# SPACE WEATHER STUDIES USING LOW-FREQUENCY INTERPLANETARY SCINTILLATION OBSERVATIONS

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## ABSTRACT

Plasma disturbances originating on the Sun, such as coronal mass ejections (CMEs), are a major factor in determining 'space weather' in the near-Earth environment. Virtually the only current source of routine observations of these disturbances as they propagate through the interplanetary medium are interplanetary scintillation (IPS) data. We review current work on time-dependent tomographic reconstructions of the heliospheric density and velocity based on currently available IPS remote sensing observations. We discuss the importance of the tomographic analysis of IPS data for an effective space weather forecast system, in particular in connection with the future Low Frequency Array (LOFAR) instrumentation.

## INTRODUCTION

Space weather in the near-Earth environment is closely linked to disturbances originating at the Sun. Large-scale solar coronal mass ejections (CMEs) travel through the inner heliosphere at speeds of up to 1000 km/sec, reaching the space environment of Earth within one to three days and carrying with them the potential for major geomagnetic disturbances.

Strong interaction of CMEs with earth's environment causes serious space weather effects throughout the coupled magnetosphere-ionosphere-atmosphere system. Compression of the magnetosphere perturbs auroral particles, leading to precipitation-produced communications outages and to strong ground-induced currents which in turn impact power grids. A wide array of further space weather effects at satellite altitudes and in the lower atmosphere relate directly to geomagnetic storms induced by CMEs and solar wind perturbations.

Monitoring of the Sun provides information about the onset of these dramatic events, e.g. through observations of flares and filament eruptions, and, more directly, through observations of white-light CMEs at visible wavelengths. These white-light observations have been available since the 1970s from coronagraphs on OSO-7 [1] and Skylab [2]. Since 1996 the Large Angle Spectroscopic Coronagraph (LASCO [3]) instrument on the SOHO spacecraft provides these data out to 30 solar radii (0.14 AU). *In situ* solar wind monitors, such as the ACE spacecraft near the L1 Lagrange point between Sun and Earth at 0.99 AU, detect the arrival of solar disturbances from a vantage point in the solar wind about 30-60 minutes upstream from Earth. The intermediate gap between near-Sun and near-Earth is currently covered only by interplanetary scintillation (IPS) observations, described more fully in the next section. However, analysis of these remote sensing IPS data has proven difficult in the past. Only in the last few years, with the advent of tomographic techniques, has it become possible to track CMEs using IPS. Due to the scarcity of information about solar disturbances while they cross the gap between Sun and Earth it is still very difficult to predict with any accuracy whether or not a particular solar-wind disturbance observed near the Sun is on a collision course with Earth. Hence it is also difficult to predict with any accuracy what its implications for space weather will be.

A significant advance in space weather monitoring can be achieved if CME's and other solar wind features with a potential impact on the near-Earth environment, are tracked with good enough angular and time resolution to determine their characteristics and evolution while they propagate through the interplanetary medium. Tomographic techniques applied to such data allow a reconstruction of the shape and structure of the disturbances and the determination of their trajectory, thus enabling an accurate prediction of whether or not the structures impact Earth. The capability to track solar disturbances through interplanetary space and, more generally, to determine the three-dimensional structure of the solar wind in the inner heliosphere will be a crucial component in the development of any reliable space weather forecast system. The Low Frequency Array (LOFAR), optimized for observing IPS, holds the promise of observing heliospheric structures in near-real time and has the potential to be a uniquely capable instrument for IPS measurements in support of space weather forecasts.

## HELIOSPHERIC REMOTE SENSING

IPS is caused by small-scale (~200 km) density fluctuations in the solar wind (including those associated with CMEs) traveling across a line of sight extending from an observer out towards a compact radio source, e.g. a quasar [4, 5]. Scattering upon these density fluctuations introduces amplitude and phase changes in the incoming radio waves. The observed, fluctuating IPS signal is the result of scattering contributions everywhere along the line of sight. Once a CME has passed beyond the field of view of a typical coronagraph, it becomes difficult to observe, and here IPS provides virtually the only current source of routine remote sensing observations.

Heliospheric remote sensing observations, such as IPS, probe the global extent of the solar wind over a wide range of solar elongations. They also extend across the high-latitude regions over the solar poles, which are difficult to access by any other means. However, because these data are a line-of-sight integration, drawing unambiguous conclusions about solar wind structure is challenging. Tomography provides a general methodology to address this problem by using views of a structure from many different perspectives to reconstruct its 3D shape. Our group at UCSD has developed a tomographic technique that can be applied to heliospheric remote sensing data from a single, earth-bound observing location. Solar rotation and outflow in the solar wind provide perspective information. When structures do not evolve significantly (except for corotation) on a time scale of a solar rotation period, then solar rotation provides sufficient information for a reconstruction of the quiet or corotating solar wind. The large range of elongations covered provides additional perspective information: as a structure rotates and/or flows past it is observed from widely different directions. This is essential for the analysis of transient structures, such as CMEs, over time scales of days.

## MEASURING IPS

IPS scintillation indices have been measured in the past primarily with single-site radio arrays having a steerable beam (e.g. the Cambridge, UK, IPS array). This enabled the measurement of the scintillation index for a large number of IPS sources (~1000 per day). These data provide information about density variations in the solar wind, and, indirectly, about the solar wind density itself. IPS velocities have so far been measured by combining signals from mechanically-fixed radio systems at several (typically three or four) sites, separated by 100-200 km. If the same radio source is observed simultaneously from these multiple locations, cross-correlation of the signals gives the velocity with which the intensity patterns travel between stations. These IPS velocities are currently the only remote sensing proxy available for the solar wind velocity. Since early 1997 both types of data are available simultaneously in near-real-time from the STE-Lab IPS system in Nagoya, Japan, observing at a frequency of 327 MHz. However, the coverage of this system is limited to only a few dozen sources measured when they cross the local meridian. In addition the geographic location limits the range of declination covered to sources above $\sim -20°$ declination. The separation of the IPS stations is important. If too widely separated, intrinsic variations in the solar wind degrades the cross-correlation; too close together and time delays become ureliably small. In general IPS velocity determinations are less susceptible to interference than the scintillation index, primarily because the most damaging sources of man-made and natural interference do not often affect IPS arrays separated by a few hundred km at the same time.

The physical size, sensitivity and digital beam-forming capabilities of LOFAR enable its use as an IPS monitor, for the first time providing multiple measurements each day for a large number (potentially several hundred) of compact radio sources of both IPS velocity and scintillation index. Extracting these IPS data from the LOFAR data stream poses many interesting challenges in algorithm development, simulation, design and testing; especially given that these data are required in real time for efficient space weather forecasting. LOFAR will be in operation for many years and, when operated as an efficient solar wind/CME monitor, will provide a unique and continuous source of heliospheric remote sensing observations.

## IPS TOMOGRAPHY

The UCSD tomography can be applied to either IPS velocity or scintillation index data, but gives better results when both are available simultaneously. The reconstruction technique takes into account the fact that line-of-sight observations are dominated by contributions from material closest to the Sun, but it makes no explicit assumptions about the distribution of velocity and density along these lines of sight. Observations sampling outward-moving solar wind structures from many different directions are combined to construct a solar wind model that best reproduces the observations based on a least-squares criterion. Presently, the technique incorporates a purely kinematic solar wind model. Given the velocity and density on a 'source surface' (usually located at a few solar radii from the Sun), a fully 3D solar wind model follows by assuming radial outflow and enforcing conservation of mass and mass flux [6].

The reconstruction of CMEs requires a technique that not only handles corotating structures but also shows the dynamics of structures as they move away from the Sun. The UCSD tomography allows reconstruction of heliospheric changes on a time scale determined by the cadence and amount of remote sensing data. For IPS the time resolution is about one day. Current IPS data (primarily those from the Nagoya IPS system) only allow the largest structures in the solar wind to be reconstructed. This provides information about the gross extent and structure of CMEs and corotating regions in the heliosphere, and hence allows the determination of global characteristics, such as speed, total mass and kinetic energy.

An example is shown in Figures 1 and 2. IPS velocity and g-level observations from July/August 2002 (covering Carrington rotation 1965) are used to reconstruct the time-dependent solar wind for that period, including the CME connected with the 14 July 2000 'Bastille Day event'. Figure 1 shows the density distribution of the CME close to the time when it reaches Earth. Two different perspectives are shown: looking from a distance of 3 AU back toward the Sun in the ecliptic and from 3 AU along the ecliptic north pole. The main body of the CME passes Earth toward the west; only the eastern edge of the CME hits Earth causing the density peak observed by the ACE spacecraft. Figure 2 shows the ACE density time series in comparison with the time series derived from the tomographic reconstruction.

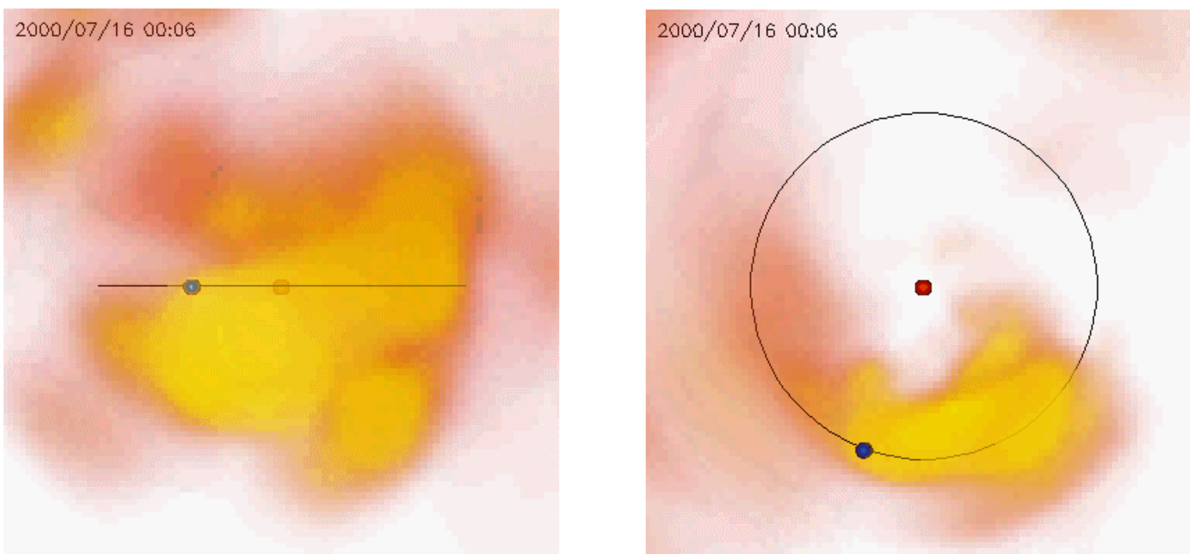


Fig. 1. Example of a time-dependent tomographic reconstruction based on Nagoya IPS data. Data used are for 10 July 2000 through August 2000 (Carrington rotation 1965) showing the mass distibution of the CME related to the 'Bastille Day event'. The images show perspective projections from a viewer location at 3 AU looking back to the Sun. The black line indicates Earth's orbit in the ecliptic plane; the red dot is the Sun, the blue dot is Earth. The field of view is 60°×60°. (a) Viewer at 3 AU in the ecliptic 20° west of the Sun-Earth line; (b) Viewer at 3 AU and ecliptic latitude 90° looking down on the ecliptic.

LOFAR will allow the observation of many more IPS sources than the Nagoya IPS system, currently the only IPS system providing data in near-real time. This will directly result in sky coverage with a much better angular resolution. In turn, this enables tomographic reconstructions with higher resolution in both space and time than possible at present. IPS velocity observations from LOFAR will be the most valuable contribution to any space weather forecast capability, since IPS is the only proven observational means to obtain global velocity information about the solar wind in the inner heliosphere. Scintillation index (or g-level) observations also are useful, but since the scintillation level depends on density *fluctuations* in the solar wind rather than the density itself, knowledge about the relationship between these two is required to use the g-level as a proxy for the solar wind density. Empirical forms of this relationship are available typically in the form of a power law between g-level and solar wind density (e.g. [7]), but these remain controversial. In

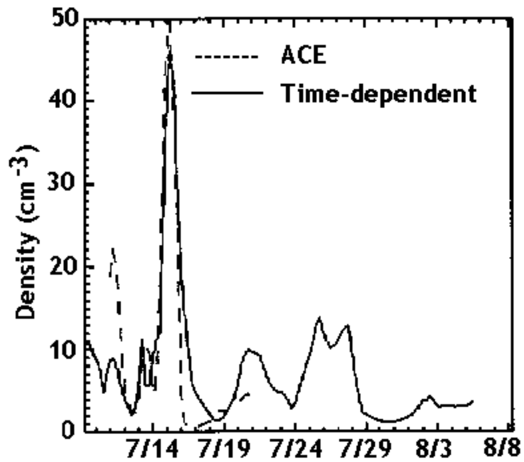


Fig. 2 Time series showing the comparison of the density observed by ACE at the L1 Lagrange point, in comparison with the density derived from the time-dependent tomographic reconstruction of Figure 1.

the near future white light camera systems, such as the Solar Mass Ejection Image (SMEI; [8, 9]) and as included in the payload for the STEREO mission, will monitor the Thomson scattering brightness across a significant fraction of the sky. This brightness is directly proportional to the electron density in the solar wind. These data provide a viable alternative to IPS scintillation data as a proxy for the solar wind density.

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