STEREO-Era Solar Mass Ejection Imager (SMEI) Observations

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Abstract: White-light Thomson scattering observations by the Solar Mass Ejection Imager (SMEI) have recorded the inner heliospheric response to corotating structures and coronal mass ejections (CMEs). Some of the CMEs are also observed by LASCO and, most recently, the STEREO spacecraft. Here we detail several events in SMEI observations that have also been observed by the LASCO coronagraphs and STEREO spacecraft. We show how SMEI is able to measure CME events starting from their first observation at as close as 20° from the solar disk until they fade away in the SMEI 180° field of view. Our 3D reconstruction technique provides perspective views as observed from Earth, from outward-flowing solar wind. This is accomplished by iteratively fitting the parameters of a kinematic solar wind density model to the SMEI white-light observations and, where possible, including interplanetary scintillation (IPS) velocity data. Comparisons with LASCO and STEREO images for individual events or portions of them allow a detailed view of changes in their structure shape and mass as they propagate outward.

Introduction:

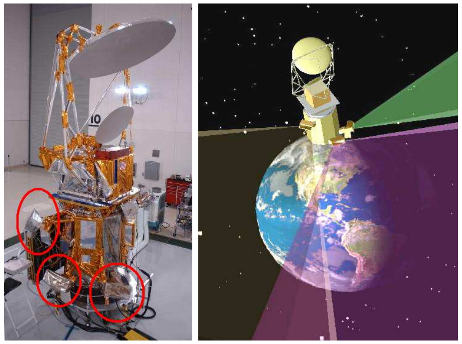
Following the launch of the Solar Mass Ejection Imager (SMEI) on 6 January 2003, we have been developing an image analysis technique that, as much as possible, retains the long-term brightness variation and data frame resolution of the instrument (see Jackson *et al*., 2004). We provide this data-base partially to provide a tomographic analysis of heliospheric structures that include both CMEs and longer-term heliospheric density structures such as the extensions of coronal streamers. UCSD maintains an archive of the SMEI data sets and provides an analysis of these data sets at UCSD-based website: **http://smei.ucsd.edu/**. UCSD analysis of SMEI data frames and sky maps is available through 9 June 2007. SMEI is currently operating well, and is expected to provide data through the current pole-to-pole pass of the Ulysses spacecraft around the Sun and as the STEREO spacecraft become more separated from the Earth in the coming months. A real-time data-base of SMEI data is kept at the National Solar Observatory (NSO) website: **http://smei.nso.edu/**.

IPS velocity data helps in either SMEI or IPS 3D density reconstructions by determining the large-scale velocity structure over which the dense structures expand. IPS measurements are available from ground-based radio arrays of which the system of STELab, Japan (Kojima and Kakinuma, 1987) has the longest continuous history of operation. Prior to SMEI analyses, IPS scintillation-level data has been used as a proxy for interplanetary densities. The 3D density reconstructions (with velocities) are currently provided and used in real-time forecast mode at the UCSD website: **http://ips.ucsd.edu/**. We use and show both SMEI and IPS data in the following analyses.

Many problems in heliospheric physics can only be fully understood by considering them in a fully 3D context. In order that the 3D reconstructions map CMEs and other time-varying heliospheric features, we use an iterative least-squares algorithm to modify a kinematic 3D heliospheric model from the perspective of the single spacecraft point in space and use solar wind outflow to provide perspective views. The iterative procedure minimizes the differences between the actual Thomson-scattering or IPS remote-sensing observations and the values obtained by integrating through a model that varies over large elongations with time in a 'time-dependent' reconstruction of the data (Jackson *et al*., 2006).

SMEI:

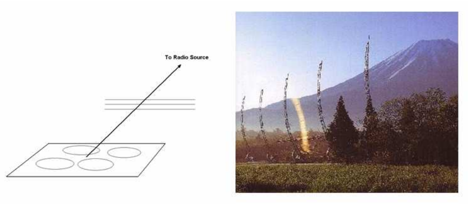
The Solar Mass Ejection Imager (SMEI) launched from the Vandenberg Air Force Base (AFB), (Figure 1a) records the whole sky data on each 102-minute orbit from 840 km. SMEI is a zenith-nadir pointing spacecraft, it rotates once per orbit (Figure 1b – artist impression) and views three strips of sky away from Earth using CCD camera technology.



(a) (b)

Figure 1. **(a)** The Coriolis spacecraft with the Solar Mass Ejection Imager (SMEI) instrument and the *Windsat* antenna prior to launch from Vandenberg AFB. The three camera baffles (circled) are seen on the lower portion of the spacecraft. **(b)** SMEI (artist impression) in its terminator polar orbit at 840 km with an orbital inclination of 98°. SMEI looks away from the Earth at 30° above the local horizontal to avoid sunlight reflected from the Earth, and from the *Windsat* antenna. The fields of view of the three cameras (each shown as shaded extensions from the satellite) together cover nearly 180° of sky, and as the instrument orbits Earth, map out nearly the whole sky around it.

IPS:

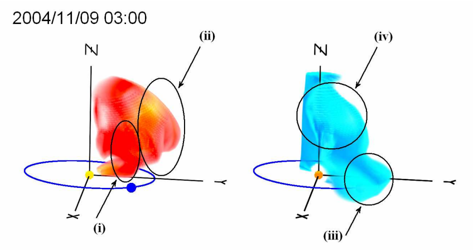


(a) (b)

Figure 2. (a) Depiction of intensity scintillation. A light and dark intensity pattern on the surface of the ground is formed from point radio sources. The pattern is convected outward in the solar wind at solar wind speeds. The passage of this pattern past a radio array determines both the level of scintillation, and by correlating this pattern from one radio array to another, the speed of the pattern motion. **(b)** A photograph of one of the STELab radio arrays, this one is near Mt Fuji, Japan.

The 4-7 November 2004 CME Event Sequence:

The 4-7 November 2004 coronal mass ejection (CME) sequence is associated with a series of solar flares in this same time interval. The IPS manifestations of these events are shown as a 3D tomographic reconstruction as a remote observer would view the heliosphere from East of the Sun-Earth line and a few degrees above the ecliptic plane as derived from STELab IPS data at 03:00 UT on 9 November 2004 (taken from Hara *et al*., 2007). There are few STELab radio sources to the South of the Sun during this time period, and for this reason the reconstructions are limited to features observed in the northern heliospheric hemisphere. Figure 4 shows a meridian cut of density as derived from the SMEI reconstructions at about this same time. Figures 3 and 4 are typical of the analyses possible with these data for specific events.



(a) (b)

Figure 3. 3D tomographic reconstruction in electron density **(a)** and speed **(b)** for 9 November 2004 at 03:00 UT. For the reconstructed heliospheric structures, the brighter the color, the greater the value for both the electron density (between 15 cm^{-3} and 50 cm^{-3}) and speed (from 900 km s^{-1} up). Everything in the southern hemisphere, in the foreground, and behind the Sun (away from the Earth), has been removed for clarity and to limit obscuration of the points of interest. In this Figure: (i) is the 7 November event as seen in LASCO C2 at 16:54 UT, (ii) is the combination of two 6 November events as seen in LASCO C2 at 01:31 UT and 02:06 UT, (iii) shows high speed engulfing the Earth which lags the 6 November events but precedes the 7 November event and is comparable in speed to that detected by LASCO C2 for the 7 November event, and (iv) shows high speed solar wind going mainly northward, consistent with the speeds of (iii).

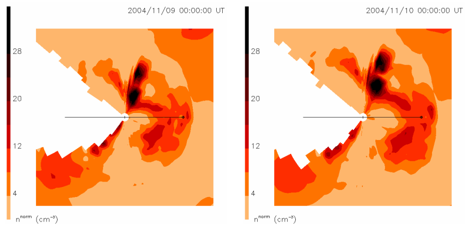
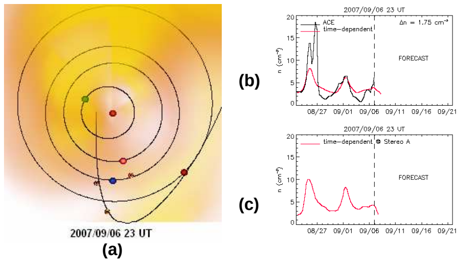


Figure 4. 3D SMEI tomographic reconstruction in electron density for these same heliospheric structures at 00:00 UT on 9 (left) and 10 (right) November 2004 (adapted from Bisi *et al*., 2007). As in Figure 3, an r^{-2} radial density fall-off has been removed from the analysis.

IPS Forecast Web Page:

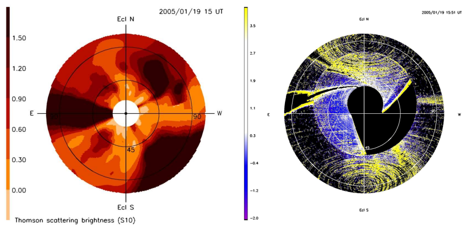
The STELab IPS data set have been used to reconstruct 3D densities and velocities over the entire heliosphere when data from the IPS arrays are available, and these are made available at the inner planets and at the Ulysses and STEREO spacecraft (see Figure 5).



(a) (b) (c)

Figure 5. Time-dependent IPS density reconstructions from the UCSD website: **http://ips.ucsd.edu/index_ss.html** on 2007/09/06 at 23:00 UT. **(a)** A remote view of the ecliptic-plane from the North as an observer would view it from 3 AU showing the orbits and locations of the inner planets and the locations of Ulysses and the STEREO spacecraft. Electron density is scaled from 5 $e^- cm^{-3}$ to 40 $e^- cm^{-3}$ with an r^{-2} radial fall-off removed in the remote view. **(b)** Model values determined at the location of Earth (red) and a comparison with the ACE spacecraft (black). **(c)** Model values at the location of the STEREO A spacecraft (red). These values are slightly different from those measured at Earth.

Fisheye Comparison Sky Maps : 19 January 2005 (DOY 19)



(a) (b)

Figure 6. Comparison sample of SMEI data available from the UCSD website **http://smei.ucsd.edu. a)** 3D reconstructed image **b)** Direct image with a scale about 4 times less intense than that given in (a).

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