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14. ABSTRACT

Solar disturbances produce major effects in the corona, its extension into the interplanetary medium, and ultimately, the Earth's environment. The ability to forecast the arrival at Earth of these disturbances and to determine their effects on the geospace environment is of primary interest to the Air Force, which communicates through and maintains satellites within this environment. It is now understood that the largest of these disturbances, called coronal mass ejections or CMEs, are the most important cause of major geomagnetic disturbances at the Earth. We have been at the forefront of studies of the origins and propagation of CMEs, and their effects on geospace. We have developed a tomographic technique to display and measure these disturbances as they move away from the Sun. This capability and knowledge has begun to revolutionize the study of heliospheric space plasma interactions with the Earth's environment.

Development of powerful analysis and modeling techniques is a serious challenge that must be addressed in order to maximize the scientific and forecasting return from remotely sensed solar data. An important requirement for the efficient analysis of these observations will be the ability to trace solar plasma changes near Earth and elsewhere in the interplanetary medium in three dimensions, thereby enabling us to model and study the physics of heliospheric disturbances from a three-dimensional perspective.

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Abstract. Solar disturbances produce major effects in the corona, its extension into the interplanetary medium, and ultimately, the Earth's environment. The ability to forecast the arrival at Earth of these disturbances and to determine their effects on the geospace environment is of primary interest to the Air Force, which communicates through and maintains satellites within this environment. It is now understood that the largest of these disturbances, called coronal mass ejections or CMEs, are the most important cause of major geomagnetic disturbances at the Earth. We have been at the forefront of studies of the origins and propagation of CMEs, and their effects on geospace. We have developed a tomographic technique to display and measure these disturbances as they move away from the Sun. This capability and knowledge has begun to revolutionize the study of heliospheric space plasma interactions with the Earth's environment.

Development of powerful analysis and modeling techniques is a serious challenge that must be addressed in order to maximize the scientific and forecasting return from remotely-sensed solar data. An important requirement for the efficient analysis of these observations will be the ability to trace solar plasma changes near Earth and elsewhere in the interplanetary medium in three dimensions, thereby enabling us to model and study the physics of heliospheric disturbances from a three-dimensional perspective. In particular our current efforts are directed toward using IPS data to more accurately forecast the arrival of heliospheric disturbances at Earth, and the strength of their effect on the geospace environment. However, the techniques we develop are also applicable to other solar and heliospheric remote sensing data. Other Air Force efforts such as the long-standing solar observations at the Sacramento Peak Observatory and the future images from the Solar Mass Ejection Imager (SMEI) launched January 6, 2003 on the Air Force space test satellite Coriolis will surely benefit from these analysis techniques.

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I. Introduction

The outermost parts of the solar atmosphere - the corona and solar wind - experience dramatic perturbations related to flares and mass-ejection transients. These disturbances extend to the Earth's magnetosphere and to Earth itself. In the past, observations of the origins of these disturbances in the lower corona have been restricted to coronal emission-line observations and the meter-wave radio band, but since the 1970's we have seen the addition of powerful new observing tools: sensitive coronagraphs, both in space and at terrestrial observatories; X-ray imaging telescopes; low-frequency radio telescopes; space-borne kilometric wave radio receivers; and interplanetary scintillation data.

The primary goal of our earlier research has been to understand the physics and spatial extent of *heliospheric* structures such as coronal mass ejections and streamers. In comparison with spacecraft *in situ* and ground-based data, this leads to a better determination of the total mass and energy of these structures. In addition, we have addressed the question of how easy these features are to observe and how we can forecast their effects at Earth. These studies were primarily based on data from the zodiacal light photometers on board the HELIOS spacecraft and to a lesser extent on data from ground-based interplanetary scintillation (IPS) and spaceborne coronagraph observations.

In the next section of this report we give the general scientific background for this project. In Section III we describe our recent results using HELIOS photometer and IPS observations of mass ejections, corotating density enhancements and other heliospheric features. The research performed over the last three years is given in Section IV of this final report. Section V gives the journal articles and presentations made from the beginning of the report period. Section VI is a listing of the personnel supported by this project. We conclude in Section VII.

II. Background

The Sun emits clouds of ionized gas and entrained magnetic fields ('coronal mass ejections or CMEs') and hydrodynamic disturbances ('shock waves') which are responsible for most sudden commencements and magnetic storms occurring at the Earth. CMEs are the most dramatic disturbances of the heliosphere and the ones first detected in the HELIOS photometer data (Richter *et al.*, 1982). As shown by Webb *et al.* (1980), the mass ejecta at the time of a solar flare may be more important energetically than its other manifestations in the lower solar atmosphere. Thus, it is imperative to study the masses and 3-dimensional structures of the mass ejections in order to understand the flare process. This provides an additional incentive for the study of mass ejection phenomena, over and above our interest in the physical mechanisms involved in the acceleration of mass and particles associated with the mass motions themselves.

In the lower corona the lower portions of mass ejections observed in Hα are termed 'eruptive prominences,' and are typically associated with a particular kind of flare characterized by two expanding bright ribbons in the chromosphere and a growing system of hot coronal loops rooted in these ribbons (*e.g.*, Švestka, 1986). These loop arcades appear in X-rays to move gradually upward in a steady sequence of diminishing temperature and velocity, and their emission decays with time scales of hours (*e.g.*, Švestka, 1981). These long-decay X-ray events (Kahler, 1977; Sheeley *et al.*, 1983) are well-correlated with the ejection of mass into the corona (CMEs), the acceleration of interplanetary protons (Kahler *et al.*, 1978), and meter-wave radio phenomena (Webb and Kundu, 1978).

The rising coronal X-ray loops suggest the eruption and subsequent reconnection of the strongest magnetic field lines associated with the CME. In models describing this process, field lines stretched open during the eruption of a prominence and CME reconnect near the surface to form a magnetic loop system (*c.f.*, Švestka and Cliver, 1992). Such arcades appear to involve a simplification of the pre-event magnetic structure. Yohkoh results have provided details of this process, although rarely are all of these following features observed in a single event. Early on a thin, string-like brightening appears along the filament channel and may move outward (e.g., Gopalswamy *et al.*, 1999). As the filament is activated, an S-shaped structure, called a sigmoid by Rust and Kumar (1996), develops. This structure denotes the dominant helicity in a given hemisphere, being S-shaped or right-handed in the south and reverse-S or left-handed in the north. Eventually an eruptive flare occurs resulting in an arcade of loops, the highest of which can have cusps at the top. Sterling *et al.* (2000) call this process 'sigmoid-to-arcade' evolution.

Dimming regions observed in X-rays and the EUV imply that material is evacuated from the low corona. Before Yohkoh, transient dimmings in the low corona had only rarely been reported. Hansen *et al.* (1974) first noted the depletion of lower coronal material in white light MLSO data during eruptive events. Rust (1983) described 'transient coronal holes' observed with Skylab which were darkenings usually associated with filament eruptions and X-ray arcades. Yohkoh SXT and SOHO EIT images now reveal areas of subtle dimming, or depletion above or near brightening X-ray arcades. One interpretation of the dimming signature is that the initially closed field lines are opening during the early phase of a CME, in analogy to transient coronal holes observed against the disk. The dimming events appear to be one of the earliest and best-defined signatures in soft X-ray and EUV emission of the mass ejection in the low corona (see Hudson and Webb, 1997, for a review).

The quantitative study of mass ejections essentially began with the Skylab coronagraph observations (*e.g.*, Rust *et al.*, 1980), and has been greatly enhanced by the advent of new coronal instruments. There are data available from the P78-1 and SMM spacecraft, and from mountaintop observatories such as Sacramento Peak and Mauna Loa. Coronagraph observations of CMEs depend on the Thomson-scattering process and, hence, are most sensitive to those events that move outward above the limb of the Sun. Occasionally, some CMEs can be observed in a coronagraph to partially surround the Sun (like a 'halo') (Howard *et al.*, 1982; Jackson, 1985a), and are interpreted as either moving towards (or away from) the Earth. On January 6, 1997 a halo CME was observed by the LASCO coronagraphs on the SOHO spacecraft and forecast to arrive at Earth (Fox *et al.*, 1998; Webb, *et al.*, 1998a) 3 days later. Indeed, on January 10-11 a magnetic cloud event was detected at the Wind spacecraft followed by a moderate geomagnetic storm at Earth. Subsequent to this event, preliminary studies have shown a strong association between 'front-side' halo CMEs and shocks, magnetic clouds and storms at 1 AU (e.g., Brueckner *et al.*, 1998; Webb *et al*, 2000a).

CME observations from the HELIOS spacecraft photometers (Leinert *et al.*, 1981) provide a link between coronal observations and those obtained *in situ* in the heliosphere. The HELIOS observations have been used to map CMEs to elongations (angular distances from the Sun) which extend from 15° to as great as 165°. Global observations over a large range of elongations (up to 90°) can unambiguously determine whether or not CMEs are heading towards the Earth and provide accurate determinations of their arrival times. CMEs originate in the lower corona in closed magnetic field configurations associated with helmet streamers (*e.g.*, Jackson, 1981). It is generally assumed that the closed topology is maintained as the CME moves outward into the heliosphere. The magnetic field lines of the CME expand outward, but their footpoints may remain rooted connected to the solar surface, forming magnetic 'bottles', loops or flux ropes in the solar wind. In some cases reconnection may lead to the formation of a magnetic structure completely detached from the Sun and convecting outward embedded in the solar wind (a 'plasmoid'). X-ray arcades often accompany CMEs, indicating a form of large-scale coronal reconnection, and concave-outward structures have increasingly been detected following CME fronts by LASCO (St. Cyr *et al.*, 2000). Chen *et al.* (1997) modeled a LASCO CME having a circular shape as an erupting flux rope and other LASCO CMEs appear to contain flux ropes. But we do not know if the concave-outward structures are evidence of flux ropes either formed through reconnection or convected as preexisting structures into the solar wind, or of large-scale disconnected plasmoids, or all of these.

The most energetic CMEs, with propagation velocities significantly higher than the ambient solar wind, drive shock waves ahead of them. Interplanetary signatures of CMEs have usually been identified from searches for 'unusual' (as compared to the undisturbed solar wind) particle, plasma and/or magnetic field properties of the solar wind behind these interplanetary shocks. Such signatures (*e.g.*, Schwenn, 1986; Gosling, 1993; Webb, 1995) include high magnetic field strength and gradual rotation (over many hours) of the magnetic field vector over large angles, low field variance, low temperature, low plasma beta and high helium abundance. It seems reasonable to expect that some of these signatures will continue to be present when less-energetic CMEs, moving too slowly to cause the formation of a shock, move past a spacecraft in the inner heliosphere. Probably the best indication of the passage of a CME is the identification of a 'magnetic cloud', defined as having high field strength, low temperature and a large coherent rotation (Burlaga, 1991). Magnetic clouds are probably only a subset of all CME events, although most halo CMEs are associated with magnetic clouds (Webb *et al.*, 2000a).

IPS observations from meter-wave intensity variations of point radio sources are an additional source of information about heliospheric disturbances. These data have long been used to measure small-scale (~200 km) heliospheric density variations along the line of sight to the source (Hewish *et al.*, 1964, Ananthakrishnan *et al.*, 1980). These observations are global and can be used to unambiguously map heliospheric disturbances headed towards the Earth, but only with a daily temporal cadence.

IPS observations can highlight heliospheric disturbances of large scale that change from one day to the next and are often associated with geomagnetic storms on Earth, such as CMEs (Gapper *et al.*, 1982). IPS observations from the Cambridge, England, array (Houminer, 1971) show a predominance of disturbances that appear to corotate with the Sun as inferred from the list of events and their associations (Hewish and Bravo, 1986). On each day it is possible to determine an approximate size and shape of the structures that move past Earth beyond ~50° (≥0.75 AU). These features, presumably modified significantly by their passage through the interplanetary medium on the way to 1 AU, can be classified as structures that are either corotating or detached from the Sun (*e.g.*, Behannon *et al.*, 1991).

These analyses are of interest to the Air Force for several reasons. The Air Force Research Laboratory has a long-standing interest in determining the best technique to forecast the arrival at Earth of CMEs, heliospheric shocks and corotating regions. Using current data sets we are developing a data analysis system that can effectively use ground and space-based imaging data to provide these forecasts. The Solar Mass Ejection Imager (SMEI), launched on January 6, 2003 on the Air Force space test satellite Coriolis, will benefit greatly from the availability of these forecast techniques

To demonstrate the techniques that allow accurate forecasting, we utilize existing real-time IPS observations available from Nagoya, Japan and scintillation-level measurements from other IPS stations. These ground-based data are revolutionizing how we forecast the arrival of heliospheric structures at Earth. The data from the HELIOS spacecraft photometers are the most like the data that will be obtained from spacecraft imagers such as SMEI, and they provide a valuable test-bed for data analysis procedures and imaging techniques to be used in the processing of these Thomson scattering observations. Through our analyses of the IPS data we will maintain our collaborative effort with the groups providing these data and share their forecasting expertise.

The ability to observe the outward propagation of structures from the Sun allows researchers to understand how to forecast their arrival at Earth. This in turn leads to both a better understanding of how these features interact with the Earth's environment and how to forecast their effects on Air Force and DoD space and communication systems. Therefore, understanding these processes in the heliosphere and its plasma environment are of great importance to the Air Force.

III. Recent Results

We have researched the archival HELIOS photometer data sets and IPS observations by employing a variety of techniques. In particular, we have continued development of a tomographic analysis technique to determine the three-dimensional structure of the quiet solar wind into which the CMEs emerge. We have subsequently refined this technique using a 'time dependent' tomography code so that it can be used to map transient heliospheric structures as well as corotating ones. The usefulness of these analysis techniques is well demonstrated by the scientific results obtained with current (IPS and coronagraph) and archival (HELIOS and IPS) data sets that future more advanced IPS telescopes and the Solar Mass Ejection Imager (SMEI) observations will augment and supplant.

We have also begun a real-time analysis using current IPS velocity and g-level observations with our Japanese colleagues, and have added extrapolation of magnetic fields measured at the solar surface to this. These analyses, which operate continuously, employ and help certify our latest techniques and scientific research used to forecast solar wind conditions at Earth. The technique can be used with other currently available observations, and SMEI and other spacecraft imaging data when they become available.

The scientific background and recent results of progress in this endeavor over the last few years are described below.

A. Heliospheric Imagers

SMEI was launched into a near perfect polar Sun-synchronous polar orbit on January 6, 2003 near the end of this three-year contract period. The overall configuration of SMEI progressed over a period of more than a decade (Jackson *et al.*, 1989; 1991; 1995; 1997b; Keil *et al.*, 1996). UCSD was responsible for the overall preliminary design of the instrument, early baffle design and baffle prototype development and CCD testing, and more recently CCD selection and optics construction. SMEI was designed for Earth orbit (Figure 1 schematic) and is currently the best design we know for operation near Earth where the Moon and stray light from spacecraft bus appendages have the potential to overwhelm the faint brightness signal from heliospheric electrons. Currently, UCSD, Boston College and the University of Birmingham, England, in conjunction with the Air Force Research Laboratory are involved with SMEI data analysis. This instrument was originally designed to be placed on the WIND spacecraft in a configuration similar to that of the HELIOS spacecraft photometers. Data from the HELIOS spacecraft has been used to measure CMEs at solar distances beyond 1 AU, proving that SMEI in Earth orbit could measure such structures. Figure 2 shows just such an example using a set of contour plot images obtained during a solar mass ejection on January 2-6, 1979 when HELIOS 2 was almost 1.0 AU from the Sun and very near Earth. Additional information about this CME can be found in other studies (Burlaga *et al.*, 1981). Over the years, with the availability of good space-qualified CCD cameras, the instrument design was modified to incorporate the HELIOS concept on an orbiting spacecraft near the Earth. The SMEI instrument and the NRL Windsat radar antenna are the only two experiments on board on the Air Force Space Test Program Coriolis Mission spacecraft bus designed by Spectrum Astro., Inc.

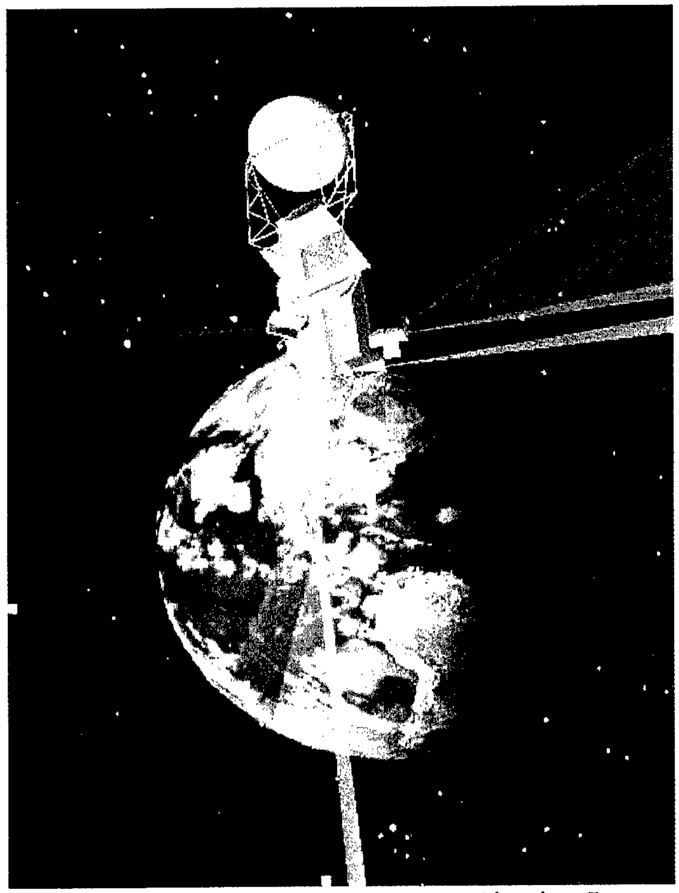


Fig. 1. Depiction of the Solar Mass Ejection Imager on the Coriolis spacecraft.

In deep space or on a dedicated spacecraft in an 800km Earth orbit a lightweight version of SMEI could view the whole sky over a hemisphere or more in a single image. One of us (A. Buffington) has championed this type of imager and presented the studies of this type of design in several papers (Buffington *et al.*, 1996; 1998 and Buffington, 1998; 2000). Several NASA-proposed spacecraft including, Solar Probe and Solar Polar Sail have included this instrument in their payload complement. In addition, both ESA and Japan have included preliminary versions of this design on different proposed spacecraft. Like SMEI these instruments will provide measurements of physical parameters of CMEs and other heliospheric structures such as mass, density, speed, and location in space. These parameters can then be used to determine the extent to which these structures will affect the Earth's environment. This fundamental research enhances the prospects of these instruments being able to forecast heliospheric features arriving at Earth.

B. HELIOS Photometer Data

As noted, the Thomson-scattering data from the HELIOS spacecraft are the most similar to those expected from SMEI. The twin HELIOS spacecraft, launched into heliocentric orbits in 1974 and 1975, contained sensitive zodiacal-light photometers (Leinert *et al.*, 1981). Each of the two HELIOS spacecraft contained three photometers for the study of the zodiacal-light distribution. These photometers, at 16°, 31°, and 90° ecliptic latitude, swept the celestial sphere to obtain data fixed with respect to the solar direction, with a sample interval of about five hours. The spacecraft were placed in solar orbits that approached to within 0.3 AU of the Sun. The photometers of

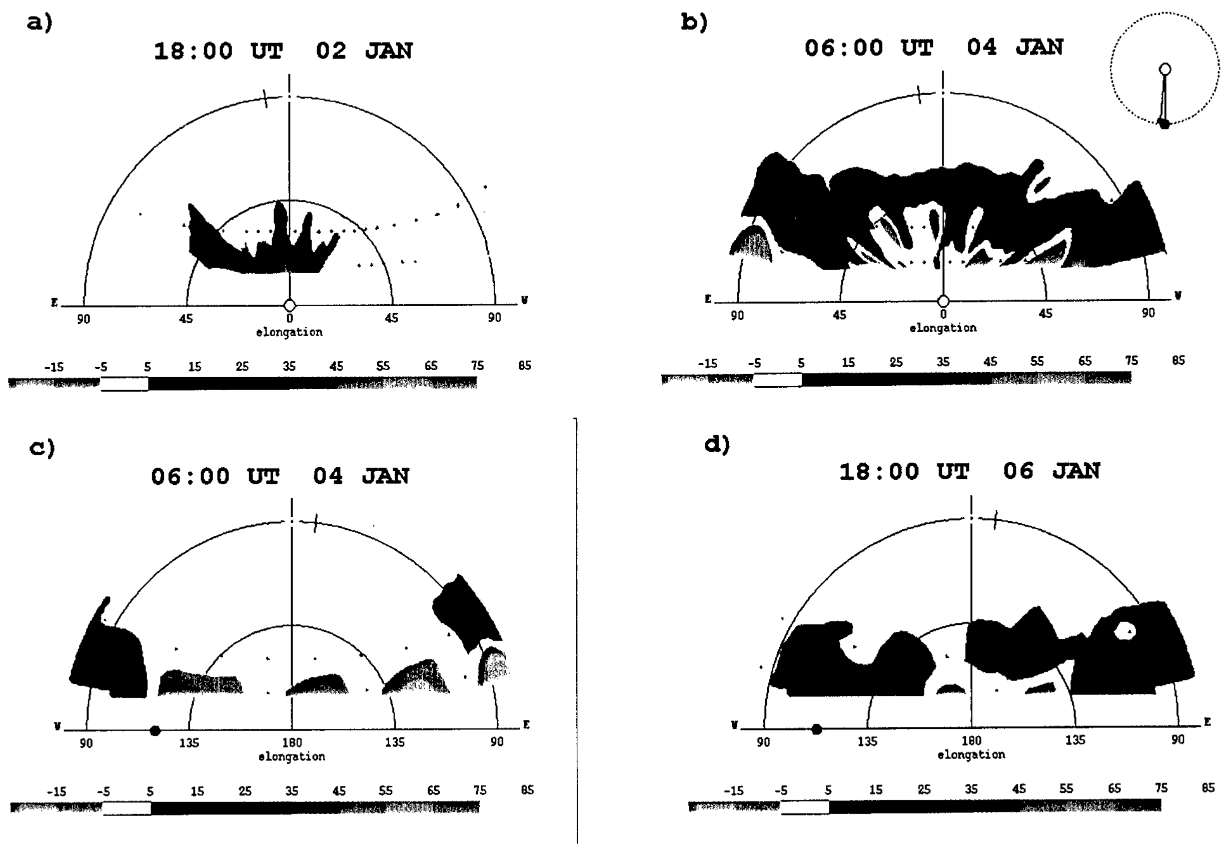


Fig. 2. Heliospheric images derived from the photometers on board the HELIOS 2 spacecraft when HELIOS 2 was 0.94 AU from the Sun. A CME is the primary structure imaged from 2 to 6 January 1978. The CME is observed to begin outward motion near the Sun and then move past the spacecraft. A diagram in the upper right of the figure indicates the position of the Earth, Sun and HELIOS 2. Electron column density is contoured in levels of 10^{14} cm^{-2}. **a)** and **b)** The Sun is at the origin with the horizontal axis representing the ecliptic plane. Radial distance from the origin represents solar elongation (as labeled on the horizontal axis). **c)** and **d)** As in **(a)** and **(b)** but with the anti-solar direction at the origin. The Earth position is marked as a blue dot between west 90° and 135°. Chronological sequences of these images reveal the dynamics of the ejection events observed. A video sequence from images of another CME (on May 24, 1979) is available on the Web at: **http://casswww.ucsd.edu/solar/misc/heliosv.html.**

HELIOS 1 viewed to the south of the ecliptic plane, and HELIOS 2 to the north. These photometers were first shown to be sufficiently sensitive to enable detection of variations in density from CMEs by Richter *et al.* (1982). Although most of the bright transient events observed by the HELIOS photometers were CMEs, elongated features that corotated with the Sun were also observed. Mass ejections were distinguished by their apparent outward motion that was primarily symmetrical to the east of the Sun as well as to the west. Corotating structures, on the other hand, could be observed as they moved from east to west with time over many days.

A major achievement of past research at UCSD has been the measurement of interplanetary masses and speeds of CMEs observed with coronagraphs, by interplanetary scintillation techniques and *in situ* spacecraft measurements. The combination of these data allow spatial configurations to be determined for each CME studied (Jackson, 1985a; Jackson *et al.*, 1985; and Jackson and Leinert, 1985; as reviewed in Jackson, 1985b). The 2-D imaging technique used to display HELIOS data has been developed at UCSD. Nearly 160 CMEs observed by the HELIOS photometers have been imaged in the manner shown in Figure 2. The masses obtained from these observations indicate that indeed the material of a mass ejection in the lower corona moves coherently outward into the interplanetary medium, and that the mass flow extends over times that can be significantly longer than one day.

From the complete data set from HELIOS 1 and 2, we selected all of the transient events that appeared bright in the 90° photometers (and that were present in the 16° and 31° photometers) (~300 events) for further study. This list of 90° events has been published (Jackson *et al.*, 1994) and distributed to the community. Using this list we published a preliminary study of the solar cycle variation of these data (Webb and Jackson, 1993) that was subsequently included with other CME data by Webb and Howard (1994) to show that CMEs are more frequent during the maximum of the solar activity cycle. Using these results Crooker *et al.* (1993) developed a model wherein the heliospheric current sheet acts as a conduit for CMEs and, thus, CMEs can be frequently associated with coronal streamers and the high density corotating regions. These analyses and the ready availability of the photometer data have lead to a variety of other studies such as reported in papers by Webb *et al.* (1993a; b) and Jackson *et al.* (1993). Webb and Jackson (1990; 1992; 1996), Jackson and Webb (1994), and Webb *et al.* (1995) have continued analyses of the 90° events using the complete data set. In these studies we determined the solar cycle variation of the CMEs and compared them with *in situ* plasma and interplanetary magnetic field flows at the HELIOS spacecraft. Webb *et al.* (1995) compared SOLWIND and SMM coronagraph and HELIOS observations to determine CME masses and energies. These studies show that CMEs measured in the inner heliosphere are more massive than when measured by a coronagraph in the lower corona, a result recently confirmed by Howard *et al.* (1997) using the wide LASCO field of view.

Persistent corotating structures (CRSs) near the solar surface that rotate with the Sun and extend outward in the form of streamers are the most prominent coronal structures observed at the time of an eclipse. In the solar wind, similar dense regions that reappear on consecutive solar rotations are also observed. The HELIOS observations have been used to measure the extent of these features (Jackson, 1991). Jackson *et al.* (1993) showed that about one-third of the CRSs are associated with sector boundaries observed in the solar wind.

The data from the HELIOS spacecraft photometers and the SOLWIND coronagraph have been used to reconstruct the three-dimensional shapes of coronal mass ejections in the interplanetary medium through computer-assisted tomography (CAT) techniques (Jackson *et al.*, 1988; Jackson, 1989; Jackson and Froehling, 1995). These results were also described in Jackson and Hick (1994).

A procedure was developed at UCSD to use month-long stretches of photometer data to display heliospheric brightness in the form of synoptic charts (Hick *et al.*, 1990). These latitude-longitude contour plots give the heliospheric locations of persistent bright structures. Over the years this technique was transformed into a tomographic program that has been used to accurately reconstruct corotating heliospheric densities and velocities using both IPS (Jackson *et al.*, 1997a; c) and HELIOS (Hick and Jackson, 1998; Jackson and Hick, 2000; 2002) photometer data sets. The location of these structures is important because it has been shown that dense corotating regions are often associated both with CMEs and geomagnetic storms (Crooker *et al.*, 1993). The low-density coronal hole regions between these dense regions cause low-level geomagnetic activity due to their enhanced Alfven-wave flux (Tsurutani *et al.*, 1995). In addition, the dense corotating structures in the solar wind form a background that can obscure the detection and forecasting of CMEs.

These observations beyond the acceleration region of the solar wind allow direct comparison of the solar wind density variations with solar wind speed from IPS velocity data. The combined density observations from HELIOS and velocity measurements from IPS have permitted investigation of the variations of mass, momentum and energy flux in the solar wind as functions of heliographic latitude and solar wind speed. Hick and Jackson (1994) and, more recently, Leinert and Jackson (1998) showed that the momentum flux (mV^2) [and not mass flux (mV) or energy flux (mV^3)] is the same for the high latitude, fast solar wind and low latitude, slow solar wind over the solar cycle. The implication of conservation of momentum flux poses a valuable constraint on solar wind modeling. In particular, this implies that the total energy input to the solar wind, other than that associated with CMEs, is constant over latitude and not enhanced significantly by the strong solar magnetic field near the solar surface above the regions of high solar activity.

C. IPS Observations

Daily IPS observations are highly sensitive to the dense structures present in the solar wind along the line of sight. The so-called point-P technique assumes that all the response from the IPS signal is at the closest approach of the line of sight to the Sun. To address criticisms of this technique (the near line of sight features can obscure features more distant from the observer), we developed our tomographic modeling technique which allows us to automatically take into account the line-of-sight contribution to the observed data. The technique allows us to locate the position of the material along the line of sight by viewing it from different perspectives. This tomographic technique (Jackson *et al.*, 1998; Jackson *et al.*, 1999a) uses an iterative least-squares fitting procedure to determine a precisely-defined kinematic three dimensional heliospheric model that best fits the observations.

In current analyses these tomographic heliospheric representations show essentially the same thing as the point-P analysis with respect to the position of dense structures but with much higher contrast and better definition. The dense structures present in the IPS data usually map to solar active regions, *not* the heliospheric current sheet as expected from previous models. The velocity IPS data analyzed using a similar tomographic technique (Kojima *et al.*, 1997) show that these regions also have very slow solar wind velocity.

D. Research on Coronal Mass Ejections (CMEs)

Different kinds of CME studies will be necessary to permit us to understand CMEs and forecast their effects. We need to improve our understanding of the surface manifestations of CMEs, how they relate to the ensuing disturbance in the interplanetary medium, and how reliable these measurements are. We also need to know the most reliable indicators on and near the solar surface of the launch of CMEs and what these tell us about how geoeffective a given CME will be. Of most interest is what parameters of CMEs observed both near the Sun and in the interplanetary medium are important for driving the largest, most hazardous geomagnetic storms. Thus, part of our work effort has involved studies of the environment, especially the magnetic field structure, of the sites of origin of CMEs, how they develop in the corona, and what their signatures are in and how they propagate through the interplanetary medium.

1. HELIOS Photometer Studies

CME research is one of the most significant kinds of studies that resulted from the HELIOS photometer observations. In the past we have published many results using the HELIOS CME data. For this effort we are pursuing several follow-up studies using these data sets, including determination of the signatures of geoeffective solar ejecta propagating through the interplanetary medium, and which properties of such interplanetary CMEs, such as mass, momentum, speed and total pressure, are best correlated with geomagnetic storms. We have published several preliminary papers (Webb *et al.*, 1997a, b) on the results of studying HELIOS CMEs that were aimed at Earth.

In another study we determined the speeds in the inner heliosphere for ~130 of the 160 CMEs observed by the HELIOS photometers published earlier (Jackson *et al.*, 1994). For these events we are revising a manuscript to be submitted for publication that details the speeds of CMEs in the solar wind and compares these speeds to other published observations (Jackson and Webb, 2003).

2. Sources and Geoeffectiveness of SOHO Halo CMEs

During the past several years we studied the characteristics of the source regions of CMEs and what the solar surface manifestations and development of CMEs can tell us about their geoeffectiveness. Of most interest is what the characteristics are of those CMEs that result in the largest geomagnetic storms.

One of the major discoveries with the SOHO LASCO coronagraph data has been the imaging of enhanced outward-flowing material surrounding the occulted solar disk during a CME. These so-called 'halo' events imply that the CME is either aimed toward Earth (i.e., the SOHO spacecraft is at the L1 point in front of Earth) or in the opposite direction away from Earth. When halo CMEs are accompanied by surface activity on the visible solar disk, it is likely that the event is on the frontside of the Sun and, therefore, aimed toward Earth. We have studied both the nature of this associated surface activity (Hudson *et al.*, 1998; Webb *et al.*, 1998a, 2000a) and the effects of the halo events at Earth (Webb *et al.*, 1997d; Webb *et al.*, 1998c, d; Webb *et al.*, 2000a, b). In the former case we find that, during the period just after this past solar minimum (1996-1997), halo CMEs were typically associated with small, long duration X-ray arcade flares, EUV waves, transient coronal dimming regions, and erupting filaments, all within about half a solar radius of Sun center.

However, this associated activity was highly variable from event to event and, in the case of the January 1997 halo CME, the significant geomagnetic effects would not have been forecast if the halo CME had not first been observed by LASCO (Webb *et al.*, 1998a). Except for the newly discovered EUV waves, all of these types of activity have been well associated with CMEs in the past. At the Earth the LASCO halo events associated with frontside activity were followed, in 6 out of 7 cases, 3-5 days later by an interplanetary shock, a magnetic cloud and a moderate-level (Dst > -50 nT) or greater geomagnetic storm. This is despite the fact that these events appeared to be relatively weaker as expected for near-solar minimum activity. The one miss is instructive because it was associated with surface activity 75° from Sun center. All other halo CMEs had associated activity within about half a solar radius of Sun center. We extended this analysis to include all complete (360°) halo CMEs observed by LASCO from 1996 through 1999. Preliminary results generally confirm the earlier study except that there is evidence that the CMEs detected as halos by LASCO are denser and faster than the average CME (Webb *et al.*, 2000c). The average travel time from the onset of the CME to the onset of the magnetic cloud at 1 AU is 3.6 days.

Thus, it appears that shocks and magnetic clouds or flux ropes appear to be characteristic of at least the more energetic CMEs, and that these features are most notable in this data set because we are sampling the CME material along its central axis at 1 AU. Such flux ropes may be associated with depletions of the coronal material at their feet. The importance of such observational studies to developing forecasting techniques for future instruments like SMEI and STEREO is clear.

3. The Magnetic Field Structure of CMEs and Magnetic Clouds

As part of the study of the origins of CMEs, we have also studied the magnetic topologies of CMEs, especially their source regions and how they erupt and develop into interplanetary disturbances, such as magnetic clouds. Earlier we published a paper providing strong evidence that the source regions of many CMEs involve complex magnetic topologies, especially quadrupolar structures (Webb *et al.*, 1997c). One aspect is that the span of typical CMEs can cross 2 or more neutral lines at the surface, suggesting that multiple closed-field arcades lay underneath the CME before its eruption. CMEs can also arise over convoluted neutral lines, such as those having a 'switchback', or hairpin appearance, as has also been noted by McAllister and colleagues. This study was done before the launch of SOHO. The extended field-of-view LASCO observations have revealed that this pattern was dominant during the recent solar minimum, 1996 to early 1997, in that the streamer belt observed in the C2 and C3 coronagraphs appeared as a simple, bipolar structure. Nevertheless, the streamer belt overlay twin arcades flanking the equator as observed in Fe XIV emission near the surface by the C1 coronagraph (Schwenn *et al.*, 1997). The eruption of such a helmet streamer as a CME would then suggest a quadrapolar magnetic source region with more than one neutral line.

We also worked on a paper wherein two Yohkoh X-ray events exhibiting quadrupolar structure are compared with white light CMEs and with the recent multipolar CME model of Antiochos *et al.* (1999). We earlier presented the preliminary results (Webb *et al.*, 1998c). We examined the Yohkoh and EIT data for other multiple arcade coronal events that are associated with CMEs to see how common they are, and, *e.g.*, whether complex magnetic structures are a necessary condition for the occurrence of a CME.

We have also performed two preliminary studies of the observational evidence for and the characteristics of reconnection/disconnection of magnetic field lines involved with CMEs. The first study was of the characteristics of disconnection events observed with the SMM coronagraph from 1984-1989 (Webb and Burkepile, 1998). About 10% of all SMM CMEs exhibited such concave-outward structures. These events often involved the blowout of a pre-existing streamer and in half of them a narrow, bright ray suggesting a current sheet appeared ~12 hr. later. The disconnection structures tended to be half as wide and half as slow as their associated CMEs and about 1/3 showed acceleration.

The LASCO data has been studied by Webb *et al.* (1998b) and St. Cyr *et al.* (2000) who found that LASCO detected concave-outward structures much more frequently than with previous coronagraphs. During 1997 such structures were found within nearly half of all CMEs. However, as discussed above, LASCO is also seeing complete circular structures within many CMEs, some of which have been modeled as flux ropes (*e.g.*, Chen *et al.*, 1997; 2000). Reconnection/ disconnection may or may not be important in the formation of such events.

Finally, we have been involved in several collaborations and campaigns featuring comparisons of LASCO halo CMEs with space weather at Earth. The May 12-15, 1997 event is important in many respects. The CME was associated with a filament eruption and sigmoid arcade near Sun center as well as an EIT wave and twin dimming regions. It was associated with a shock, flux rope and magnetic storm at Earth. Webb *et al.* (2000b) compared the orientations, magnetic helicity and total flux, and the timing of the solar structures and the ensuing flux rope at 1 AU and found general agreement. This suggests that, in well-observed events, the solar data might be used to predict the orientation and variation of the southward field and the field magnitude of the resultant flux rope at Earth.

E. Tomographic Analysis

The perspective views of the heliosphere formed by solar rotation and outward solar wind flow are used in our tomographic technique to determine three-dimensional heliospheric structure in an iterative process. The technique least-squares fits a kinematic three-dimensional solar wind model to available data. The three-dimensional model from this analysis can incorporate both the IPS scintillation level enhancements (from Cambridge, England (1991-1994), Ooty, India and Nagoya, Japan) and IPS velocities from UCSD (1965-1985) and Nagoya, Japan (1985-present).

These studies resulted in a series of papers about the tomographic technique written jointly by the groups in Toyokawa City and UCSD. In these papers (Jackson *et al.*, 1998; Kojima *et al.*, 1998; Asai *et al.*, 1998) the tomographic method (slightly different at the two laboratories) is described and comparisons with other data sets are made. Because the kinematic model is three-dimensional, we can form a Carrington synoptic map presentation at different heights as constant solar distance cuts through the model and also present the results in three-dimensions as in Figure 3.

These data can be related to the location of spacecraft, and mapped as *in situ* measurements of density and velocity observed at the spacecraft to determine the validity of the model and the accuracy of the observational fits. We are able through this technique to map the degree of scintillation level to density measured by spacecraft *in situ*. The velocities are also compared to *in situ* measurements and these correlate one-to-one with *in situ*-measured velocities.

1. HELIOS tomographic analyses

The tomographic technique has also been used on Thomson-scattering white light data from the HELIOS photometers in a manner similar to the IPS analyses. In these studies we have successfully mapped heliospheric structures and these appear to look much like those observed in the IPS tomography analyses. Preliminary papers by Hick and Jackson (1998) and Jackson and Hick (2000; describe the results of this technique that has been more thoroughly described in Jackson and Hick 2002). The results of the study of one month of HELIOS 1 and 2 data obtained by the spacecraft in 1977 are shown in Figure 3.

2. Heliospheric Densities from IPS Tomography

A comparison of YOHKOH and Sacramento Peak Fe XIV data on a rotation by rotation basis shows a great similarity of bright structures (active regions) with IPS enhancements observed from 0.5 to 1.0 AU. However, this correspondence is not observed in the solar magnetic field data extrapolations to 1 AU (Hick *et al.*, 1995a; b; c; 1999). These comparisons indicate that solar active regions are sources of the slow solar wind and that these regions add significant mass to the interplanetary medium. These regions, not the heliospheric current sheet, dominate the IPS observations of the quiet solar wind at 1 AU. The regions of enhanced scintillation are generally regions of denser solar wind (Jackson *et al.*, 1998). This distinction would have gone unnoticed except that the current paradigm is that solar active regions are closed magnetic structures that constrain dense material to the low corona, whereas the slow solar wind emanates from coronal streamers which form the base of the heliospheric current sheet.

Švestka *et al.*, (1997; 1998) and Hick *et al.* (1999) have used these techniques to study X-ray and IPS signatures of mass outflow from active regions following the occurrence of a flare or CME. They conclude that the 'opening' of the magnetic field as a result of the CME or eruptive flare creates conditions favorable for a steady mass outflow from the active region following the eruptive event. This mass outflow persists long after the CME has moved out of the low corona, and is hence not related to the outflow of mass in the CME itself.

Fig. 3. View of the corotating component of the plasma density in the inner heliosphere (out to 1.5 AU) derived by tomographic reconstruction from HELIOS 1 and 2 photometer data and IPS velocity data from UCSD for Carrington rotation 1653 (March 21, 1977, to April 18, 1977). The density is normalized by the removal of an r^{-2} distance dependence. The Sun is at the center; the Earth is marked in blue in its orbit around the Sun. The view is from 15° above the plane of the solar equator. Clearly seen is the Archimedean spiral structure of the solar wind (as presented in Jackson and Hick, 2002) An animated version of these data is available on the Web at: **http://casswww.ucsd.edu /solar/tomography/slow_helios_1653.html**

3. Time-Dependent Tomography

The effective analysis of heliospheric remote sensing data (such as will be available from SMEI) requires a tomographic technique that not only shows corotating structure but also the dynamics of this structure as it moves outward towards Earth. Modifications of the Thomson-scattering tomographic technique now enable this type of analysis. This complex modification of the computer programming technique has been termed 'time-dependent' tomography because it allows temporal changes to be mapped in heliospheric structures. When short intervals of time are reconstructed in three dimensions, this is akin to an analysis that derives its perspective views from the outward plasma flow alone. Early versions of this technique allowed temporal changes of one day and greater to be used in the mapping.

The best results using this technique will come from data sets with the least amount of noise, and with the most observations. This technique has been demonstrated using Cambridge, England, scintillation-level data and temporal intervals as short as one day and HELIOS photometer data using temporal intervals as short as 10 hours. Comparisons of the Cambridge and STELab, Nagoya time-dependent tomographic g-level results with *in situ* density observations at Earth as well as those using the Nagoya velocity IPS observations are considerably better than those using the assumption of corotation alone. Thus, we have felt justified in presenting the three-dimensional

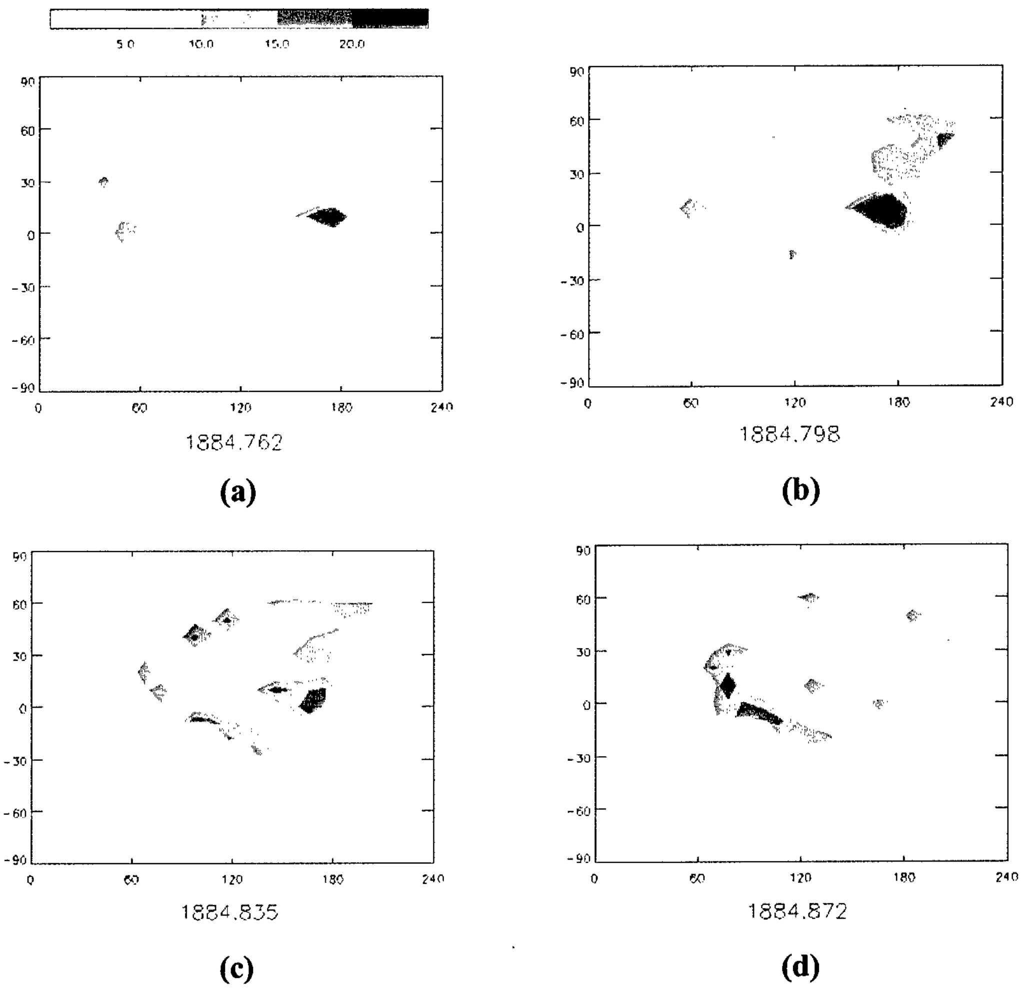


Fig. 4. a-d show cuts through a three dimensional model of deconvolved Cambridge IPS *g*-level data (Carrington longitudes 0° - 240°) at 1 AU at four times separated by one day. Heliographic spatial resolution is tailored to the Cambridge IPS data set and the numbers of lines of sight per day available (about 250). The *g*-level values have been converted to an equivalent density at 1 AU (shown on the maps) by calibration with *in situ* spacecraft densities. The Earth moved from ~100° to 40° longitude during the time of the observations.

results of the time dependent technique (Jackson *et al.*, 1999a, b) (Figure 4 and 5) as accurate representations of heliospheric CME structures. Additional comparisons of both IPS and Helios photometer models using this technique can be found in Jackson et al. (2003a; b). We have tested and are still testing this technique in many ways to refine our tomographic programming techniques, and have incorporated the use of this technique in the real-time analyses described next.

F. Solar Wind Real-Time Observations

The interplanetary scintillation data set that is currently available is from the IPS array system located near Nagoya in central Japan and operated from the Solar-Terrestrial Environment Laboratory (STEL) located in Toyokawa City. Following his stay as a visiting professor in the latter part of 1995, B. Jackson and M. Kojima began a joint STEL - UCSD cooperative agreement between the two laboratories. The five-year agreement began on December 15, 1997. The intent of the agreement is to provide collaborative exchange of ideas, personnel, current IPS data and

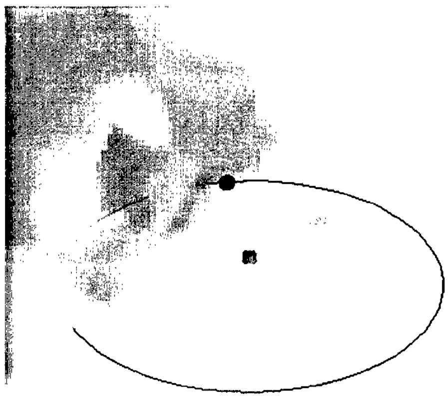


Fig. 5. A three dimensional model projection of the heliosphere from an observer's perspective situated at 3 AU, 30° above the ecliptic plane opposite the position of Earth. The projection shown is at the same time as the data displayed in two dimensions at 1 AU in Figure 4c. As in Figure 2, density is normalized by the removal of an r^{-2} distance dependence. A solar ejection is observed moving outward to the west of the Sun as seen from Earth.

ultimately SMEI data, and to make these data available as a forecast tool in both countries. The Nagoya data gives solar wind velocities from multi-site radio telescopes, which map the motion of the intensity-scintillation pattern across the surface of the Earth. Under the auspices of this cooperative agreement, we have been able to obtain these velocity scintillation data in real-time. We were able to modify our HELIOS photometer data display programs to produce interplanetary scintillation daily maps of the sky surrounding Earth (Figure 6a), much as was done at NOAA in their attempts to forecast the arrival of heliospheric disturbances at Earth. Since only approximately 20 sources are tracked regularly each day, the data have a rather low spatial and temporal resolution. Nevertheless, these data can be used to indicate the approach toward Earth of fast transient structures superposed on the quiescent background solar wind structures. In fact in one instance these data forecast the heliospheric disturbance that one day later caused the geomgnetic storm of 25 May 2000 when other techniques failed.

To test forecast programs that can be used to accurately predict the arrival of corotating structures and CMEs at Earth, the real-time space weather program begun at UCSD using IPS velocity data from Nagoya, Japan has new data delivered to UCSD on a daily basis. The Fortran programs that provide the tomographic results and IDL programs that create image displays operate automatically once the data arrive at UCSD. The analysis system provides a near real-time daily map of solar wind structures surrounding Earth. These programs are run using Red Hat LINUX 'Cron. Jobs' operated on a PC. The analysis is compared hourly with measurements from the ACE spacecraft at the L1 Lagrange point in front of Earth. These programs thus provide daily comparison tests of the tomographic analysis. They show just how well real-time forecasting works using current data sets, and show how other data sets will be able to improve these forecasts in the future. The results of these real-time analyses can be viewed on our UCSD Web site at:
http://casswww.ucsd.edu/solar/forecast/index.html.

In real-time the three-dimensional velocity least-squares fit model is plotted in two dimensions (Figure 6b). The structures shown in Carrington coordinates at 1 AU give the best least squares fit to our 3-D tomographic model assuming corotation of the structures. The three-dimensional model from which the map is determined is also used to obtain a trace of the velocity at Earth, and this velocity profile is plotted below the Carrington Map. At the time in the solar cycle of this plot (November 1999) there were many high-speed structures present in or near the heliospheric equator. We suppose that these structures are primarily transient ones that persist long enough to be observed as enhancements in solar wind velocity at Earth. More definitive determinations of the nature of these structures will become possible using the current time-dependent tomography. We have modified our time-dependent tomography technique to reconstruct daily differences in structure and are using it with velocity and g-level IPS data from STEL, Japan. To do this we have had to limit the spatial resolution to 20° by 20° in heliographic latitude and longitude. The current IPS tomographic analyses converge when we do this, but because of the limited spatial resolution reconstruction of only the largest heliospheric features is possible. Nevertheless, when this is done we have shown that far better fits to the *in situ* data at Earth are possible.

To evaluate these different modeling techniques we compare them with *in situ* velocity measurements from the ACE spacecraft at L1. In Figure 6c we show our preferred model (which currently assumes the velocity structures corotate) using the UCSD reconstruction technique, and in Figure 6d we show three different models using different tomographic techniques including two versions of the time-dependent technique. As we continue to make these comparisons and improve our models, we expect some aspects of these techniques to survive while others will not.

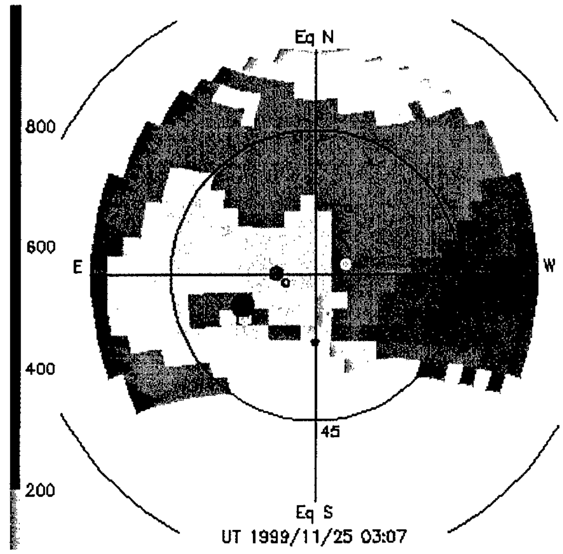


Fig. 6a. A recent sample sky sweep map showing the ambient solar wind velocities as observed from Earth with the IPS sources observed over the most recent 24-hour period superposed. The color of the source is the velocity observed for that source and the size of the source depicts the velocity difference of the source from the nominal at that location.

IV. Research Completed Under This Contract

Both interplanetary scintillation observations and the HELIOS photometer data set have been employed to map various aspects of the solar wind using a variety of techniques. Especially, though, we have continued development of a tomographic analysis technique to determine the three-dimensional structure of the quiet solar wind into which the CMEs emerge and to refine this technique so that it can be used to map transient structures as well as corotating ones.

We have also continued our real-time analysis of IPS observations with our Japanese colleagues. These analyses operate continuously and are used to forecast solar wind conditions at Earth in a technique similar to one that can be used with SMEI data when

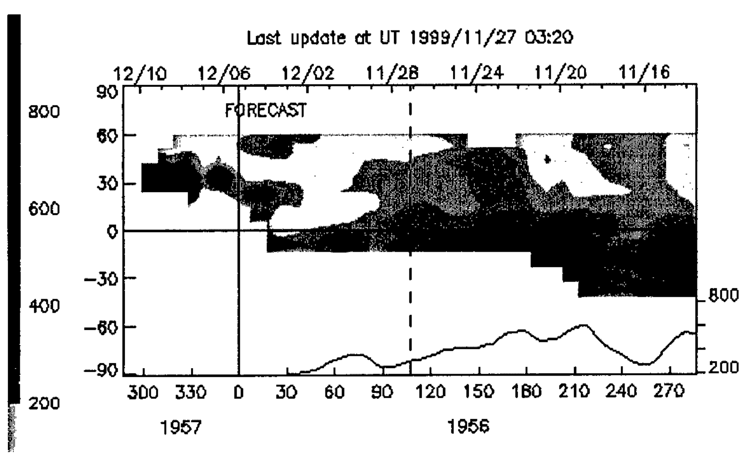


Fig. 6b. Carrington synoptic presentation of real-time solar wind velocity. The Earth is centered in the plot at the location of the dashed line. A trace of the velocity at Earth is shown below the map.

it becomes available. Specific progress during the contract is described below.

A. Tomographic Analysis Program Improvements

There have been improvements made to both the corotating and time-dependent tomography. These are provided as they become known to help make the routines more stable to data noise and to enable a more complete heliospheric model to be formed. These have allowed significant improvement in the global heliospheric model, and now provide a better forecast capability and will enhance this capability in the future. Late in this contract time period we made available both corotating and time dependent tomography programs to the Community Coordinated Modeling Center (CCMC) at the Goddard Spaceflight Center.

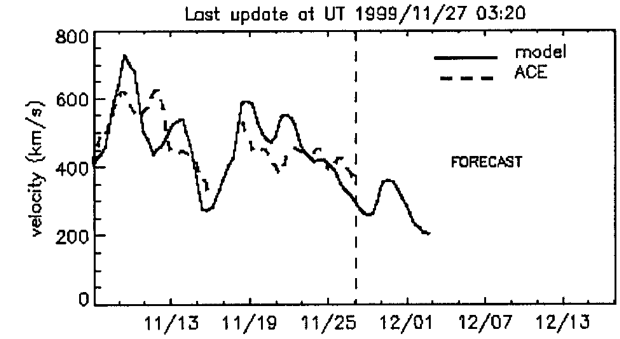


Fig. 6c. Time series presentation (time runs left to right) of IPS and ACE (*in situ*) velocity data. The model data is the same as plotted below the synoptic presentation in Figure 6b, and shows the least squares fit to corotating structure. In order that the ACE data compare in resolution with the

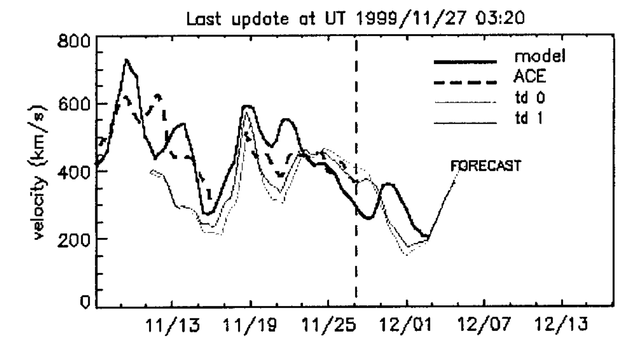


Fig. 6d. Comparison between IPS model and ACE velocity data. Our 'preferred' corotating model (from Figure 6c) is shown along with two versions of our time-dependent velocity model mapped to Earth. Future predicted 'FORECAST' values are shown to the right of the dashed vertical line.

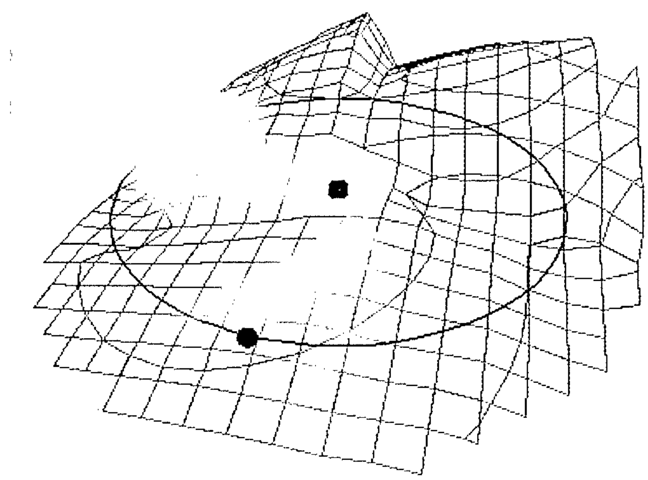
1. Corotating Tomography

The tomographic technique has been used on Thomson-scattering white light data from the HELIOS photometers in a manner similar to the IPS analyses. These studies are shown to successfully map heliospheric structures and they appear to look much like those observed in the IPS tomography analyses. Preliminary papers by Hick and Jackson (1998), Jackson and Hick (2000), and Jackson *et al.* (2001) describe the results of this technique. The results of the corotational model study of one month of HELIOS 1 and 2 data obtained by the spacecraft in 1977 are shown in Figure 3 (from Jackson and Hick, 2002). A more complete description of both techniques and the advantages of each are given in Jackson and Hick (2003).

2. Time-Dependent Tomography

Modifications of the Thomson-scattering and IPS tomographic technique now enable a time-dependent analysis that shows CMEs as well as corotating structures. Considerable effort has gone into making this tomographic technique stable to noise in the IPS data since there are few sources per day available to give the global results, especially in real time. A large share of these problems has been overcome, and in July 2002 we began operating our Web site to show transient heliospheric structures in real-time in three dimensions. We continue to test these analyses to show that they give reliable results. Figure 7 depicts a period of time in 1977 that was studied extensively by Burlaga *et al.* (1980). Reconstructions using the time-dependent tomography successfully reproduce the corotating structure observed in the analyses, show the location of the CME (only implied in the Burlaga *et al.*, 1980 paper), and the density enhancement behind a shock. This reconstruction, and the earlier depiction of the time interval from the 1980 paper appeared as a Goddard "nugget" and a "New Years" greeting from Len Burlaga in early 2002.

Most of the work on this tomographic analysis program during 2002 included alterations to allow inclusion of an external model to provide updates to the tomography. This interface to the tomography program currently requires that both programs be in Fortran and that both operate on the same computer. The interface allows the time-dependent tomography to run one iteration through all time steps, and then the external model with the tomography updates to run through all time steps. We have tested this model using an external model simulator and have found that it works adequately. The first application of this interface will probably be the 3D MHD code from NOAA provided by Tom Detman. This 3D-MHD code currently operates on our computer at CASS, and we have begun the process required to tailor this code to the tomography program.



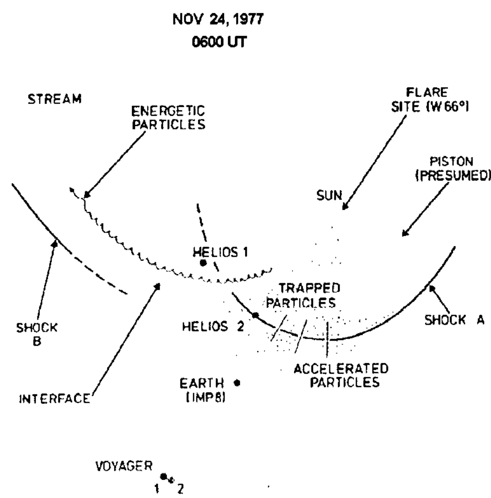


Fig. 7. Left is a three-dimensional reconstruction of corotating and coronal mass ejection (CME) solar wind density structures with the heliospheric current sheet superposed is shown. The Sun is depicted as a red dot in the center of the display. Earth's orbit is an ellipse in perspective with Earth as a blue dot towards the lower left. Densities are plotted after removing an inverse-square distance dependence. The solar wind densities during Carrington Rotation 1662 (November 24, 1977) are reconstructed by fitting HELIOS spacecraft white-light photometer observations over a month-long time interval (Jackson *et al.*, 2002b). The heliospheric current sheet was extrapolated outward from the solar surface using tomographically reconstructed interplanetary scintillation (IPS) velocities from the UCSD IPS array system during the same time interval. Magnetic field information from Wilcox Solar Observatory data and a modified potential field model (The CSSS model, Zhao and Hoeksema, 1995) was used to provide magnetic field measurements. The reconstructed density near Earth (as presented in Jackson *et. al.*, 2002a) accurately reproduces *in situ* observations of heliospheric features studied by Burlaga *et al.* (1980) shown to the right above.

Previous versions of the time-dependent tomography program only allowed radial outward flow. To accommodate non-radial motion in the heliosphere that may be observed in the higher-resolution SMEI data we have had to modify the time-dependent code to shift packets of heliospheric plasma outward in latitude and longitude as well as time. This addition of two more dimensions into the time-dependent code now operates successfully. Tested in a form where only time shifts are allowed (as before) shows that the program gives exactly the same answer as its earlier version.

In the early part of 2003, the time-dependent analysis again underwent considerable modification that now allows time to be input in the data calculated in double precision days from the beginning of the year. When SMEI data are used in these analyses temporal values of this precision are essential. This revised program is now used as standard in the IPS real-time analysis. These modifications had a added benefit in that the time-dependent tomography is now a far more stable iterative procedure and gives the same result no matter what time period beginning and ending is used within the same temporal range.

Current versions of this time-dependent technique now allow changes from a few hours to a half of a Carrington rotation temporal interval to be used in the mapping, and in theory spatial scales as high as one degree or better. These analyses show that PCs can be used for most conceivable research projects using IPS and Helios photometer data. However, when SMEI begins working the amount of data from this instrument will be well beyond the ability of such computers to keep up (or even proceed with) the analysis at resolutions commensurate with the data amount. The data from SMEI can always be averaged so that a Personal Computer is able to complete the analysis, but through our contact at Sacramento Peak Observatory (Joel Mozer) we have been able

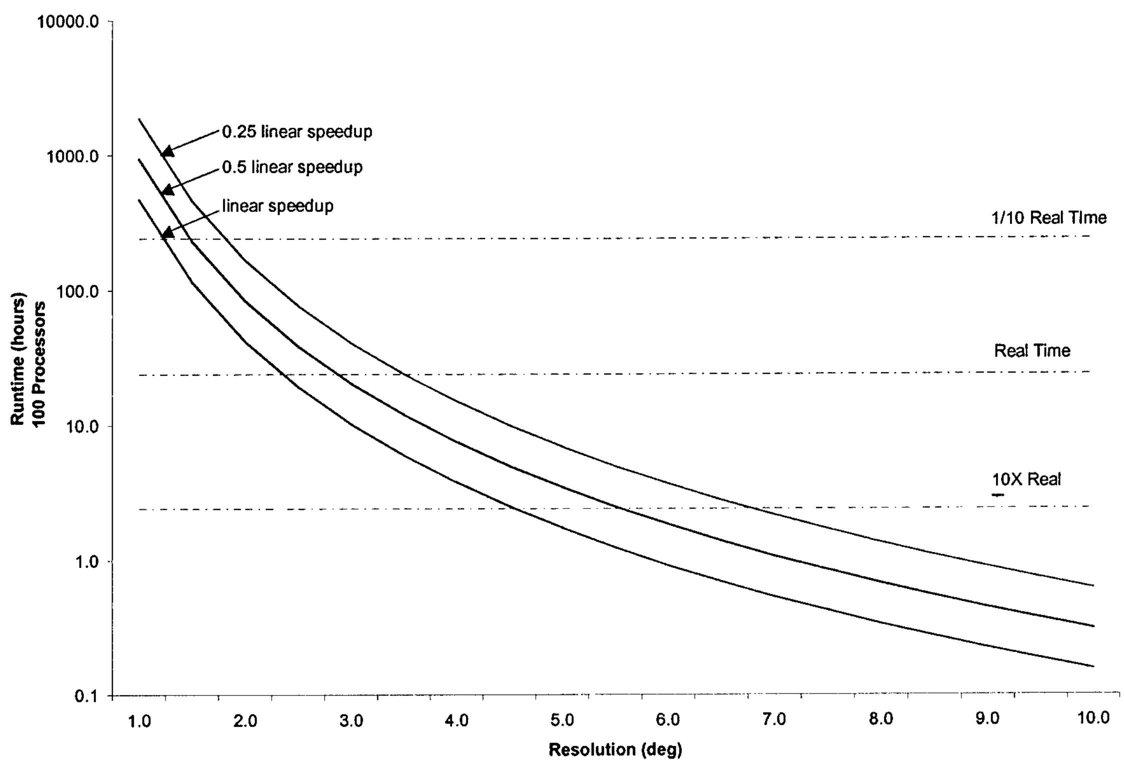


Fig. 8. Runtime estimates for 100 processors assuming linear speedup, and fractional linear speedup as a function of spatial resolution of the time-dependent tomography imagery. These estimates are based on runs using the scalar code on a 1.3GHz PC

to acquire considerable computer time (up to 900,000 hours) at the Maui High Performance Computer Center (MHPCC). In addition our contacts at the San Diego Supercomputer see our project as important in their multi-node processor analyses. Thus, we prepare a version of the time-dependent tomography program to operate on multi-node processors. Figure 8 (from our successful "grand-challenge" proposal) shows the approximate run-time estimates of the current time-dependent program for various spatial resolutions.

B. Solar Wind Real-Time Observation Improvements

In order to test the higher-level forecast programs for SMEI that will be used to forecast the arrival of corotating structures and CMEs at Earth, we have continued a real-time space weather program at UCSD. The Fortran programs that provide the tomographic result and the IDL images that are produced by these analyses to provide Web images operate without human intervention once the data arrive at UCSD. These programs are run and continuously updated using Redhat LINUX 'Cron. Jobs' operated on a PC. The real-time analysis provides a daily map of solar wind structures around Earth (Figures 6a-d). The results of this analysis at Earth are checked hourly by comparison with measurements available from the ACE spacecraft operated from the L1 LaGrange point between Sun and Earth. These programs, which provide a daily comparison of the tomographic programming, show just how well real-time forecasts using current data sets work, and they show the way SMEI will be able to help in these forecasts in the future. The results of these real-time analyses are on the Web at: **http://casswww.ucsd.edu/solar/forecast/index_v_n.html.**

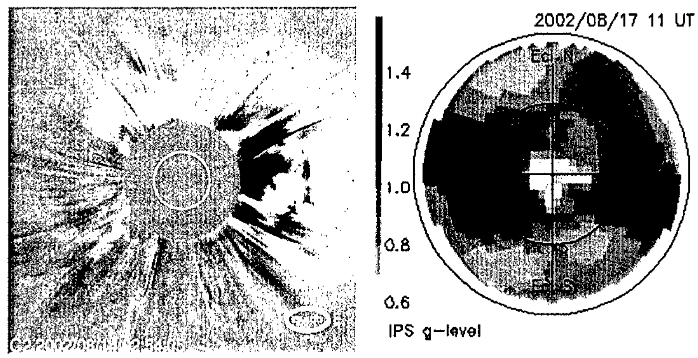


Fig. 9. Typical sky map comparison between LASCO C2 coronagraph and IPS model *g*-level 'fish-eye' observations. The IPS *g*-level observations that present a Sun-centered map to almost 90° elongation (outer circle) show the halo CME observed in LASCO August 14 when the outer edge of the material has reached 90° on August 17. The enhanced *g*-level feature to the left corresponds with a second fast halo CME observed by LASCO a day earlier (on August 16).

New in these displays is a real time time-dependent tomography section as extensive as the previous corotating tomography section. These time-dependent analyses are expected to have more problems than the corotating tomography when only a few radio sources are present to provide a stable solution. However, it has become apparent since mid-2002 that this Web site time-dependent tomography technique gives nearly one-to-one correspondence of *g*-level IPS images with bright CMEs observed a few days earlier in LASCO coronagraph observations. The time-dependent 'fish-eye' sky maps of velocity and density (Figure 9, right) are most like coronagraph views. They show a region of space outward from about 10° elongation. Not only do these images show CMEs but the additional information on the Web also maps their shape in three-dimensions and indicate whether or not they will impact Earth. As an example of this, Figure 10 shows a remote observer view (right) of the disturbance associated with a halo CME that was first observed on the Web in IPS analysis in real time late July 27. This was prior to an announcement by the coronagraph group (on July 29) that a halo CME had occurred in the LASCO data Figure 10 (left). Additional information and further observations including a video animation of the remote observer view, a synoptic map that more accurately locates this CME and a remote observer view of the velocity model can be found at the UCSD Web site. The major portion of the IPS disturbance caused by the halo CME passed south of Earth, but it may have been partly responsible for a magnetic storm on August 1-2.

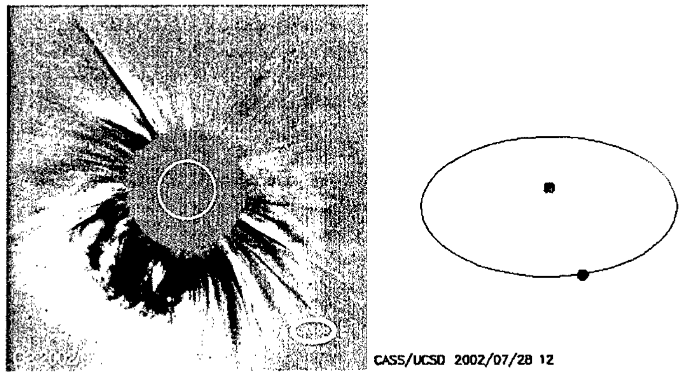


Fig. 10. Halo CME of 26 July 2002 observed in LASCO C2 observations compared with the IPS remote-observer view of the same CME observed nearly two days later as it was about to pass south of Earth.

C. Inclusion of the CSSS Magnetic Field Model into the Tomography

The most serious omission in all of these heliospheric analyses (with the exception of 3D-MHD modeling) is the magnetic field. Magnetic field is an illusive quantity with the best observations available on the solar surface from magnetograph observations, in-situ measurements from spacecraft (mostly near the Earth) and almost no observations in between to enable accurate extrapolations outward from the Sun. The best current real-time extrapolations of magnetic field that preserve its radial magnitude and direction use the CSSS model (Zhao and Hoeksema, 1995). Thus, over the last year (thanks to X. Zhao of Stanford University) we have built an interface using his 3D model so that it runs on our PCs to provide a real-time source surface magnetic field map at 15 Rs that can be used as input to the UCSD tomography (Dunn et al., 2003). The magnetogram observations that provide these extrapolations from ground-based observatories are nearly all sent or accessed via the Internet to be used by NOAA.

In 2002 we organized these analyses so that 1) they can be accessed in real-time from NOAA and 2) they all have the same format, or at least a format that can be used in the UCSD tomography and by other specific users of the data. To this end we have funded N. Arge of NOAA, Boulder (through a small NSF grant) to help in this effort. We intend to test each observatory's magnetic data analysis to determine which is best and most consistent. In 2003 we made available real time daily updates of these magnetic field results and presented them on our forecast website. Eventually we intend to combine observations from each location when there are outages at any one, and learn from the differences so that all ground-based observatories benefit. Our criteria of data quality for different observations will be placed on the Web in the form of correlation coefficients that match our extrapolations to spacecraft in situ measurements. In mid-2003 we began operation of an additional Web site in real time that allows these magnetic field forecasts. Figure 11 shows a recent version of this presentation of radial and tangential magnetic field components and their forecast correlations as given recently on our Web site at: **http://cassfos02.ucsd.edu/solar/forecast/index_br_bt.html**. Correlations of forecast radial and tangential components of the magnetic field can be extremely high as shown in the example.

Daily or even more frequent updates of the potential field model sometimes show magnetic field changes – *i.e.*, an opening of the magnetic field lines associated with some CMEs (Luhmann *et al.*, 1998). Because the CSSS model enforces a strict radial field at the outer source surface boundary, only the southward magnetic field component relative to Earth's geomagnetic field can be derived from this model when it is assumed to represent magnetic field statically. However, a given field line on the source surface can *change* location from one time period to another over a short time interval (*e.g.*, the rapid opening of the magnetic field found by Luhmann *et al.* (1998). In the heliosphere above the source surface this amounts to a non-radial component that must be

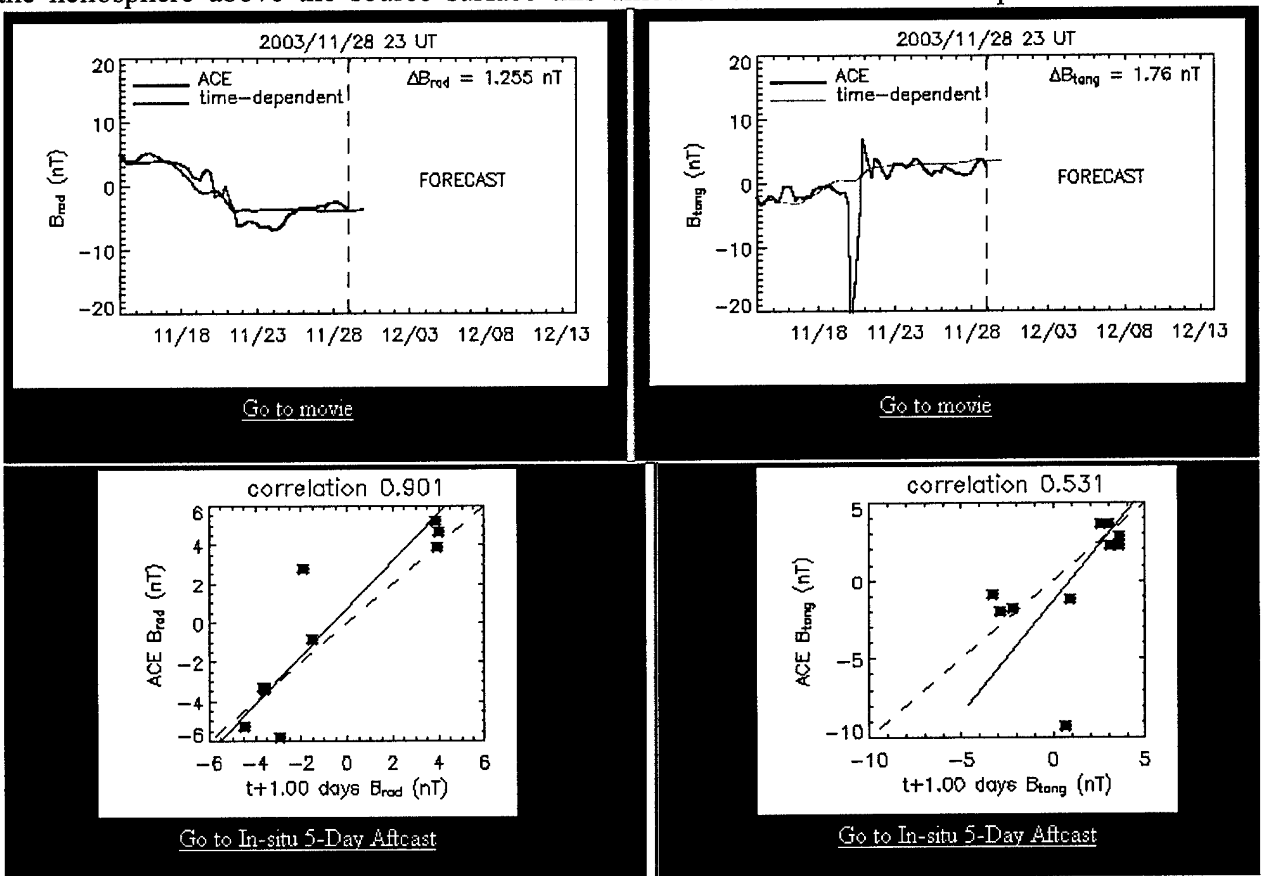


Fig. 11. Real-time radial and tangential magnetic field forecasts from the UCSD Web site using the time-dependent velocity tomography analysis as input to extrapolate solar surface magnetic field observations outward as described in the text. Correlations as good as these are typical using magnetic field data updated daily from NOAA. Because of magnetic field data latency, the time-dependent tomography allows at most only a few days forecast. The corotational tomography allows a far greater advance time forecast at a somewhat reduced correlation.

reckoned with. We now know how to include this non-radial term in our analysis and to check if the results give a better correlation with all three components of the observed *in situ* magnetic field. We expect that if the analysis by previous groups is correct, we will find a positive correlation for these comparisons that is especially meaningful for the Bz magnetic field component.

D. VolumePro Technology Transfer

TeraRecon, Inc. (**http://www.terarecon.com/products/vp_1000_1_prod.html**) has made available their prototype PC VolumePro 1000 computer board for use at UCSD. This PC hardware renders three-dimensional volumes into two-dimensional images by on-board summing at refresh speeds of up to 1/30th of a second. This hardware allows real-time manipulation of three-dimensional volumes of up to 512 pixels cubed while they are animated, and can provide perspective views of the volumes by launching non-parallel rays through the volume. This board has been put to use at UCSD to explore the three-dimensional heliospheric density, velocity and magnetic field structure and its morphology. To do this, the visualization group at the San Diego Supercomputer Center has built a C widget interface to the VolumePro board. Most utilization of this board and of the widget interface produced by the San Diego Supercomputer Center has been from the medical community who use the technology to enhance and manipulate three-dimensional data sets obtained by X-ray, MRI and ultrasound technology.

Most of the funding for the VolumePro technology transfer has come from highly leveraged work at the San Diego Supercomputer Center and a current NASA grant to UCSD. However, the three-dimensional data sets that have been showcased using these analyses by the San Diego Supercomputer are those produced for three-dimensional heliospheric real-time data analysis, and in fact beginning in the spring of 2003 we began making these volumes automatically available through our Web page. For these studies UCSD has optimized the PC board utilization and have made available these IDL programs to the solar and heliospheric community through SolarSoft and at our Web site: **http://casswww.ucsd.edu/solar/visualization/index.html**. This technology was recently acclaimed in an international presentation produced by Discovery Channel TV affiliates. Graduate student Cindy Wang, who works with our group, has recently modified widgets and other C^{++} access to this board so that they 1) include surface and line volumes (Earth, Sun and the Earth orbit) drawn using open GL technology, and 2) provide these presentations in stereo. In 2003 the widget and programming was modified to allow a perspective view of the volumes, a cursor probe of the volumes, and a summation of mass and volume within a highlighted area.

V. Recent Publications

The publications that have benefited from this grant or form the basis of research from it follow:

Research Articles:

Current research articles pertaining to the *present* grant include:

1. Jackson, B.V. and P. Hick, "Three Dimensional Tomography of Heliospheric Features Using Global Thomson Scattering Data", *Adv. in Space Res.*, **25**, No. 9, 1875, 2000. (4 pages). +

2. Buffington, A., "Improved Design for Stray-Light Reduction with a Hemispherical Imager", *Applied Optics*, 39, No. 16, 2683, 2000 (4 pages).

3. Killen, R.M., Potter, A.E., Reiff, P., Sarantos, M., Jackson, B.V., Hick, P. and Giles, B., "Evidence for Space Weather at Mercury", *J. Geophys. Res.***106**, No. E9, 20,509, 2001 (17 pages).

4. Jackson, B.V., Buffington, A. and Hick, P.P., "A heliospheric imager for Solar Orbiter", *Proceedings of Solar Encounter: The First Solar Orbiter Workshop, Puerto de la Cruz, Tenerife, Spain 14 –18 May, 2001*, (*ESA* **SP-493**, September 2001) 251, 2001 (4 pages). +

5. Hick, P.P, Jackson, B.V. and Buffington, A., "Space weather studies using low-frequency interplanetary scintillation observations", XXVIIth General Assembly of the International Union of Radio Science, Maastricht, Netherlands, August 17 – 24, 2002 (4 pages).

6. Jackson, B.V. and Hick, P.P., "Corotational tomography of heliospheric features using global Thomson scattering data", *Solar Phys*., **211**, 344, 2002 (12 pages). +

7. Jackson, B.V., Hick, P.P., Buffington, A., Kojima, M., Tokumaru, M., Fujiki, K., Ohmi, T. and Yamashita, M., 2002, Time-dependent tomography of heliospheric features using interplanetary scintillation (IPS) remote sensing observations, *Solar Wind X*, Pisa, Italy, 17-21 June, 2002, Velli, M., Bruno, R. and Malara, F., eds., *A.I.P.,* **679**, 2003, 75. (4 pages) +

8. Jackson, B.V., and Hick, P.P., "Three-dimensional tomography of interplanetary disturbances", in Space Weather Radiophysics, Gary, D.E., and Keller, Ch.O., eds, Kluwer ASSL volume, (in press) 2003 (32 pages). +

9. Jackson, B.V., Hick, P.P. and Buffington, A., 2002, Time-dependent tomography of heliospheric features using the three-dimensional reconstruction techniques developed for the Solar Mass Ejection Imager (SMEI), *Proc. SPIE, Waikoloa*, 22-28 August 2002, **4853**, 2003, 23 (8-pages). +

10. Buffington, A., Jackson, B.V., and Hick, P.P., 2002, Calculations for, and laboratory measurements of a multistage labyrinthine baffle for SMEI, *Proc. SPIE, Waikoloa*, 22-28 August 2002, **4853**, 2003, 490 (12 pages).

11. Dunn, T.J., Hick, P.P., Jackson, B.V. and Zhao, X., 2002, Inclusion of the CSSS magnetic field calculation into the UCSD tomographic solar wind model, *Proc. SPIE, Waikoloa*, 22-28 August 2002, **4853**, 2003, 504 (7 pages). +

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13. Jackson, B.V., Hick, P.P. and Buffington, A., Time-dependent tomography of heliospheric structures using IPS and Thomson scattering observations, *Proc ISCS Symposium*, 23-28 June, 2003, *ESA* SP-**535**, 2003, 823 (11 pages).

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Abstracts:

The *current* Air Force contract abstracts include:

1. Jackson, B.V. and P.P. Hick, "Time-Dependent Tomography Of Heliospheric Features Using Global Thomson-Scattering Data From the Helios Spacecraft Photometers"", presented at the SHINE 2000 Workshop, June 14-17, (2000) (1 page).

2. Hick, P.P., B.V. Jackson and A. Buffington, "Prediction of Solar Wind Conditions in the Inner Heliosphere Using IPS Tomography"", *BAAS*, **32**, 818, (2000) (1 page).

3. Jackson, B.V. and P.P. Hick, ``Time-Dependent Tomography Of Heliospheric Features Using Global Thomson-Scattering Data From the Helios Spacecraft Photometers", *BAAS*, **32**, 829, (2000) (1 page).

4. Space Weather write-up in UniSci (Daily University Science News) June 6, 2000.

5. Space Com News write-up and citation June 10, 2000 at:
http://www.space.com/scienceastronomy/solarsystem/solar_eruption_000612.html

6. Space Weather write-up in AScribe, the public interest newswire, June 14, 2000.

7. Jackson, B.V. and P.P. Hick, "Space Weather Using Remote Sensing Observations", to the NASA Applied Information Systems Research Program (AISRP) 2000 Workshop held in Boulder, Colorado 20-22 September, p. 1.2.3., 2000 (1 page).

8. Hick, P.P. and B.V. Jackson, "Visualization of Remotely-Sensed Heliospheric Plasmas", to the NASA Applied Information Systems Research Program (AISRP) 2000 Workshop held in Boulder, Colorado 20-22 September, p. 2.2.2., 2000 (1 page).

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12. Jackson, B.V., "CMEs in Three Dimensions – Techniques Used in Their Tomographic Analyses", *EOS*, **81**, F979, 2000 (1 page).

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18. Buffington, A., Jackson, B.V. and Hick, P.P., "Certifying Stray-Light Rejection and Photometric Performance for SMEI", *BAAS*, **32**, 1488, 2000 (1 page).

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23. Jackson, B.V., Hick, P.P. and Buffington, A., "Space Weather Using Remote Sensing Data", *Space Weather Working Group 3,* June, 13-15, 2001 (1 page).

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26. Webb, D.F., Tokumaru, M., Jackson, B.V., Hick, P.P., "Study of ICME Structure Using LASCO White Light and STE Lab IPS Observations of Halo CMEs", *EOS Trans. AGU*, **8? (2?)**, S???, 2001 (1 page).

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29. B.V. Jackson, P.P. Hick, A. Buffington, T. Dunn and S. Rappoport, "Space Weather Using Remote Sensing Data", at the SEC Space Weather Week, April 16-19, Boulder, Colorado 2002 (1 page).

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42. Dunn, T., Hick, P.P., and Jackson, B.V., "Comparative analyses of the CSSS magnetic field calculation in the University of California/San Diego tomographic solar wind model with in-situ spacecraft observations", the SPIE 48th Annual Meeting, San Diego, 3-8 August, 2003, 69 (1 page).

43. Hick, P., Wang, X., Jackson, B.V., and Bailey, M., "Visualization of remotely sensed heliospheric plasmas", the SPIE 48th Annual Meeting, San Diego, 3-8 August, 2003, 70 (1 page).

44. Buffington, A., Jackson, B.V., and Hick, P.P., "Space performance of the multistage laborinthine SMEI baffle", the SPIE 48th Annual Meeting, San Diego, 3-8 August, 2003, 70 (1 page).

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VI. UCSD Personnel Supported by this Contract

UCSD supported in part by this contract are listed below.

B. Jackson - Research Physicist

A. Buffington - Research Physicist

P. Hick – Associate Project Manager

Yokobe, T. Ohmi, T. Dunn, C. Wang – graduate students

S. Rappoport, K. Nguyen, P. Martinez, E. Khaleghi, A. Smith, A. Duncan – students

VII. Conclusions

Solar disturbances produce major effects in the corona, its extension into the interplanetary medium, and ultimately, the Earth's environment. The ability to forecast the arrival at Earth of these disturbances and to determine their effects on the geospace environment is of primary interest to the Air Force, which communicates through and maintains satellites within this environment. We have developed imaging and other techniques for use in mapping these disturbances (mainly coronal mass ejections or CMEs) as they move away from the Sun. This capability has begun to revolutionize the study of large-scale heliospheric space plasma interactions. The Solar Mass Ejection Imager (SMEI), now being developed and constructed, will have an angular and temporal resolution far better than the data sets (interplanetary scintillation and Thomson scattering observations from the HELIOS photometers) for which our imaging techniques were originally developed. SMEI will produce a thousand times as much data as previously available, exceeding our current data analysis capabilities. We are developing the algorithms for SMEI data analysis and model development. We intend to test these algorithms using data obtained from a ground-based prototype SMEI optical system. Furthermore, we are creating imaging and analysis tools adapted specifically for use with SMEI observations. An important requirement for the efficient analysis of SMEI observations will be the ability to trace solar plasma changes near Earth and elsewhere in the interplanetary medium in three dimensions, thereby enabling us to model and study the physics of heliospheric disturbances from a three-dimensional perspective. The development of adequate analysis and modeling techniques for SMEI data is a serious challenge, which must be addressed in order to maximize the scientific return from the SMEI mission, in particular with respect to our ability to accurately forecast the arrival of heliospheric disturbances at Earth.

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