

A Search for Periodicities in the IUE Daily Peak Radiation Data

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I. Introduction

During a portion of each orbit, the IUE satellite passes through the outer layers of the van Allen radiation belts. The increased particle flux encountered by the spacecraft in this region is detected as an increased output voltage of the Flux Particle Monitor (FPM) during US2. This preliminary study presents the results of a search for periodicities in the daily peak FPM values, determined from strip chart recordings of the radiation data, from February 1978 through February 1989. These results indicate that the behavior of the radiation seen by IUE is modulated to a significant extent by solar active regions rotating in and out of view, and that evidence for fluctuations on a shorter time scale and for seasonal variations is also present in the data.

The analysis is applied to the 4044 point data set in its entirety, and to three 366 point subsets representing a) solar maximum (June 1979 to June 1980), b) an interval between solar maximum and solar minimum (June 1982 to June 1983; hereafter called "mid cycle", although this time actually occurs a quarter of the way through the solar cycle), and c) solar minimum (1986) as determined by sunspot numbers (Solar Geophysical Data Prompt Report 1988). The primary analytical tools employed are the Discrete Fourier Transform as implemented on the Vax IDL software system, and a correlation technique suggested by the work of Kwee and van Woerden (1956). The results of Maximum Entropy (see, e.g., Press et. al. 1986) and Phase Dispersion Minimization (Stellingwerf, 1978) analyses, also applied to the data, are consistent with the results yielded by the above methods, but are not discussed in detail here.

II. Results

a. Complete Data Set

Figure 1a. shows the power spectrum calculated using the entire 4044 point data set, and is obtained in the following manner. The FPM values are assumed to represent a stationary time series, i.e. the basic behavior of the radiation is assumed not to change drastically over the time interval covered by the data (since the data extends over almost a full solar cycle, this assumption is unlikely to be strictly correct, but it is sufficient for the level of analysis considered here). The untapered data is divided into 21 segments of 366 points each (without "packing" by leading or trailing zeros), with each subset overlapping the previous subset by half a segment. The mean of each segment is subtracted from that data, so that the large zero frequency (DC) term is eliminated from the power spectrum, and the power spectrum of the data in the subset is calculated. The 21 individual power spectra are then averaged, and the resulting spectrum

is smoothed using a three-element boxcar filter. This process reduces the noise in the final power spectrum, at the expense of frequency coverage and resolution.

Three prominent peaks are evident in Figure 1a, corresponding to periods of 30.5, 26, and 14 days (the peak near zero frequency is likely an artifact of the finite length of the data set). While the separation of the 30.5 and 26 day peaks is at the limit of the frequency resolution of the data, the power in both peaks is well above the noise in the spectrum. The two time intervals are comparable to the extremes of the solar synodic rotation periods for the regions at which sun spots appear; the sun rotates, as seen from Earth, in 27 days at its equator, and in 29 days at 40 degrees latitude (Allen, 1973). A connection between the solar rotation and the radiation is expected on physical grounds, since active regions on the sun provide the particle flux to populate the Earth's magnetosphere and distort its shape. The 14 day period occurs near a harmonic of the average of the two longer periods, and is approximately equivalent to half a solar rotation period. When more than one active region is present on the sun, a modulation of the peak FPM values on a time scale less than a full solar rotation is physically reasonable (cf. Sec. IIb). Finally, there is a gradual increase in the baseline of the power spectrum toward low frequencies. This feature may have several origins, such as a long-term variation in the radiation (see e.g., Sec. III), random noise in the data, or the assumption of a periodic data set in the Discrete Fourier Transform formalism (see below).

The reliability of the above results can be tested by calculating the power spectrum in somewhat different ways. To obtain the spectrum shown in Figure 1b, the individual segments are tapered by a Welch window before being transformed, the weighting vector being

$$W(i) = 1 - \{[i - 0.5(N-1)]/[0.5(N+1)]\}^2, \quad (1)$$

where $i=0,1,2\dots N-1$, and $N=366$ in the present case. The Welch window degrades the frequency resolution of the power spectrum to some extent, but its transform has lower sidelobes than that of the rectangular window implicitly used to obtain the spectrum in Figure 1a. The possibility of "leakage" of power from a peak at one frequency into other frequencies is thus reduced. The peaks observed in Figure 1a are also apparent in Figure 1b with similar relative amplitudes (note that no renormalization has been done), suggesting that leakage alone cannot account for the features seen in the power spectra. In addition, "packing" each of the windowed data segments with 366 trailing zeros yields a power spectrum showing the same periods evident in the previous two spectra, indicating that these features are not due to errors introduced by the finite length of the segments. Finally, "aliasing" of a high frequency modulation into lower frequencies due to gross undersampling must be considered. Bearing in mind that the analysis concerns daily peak FPM values only, such aliasing is unlikely to occur because the data is sampled at regularly spaced one day intervals, and because the behavior of the radiation between samples (generally bimodal with a well defined peak during US2) is well known. However, it is important to bear in mind that the regular spacing of the data samples does allow for the

appearance in the power spectrum of harmonics of a single fundamental frequency (see e.g., Blackman and Tuckey 1959); all of the periods discussed above need not be real (although the periods are physically reasonable). Thus, the peaks in the power spectra are likely to represent at least one actual periodicity present in the data, the period indicating a modulation of the particle radiation by the solar rotation.

b. Solar Maximum, "Mid Cycle", and Solar Minimum.

Figures 2, 3, and 4 display the results of the analysis of the three 366 point segments spanning solar maximum, "mid cycle" (between solar maximum and minimum), and solar minimum respectively. Figures 2a, 3a, and 4a show the power spectra of the segments, smoothed by a 3 element rectangular filter, calculated without tapering or packing in the time domain. Including the latter operations makes no significant difference in the results (except for a feature in the solar maximum spectrum, as described below). The spectra in Figures 2b, 3b, and 4b represent the average of the power spectra of five 61 point segments; the segments overlap by half a segment length. Figure 5 displays the results of an application of a correlation analysis (suggested by Kwee and Van Woerden, 1956) to the data. The ordinate in Figure 5 is

$$Y(\Delta T) = \sum_{T=0}^{N/2} [FPM(T) - FPM(T+\Delta T)]^2, \quad (2)$$

where T is the day number of a given FPM value. The "lag", ΔT , varies from 1 to $(N/2)-1$, and $N=366$. Lags at which the radiation is correlated appear as minima in the curves. Note from eq. 2 that the sum for each lag is calculated from the same number of data pairs, but not necessarily from the same data.

An examination of Figures 2-4 reveals evidence for the existence in each of the data sets of a long period of 26 to 33 days, and a shorter period of typically 13 to 17 days. At solar maximum and mid cycle, the peak corresponding to the shorter period dominates the power spectrum, while at solar minimum the 28 day period is most prominent (when the solar maximum data is packed with trailing zeros, the 28 day period in that spectrum shows evidence of splitting into 25 and 32 day periods, although the peaks are not far above the noise). These results are consistent with the behavior of the solar active regions during the solar cycle. At solar maximum and mid cycle, it is possible that more than one active region may be distributed over the sun's surface, and the radiation will vary on a time scale that is some fraction of the solar rotation period. At solar minimum, when only a single active region may be present at any given time, the radiation will be strongly modulated by the full solar rotation period.

There is some evidence in Figures 2-4 for the presence of even shorter periods in the data. A strong peak representing a 9 day period is visible in the mid cycle spectrum, while the solar minimum spectrum contains a number of possible short period features just above the noise. The origin of these features, if they are indeed real, is unclear. The periods may reflect the occurrence of small amplitude fluctuations in the radiation data due to activity on the

sun, or may result from processes intrinsic to the Earth's magnetosphere.

The periods visible in the power spectra are approximately harmonics of one another, raising the possibility that some of these features may be artifacts of the Discrete Fourier Transform analysis (i.e., aliases). This question could be addressed by rebinning the data so that the data points are no longer evenly spaced, and then applying one of the many DFT algorithms developed to deal with such data. For the present, reference will be made to the correlation curves of Figures 5, which are sufficient to show that the strongest features seen in the power spectra represent real periods in the data. Examination of Figure 5 show that the FPM data are strongly correlated at lags of 17, 15, and 28 days for solar maximum, mid cycle, and solar minimum respectively, in close agreement with the results obtained from the power spectra. The mid cycle curve also suggests that a 27 day period is present in that data, although the significance of the longer period minima are difficult to interpret, since the correlation technique will clearly detect all of the harmonics of any short period existing in the data. None of these curves display minima at the very short periods (7-13 days) described above; bear in mind that these periods could represent small amplitude fluctuations in the FPM values. Note also that there is a deep minimum in all of the curves at a very long period (e.g., 128 days for solar maximum). Whether this feature is indicative of a real periodicity in the data, or simply results from a conjunction of the undertones of the higher frequencies, is unclear from the data at hand (see, however, Sec. III).

III. Other Evidence for Short and Long Periods in the Radiation

a. Seasonal Variations

A pronounced seasonal variation in the radiation data can be identified in the following manner. The average peak FPM value for each of the annual day numbers 1 to 365 is calculated using the data for years 1979 through 1988; leap days are counted the same as other days for the purposes of this calculation. The resulting radiation history for this "average year" is shown in Figure 6, which indicates that (on average) the radiation peaks at higher values during the latter half of the year than it does during the first half.

The radiation seen by IUE is undoubtedly a complicated function of the satellite's altitude, the orientation of its orbit, and the three dimensional distribution of charged particles in the magnetosphere. However, a possible origin of the asymmetry seen in Figure 6 can be identified by considering a simple hypothetical model of the changing relative geometry of the orbit of IUE and the Earth's magnetosphere during the year (see, e.g., Imhoff 1985). For part of the year, IUE is at low altitude (and thus enters the outer portion of the van Allen belts) while in the equatorial plane of the magnetic field over the sunward side of the Earth, where the magnetic field lines are compressed by the solar wind. In this hemisphere, the particle density in the inner belts may be high due to the field compression, but the density gradient may also be steep, so that IUE detects a low particle flux at this time. Later in the year, the low altitude

equatorial passage occurs on the night side of the magnetosphere, where the field lines are extended into a magnetotail. In this region the particle density gradient is likely to be shallow, so that the satellite encounters a higher particle flux, thus producing the asymmetry evident in Figure 6. A real understanding of the seasonal dependance of the FPM values requires a careful analysis of the relative aspects over time of the IUE orbit and the Earth's magnetosphere.

b. Short Periods

The possibility that short term (less than 13 days), low amplitude variations occur in the peak FPM data can be examined again by directly measuring the interval between neighboring local maxima, after smoothing the data in the following way. The transform of the complete 4044 point data set is weighted in frequency space (equivalent to smoothing in the time domain), and the inverse transform is then calculated; this smoothed inverse transform serves as the new data set. This tapering in frequency space is chosen entirely for illustrative purposes; other smoothing techniques are certainly possible. The smoothing function is

$$\begin{aligned} S(f) &= 1 & f \leq I0 \\ S(f) &= \exp\{-0.5[(f-I0)/\text{SIGMA}]^2\}, & f > I0 \end{aligned} \quad (3)$$

where $I0$ is a frequency beyond which the power spectrum appears to contain only noise, and SIGMA determines the steepness of the tapering at $f > I0$. Figure 7 shows the first 100 points obtained with $I0=220$ and $\text{SIGMA}=221$.

Figure 8 is the histogram obtained by measuring the time intervals between successive peaks in the smoothed FPM data. For the purposes of this measurement, any local maximum is considered to be physically significant, since the data are now heavily smoothed. It can be seen from Figure 8 that the most common time interval between peaks is 10 days (for comparison, $I0 = 220$ corresponds to a period of 18 days). As $I0$ and SIGMA are increased, the smoothing of the data is reduced, and the increased noise causes the peak of the histogram to shift to shorter time intervals. For example, for $I0=330$ and $\text{SIGMA}=331$, the most common separation between maxima is 7 days. Therefore, the results illustrated in Figure 8 are not proof that a given short period oscillation is present in the data, but rather provide a plausibility argument that some short period modulation(s) of the peak FPM values occurs.

IV. Summary

The daily peak FPM values recorded from February 1978 to February 1989 are examined for periodic behavior using Discrete Fourier Transform and Correlation analyses. Evidence for periods of 26-33 days and 13-17 days is found in the data, with the longer period being most prominent near solar minimum. These results indicate that the radiation is modulated to a large extent by the appearance and

disappearance (as seen from Earth) of active regions on the sun due to solar rotation. The peak FPM values are also found to be higher, on average, during the latter half of the year. Finally, a straightforward search of the smoothed FPM data for very short period variations (e.g., 10 day or less) supports the possibility that such periods are present in the data, although these results cannot be considered conclusive. The above results suggest the possibility that a more complete analysis of the extensive IUE radiation data base, using more elaborate analytical tools than that applied here (perhaps using new data collected especially for this purpose) and taking into account the instrument response, would lead to interesting conclusions relevant to astrophysics and geophysics.

References

- Allen, C.W. 1973, Astrophysical Quantities (London: Athlone Press), p. 180.
- Blackman, R.B., and Tuckey, J.W. 1959, The Measurement of Power Spectra (New York: Dover), p. 31.
- Coffey, H.E., and McKinnon, J.A. 1988, Solar Geophysical Prompt Report, 530, 16.
- Imhoff, C.L. 1985, International Ultraviolet Explorer (IUE) NASA Newsletter, 27, 9.
- Kwee, K.K., and van Woerden, H. 1956, Bull. Astron. Soc. Neth., 12, 327.
- Press, W.H., Flannery, B.P., Teukolsky, S.A., and Vetterling, W. T. 1986, Numerical Recipes (New York: Cambridge University Press), pp. 422-435.
- Stellingwerf, R.F. 1978, Ap. J., 224, 953.

FIGURE CAPTIONS

Figure 1. Average of the power spectra of twenty-one 366 point segments formed from the complete data set. The segments overlap by half a segment length. No tapering has been applied to the segments in 1a, while a Welch window is used to produce 1b. The prominent peaks in the figure are labeled by their corresponding periods.

Figure 2. Figure 2a shows the power spectrum of a 366 point segment covering solar maximum. The segment is not tapered or packed with trailing zeros. In Figure 2b, the power spectrum is obtained by dividing the 366 point segment into five 122 point subsets which overlap by half a segment length, and averaging the individual power spectra of these subsets.

Figure 3. Power spectra for a 366 point segment covering a period midway between solar maximum and solar minimum, calculated as in Figures 2.

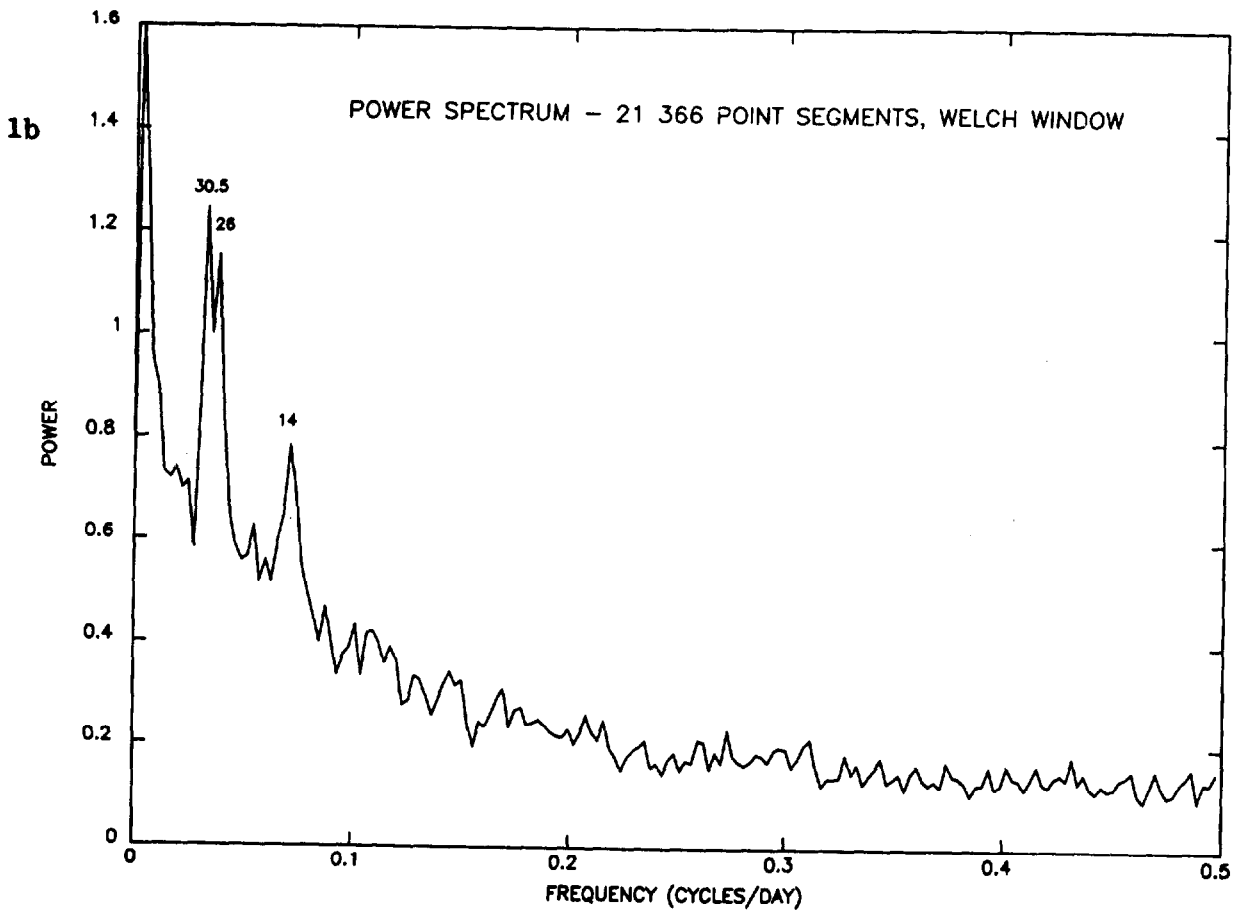
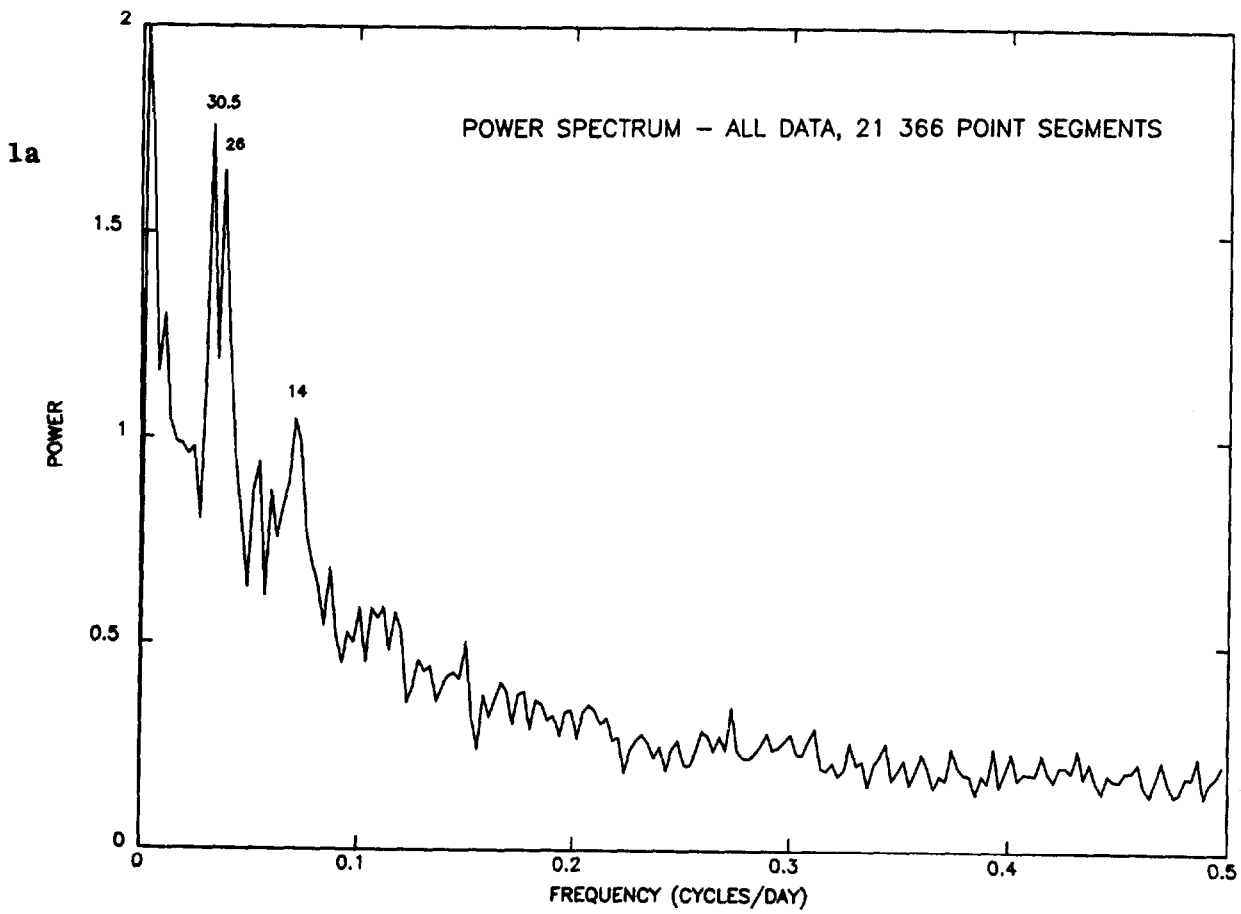
Figure 4. Power spectra for a 366 point segment covering solar minimum, calculated as in Figures 2.

Figure 5. Correlation curves for 366 point segments for time intervals as in Figure 2. The curves represent the sum of the squared difference of FPM values within a segment separated by various lags. Lags at which the radiation is strongly correlated are labeled in the figure.

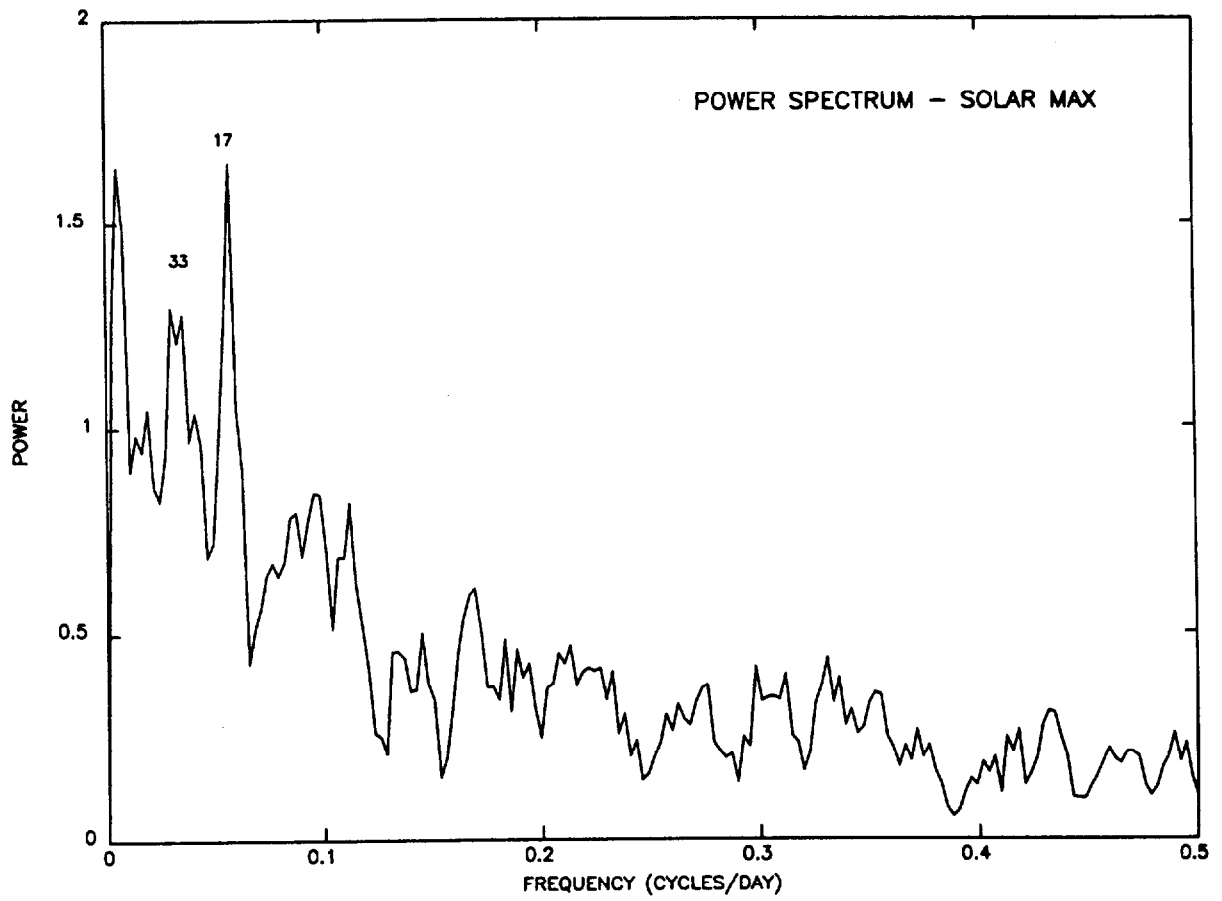
Figure 6. Average peak FPM value vs. day of the year for the years 1979 through 1988. Note the increase in the average peak radiation during the latter half of the year.

Figure 7. First 100 points of the complete data set after smoothing the data by tapering its transform in frequency space.

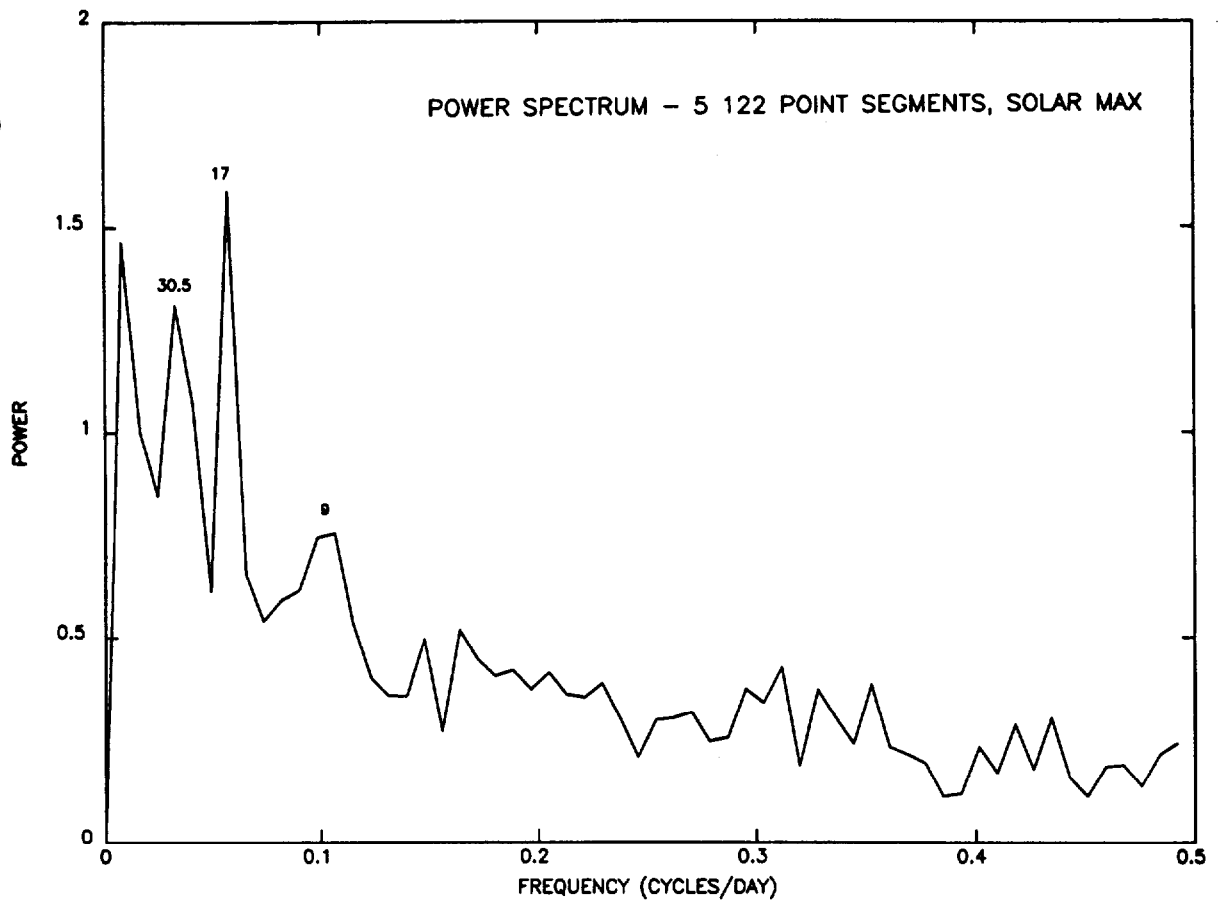
Figure 8. Histogram of the number of pairs of successive peaks in the complete data set, smoothed as in Figure 7, separated by an interval ΔT .

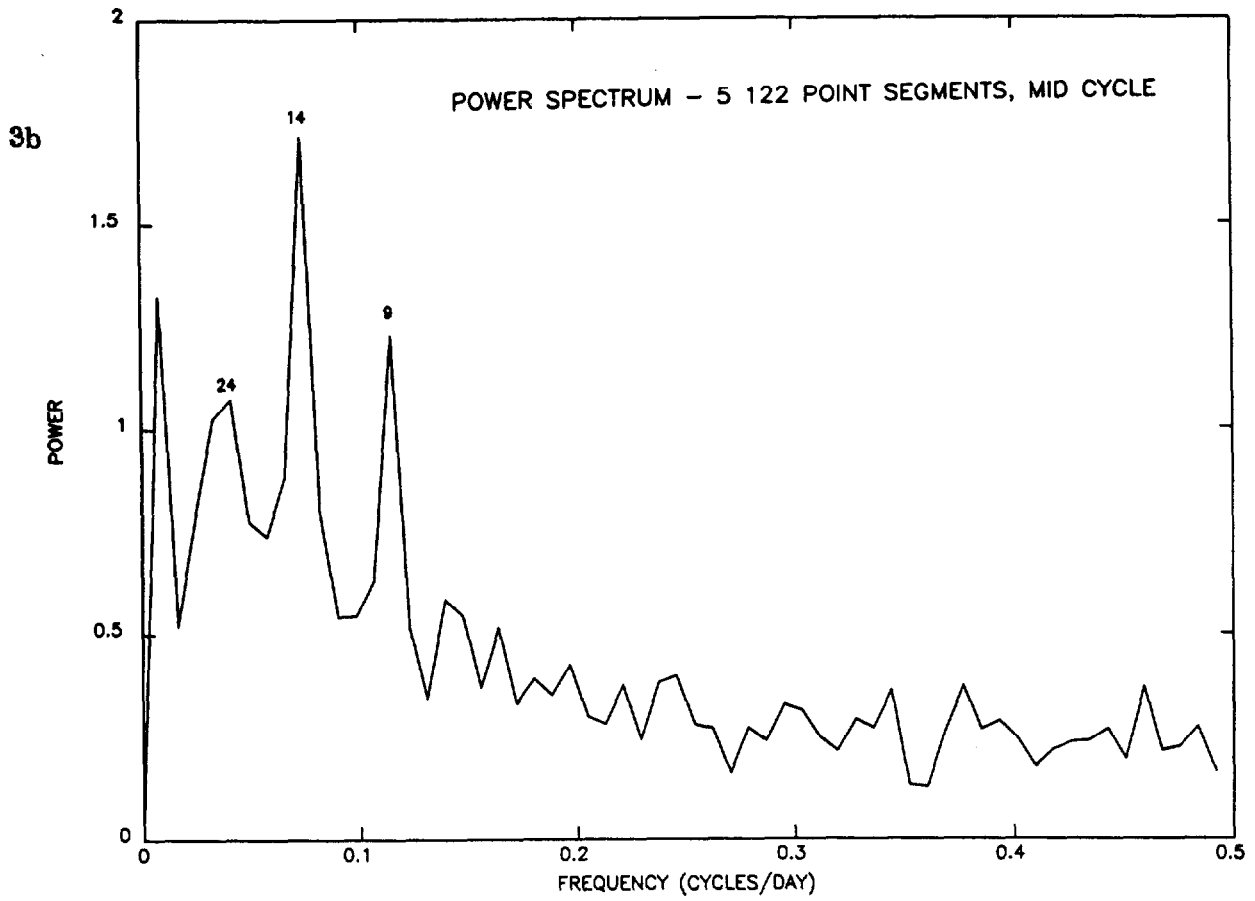
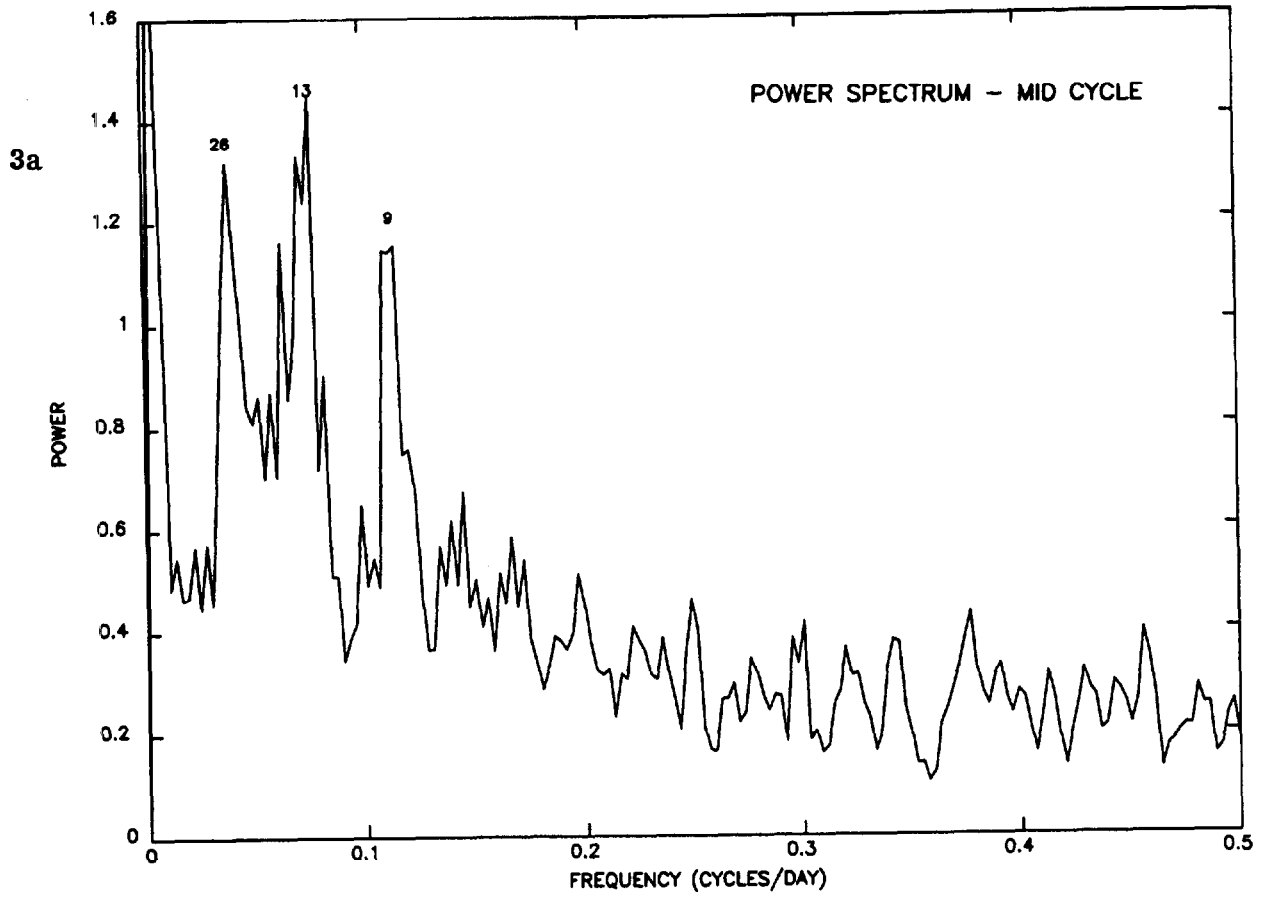


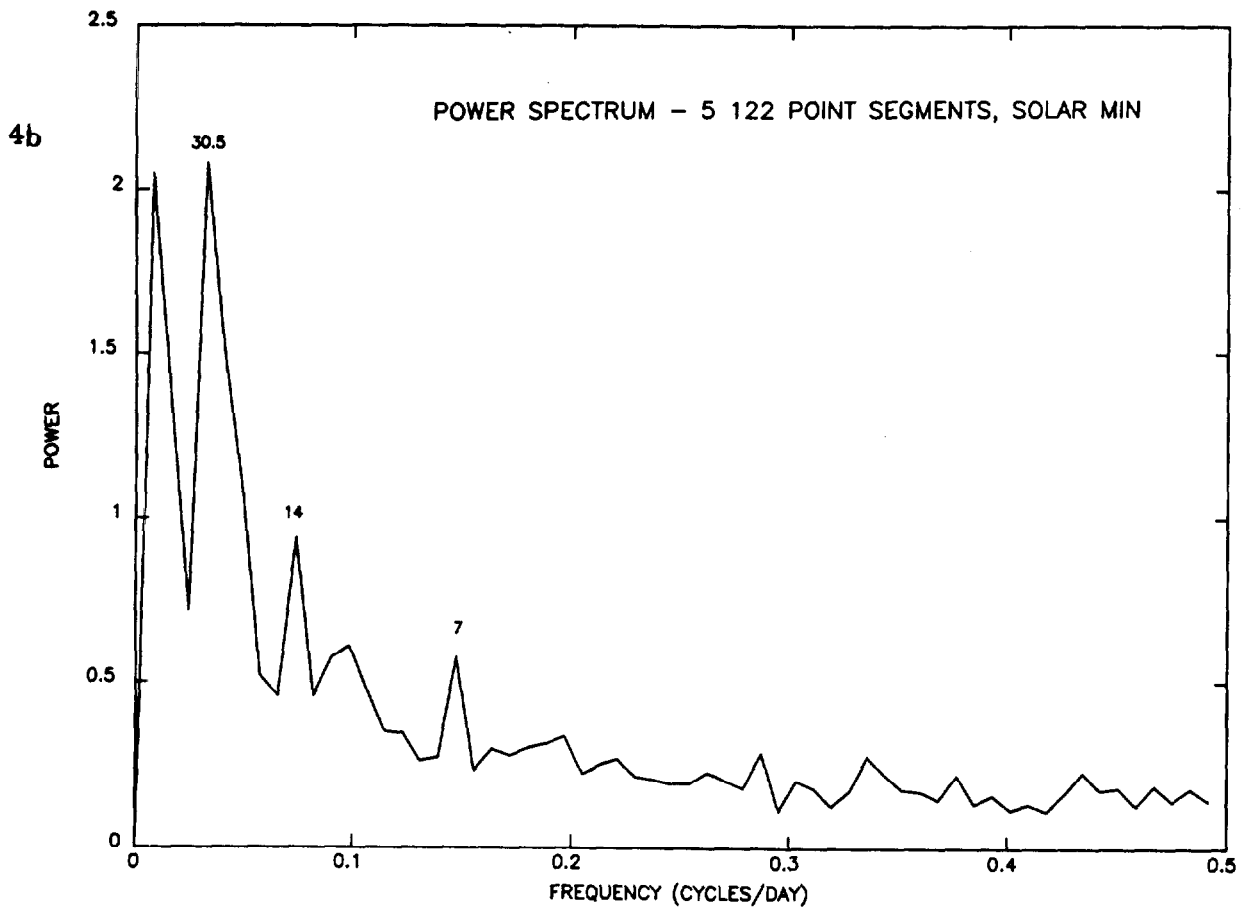
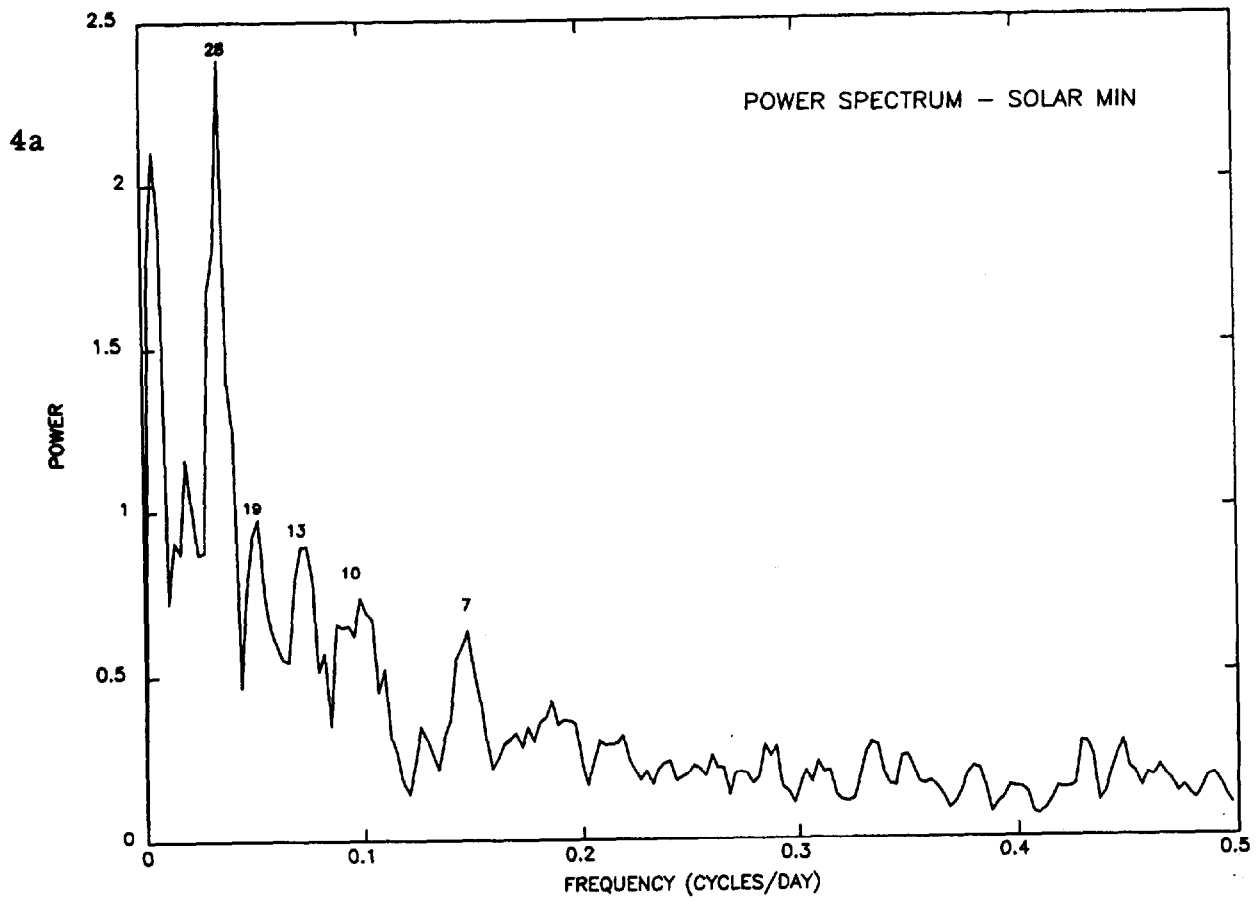
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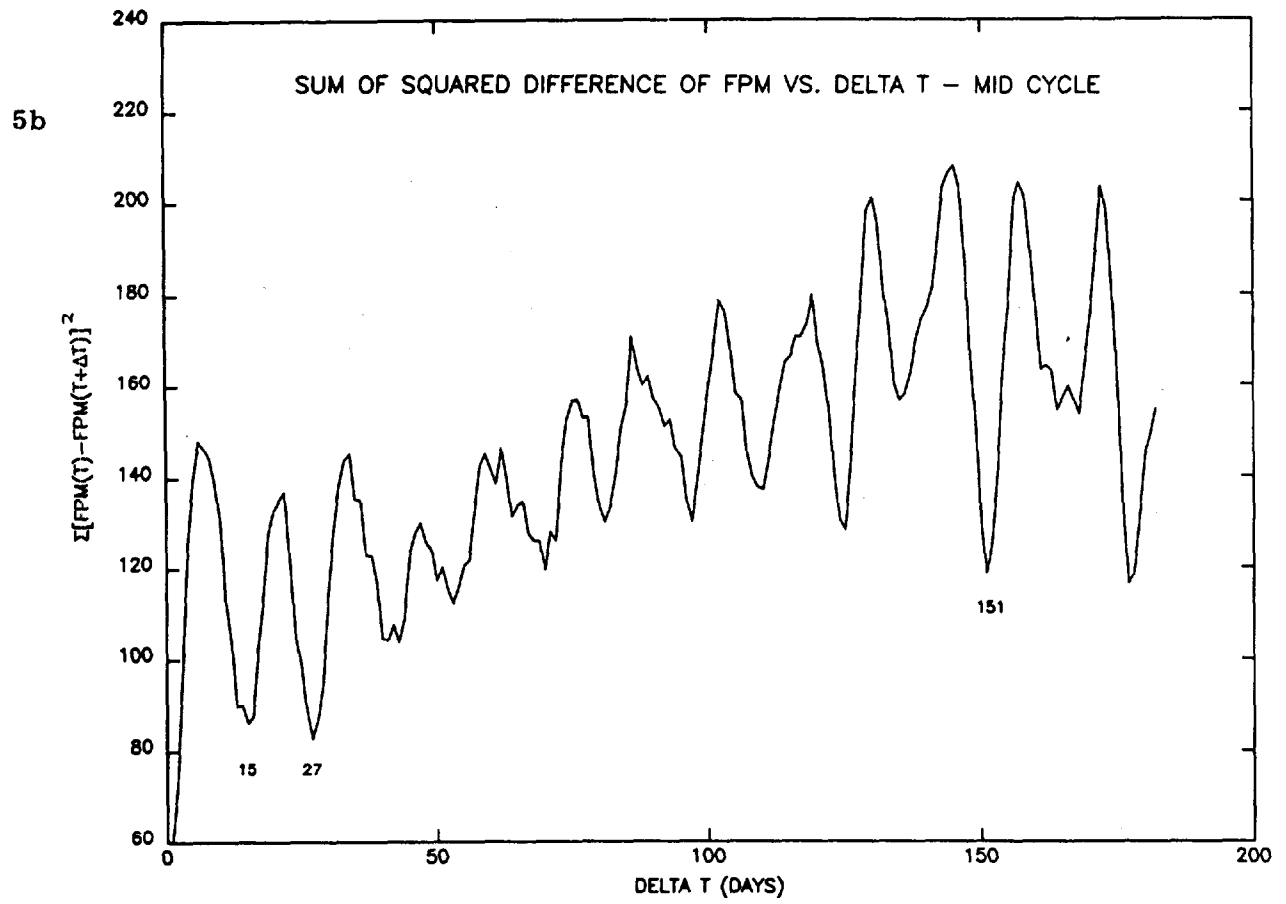
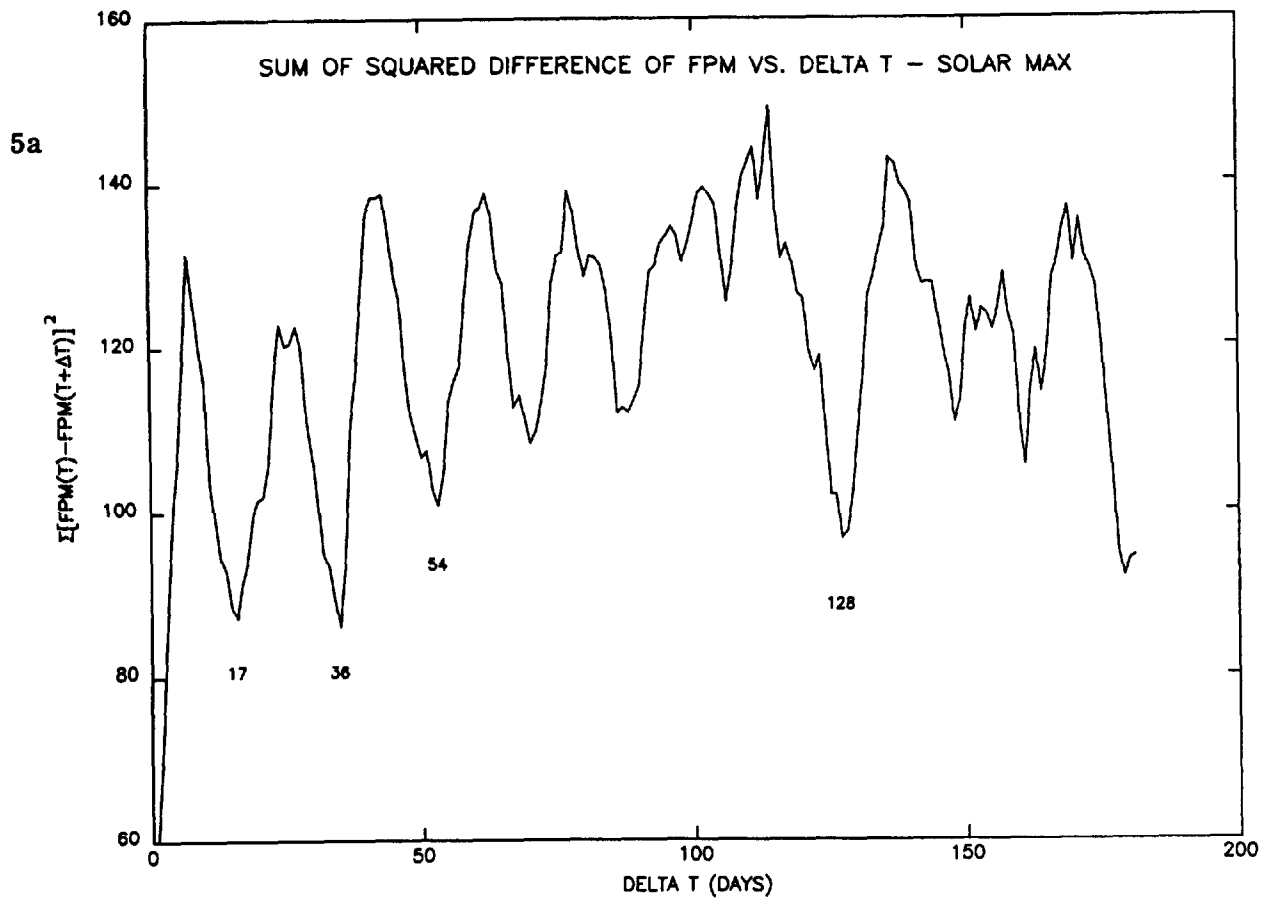


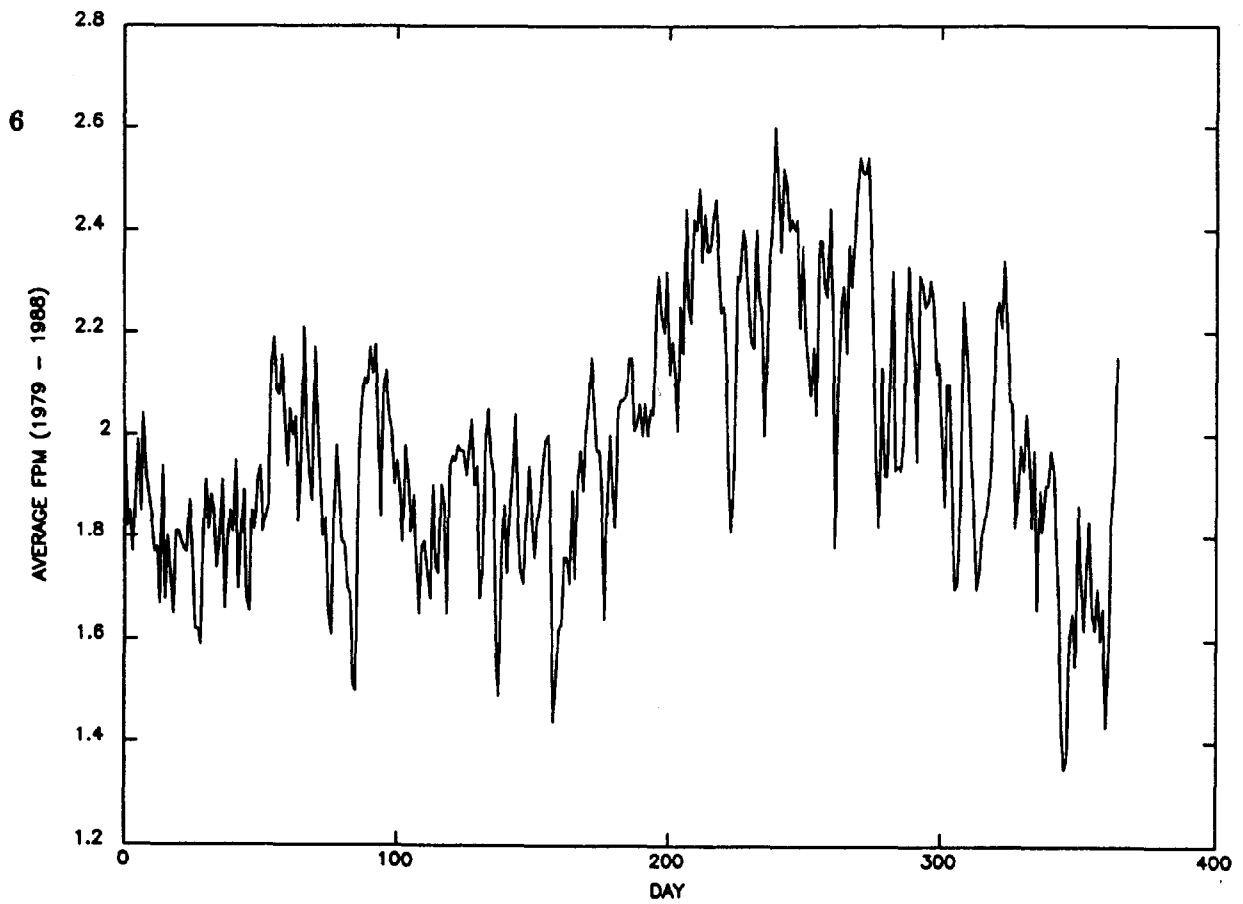
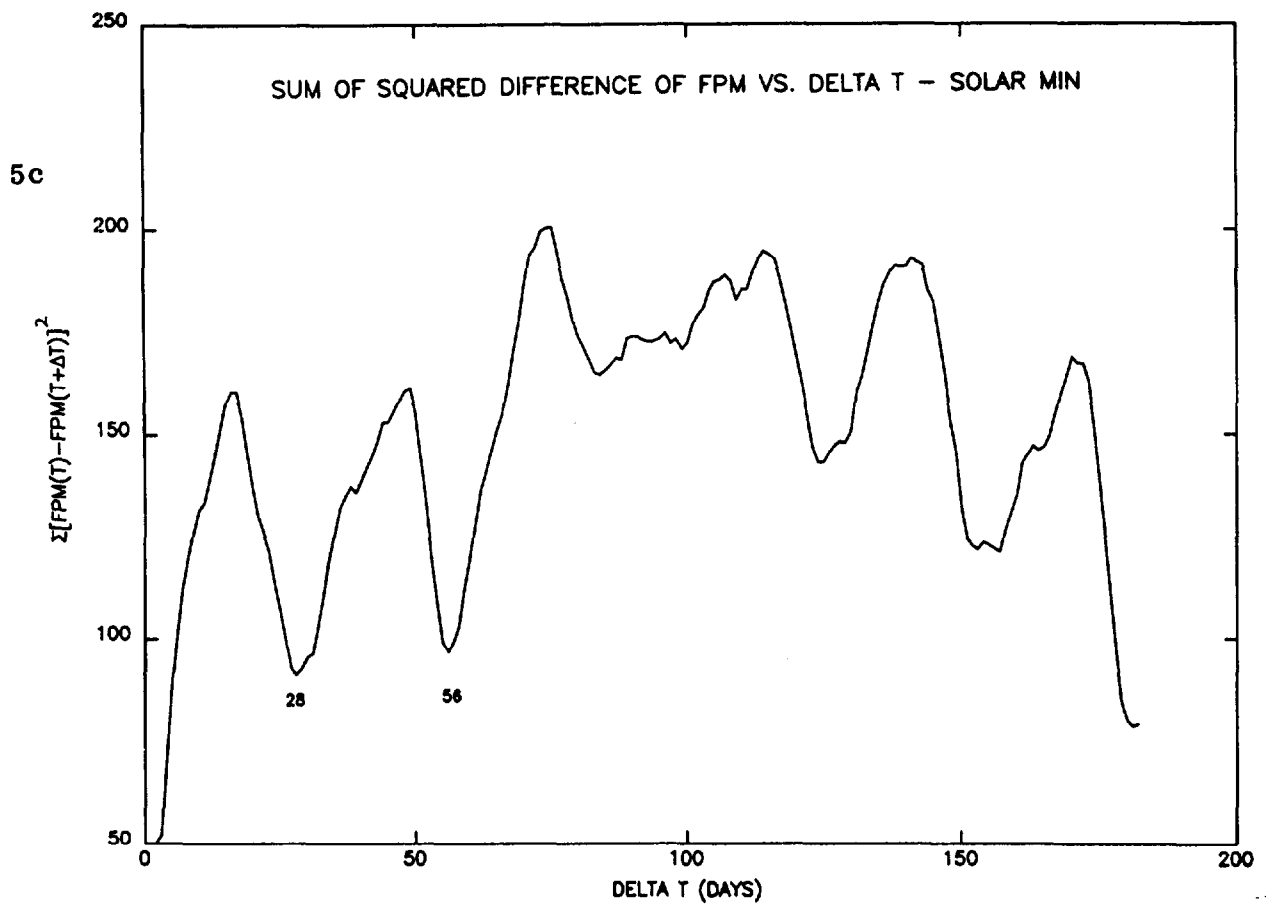
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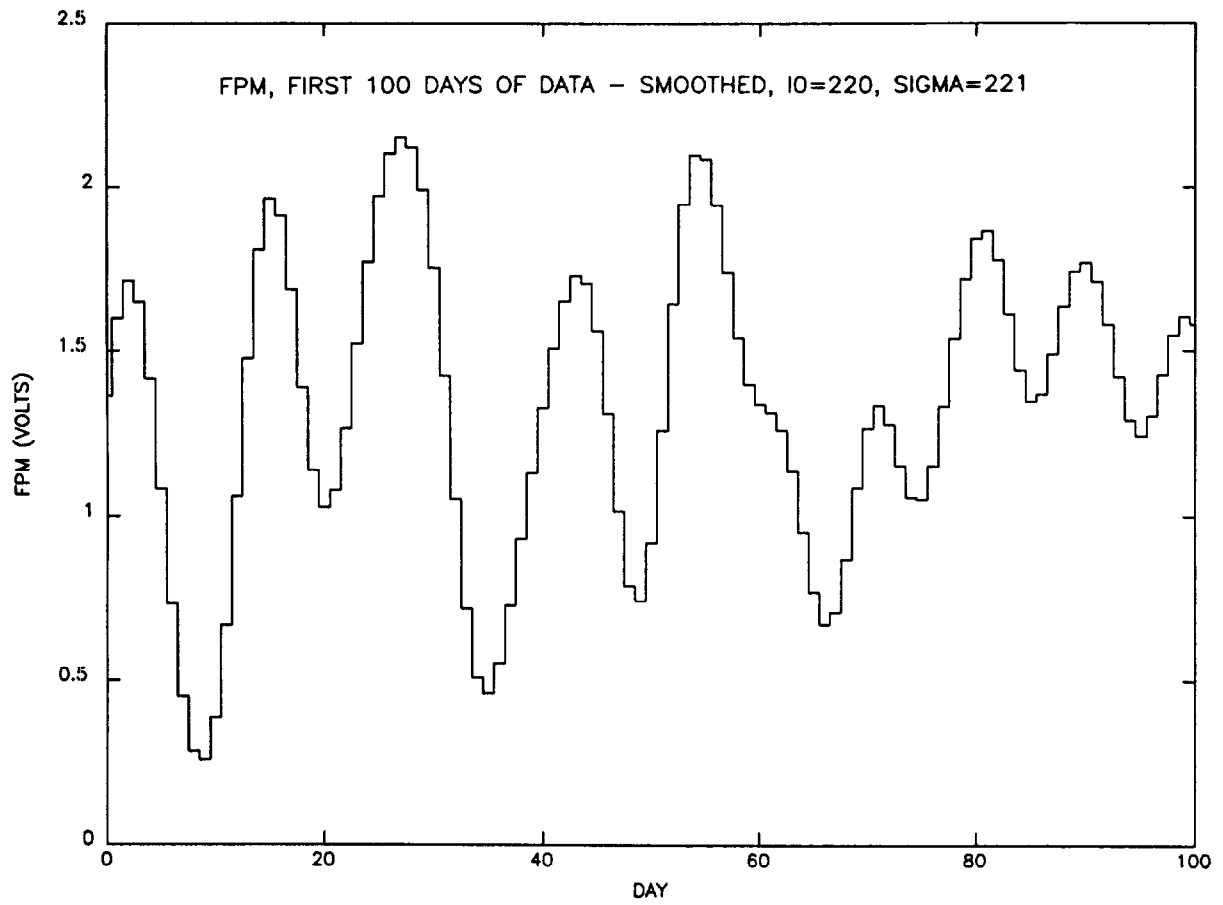








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