Reconstruction of the solar spectral irradiance from magnetograms: a data-driven approach

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1. Objective: get the real-time UV flux

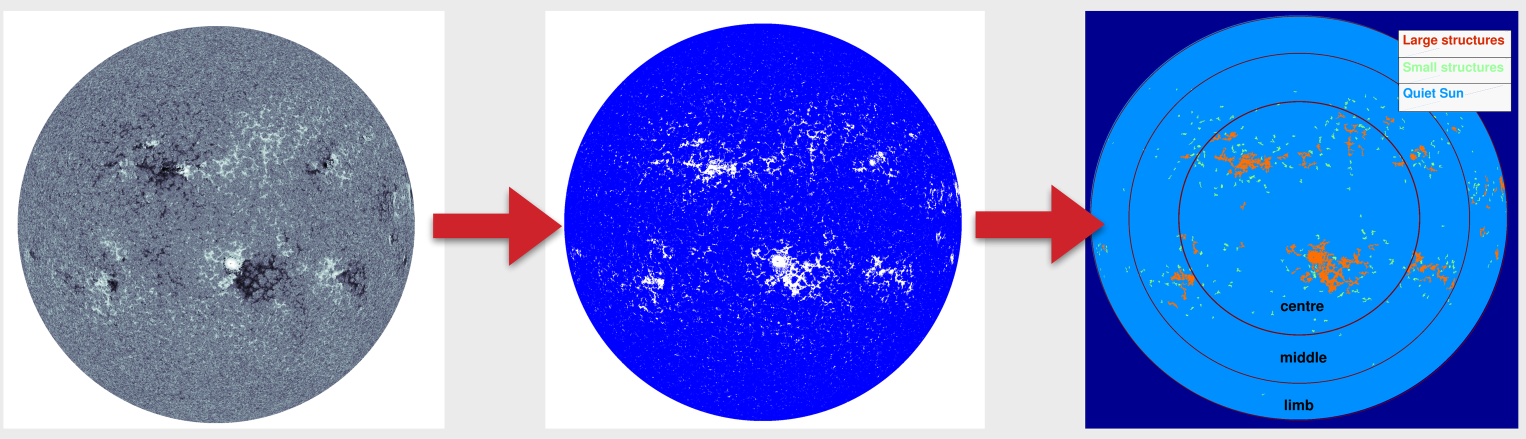
The Solar Spectral Irradiance is a key input for space weather users and for space climate. However, present observations (SORCE, TIMED) and models (NRLSSI, SATIRE, SOLAR2000, ...) hardly provide it in real time.

Here we show how the spectral irradiance in the UV (6-309 nm, without flares) can be reconstructed automatically using an empirical model that uses solar magnetograms as sole input.

2. The Model: surface magnetism says it all

Many studies have shown that solar surface magnetism governs irradiance variations on time scales ≤ few solar cycles [Wenzler, Unruh, Preminger, Lean, Fröhlich, Solanki, Domingo, Ball, etc.].

We segment solar magnetograms from SDO/HMI into different features. Most do this according to intensity; **we segment instead according to the size of the features**, which alleviates some of the magnetic field calibration problems.



Solar magnetogram (from SDO/HMI)

Mask to extract outstanding magnetic structures (|B| > 30 G)

Segmentation with 3 classes of features: large, small, and the remaining « quiet » Sun

We assume a linear model (as for SATIRE, etc), wherein each class contributes to the spectrum proportionally to its total area (filling factor F)

$$I(t,\lambda) = \sum_{\substack{\text{class}\\k}} S_k(\lambda) \cdot F_k(t) + \epsilon(t,\lambda)$$

spectral irradiance — **characteristic spectrum of each class** — **filling factor of each class, from magnetogram**

Geometric projection effects are taken care of by splitting the solar surface into different annuli that may have different contributions. Finally

$$I(t,\lambda) = \sum_{\substack{\text{annulus}\\i}} \sum_{\substack{\text{class}\\k}} S_{k,i}(\lambda) \cdot F_{k,i}(t) \; + \; \epsilon(t,\lambda)$$

In most models, the spectra $S_{k,i}(\lambda)$ are derived from model atmospheres. We, on the contrary, estimate them from the observations. **Our model is thus empirical and data-adaptive.**

3. Model validation

We train the model by using 3 years of observations (April 2010-July 2013) from SORCE/SOLSTICE (120-309 nm), TIMED/SEE (37-120 nm) and SDO/EVE (6.5-37 nm), with a daily cadence and 1 nm resolution. Our model therefore is only as good as the input UV observations are!

The model is trained by using 80% of the observations, and then tested on the remaining 20%.

The model performance is quantified by means of the root mean square error (RMSE), normalized to the standard deviation (= solar cycle variability) of the observations

$$RMSE(\lambda) = \frac{\sqrt{\langle \epsilon(t,\lambda)^2 \rangle_t}}{\sigma(\lambda)}$$

Do we need a non-linear model ? No, this does not lead to a significant reduction in the RMSE.

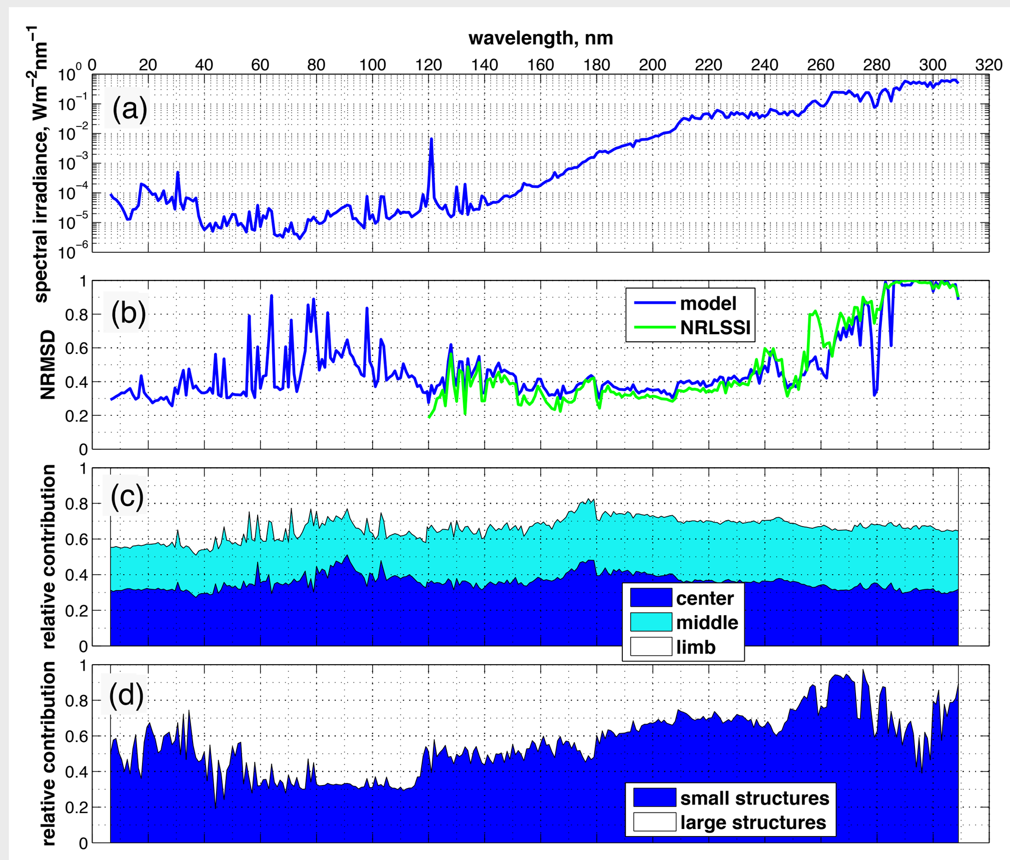
3. How complex should the model be ?

Two key questions are:

- How many types of solar features do we need to distinguish? Most models impose 3-7 classes without true justification.
- How many annuli do we need to properly capture centre-to-limb effects? Most models use 3-12 annuli. Again with little justification.

Only 3 types of structures (large, small, quiet Sun) are required to properly fit the observations, given their uncertainties. No more than 3 annuli are needed = less than expected!

4. How well does the model perform ?



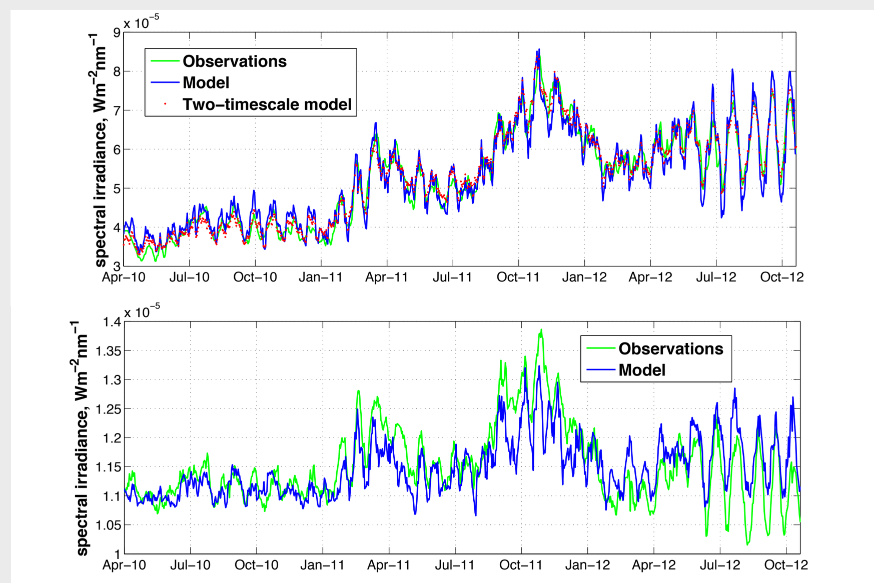
Average solar spectrum

Model fit (RMSE). In green, the RMSE for the NRLSSI model

Relative contribution of the three annuli to the spectral irradiance

Relative contribution of the two classes (quiet Sun excepted)

The model performs remarkably well: its performance is comparable to that of the better-known NRLSSI model, which uses solar proxies only.



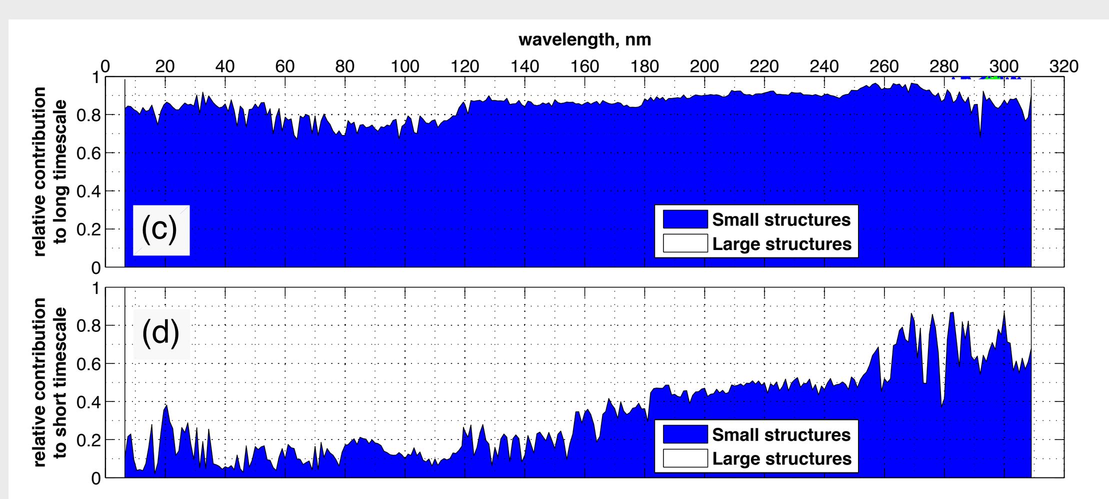
Example: reconstruction of the spectral irradiance at 8 nm.

Example: reconstruction of the spectral irradiance at 78 nm: this band has instrumental problems

5. Future improvements

This model is ready to be run in real-time, but still needs several fixes:

- The reconstruction improves by 0-10% when the filling factors F are first decomposed into 2 time scales, with a cutoff around 3 solar rotations. This unexpected effect is likely caused by the contribution of structures near or behind the limb.
- An extension to the visible requires a segmentation of continuum images, in addition to magnetograms.



Relative contribution of large/small features to time scales > 80 days

Relative contribution of large/small features to time scales < 80 days

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