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Three-dimensional reconstruction of heliospheric structure using iterative tomography: A review

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A B S T R A C T

Current perspective and in-situ analyses using data from NASA's twin Solar TErrestrial RElations Observatory (STEREO) spacecraft have focused studies on ways to provide three-dimensional (3-D) reconstructions of coronal and heliospheric structure. Data from STEREO are proceeded by and contemporaneous with many other types of data and analysis techniques; most of the latter have provided 3-D information by relying on remote-sensing information beyond those of the near corona (outside 10 R_S). These include combinations of past data from the Helios spacecraft and the Solwind coronagraphs and, continuing from the past to the present, from observations of interplanetary scintillation (IPS) and the Solar Mass Ejection Imager (SMEI) instrument. In this article we review past and ongoing analyses that have led to a current great wealth of 3-D information. When properly utilized, these analyses can provide not only shapes of CME/ICMEs but also a characterization of any solar wind structure or global outflow.

1. Introduction

Current perspective analyses of data from the NASA's twin Solar TErrestrial RElations Observatory (STEREO) spacecraft (Kaiser et al., 2008) have focused coronal and heliospheric studies on ways to extract three-dimensional (3-D) tomographic information about the corona and inner heliosphere from remote-sensing views. Others (e.g., Mierla et al., 2010) have reviewed many of the techniques used in these 3-D analyses, and we do not repeat this review. While the STEREO in-situ and remote-sensing data themselves are unique (e.g., Galvin et al., 2008; Harrison et al., 2009), they grew out of much past analysis and coincide with a great body of contemporaneous work by many researchers. These include analyses of interplanetary scintillation (IPS) observations from as long ago as e.g., Hewish et al. (1964) or Houminer (1971), and of Thomson-scattering brightness data (photospheric sunlight scattered by electrons) from the Helios spacecraft photometers, the Solwind coronagraph (Jackson et al., 1985), the Large Angle Spectrographic Coronagraphs (LASCO) (Brueckner et al., 1995) on board the SOlar and Heliospheric Observatory (SOHO) (Domingo et al., 1995), and finally the Solar Mass Ejection Imager (SMEI) instrument (Eyles et al., 2003; Jackson et al., 2004) on board the Coriolis spacecraft.

Numerous attempts have been made to reconstruct the corona and heliosphere in three dimensions. Near the Sun there is a strong motivation to determine the 3-D shapes of coronal structures in order to learn about their initiation and source of energy. Coronal mass ejections (CMEs) often have a loop-like appearance when viewed with a coronagraph. If these helical loops are driven by currents as proposed early-on by Anzer (1978) and Mouschovias and Poland (1978), the shape of a CME should follow a very specific pattern. If instead a CME is a spherical bubble, then it might very well be the remnant of a large addition of energy at a single point in the low corona (Wu et al., 1976). Various techniques used to determine CME shapes from the single perspective of Earth include polarization of transient structures (Munro 1977; Crifo et al., 1983; reviewed in Wagner, 1984), and are more recently presented by Moran and Davila (2004). Depletions of the corona and an estimation of the minimum line of sight (LOS) length for three CMEs (MacQueen, 1993) also gave an indication that CMEs are extensive coronal structures. Studies using multiple different-vantage-point perspectives from the Helios spacecraft photometer remote-sensing observations and the Solwind coronagraph reached the same conclusion (Jackson et al., 1985). The extent and the shape of structures in the background corona are also important. For instance, the shapes and positions of coronal streamers indicate their location and extents relative to the magnetic structures

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on the Sun. This in turn indicates whether coronal streamers are formed by the effects of a global solar-current "pinch" effect or some more local magnetic phenomenon. Studies of the solar wind and the processes supplying its energy can only be carried out if a global description of the solar wind is available.

Forecasting in heliospheric physics requires both remote-sensing data and analyses that measure evolving 3-D morphologies of solar and interplanetary structures. In the case of flares and other large-transient changes near the solar surface this information can predict both whether that structure will erupt and given that it does, whether it will subsequently affect Earth. This premise, more than any other, has promoted the 3-D analyses of remote-sensing data from ground-based IPS, or spaceborne SMEI or STEREO instruments. In the following article, most of the analyses of eruptive events are provided by white-light Thomson-scattering observations, and for simplicity we refer to these as CMEs, rather than using the term ICME or a combination of CME/ICME in following these events to their interplanetary manifestation.

Section 2 gives a background of some of the early work utilizing both the IPS and Thomson-scattering observations to provide 3-D tomography from heliospheric data sets. This early work inspired current tomographic-analysis techniques, which assume little other than the physical principles of plasma outward flow, in order to derive the shapes of outward-flowing heliospheric structures. Section 3 gives a brief background of the particular techniques used by the University of California, San Diego (UCSD) and Solar-Terrestrial Environment Laboratory (STELab) Nagoya University Japan groups for this tomographic analysis. Section 4 gives recent results and compares these different analysis techniques. We conclude in Section 5.

2. Analyses prior to 2005

When global remote-sensing heliospheric data are available, several types of Computer Assisted Tomography (CAT) are available that reconstruct the co-rotating and outward-flowing solar wind by making use of the rearrangement of features along each LOS. These analyses generally assume no a priori information about the structures mapped except that they follow the general physical principles assumed for heliospheric outward flow, and that their LOS weighting can be readily calculated. For most versions of the UCSD STELab tomography analyses, for instance, radial outward propagation of the solar wind and conservation of mass and mass flux for different-speed solar wind structures is assumed (e.g., see Jackson et al., 1998).

2.1. Early IPS and Thomson-scattering analyses

Since the 1960s IPS has been used to probe solar wind features using ground-based meter-wavelength radio observations (Hewish et al., 1964; Houminer, 1971). Intensity-scintillation IPS observations, arising from small-scale ($\sim$150 km) density variations, show heliospheric disturbances of larger scale that vary from 1 day to the next and are often associated with geomagnetic storms (Gapper et al., 1982). These disturbances are present in the solar wind, emanate from only certain regions on the Sun, and are often found to be associated with the onset of high speed solar wind in near-Earth spacecraft measurements. As inferred from a list of events, their shapes, and their solar surface associations during observations from 1978 to 1979 (Hewish and Bravo, 1986) mapped these disturbances to the solar surface and concluded the only common identifiable surface feature to be coronal holes observed in He I 10830 Å maps. Observations from the UCSD (Coles and Kaufman, 1978) and STELab (Kojima and Kakinuma, 1987) multi-site scintillation array systems have determined velocities in the interplanetary medium since the early 1970s. Fig. 1a shows an IPS radio array currently operating in Japan, that as one of three antenna systems now operating, has provided nearly continuous heliospheric observations in real time since the mid-1990s. All antennas operate simultaneously to view one radio source at a time as it transits the central meridian above Japan in order to measure the scintillation level and the transit time of the scintillation pattern across the Earth surface (see Fig. 1b). The transit time of the scintillation pattern allows a determination of solar wind velocity perpendicular to the line of sight for each radio source viewed, as well as an independently determined scintillation-level measurement from each system that views the source.

Significant results have been obtained from IPS remote-sensing observations even with only a rudimentary locating of solar-wind structures along each LOS, i.e., the assumption that all material is at the LOS's closest location to the Sun. For instance, from IPS velocity data it was determined that the polar solar wind has high speed (Kakinuma, 1977; Coles et al., 1980; Kojima and Kakinuma, 1990) long before the Ulysses spacecraft (Phillips et al., 1994; McComas et al., 1995) measured these velocities in situ. Especially at solar minimum, regions of slow solar wind are generally found near the solar equator, and thus also near the magnetic-neutral line ("current sheet") as determined by the potential-magnetic-field model (Hoeksema et al., 1983). Scintillation level data from the Cambridge 81 MHz array have been analyzed in the same manner (e.g., Hick et al., 1995). Carrington maps produced by assuming the solar wind at the LOS location closest to the Sun show that the near-solar polar

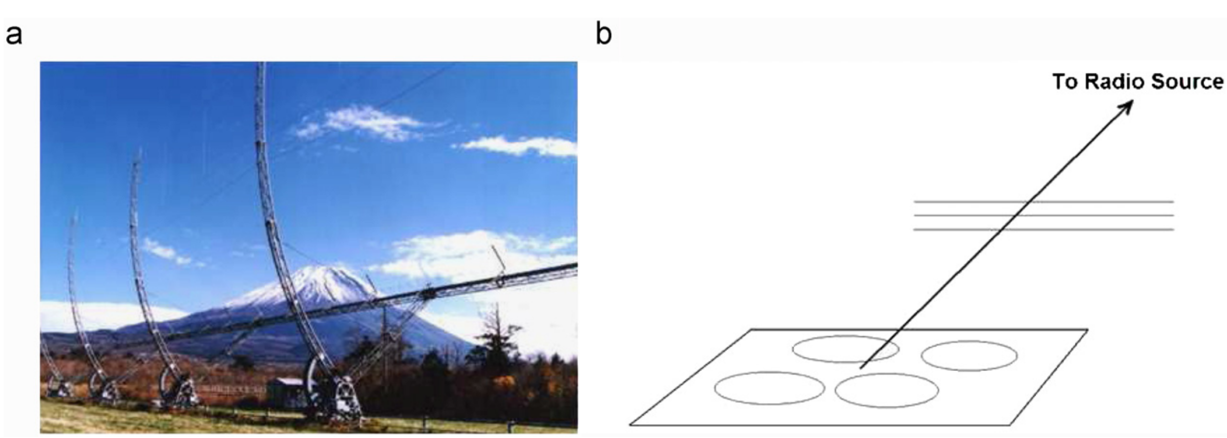

Fig. 1. (a) STELab IPS radio array at a frequency of 327 MHz (one of three now operating in Japan) near Mt. Fuji. The arrays each measure scintillation intensity (or *g*-value) for about 40 radio sources each day. Scintillation signals when cross-correlated between arrays provide a robust IPS velocity determination. (b) A depiction of the $\sim$150 km size scintillation intensity pattern on the surface of the Earth produced by interplanetary scintillation. Motion of this pattern across the Earth's surface produces intensity variations used to determine solar wind velocity and density variation.