Long-distance Correlations of Interplanetary Parameters: A Case Study with HELIOS


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Abstract.
In recent work, promising agreement has been obtained between measured indices of geomagnetic activity (Dst, and cross-polar cap potential) and their predicted values using interplanetary input from probes in the inner heliosphere (≈0.7 AU) when the probe was close to, (5), and even substantially displaced from, (4), the Earth-Sun line. Implicit in this agreement is a good correlation of, at least, the basic temporal profiles of the major interplanetary parameters at the two observing sites. In this work we discuss a case study using Helios 1 and 2 data when the spacecraft are lined-up and separated by an almost constant radial distance of 0.2 AU. In the period studied, the interplanetary medium consists of a fast stream being trailed by a magnetic cloud in a slower flow. Good correlation is found between the plasma and field observations at the two sites. Two lag times, reflecting the two types of major structures in the interval chosen, are determined. Evidence of evolutionary processes are briefly discussed. Spectral analysis confirms the results obtained from time series analysis.

INTRODUCTION AND AIMS OF THE STUDY
Together with accuracy, a long lead time is a desideratum of space weather predictions. In recent years good prediction of the temporal variation of the Dst index and cross-polar cap potential has been achieved using solar wind measurements in the inner heliosphere. Thus (5) could predict many features and long-term trends of the storm-time Dst index with (2)'s empirical formula, using data from monitors located at ≈0.7 AU and close to the Sun-Earth line at low heliographic latitudes. This would yield a lead time of ≈1 day. In a study on the effect of heliographic longitude on the quality of predictions, (4) examined a disturbed period in March 1979. They used a drift-loss model for the energization of the ring current (e.g., 3) with interplanetary inputs from 2 probes: Helios 2, at 0.7 AU and displaced east of the Sun-Earth line by 30°, and from ISEE 3, orbiting the L1 Lagrangian point. The temporal variation of the Dst measurements during three storms could be well reproduced in both cases. Further, the cross-polar cap potential calculated from (7)'s model showed a similar variation in both cases. Such results are good news for space weather efforts.

Implicit in this good agreement is a long coherence/correlation scale length of at least the gross features of major interplanetary parameters (such as V, Bz, B, etc.)

In this work we wish to pursue this issue further. To this end, we investigate a 10-day period where the Helios 1 (H1) and Helios 2 (H2) probes were approximately lined-up and separated by ≈0.2 AU. The questions we pose are: (i) Are the basic features of the solar wind well correlated 0.2 AU downstream? (ii) Do we find systematic signatures of evolution?

The solar wind segment we study consisted of two different interplanetary structures moving at different speeds. After cross-correlating various field and plasma parameters, we identify two different lag times, each reflecting these two major structures. Good correlation is found between the measurements at the two probes, indicating that the integrity of the solar wind structures is preserved, at least in this instance. We further determine empirical factors by which parameters scale with radial distance. Elements of spectral analysis are used to confirm and extend the results of the analysis in the time domain.

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HELIO S 1 AND 2 OBS ERVAT IONS ON
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Figure 1 shows an ecliptic projection of the Helios orbits in 1976. The Earth (E) - Sun (S) line is fixed. The red segments indicate the selected 10-day study period during which the spacecraft are approximately lined up. The spacecraft separation varies between $R_{BP}/A_0 = 0.21$ and $0.24$ AU, and their longitudinal separation, $\Delta F$, from $-3.6$ to $12.3^\circ$, as can be seen in Figure 2 where we plot the heliospheric radii of the probes (top panel) and the difference in their longitudes.

Figure 3 shows the variation of select parameters, namely, the density, $n_p$, bulk speed, $V_p$, total field $B$, its $z$-component, $B_z$, in solar ecliptic (SE) coordinates, and proton temperature $T_p$. Visually, it is clear that both spacecraft observe the same structures: (i) a high frequency oscillation lasting many days riding on a fast ($\sim 700$ km s$^{-1}$) solar wind stream. These are most probably Alfvén waves. (ii) A low-temperature, enhanced-field region embedded in a depression of the bulk flow speed. In interval (ii) $B_z$ and other magnetic field components (not shown) execute smooth rotations. Taken together, observations in (ii) are signatures of a magnetic cloud (1).

In Figure 4 we overlay the temporal profiles. A time shift of 17 hours aligns the magnetic signatures of the magnetic cloud well. The leading edge of the high speed stream trailing the cloud is overtaking the ejecta, as evidenced by the mismatch at the speed gradient. We may obtain how these parameters scale with heliospheric radius, $R$, treating the high-speed stream and the magnetic cloud separately. For the high speed stream between hours 17 and 140 in the figure we have: $n_p \sim R^{-2.1 \pm 0.2}$, $B \sim R^{-1.5 \pm 0.4}$, while $V_p$ and $T_p$ are approximately the same. For the magnetic cloud between hours 180 and 190: $n_p \sim R^{-2.6 \pm 0.4}$, $B \sim R^{0.9 \pm 0.5}$, and $T_p \sim R^{-2.2 \pm 1.8}$, the latter reflecting a cooling presumably due to the radial expansion of the magnetic cloud.

CROSS-CORRELATION ANALYSIS

We first have to equalize the time resolutions of the H1 and H2 data sets. We interpolate and/or average the data to a uniform 10 minute resolution. Data are analyzed in the time domain first and then in the frequency domain. The two approaches are complementary to each other. In the time domain, data are shifted in time in order to determine the lag corresponding to maximum correlation.
FIGURE 4. Same as Figure 3 but the universal time of H1 measurements have been delayed by 17 hours, this being the delay time we determine for the magnetic cloud signatures.

FIGURE 5. The correlation coefficient of $n_p$ as a function of lag time (in units of 10 min) (bottom) and the superposition of the profiles.

between the spacecraft (see below).

As a first step we study the inter-spacecraft correlations of a plasma ($n_p$) and two magnetic field parameters ($B$, and $B_z$). The correlation coefficient of $n_p$ is shown as a function of lag time (in units of 10 min) in the bottom panel of Figure 5. A peak cross-correlation of 0.85 is reached at a lag time of 17 hours. The resulting profiles are shown superposed in the top panel. Note that the density at H2 has been multiplied by a factor 2. The agreement is seen to be good. A second peak in the cross-correlation is present, corresponding to a lag of about 8 hours. We discuss this below when we consider correlations on $B$, where the two-peaked correlation plot is more pronounced.

FIGURE 6. The correlation coefficient of $B$ as a function of lag time. The correlation peaks at 2 different times, already evident in Figure 5. Top panel shows the superposition of the profiles with the longer delay time taken into account.

FIGURE 7. Similar to Figure 6 but for $B_z$.

Figure 6 shows the cross-correlation results for the total field, $B$, As the bottom panel shows, the routine picks out two peaks with the same lag times as those for the density. In the top panel we overlay the two time series using the longer time delay. This aligns the magnetic field in the magnetic cloud (indicated by the right vertical guideline). The slanted lines indicate correspondences of features in the high speed stream and confirms that these are subject to a different lag.

Figure 7 shows a similar calculation for the $B_z$ component of the magnetic field. One peak, at a lag of $\sim 18$ hours, is evident in the bottom panel. This corresponds to the large rotation of the field in the magnetic cloud. At this (low) resolution, the second, weaker peak corresponding to the oscillation in the high speed stream is not seen. Note that we use smoothed $B_z$ data. This we believe is justified because, as we show below, the high frequency components lose coherence over very short distances and high coherence between two different points in the solar wind is carried by the low frequency components of the signals, i.e. their long-period variations.
SPECTRAL ANALYSIS

We have also examined the data using a spectral analysis. The technique is described in detail in (6), to which we refer the reader. Typically one can obtain the coherence, the phase lag and amplitude ratio between the signals at the two spacecraft. In the interests of brevity, we discuss here the coherence only, reserving a fuller discussion to a future publication.

Figure 8 shows the coherence of \( N_p \), \( B_z \) and \( B \) as functions of frequency. The data sampling interval is 10 min and the number of data points per FFT is chosen as 512, so that the time interval needed to obtain one spectrum is 5120 min (= 85.3 hours). In Figure 8, we have first shifted the H1 data forward by 17 hours, taking this result from the time series analysis reported above.

We may see that at low frequencies the coherence is relatively large for \( N_p \) and \( B_z \), while it is small for \( B \). The frequency at which the coherence drops below \( \sim 0.5 \) is \( f \sim 0.001 \text{ min}^{-1} \). The coherence is being maintained by the low-frequency components of the signals, as shown in (6) and anticipated above.

When we examine the phase lag diagram (not shown) we find that there is a shallow linear gradient in the lowest frequency range (\( \leq 0.0005 \text{ min}^{-1} \)). The phase lag \( \Delta \phi \) is related to the frequency by \( \Delta \phi = 360f\Delta t \text{ (deg)} \), where the \( \Delta t \) is the propagation delay time. From the shallow gradient we infer an additional time shift of \( \sim 1.5 \) hours to the lag estimated from time series. Thus the time- and frequency-analyses agree well with each other.

CONCLUSIONS

We have examined Helios 1 and 2 magnetic field and plasma data for a 10-day interval in 1976 when the spacecraft were approximately aligned and close to the Sun-Earth line. The solar wind segment we examined consisted of 2 structures: (i) large-amplitude waves in a high speed stream, and (ii) an interplanetary magnetic cloud embedded in a slower flow. Motivated by recent successes in predicting gross features of geomagnetic disturbances from interplanetary measurements made in the inner heliosphere, we concentrated on large separations (fraction of an AU). Here, Helios 2 was \( \sim 0.2 \text{ AU} \) downstream of Helios 1.

We pursued the questions: (i) Are basic features of the solar wind still correlated so far downstream? (ii) And do we find evidence of evolutionary signatures? The cross-correlation analysis gives an affirmative answer to the first question. It furthermore picks out two delay times which reflect the two main structures in the wind and their different evolution over 0.2 AU. We also determined empirical scaling factors of interplanetary parameters with heliospheric radius. We noted that these scaling factors are different in the fast stream and in the magnetic cloud. This latter point is a subject of future detailed study because of its relevance to space weather predictions from inner heliospheric probes.

Spectral analysis yielded lag times similar to those in the time series analysis. High signal coherence was reached for \( f < 0.0005 \text{ min}^{-1} \), which is the typical frequency of variation in the line plots. At higher frequencies the coherence is lost. As noted above, spectral analysis has increased frequency resolution but at the expense of time resolution.

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