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31 December 2009

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Dear Lt. Shepherd,

Attached find copies of our final report for award **FA9550-06-1-0107** for "A Study of the 3-D Reconstruction of Heliospheric Vector Magnetic Fields from Faraday-Rotation Inversion" for work performed from 2005 – 2009 by the University of California at San Diego.

There are three aspects to this research: 1) The inversion of simple synthetic Faraday-rotation measurements that can be used to demonstrate the feasibility of performing this inversion when and if Faraday-rotation observations become available. 2) The inversion of modeled heliospheric density and magnetic field data to provide these same results for complex structures. 3) The use of a 3-D MHD kernel in a time-dependent heliospheric tomographic inversion technique in order to demonstrate that the 3-D MHD model can be iteratively inverted to provide not only 3-component magnetic fields, but also other heliospheric solar wind parameters that incorporate these magnetic fields, as well as solar wind density and velocity.

We made progress on all aspects of this research, and have added a new forecast aspect in lieu of not having data with which to attempt the inversions of Faraday rotation from the Murchison Widefield Array (MWA) or other low-frequency radio system. There are 36 journal articles, and over 80 conference proceedings abstracts associated with this contract.

Sincerely yours,

A handwritten signature in blue ink that reads "Bernard V. Jackson".

Bernard V. Jackson

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14. ABSTRACT One of the most-sought heliospheric parameters is the vector (three-component) magnetic field. The magnitude and direction of magnetic field is of interest scientifically as parameters that characterize the heliosphere and relate outward-flowing solar wind plasma to the density and velocity structures that provide its transport. Moreover, it is this field that interacts with other objects imbedded in the interplanetary medium. For the Air Force, these interactions are of primary interest at Earth where a southward interplanetary magnetic field (Bz negative) can couple with the Earth's magnetic field at the boundary of the magnetosphere, causing geomagnetic storms. In addition, solar energetic particles (SEPs) which account for some of the most damaging radiation hazards to high-flying aircraft and astronauts are confined to magnetic fields that connect Sun with Earth. At UCSD we have provided an inversion mechanism that can remotely determine heliospheric vector magnetic fields, their strength, and location in 3-D, and provided a mechanism to image these. We have also shown how these can be modeled, extrapolated, and refined in 3-D using MHD simulations. In addition we have developed an extension to the UCSD 3-D inversion technique that allows far more accurate forecasts of these vector fields prior to their Earth-arrival.					
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A Study of the 3-D Reconstruction of Heliospheric Vector Magnetic Fields from Faraday-Rotation Inversion

(Final Report for AFOSR award FA9550-06-1-0107)

Objectives:

One of the most-sought heliospheric parameters is the vector (three-component) magnetic field. The magnitude and direction of magnetic field is of interest scientifically as parameters that characterize the heliosphere and relate outward-flowing solar wind plasma to the density and velocity structures that provide its transport. Moreover, it is this field that interacts with other objects imbedded in the interplanetary medium. For the Air Force, these interactions are of primary interest at Earth where a southward interplanetary magnetic field (B_z negative) can couple with the Earth's magnetic field at the boundary of the magnetosphere, causing geomagnetic storms. In addition, solar energetic particles (SEPs) which account for some of the most damaging radiation hazards to high-flying aircraft and astronauts are confined to the magnetic fields that connect Sun with Earth.

Current analyses rely on the extrapolation of magnetic field from the solar surface upward through the interplanetary medium. These solar surface extrapolations have one great difficulty: they do not show the major coronal changes in magnetic field responsible for Coronal Mass Ejections (CMEs) that have the greatest effect on the Earth's magnetosphere, and that produce the most damaging SEPs. While many attempts have been made to characterize the eruption of CMEs and CME energetics, the major CME energy release is presumed to take place in the solar corona. As yet these changes that take place above the solar surface have not been observed directly. Here we have proposed to study a method which would directly observe vector magnetic fields as they move outward from the Sun into the interplanetary medium and to determine their strengths and direction.

There are three aspects to this research: 1) The inversion of simple synthetic Faraday-rotation (FR) measurements that can be used to demonstrate the feasibility of performing this inversion when and if FR observations become available. 2) The inversion of modeled heliospheric density and magnetic field data to provide these same results for complex structures. 3) The use of a 3-D MHD kernel in a time-dependent heliospheric tomographic inversion technique in order to demonstrate that the 3-D MHD model can be iteratively inverted to provide not only 3-component magnetic fields, but also other heliospheric solar wind parameters that incorporate these magnetic fields, as well as solar wind density and velocity.

Final Status:

During this contract we used both kinematic and MHD solar wind models to provide inputs to the 3-D reconstruction process, and we tested the 3-D FR inversion process we developed using realistic test inputs. We also provided a standardized data format for the IPS data proxy to be used to determine density from IPS arrays. This standardized IPS data format will allow different radio arrays to provide similar density measurements that can be used to reconstruct the FR results used to map densities to spacecraft *in-situ* measurements. In addition, we invented an extension to the UCSD inversion technique to incorporate *in-situ* measurements into the tomographic analyses. This inversion, a combination of remote sensing and *in-situ* measurements, allows far more accurate data forecasts from already-measured values, and can be extended to vector magnetic fields using FR.

A Study of the 3-D Reconstruction of Heliospheric Vector Magnetic Fields from Faraday-Rotation Inversion

(Final Report for AOFSR award FA9550-06-1-0107)

For this contract we programmed, refined and tested a Faraday-rotation (FR) inversion analysis that allows a measurement of 3-component heliospheric magnetic fields using our time-dependent computer analysis. This included inputs of realistic magnetic field signals and the application of UCSD-based imaging to display these results (Jensen *et al.*, 2006; 2009). The analysis works in our tomographic technique by changing the rotation variable from a positive–negative value by expansion in a Taylor series and then changing back after the inversion is performed (Jackson *et al.*, 2008b). This promises a means to map the vector component of the magnetic field in and around coronal mass ejections (CMEs) and other heliospheric transient magnetic structures if the FR and electron density of the media can be learned accurately-enough. This software development is intended to be combined with radio FR observations when they are measured. To this end we have also explored observations of electron density proxies as well as our inversion technique prior to obtaining FR data from ground-based radio arrays.

The Murchison Widefield Array (MWA) partially funded by the National Science Foundation and the Air Force, and sited in Western Australia is one of the primary possibilities for testing this inversion technique with real data. The radio array now under construction is planned as a frequency-agile low-frequency array that has space weather as one element of its scientific goals. In December of this year, the initial 32-element MWA antenna system has shown that it can obtain signals from bright radio sources. For measurement of FR from this system we expect a larger number of antenna elements to be deployed (512 elements were proposed for the original low-frequency demonstration). If FR signals from this system are simultaneous with Solar Mass Ejection Imager (SMEI) currently in operation, and/or interplanetary scintillation (IPS) data, we will combine them in a scientific investigation to determine the extent to which they answer questions about CME density, velocity, and *magnetic field* structure. Slow progress in providing polarized measurements from the MWA has caused us to re-think the potential analysis to be done in the immediate future with this system, and we have also begun courting these same analyses using the European-based LOw Frequency Array (LOFAR) system. LOFAR is not at an optimal site for solar observations. However, the LOFAR system can certainly be used to ascertain the validity of the UCSD inversion algorithm using real data, as long as data from LOFAR can be made available. Partially to this end, the NSF and UCSD helped sponsor the Aberystwyth Remote-Sensing Workshop convened in May 2009 allowing LOFAR representatives the opportunity to view progress in the display, measurement, and forecast of heliospheric data using these algorithms and imaging techniques. This has resulted in a special issue of *Solar Physics* highlighting these efforts.

Currently, magnetic field magnitudes and direction in the heliosphere are mapped upward from the surface of the Sun using techniques that do not allow measurement of coronal magnetic field change. It is this change and these magnetic fields that are most responsible for the large changes in the Earth's magnetic field during the passage of CMEs near Earth. Large, organized loop-shaped magnetic field structures associated with CMEs can sometimes be observed, and these reconstructed by *in-situ* techniques after Earth passage. Figure 1 shows one of these events during the 2003 Halloween-storm CME events (see Jackson *et al.*, 2006). This is one of the events we have chosen to test our FR inversion analyses, and that was used to provide realistic inputs to UCSD imaging algorithms (Jensen *et al.*, 2006, 2009). In the Jensen *et al.* (2009) simulation of FR using this event,

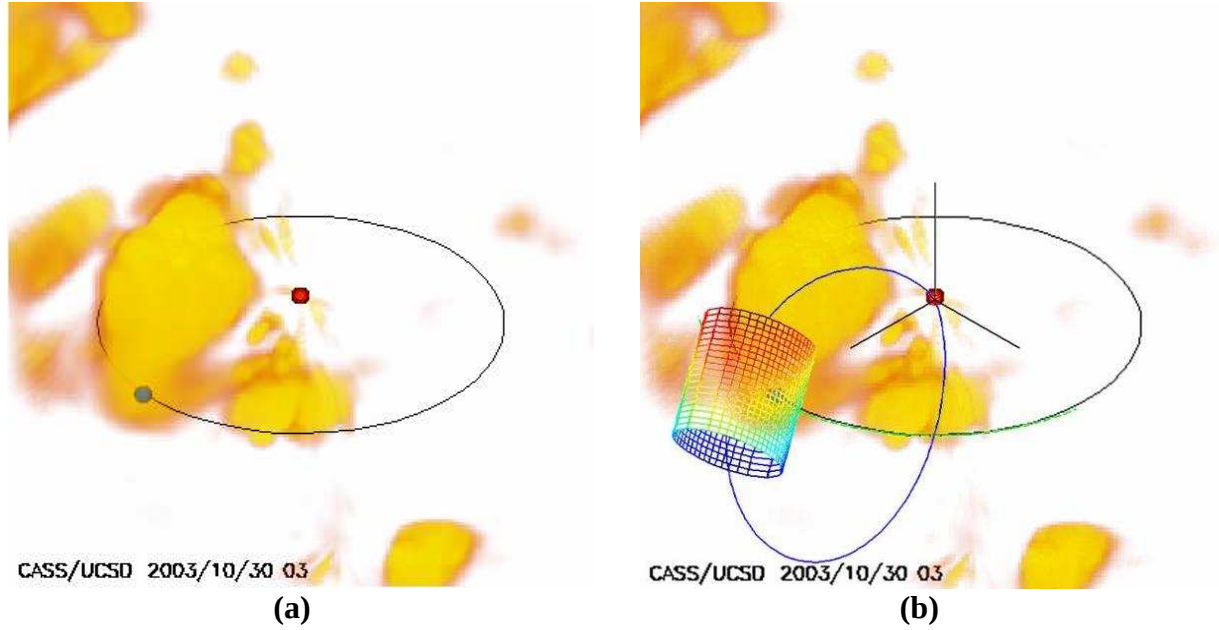


Figure 1. (a) Solar Mass Ejection Imager (SMEI) 3D density reconstruction of the heliospheric response to the 28 October 2003 CME viewed from 3 AU 30° above the ecliptic plane and 45° west of the Sun-Earth line. The Earth is indicated as a blue circle in its elliptical orbit. The Sun is indicated by a red circle. Contours are from $10 \text{ e}^- \text{cm}^{-3}$ to $30 \text{ e}^- \text{cm}^{-3}$ and have an r^{-2} density gradient removed. A portion of the ejecta associated with a solar prominence is observed to the south of the Sun in this view from Jackson *et al.* (2006). The density structure of the CME populates the inner core of the giant magnetic loop for this event. These are the best available *realistic* CME 3D density reconstructions (*and not simulations*) available to date. **(b)** Same as (a) with reconstructed flux rope cylinder from ACE superposed (as in Jensen *et al.*, 2006; 2009).

a simulated uniform shock sheath addition to the analysis was added to the CME plus extrapolated solar surface magnetic fields (Dunn *et al.*, 2005) to provide inputs of this type CME feature to the FR analysis. The shock sheath is not shown in the low-resolution (Figure 1) 3-D reconstructions of this event, but has been reconstructed in more recent higher-resolution 3-D analyses of SMEI inversions as a density enhancement to the west of the Sun-Earth line (Figure 2). These analyses show an interesting and challenging aspect for heliospheric shock sheaths - that they are not a uniform front ahead of a driver (such as a CME), but that they generally form a piecemeal density front moving outward into interplanetary space. This is noted in articles and recent presentations partially sponsored by this research (Jackson *et al.*, 2009b,e).

FR observations Φ measure both density and magnetic field along the line of sight: these are an integral combination of magnetic field strength and density,

$$\phi \propto \lambda^2 \int n_e \vec{B} \cdot d\vec{S} \quad (1)$$

where λ is the wavelength, n_e is the electron density along the line-of-sight interval dS , and B is the magnetic field vector. A FR simulation of the same 2003 Halloween-storm CME event during passage by Earth of the large organized loop is shown in Figure 3.

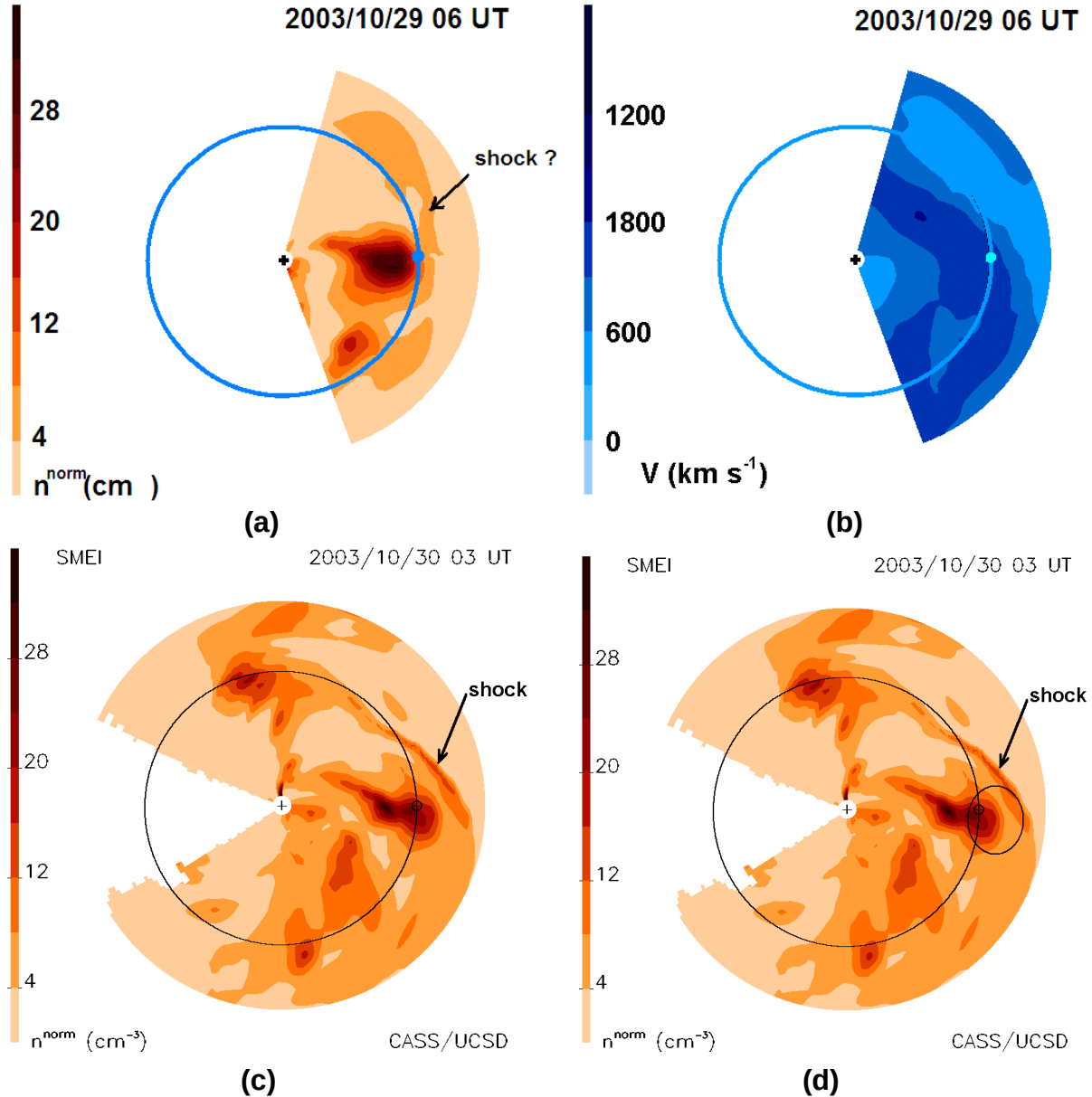


Figure 2. Ecliptic plane cuts of the 28 October 2003 CME at the time indicated. **(a)** Low-resolution SMEI 3-D density reconstruction of the 28 May halo CME as it reaches Earth as in Figure 1a. Earth is to the left of the image as a blue dot, and the density scale is given to the left of this presentation. The main structure that has just arrived at Earth is associated with the halo CME observed by LASCO on 27 October 2003. In front and to the flanks of this dense material, a density enhancement that has the manifestations of a shock from the CME can be observed in the analysis. **(b)** Low resolution STELab 3-D velocity reconstruction at the same time showing the general extent of the high speed solar wind region that follows the shock into the heliosphere. **(c)** The newer higher-resolution reconstruction ecliptic cuts of this event available since spring 2008 (for a slightly later time – the same time as presented in Figure 1). **(d)** The location of the reconstructed flux rope for this CME event superimposed onto density analysis.

As a heliospheric structure passes Earth, we expect the perspective views provided by the passage of a structure to allow resolving the degeneracy of where each structure lies along the line of sight. We currently provide a similar reconstruction of line-of-sight velocity and density from IPS observations in real time (see <http://ips.ucsd.edu/>), and from SMEI white-light observations (see

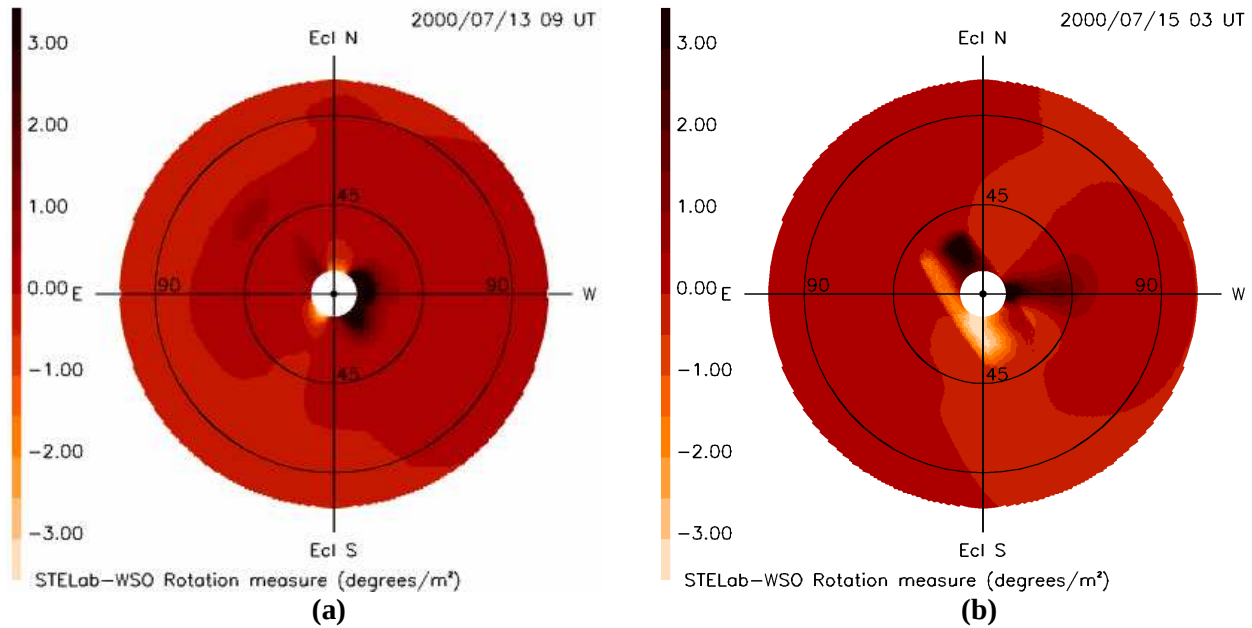


Figure 3. (a) Rotation Measure (RM) shown for with background magnetic field extrapolated from the solar surface to provide the FR signal (from the densities reconstructed during the Bastille Day CME). **(b)** The same density but with the magnetic loop as observed in ACE for this CME added to the IPS 3D reconstructed velocity to provide a sky map of Faraday rotation. The minimum signal from the MWA (expected to be a few degrees at 100MHz or $\sim 3\text{m}$) should be adequate to reconstruct this loop using the signals obtained from these RM measurements provided there are enough lines of sight covering the sky throughout the period of observation. The density loop and the magnetic loop (2 giant heliospheric loops systems) derived from these two very different 3D reconstruction techniques are not superimposed for this FR result.

<http://smei.ucsd.edu/>). The extension of this technique will allow 3D reconstruction of the large-scale CME magnetic fields that directly couple with the Earth's magnetosphere (B_z negative) prior to their Earth arrival. It will also allow a low-resolution determination of 3D magnetic field components *throughout the heliosphere* in order to determine interactions at other locations such as at planets and comets.

Our IPS analyses provide volumetric density (also velocity) data in real time made available on our Web sites from data from the Japanese (STELab, Nagoya University) IPS arrays operate (currently from May-December). That STELab IPS analyses can roughly match spacecraft densities (and velocities) measured *in situ* has been shown in many articles (Bisi *et al.*, 2007; 2009a,c). We have also successfully provided these same densities using IPS data from a currently-operating Ootacamund (Ooty) array in India, and it is this system that will be most nearly like the IPS system developed for use at MWA or LOFAR. Current efforts are underway to determine the validity of the Ooty data during the current period of solar minimum activity. So far these analyses have not been very successful even though periods during solar maximum have been reconstructed well (Bisi *et al.*, 2008a; 2009b) (Figure 3 and Figure 4 are from these articles.). The SMEI instrument has also provided extremely fine measurements of archival heliospheric density data for select intervals (Jackson *et al.*, 2008a, Bisi *et al.*, 2008b), and in the latter article these analyses were used to drive a time-dependent 3-D MHD model that compares successfully with the kinematic model usually used as a kernel in the UCSD 3-D reconstruction program. We continue to upgrade these volumetric density data at ever-higher resolution over the whole of the SMEI data set using different displays

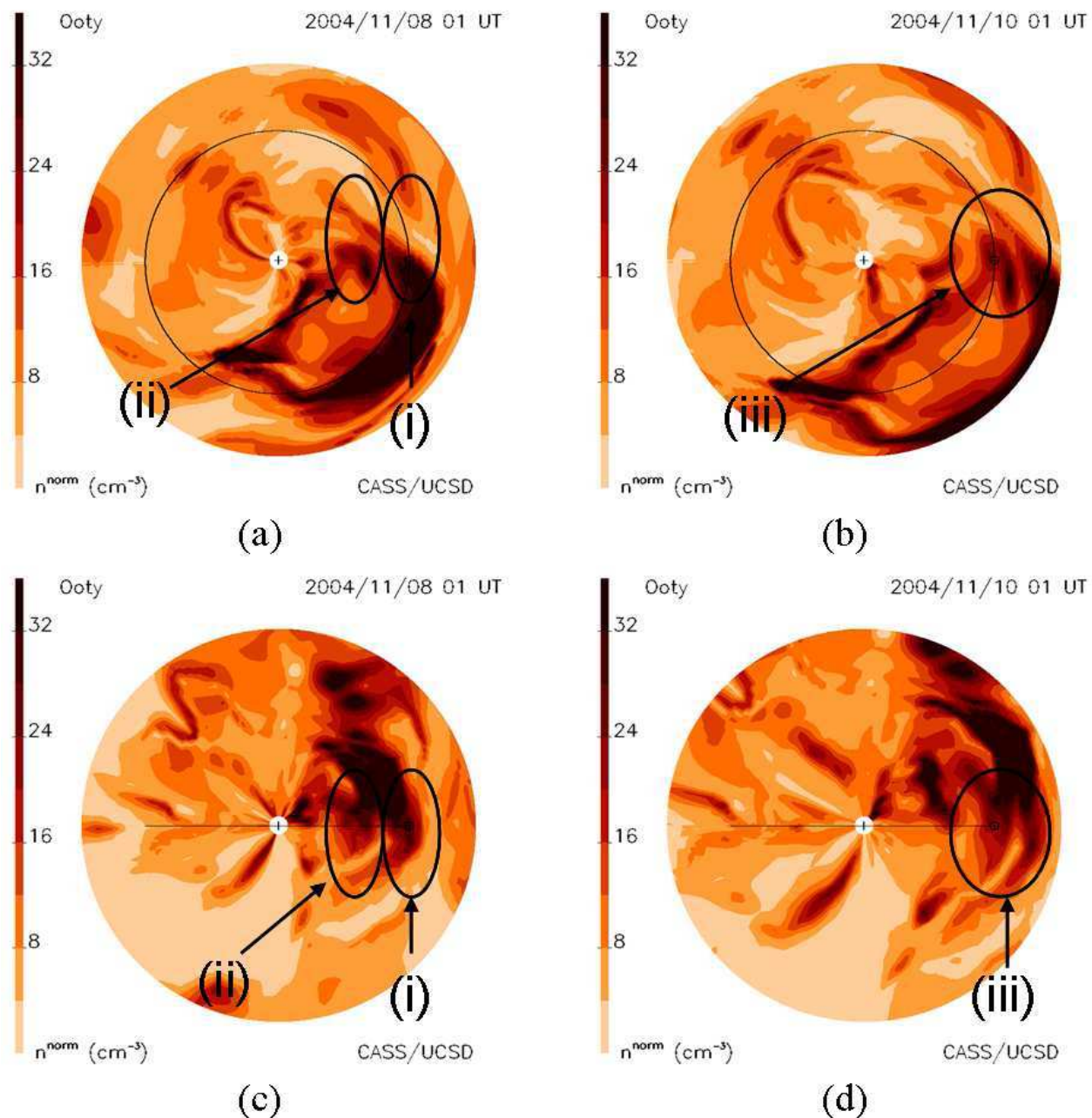


Figure 4. Summary figure of the Ooty ecliptic-, (a) and (b), and meridional-, (c) and (d), cuts through the 3D density reconstruction out to 1.5AU at the times shown. Various features of the several CMEs that pass the Earth are circled in the images which are also related to features seen in the LASCO coronagraphs. Earth's orbit is shown as a near-circle or line with the Earth, $\oplus$, indicated on each plot. The expected r^{-2} density fall-off scaling is used to normalize structures at different radii. Density contours to the left of each image are scaled to 1AU (from Bisi *et al.*, 2009b).

and analyses to certify these results (Jackson *et al.*, 2009a,b,c,d,e). These data analyses are available on our Website and the SMEI brightness data that allows the SMEI proxy density to be derived (through mid 2009) is now available on line in image format (see <http://smei.ucsd.edu/>). How these time-dependent analyses are performed (Hick and Jackson, 2004) are now written-up in a comprehensive article (Jackson *et al.*, 2009c). The IPS density volumes (either from STELab or

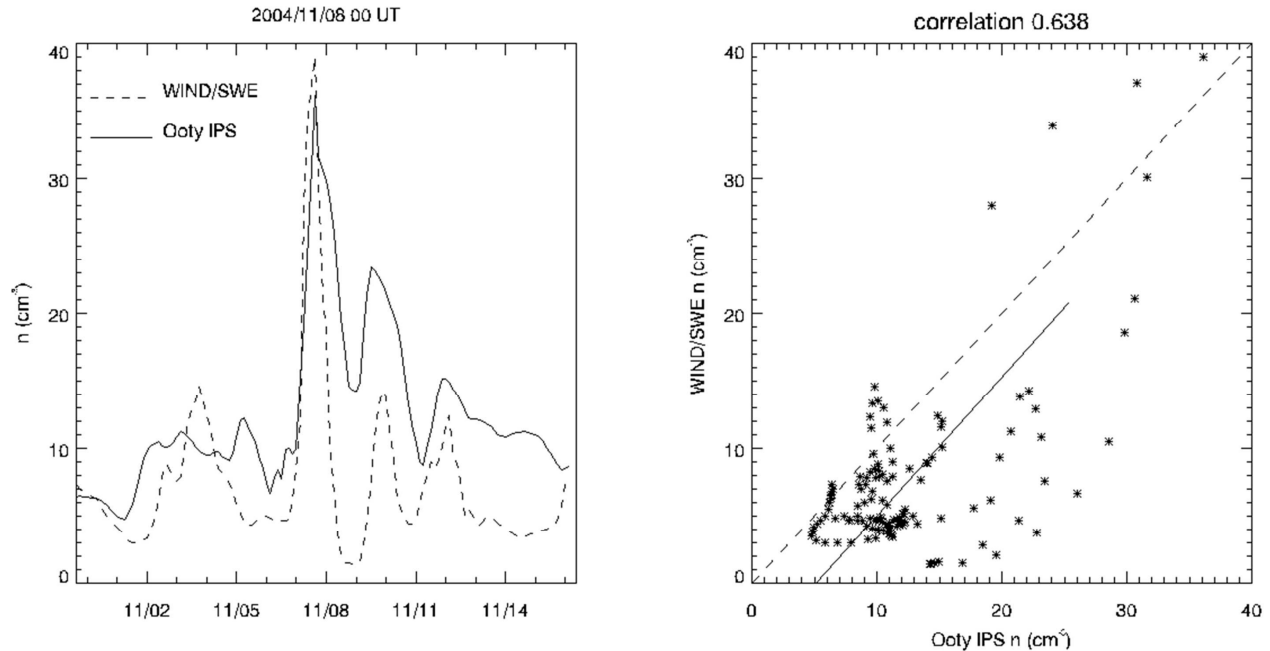


Figure 5. A time-series comparison of the 3D Ooty reconstruction evaluated at the Sun-Earth L_1 -Point and compared with solar wind plasma measurements taken by the Wind spacecraft in the left-hand plot. The right-hand plot shows a correlation of the time series (from Bisi *et al.*, 2009).

from other IPS radio sites) will allow a test of the feasibility of FR magnetic field reconstruction when ground-based FR observations become available, and if SMEI data are available at the same time, these data can be used to determine an even better density proxy for magnetic field reconstruction results.

Not being able to test available algorithms to invert real FR measurements has led our group to invent yet another technique to be used in forecasting solar wind parameters at the Earth. In this we have incorporated measurements of *in-situ* solar wind velocity from the ACE spacecraft so that it, plus remote sensing data sets, can be used simultaneously to converge to a forecast measurement at Earth. This allows an extremely good fit of remotely-sensed and *in-situ* inverted data up to the time that there is no longer available *in-situ* measurements. Not only does the forecast algorithm have far less work to do following the end of the *in-situ* measurements, but potentially the system also allows a quick calibration of the remote-sensing parameters.

Figure 6 (from Hick *et al.*, 2009) gives an example of the velocity convergence for European Incoherent SCATter (EISCAT) IPS velocity measurement observations (Bisi *et al.*, 2009d) for the time this European instrument system was run in campaign mode (April-May, 2007). That there is *any* correlation between remotely-sensed IPS velocities for these high-radio-frequency (~ 1000 MHz) observations, and those measured *in situ* is astounding in its own right. This attests to how well extremely good (but very sparse) IPS velocity measurements can be inverted to give good 3D time-dependent results using the UCSD 3D reconstruction algorithm. The addition of the *in-situ* measurements to provide better convergence in velocity does so with little change in the overall solar wind structure that is remotely viewed, and this also says that global solar wind structure is not unduly affected by the immediate measurements near Earth even though these are used in the line-of-sight measurements that determine the global structure. A far more comprehensive explanation of this type of forecast algorithm and its use with STELab IPS data (see Figure 7) has been submitted

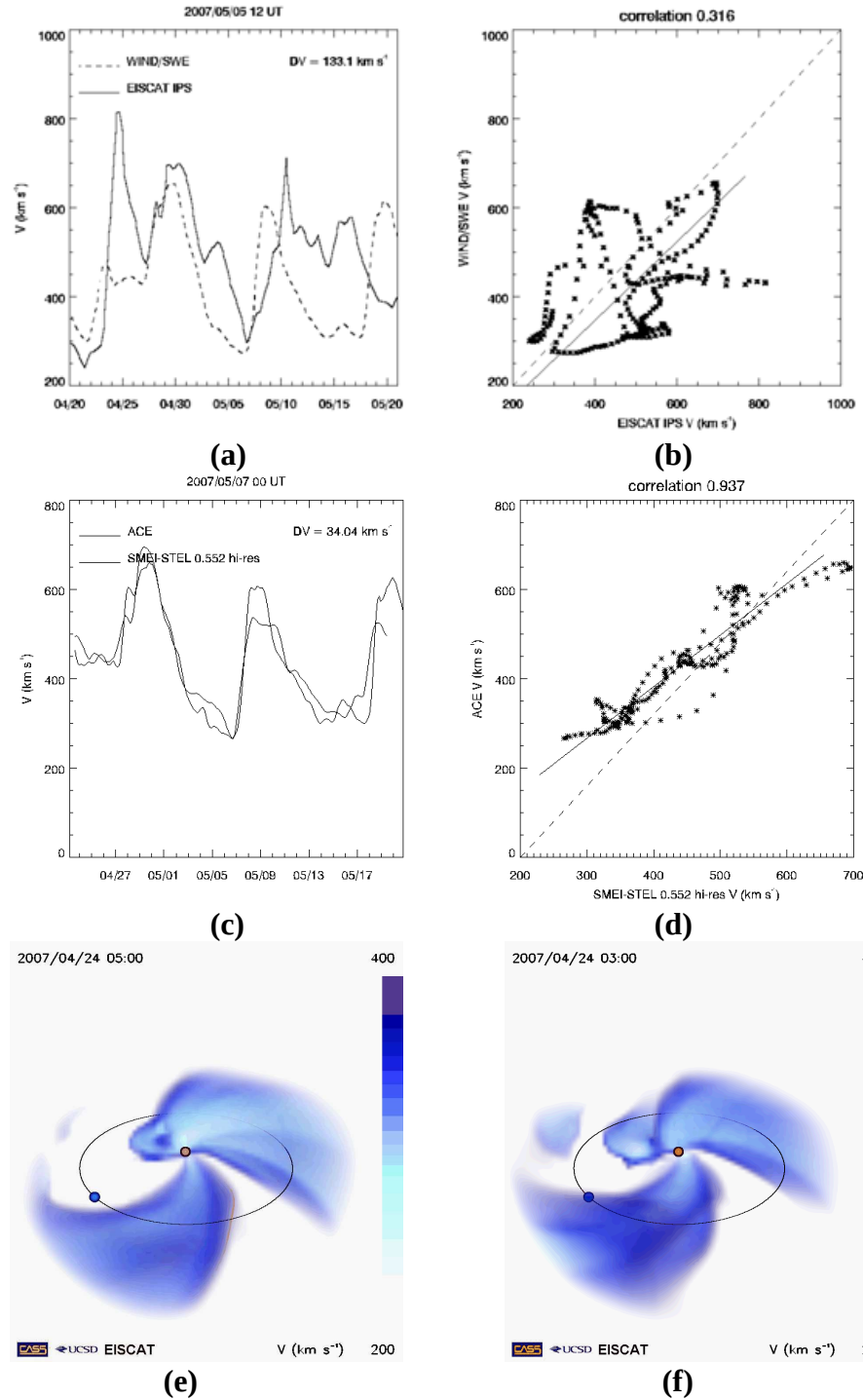


Figure 6. (a) and (b) Velocity time series from the EISCAT time-dependent 3D reconstructions and its correlation. (c) and (d) The same velocity time series with *in-situ* measurements added to the 3D time-dependent 3D reconstructions. (e) and (f) Velocity as a remote observer would observe it from about 45° West of the Sun-Earth line and 30° above the ecliptic. Only the slow velocities are shown, and these are located primarily in the ecliptic plane. The low velocities shown in this time-dependent 3D-reconstruction form the Archimedean spiral structure often present in the slow solar wind. The left panel (e) shows 3D reconstructions of (a) and (b), with (c) and (d) shown right in (f). There is little difference noted in the two sets of data except along the radial that incorporates the Sun-Earth line.

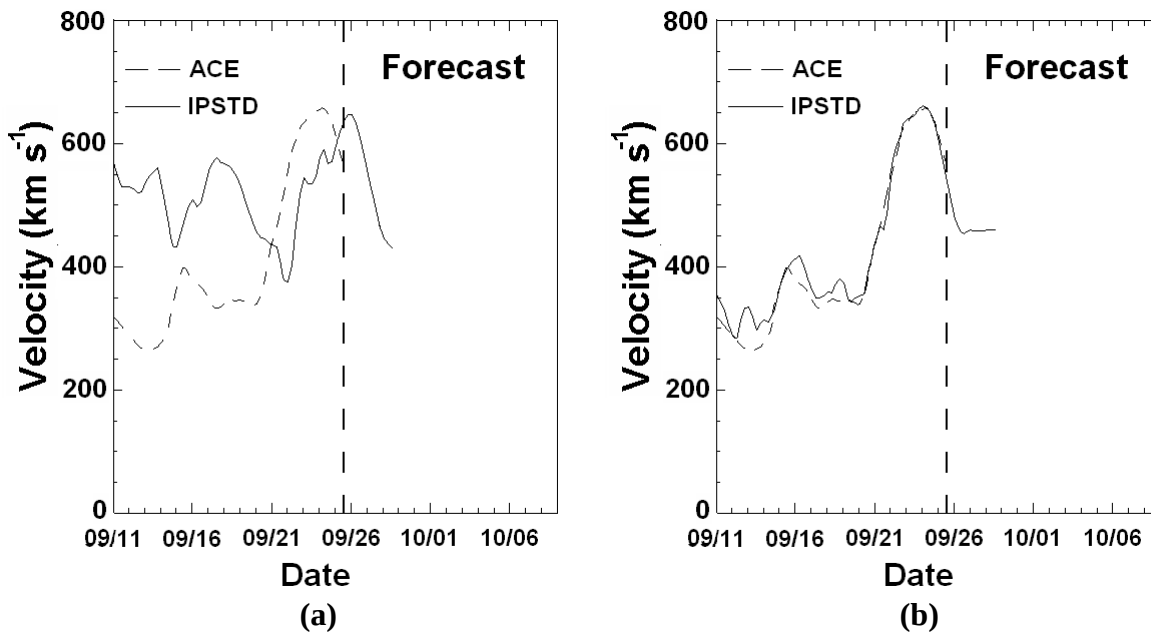


Figure 7. Velocity time series from the STELab time-dependent 3-D reconstruction forecast analysis for CR 2061 using only data prior to the cut-off time of 12:00 UT on 25 September 2007 (shown as a vertical dashed line). Forecast values appear to the right of this line. **(a)** Analysis where only IPS remote-sensing data are used. These give a very poor correlation with the in-situ measurements shown as a dotted line. **(b)** Analysis where *in-situ* measurements are also included. This analysis gives an extremely good correlation (0.99) with *in-situ* velocities up to the time none are available, and considerably better forecast correlations up to 3 days following the time of *in-situ* data cut-off (from Jackson *et al.*, 2009f).

and is now under review at Solar Physics (Jackson *et al.*, 2009f). This article shows that a substantial enhancement in velocity forecast capability arises using the inclusion of the *in-situ* measurements for STELab remotely-sensed velocities. We expect that this enhancement comes not only from a smoothing of the measurements near Earth into those remotely-sensed, but that the additional information added near Earth along each line of sight adds information to the line of sight that then extends more precise measurements to the volume that can only be accessed remotely.

IPS velocity measurements from both the remote sensing 3-D reconstructions and *in-situ* measurements give very similar results. Thus for velocity measurements, a calibration using the *in-situ* measurements is not as important as for other solar wind parameters. However, for density measurements from both remote-sensing Thomson-scattering (SMEI) and IPS *g*-level measurements there are several parameters that set the level of the current 3D results from existing solar wind average values. These solar wind modeling parameters are far-better obtained from an iterated composite using both remotely-sensed observations and *in-situ* measurements density, and this ability is now shown possible from these analyses.

For space-weather forecast analyses it is clearly possible to use a similar approach for any plasma parameter that can be measured or inferred remotely. This includes density inferred from the IPS *g*-level proxy, or from brightness measured from electron Thomson-scattering as from SMEI. It also applies to Faraday rotation observations (planned using the MWA and/or LOFAR systems) that remotely measure a combination of density and magnetic-field strength parallel to the LOS, and that have been shown to allow a 3-D inversion of the heliospheric magnetic-field vector (Jackson *et al.*, 2008b).

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Journal Articles and pertinent publications associated with this AFOSR contract:

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Interactions/Transactions: (see body of text, references and article list above)

New Discoveries: none

Honors/Awards:

J. Geophys. Res. editors choice awards:

Bisi, M.M., Jackson, B.V., Hick, P.P., Buffington, A., Odstroil, D., and Clover, J.M., 2008, '3D Reconstructions of the Early-November 2004 CDAW Geomagnetic Storms: Analyses of STELab IPS speed and SMEI density data', (CDAW) *J. Geophys. Res.* Special Edition - Geomagnetic Storms of Solar Cycle 23, 113, A00A11, doi:10.1029/2008JA013222.

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