COMMENTS ON THE MEASUREMENT OF POWER SPECTRA OF THE INTERPLANETARY MAGNETIC FIELD

Christopher T. Russell

ABSTRACT

Examination of the possible sources of noise in the measurement of the power spectrum of fluctuations in the interplanetary magnetic field shows that most measurements by fluxgate magnetometers are limited by digitization noise whereas the search coil magnetometer is limited by instrument noise. The folding of power about the Nyquist frequency or aliasing can be a serious problem at times for many magnetometers, but it is not serious during typical solar wind conditions except near the Nyquist frequency. Waves in the solar wind associated with the presence of the earth's bow shock can contaminate the interplanetary spectrum in the vicinity of the earth. However, at times the spectrum in this region is the same as far from the earth. Doppler shifting caused by the convection of waves by the solar wind makes the interpretation of interplanetary spectra exceedingly difficult.

INTRODUCTION

The interplanetary magnetic field has been probed by many spacecraft, and it has been popular to calculate the power spectrum of the fluctuations in the interplanetary magnetic field with the hope of gaining some insight into the physical processes occurring in the solar wind. Power spectra have been obtained from Pioneer 5 [*Coleman,* 1964], Mariner 2 [*Coleman,* 1966], OGO-1 [*Holzer et al.,* 1966], Mariner 4 [*Siscoe et al.,* 1968], Pioneer 6 [*Sari and Ness,* 1969], Mariner 5 [*Belcher and Davis,* 1971] and OGO-5 [*Childers et al.,* 1971]. Although the calculation of power spectra is quite straightforward analytically, there are many technical difficulties involved in determining the power spectrum of solar wind fluctuations. They stem mainly from the fact that the magnetic field and its fluctuations are quite small. Thus, it is possible that noise sources inherent in the measurement process could significantly add to the measured power spectrum. In addition, since many instruments have much wider pass bands than the bandwidth of the power spectrum being measured, noise from outside the nominal frequency band of the spectrum may be folded into the spectrum. This effect, called *aliasing*, in some cases can alter the spectrum significantly. Further, a spectrum measured in the solar wind may not be truly representative of the interplanetary medium if it is measured near the earth, since waves, apparently radiated from the earth's bow shock, are present for large distances (up to 46 R_E) from the shock in the solar wind [*Fairfield,* 1969; *Russell et al.,* 1971]. Here we examine the extent that these problems have affected measured interplanetary spectra, and in this light construct a meaningful typical interplanetary spectrum. Finally, we shall make some comments on the interpretation of interplanetary power spectra, mainly as a guide to the uninitiated.

The author is at the Institute of Geophysics and Planetary Physics, University of California at Los Angeles.

INSTRUMENT NOISE LEVELS

Since the interplanetary field is so small, approximately 10^{-4} of that at the surface of the earth, one of the first questions that might be asked is whether the inherent noise levels of the magnetometers are comparable to the noise being measured. In particular, we would like to compare the spectrum of the instrument noise with the measured interplanetary spectrum. Unfortunately, very few magnetometer experimenters have made this comparison. Usually, at best, an rms amplitude noise over some bandwidth is quoted with no clue as to the distribution of the noise over this band. Figure 1 shows instrument noise levels for the OGO-3 search coil magnetometer [*Russell et al.,* 1970] and for two fluxgate magnetometers, which were backup units for two different deep space missions. Also on this figure is a curve representing a typical quiet spectrum of one component of the interplanetary field in this frequency range. The justification for this curve will be given later.

We see that the noise spectrum of both fluxgate magnetometers has a frequency dependence proportional to $1/f$ whereas the search coil noise has a $1/f^3$ spectral dependence. The inverse cube dependence of the search coil noise results from a $1/f$ noise in field derivative units $(\gamma/\text{sec})^2/\text{Hz}$ (the search coil measures the derivative of the field), which is converted to field units γ^2/Hz by dividing by $(2\pi f)^2$, where f is the frequency in hertz. The interplanetary power spectrum, however, is proportional to $1/f^2$. Due to their different slopes all three spectra cross. The fluxgates intersect the quiet interplanetary spectrum at about 1 Hz. Thus, to the extent that these are representative of fluxgate magnetometers in actual operation in space, fluxgates should be able to measure the quiet interplanetary spectrum to about 1 Hz. Since the search coil noise spectrum crosses the fluxgate noise spectrum at about 4 Hz, the search coil is the better high-frequency instrument. We note, however, that the search coil does not intersect our hypothesized quiet interplanetary spectrum until 15 Hz. Thus, to the extent that fluxgates A and B are typical of fluxgates used on actual missions we would expect that the quiet interplanetary spectrum from 1 to 15 Hz remains unmeasured. We shall see in fact our assumption for the quiet interplanetary spectrum must not extend to frequencies much above 1 Hz and in reality the entire interplanetary magnetic spectrum above 1 Hz remains unobserved. In addition there are other sources of noise which limit the detection of the interplanetary spectrum at lower frequencies.

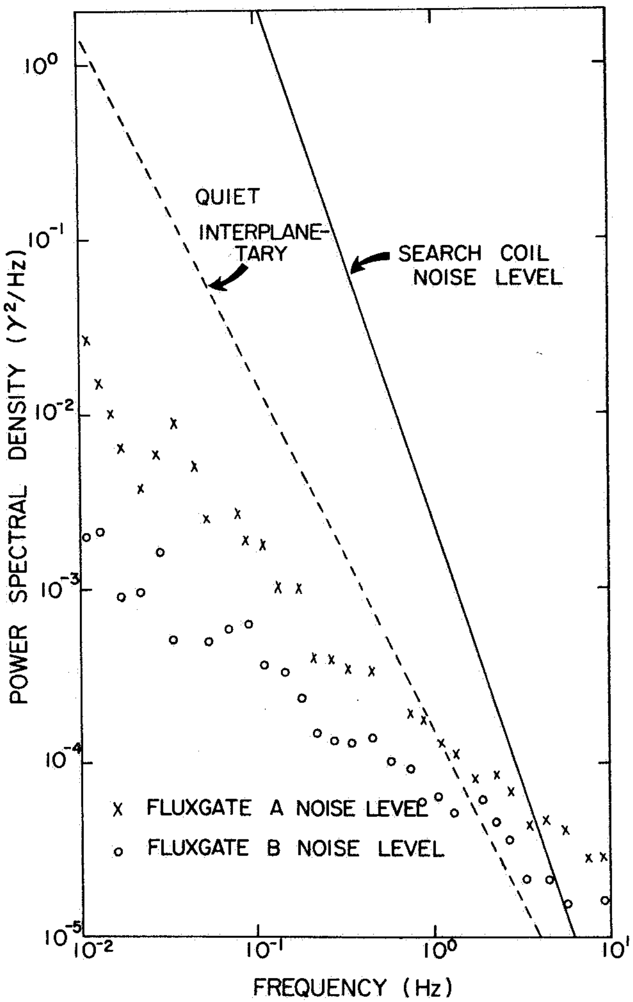

Figure 1. *The instrument noise levels of three magnetometers. Fluxgates A and B were not flown aboard spacecraft but served as backup units for space missions. The search coil noise level is that of the OGO-3 instrument [Russell et al., 1970]. The dashed line is an extrapolation of the quietest interplanetary power spectrum obtained by Siscoe et al. [1968] assuming an f^{-2} spectral dependence.*

ALIASING

Aliasing is the folding of power about the Nyquist frequency (half the sampling frequency) into the analysis band during spectral analysis of discretely sampled time series. It does not create any power not originally present in the signal, but since it adds power from outside the analysis band it can have drastic consequences on the measured spectrum. The way to avoid this addition of power due to aliasing is to remove any power above half the sampling frequency from the signal to be measured *before* the data are sampled by the telemetry system. Many times this has not been done on interplanetary magnetometers. Table 1 lists the Nyquist frequency and the upper cutoff frequency of the instrument for a number of magnetometers which have made measurements in the interplanetary medium. The entries are ranked according to ratio of these two frequencies. A large ratio indicates a possible serious aliasing problem. Many of the numbers used in the constructing of this and succeeding tables can be found in *Ness* [1970].

To examine the effect of aliasing on measured spectra, let us assume that the ratio R in table 1 equals $2K + 1$

Table 1. *The Nyquist frequency (half the sampling frequency), the upper frequency cutoff of the instrument's passband, and the ratio of these two frequencies for spacecraft probing the interplanetary medium*

Spacecraft	Nyquist frequency, Hz	Upper cutoff frequency, Hz	Ratio
IMP 1, 2, 3	0.025	5.0	200
IMP 4, 5	0.20	12.0	60
Explorer 33, 35[a]	0.10	5.0	50
Mariner 2	0.0135	0.33	24
Pioneer 6, 7, 8	0.33	5.0	15
Mariner 5	0.119[b]	0.80	6.7
Mariner 4	0.159[b]	0.80	5.0
Pioneer 9	1.7	1.7	1.0
Explorer 33, 35[c]	0.08	0.05	0.63
OGO 5[d]	0.43 3.54 27.8	0.22 1.77 13.9	0.50 0.50 0.50
OGO 1,3[e]	2.2 17 139	0.8 0.8 70	0.36 0.05 0.50

[a] *GSFC magnetometer*

[b] *Calculated from average sample rate for high telemetry rate*

[c] *Ames Research Center magnetometer*

[d] *UCLA fluxgate magnetometer*

[e] *Search coil magnetometer*

where K is integral. Then, it is easy to show that the measured power spectrum $P'(f)$ after aliasing is

$$P'(f) = P(f) + \sum_{n=1}^{k} [P(2nf_N - f) + P(2nf_N + f)]$$

where $0 \leq f \leq f_N$, f_N is the Nyquist frequency and $P(f)$ is the true spectrum at frequency f. Figure 2 shows the result of aliasing for a magnetometer with $R = 51$ for $1/f$ and $1/f^2$ spectra. We see that the effect of aliasing is significant over the whole frequency band for the $1/f$ spectrum but is significant from only about $0.5\,f_N$ to f_N for the $1/f^2$ spectrum. Table 2 lists the additional power added to the spectrum at various frequencies for these two spectra and a $1/f^3$ spectrum. We note the aliasing

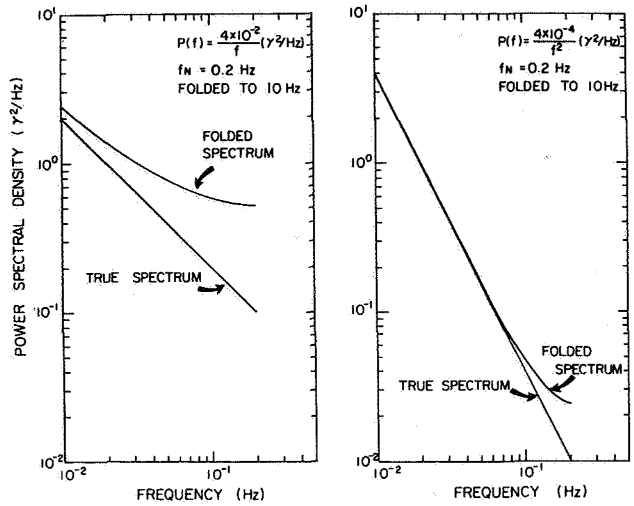

Figure 2. *The effect of aliasing on digitally sampled time series for a spectrum proportional to f^{-1} and one proportional to f^{-2} when the Nyquist criterion for reconstructing the spectrum is violated. In this example signals up to 10 Hz were allowed to fold into the analysis band of 0-0.2 Hz.*

Table 2. *The additional power added to the true spectrum by aliasing, for a magnetometer whose bandwidth is 50 times greater than the analysis band allowed by the sampling rate, for three spectra with slopes proportional to f^{-1}, f^{-2} and f^{-3}*

f/f_n	Additional $1/f$, percent	Folded $1/f^2$, percent	Power $1/f^3$, percent
0.01	3.8	0	0
0.10	38	0.9	0
0.25	96	5.0	0.5
0.50	195	23	5.0
0.70	279	33	19
0.80	323	73	35
0.90	370	103	62
1.00	420	145	110

always at least doubles the power at the *Nyquist* frequency.

In the vicinity of the Nyquist frequencies of the instruments listed in table 1, the typical spectrum of the interplanetary field has at least a $1/f^2$ dependence. Thus aliasing should only be a problem during typical interplanetary conditions in the vicinity of the Nyquist frequency. However, the instrument noise levels for the fluxgate magnetometers shown in figure 1 had $1/f$ dependences. This noise is subject to aliasing, too. Examining table 2 we see that the noise level at the Nyquist frequency was raised by a factor of 5 in this example due to aliasing. Thus, for those instruments with much larger upper cutoffs than Nyquist frequencies we must reinterpret our conclusions about their capability to resolve the quiet interplanetary spectrum. Examining figure 1, we see that this spectral folding of the instrument noise would limit them to measurements below from about 0.1 to 0.2 Hz.

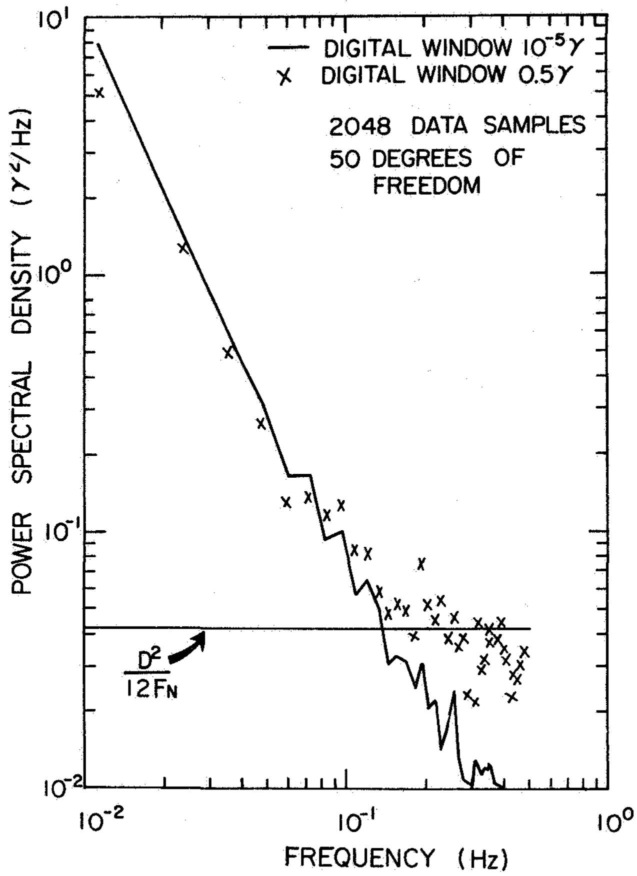

Figure 3. *Two spectra of the same time series: one sampled with a digital window of 0.5 γ and one sampled with a digital window of 10^{-5} γ. The original spectrum was proportional to f^{-2}. The horizontal line is the power expected if the rms digital noise, $D^2/12$, due to the digital window ($D = 0.5$ γ), were spread uniformly over the band 0 to f_N where f_N is the upper frequency of the analysis band, the Nyquist frequency.*

DIGITAL NOISE

The process of digitizing the magnetic field data adds further noise to the spectrum. This noise is subject to aliasing also, but in this case the folded power cannot be removed in the instrument design. The rms noise due to the digitization process can easily be shown to be $D^2/12$, where D is the size of a digital window [*Bendat and Piersol,* 1966]. To understand how this noise affects a measured spectrum, however, we must determine how it is distributed over the power spectrum. The most straightforward way to accomplish this is to compare two spectra of the same time series: one digitized with a large digital window, and one digitized with an extremely small digital window. For this purpose, time series were generated with a random number generator with a gaussian distribution of amplitudes. These time series were then filtered with a digital single section low-pass filter with a corner frequency below the analysis band. The time series thus formed had a $1/f^2$ power spectrum.

Figure 3 shows two power spectra of the same time series with digital windows of 10^{-5} γ and 0.5 γ. The spectra were computed from 2048 points with 50 degrees of freedom. We note that there were only 315 steps between digital windows in the coarsely digitized time series. The horizontal line is the power spectral density to be expected if the digitization noise of 0.021 γ^2 were spread uniformly over the analysis band of 0.5 Hz. The most obvious feature of figure 3 is that the spectrum of the coarsely digitized signal deviates strongly from the finely digitized spectrum at high frequencies and approaches the line expected if the noise were spread evenly across the band ($D^2/12f_N$). A surprising feature is that at low frequencies the coarsely digitized power spectrum is less than that of the finely digitized power spectrum. In other words, at low frequencies the digitization process has consistently reduced the power, whereas at high frequencies it has raised the power. This is not a chance event, but has been observed in every test case.

Figure 4 shows the difference between these two

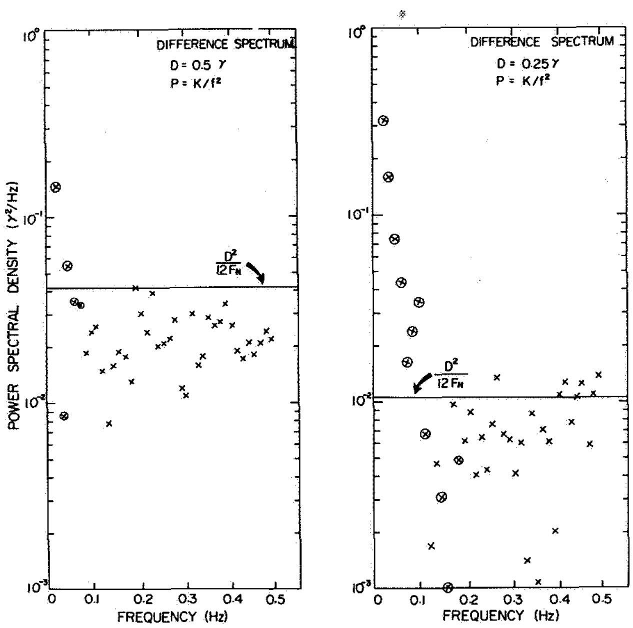

Figure 4. *The difference between two pairs of spectra of a random time series with an f^{-2} spectral shape. One spectrum of each pair had a digital window of 10^{-5} γ. The other spectrum had a digital window of 0.5 γ in the first case and 0.25 γ in the second case.*

power spectra on a semilog plot together with a second test case. The second test case was performed on a different random time series but with the same spectral shape and integrated power. However, for the second case, the coarse digital window was set at 0.25 γ. This coarsely digitized time series had 705 digital steps in the 2048 points. The circled points indicate that the coarse digitization spectrum was less than the fine digitization spectrum. We see that at high frequencies the formula $D^2/12f_N$ is a good predictor of the digitization noise added to the spectrum, but that at low frequencies digitization actually reduces the power spectral density.

Table 3. *The digital window, Nyquist frequency and digital noise level for spacecraft probing the interplanetary medium. The digital noise level given assumes that the digital noise is spread uniformly across the analysis band*

Spacecraft	Digital window, γ	Nyquist frequency, Hz	Digital noise level, γ^2/Hz
Mariner 2	0.7	0.0135	3.02
IMP 1, 2, 3	0.8	0.025	2.13
Mariner 4	0.7	0.159[a]	0.26
Explorer 33[b]	0.5	0.10	0.21
Explorer 33, 35[c]	0.4	0.08	0.17
Mariner 5	0.4	0.119	0.11
IMP 5	0.4	0.2	6.7×10^{-2}
Pioneer 6	0.5	0.33	6.3×10^{-2}
IMP 4	0.32	0.20	4.3×10^{-2}
Explorer 35[b]	0.19	0.10	3.0×10^{-2}
Pioneer 7, 8	0.25	0.33	1.6×10^{-2}
Pioneer 9	0.40	1.75	7.6×10^{-3}
OGO 5[d]	0.125	0.43	3.0×10^{-3}
	0.125	3.47	3.8×10^{-4}
	0.125	27.78	4.7×10^{-5}

[a]*Calculated using average sample rate at highest telemetry rate*
[b]*GSFC magnetometer*
[c]*Ames Research Center magnetometer*
[d]*UCLA fluxgate magnetometer*

In table 1 we ranked magnetometers by the amount of spectral folding present. Table 3 also ranks these instruments but this time by their digital noise level as calculated from $(D^2/12\,f_N)$. This table is not as revealing as it may seem at first, because a digital noise level for a magnetometer with a high Nyquist frequency, will alter the apparent shape of the spectrum much more than the same noise level for a magnetometer with a low Nyquist frequency. This is illustrated more clearly in figure 5 where the digital noise level is plotted as a horizontal line for each of the magnetometers listed in table 3, from the magnetometer's Nyquist frequency to our assumed typical quiet interplanetary spectrum. If the interplanetary field were "quiet" and digital noise were the only noise source present in the measured spectra, then we would expect that spectra derived by these various magnetometers would follow the dashed line at low frequencies and asymptotically approach the horizontal noise line given for that magnetometer at high frequencies. Naively, we could interpret the length of

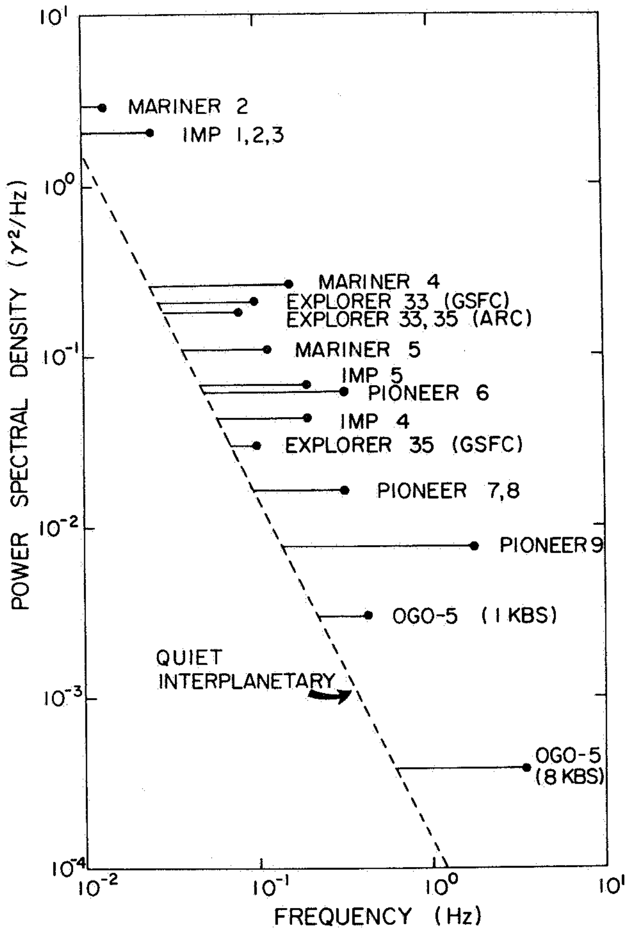

Figure 5. *The digital noise level and Nyquist frequency of a majority of the magnetometers which have measured the interplanetary magnetic field. The horizontal line marks the digital noise level. The dot marks the Nyquist frequency. The dashed line shows the expected quiet interplanetary spectrum.*

the horizontal lines as the amount of wasted telemetry during quiet conditions in the interplanetary medium. However, conditions are not always quiet nor do all these spacecraft remain solely in the interplanetary medium. Figure 5 does not show the noise level of the UCLA OGO-5 fluxgate magnetometer at its highest telemetry rate because from figure 1 we expect that the instrument noise level is greater than the quiet interplanetary spectrum above 1 Hz. Similarly, the digitization noise level of the OGO-1 and 3 search coil magnetometer is not shown because its instrument noise level is greater than its digital noise level except in its two low gain states.

MEASUREMENT OF THE INTERPLANETARY FIELD NEAR THE EARTH

It is now well established that near the earth but upstream from the bow shock, waves are present in the interplanetary medium that are not present far from the earth [*Fairfield,* 1969; *Russell et al.,* 1971]. While these waves do not apparently affect the average magnetic field strength [*Fairfield,* 1969], they do increase the power in the frequency range from 10^{-2} to 1 Hz. Although the waves are seldom present unless the field line simultaneously threads both the satellite and the bow shock, it is difficult in practice to determine whether a particular field line intersects the shock because of the variability of the position of the shock and the uncertainty in the direction of the field due to the presence of the waves. Thus, even when the orientation of the interplanetary field is known, care must be exercised in the interpretation of interplanetary spectra obtained near the earth. However, from figure 5, we see that to extend our knowledge of the interplanetary spectrum much above 0.1 Hz we must examine near-earth data.

Figure 6 shows a power spectrum obtained in the interplanetary medium by the OGO-1 search coil magnetometer [*Holzer et al.,* 1966]. We see that it is at least a factor of 2 higher than the noise level of the similar instrument on OGO-3 but has a very similar slope. The increased power at low frequencies could be due to interference near the OGO-1 spin frequency of 0.08 Hz, which was not present in OGO-3 search coil magnetometer data. Besides the possibility that this spectrum simply shows the noise level of the magnetometer, there is the possibility that this spectrum was contaminated by bow shock associated waves. This spectrum was obtained near the earth (the apogee of OGO-1 was 24 R_E), and no data were available on the orientation of the interplanetary magnetic field at this time. Furthermore, this spectrum differs significantly from others measured in the same region.

Figure 7 shows power spectra of the three components of the interplanetary magnetic obtained by the UCLA OGO-5 fluxgate magnetometer in solar ecliptic coordinates calculated from 24,500 points with 500 degrees of freedom. At the time of this measurement, the interplanetary field measured upstream from the bow shock by both Explorer 33 and 35 magnetometers had a roughly constant solar ecliptic longitude of 260° and a latitude that varied from about 0° to 20°. Using this orientation and extrapolating from the OGO-5 solar ecliptic position of (9.5, –10.8, 15.2) the field line did not intersect the average position of the bow shock.

Thus, it is reasonable to assume that this spectrum is

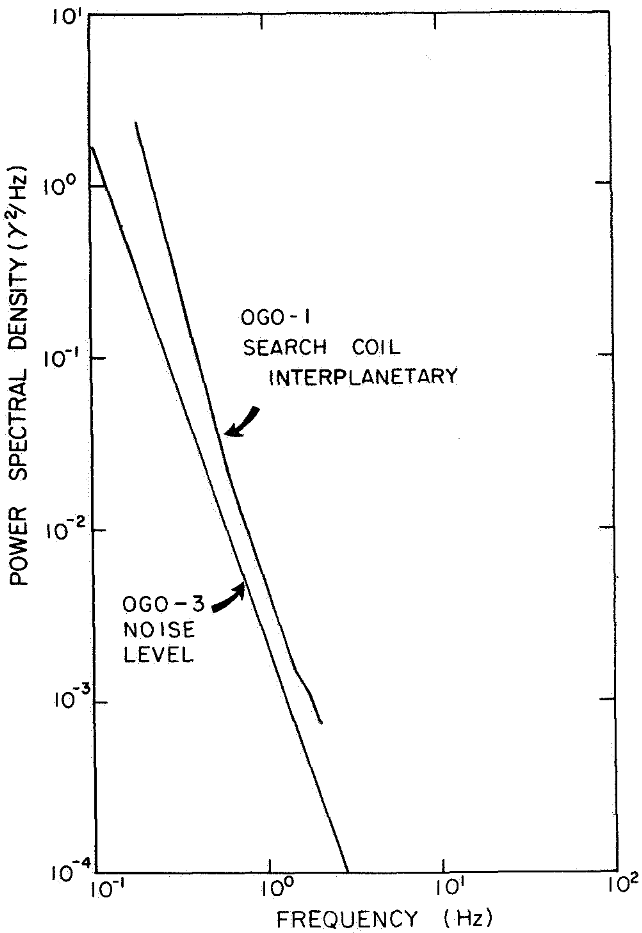

Figure 6. *A comparison of the OGO-1 search coil measurement of the spectrum of the interplanetary magnetic field [Holzer et al., 1966] with the noise level of a similar instrument on board OGO-3 [Russell et al., 1970].*

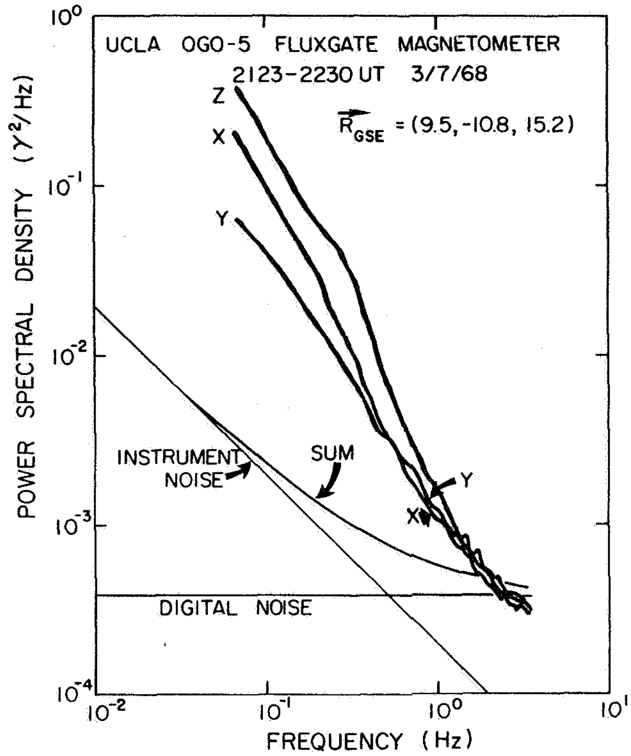

Figure 7. *Power spectra of the three solar ecliptic coordinates of the interplanetary magnetic field obtained by the UCLA OGO-5 fluxgate magnetometer from 2123 to 2230 UT on March 7, 1968. At this time, the field line through OGO-5 did not intersect the expected position of the bow shock. The expected instrument noise level, the digital noise level, and their sum are also shown.*

unaffected by the presence of upstream waves and represents a true interplanetary spectrum at 1 AU. However, one spectrum cannot be considered "typical" and further work is being undertaken to establish what the typical spectrum is. However, we note that during this spectrum the solar wind velocity was approximately 400 km/sec and the density was 3.3 cm^{-3} and both quantities were changing only slowly over the course of the day [*J. Binsack*, private communication 1970]. In other words, the solar wind was average during this period of time.

POWER SPECTRAL DENSITY OF THE INTERPLANETARY MAGNETIC FIELD

Having discussed the possible errors in the measurement of the interplanetary power spectrum, we will now put together what we feel is the best estimate of the interplanetary power spectrum. This is shown in figure 8. At the lowest frequencies (10^{-6} to 10^{-4} Hz), to define accurately the power spectrum requires continuous data in the interplanetary medium for many days. Earth orbiting spacecraft cannot acquire such continuous data. Of the two series of interplanetary probes, the Mariner series and the Pioneer series, spectra have been published for the lowest frequencies only for the Mariner 2 [*Coleman*, 1968] and Pioneer 6 data [*Sari and Ness*, 1969]. However the normalization of the power spectra of *Sari and Ness* [1969] are obviously incorrect and so we have used the Mariner 2 data in figure 8. Mariner 2 was launched during a very active period of time and inward toward Venus. These two effects would tend to increase the power observed and indeed the Mariner 2 curve appears to be somewhat high. We note that since tables 1 and 2 indicate a possible spectral

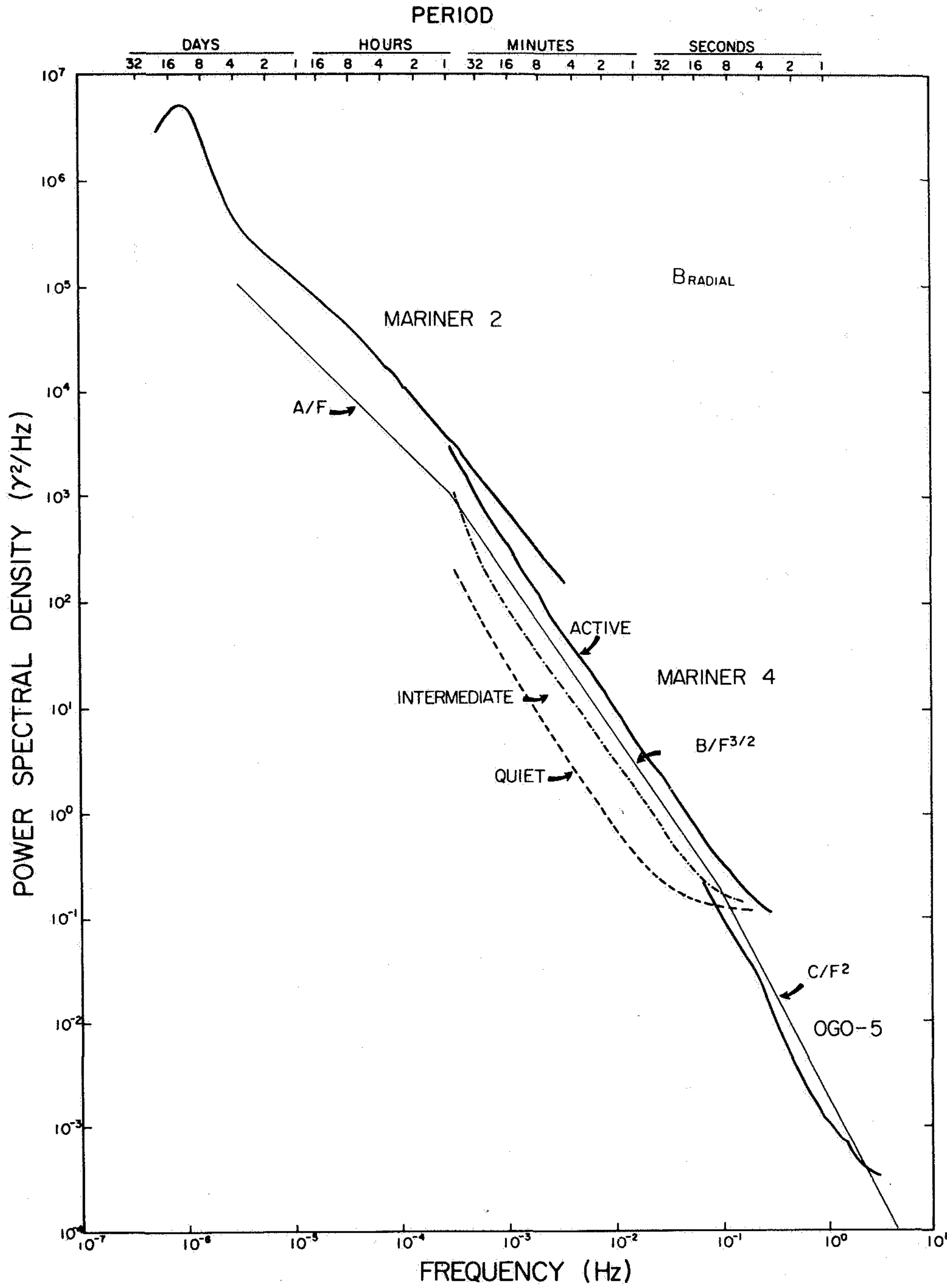

Figure 8. *A composite spectrum of the radial component of the interplanetary magnetic field as observed on Mariner 2 [Coleman, 1968], on Mariner 4 [Siscoe et al., 1968], and on OGO-5. Three spectra showing the range of variability of the interplanetary spectrum are shown for Mariner 4. Since the Mariner 2 data are consistently higher than the Mariner 4 data in the overlapping range of frequencies, it is assumed that the Mariner 2 data were obtained during an unusually disturbed period of time, and the typical spectrum has lower power. Three straight line segments have been drawn with slopes of −1, −1.5, −2 to roughly represent the expected average spectrum near 1 AU.*

folding problem, we have plotted the Mariner 2 data only to one-quarter of its Nyquist frequency.

At the intermediate frequencies, the Mariner 4 [*Siscoe et al.*, 1968] data have been used because these data have been analyzed to show the range of variability of the spectrum. Active, intermediately active and quiet spectra are shown. We note that the Mariner 4 spectra asymptotically approach a value of about 0.1 γ^2/Hz at high frequencies, which is a factor of 2 lower than our estimate of the digitization noise in table 3. This is possibly because the Mariner 4 data samples are not equi-spaced as we have assumed in the calculation of the digital noise level. Finally, at the highest frequencies we have used the OGO-5 power spectrum shown in figure 7, which, as suggested in the previous section, appears to be typical of average solar wind conditions since it joins smoothly with the intermediate activity spectrum of Mariner 4. We note that although we have chosen to plot only the power in the radial component on this figure, the other components have similar spectral form.

On this figure we have drawn three straight lines with slopes of −1, −1.5, and −2 with changes in slope occurring at 3×10^{-4} and 10^{-1} Hz. We see that these straight lines are roughly parallel to the spectrum in the three frequency ranges. The two breaks in the spectrum are somewhat arbitrary, however, and *Sari and Ness* [1969] claim that the break between $f^{-3/2}$ and f^{-2} occurs at about 5×10^{-4} Hz. However, this is not clear from their data since they present no spectra that cover the region of their hypothesized change in slope.

Since *Russell et al.* [1970] showed that power spectra obtained in the interplanetary medium from 1 to 140 Hz with the search coil magnetometer were at the instrument's noise level, there must be a further increase in the slope of the spectrum possibly from f^{-2} to f^{-3} above 1 Hz. However, no other limits on the possible spectrum above 1 Hz can be determined with the present data.

THE INTERPRETATION OF POWER SPECTRA OF THE INTERPLANETARY MAGNETIC FIELD

It is tempting to interpret the changes in slope in figure 8 as changes in allowed wave modes, and the like. However, all power spectra obtained in the interplanetary medium are measured in a frame of reference that is moving at a very high velocity relative to the plasma rest frame. For example, a 340-km/sec solar wind with a number density of 4 cm^{-3} and a magnetic field of 5 γ is streaming past a spacecraft with a velocity of 6 times the Alfvén velocity. Thus, waves propagating in the solar wind are severely Doppler shifted. The amount of Doppler shifting depends on the size of the component of the solar wind parallel to the phase velocity of the wave. If a wave is propagating perpendicular to the solar wind velocity, therefore, the Doppler shifting is zero. However, if a wave with phase velocity less than that of the solar wind (most electromagnetic waves under typical solar wind conditions) is propagating parallel or antiparallel to the solar wind it will be severely Doppler shifted. Waves propagating parallel to the solar wind will be Doppler shifted to higher frequencies maintaining their sense of polarization, and waves propagating antiparallel to the solar wind will be Doppler shifted to lower frequencies if their phase velocity is greater than half the solar wind velocity and to higher frequencies if their phase velocity is less than half the solar wind velocity. In both antiparallel propagation cases, however, the wave polarization observed in the satellite frame is reversed unless the phase velocity is greater than the solar wind velocity. In short, then, the fact that the solar wind is flowing past the observer and is, in fact, usually super Alfvénic and supersonic, mixes the power spectrum of the signal in the plasma rest frame as well as mixing cross correlations between components. Thus, it is not simple to interpret these power spectra.

To understand the physical processes occurring in the magnetic field, such as which wave modes are present, it is essential to perform cross correlations with other plasma parameters.

At present there is some controversy as to the importance of discontinuities versus waves in determining the interplanetary power spectrum [*Sari and Ness*, 1969; *Belcher et al.*, 1970]. Step functions in the magnetic field, whether they are propagating as waves or whether they are simply convected with the solar wind velocity, will both contribute to a $1/f^2$ spectrum at high frequencies. (We note that the low-frequency spectrum, below approximately the frequency corresponding to the average spacing of the discontinuities, need not be proportional to $1/f^2$.) Furthermore, there is no necessity that the natural wave spectrum between discontinuities *not* be proportional to $1/f^2$. Thus, the spectral shape of the interplanetary spectrum provides no simple answer to this controversy. To distinguish between propagating and nonpropagating structures requires examination of both the field and plasma behavior. We note the anisotropies in the solar wind plasma distributions further complicate these identifications [*Hudson*, 1970].

SUMMARY

From our examination of the noise levels of two typical fluxgate magnetometers, it appears that most power spectra of the interplanetary field fluctuations are limited by digital noise rather than instrument noise.

However, we have no guarantee that all magnetometers are this quiet. The OGO-1 and 3 search coil magnetometer, however, is limited by its inherent noise level rather than digital noise; in fact, the spectrum of this noise level is greater than the power spectrum of the average interplanetary magnetic field at 1 AU. We note, however, the search coil magnetometer is a more sensitive instrument than the fluxgate magnetometer above about 4 Hz.

From our test cases, it appears that digital noise is distributed uniformly over the power spectrum at least at high frequencies. However, at low frequencies digitization actually reduced the power. Although this undoubtedly altered the power spectra obtained in the interplanetary medium, its effect is small (fig. 3) and cannot account for the observed changes in slope.

Aliasing could be a problem in the creation of power spectra from the data for many of the interplanetary magnetometers. However, due to the observed natural spectrum of interplanetary fluctuations this should only be a serious problem for frequencies above one-half the Nyquist frequency.

Although the interplanetary spectrum near the earth can be contaminated by waves associated with the earth's bow shock, we can combine OGO-5 data with the Mariner 2 and 4 interplanetary spectra to create the spectrum from about 5×10^{-6} Hz to 1 Hz, if care is taken to exclude times when the magnetic field line threads both OGO-5 and the shock front. The spectrum of the radial component is approximately proportional to f^{-1} up to 3×10^{-4} Hz; then it is proportional to $f^{-3/2}$ up to about 10^{-1} Hz; and finally it is proportional about f^{-2} up to at least 1 Hz. It is quite probable that the spectrum undergoes another change in slope above 1 Hz.

Finally, we stress the difficulty in interpreting the power spectrum of the interplanetary magnetic field by itself. Doppler shifting mixes frequencies and different physical processes can result in the same spectrum. Cross correlations with simultaneous plasma data are necessary. Multispacecraft studies could also be very fruitful.

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