Using ground-based data with SDO space-based images to further our understanding of solar irradiance variation

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The Solar Irradiance Variation Question

Spacecraft experiments show that Total Solar Irradiance (TSI) varies with the solar activity cycle, with maximum irradiance at times of maximum activity. Obtaining sunspot deficit and facular excess values through feature-identification on ground-based images allows the development of a two-parameter model that, when regressed against space-based TSI, helps in the understanding of irradiance variation. The question here is whether or not facular excess information can be obtained from space-based images, in particular, Solar Dynamics Observatory 1600Å and 1700Å images, in order to add to our understanding of this variation? And can we build a meaningful dataset from images at these wavelengths?

Examining solar irradiance variation using a two-parameter model

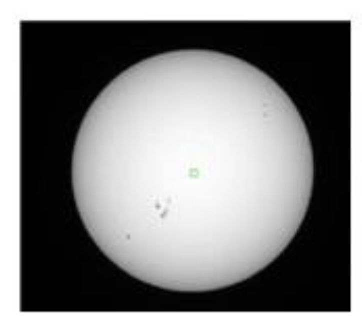
- The San Fernando Observatory approach to understanding irradiance variation uses two separate two-parameter models based on
- (1) sunspot and faculae information obtained from active-region feature identification or
- (2) photometric sums (Σ) from red and Ca II K photometric images.
- These values are regressed against Total Solar Irradiance (TSI) to determine how well they explain variation.

SFO data set: image acquisition

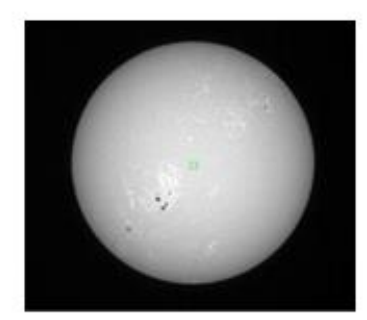
- The San Fernando Observatory (SFO) has a long dataset beginning in 1986, the product of two different-sized aperture telescopes (CFDT1 and CFDT2) that take full-disk photometric images in several different wavelengths. (Walton *et al* (1998 *Sol.Phys.* **179**, 31; www.csun.edu/sfo))
- Each telescope uses a linear diode array, requiring a drift-scan method for obtaining full-disk images in order to build a square image, either 512 x 512 pixels (5" resolution) for CFDT1 or 1024 x 1024 pixels (2.5" resolution) for CFDT2. A scan takes approximately 2 ½ to 3 minutes to complete.
- Primary wavelengths are red (672.3nm, 10nm bandpass) from which sunspot information is extracted and Ca II K (393.4nm, 1nm bandpass) from which faculae information is obtained.

Two Examples of SFO images
September 4, 2001

CFDT1 red (672.3nm)



CFDT1 CaK (393.4nm)



SFO dataset: extracting solar information

- Images are processed within the IRAF environment using software algorithms developed primarily in-house.
- Algorithms produce calibrated photometric contrast images and determine relative irradiance contributions of solar surface features (sunspots, faculae, and plage) from these images. (Walton *et al* (1998 *Sol.Phys.* 179 31))
- Several solar indices are computed, including photometric sums (Σ), sunspot areas and deficits, and faculae areas and excesses, for the purpose of TSI modeling. (Preminger, Walton, & Chapman 2001, *Sol.Phys.* **202** 53)
- Two methods are used to determine solar information. The first uses a threshold method to identify contiguous pixels that are darker or lighter than the surrounding quiet Sun based on a pre-determined contrast criteria. This method identifies sunspots on red images and faculae on Ca II K images.

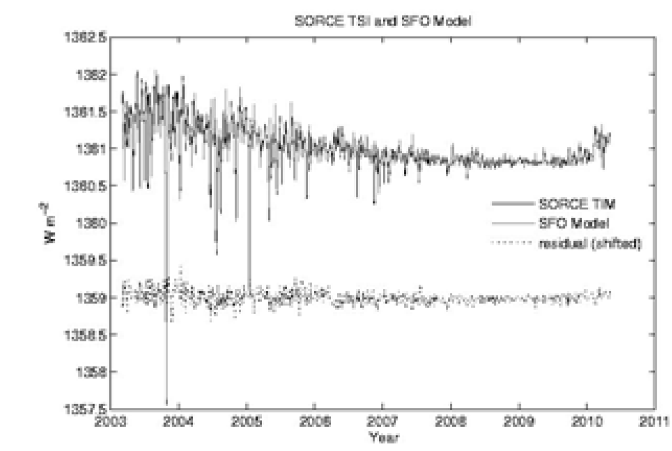
Two methods for constructing a two-parameter model

- **Feature identification** uses a threshold method to identify contiguous pixels on a photometric contrast image that are either darker or lighter than the surrounding quiet Sun surface based on a pre-determined contrast criteria. This method identifies sunspots on red (672.3nm) images and faculae on Ca II K (393.4nm) images. We then primarily compute sunspot areas and deficits; and faculae areas, faculae excesses, and Ca II K excesses. Secondary indices are also computed for possible use in other projects.
- **Photometric sum (Σ)**, which does **not** rely on feature identification, has proven to be one of the most successful photometric indices produced (Preminger, Walton, & Chapman 2002, *JGR*, **107** 6). **Σ** measures the relative change in spectral irradiance in filter passband due to all features and assumes image noise is symmetric around zero, causing bright and dark noise pixels to cancel, leaving only contributions from real features.

  Σ_r and Σ_K are disk-integrated sums determined from red and Ca II K contrast-image pixels, respectively; each pixel is weighted by the appropriate limb-darkening.

  Σ_r measures irradiance contributions from photospheric structures seen in red continuum images. Σ_K measures variability of the upper photosphere/lower chromosphere seen in Ca II K images.

Previous work has shown that a combination of SFO Σ_r and Σ_K closely correlates to SORCE TSI with R^2=0.95. The Σ indices sum all dark and bright pixels across an image (red and Ca II K) to obtain a single value for that image, with no explicit feature identification. The remaining 0.05 can be attributed to noise, both instrumental and solar intensity.



Solar Dynamics Observatory datasets

- We chose wavelengths that originated close to the regions observed by SFO's Ca II K. We also needed images that had a clear and discernable limb in order for SFO's software to work.
- Ca II K (393.4 nm) looks at the upper photosphere/lower chromosphere.
- SDO 1600Å originates in the upper photosphere and in the transition region between the chromosphere and corona.
- SDO 1700Å is in the ultraviolet continuum, looking at the surface of the Sun and the chromosphere.

(www.nasa.gov/content/goddard/sdo-aia-1600-angstrom)
(www.nasa.gov/content/goddard/sdo-aia-1700-angstrom)

The method for determining the feasibility of using SDO 1600Å and 1700Å for solar faculae information

- Data extracted from SFO and SDO images, both sets processed with the SFO algorithms and software, were used in a series of multi-variable linear regressions against space-based TSI [SORCE/TSI].
- The data cover an 8-year period from 2011-01-01 through 2018-12-31.
- Numerous data gaps occur in all data sets due to ground-based weather conditions and/or instrumental issues. Space-based TSI has an instrumental data gap; SDO 1600Å and 1700Å sets are of different lengths. Data sets vary from 784-801 data points.

The regressions: 8 sets of data

- Sunspot deficit and Σ_r data come from SFO red images, both CFDT1 and CFDT2, for all regressions.
- Facular excess and Σ_K data come from both CFDT1 and CFDT2 SFO Ca II K images and SDO 1600Å and SDO 1700Å.
- Feature identification and photometric sum Σ were both used.
- SFO K data comes from three different indices. CFDT1 produces one set of data; CFDT2 produces one set of data; and a composite K-line dataset is produced to account for filter changes in CFDT1 over the length of the project.

R^2 from multi-linear regressions using CFDT1 spot deficit (def) and Σ_r

SDO 1600Å

Feature identification
(CFDT1 spot deficit & K excess) v TSI
(def + cfdt1K) = 0.8224
(def + comp K) = 0.8306
(def + cfdt2 K) = 0.8267
(def + **SDO 1600 K**) = 0.7241

Photometric sum Σ
(CFDT1 Σ_r & Σ_K) v TSI
(Σ_r + cfdt1 Σ_K) = 0.8779
(Σ_r + comp Σ_K) = 0.8782
(Σ_r + cfdt2 Σ_K) = 0.8700
(Σ_r + **SDO 1600** Σ_K) = 0.7934

SDO 1700Å

(CFDT1 spot deficit & K excess) v TSI
(def + cfdt1K) = 0.8262
(def + comp K) = 0.8343
(def + cfdt2 K) = 0.8303
(def + **SDO 1700 K**) = 0.8514

SDO 1700Å
(CFDT1 Σ_r & Σ_K) v TSI
(Σ_r + cfdt1 Σ_K) = 0.8807
(Σ_r + comp Σ_K) = 0.8809
(Σ_r + cfdt2 Σ_K) = 0.8727
(Σ_r + **SDO 1600** Σ_K) = 0.8957

R^2 from multi-linear regressions using CFDT2 spot deficit (def) and Σ_r

SDO 1600Å

Feature identification
(CFDT2 spot deficit & K excess) v TSI
(def + cfdt1K) = 0.8267
(def + comp K) = 0.8364
(def + cfdt2 K) = 0.8337
(def + **SDO 1600 K**) = 0.7237

Photometric sum Σ
(CFDT2 Σ_r & Σ_K) v TSI
(Σ_r + cfdt1 Σ_K) = 0.8819
(Σ_r + comp Σ_K) = 0.8848
(Σ_r + cfdt2 Σ_K) = 0.8809
(Σ_r + **SDO 1600** Σ_K) = 0.8155

SDO 1700Å

(CFDT2 spot deficit & K excess) v TSI
(def + cfdt1K) = 0.8278
(def + comp K) = 0.8374
(def + cfdt2 K) = 0.8347
(def + **SDO 1700 K**) = 0.8536

SDO 1700Å
(CFDT2 Σ_r & Σ_K) v TSI
(Σ_r + cfdt1 Σ_K) = 0.8822
(Σ_r + comp Σ_K) = 0.8851
(Σ_r + cfdt2 Σ_K) = 0.8812
(Σ_r + **SDO 1700** Σ_K) = 0.8912

Results/Conclusions

- For all regressions using only SFO data, Σs give better fits than feature identification. The slight differences between sets using SDO 1600Å and SDO 1700Å are due to the differences in the number of data points the wavelength set.
- SDO 1600Å gives poorer fits than SFO data for both feature identification and photometric sum Σ.
- SDO 1700Å gives slightly better fits than SFO for both feature identification and photometric sum Σ.
- While SDO 1700Å fits give only slightly better fits than SFO data alone, SDO 1600Å fits are significantly poorer.
- It comes as no surprise that 1700Å gives closer results to Ca II K than 1600Å since they originate in very similar regions of the solar atmosphere. Ca II K (393.4 nm) looks at the upper photosphere/lower chromosphere and SDO 1700Å is in the ultraviolet continuum, looking at the surface of the Sun and the chromosphere.

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- SORCE Total Irradiance Data: http://lasp.colorado.edu/home/sorce/data/tsi-data