Comparison of Two Techniques for Magnetically Connecting In-situ Observations with Solar Sources

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Abstract

The Sun continually sends out streams of energetic particles via the solar wind. Generally, this output of energy varies by an 11-year solar cycle. However, certain events take place on the sun (solar flares, coronal mass ejections, etc.) that can cause significant increases in energy output ranging from several minutes to hours or days at a time. The interplanetary magnetic field (IMF) is the primary transport vehicle for the solar energetic particles (SEP) generated by such events. Studying SEPs may provide answers regarding solar phenomena such as magnetic reconnection and wave-particle interactions as well as particle acceleration mechanisms and transfer of energy. Understanding these phenomena may enhance our ability to forecast SEP events.

This enhanced ability has several potential positive outcomes. Our ability to accurately forecast SEP events would allow us to more effectively forecast long-range high-frequency radio communication disruptions and could provide an enhanced ability to protect valuable assets in space, including personnel and vehicles. Our hypothesis is that by using the Wang-Sheeley-Arge coronal model (WSA) to establish solar wind parameters and the source of the magnetic field lines at 1 AU we will be able to: (1) test the Parker spiral model (PS) to establish the degree of connectedness between the Sun and Earth; (2) trace the magnetic field lines back from 1 AU to the Sun; (3) establish source footpoints of SEP events. Being able to establish the source footprint is a key parameter for understanding SEP events as well as other related solar phenomena.

Introduction

An important component in the study of SEPs is the Coronal Mass Ejection (CME). CMEs are important to studies of SEPs because of the shock produced by fast CMEs as they propagate through the solar wind and the IMF. (Note, a “fast CME” is one with an average speed of roughly 500 km/s or greater.) (Gopalswamy, 2015)

During solar maxima there are on average about 3.5 CMEs per day. During solar minima there is one CME about every 5 days. Unlike solar flares that release mostly electromagnetic energy, the material ejected by a CME is plasma consisting mostly of protons and electrons embedded in a magnetic bubble. Estimates are that roughly $5 \times 10^{13} \frac{kg}{s}$ of matter are released by a CME at speeds ranging from 400 $\frac{km}{s}$ to in excess of 1000 $\frac{km}{s}$.

CMEs are associated with major changes and disturbances in the magnetic field of the solar corona. Since CMEs seem to originate in the corona, and since the corona is apparently dominated by magnetic energy, it seems evident that the source of energy driving a CME is magnetic in nature.
CMEs interact with the solar wind and the IMF. If the CME is “slow,” it tends to be accelerated to the speed of the ambient solar wind. If the CME is fast, it tends to be decelerated to the speed of the ambient solar wind. It is the latter case of the fast CME that apparently causes the shocks that accelerate SEPs to very high velocities and energies. Hence, fast CMEs are closely linked to SEP events (Owens, et al, 2013).

One can think of a CME as a giant bubble being released from the surface of the Sun during a magnetic reconnection event with the CME “bubble” carrying a significant fraction of the solar coronal mass with it. But what is a magnetic reconnection event? A closed-loop magnetic field line will have a source and a sink on the surface of the Sun (footpoints). Many magnetic field lines may exist in close proximity. As the overall magnetic field of the Sun ebbs and flows, magnetic fields lines may “reconnect” with other adjacent field lines, altering their source and/or sink locations with those of the nearby field lines. Since magnetic energy is stored in the field, it seems likely that as the field lines change and reconnect, magnetic energy stored in the original field may be released. Therefore, as a result of magnetic reconnection magnetic energy may be converted to kinetic energy, thermal energy, or particle acceleration. Hence, magnetic reconnection and SEPs are related. Magnetic reconnection causes CMEs. Fast CMEs cause shocks. Shocks accelerate particles, and accelerated particles become SEPs (Kozarev et al, 2015). Being able to trace an SEP event back from 1 AU to its source could tell us a great deal about CMEs and shocks which in turn could allow us to increase our understanding of what solar parameters drive magnetic reconnection, how magnetic reconnection drives CMEs, and how CMEs cause SEPs. This in turn may allow us to more efficiently forecast SEP events.

Experiment

Our hypothesis is that by using the WSA model to establish solar wind parameters and the source of the magnetic field lines at 1 AU we will be able to: test the Parker spiral model; trace the magnetic field lines back from 1 AU to the sun; establish source footpoints of SEP events. The purpose of the experiment is to compare the predicted WSA source point with the Parker spiral projection of the source point using the solar wind speed generated by the WSA model. The purpose of this TEM is to report on the experiment and its findings, not to describe in great detail the insides of the “black box” that is the WSA model. Several excellent reports are available to describe how WSA functions (MacNeice (1) 2009, MacNeice (2) 2009, MacNeice et al 2011, Owens et al 2008, Arge, et al (2012), Norquist 2013).

The initial goal was to select several Carrington Rotations where a good fit existed between the WSA model and observed solar wind conditions. Overall we were searching for

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1 An Astronomical Unit (AU) is the mean radial distance from the Sun to the Earth. On average it is about 150 million km.
2 The Sun rotates at different velocities at the poles and equator. Since we’re concerned mostly with radial flow we’re mostly interested at this point with the angular velocity at the solar equator. If you were motionless out in space watching the Sun, you would notice that at the equator the period of rotation is about 25 days. However, from Earth it’s a little different. Recall that on any given day we see half of the sun. Since Earth is moving in the same direction around the Sun that the Sun rotates, from our moving vantage point on earth it takes about 27 days for us to see a full rotation. Each Carrington Rotation takes about 27.3 days. Hence, a bookkeeping system has been established to keep track of the angular position of the Sun relative to a radial line connecting the Sun and Earth.
periods that contained SEP events but a low number of interplanetary CMEs (ICME). This proved somewhat problematic due to the relationship between SEPs and ICMEs. The first step was to accumulate a list of SEP events. This was done by consulting available resources documenting start/stop date and time as well as date/time of SEP maximum (see Sources). This list was then compared with a list of registered ICME events. The two tables were compared and a list of dates was compiled. From that list 16 candidate periods were initially chosen that exhibited at least 1 SEP event during the CR but a minimal number of ICMEs during that rotation. Other periods were also chosen where no SEP events were manifest in order to examine a variety of data.

The next step consisted of using the WSA model for the selected CRs to find periods where the WSA predictions provided a relatively good fit of predicted solar wind speed with ACE observations of solar wind speed. This step included several processes that are each described briefly.

**GONG**

WSA uses data provided by the Global Oscillation Network Group (GONG). GONG is a system of Earth-bound observatories that look at the Sun. One important bit of information they gather is the status of the solar magnetic field. This produces a magnetogram. At any given moment on a single day, GONG is able to “see” about half of the solar sphere, or “disk.” Due to limb effects only about 50-60% of the observable solar disk provides useable data. To provide data for the entire solar surface takes about 27 days, a Carrington Rotation. Hence, the magnetogram is made up of 27 separate slices, each covering about 13 degrees of the solar surface.

**ADAPT**

Another way to produce a magnetogram is using the Air Force Data Assimilative Photospheric Flux Transport (ADAPT). ADAPT takes the “snapshot” of data from each day and creates a map of the entire solar surface based on the available data. Each day the newly acquired data is assimilated into the model. Therefore, conditions are adjusted daily. ADAPT provides a full map of the entire solar surface (photosphere) based on observed conditions that day and previous data during the CR. The advantage is that ADAPT provides a map of the entire photosphere based on currently evolving conditions rather than a map that consists of data that could be as old as 27 days. ADAPT “…provides more realistic estimates of the instantaneous global photospheric magnetic field distribution than those provided by traditional synoptic maps.” (Arge, et al, 2015).

**WSA**

WSA uses the data from a magnetogram, whether from ADAPT or a synoptic map, to create predictions of solar wind speed and the IMF. WSA uses the inputs for a given day and creates forecasts based on 1-7 day projections (Arge, 2012). Since it usually takes about 3-4 days for the solar wind to reach 1 AU, typically the 3 or 4 day projections seem to provide the best results (NOAA website)\(^4\). Another interesting feature of WSA is the ability to slightly alter

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\(^3\) ACE, the Advanced Composition Explorer, is a NASA Explorers program Solar and space exploration mission to study matter comprising energetic particles from the solar wind.

\(^4\) However, since we were using a single ADAPT map to generate predictions for an entire CR, we found that generally 1-4 day predictions were identical.
certain coronal field transport parameters\textsuperscript{5}, providing different predictions based on the altered conditions. These alterations are referred to as “realizations.” Each run is capable of producing as many as 12 different realizations for a given input map.

![Observed Photospheric Field from AGN](image)

Fig 1. Typical ADAPT map of the Photosphere.

We chose to use ADAPT maps rather than synoptic maps due to their more realistic estimates as noted above. The procedure then became a matter of selecting a range of ADAPT maps during a particular CR, processing the data from these maps using WSA, then evaluating the different realizations to find a best-fit prediction.

\textsuperscript{5} These parameters have to do with the fine structure of solar granulation.
It is important to understand that WSA produces a prediction of SW conditions for an entire CR based on an ADAPT map for a single day. It is therefore possible to produce as many as 27 different predictions (one ADAPT map for each day during the rotation), with each prediction having as many as 12 different realizations.

It was observed that generally a more significant change in the predictions occurred when using ADAPT maps from different dates throughout a CR. This is logical since conditions on the far-side of the solar surface may not be known. As those conditions become visible they are incorporated into the revised map for that day. Hence, conditions can change on a day-to-day basis. It was also observed that for a given map, the realizations tended to provide more subtle changes. The general process then became evaluating days near the beginning, middle, and end of each CR, then checking the different realizations to find a best-fit.

Figure 3: Illustration of the Parker spiral pattern. It is assumed that the flow is uniform and radial. The spiral effect is due to the magnetic field lines of the IMF being “frozen” into the SW plasma. The equation to calculate the longitude of a connection point is given below. (Image courtesy of R. W. Schunk)
WSA then outputs several parameters including predicted solar wind speed and the predicted solar longitude of the source point. We then use the Parker spiral projection to compare the WSA prediction of the source point with the PS projection of the source point. The PS equation for the solar longitude, $\varphi_{Sun}$, is typically expressed as,

$$\varphi_{Sun} = \frac{\Omega_{\odot} r}{u_{SW}} + \varphi_{Earth}$$

In this experiment we use a potential field source surface (PFSS) model. The PFSS model assumes that beyond some multiple of solar radii (generally 2.5 or 5 $R_{\odot}$) all magnetic field lines are open and propagate radially. We assume the PFSS to be 5 $R_{\odot}$.

**Data/Results**

We found that generally a good match existed between the WSA prediction and the PS approximation of the source point.

![Figure 4: Longitude comparison of PS projection (Red) and WSA prediction (Blue) of the source point.](image)

In the above figure we see that generally, the blue line appears to be superimposed over the red line. This shows how well the agreement is. However, there are several noticeable areas where PS and WSA did not agree. Further investigation was called for in these areas.

First we compared several plots to see if there was similar behavior. We noted that generally the larger differences occurred at times when the solar wind speed was changing significantly; in particular when the SW speed was increasing. Figure 4 proved quite informative. We noticed that the differences coincided with steep spikes in solar wind speed changes.
It became quite helpful to plot the solar wind speed against the net difference between the WSA prediction and the PS projection. This revealed a more specific correlation between the change in solar wind speed and the difference between the WSA prediction and the PS projection. In an attempt to find a trend we next evaluated the area where a significant difference occurred.
We found a general pattern emerging when we looked at a specific region of the solar wind speed plot. Just before a big jump in speed, there would be a series of data points that would have an arbitrarily small change in time with a constant speed (Red line in Fig 6). Since the PS equation depends on the Earth Longitude which is in turn dependent on time, during the period of time when the time change was very small, the PS projection would change very little. Hence, the PS projection would lag further and further behind the WSA prediction as the predicted longitude moved from 360 toward 0 degrees. Once the velocity bumped up to the new speed as indicated by the red spike in Fig 6, the PS projection and WSA predictions of the solar source point longitude would again be in good agreement. As can be observed in Fig 6, during periods of small oscillations of the speed WSA and PS were in good agreement. We found the behavior to be consistent in all CRs that we evaluated.

We discussed this behavior with Nick Arge, one of the developers of the WSA model and discovered that this behavior is an “ad hoc” method of dealing with the physical situation of the SW speed increasing over a fairly short time period. In the physical realm, these events have been referred to as High Speed Enhancements (HSE), (Owens et al, 2008, Norquist, 2013). In these cases it appears that WSA is predicting HSEs. As the faster-moving particles encounter the slower-moving particles a means had to be devised for WSA to process the situation, otherwise there would be plots with overlapping data points and a non-physical situation would develop. The fix was to have the particles “stack up” for a length of time until the acceleration period had past. With the exception of the HSEs, we found WSA predictions and PS projections to be in good agreement nearly always.

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6 We calculated “PS Difference” by subtracting the PS projection from the WSA prediction, WSA-PS. Hence, when \( dt \) became very small PS would be unchanging. Yet, WSA continued to move toward 0 degrees at a rate of roughly 2.5 degrees per time step. Thus WSA would be smaller than PS, which accounts for PS Difference being generally negative.

7 Our observation was that during these periods the time step would be on the order of 8-10 seconds, with anywhere from 2-15 time steps, though this varied considerably.
It should be apparent when looking at Fig 2 above and Fig 7 below that WSA is not always in agreement with observed conditions (MacNeice, et al 2011). The question we asked ourselves was if it mattered. Was there anything different that could be going on that would cause the WSA/PS relationship to differ during periods of good agreement between WSA predictions and ACE observations versus periods of non-agreement. We found that WSA and PS were always in good agreement except during HSEs. Our conclusion was that during periods of good agreement between WSA predictions and ACE observations one should expect good agreement between WSA predictions and PS projections except during HSEs.

**Figure 8:** Note the good agreement in Region 2 between WSA prediction and ACE observations.

A good example of this is found in Figure 8. We see that for about 5-6 days there is very good agreement between WSA predictions and ACE observations. The following plot, Figure 9, shows that throughout the period in question WSA predictions and PS projections are in very good agreement.
Discussion/Conclusion:
This research was a first-step in evaluating the efficacy of using Parker spiral projections to predict solar source points. We found that when compared with a current state-of-the-art coronal model, WSA, the solar source points projected by the Parker spiral model were generally in very good agreement with Wang-Sheeley-Arge predictions of solar source points, except during high speed enhancement events. Further studies would investigate the connection from the potential-field source surface to the photosphere as well as variations due to latitude. Also, comparisons with physics-based models such as ENLIL or CORHEL (Owens et al 2008) would be a plausible next step.

An understanding of solar phenomena is critical to our ability to effectively forecast space weather; effectively forecasting space weather will allow us to forecast disruptions in long-range HF radio communications and protect valuable assets and personnel in the space environment.

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References/Sources

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NOAA Website, legacy-www.swpc.noaa.gov/ws
The Wang-Sheeley-Arge Model


**Sources:**

Carrington Rotation Start Dates:
A.L.P.O. Solar Section, alpo-asatromony.org/Solar/rotn_nos.html

SEP Events/Dates:
NOAA Space Environment Service Center, Solar Proton Events Effecting the Earth Environment, umbra.nascom.nasa.gov/SEP/

CME Dates:
Near-Earth Interplanetary Coronal Mass Ejections Since January 1996, compiled by Ian Richardson and Hilary Cane,
Appendix I

Table of Carrington Rotations/SEP Events
List of Carrington Rotations and associated SEP events and CME events

<table>
<thead>
<tr>
<th>CR #</th>
<th>Start Date</th>
<th>Events</th>
<th># CMEs</th>
<th>High-Speed Enhancements*</th>
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*Predicted HSE: In eyeballing the chart, if there was a gap of about 100 km/s between successive data points this was considered a predicted HSE.
Appendix II
Equation used in this project

To get the Earth Longitude from the Truncated Julian Date:

\[ JD = JD_T + 2440000 \]

Where \( JD_T \) is the truncated Julian Date, a NASA invention from the 1970’s that was tweaked slightly for WSA purposes.

\[ \varphi_E = 360 \left( 1 - \frac{(JD - JD_I)}{T_{CR}} \right) \]

Where \( JD_I \) is the initial Julian Date of a Carrington Rotation and \( T_{CR} \) is the period of a Carrington Rotation, which in this case is defined as 27.2753 days per rotation.

To calculate the Parker Spiral:

\[ \varphi_S = \frac{\Omega_s D}{V_{SW}} + \varphi_E \]

Where \( \varphi_S \) is the longitude at the PFSS, \( V_{SW} \) is the WSA prediction of the SW speed, \( D \) is the distance, in this case starting with 1 AU, but subtracting out the distance from the center of the Sun to the PFSS @ 5 solar radii. Hence, \( D \approx 146,120,371 \text{ km} \), and \( \varphi_E \) is the Earth Longitude given above.

Difference:
The difference is just the net difference between the PS approximation and the WSA footpoint at 5 Solar Radii: \( WSA - PS = PS \text{ Difference} \).

Change in SW Speed:
This is the “instantaneous” change in speed between data points. I assume the first data point is the initial condition, the find a \( dV \) for each subsequent data point which is simply the new speed minus the old speed,

\[ \Delta V = V_f - V_i \]

Change in Time:
Using the same process as above, I assume the first time given is the initial time, then calculate the change in time (seconds) between each time step,

\[ \Delta t = t_f - t_i \]

\( \Delta V/\Delta t \) is the change in speed over the change in time as determined above.

\( \Delta V/\Delta t \) Check:
Here I apply the equation described in the paper describing potentially non-physical situations arising due to earlier arriving faster SW leaving the Sun after later arriving slower SW,
In this equation I use $\Delta V / \Delta t$ from the data point along with the corresponding value for $V_{SW}$ for the same data plot.

**Change in Solar Longitude:**
This is the net change per time step of the WSA-given footpoint on the PFSS,

$$\Delta \varphi_S = \varphi_f - \varphi_i$$

Then using the above I get the rate of change of the Solar Longitude,

$$\frac{\Delta \varphi_S}{\Delta t}$$

**Change in Parker Spiral:**
Finally I do the same thing for the PS approximation for each time step.