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Time-Frequency Analysis of Total Solar Irradiance Variations

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Abstract. Continuous wavelet analysis of the Total Solar Irradiance (TSI) time series accurately describes its non-stationary, multi-scale variations over a wide time-scale domain. The analysis was also applied to Photometric Sunspot Index (PSI) and full-disk Calcium II K-line Photometric Facular Index (PFI) time series to identify the contributions of sunspots and faculae/magnetic-network to the time-frequency behavior of TSI. Significant spectral power is found near 27-days in the time series spectra of TSI, PSI and PFI, confirming sunspot and facular phenomena as the primary causes of TSI variability near the average solar rotation rate for active regions. The spectra of both PFI and TSI exhibit correlative trends to longer periodicities during solar cycles 21 and 22, demonstrating the dominant influence of faculae and magnetic network on TSI during the declining phase of these solar cycles.

1. Introduction

Long-term TSI measurements obtained from the space flight experiments: Nimbus-7/ERB (1978–1993), SMM/ACRIM-I (1980–1989), ERBS (1984 →), UARS/ACRIM-II (1991 →), and SOHO/VIRGO (1996 →) now span more than twenty years. Composite TSI time series have been constructed using different strategies for relating the components of this set of observations [*Willson*, 1997; *Fröhlich and Lean*, 1998]. Small differences between them in absolute value and long term slope do not significantly impact the time-frequency analysis. The composite time series are comprised primarily of the high precision results from the two ACRIM experiments. The ERB and ERBS results, while of lower precision, provided essential correlative information for relating ACRIM I and II observations and bridging the two year gap in the ACRIM database (1989–1991). The VIRGO results are high precision but are, as yet, of relatively short duration.

Wavelet spectra clearly and comprehensively characterize the spectral composition of TSI data as well as its temporal changes, displaying both non-stationary behavior and recurrent periodicities. Temporal changes of TSI and their power spectra have been investigated previously using analytical approaches that cannot fully characterize non-stationary time series [*Willson et al.*, 1981; *Foukal and Lean*, 1988; *Willson,* 1988, 1991; *Fröhlich and Pap*, 1989]. Some aspects of the analysis of TSI time series using wavelets have been demonstrated by *Vigouroux et al.* [1997] and *Crommelynck and Dewitte* [1997]. Here we apply a comprehensive, continuous wavelet analysis to the TSI, PSI and PFI solar parameters to fully characterize their non-stationary, multi-scale variations over a wide time-scale domain.

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2. Wavelet Analysis of TSI

A continuous wavelet transform of a signal $s(t)$ is its convolution with a set of analyzing wavelet functions Ψ, which are localized both in time and in frequency domains

$$W(a,b) = |a|^{1/2} \int_{-\infty}^{\infty} s(t)\Psi\left(\frac{t-b}{a}\right) dt. \qquad (1)$$

Wavelet parameters a and b control the time scale and position of the wavelets. Analyzing wavelets are generated from the basic one that is scaled and translated along the time axis to create a basis for signal decomposition. There are no restrictions on wavelet parameters for continuous wavelet transform. Therefore we can estimate a wavelet spectrum with good time-scale resolution taking into account only the uncertainty principle. The continuous wavelet transform is an effective tool for event finding. We choose the complex Morlet wavelet as the basic one. In practice, equation (1) is discretized and the integral is replaced by summation. Then we adopt the wavelet parameters as $a_k = 2^{k/M}$, $b_j = j \cdot \Delta t$, where Δt is a sampling step and $j = 1, 2, \ldots, N$, $k = 1, 2, \ldots, K \cdot M$. The indices j, k refer to the time and time scale, respectively, with $N = 7154$, $K = 10, M = 12$ to cover the time-scale domain of interest [*Lui and Najmi*, 1997]. Now we can estimate the complex wavelet coefficients directly from equation (1). The boundaries of the end distortions are shown by small dots in the wavelet spectrum.

Figure 1 shows the composite TSI time series and the modulus of its continuous wavelet transform $(W * W)^{1/2}$. The modulus is normalized to its maximum value, and is shown on a decibel unit scale. Each color in the plot represents a corresponding amount of oscillatory power for a given periodicity and time. The wavelet spectra display a wealth of unsteady and multi-scale structures. The most pronounced features are the solar rotational modulation and long-term periodicities.

Spectral power is concentrated near the 27-day time scale associated with the average solar rotation period for active regions. This periodicity is enhanced during times of maximum solar activity but persists throughout the record.

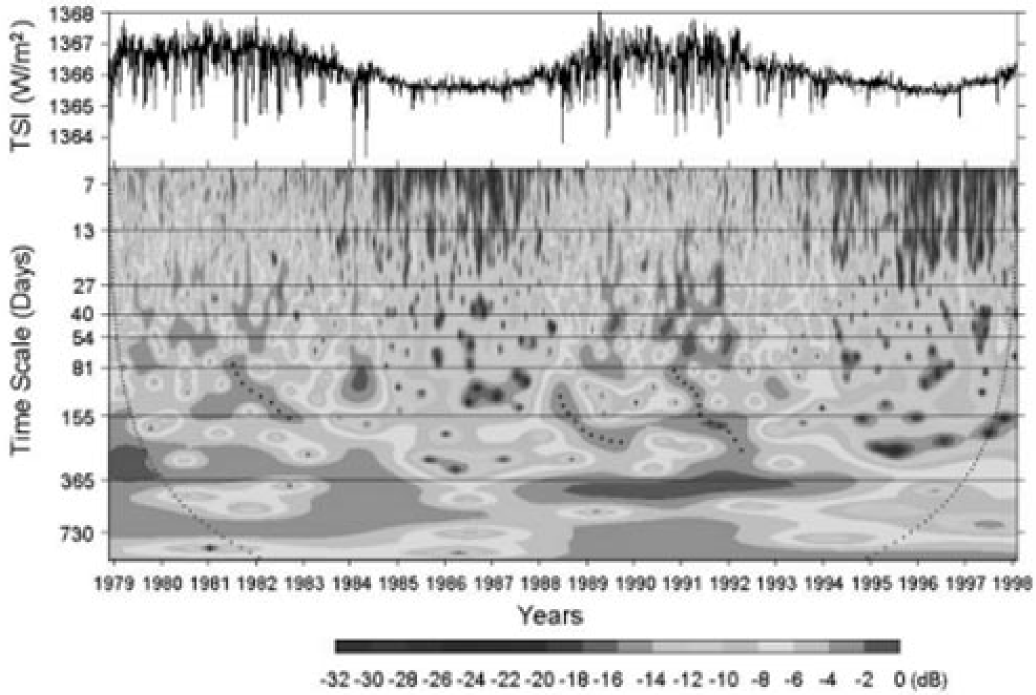

Figure 1. The composite TSI time series (upper) and the modulus of wavelet transform normalized to its maximum value (lower). The maximum modulus corresponds to 0 dB. The confidence boundaries are shown by dots.

Episodically spectral power is also concentrated near 13, 40, 54, and 81 days, corresponding to multiple and combinatory time scales of the 27-day periodicity. An interesting question is whether a 13.5-day periodicity, previously reported as the presumed effect of active regions located oppositely in solar longitude [*Donnelly and Puga*, 1990], was in fact an harmonic of the 27-day period. One event stands out in Figure 1 as a practical demonstration of this technique. In 1984 two deep sunspot deficits in the TSI are separated by about 80 days. In accord with this the spectral power increases dramatically near the 80-day periodicity at that time.

Evolutionary changes in the distribution of spectral power on time scales ranging from about 80 to 240 days can be seen during the most active periods of solar cycles 21 and 22. (Emphasized by the dots in Figure 1) This corresponds to the average range of lifetimes for solar activity complexes including their sunspot and facular components. As activity complexes disappear the thermo-magnetic perturbations relax, and their energy transfers to greater spatial and temporal scales.

Annual variations in the TSI wavelet spectrum are clearly seen during periods of enhanced solar activity. These derive from the motion of the Earth in its orbit relative to the solar equatorial plane. The latitude of the satellite experiments solar nadir changes along with its view of the primary belts of solar activity in the Northern and Southern hemispheres over the year. This subtle affect on the long term TSI database has not previously been observed to our knowledge. It should be detectable in the results of sensitive solar monitors during solar active periods.

3. Comparative Wavelet Analysis of PSI

We analyzed the wavelet spectra of the PSI time series to isolate and evaluate the sunspot contribution to TSI variability. A time series of PSI for 1978-1997 was taken from the web site of the World Radiation Center.

Figure 2 shows the PSI data set and its wavelet spectrum. There is significant power concentrated at time scales corresponding to the solar rotational and combinatory frequencies, as was the case for TSI. This was found for both the primary and secondary activity increases of solar cycles 21 and 22, occurring in 1980, 1981-1982 and in 1989 and 1991, respectively. There is significant power in the vicinity of a two-year periodicity during the maximum activity times of cycles 21 and 22. A similar quasi-biennial periodicity was found in the TSI spectra as well. Enhanced spectral power during the primary and secondary maxima of cycles 21 and 22, and subsequent weak activity enhancements following at time intervals of about two years are seen in Figure 2. These result from known eruptions of magnetic fields on this time scale [*Erofeev*, 1996].

4. Comparative Wavelet Analysis of Ca II K line index (PFI)

A comparative analysis of the full-disk Calcium II K-line index or PFI was carried out to identify facular and magnetic network contributions to TSI variability. PFI characterizes the excess spectral radiance of faculae and the magnetic network, relative to the unperturbed solar atmosphere. The PFI time series used here is based on 1988–1997 observations by the San Fernando observatory [*Chapman et al.*, 1992]. A plot of PFI and its wavelet spectrum are shown in Figure 3. The solar rotational periodicity is the most dominant feature of the spectrum. It persists even during the epochs of activity minimum when identifiable solar active regions and their sunspots rarely appear.

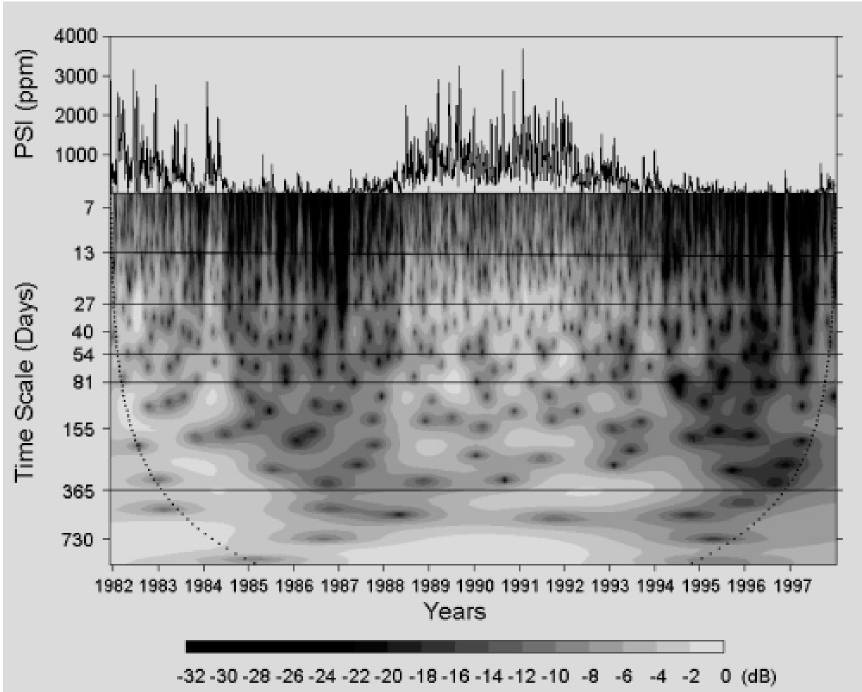

Figure 2. The plot of PSI data set (upper) and its wavelet spectrum (lower).

Of special interest are concentrations of spectral power in the 130-240 day periodicity range during 1989-1994. Appearing as inclined light bands (marked by dots) the peaks of their spectral power correlate with the primary and secondary solar activity peaks in 1989 and 1991. There is a decreasing trend between 1989 and 1994 evidencing a transition from periodicities well within the range of active region lifetimes to much longer persistence times characteristic of the magnetic network. We interpret this cascade towards greater time scales to reflect the process of energy transfer from active region faculae to the magnetic network during the solar cycle on this time scale.

Characteristic time scales in the range of 140–160 days have been found in the variations of many solar parameters that appear to be caused by long-lived eruptions of magnetic activity in the solar chromosphere [*Bai*, 1997; *Chapman et*

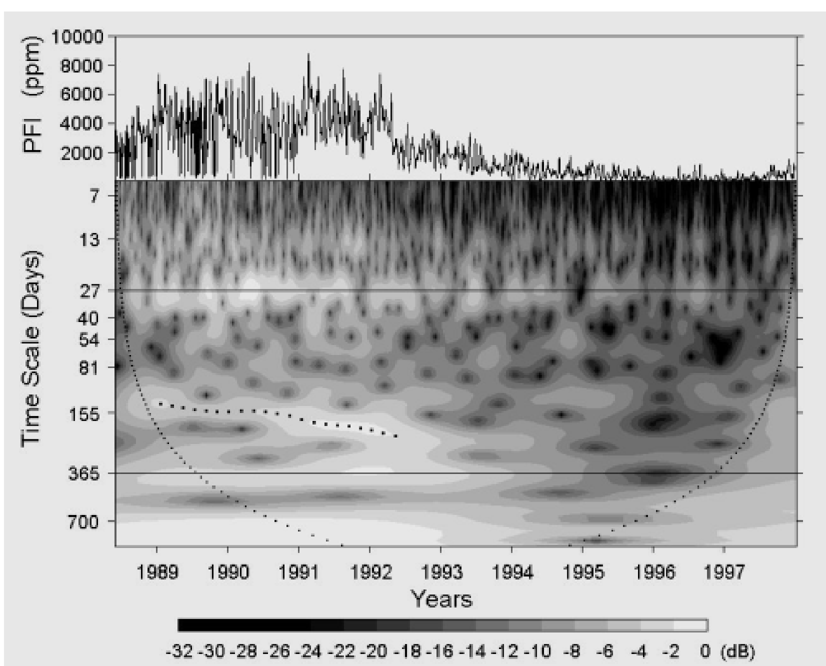

Figure 3. Daily full-disk Calcium II K-line index, and the wavelet spectrum.

al., 1997] Our wavelet spectra demonstrate that the lifetime of these eruptions increases as the solar cycle progresses.

Analogous solar cycle trends in the TSI wavelet spectrum demonstrate that faculae and magnetic network contributions cause the slope of the loci of maximum power in this frequency range. This correlates with the downward trend in TSI attributed to faculae and bright network features during solar cycle 21 by *Foukal and Lean* [1988] based on regression analysis. Our confirmation of the faculae/magnetic-network source of the trend provides a more rigorous and physical basis for their finding.

5. Conclusions

Wavelet analysis is highly successful in describing the time series of TSI measurements and solar activity indices. The spectra shown here present comprehensive pictures of non-stationary and multi-scale changes of solar parameters in a wide time-frequency domain. Spectral signatures of sunspots, faculae, magnetic network, activity complexes and annual as well as quasi-biennial variations are superimposed over the solar cycle.

Spectral energy of TSI variability concentrates about periodicities corresponding to multiple and combinatory frequencies of the average 27 day solar rotation period of the principal activity latitudes. Annual TSI variation results from the view factor changes caused by the Earth's orbital excursions about the solar equator. Wavelet analyses of TSI and PFI time series demonstrate intermediate changes on time scales of four to seven months corresponding to the decay of active regions and dispersion of active region faculae to the magnetic network. As the solar cycle progresses the spectral energy of its radiative features cascades to greater time scales in general, corresponding to a relaxation of thermo-magnetic perturbations in the outer solar atmosphere.

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