During the overlap periods with these other missions a measurement is acquired at least every 2 days with weekly measurements during the intervening period. *The TCTE must meet its stability requirement of 10 ppm/year and its accuracy requirement of 350 ppm.* The stability requirement helps propagate the TSI record forward with needed long-term solar trend detection capability, while the accuracy requirement reduces offsets between the SORCE and TSIS TIMs should overlap not be achieved.

3.1.2. Minimum Success Criteria

1. *Assuming overlap with SORCE*: Minimum Success is 2 months of overlap with 1 measurement every 2 days followed by 1 year of data at 1 measurement per week, sufficient to improve the record over that provided by other extant means.
2. *Assuming no overlap with SORCE*: Minimum Success is a 3-year duration of daily measurements. This will have lower uncertainty than any other measurement or model, justifying filling the TIM gaps on either side of TCTE.

In either case, *the TCTE must meet its stability requirement of 10 ppm/year*.

3.2. Strengths of TCTE Approach

The TCTE benefits from the following:

- It utilizes a SORCE-like TIM originally built alongside the SORCE Flight instrument, and should have comparable well-characterized performance;
- Being already built, the instrument is available for an imminent launch to increase likelihood of acquiring overlapping measurements with the SORCE/TIM;
- It benefits from improved ground calibrations not available at the time of the SORCE launch – particularly superior electrical power calibrations and irradiance measurements in the TSI Radiometer Facility – and has undergone testing at NIST and comparisons with the World Radiometric Reference, so helps transfer those SI-traceable reference measurements to space;
- Updates to the instrument for accommodation on the selected spacecraft were completed on schedule, and the mission is proceeding as intended, ready for a mid- to late-2013 launch.

3.3. Weaknesses of TCTE Program

The TCTE is intended to reduce the severity of a measurement gap between the SORCE and the TSIS TIMs, but is not a replacement for either.

- The TCTE acquires only intermittent observations rather than the continual measurements of the SORCE and TSIS TIMs. The minimum TCTE observations given in §3.1 can be as infrequent as one orbit per week. While helpful for discerning long-term solar changes from effects due to instrument offsets (assuming overlaps with both SORCE and TSIS are achieved), these observations sub-sample solar variability. This observational aliasing precludes the low noise measurements needed to meet CDR requirements (see §4.3).
- The infrequent TCTE observations do not provide the daily record of TSIS-required fidelity needed for improving proxy-based solar models such as those described in §5.
- Intended as a 1-year mission with an 18-month goal largely limited by the spacecraft bus, the STP-Sat3 duration is unlikely to provide overlap with the TSIS/TIM intended for launch no earlier than mid-2016. Thus TCTE postpones, but likely does not prevent, a pre-TSIS TSI measurement gap.
- Because of a classified instrument on the STP-Sat3, all telemetered data from the spacecraft are initially classified. The Air Force currently lacks any means of declassifying the TCTE data. While intended for public release eventually, these data will likely remain classified until well after launch, precluding broad community assessments of the data quality and approval of operations scenarios initially. (The TIM Science and Operations Teams are acquiring security clearances to assess instrument state of health and acquisition of intended data for this planned initial mode of operation.)

4. Extending the Solar Data Record from SORCE to TSIS Using TCTE

4.1. Background on Gap Filling

We outline in §4.1 the procedure for estimating the uncertainties induced in a data record when filling a measurement gap between two instruments by other methods. We then apply this procedure in the remainder of §4 to estimate quantitative uncertainties induced in the TSI record by spanning the expected SORCE-to-TSIS TIM measurement gap under different scenarios.

For a very long-duration gap, absolute accuracy of the two bracketing instruments may be superior to continual measurements. For example, a long-term change in TSI of 0.1% over 100 years would be a 1-sigma detection for continual measurements having 10 ppm/year stability uncertainty (using the CDR measurement requirements in Table 1), but a 7-sigma detection for two 100-ppm accuracy instruments separated by those 100 years. Sufficient absolute accuracy reduces the reliance on measurement continuity and instrument stability for long-term trend detection.

Over short time spans however, measurement continuity from stable instruments is generally more capable of trend detection. A change of 0.01% over 5 years would be a 0.7-sigma detection for two 100-ppm accuracy instruments separated by those 5 years, but a 2-sigma detection for a single 10 ppm/yr stability instrument operating over that duration.

Since the SORCE-to-TSIS gap is expected to be about 4 years in duration rather than decades, we focus in this report on maintaining the TSI record via measurement stability as opposed to absolute accuracy.

A data record provided by a single instrument has stability uncertainties determined completely by that instrument. Transitioning measurements from one instrument (or model) to another induces additional uncertainties which depend on the duration of an overlap period where both are operating; longer overlap durations reduce these uncertainties by providing more measurements, which lowers offset uncertainties due to noise (scaling as time$^{-1/2}$) and improves relative stability knowledge of the two (as quantitatively shown in Table 4 and Figure 7).

For the analysis here, the net uncertainty induced in the TSI record between two instruments, A and B, separated by a gap of length t_{gap} during which data are provided by a third instrument or model C having some number of overlapping measurements N_{overlap} (which scales with overlap duration) with A and B is thus the quadrature sum of the uncertainty determining the instrument offsets,

$$\sigma_{\text{offset}} = \sqrt{\left(\sigma^2_{A\_\text{noise}} + \sigma^2_{C\_\text{noise}}\right)\Big/ N_{\text{overlap\_A}} + \left(\sigma^2_{B\_\text{noise}} + \sigma^2_{C\_\text{noise}}\right)\Big/ N_{\text{overlap\_B}}}\,,$$

and the stability uncertainty of the intervening data from C during the gap (using the appropriate stability uncertainty for the actual overlap duration, as in Table 4),

$$\sigma_{\text{stability\_gap}} = \sigma_{C\_\text{stability}} \cdot t_{\text{gap}}\,.$$

4.2. Baseline (no TCTE) SORCE-to-TSIS Gap

Study A focused on methods of spanning the expected measurement gap between the stable SORCE/TIM TSI measurements and those expected from the TSIS/TIM. That study reviewed approaches available at the time, including using VIRGO, ACRIM3, and PREMOS measurements as well as empirical solar TSI models based on proxies from space- and ground-based observatories. The conclusion was that VIRGO provided the best means of spanning a short duration (1.5 year) gap due to its stability and noise, while models provided the next best means, but neither came close to achieving the desired stability levels.

Since that time:

- The ACRIM3 data processing has been updated to correct a previous thermal artifact causing high noise (see §2.3).
- CNES decided to turn off the PICARD mission, meaning PREMOS TSI data will not be available in the post-SORCE era (§2.2).
- JPSS/TSIS spacecraft procurement delays have postponed its launch.

- JPSS's TCTE was initiated to acquire additional measurements in the SORCE-to-TSIS time frame.
- SORCE's battery has degraded further such that operation through the end of 2013 may be optimistic.

These effects lengthen the expected SORCE-to-TSIS gap. For a realistic gap from the end of 2013 to the end of 2016, TSI values would best be provided by VIRGO data based on the stability and noise results in Table 5. Using the methodology of §4.1, the net uncertainty induced in the TSI record over the 4-year period between the present (early 2013) and the TSIS launch (end of 2016) is **97 ppm, or 24 ppm/yr**, mainly due to the 3-year TIM measurement gap from late 2013 to late 2016 spanned by VIRGO having 1-year overlaps with both SORCE and TSIS. The next most stable gap filling source, the NRL solar model, would induce a net uncertainty of 154 ppm.

4.3. TCTE Measurement Cadences and Effects on Uncertainties

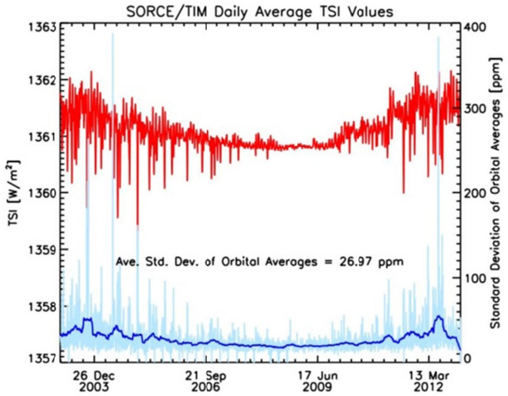

Figure 9: The reported Level 3 SORCE/TIM daily TSI values are averages of high-cadence (50 second) solar irradiance measurements acquired fairly uniformly throughout each day and therefore representative of the day's TSI. The TCTE will acquire only a single orbit of measurements each day. The standard deviation of the orbital averages from SORCE/TIM data (light blue) show variability through the solar cycle in matching the true daily average (red). The mean of these orbital average standard deviations is about 27 ppm, but can be much higher during times of solar activity. Thus the TCTE's sub-sampling will alias solar variability into its results, precluding achieving the desired CDR's low-noise measurements.

The TCTE acquires TSI measurements during one orbit per day at most. This subsamples actual solar variability, since a single orbit is not necessarily representative of the daily average TSI value. The standard deviations of orbital averaged TSI measurements during each day of SORCE/TIM data are shown in Figure 9, and indicate agreement only to 27 ppm, with greater deviations during times of higher solar activity. This subsampling limits the expected agreement of TCTE data to other instruments or models over short time durations by effectively increasing the "noise" of the TCTE data to ~50 ppm at times of high solar activity, such as when the STP-Sat3 is expected to launch; however, the agreement over long durations, where multiple orbital values can be averaged, will be much better.

The TCTE minimum observing cadence is weekly, which complicates comparison timing with other instruments or models and requires longer overlap duration times to acquire the amount of overlapping data points needed to reduce uncertainties.

4.4. TCTE Does Not Overlap with Either SORCE or TSIS

STP-Sat3 carrying TCTE is expected to launch in Aug. 2013 as a 1-year mission with an 18-month goal. If SORCE were to fail imminently and STP-Sat3 achieves its 1-year duration requirement, there will be a 6-month gap between the SORCE and TCTE TIMs followed by 1 year of stable TCTE measurements and then a 2.5-year gap between TCTE and TSIS.

VIRGO again provides the most stable and lowest noise means of filling the gaps, assuming it remains operational to provide 1 year of overlap after the TSIS launch presumed here at the end of 2016. The low – in this case, weekly – TCTE observing cadence slightly increases the noise connecting the TCTE record to that of VIRGO. Spanning both the SORCE-to-TCTE and the TCTE-to-TSIS gaps with VIRGO induces a net uncertainty to the TSI record of **98 ppm (24 ppm/yr)**, with 15 ppm attributable to the SORCE-to-TCTE gap, 10 ppm to the TCTE stability during one year of operation, and 73 ppm to the 2.5-year TCTE-to-TSIS gap.

This case is no improvement over that in §4.2 because it assumes the imminent loss of the stable SORCE/TIM measurements, whereas in §4.2 the SORCE/TIM continued until the end of 2013. Repeating the analysis of §4.2 for an imminent failure of the SORCE mission gives a net induced uncertainty of 116 ppm (29 ppm/yr) for better comparison with the result here.

Lacking overlap with both SORCE and TSIS and having only a 1-year duration, TCTE provides little improvement for spanning the SORCE-to-TSIS gap (compare to §4.2).

4.5. TCTE Overlaps with SORCE Only

If SORCE lasts to provide a minimum of 2 months of overlap with TCTE, during which time TCTE acquires its minimum of one orbit of measurements every two days, the continuity of the TSI record in the near future is greatly improved. The SORCE/TIM's low measurement noise allows nearly cotemporaneous high cadence data comparisons between it and the TCTE's orbital measurements, reducing offset uncertainties due to the TCTE's subsampling of solar variability and improving connection of the two data records.

VIRGO is still chosen to fill the TCTE-to-TSIS gap of 2.5 years. In this scenario, the net uncertainty induced in the TSI record is **88 ppm (22 ppm/yr)**, with 5 ppm from the 6-month SORCE-to-TCTE period, 10 ppm for the TCTE's 1-year duration of measurements, and 73 ppm for the 2.5-year TCTE-to-TSIS gap.

This scenario is similarly limited by the TCTE-to-TSIS gap filled by VIRGO, as in §4.4; so *while TCTE provides very little improvement over a SORCE-to-TSIS gap, it prolongs* *the stability of the TSI record until the end of the TCTE mission*, which may allow time to implement alternate measurement approaches.

4.6. TCTE Overlaps with SORCE and TSIS

If SORCE lasts to provide 2 months of overlap with the TCTE and the TCTE lasts to provide 2 months of overlap with the subsequent TSIS/TIM, assumed here to start in late 2016, expected uncertainties induced in the TSI record over these four years from the three stable and overlapping instruments are **40 ppm (10 ppm/yr)**, with 5 ppm from the 6-month SORCE-to-TCTE period, and 35 ppm for the following continuous TCTE operations.

If the STP-Sat3 – despite its 1-year lifetime requirement – lasts 4 years and provides 2 months of overlap with the TSIS/TIM, the stability of the TSI record is maintained with CDR levels of stability.

5. Extending the Solar Data Record from SORCE to TSIS Using Models

The record of TSI that SORCE/TIM established beginning in 2003 has an estimated absolute accuracy uncertainty of 350 ppm and a stability uncertainty of 10 ppm per year. These capabilities exceed those of other ongoing TSI measurements by VIRGO, ACRIM3, and PREMOS; Figure 6 and Table 5 show that these instruments drift relative to the TIM by much more than the required long-term stability. The TIM instrument planned for TSIS is expected to have accuracy 100 ppm and stability 10 ppm per year (Table 1).

Models of TSI variability constructed from the SORCE/TIM data are unavoidably less accurate and less repeatable than the direct TIM observations because of additional uncertainties accruing from the proxy indices that the model uses, the assumption that these proxies are able to reproduce the actual physical causes of TSI variability, and the statistical uncertainties in the coefficients that relate the model's proxies with the direct observations. A model's absolute scale is on average that of the instrument database used to construct it; the models make no attempt to estimate the actual TSI absolute value. A model's stability – and hence its capability of estimating true TSI variability during a measurement gap – depends crucially on drifts in the proxy indices that the model uses. For any model of TSI variability to be useful in mitigating gaps between direct TSI observations, these indices must have appropriately low long term stability uncertainties for the duration of the gaps, which may range from years (in the case of no direct measurements between SORCE and TSIS, as assessed in Study A, or TCTE, as assessed in this Study B) to days or weeks (in the case of the proposed minimum one-measurement-per-week with TCTE/TSIS that this Study B assesses).

5.1. Formulation of TSI Variability Regression Models

Models of TSI variability have been developed by combining indices representative of solar activity. Two prominent such indices are sunspots darkening and facular brightening, which are known primary solar sources of irradiance variability. The sunspot and facular indices, I_{spot} and I_{fac}, are obtained from a variety of ground and space-based datasets and converted to equivalent change that each produces on the TSI according to

$$\mathrm{TSI(t)} = \mathrm{TSI_0} + \Delta\mathrm{TSI_{spot}(t)} + \Delta\mathrm{TSI_{fac}(t)}$$

$$\Delta\mathrm{TSI_{spot}(t)} = \mathrm{a_0} + \mathrm{a_1 I_{spot}}$$

$$\Delta\mathrm{TSI_{fac}(t)} = \mathrm{b} + \mathrm{b_1 I_{fac}}$$

The coefficients a_0, a_1, b_0, b_1 and TSI_0 are determined from multiple linear regression of the sunspot and facular indices against the directly observed TSI.

5.2. TSI Observations for Model Construction

The models of TSI variability used in this study are constructed using the TSI measurements made by TIM for the duration of the SORCE mission and, for comparison, an average of the TSI composites based on SoHO/VIRGO (the PMOD composite) and the ACRIM instruments (the ACRIM composite) from 1978 to the present. Figure 1 and Figure 2 illustrate and compare these composites. Prior to constructing TSI variability models, the PMOD and ACRIM composites are adjusted to the TIM absolute scales by applying absolute calibration differences of -4.45 $\mathrm{Wm^{-2}}$ and 0.49 $\mathrm{Wm^{-2}}$, respectively (Table 2).

5.3. Sunspot Darkening Indices

Sunspot darkening (also called the sunspot blocking function, or the photometric sunspot index) is specified using indices derived independently by five different groups from a variety of ground- and space-based observations of the Sun (typically magnetograms and white light images). Figure 10 illustrates the following sunspot darkening indices: the sunspot blocking function derived at NRL using sunspot regions that the USAF reports from multiple white light solar images in the SOON network; the Mt. Wilson sunspot area index derived from ground-based magnetograms; the STARA daily projected sunspot area obtained by processing SoHO/MDI and SDO/HMI full-disk images; the San Fernando Observatory sunspot deficit index; and the Debrecen projected sunspot area index derived from ground-based images.

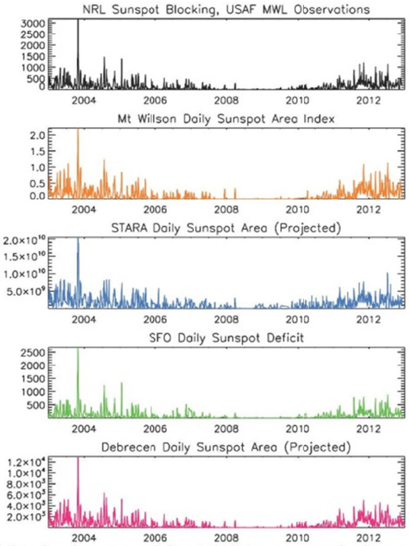

Figure 10: Compared for the duration of the SORCE mission, which is approaching one solar cycle, are five different time series that are used as proxy indicators of sunspot darkening in models of TSI variability. The NRL sunspot blocking function (top) and the SFO daily sunspot deficit both account for the projected sunspot area and contrast, whereas the Mt. Wilson, SFO, and Debrecen daily sunspot time series do not account for sunspot contrast, which some studies indicate is area dependent.

5.4. Facular Brightening Indices

Facular brightening (also called the photometric facular index) is specified using indices derived from both space- and ground-based observations of the Sun. Figure 11 illustrates the following facular brightening indices: the Mg II irradiance (i.e., sun-as-a-star) index derived from solar spectra in the vicinity of 280 nm measured by SORCE/SOLSTICE; the Mt Wilson facular area index derived from ground-based magnetograms; and the San Fernando Observatory facular area and facular excess indices, and the Ca II K line emission index derived from ground-based images. Additional facular indices are also available from measurements of the Ca II K line emission (in the vicinity of 390 nm) made by the KPNO SOLIS and Sacramento Peak programs and by the Kitt Peak Vacuum Telescope.

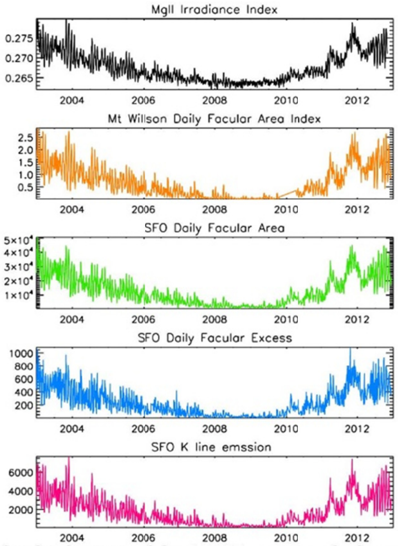

Figure 11: Compared for the duration of the SORCE mission, which is approaching one solar cycle, are five different time series that are used as proxy indicators of facular brightening in models of total solar irradiance variability. The Mg II index (top), the SFO Daily Facular Excess, and the SFO K line emission are global (i.e., sun-as-a-star irradiance) indices that record the integrated emission from bright areas on the solar disk, projected to Earth. The Mt. Wilson and SFO Daily Facular Area time series do not account for facular contrast or center-to-limb variations.

5.5. Models of TSI Variability

Multiple models of TSI variability are constructed for this report using selected combinations of sunspot and facular indices, determining the models' parameters by fitting to the direct TIM TSI observations (from 2003 to 2012) and to the average of the PMOD and ACRIM TSI composites (from 1978 to 2012). Table 6 provides statistical comparisons of each of ten different models of TSI variability constructed based on the SORCE/TIM observations (upper portion of table) and the average PMOD and ACRIM composites (lower). Figure 12 compares four models constructed from the TIM observations with the directly measured daily averaged time series, and Figure 13 compares four models constructed from the average PMOD and ACRIM composites with the daily averaged composite time series.

According to the metrics in Table 6, of the ten models considered, the NRL TSI variability model reproduces the SORCE/TIM observations with the highest fidelity: the correlation coefficient is highest (with r=0.961, the model explains 92% of the variance that the TIM observes), and both the standard deviation of the model's differences from the observations and the long term slope in these differences are lowest. The slope of the differences over the entire 10 years is 0.0055 W m^{-2} yr^{-1} (4 ppm per year) with this model, which is less than the TIM long-term stability uncertainty (estimated to be 10 ppm per year). This model uses the sunspot darkening calculated from USAF ground-based multiple white light images and the Mg II index for facular brightening measured by the SORCE/SOLSTICE instrument. A part of the reason for the NRL model's better statistical metrics is likely due to the higher (daily) cadence of the model values. In comparison, the Mt. Wilson Observatory and the San Fernando Observatory record the sunspot and facular indices less frequently than daily.

While the models of total solar irradiance have comparable stability (< 10 ppm per year) to the direct TIM observations when assessed over ten years, differences are larger on shorter time scales, as seen in Figure 12 and Figure 13.

Table 6: Comparison of TSI Models and Observations During the SORCE Epoch (2003-2012).

Observations, Model Sunspot and Facular Indices (# of days)	**Correlation Coefficient of Model with Observations**	**Standard Deviation of Model Differences from Observations W m^{-2}**	**Slope of Model Differences from Observations W m^{-2} yr^{-1}**
TIM NRL USAF Spot Blocking, Mg Index (3448) NRL Debrec Spot Area, Mg Index (3462)	0.961 0.956	0.102 0.108	0.0042 0.0052
TIM Mt. Wilson Spot Area, Facular Area (2564)	0.913	0.150	0.0124
TIM SFO Spot Area, Facular Area (1794)	0.938	0.131	0.0106
TIM SFO Spot Deficit, Facular Excess (1788)	0.942	0.127	0.0055
PMOD+ACRIM Average NRL USAF Spot Blocking, Mg Index (10931) NRL Debrec Spot Area, Mg Index (10902)	0.895 0.894	0.266 0.267	-0.0042 -0.0007
PMOD+ACRIM Average Mt. Wilson Spot Area, Facular Area (8143)	0.817	0.337	-0.0018
PMOD+ACRIM Average SFO Spot Area, Facular Area (4602)	0.872	0.280	-0.0093
PMOD+ACRIM Average SFO Spot Deficit, Facular Excess (4597)	0.894	0.257	-0.0061

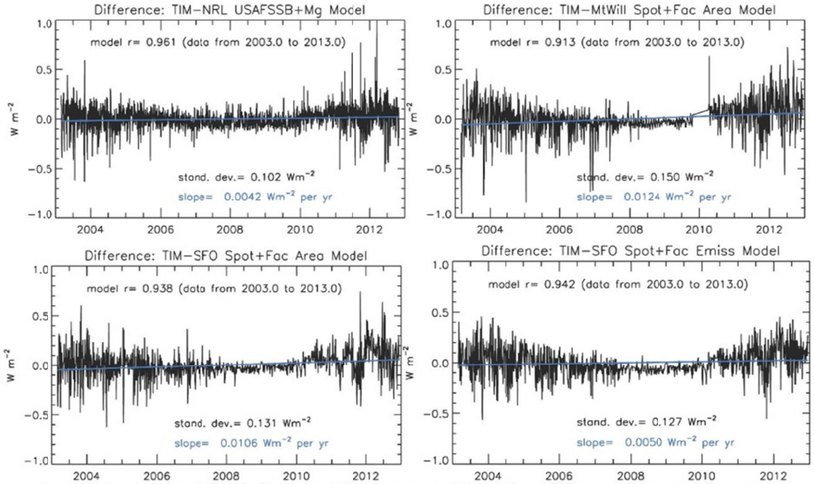

Figure 12: Models of the daily mean TSI constructed from four different datasets of sunspot darkening and facular brightening fitted to SORCE/TIM data.

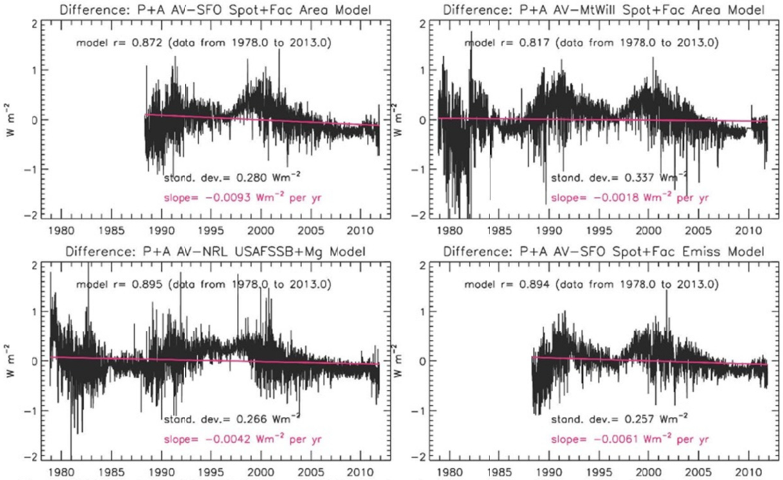

Figure 13: Models of the daily mean TSI constructed from four different datasets of sunspot darkening and facular brightening over the duration of the spaceborne TSI data record.

5.6. Scenarios for Model Comparisons with TCTE/TIM

Maintaining the TSI climate data record in the near future relies on 1) cross calibration of overlapping TSI measurements made with high absolute accuracy, 2) continuous monitoring of TSI variations as the solar cycle evolves with high instrument stability (long-term repeatability) on time scales of years to decades, and 3) frequent sampling of the TSI variations throughout each day with high precision (low noise).

Measurement overlap remains essential because uncertainties in the absolute accuracies of different TSI measurements exceed the amplitudes of true solar irradiance variations (see Figure 3). Long term continuous monitoring of TSI variations with good stability is essential to both characterize solar cycle amplitudes, and ultimately, for the detection of possible longer-time scale changes that may underlie the solar activity cycle. The frequent sampling throughout each day is necessary because TSI can vary over a day and from day-to-day by amounts comparable to its variations during the solar cycle; if not properly sampled, this natural variability can add significant uncertainty to the radiometric comparisons needed to cross calibrate different TSI observational datasets, thus affecting long term trend determination, and to refine TSI models. Since day-to-day variability is significantly larger during higher solar activity than during solar minimum, this uncertainty can depend on the phase of the solar cycle during overlap periods.

A limitation of the TCTE/TIM measurements is their infrequent cadence of a minimum of one orbit per week. To assess the ability of models of TSI variability to provide additional information that may reduce uncertainties in the solar irradiance CDR arising from gaps among TSI observations, scenarios are considered in which the TCTE/TIM provides one measurement of TSI per week for one year at different phases of the solar cycle.

Each TSI variability model is adjusted to the simulated TCTE/TIM measurements by a scaling determined in one-year intervals. Augmenting the TCTE/TIM measurements with these (scaled) model values provides a record of TSI variability with higher daily cadence than is afforded by TCTE/TIM direct measurements alone. In these scenarios, SORCE/TIM's daily mean observations are assumed to be the "true" total solar irradiance. The TCTE/TIM measurements of this quantity one-orbit-per-week are represented by selecting one SORCE/TIM measurement per orbit on one day of each week. The resultant TSI time series constructed using these representative TCTE/TIM observations combined with the scaled model values is then compared with the full SORCE/TIM dataset of daily mean observations by evaluating the standard deviations and the slopes of the daily observation-to-model differences.

Figure 14 shows annually averaged values of the simulated TCTE TSI record, compared with SORCE/TIM's directly measured daily averaged TSI. The annual averages of the standard deviations and slopes of the daily differences are also shown; each of these annual values simulates the uncertainty in true TSI for a one-year duration TCTE mission augmented with scaled values from TSI variability models. The second top panels in Figure 14 show that during low to moderate solar activity (2006-2011) the simulated TCTE TSI values, on average, agree with the "true" (i.e., SORCE/TIM) annual average values to within 20 ppm. The agreement deteriorates to as much as 40 ppm differences during higher solar activity (2003, 2012). The bottom panels show that the slopes of the TCTE TSI for any individual year can differ from the "true" TSI trend by up ±50 ppm per year. Comparison of the figures on the right and left show that these statistical parameters can differ slightly depending on the phasing of the TCTE measurement cycle within the week. Only in some select years, under certain conditions (e.g. in 2006-2012 in the right panel), do simulated TCTE TSI time series achieve the CDR requirement of maintaining the long term TSI precision to within 10 ppm per year.

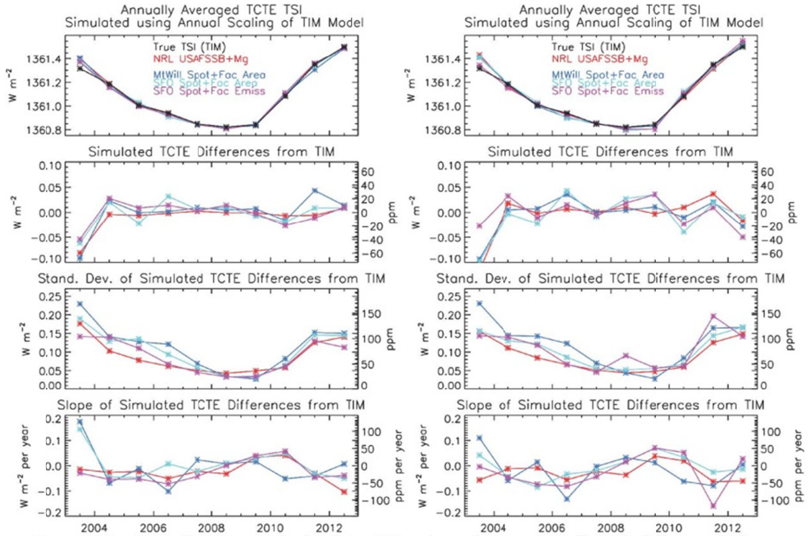

Figure 14: Annually averaged absolute TSI values (upper panel) and differences from SORCE/TIM's direct observations (second panel) of TSI time series simulated for TCTE/TIM, with one observation per orbit per week and assimilation of various TSI variability models (indicated by different colors). Shown in the two bottom panels are the standard deviations and slopes of the daily differences between the observed (TIM) and simulated (TCTE) TSI values, for each year from 2003 to 2012. The right- and left-hand figures correspond to TCTE direct observations made on 2 different days (0, 2) of the week.

5.7. *Future Availability of Model Inputs*

Each of the models of TSI variability used for assimilation into the one orbit per week TCTE/TIM simulations requires two inputs: an index of sunspot darkening and an index of facular brightening. None of these indices is produced with an operational program that has the express purpose of generating inputs for TSI variability models.

Thus, there is no guarantee that all, or even any, of the indices that enable current models of TSI variability will be acquired or available during the TCTE measurement period. And for those indices that are available, there is no guarantee that the measurement cadence will be daily, or even weekly, but rather when opportunity, viewing conditions, and funding allow. During the TCTE measurement period, sunspot indices suitable for modeling TSI variability are more likely to be available than are facular indices. The lack of the stable, reliable Mg II facular index, currently being provided by the SORCE/SOLSTICE, is likely the largest single factor that will degrade the TSI variability model capability (long-term stability) below that assessed in this analysis.

6. Summary

Neither alternate currently on-orbit TSI instruments nor solar models can fill an expected SORCE-to-TSIS TIM measurement gap with the required solar climate data record stability. With a TSIS launch late in 2016 and a 1-year baseline TCTE mission duration beginning in late 2013, as analyzed in this report, TCTE will maintain the record's current level of stability for the duration of the STP-Sat3 mission if it overlaps with SORCE, but will otherwise provide only marginal stability improvement to the TSI record across a SORCE-to-TSIS gap because of its short duration and lack of direct connectivity to the SORCE/TIM record. Only if the TCTE overlaps with both SORCE and TSIS are the CDR stability requirements maintained until TSIS launches.

Although they fail to meet the TSIS CDR requirements by a factor of three, we show that VIRGO data provide the best TSI values in both stability and noise for filling TIM measurement gaps of the anticipated durations. The NRL model provides the next best alternative should the VIRGO data not be available.

We find that the planned TCTE low observing cadence does not limit the TSI record long-term stability provided that the TCTE overlaps with each of the surrounding instruments for two months.

D
Biographical Sketches of Committee Members

Graeme Stephens (Chair) is currently the Director of the Center for Climate Sciences at the Jet Propulsion Laboratory at the California Institute of Technology. Dr. Stephens completed his B.S. with honors from the University of Melbourne in 1973 and received his Ph.D. in 1977 from the same university. He was appointed to the CSIRO Division of Atmospheric Research in 1977 as a Research Scientist and promoted to Senior Research Scientist in 1982. From 1979 to 1980, Professor Stephens served as a Post-Doctoral Research Student at the CSU Department of Atmospheric Science. He joined the faculty as an Associate Professor in 1984 at CSU in the Department of Atmospheric Science, was promoted to full professor in 1991 and was appointed as a University Distinguished Professor in 2005. Dr. Stephens' research activities focus on atmospheric radiation including the application of remote sensing in climate research to understand the role of hydrological processes in climate change. He also serves as the Primary Investigator (PI) of the NASA CloudSat Mission. In 2008 he was appointed as Direct of the NOAA Co-operative Institute for Research in the Atmosphere (CIRA) and has served as chairman of a number of national and international panels.

Joanna Haigh is a Professor of Atmospheric Physics and Head of the Department of Physics at Imperial College London. Dr. Haigh completed her M.Sc. at Imperial College London and received her D.Phil. from the University of Oxford. She has published widely in the area of radiative transfer in the atmosphere, climate modeling and radiative forcing of climate change. Professor Haigh is President of the Royal Meteorological Society and Editor of the Journal of Atmospheric Sciences, she was a Lead Author of the Intergovernmental Panel on Climate Change Third Assessment and has served on many UK and international scientific panels. She is a Fellow of the Institute of Physics and of the Royal Meteorological Society; she received the 2004 Institute of Physics Charles Chree Medal and Prize and the Royal Meteorological Society 2010 Adrian Gill Prize for her work on the influence of solar irradiance variability on climate. In 2013 Dr. Haigh was elected a Fellow of the Royal Society of London.

John W. Harvey is an Astronomer at the National Solar Observatory in Tucson, Arizona. He received his M.A. in Astronomy from the University of California and his Ph.D. in Astro-Geophysics from the University of Colorado. Dr. Harvey's main research interests include helioseismology, polarimetry, magnetic fields, and the solar cycle. He received a NASA Exceptional Scientific Achievement Medal in 1990 for research on the solar interior conducted in Antarctica. In 1999, he received the George Ellery Hale Prize, an award that is given annually by the Solar Physics Division of the American Astronomical Society for outstanding contributions to the field of solar astronomy. In 2011, he was awarded the Arctowski Medal by the National Academy of Sciences for studies in solar physics and solar-terrestrial relationships. Dr. Harvey is a member of the American Astronomical Society, the American Geophysical Union, the Committee on Space Research, the International Astronomical Union, and the Institute of Electrical and Electronic Engineers. During his career, he has also served on several panels and committees at The National Academies, including most recently, the NRC's Panel on Solar and Heliospheric Physics.

Charles Ichoku is a Research Physical Scientist at NASA Goddard Space Flight Center in Greenbelt, Maryland. He earned his B.Sc. Degree in Surveying, Geodesy, and Photogrammetry, and his M.Sc. in Photogrammetry and Remote Sensing from the University of Nigeria, Enugu Campus. Dr. Ichoku completed his doctoral studies in France at the Université Pierre et Marie Curie (UPMC), Paris, where he received a Diplôme d'Etudes Supérieures Spécialisées (DESS) degree in Remote Sensing and a Ph.D. in Earth Sciences, in 1989 and 1993, respectively. Dr. Ichoku's activities over the years have included developing and applying both experimental and remote sensing approaches to research in various branches of the earth and atmospheric sciences. Currently, he is actively involved in the development of innovative remote sensing techniques for global characterization of fires, their smoke emissions, and atmospheric aerosols in general, as well as evaluating their impacts on the environment and climate. He has won several NASA individual and group achievement awards, and has published more than 40 papers in peer-reviewed scientific journals. In addition to leading several research projects, he has also served in various program-type leadership roles, including research Program Management at NASA Headquarters (2009 – 2011). Dr. Ichoku is currently serving as the Deputy Project Scientist of the Total and Spectral Solar Irradiance Sensors (TSIS) to be launched aboard the NASA/NOAA Joint Polar Satellite System's (JPSS) Free Flyer Mission.

Kuo-Nan Liou (NAE) received his B.S. degree from National Taiwan University in 1970 and his Ph.D. in Meteorology and Oceanography in the School of Engineering from New York University in 1970. After a postdoctoral research associate position at the Goddard Institute for Space Studies/Columbia University and a research faculty position at the University of Washington, Dr. Liou subsequently become an Associate Professor at the University of Utah in 1975 and was promoted to Full Professor in 1980. He served as Director of the Center for Atmospheric and Remote Sensing Studies from 1987-1997 and Chair of the Meteorology Department from 1996-1997. Dr. Liou joined UCLA in 1997 and served as Chair of the Atmospheric and Oceanic Sciences Department from 2000-2004. He is currently a Distinguished Professor of Atmospheric Sciences and, since 2006, Director of the Joint Institute for Regional Earth System Science and Engineering. Professor Liou has held joint appointments with the Mechanical and Aerospace Engineering Department since 2003 and the Electrical Engineering Department since 2010. Dr. Liou was elected to the National Academy of Engineering (NAE) in 1999 for contributions in the theories of radiation transfer and light scattering, with applications to remote sensing technology and climate modeling. He was Chair of the NAE's Special Fields and Interdisciplinary Engineering Section from 2008-2010 and is currently a member of its Nominating Committee. Dr. Liou has served NRC on numerous occasions as a Report Review Monitor and Coordinator. His current research interests include electromagnetic scattering by ice crystals and aerosols, satellite remote sensing, radiative transfer, and climate modeling. Specifically, his research activities span from regional climate modeling and validation using satellite data to direct and indirect effects of aerosols on cloud radiative forcing and snow-albedo feedback, radiative transfer in 3D mountains and surface energy balance in climate models, and laboratory light scattering and spectroscopy involving small ice crystals and aerosols.

Joseph Rice performs research and develops novel systems for electro-optical instrument calibration, validation, and performance evaluation at the National Institute of Standards and Technology (NIST). These systems have included a NIST primary standard facility for optical power responsivity measurements and portable radiometers for transferring NIST radiometric scales to other calibration facilities. Currently he is leading the NIST efforts in development of the Hyperspectral Image Projector (HIP), and he serves as the Group Leader of the Infrared Technology Group in the Sensor Science Division at NIST. Dr. Rice is a member of the Optical Society of America (OSA), the Society of Photo-Optical Instrumentation Engineers (SPIE), the Council for the Optical Radiation Measurements (CORM), and the American Geophysical Union (AGU). He was the recipient of a NIST Bronze Medal in 2004 for developing the Thermal-infrared Transfer Radiometer (TXR), a NIST Bronze Medal in 2011 for developing the HIP, and a Department of Commerce Gold Medal in 2012 for leading the NIST contributions toward understanding sources of differences in absolute measurements reported by different Total Solar Irradiance (TSI) satellite instruments. Dr. Rice was also awarded a National Research Council Post-doctoral Research Associateship in 1992.

William Smith is a Distinguished Professor of the Department of Atmospheric and Planetary Sciences at the Hampton University, Hampton Virginia and Professor Emeritus of the Department of Atmospheric and Oceanic Sciences at the University of Wisconsin – Madison. Professor Smith was the Principal Investigator of several satellite programs for NOAA (1966-1984), Professor of Atmospheric and Oceanic Sciences at the University of Wisconsin-Madison (1984-1997) where he also directed the Cooperative Institute for Meteorological Satellite Studies (CIMSS) and subsequently the positions of Chief, Atmospheric Sciences Division, and Senior Scientist at the NASA's Langley Research Center (1997-2004). Dr. Smith is an active satellite and airborne experimentalist. Most notably, Dr. Smith pioneered the hyper-spectral resolution sounding technique that is being used for current and future polar satellite advanced infrared sounding systems (e.g., the Aqua/AIRS, MetOp/IASI, and NPP/NPOESS CrIS). Dr. Smith has published more than 150 papers in the scientific literature and has contributed to books used for scientific research and teaching. Dr. Smith has received numerous awards for his research accomplishments in the field of atmospheric science.

Bruce Wielicki is a Senior Scientist for Radiation Sciences and Science Directorate at NASA Langley Research Center. He currently serves as Science Team lead for the CLARREO (Climate Absolute Radiance and Refractivity Observatory) decadal survey mission. He served as Principal-Investigator on the CERES Investigation for 18 years, and as a Co-Investigator on the NASA CloudSat and Cloud-Aerosol Lidar and Infrared Pathfinder Satellite. For over twenty years, Dr. Wielicki's research has focused on clouds and their role in the Earth's radiative energy balance. Specific research interests include the following: remote sensing of single and multiple cloud layer properties from multispectral imagery; validation of remotely-sensed cloud properties; effect of clouds on the Earth's radiation budget; and cloud radiative transfer modeling. Dr. Wielicki received his B.S. degree in Applied Math and Engineering Physics from the University of Wisconsin - Madison in 1974 and his Ph.D. degree in Physical Oceanography from Scripps Institution of Oceanography in 1980. He received a NASA Exceptional Scientific Achievement Award in 1992 and the Henry G. Houghton Award from the American Meteorological Society in 1995.