CAWSESII-TG3 Subgroup 5
The 3D structure of ICMEs and the Solar Wind

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Abstract:

The three dimensional structure of interplanetary coronal mass ejections (ICMEs) and the solar wind is the fundamental subject in space weather research, and has been extensively studied using radio observations of interplanetary scintillation (IPS) as well as Thomson scattered light observations with interplanetary missions such as SMEI (solar mass ejection imager) and STEREO. Time dependent tomography analyses have been developed using these observations, and are useful in revealing the 3D structure of the solar wind and ICMEs.

1. Introduction

IPS (interplanetary scintillation; Hewish *et al*., 1964) analyses and the activity using these data sets have increased significantly in the last five years. IPS has become a fairly mature science, and now has over a 50-year history of progress. Existing radio facilities have been upgraded for use in dedicated IPS analyses, and several new radio facilities around the world have been begun or utilized to provide these measurements. With current NASA programs having insufficient funding for many space-borne heliospheric projects, more cost-effective ground-based facilities have been searched as a way to provide similar heliospheric analyses, and an entry into space weather forecasting without spacecraft instrumentation. Unique to IPS measurements to date is its ability to view solar wind velocities around the Sun. Combining the IPS remote measurements with tomographic techniques gives a way to determine more accurate three-dimensional (3D) values from the data. Scintillation-level measurements have been used as a proxy for density for many years (Jackson *et al*., 2011), and earlier reports of widely-varying responses to different heliospheric structures that would make this proxy nugatory have been shown, in most situations, to be unfounded.

2. IPS Array progress

The UHF IPS antenna at Toyokawa (Kojima *et al*., 2002; Tokumaru *et al*., 2011; Figure 1) began full-time operation in late 2010. This has increased the numbers of radio sources observed daily in scintillation level from Japan by nearly an order of magnitude. These data in the form of g-levels for each radio source are available on the STEL website at**:** **http://stesun5.stelab.nagoya-u.ac.jp/ips_data-e.html**. These analyses include near real time updated files of the IPS measurements obtained daily the morning following their observation. Many other higher-level data products are also available at this URL. The whole STEL IPS system is currently undergoing a renewal that includes upgrades of the antenna receivers, and mechanical systems.

A new radio array has been constructed for dedicated IPS use on Jeju Island, South Korea by the Korean Space Weather Center (KSWC) (Figure 2). The radio array saw

Figure 1. The STEL Toyokawa IPS 3,432 m^2 array that began year-round operations in late 2010.

Figure 2. The KSWC IPS 700 m^2 327 MHz IPS radio 32 tile array, Jeju Island, South Korea.

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"first light" spring of this year and is now providing IPS data from a few radio sources. These data are available at: **http://www.spaceweather.go.kr/observation/service/ips#** for download from the KSWC server daily. The MEXican ARray Telescope (MEXART) (Figure 3) is now also operating on a daily basis near Michiocán, Mexico. Early this year, the central core of the LOw Frequency ARray (LOFAR) situated in the Netherlands (Figure 4) was used to provide multi-frequency IPS measurements that are unique in that they span radio frequencies from 110 to 190 MHz enabling a simultaneous analysis of radio source time series at these different frequencies for the same observing period.

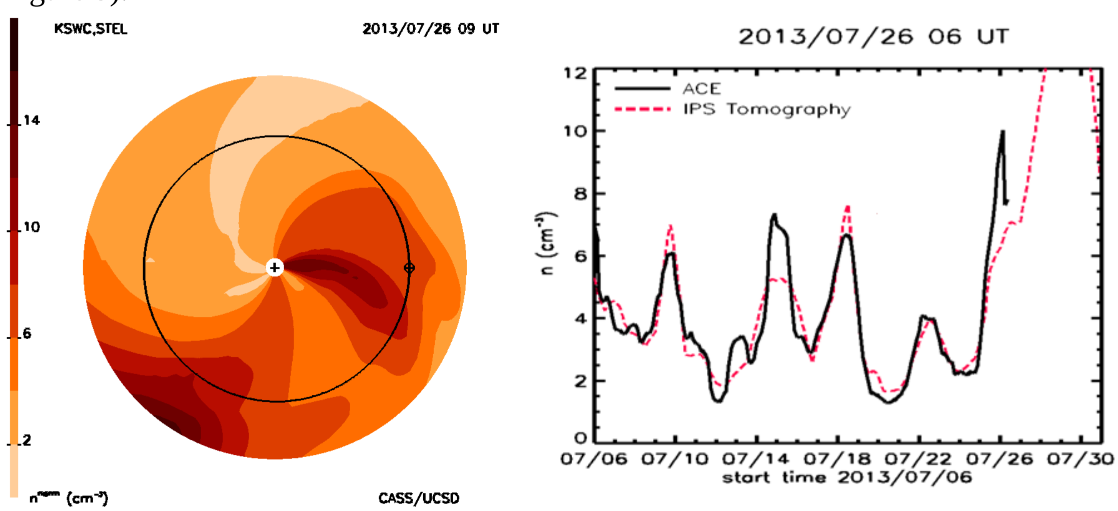
Figure 3. The MEXART 10,000 m^2, 140 MHz, radio array located in Michoacán, México (see website: http://www.youtube.com/watch?v=GNadikiR-IQ).

Figure 4. LOFAR central core "superterp" radio array system.

3. IPS Observations

The current peculiar solar cycle has been studied in several recent journal articles (Tokumaru *et al*., 2010; Manoharan, 2012). Tokumaru, *et al*., 2010 show that solar wind fast solar wind speed areas increase and that the slow solar wind areas decrease systematically as solar activity decreases. Peculiar about the latest 2008 minimum is that the fast wind areas showed a marked increase at low latitudes consistent with *in-situ* observations at 1 AU, and a distinct decrease at high latitudes resulting in a net decrease at all latitudes compared with the earlier minimum in 1996. Manoharan, 2012 measured turbulence level and found a overall decrease in this quantity over the same period that was roughly the same for both equatorial and polar regions.

Jackson *et al*. (2010, 2013) have furthered IPS forecasting progress by incorporating *in-situ* velocity and density observations into the tomographic analyses near Earth. This innovation allows the remotely–sensed IPS measurements to be heavily weighted to give an answer that agrees with *in-situ* measurements at Earth up until the time of the last observations. Following this last observation time, and for heliospheric regions other than those along the Sun-Earth line, the IPS observations complete the global analysis. Because most forecasting measurements are interested in determining a change from current conditions, this allows the change from *in-situ* measurements to future remotely-sensed observations to be smoothly incorporated into the analyses. Additionally, Jackson *et al*. (2010), find that the incorporation of *in-situ* results into those remotely sensed helps stabilize the remotely-sensed observations giving better *in-situ* results distant from the Earth. This same innovation is also useful in determining the best global values for these parameters for use when one wants to know best values throughout the heliosphere globally or to fill in observations in the ecliptic when IPS observations for short periods are sparse or non-existent. Forecast analyses using this technique and STEL data are currently operating at UCSD (at: **http://ips.ucsd.edu**), the NASA-Goddard Community Coordinated Modeling Center (CCMC), and the Korean Space Weather Center (see Figure 5).



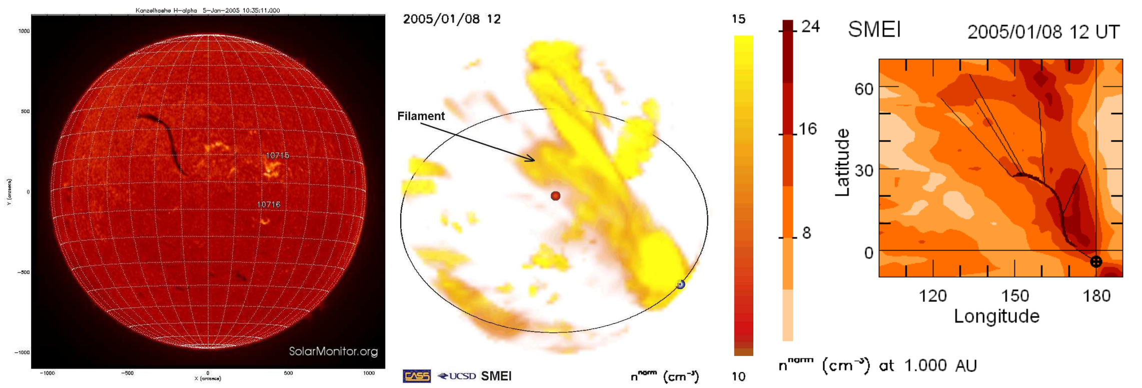
(a) **(b)**

Figure 5. KSWC IPS forecast using STEL IPS data showing a CME that has just arrived at Earth. **a)** Density cut in the ecliptic plane. **b)** Density at Earth including its forecast.

3. SMEI Observations

After nearly 8½ years of successful operation, the Air Force decided to close the Solar Mass Ejection Imager (SMEI) instrument during a period of austerity and budget constraints in the US. UCSD maintained and has recently upgraded a website at **http://smei.ucsd.edu** that has increased the usefulness of these data and provided tomographic analyses and images throughout the SMEI lifetime. These analyses are shown as remote-observer views, ecliptic and meridional cuts and other higher-level data products. This Website also provides images of IPS velocities in the same format as the SMEI analyses, but at lower resolution. Also included on the Website are photometric time series of the nearly 6000 bright point objects (mostly stars) that were observed by SMEI throughout its lifetime and removed from the images.

Current work using the SMEI tomographic measurements have centered on tomographic analyses performed at even greater resolutions than those shown on the SMEI Website. This has, for instance, allowed the detailed study of CME structure in conjunction with STEREO heliospheric imager observations (Webb *et al*., 2013), the outflow of the density enhancements from the jet response into the solar wind (Yu *et al*., 2012; 2013), and the measurement and morphology of filament structure near 1 AU (Sharma *et al*., 2013). Figure 6 presents a description of the analysis of a filament that erupted from the Sun to the north and east of disk center on 5 January, 2005.



(a) **(b)** **(c)**

Figure 6. a) The solar disk in Hα on 5 January 2005 at 10:35 UT. **b)** A high-resolution remote-observer plot of density from 45 degrees above the ecliptic plane and 45 degrees west of the Sun-Earth line on 8 January 2005 at 12 UT. **c)** A high-resolution synoptic plot density cut at 1.00 AU. The plot is annotated showing the location of the filament at the time of eruption and its approximate expansion to its new location at the time of its near-Earth (⊕) *in-situ* passage. In this and the earlier remote-observer view, density is normalized to 1 AU and an R^{-2} falloff is imposed.

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