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Search for periodicities of the solar irradiance data from the Earth Radiation Budget Satellite (ERBS) using the periodogram method

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Abstract We have analyzed the solar irradiance data from the Earth Radiation Budget Satellite (ERBS) during the time period from 1984 October 15 to 2003 October 15. By first filtering the data by Simple Exponential Smoothing, we have applied the periodogram method to the processed data in order to search for its time variation. The study exhibits multi-periodicities on these data around 110, 118, 574 and 740 d with very high confidence levels (more than 99%). These periods are significantly similar to the periods of other solar activities which may suggest that solar irradiance may be associated with other solar activities.

Key words: Sun: activity — Sun: fundamental parameters

1 INTRODUCTION

Total Solar Irradiance (TSI) describes the electromagnetic energy emitted by the sun over all wavelengths that are incident on a unit square meter outside the surface of the earth's atmosphere. Solar irradiance refers to electromagnetic radiation in a spectral range of approximately 1 nm to 1 mm where the shortest wavelengths are in the ultraviolet region of the spectrum, the intermediate wavelengths in the visible region and the rest of the longer wavelengths are in the near infrared and infrared region. TSI means that the solar flux has been integrated over all wavelengths to include the contribution from ultraviolet, visible, and infrared radiation (Oncica et al. 2002). TSI has been monitored from several satellites, e.g. Nimbus 7, the Solar Maximum Mission (SMM), the NASA Earth Radiation Budget Satellite (ERBS), NOAA9, NOAA10, Eureka and the Upper Atmospheric Research Satellite (UARS), SOHO, etc., outside the terrestrial atmosphere.

Before measuring it from outer space, this quantity was thought to be constant, because the precision and accuracy of ground based instruments at that time was not high enough to detect a small change and it consequently had the name of 'solar constant' which had a value of only 1353 W m^{-2}, because a part of the solar radiation is absorbed by the earth's atmosphere. However, the data sent by the aforementioned spacecrafts and satellites revealed that the solar irradiance varies by a small fraction of about 0.1% over a solar cycle with it being higher during maximum solar activity conditions (Oncica et al. 2002; Raychaudhuri 1971). A major part of the solar irradiance variation is explained as a combined effect of the sunspot blocking and the intensification due to bright faculae and plages, with a slight dominance of the bright feature effects during the 11-year solar cycle maximum. Solar irradiance within a solar cycle is thought to be due to the changing emission of bright magnetic elements, including faculae and the magnetic network (Raychaudhuri 1971).

The variation of the TSI is very important for the understanding of solar internal structure and solar-terrestrial relationships. The radiative output of the sun controls the earth's radiation environment and influences its temperature and atmosphere. It has been suggested that small persistent variations in energy flux may play an important role in climate changes.

Patra et al. (2009) analyzed the solar irradiance data from ERBS during the time period from 1984 October 25 to 2003 October 15[1] for finite variance scaling analysis in order to find the corresponding Hurst exponent. The magnitude of the Hurst exponent was obtained to be 0.1158 (Patra et al. 2009) which clearly indicates the anti-persistent behavior of the TSI data. Again, since the corresponding magnitude of the Hurst exponent is much smaller than 0.5, it may represent a multi-periodic phenomenon for these data as a whole instead of having only one or two sharp periods (Patra et al. 2009).

In the present paper, we have applied the Scargle method of periodograms (Schuster 1898; Scargle 1982) to the same data after filtering it by Simple Exponential Smoothing (Makridakis & Winkler 1983; Makridakis et al. 1982; Winkler & Makridakis 1983) in order to search for its time variation.

2 THEORY

2.1 Filtering of Data: Simple Exponential Smoothing

In the case of Simple Exponential Smoothing, the prescribed model for time series data x_i; $i = 1, 2, 3 \ldots, n$ is (Makridakis & Winkler 1983; Makridakis et al. 1982; Winkler & Makridakis 1983)

$$y_1 = x_1 \, ,$$

and

$$y_i = \alpha x_i + (1-\alpha) y_{i-1}, \qquad i = 2, 3, \ldots, n, \tag{1}$$

where y_i is the smoothed data at the i-th position and ($0<\alpha<1$) is a parameter. This is analogous to

$$y_1 = x_1 \, ,$$

and

$$\begin{aligned} y_i \; = \; & (1-\alpha)^{i-1} x_1 \alpha (1-\alpha)^{i-2} x_2 + ... + \alpha (1-\alpha)^2 x_{i-2} + ... \\ & + \alpha (1-\alpha) x_{i-1} + \alpha x_i, i = 2, 3, ..., n, \end{aligned} \tag{2}$$

where the sum of the corresponding weights α, $\alpha(1-\alpha)$, $\alpha(1-\alpha)^2$, …, $\alpha(1-\alpha)^{i-2}$ and $(1-\alpha)^{i-1}$ is equal to unity. Thus in effect, each smoothed value is a convex linear combination of all the previous observations as well as the current observation. Looking at Equation (2), α should fall into the interval between 0 and 1. Values of α close to 1 have a lesser smoothing effect and give a greater weight to recent changes in the data, while values of α closer to 0 have a greater smoothing effect and are less responsive to recent changes. Optimizing the method of simple exponential smoothing

[1] *http://www.ngdc.noaa.gov/stp/SOLAR/IRRADIANCE/erbs.html*

then becomes a matter of determining the best smoothing constant α. Large values of the smoothing constant correspond to quickly damping out the effects of older observations, while small values of α put stronger weight on older observations. However, Makridakis & Winkler (1983); Makridakis et al. (1982) and Winkler & Makridakis (1983) suggested that a value of α above 0.3 frequently yields the best forecasts. In addition to this argument, we also have taken into account the positional importance of the entire process, i.e. if $\{y_i\}$ represent the newly developed time series data by filtering the old one $\{x_i\}$; $i = 1, 2, \ldots, n$, the y_i's must mostly be generated from the corresponding x_i's. In order to maintain that positional importance in this smoothing, we must have the weights in (2) in ascending order and it is possible only when $\alpha > 0.5$. Again for sufficiently large n in order to have a sizable amount of reduction in the total error, we cannot go very far from 0.5 and we confine our α in the right-hand neighborhood of 0.5. Makridakis & Winkler (1983); Makridakis et al. (1982) and Winkler & Makridakis (1983) made no discussion of the issue if the time series has gaps whether their smoothing is applicable. In fact, because there is no explicit dependence of their model on time interval, it may be considered that this smoothing technique can run satisfactorily in the environment in which data have uneven gaps. Anyway, we have gone through the entire data of the solar irradiance in the present case and have found no such occasion where the data have gaps and the entire time series follows a pattern of equally spaced observations.

2.2 Scargle Method of Periodogram of a Time Series

A periodogram is a device for analyzing a time series based on the assumption that it is made up of sine and cosine waves with different frequencies. Schuster (1898) first introduced this concept in order to investigate the hidden periodicities in a time series observed at equally spaced instants of time. Any time series observed at unequally spaced intervals of time can be converted into an equally spaced time series by implementing the suitable interpolation or smoothing like an exponential smoothing technique in order to make it compatible to employ this mathematical framework.

Scargle (1982) introduced a newer version of the periodogram which can be usefully applied to any time series whether observed at equally spaced instants of time or not. For a time series $X(t_i)$, where $i = 1, 2, \ldots, N$, the periodogram as a function of the frequency ω is defined as Scargle (1982)

$$P_x(\omega) = \frac{1}{2\sigma^2}\Big[\frac{(\Sigma_{i=1}^{N}\{x(t_i) - \bar{x}\}\cos\{\omega(t_i-\tau)\})^2}{\Sigma_{i=1}^{N}(\cos\{\omega(t_i-\tau)\})^2} + \frac{(\Sigma_{i=1}^{N}\{x(t_i) - \bar{x}\}\sin\{\omega(t_i-\tau)\})^2}{\Sigma_{i=1}^{N}(\sin\{\omega(t_i-\tau)\})^2}\Big], \quad (3)$$

where ω is the trial frequency, σ^2 is the variance of the entire time series and τ is given by the following Equation (4)

$$\tan(2\omega\tau) = \Big(\sum_{i=1}^{N}\sin(2\omega t_i)\Big)\Big/\Big(\sum_{i=1}^{N}\cos(2\omega t_i)\Big). \quad (4)$$

We then further normalize the $P_x(\omega)$ by the following way:

$$\text{Normalized } P_x(\omega) \text{ or } P_{\text{norm}} = \frac{P_x(\omega) - \overline{P_x(\omega)}}{\sigma_P}\,, \quad (5)$$

where $\overline{P_x(\omega)}$ is the mean and σ_P is the standard deviation of all the $P_x(\omega)$'s. Finally, the considered ω's and P_{norm}'s are tabulated for subsequent analysis. The values of ω which give significant peaks for P_{norm} are expected to provide possible periods.

2.3 Investigation of Confidence Levels of the Peaks

For the Scargle method of periodograms, there is no consensus about the number of frequencies to use in the graph. We require enough trial frequencies so that no peak is missed in the process. We have to consider the number of independent frequencies since this expression helps us to estimate the statistical significance of any peak in the periodogram. Horne & Baliunas (1986) proposed a formula for this number of independent frequencies, $N_{\rm independent}$, which is given by

$$N_{\rm independent} = -6.362 + 1.193N + 0.00098N_2\,, \tag{6}$$

where N is the size of the time series. If we go through some $N_{\rm independent}$ frequencies and a peak at $Z = P_{\rm norm}$, the probability that no other peak will give a larger value is given by $[1 - \exp(-z)]^{N_{\rm independent}}$, which is the expression of the statistical confidence level of the peak.

3 RESULT

Before trying to apply this method, a prerequisite is to smooth the data in order to remove the random errors and noise. Here, we have applied the Simple Exponential Smoothing (Patra et al. 2009; Makridakis & Winkler 1983; Makridakis et al. 1982; Winkler & Makridakis 1983) to the Solar Irradiance Data from ERBS[2] during the time period from 1984 October 25 to 2003 October 15 taking the parameter α as 0.54. Figure 1 depicts the original data against time and Figure 2 exhibits the filtered data against time.

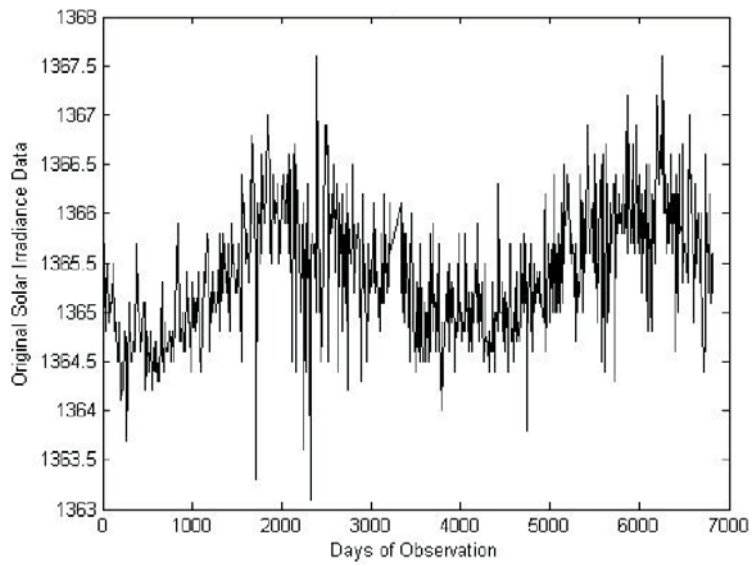

Fig. 1 Original Total Solar Irradiance data with respect to Time (d).

For the present time series, we altogether have 755 equally spaced observations during the above mentioned time period. Next, we applied the Scargle method of periodograms (Scargle 1982) to the filtered data set in order to search for its periodicities. We present the T-$P_{\rm norm}$ profile (T being the trial periods given by $T = 1/\omega$) in Figure 3.

Calculation is performed by taking trial periods in the range 1–6000 d with equal intervals of one day. We obtain strong peaks around 110, 118, 574 and 740 d with confidence levels of 99.72%, 99.23%, 99.85% and 99.67% respectively. There are certain negative values of $P_{\rm norm}$ but these values are very near to zero. So without any loss of information in Figure 3, the graph is scaled by

[2] *http://www.ngdc.noaa.gov/stp/SOLAR/IRRADIANCE/erbs.html*

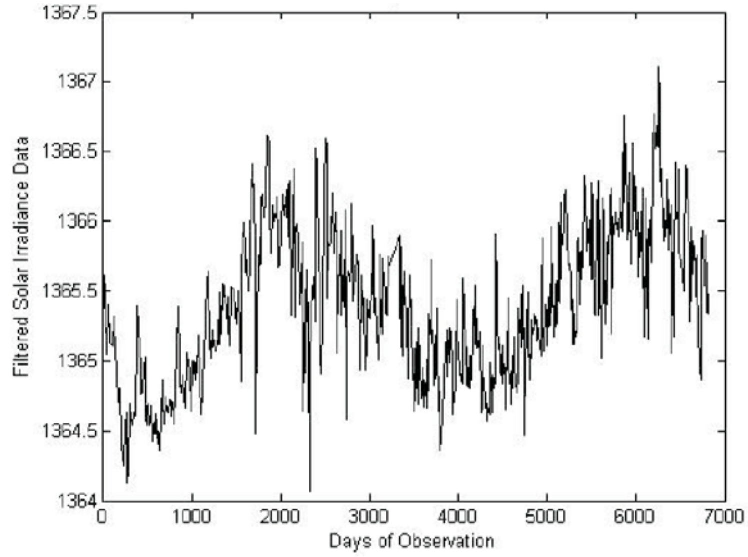

Fig. 2 Filtered Total Solar Irradiance Data with respect to Time (d).

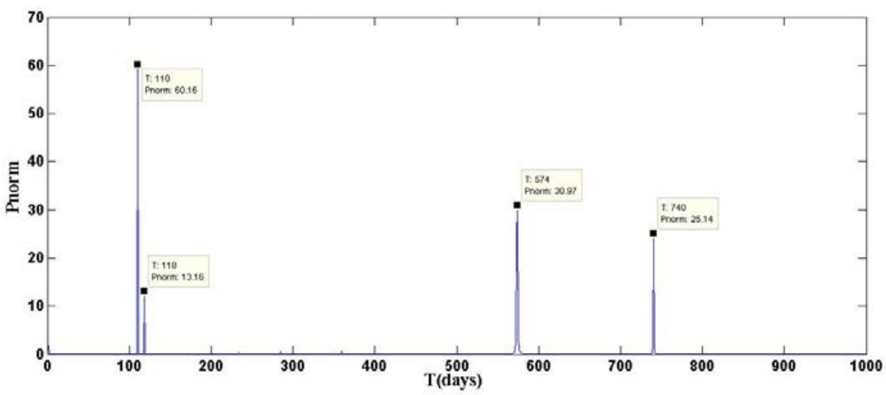

Fig. 3 Normalized Periodogram of the Total Solar Irradiance Data.

taking the lower limit of P_{norm} as zero. Again, because after the peak at 740 d all the values that neighbor P_{norm} are very near to zero, we have omitted the portion of the graph with higher values of T and presented the graph by taking the upper limit of T as 1000 d.

4 DISCUSSION

The variation of TSI may provide an indication of a secular change that might be related to a subtle change in the solar radius. Short term changes of TSI during the solar activity cycles are expected to be due to the luminosity changes connected to the temperature fluctuation of the solar surface and may also be due to the redistribution of the solar radiation by sunspots and the population of active regions. We earlier observed periodicities in the same data by using the Rayleigh Power

Spectrum Analysis at 104, 130, 536 and 752 d (Patra et al. 2009) which are more or less similar to the periodicities obtained here at 110, 118, 574 and 740 d. Application of FFT to the present data extracts periodicities of around 101, 125 and 729 d (Hossain et al. in press) which are compatible with the periodicities obtained in the present analysis at 110, 118 and 740 d.

We compare our results with the corresponding published periodicities of other solar activities in Table 1.

Table 1 Comparison of Periodicities between TSI Data and Other Solar Activities

Sl.	Solar Activities (Refs.)	Corresponding Periods	Similar periods obtained in present work (d)
1.	Solar Filament Activity (1)	367, 795, 1141 and 1557 d	740
2.	Solar electron flare occurrence (2)	152 d for cycle 21, 330 and 604 d for cycle 22, 152 and 176 d for the current cycle 23	118, 574
3.	Solar Flare Rate (3)	51, 78, 102, 128 and 154 d	110, 118
4.	Solar Proton events (4)	154 d	110, 118
5.	Solar Neutrino Flux (5)	For 5 d long samples 7.5, 699.9, 1012.5 and 1282.5 d; for 10 d long sample 15, 30, 845, 1575 d; for 45 d long samples 495 and 855 d	574, 740
6.	Total area of coronal holes enclosed within a latitude band of 10°–50° S (6)	592 d	574
7.	Solar flare occurrence Cycle 20 (7)	84 and 129 d	110, 118
8.	Solar flare occurrence Cycle 21 (7)	153 d	110, 118
9.	Solar flare occurrence Cycle 23 (7)	33.5 and 129 d	110, 118

Refs. (1): Song & Wang (2007); (2): Chowdhury & Ray (2006); (3): Lou (2000); (4): Gabriel et al. (1990); (5): Ghosh & Raychaudhuri (2006); (6): McIntosh et al. (1992); (7): Bai (2003).

It is clearly evident from the comparisons in Table 1 that our obtained results of periodicities for the present solar irradiance data by using the Scargle Method of Periodogram are interestingly close to the results of periods for other different solar activities. So, it may be interpreted that as a whole, TSI has association with other solar activities which in turn may suggest that these other solar activities, together with solar irradiance, may be coming from the same origin. As the total solar irradiance variations may have an impact on the solar – terrestrial relations, the phases of the total solar irradiance can have some significance on the terrestrial climate variation. The fluctuations in the sun's radiative output during the solar activity cycle can potentially affect global surface temperatures and influence terrestrial climate and weather and can change the planet's ozone layers, etc.

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