Modeling solar wind with boundary conditions from interplanetary scintillations

P Manoharan¹, T Kim¹, N V Pogorelov³, C N Arge² and P K Manoharan⁴
¹Center for Space Plasma and Aeronomic Research, University of Alabama in Huntsville, USA
²AFRL/RVBXS, USA
³Radio Astronomy Centre, NCRA, Tata Institute of Fundamental Research, India

Abstract. Interplanetary scintillations make it possible to create three-dimensional, time-dependent distributions of the solar wind velocity. Combined with the magnetic field observations in the solar photosphere, they help perform solar wind simulations in a genuinely time-dependent way. Interplanetary scintillation measurements from the Ooty Radio Astronomical Observatory in India provide directions to multiple stars and may assure better resolution of transient processes in the solar wind. In this paper, we present velocity distributions derived from Ooty observations and compare them with those obtained with the Wang-Sheeley-Arge (WSA) model. We also present our simulations of the solar wind flow from 0.1 AU to 1 AU with the boundary conditions based on both Ooty and WSA data.

1. Introduction
The solar wind originates from the corona where the magnetic field in an open configuration, and the flow can accelerate along flux tubes. Depending on the source region of the solar wind (e.g., edge of closed-field region or open-field coronal hole), the solar wind speed can vary between 300 and 800 km/s. Interplanetary Scintillation (IPS) measurements represent one of the many “remote sensing” techniques, which can inform us of the three-dimensional structure of the heliosphere. Here, IPS observations are combined with the Wang-Sheeley-Arge (WSA) semi-empirical solar wind model to simulate the solar wind in a time-dependent manner. The WSA model is based on photospheric magnetic field measurements, and the current version we use employs the Air Force Data Assimilative Photospheric Flux Transport (ADAPT) maps from ground-based observations of photospheric magnetic field to determine the coronal field configuration at the source surface, normally at $R = 2.5 R_s$ ($R_s =$ solar radius), the expansion factor of the magnetic flux, and the coronal hole boundary distance to estimate the distribution of the speed of the solar wind [2, 3, 4]. Approximated outflow at the base of the solar wind with sophisticated three-dimensional magnetohydrodynamic numerical model simulates the resulting flow evolution out to Earth. The model provides radial magnetic field and solar wind speed [17].

2. The Ooty Interplanetary Scintillation Measurements
Interplanetary scintillation (IPS) exploits the scattering of compact radio source by the electron-density irregularities in the solar wind (i.e., IPS is the radio analogy of optical twinkling of star). For example, the plane-wave front traveling through the solar wind is phase modulated by the variations of refractive index of the irregular solar wind density and the random phase modulation leads to a
diffraction pattern on the ground. Since the solar wind irregularities drift past the observer's line-of-sight at a velocity $V$ (solar-wind velocity) and the motion of these irregularities converts the diffraction pattern into the temporal intensity fluctuations, which are observed as IPS. The temporal power spectrum of the intensity scintillation observed at the Earth is in fact two-dimensional spatial-intensity spectrum due to strip scans along the line-of-sight, transverse to the solar wind velocity vector [13]. From the spectrum of intensity scintillation the speed of the solar wind, shape of density turbulence spectrum, and the structure of the radio source can be derived [14].

The Ooty Radio Telescope (ORT) is a parabolic cylinder 530-m long in the north-south direction and 30-m wide in the east-west direction [20]. The equatorially mounted ORT can track a radio source for ~10 hours in the east-west direction and its electronics system supports a declination coverage of ±60 degrees. The high sensitivity and tracking ability of the ORT allows observation of IPS on a large number of radio sources. The Ooty IPS observations can cover a heliocentric distance range of $R \sim 10 - 250 R_s$ and at all heliographic latitudes.

3. Wang-Sheeley-Arge Model
The Wang-Sheeley-Arge (WSA) model [8, 6, 5] is a combined empirical and physics based model of the corona and solar wind and an improved version of the original Wang and Sheeley model [21, 22]. The WSA model input is the ground based line-of-sight (LOS) observations of the Sun's magnetic field, in the form of synoptic map. These maps are then used in a magnetostatic potential field source (PFSS) model [19, 1, 22], which determines the coronal field out to 2.5 solar radii ($R_s$). The output of the PFSS model serves as input to the Schatten Current Sheet (SCS) model [18], which provides a more realistic magnetic field topology of the upper corona. Only the innermost portion (i.e., from 2.5 $R_s$ to between 5 and 30 $R_s$) of the SCS solution, which actually extends out to infinity, is used. (The user sets this outer coronal boundary radius).

An empirical velocity relationship [6, 7] is then used to assign solar wind speed at this outer boundary as a function of two coronal parameters: (1) flux tube expansion factor ($f_s$) and (2) the minimum angular separation ($\theta_b$) at the photosphere between an open field footpoint and the nearest coronal hole boundary. Starting at the center of each of the grid cells on the outer coronal boundary surface and tracing the magnetic field lines down to their footpoints rooted in the photosphere determine these parameters. The flux tube expansion factors are calculated using the traditional definition $f_s=(R_{ph}/R_{ss})^2[B_{ph}/B_{ss}]$ [21], where $B_{ph}$ and $B_{ss}$ are the field strengths, along each flux tube, at the photosphere ($R_{ph}=1R_s$) and the source surface ($R_{ss}=2.5R_s$), respectively. The model provides the radial magnetic field and solar wind speed at the outer coronal boundary surface and this may then be fed into an advanced three-dimensional MHD solar wind propagation model.

4. Results
In order to simulate the solar wind outflow to Earth and beyond, the boundary conditions at the source surface are essential. Moreover, the position of the source surface should be close to the Sun and the inner boundary of the heliospheric MHD model is considered in the region where the solar wind can be assumed to be supersonic everywhere. The IPS measurements from Ooty have been traced backward to a surface, from where solar wind propagates steadily. Ooty IPS data measurements are analyzed for a period of about three Carrington rotations from June 1, 2012 to August 31, 2012. Figure 1 shows the time dependent solar wind velocity distributions at 0.1 AU. Due to the limitations of spatial resolution in the IPS measurements, an average solar wind estimates on 70 sources have been considered for each day in the +90 to -90 degree latitude and 180 degree longitude ranges. To overcome this limitation, the velocity maps are created for each day using data from 13 days prior and after. Thus resulting in a plot with more than 1000 sources, providing a better coverage of the entire solar surface. However, since the accuracy of the solar wind velocity measurements essentially depends on the high signal-to-noise ratio of the power spectrum, the number of IPS estimates used in the velocity distribution plot is limited to about 75 percent of the total number. The velocity distribution has been smoothed by a two-dimensional Gaussian of width ~27 degrees. The
velocity distributions are presented for the days June 15, 2012 July 15, 2012 and August 15, 2012. It is evident that there is a significant restructuring of the solar wind velocity structure over the period of two Carrington rotations. This is also observed in the synoptic solar wind velocity map from the IPS observations at the Solar-Terrestrial Environment Laboratory (Nagoya University, Japan). Figure 2 shows the considerable changes occurring in solar wind velocity throughout the year 2012 as observed from STEL.

**Figure 1.** Distributions of solar wind velocity data points at 0.1 AU using IPS measurements (left panel). Time dependent solar wind velocity maps using IPS measurements and Gaussian smoothing (right panel).

**Figure 2.** Solar wind velocity map from the STEL using IPS observations for the year 2012
Figure 3. IPS solar wind velocity compared with WSA velocity and magnetic field maps for June 1, 2012, in km/s and nT respectively.

The IPS and WSA velocity maps compare reasonably well in the large scale, though there are some sizable discrepancies where IPS data has spotty coverage. Figure 3 shows the comparison of solar wind velocity distribution from IPS data and magnetic field and velocity data derived from WSA model. It is also seen that towards the northern pole slow solar wind \( V \leq 400 \) km/s is observed and towards the southern pole fast solar wind \( V \geq 400 \) km/s is observed. The slow wind component seen in the WSA velocity map, around the heliospheric current sheet, is also observed in the IPS velocity map. The change in solar wind speed is also seen in the structure of the WSA magnetic field and magnetic field strength.

In the next step of this study, the velocity estimates from IPS measurements, implemented with the WSA model data for the magnetic field, are used as boundary conditions for the Multi-Scale Fluid-Kinetic Simulation Suite (MS-FLUKSS), which has been developed and used by the Center for Space Plasma and Aeronomic Research at the University of Alabama in Huntsville. MS-FLUKSS is a tool for modeling discontinuous flow of partially ionized plasma and plasma-neutral interactions in the heliosphere [15, 16]. Time varying boundary conditions are applied to further investigate the solar wind evolution between 0.1 to 1.5 AU for the period under study.

The ADAPT-WSA model is very good in reproducing the background solar wind speeds at 1 AU [2]. However, the WSA velocities must be reduced substantially at the inner boundary in order to drive a heliospheric MHD model such as Enlil and make reasonable predictions at Earth for the background solar wind [12]. This study was conducted to test whether the IPS data could reproduce the solar wind parameters at 1 AU without having to make such ad hoc velocity adjustments. IPS observations have been incorporated in MHD models to perform various heliospheric measurements [10, 11, 23].

The MHD simulation provides solar wind parameters in the three-dimensional heliosphere. The update rate of the MHD model is typically less than a minute (20-30 seconds per time step). Linear interpolation between the two nearest frames is performed to update the inner boundary at each time step. The solar wind velocities have been extracted at the location of the Earth and are compared with daily averages provided at the OMNI database, as shown in figure 4. Additionally, the simulated radial velocities at the locations of STEREO A and STEREO B are also obtained and compared with the actual observed data sets.
Figure 4. Comparison of radial velocity (km/s) at Earth (top), STEREO-A (middle) and STEREO-B (bottom) with MHD solutions.

It is evident from the above plots that there is a large-scale (i.e., overall) consistency between the in-situ measurements and simulated results. Since the simulated result largely depends on the boundary conditions obtained from the IPS estimates, simulation can be improved by increasing the temporal resolution of the IPS data along with the spatial resolution. Moreover, we can create velocity
maps by assigning maximum weightage to estimate obtained on the given day of observation and a
decreasing weighting function for measurements taken after and before the day of observation. In this
case, the smoothing technique employed by the two-dimensional Gaussian would use varying widths
depending on the day of observation. Figure 5 shows velocity distribution maps using varying
Gaussian width.

Figure 5. Time dependent IPS velocity maps created using Gaussian smoothing with varying widths.

5. Summary and Conclusion
In this study, time-dependent IPS observations have been used as the time varying inner boundary
conditions for the solar wind velocity, together with the magnetic field data derived from the WSA
model. This has been used to perform simulations to study the evolution of the solar wind from 0.1 to
1.5 AU. There are discrepancies between in-situ measurements and our MHD simulation results. This could very well be because of the limitations posed from temporal and spatial resolution of the IPS measurements. Further analysis would include using boundary conditions with corrections for the back tracing of the IPS velocity to correct the shift observed in the MHD simulations. Additionally, solar wind heating by turbulence produced by the instability of non-thermal ions in the solar wind should also be analyzed, since it is an observable quantity in a number of spacecraft.

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