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Key Points:

- We present a new approach for merging different solar irradiance time series into a single composite
- We provide a new and fully traceable composite of the total solar irradiance
- We quantify uncertainties in the total solar irradiance composite and demonstrate a $1/f$ scaling in them

Supporting Information:

- Supporting Information S1

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Methodology to create a new total solar irradiance record: Making a composite out of multiple data records

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Abstract Many observational records critically rely on our ability to merge different (and not necessarily overlapping) observations into a single composite. We provide a novel and fully traceable approach for doing so, which relies on a multiscale maximum likelihood estimator. This approach overcomes the problem of data gaps in a natural way and uses data-driven estimates of the uncertainties. We apply it to the total solar irradiance (TSI) composite, which is currently being revised and is critical to our understanding of solar radiative forcing. While the final composite is pending decisions on what corrections to apply to the original observations, we find that the new composite is in closest agreement with the PMOD composite and the NRLTSI2 model. In addition, we evaluate long-term uncertainties in the TSI, which reveal a $1/f$ scaling.

1. Introduction

Combining different (and only partly overlapping) time series of the same physical quantity into a single composite is both a scientific and a statistical challenge that arises in many contexts, in particular in paleoclimatic reconstructions [Mann *et al.*, 2008]. In space sciences, observations are often constrained by the finite lifetimes of satellites, making composites the key to investigation over long timescales. A timely and demanding application is the reconstruction of the total solar irradiance (TSI), which is the spatially and spectrally integrated radiant output from the Sun at a mean Sun-Earth distance of 1 AU [Kopp, 2014].

The TSI has been continuously measured since November 1978 by over a dozen instruments and is paramount to understanding the Earth's global energy budget [Trenberth *et al.*, 2009]. Weak secular variations in the TSI are hotly debated, as they may have large implications on our understanding of the role of the Sun in climate change [Ermolli *et al.*, 2013].

The nominal value of the TSI, averaged over Solar Cycle 23 (which lasted from 1996 to 2008), is 1361.0 ± 0.5 (W/m^2), with a weak peak-to-peak solar cycle modulation of 0.08% that is in phase with the 11 year cycle [Kopp, 2016]. Assessing such tiny modulations requires not only high radiometric accuracy but also considerable care in the making of the composite record.

There currently exist three commonly used TSI composites [Willson, 1997; Fröhlich and Lean, 2004; Mekaoui and Dewitte, 2008], all of which are made by daisy chaining: different records are stitched together by comparing them during an overlap period when at least two instruments are observing [e.g., Fröhlich and Lean, 1997]. This approach has several shortcomings. For each day, only a single instrument is selected for building the composite, and thus, complementary cotemporal information is lost. In addition, the choice of the most trustworthy instrument introduces a bias toward preconceived ideas of how the TSI should vary.

Largely because of these shortcomings, these three composites show different trends in time [Zacharias, 2014], which has fueled a continuing debate. A trend in the TSI measurement record, if any, would have major implications on the historical reconstruction of TSI from models. To address this issue, the decision was made to create a new composite that would be fully traceable and based on community involvement. This composite should combine the original records with no reliance on any external proxy by using state-of-the-art statistical methods. Here we concentrate on this methodology and introduce a novel, probabilistic approach that can be readily exported to other contexts.

Table 1. Observations Used in This Study^a

Instrument	Version	Start Date	End Date
HF/NIMBUS-7 ERB		1978/11	1993/1
ACRIM1/SMM	a	1980/2	1989/7
ERBE/ERBS		1984/10	2003/8
ACRIM2/UARS	b	1991/10	2000/9
VIRGO/SOHO	c	1996/1	active
ACRIM3/ACRIMSAT	d	2000/04	2013/2
TIM/SORCE	e	2003/3	active
PREMOS/PICARD	f	2010/07	2014/2

For details on the individual instruments, see Fröhlich [2012]. All instruments provide daily values except for ERBE. Some instruments that are less frequently used and/or have been observing for shorter periods are not included in this list. Version: (a) 1, (b) 7/14, (c) 6.005.1602, (d) 11/13, (e) 17, and (f) 1.

2. Original Data

The eight instruments that are routinely used for making the TSI composite are listed in Table 1, and their records are illustrated in Figure 1. Most observe on a daily basis, with occasional interruptions and outliers. Usually, one to three of them are operating simultaneously, although some days are devoid of observations. Figure 1 highlights the challenge of measuring a weakly varying TSI in absolute units: all instruments agree well on the amplitude of relative variations but differ in their baseline. The two most recent radiometers (TIM and PREMOS) are the only ones that accounted for internal-instrument scatter effects prior to launch and thus do not require subsequent large corrections as the others do. These two instruments will hereafter serve as a reference for the absolute value of the TSI for this paper.

Our main working hypotheses are that all observations are (1) well dated and resolve daily variations of the TSI; (2) made on a regular time grid, which prevents needing to resample them; and (3) correct except for an offset in their absolute value and errors that are within the uncertainty. Short gaps in observations and uncorrected instrument drifts are also acceptable.

Daily TSI observations actually mask disparities: all instruments make several observations per day (with a cadence of up to 50 s for TIM) and then average these to produce a daily average. ERBE, however, on average observes the Sun once every 14 days for 3 min. Instruments also differ in the way their in-flight degradation is corrected, and several records suffer from issues such as occasional satellite off pointing. Such effects emphasize the need for including time-dependent uncertainties in the composite; these are lacking in present composites.

3. Methodology

Raw TSI data are displayed in Figure 1, showing that few instruments have observed the TSI for more than a solar cycle. One of the greatest challenges with daisy chaining is maintaining continuity across data gaps. In particular, the impact of the 2 year data gap from July 1989 to October 1991 from when ACRIM1 ceased operating to when ACRIM2 started remains hotly debated because the only instrument observing during this time, the ERBE, had no degradation-correction monitor of its single sensor.

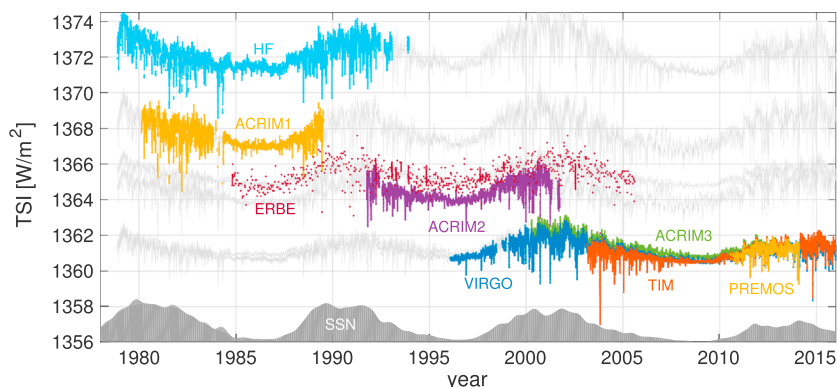


Figure 1. Original data sets used in this study, in absolute units. Also shown is the sunspot number (SSN), averaged over 6 months, in arbitrary units. The gray extension of each record represents the reconstruction obtained by expectation-maximization, see section 3. These extrapolations are used for the sole purpose of applying the wavelet transform in a systematic way and are not used for analysis purposes.

The probabilistic approach we advocate overcomes these problems in a natural way with two significant improvements over existing approaches. First, we use all available observations, weighted by their uncertainties. Ideally, we would rely on time-dependent uncertainties provided by the instrument teams. However, these are rare and, even when available, often cannot be meaningfully compared because they do not use a common estimation methodology. At best, they may serve in relative terms, for example, to indicate how the uncertainty evolved during mission life. To bypass that issue and compare the instruments more uniformly, we require a common metric for all data sets. For that purpose, we use a data-driven approach, which does not rely on any preconceived proxy or TSI model. Second, we decompose the data into different timescales and perform the averaging scalewise. While instruments may agree well on one timescale (e.g., the 27 day solar rotation period), they may give more contrasting results at other scales.

4. Uncertainty Estimation

Uncertainty of the TSI can be classified as precision, stability, or accuracy [Schöll *et al.*, 2016]. Precision is the error associated with random fluctuations and can be estimated by various means [Dudok de Wit *et al.*, 2016]. Estimating the stability, which is the error associated with long-term variations, is considerably more difficult. Finally, accuracy concerns the error on the absolute value, which is determined by instrument calibrations. Accuracy estimation is beyond the scope of this study, so we use as an absolute value the average of TIM and PREMOS, which agree with only small differences that are well within their estimated accuracy uncertainties. This value is also consistent with that reported by Kopp and Lean [2011].

Precision is usually estimated by considering the high-frequency components of the signal, which we assume to be a mix of a slowly varying solar signal with additive incoherent fluctuations that are mostly of instrumental origin. This is indeed supported by those instruments that observe with subdaily cadence. To estimate the fluctuation level, we consider an autoregressive model [Mann and Lee, 1996; Dudok de Wit *et al.*, 2016], which provides an estimate $\hat{l}(t)$ of the present value of the TSI from a linear combination of its p previous observations

$$\hat{l}(t) = a_1 l(t-1) + \dots + a_p l(t-p), \tag{1}$$

where $l(t)$ is the TSI variability relative to its time-averaged value. The difference $\epsilon(t) = l(t) - \hat{l}(t)$ between the observed and modeled TSI, which is called innovation, represents the nonreproducible high-frequency noise. We find that models of order $p \sim 5$ provide a good compromise between goodness of fit and overfitting [Percival and Walden, 1993], with no substantial decrease in the innovation for larger orders (see supporting information). In what follows we thus set $p = 5$ and fit the model independently to each record. Our precision is now given by $\sigma_l = \sqrt{\langle \epsilon(t)^2 \rangle_t}$. For this particular study, we consider σ_l as constant in time, although one could easily let it vary in time. The average precision ranges from 0.07 (W/m²) (for TIM) to 0.8 (W/m²) (for ERBE). For TIM and PREMOS, these values are within a factor of two of the precisions stated by the instrument teams. For ACRIM2 and older instruments, the precisions are systematically larger than stated.

The quantity of prime interest here is the uncertainty on longer timescales, i.e., the stability. Estimating it without the help of any external reference is a notoriously difficult task. Most studies implicitly make a white noise hypothesis, which is akin to saying that stability equals precision. While this assumption is mathematically convenient, it is unproven for existing TSI instruments.

To determine how the uncertainty scales with frequency, we consider the dispersion between the instruments. Let $I_j(t)$ be the TSI from ACRIM3, VIRGO, and TIM, which are the three instruments that have the longest overlapping period (10.5 years). After centering each record by subtracting its time-average over the considered time-interval ($\tilde{I}_j(t) = I_j(t) - \langle I_j(t) \rangle_t$) we determine the residual error, defined as $e_j(t) = \tilde{I}_j(t) - \frac{1}{3} \sum_{i=1}^3 \tilde{I}_i(t)$. This error quantifies the discrepancy between the three instruments, and its power spectral density provides a frequency scaling appropriate for the three contributing TSI instruments; see Figure 2.

Interestingly, the power spectral density of the residual error scales almost as $1/f$, where f is the frequency, and thus strongly departs from a white noise assumption. The same scaling is observed for any combination of TSI instruments with overlapping observations, regardless of their duration, and thus is a robust result. $1/f$ noise, also known as flicker noise, arises in many contexts from shot noise in resistors to seismic oscillations near sea coasts, but, to the best of our knowledge, this is the first published report of flicker noise in solar irradiance observations. If the residual error were instead dominated by linear trends, which would result in a

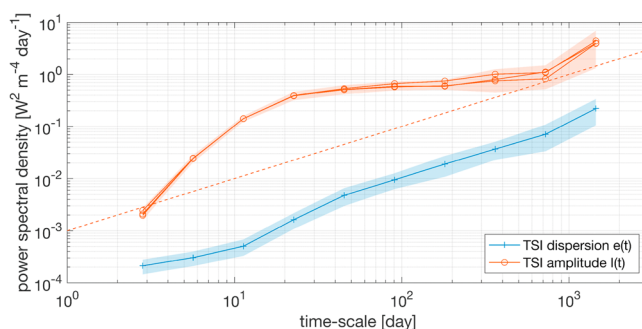


Figure 2. Red: Power spectral density of the TSI. The three curves correspond to ACRIM3, VIRGO, and TIM. Blue: Power spectral density of the residual error $e(t)$. Confidence intervals correspond to a 1σ uncertainty. The spectral density is estimated by using a discrete wavelet transform with fourth-order Daubechies wavelets. The dashed line represents a $1/f$ scaling, with $f = 1/\text{timescale}$.

$1/f^2$ scaling, stability could be defined in terms of TSI error per unit time. This concept of stability is frequently used, for example, to estimate the net uncertainty N years away simply by multiplying the current stability by N . Our findings suggest that this simple linear concept is not correct because the uncertainty is instead fundamentally timescale dependent. While net uncertainty does not increase as fast as linearly with time, it does have a long-term memory which is absent in the common white noise assumption, for which one would have a frequency-independent scaling $1/f^0$. This result cautions the confidence by which most TSI models are extrapolated backward in time by relying on only a few decades of observations.

We are unable to determine how this $1/f$ scaling extends beyond decadal timescales. Assuming that it does at least up to the 40 year duration over which the TSI has been observed, our working hypothesis will be that each instrument is contaminated by $1/f$ noise whose magnitude is set by the precision, as derived from equation (1). This gives us a realistic and fully data-driven noise model by which all instruments can be meaningfully compared without resorting to subjective criteria.

This model could be refined in several ways. For instance, including information from the instrument teams, such as increased precision uncertainty when there is documented evidence of a degradation in the observation conditions, could allow the inclusion of such a priori knowledge in the relative weighting of the data. The short-term uncertainties of ACRIM1, for example, are greater between November 1980 and April 1984 when the attitude control of the SMM satellite was degraded. Our following analyses, however, currently include no such refinements.

5. Multiscale Decomposition

A composite could in principle be built simply by doing a daily weighted average of all available observations. This, however, would introduce artifacts with amplitude jumps occurring whenever the number of observing instruments changes. To overcome this problem, we average both in time and scalewise. First we decompose each TSI record $I(t) = \sum_k I(a_k, t)$ into multiple records that contain information at specific timescales a_k . The records from different instruments are then averaged scale by scale before we recombine them into one single composite. The wavelet transform is ideally suited for this.

We require a wavelet transform that is redundant in time, translation invariant (to be able to assign a precise time tag to each value of the wavelet transform), and orthogonal, so that different scales can be processed independently. The pyramidal wavelet transform with Gaussian kernels [Mallat, 2008] fulfills these conditions.

Wavelet transforms, however, require regularly sampled records with no gaps. To overcome this, we first extrapolate all records over the full time span from 17 November 1978 to 31 December 2015, then fill in all missing values, apply the wavelet transform, and finally, for each scale a , discard the wavelet transform $I(a, t_j)$ at those times t_j for which observations are missing. The missing values are computed by expectation-maximization [Dudok de Wit, 2011]. This approach makes no assumptions regarding solar variability except for the TSI records having high coherence. In particular, we do not impose any solar cycle amplitude or trend.

After applying this expectation-maximization method, we end up with $N=8$ records (one for each instrument) of daily values that cover the same complete time span. By bootstrapping, we find the 1σ uncertainty on the

reconstructed values (for data gaps that are up to 3 months long) to be comparable to that of the observations. This gives us high confidence that the method does indeed offer a good approximation of the TSI.

When computing the wavelet transform in the vicinity of a data gap, the latter will inevitably affect the value of the transform. What could be viewed as a weakness of the wavelet transform then actually becomes one of its main strengths. Let $I(a, t_i)$ be the wavelet transform at a given time t_i with the nearest gap at time t_g . The transform will be influenced by the synthetic data from that gap only if it is located within a cone of influence, defined as $|t_i - t_g| < a$. Conversely, the wavelet transform at a data gap $I(a, t_g)$ will be influenced by nearby observations only if these are close enough. For ERBE, for example, which generally makes one measurement every 14 days, the wavelet transform associated with timescales < 14 days are primarily determined by extrapolated values of the TSI (i.e., on observations from other instruments, when available), whereas slower variations mainly reflect the observations made by ERBE and thus are much less affected by its numerous gaps.

This persistence of the wavelet transform in the vicinity of observations allows us to bridge data gaps in a natural way. In particular, it overcomes the aforementioned problem with the 2 year interruption between ACRIM1 and ACRIM2. To ensure that the method gives precedence to observations when there are nearby data gaps, we let the weight given to the wavelet transform drop off exponentially with a timescale-dependent decay time a when moving away from the nearest observation (see below). In doing so, we allow the wavelet transform at a given time to include some information from nearby synthetic observations while severely restricting its impact to the cone of influence within which the wavelet transform is highly persistent.

The largest timescale is merely the average value of the TSI, which we chose to be the average of the TIM and the PREMOS absolute values.

To summarize, we use a maximum-likelihood approach in which the composite is a weighted average of all the observations with weights that are classically defined as the inverse-squared uncertainty. This averaging is performed on a scale-by-scale basis. The main steps are the following:

1. Fill in all missing values by expectation-maximization and flag them.
2. For each record $j = \{1, 2, \dots, N\}$, estimate the precision $\sigma_j(t)$. If desired, include additional information to increase the precision manually during times when instrumental effects are known to affect the record.
3. Compute the scale-dependent uncertainty $\sigma_j(a, t)$ by extrapolating it with a $1/f$ model for the noise.
4. For each record, estimate the wavelet transform $I_j(a, t)$ at scales $a = \{2, 4, 8, \dots, 2^{N_s}\}$. For the largest scale, replace the wavelet transform by the time average.
5. For each scale a , define the composite as a weighted average

$$I_{\text{comp}}(a, t) = \frac{\sum_{k=1}^N I_k(a, t) w_k(a, t)}{\sum_{k=1}^N w_k(a, t)} \quad (2)$$

in which the scale- and time-dependent weights w are defined as follows:

$$w_k(a, t) = \begin{cases} \sigma_k^{-2}(a, t) & \text{if instrument } k \text{ is} \\ & \text{observing on day } t \\ \sigma_k^{-2}(a, t) e^{-2|T_k(t)|/a} & \text{if instrument } k \text{ is not} \\ & \text{observing on day } t \end{cases} \quad (3)$$

wherein $T_k(t)$ is the temporal distance to the nearest observation for instrument k . These weights are illustrated in the supporting information.

6. Apply the inverse wavelet transform to obtain $I_{\text{comp}}(t)$.
7. Estimate the uncertainty of $I_{\text{comp}}(t)$ by using a Monte Carlo approach in which > 1000 composites are generated with additive noise as described by the noise model.

6. The Composite

Figure 3 presents the resulting TSI composite and compares it to the three primary existing measurement-based composites (ACRIM, PMOD, and RMIB) as well as to model reconstructions by SATIRE-S [Yeo *et al.*, 2014] and NRLTSI2 [Coddington *et al.*, 2016]. We provide two versions of the composite. The first version is based on

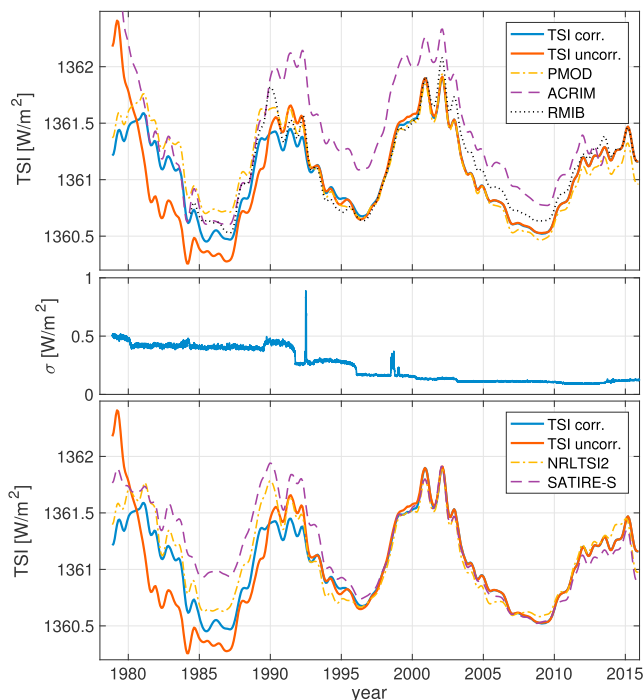


Figure 3. Composite TSI obtained from corrected and uncorrected original records, and their comparison with existing observation-based composites (top) and TSI models (bottom); also shown (middle) is the time-dependent uncertainty (standard deviation) of the composite based on our $1/f$ noise model, with daily resolution. All the other time series show 6 month averages. Note that the same vertical scale is used for all the plots.

the original TSI records as provided by the instrument teams without any correction or rescaling. However, there is evidence that some of the older instruments suffer from uncorrected artifacts. One such example is a likely early signal increase in HF, ACRIM1, and ERBE. This affects all radiometers except the TIM but is better corrected in most instruments since those earlier three. Fröhlich [2006] has corrected several of these records, which we incorporate in the second (so-called corrected) version of our TSI composite.

There is currently growing consensus that Fröhlich’s corrections are a justifiable improvement to the original data. Let us nevertheless stress that neither of our two composites is definitive; our prime objective here is merely to reveal how corrections made to the original data affect the composite.

Figure 3 shows that these corrections affect the composite most notably prior to 1985 but additionally cause a limited impact up to 1993. These early-era differences mainly stem from the initial on-orbit degradations in HF and ACRIM1, with the latter differences due to similar degradation that may affect ERBE over longer timescales. Both are within the 1σ confidence interval, but the final composite’s uncertainties could be reduced if it were known what corrections should be applied.

The decreasing uncertainty seen in Figure 3 mainly reflects an improvement in precision from the newer instruments, and to a lesser degree the larger number of simultaneous observations. Large abrupt peaks occur whenever there are lengthy measurement gaps.

Though our composites are not definitive, comparisons with other reconstructions are illuminating. The agreement of the corrected version of the composite with the PMOD composite is excellent, whereas the large upward trend exhibited by the ACRIM composite exceeds the uncertainty. Regarding models, we find a closer agreement with NRLTS12 than with SATIRE-S, whose downward trend between successive solar minima is larger than supported by the observations. Note, however, that the difference between the two models is still within the estimated confidence interval.

Of particular interest for solar and climate studies is the multidecadal trend exhibited by the TSI during successive solar minima. Both composites show an increase between the minima of 1986 and 1996, followed by a decrease. Given the instrument stabilities, only the downward trend between 1996 and 2009 is statistically

significant; see supporting information. The long-term memory effect of the $1/f$ uncertainty is an important ingredient here, for it generates more variability between the different solar minima than a classical, but unrealistic white noise model.

7. Conclusion

Our new approach brings several major improvements to the longstanding problem of merging of multiple observations into a single, fully traceable composite: (1) the method uses all the available data instead of daisy chaining or choosing a single long-duration instrument as the primary reference (the backbone method); (2) it relies on a data-driven noise model whose uncertainties are estimated in a systematic way without preconceived bias; (3) data gaps are bridged in a natural way thanks to the multiscale nature of the method.

The new TSI composite we obtain is not definitive because the original data still require some community-endorsed corrections. Future versions will also incorporate additional information, such as implementing greater uncertainties during periods of known instrument issues. Meanwhile, we find our composites in closer agreement with that from PMOD than those from ACRIM or RMIB, and similarly closer to the NRLTSI2 model than to the SATIRE-S model. Possible trends between solar minima are too weak to be statistically significant except for the downward trend between 1996 and 2009. Finally, we find the power spectral density of the uncertainty in comparisons between instruments to scale with frequency as $1/f$. As a consequence, the concept of a single-valued stability that is independent of timescale is not appropriate, which precludes extrapolating uncertainties forward or backward in time merely via simple linearly growing values.

Our approach can be readily extended to other types of data. We are presently applying it to spectrally resolved solar irradiance data. One obvious, but mathematically demanding improvement, is to move from a maximum-likelihood approach to a Bayesian one [e.g., Tingley *et al.*, 2012]. This would provide a more natural way of merging observations that scale differently to each other, such as the MgII core-to-wing index or the sunspot number record.

Most importantly, our approach decouples the statistical problem (*What is the best way of constructing the composite?*) from the scientific one (*What prior information goes into the correction of the original data sets?*). Eventually, the only means by which the user should be able to influence the composite's outcome is via estimates of the initial uncertainties, and not by adjusting the TSI records themselves. We consider this decoupling as a vital condition for obtaining an unbiased TSI composite.

Acknowledgments

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