A Preliminary Analysis of Viking S-X Doppler Data and Comparison to Results of Mariner 6, 7, and 9 DRVID Measurements of the Solar Wind Turbulence

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More than 135 passes of Viking S-X doppler data have been used to investigate the solar wind turbulence from 3 August to 15 December 1976. The results of this analysis are compared to previous investigations using Mariner DRVID data to attempt to find the changes in the turbulence over the sunspot cycle. It is found that: (1) electron density fluctuations decline with heliocentric distance as $r^{-1.8\pm0.2}$*; (2) the level of the turbulence may be a factor 2 lower near sunspot minimum than at maximum; and (3) the spectrum of the fluctuations may be steeper (*~ -3.0 *vs* ~ -2.6*) near sunspot minimum. The expected range error for various time scales and geometries is derived from the results.*

I. Introduction

Critical Voyager pre-encounter correction maneuvers will occur at small SEP angles in 1981. Because 1981 is very near the peak of the sunspot cycle (SSC) which is now beginning, there is concern that the solar wind (SW) plasma and/or its fluctuations will interfere with the stringent radio metric accuracies required. In order to investigate changes over the SSC, columnar content data from Viking have been processed in the same way as DRVID data from Mariners 1969 and 1971 (Ref. 1) obtained near the peak of the past SSC.

This is a preliminary report of that investigation. Only 15 passes of Viking data from after superior conjunction (~27 November 1976) have been processed. The long passes available from tying together doppler passes or using S-X range data to set an absolute scale have not been exploited. Furthermore, only limited comparisons to other SW or solar surface data have been made. A predictive model of radio metric data quality would be likely to emerge from such analysis. Viking data continue to be collected, and there is now a span of post-conjunction data equal to the preconjunction data investigated here. The longer time base and more complete radial (heliocentric) coverage will allow better estimates of the radial dependence and the SSC modulation of the SW turbulence.

The data coverage for this analysis is described in Section II. The analysis techniques are outlined in Section III. Section IV gives the results and discusses the implications for radio metric data.

II. Data Coverage

The data coverage for this analysis is shown in Table 1. Data from 23 September to 17 October 1976 exist but were not included because of lack of time. The second column gives the number of passes (from various 64-meter stations) included in each grouping.

All of the passes used in this analysis were at least 5 hours long and contained at least 275 points. Thus, some gaps were allowed, but none exceeding 1 hour. Most of the data were 1-minute samples, but stretches of 10-second data occur in some passes. The net average sample spacings ranged from about 55 to 65 seconds. Individual passes lasted up to 12 hours. Near and after conjunction 10-second (and even some 1 second) data were obtained in large amounts. Ten-second data from 8 to 15 December 1976 have been included in this analysis by averaging the data to 30-second sample times and then treating the data to give the same spectral resolution as the 60-second passes. The 10-second data have also been examined by themselves and show that the power spectrum continues smoothly to higher frequencies.

The coverage of one or both spacecraft is often continuous. When the doppler data overlap (or nearly), it is possible to continue the record by continuing to add the change in columnar content at each step. Records up to 32 hours (typically 15-20 hours) have been constructed in this way. The spectra from these longer records have not yet been averaged in the same way as the results presented here but will be presented in a future report.

III. Data Analysis

In order to investigate the columnar content changes under a wide range of conditions, it is necessary to have an objective measure of these changes. The power spectra of the data provide such a measure. The spectra give the mean squared fluctuation per unit frequency interval in a range of frequencies. Thus, given the power density at some frequency, $P_{\Delta I}(\nu)$, the expected change in the columnar content on a time scale $t_1 = 1/\nu$ is

$$\Delta I\,(t_1) \cong (P_{\Delta I}(\nu) * \nu)^{1/2} \qquad (1)$$

where for rapidly falling spectra at low frequencies we have approximated the frequency interval $\Delta\nu$ (spectral resolution) by ν.

The frequencies over which one can obtain reliable estimates of the spectrum from discretely sampled records of limited length are $1/2\,\Delta t \geqslant \nu \gtrsim 5/T$, where Δt is the sample rate, and T is the length of the record. For most of the data used here $1 \times 10^{-4}\,\mathrm{Hz} \leqslant \nu \leqslant 1 \times 10^{-2}$ Hz, corresponding to time scales of 2 minutes $\leqslant t_1 \leqslant 2$ hours. The longer records produced by tying passes together permit the investigation of time scales of up to 3-6 hours, while 10-second data extend the time scale down to 20 seconds ($\nu = 5 \times 10^{-2}$ Hz).

For some purposes, near-simultaneous ranging or the error of making a downlink-only measurement, the change of the columnar content on various time scales is of most interest. In other cases, two-station tracking or tracking of two separated spacecraft, the change of the SW density on various scale sizes is more important. The latter can be obtained from the former if the SW velocity is known. A typical SW velocity is 350-450 $\mathrm{km \cdot s^{-1}}$. Since our data have no direct measurement of the velocity, scale sizes inferred using 400 $\mathrm{km \cdot s^{-1}}$ could be in error by up to 50 percent. The results here are in terms of frequency.

The results below were obtained through the following steps:

(1) The columnar content change records from each pass where autocorrelated to 60 lags (~1 hour). The 10-second data were summed to ~30-second intervals and autocorrelated to 80 lags (~45 minutes).

(2) The cosine transform of the autocorrelation, smoothed with the Hanning window, was used to give the power spectrum.

(3) The individual power spectra were averaged in groups of 6 to 12. The data were grouped by the distance of the ray path's closest approach to the sun, Q. The lowest value of all the averaged points was subtracted to remove the noise.

(4) The slopes of the averaged spectra were obtained by hand. A number of estimates were made for each spectrum to determine the possible range. It is typically ±0.2.

The Viking S-X data and the Mariner DRVID were all treated in the same way except that the maximum lag for the DRVID data was ~45 minutes. None of the data have been corrected for the change in ionospheric columnar content. This change is generally $\leqslant 1.5$ meters over a pass and so is much less ($\leqslant 10$ percent) than the observed changes, except for some passes in August and September. Neglect of this correction is not thought to significantly affect any of the results.

In addition to the power spectrum analysis, the individual and long records were examined for rms variation about the mean, peak-to-peak change, maximum rate of change, and character (slope, single or multiple "humps," and time scale of significant change) of the change. The former indices are all closely related to the power spectrum. The latter observation allows some investigation of changes on longer time scales than can be done formally with the power spectrum.

IV. Results and Discussion

From the general character of the columnar content changes, especially those seen on the long (tied) passes, one can see that the power spectra extend to low enough frequencies to pick up most of the important changes. Occasionally, there are slopes or "humps" with time scales of 8-12 hours, but these occur only about once per month. Thus, the data from the power spectra provide a fairly complete and realistic description of the columnar content changes for time scales from 30 seconds to several hours.

Table 1 summarizes the results of this investigation and gives the overall average results from Mariners 1969 and 1971. The volume of Viking data is obvious.

Table 1 suggests that the average spectral index is steeper for the Viking data (~3.0) near SSC minimum than for the Mariner data (~2.6-2.8) near maximum. This result, if confirmed, could be very important for understanding the SSC modulation of the SW and could affect estimates of navigation accuracy. The result is somewhat uncertain for two reasons. First, since the spectra are only approximately power laws, there is an uncertainty of 0.2-0.3 in fitting a straight line to them. Second, because the Mariner records were shorter, the spectral resolution is less, and the low-frequency points upon which the slope relies are more uncertain. This interesting, and potentially very important, suggestion that the slope decreases near SSC maxima needs to be followed up with more data from all parts of the SSC.

Figure 1 shows the power density at 3×10^{-4} Hz ($t \sim 1$ hour) from the Mariners (each divided into four groups) plotted with the Viking data as a function of Q, the distance of the ray path's closest approach to the sun (Q[AU] = sin [SEP angle]). No corrections for possible SSC changes (see below) have been made. Again, the data are variable, but a line of slope 2.6 (log-log) or a little more provides a reasonable representation of the data. The ionosphere may bias the points at large Q upward, reducing the slope. This slope implies that the density fluctuations in the SW, Δn, decline as $r^{-1.8}$. A similar plot of the Viking power densities at 6×10^{-4} Hz shows slopes of 2.4-2.6. More data at smaller values of Q are needed to better determine these slopes. From these data one concludes that $\Delta n \propto r^{-1.8 \pm 0.2}$. This slope agrees with that found empirically by Berman et al. (Ref. 2) for doppler noise data. This is because doppler noise is a measure of the same quantity as the power spectrum, the mean *squared* density integrated along the signal path.

The data of Table 1 and Fig. 1 suggest that the power density at 3×10^{-4} Hz may be a factor 2 less near SSC minimum than at maximum. The natural variability of the data makes this difficult to establish, but the Viking values lie systematically below the Mariner ones. More Viking post-conjunction data will make this determination more definite.

In an effort to study the time variations of the Viking data, shorter groups (3-5) of spectra were averaged and scaled by Q^3 to remove the radial dependence. These data were compared by eye to averaged (3 days running) sunspot numbers. No impressive correlation emerged. A similar attempt was made with the Mariner 9 data (Ref. 1). It produced possible, but not overwhelming, correlations at the expected rotational lags (~5-7 days). The lack of correlation may lie in the fact that the sunspot number is a very crude and large scale (a hemisphere) indicator of solar activity. Other measurements with better spatial (i.e., heliographic longitude) resolution such as white light coronagraph pictures and x-ray measurements will be used in further investigations.

The Viking data summarized in Table 1 can be used to estimate the errors which may be encountered in advanced navigation techniques such as alternate ranging. The power spectrum of the columnar content data can be fairly well represented by

$$P(\nu, Q) = 5.0 \times 10^{30} \left(\frac{Q}{0.1 \text{ AU}}\right)^{-2.6} \times \left(\frac{\nu}{3 \times 10^{-4} \text{ Hz}}\right)^{-3.0} \text{cm}^{-4}\text{Hz}^{-1} \tag{2}$$

where Q is the distance of the ray path's closest approach to the sun, and ν is the frequency of the fluctuations in the columnar content, for $1 \times 10^{-4} \lesssim \nu \lesssim 1 \times 10^{-2}$ Hz, $0.03 \leqslant Q \leqslant 0.6$ AU. By using Eq. (1), one may easily deduce the rms change in columnar content from Eq. (2). The result in one-way meters of S-band range change is

$$\Delta I_{\text{rms}} (\nu, Q) = 3.4 \left(\frac{Q}{0.1 \text{ AU}}\right)^{-1.3} \left(\frac{\nu}{3 \times 10^{-4}}\right)^{-1.0} \text{meters} \tag{3}$$

Values of this expression for several values of ν and Q are given in Table 2. From the rms change, one gets the peak-to-peak change, that is, the expected run, by multiplying by 3, so $\Delta I_{pp} \cong 3\Delta I_{rms}$. The solar wind fluctuates strongly on all time scales by a factor of 2 to 3, so $\Delta I_{pp_{max}} \cong 9\Delta I_{rms}$. Finally, it was estimated above that the average power spectrum may be higher by a factor of 2 around sunspot maximum than at minimum, so for Voyager around the coming sunspot maximum one might have $\Delta I_{max} \cong 9\sqrt{2} \cdot \Delta I_{rms} = 12.6\Delta I_{rms}$. Values of this quantity, but increased by 20 percent to account for the suspected flattening of the spectrum around SSC maximum, for several values of ν and Q are given in Table 3. The values of range change given in Table 3 are large enough to be of interest to navigators. One can place the following rough interpretation upon these numbers: one would expect 2 range points taken with the specified SEP and Δt to differ by this amount once in several hundred points. If the sun is reasonably active at the coming maximum, one would expect alternate range points to differ fairly frequently (1 in 3 or 5) by amounts a factor of 3 less than those in Table 3 (i.e., ~5 times those in Table 2). Note that in any case the errors increase directly with Δt so that the usefulness of alternate ranging depends critically upon its smooth implementation. In this connection it should be noted that Wu (Ref. 3) has shown that errors of up to several (2-3) meters in range calibrations can be made because of the one-way nature of the S-X data.

The main findings of this preliminary investigation are:

(1) $\Delta n(r) \propto r^{-1.8\pm0.2}$.

(2) The power density at 3×10^{-4} Hz may be a factor of 2 less near SSC minimum than at maximum.

(3) The spectrum appears to be steeper (~3.0 vs ~2.6-2.8) near SSC minimum.

(4) The time variations are not well-correlated with sunspot number.

(5) Columnar content changes, which could be important to Voyager navigation, are shown to be likely.

References

1. Callahan, P.S., "Columnar Content Measurements of the Solar Wind Turbulence," *Astrophys. J.*, Vol. 199, p. 227, 1975.

2. Berman, A. L., Wackley, J. A., Rockwell, S. T., and Kwan, M., "Viking Doppler Noise Used to Determine the Radial Dependence of Electron Density in the Extended Corona," in *The Deep Space Network Progress Report 42-38*, pp. 167-171, Jet Propulsion Laboratory, Pasadena, Calif., Apr. 15, 1977.

3. Wu, S. C., *A Demonstration of Uplink Charged-Particle Range Calibration Technique–Viking Radiometric Data*, JPL Engineering Memorandum 315-13, Jan. 31, 1977 (JPL internal document).

Table 1. Parameters of averaged spectra of single pass data

Time period	Number averaged	Avg Q, AU	Spectral index	$P(3\times 10^{-4})$, $cm^{-4}Hz^{-1}$[a]	$P(6\times 10^{-4})$, $cm^{-4}Hz^{-1}$[a]
Mariner '69; 1970					
May 21-July 2	17	0.185	2.2-2.8	4.8E30	4.8E29
Mariner '71; 1972					
Aug 10-Oct 25	33	0.132	2.6-2.9	7.8E30	1.6E30
Viking; 1976					
B, Aug 3-Aug 12	17	0.566	3.0	1.0E29	1.0E28
B, Aug 13-Aug 20	12	0.527	3.0	1.1E29	1.0E28
B, Aug 21-Aug 26	10	0.487	3.0	1.4E29	1.2E28
B, Aug 27-Sept 1	11	0.459	3.1	7.9E28	7.2E27
B, Sept 1-Sept 6	10	0.430	3.0	1.6E29	1.8E28
B, Sept 7-Sept 10	6	0.407	3.0	1.4E29	1.2E28
A, Sept 9-Sept 15	12	0.383	3.1	6.9E28	6.5E27
A, Sept 17-Sept 21	11	0.350	3.3	4.5E29	4.5E28
A, Oct 20-Nov 7	15	0.133	3.0-3.2	2.5E30	2.4E29
B, Oct 18-Nov 13	17	0.140	3.1-3.2	2.8E30	3.5E29
A&B[b] Nov 26-Dec 2	7 (A11)	0.0286	2.8	1.1E32	1.3E31
	4	0.0185	2.6	3.7E32	5.3E31
	3	0.0359	2.7	6.6E31	5.3E30
A&B[c] Dec 8-Dec 15	8	0.0908	3.1	1.9E31	6.8E29

[a]One meter of one-way S-band range change = 1.15×10^{-13} cm^{-2} or 1 $m^2 = 1.32 \times 10^{26}$ cm^{-4}.
[b]These data were divided into 2 groups to help determine the radial dependence.
[c]These are 10-second data treated to give comparable spectral resolution.

Table 2. Rms columnar content change for Viking S-X doppler data (one-way, S-Band meters)

Q, AU	SEP, deg	ν, 10^{-3} Hz					
		16.7	3.33	1.67	1.11	0.833	0.556
		Δt, min					
		1	5	10	15	20	30
0.05	2.87	0.149	0.746	1.49	2.24	2.98	4.48
0.10	5.74	0.0606	0.303	0.606	0.909	1.21	1.82
0.15	8.63	0.0359	0.179	0.359	0.537	0.716	1.07
0.20	11.5	0.0246	0.123	0.246	0.369	0.493	0.738
0.25	14.5	0.0184	0.0922	0.184	0.276	0.368	0.552
0.30	17.5	0.0146	0.0728	0.146	0.218	0.291	0.436
0.40	23.6	0.0100	0.0500	0.100	0.150	0.200	0.300
0.50	30.0	0.00748	0.0374	0.0748	0.112	0.150	0.224
0.60	36.9	0.00590	0.0295	0.0590	0.0885	0.118	0.177

Table 3. Predicted peak-to-peak columnar content change for Voyager sunspot maximum (one-way, S-band meters)

Q, AU	SEP, deg	ν, 10^{-3} Hz					
		16.7	3.33	1.67	1.11	0.833	0.556
		Δt, min					
		1	5	10	15	20	30
0.05	2.87	2.32	11.6	23.2	34.9	46.5	69.8
0.10	5.74	0.945	4.72	9.45	14.2	18.9	28.4
0.15	8.63	0.560	2.80	5.60	8.37	11.2	16.7
0.20	11.5	0.384	1.92	3.84	5.75	7.67	11.5
0.25	14.5	0.287	1.43	2.87	4.30	5.74	8.61
0.30	17.5	0.228	1.14	2.28	3.40	4.55	6.80
0.40	23.6	0.156	0.78	1.56	2.34	3.12	4.68
0.50	30.0	0.117	0.58	1.17	1.75	2.33	3.50
0.60	36.9	0.0920	0.46	0.92	1.38	1.84	2.76

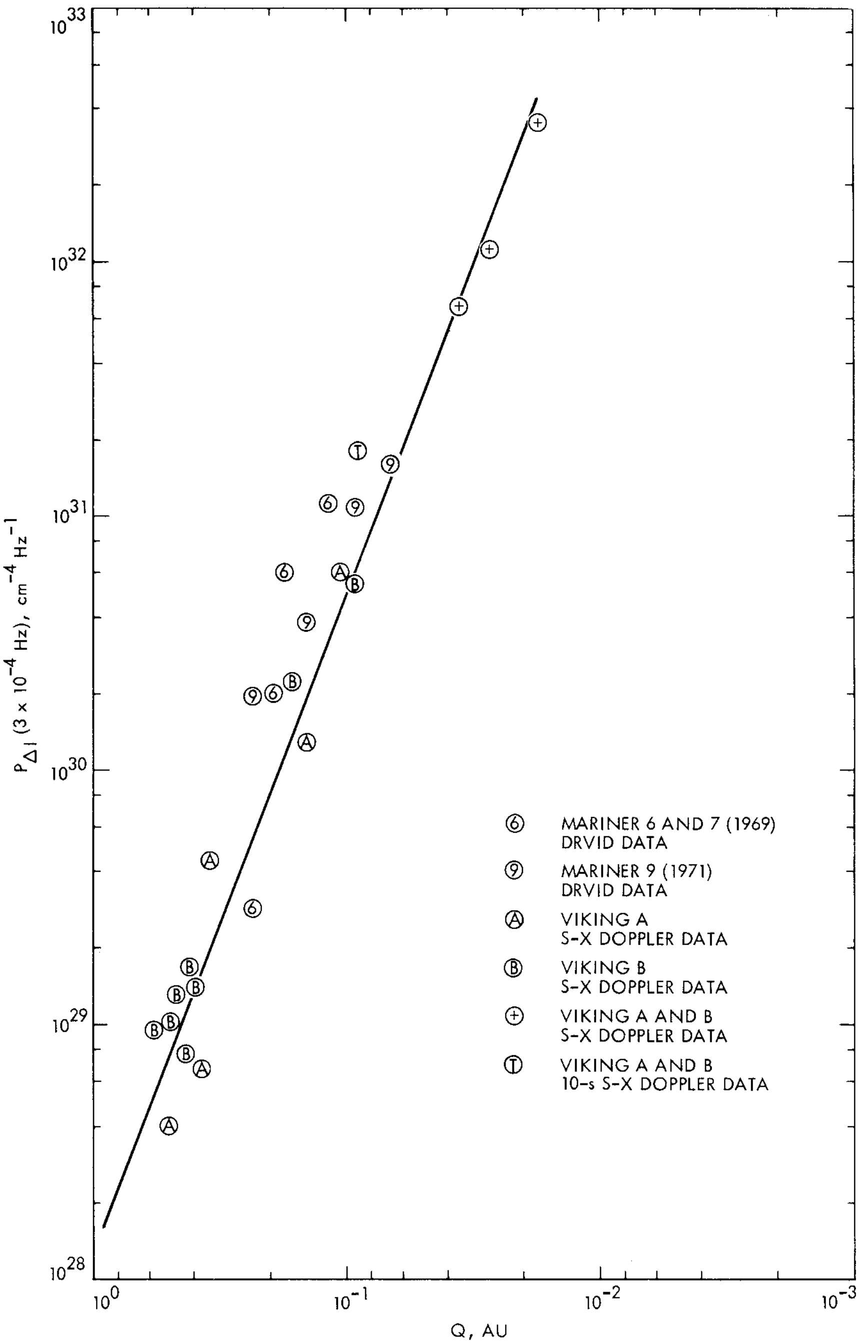

Fig. 1. Averaged power density at 3 × 10^{-4} Hz plotted against *Q*, the distance of the ray path's closest approach to the sun. The line through the points has slope 2.6. Note that the Mariner points generally lie above the Viking points. The points at large *Q* may be biased upward by the ionosphere.