The UCSD/SMEI Data Processing Pipeline

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Introduction

The Solar Mass Ejection Imager (SMEI)[1,2] measures the white-light response of the heliosphere over most of the sky in near real time. In the first three years of operation SMEI has recorded the inner heliospheric response to several hundred CMEs. We illustrate the main data reduction steps used to reduce the SMEI data from the raw CCD images to photometrically accurate maps of the sky brightness. This includes: integration of new data into the SMEI data base; conditioning to remove from the raw CCD images an electronic offset and dark current pattern; assembly of the CCD images in a high-resolution sidereal grid using known spacecraft pointing information. From the resulting skymaps we remove bright stars, sidereal unresolved background, zodiacal dust cloud, aurorae, and other unwanted signals. Time series extracted at locations away from bright stars are currently used in 3D tomographic reconstructions of the solar wind density structure. The data processing is distributed over multiple PCs running Linux using recurring batch jobs ('cronjobs'). The core routines are written in Python, Fortran, C++ and IDL.

The Solar Mass Ejection Imager (SMEI)

SMEI is a CCD camera system that observes the inner heliosphere from Earth orbit. SMEI was launched into an 840-km Sun-synchronous terminator orbit on January 6, 2003 on the Air Force Coriolis Mission, and is a joint project of UCSD, Boston College, the University of Birmingham (UK) and the Air Force Research Laboratory.

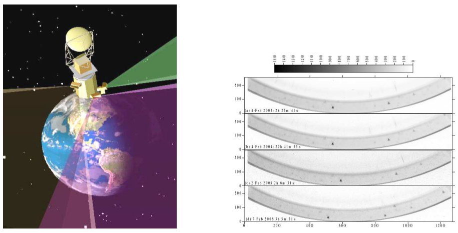

Figure 1: (left) Coriolis in its dawn-dusk terminator orbit. The fans indicate the fields of view of the three SMEI cameras. (right) 4-sec exposures from camera 3 of the same section of sky one year apart (2003-2006) after correction for pedestal and dark current. Stars appear as fish-shaped structures on the inner edge, and move across the 3° FOV in about a minute.

SMEI has 3 cameras with a FOV of $60°$x$3°$ aligned to image a strip of sky of $170°$x$3°$. Moving in a polar orbit, SMEI continuously takes 4-s exposures sweeping the sky each 102-minute orbit (Figure 1).

The primary objective of SMEI is to provide photometric measurements of the Thomson scattering intensity of scattered sunlight from electrons in the solar wind across the sky. This brightness relates directly to the solar wind density and provides a way to observe the heliospheric response to solar disturbances, such as CMEs. Thus, SMEI tracks CMEs across the observational gap between near-Sun coronagraphs and near-Earth in situ instruments.

Photometric Thomson scattering measurements are obtained after careful processing to remove instrumental contributions (pedestal offset, dark current); contaminations by cosmic rays and space debris, and other sources of white light (stars and galaxies, the zodiacal dust cloud, and aurorae). After removing these signals sky maps of the Thomson scattering brightness result to the original specifications and angular resolution of the SMEI design (requiring differential photometry of 0.1% for each square degree of sky).

Main Data Reduction Steps

Frames from one orbit (about 1500 for each camera) combine into one full-sky map (Figure 2) on an equatorial grid with an angular resolution of $0.2°$. Each sidereal location in the sky receives contributions from a sequence of subsequent frames taken as the FOV sweeps across, with each frame contributing a pixel covering $0.2°$ on the sky.

To maintain the required photometric precision point sources brighter than 6^{th} magnitude (stars and the brightest planets) are removed individually by a least-squares fit using the known PSF (Figure 3). As a spin-off product we obtain stellar time series for these stars with time resolution of 102 minutes.

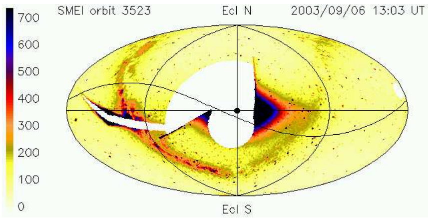

Figure 2: Sun-centered Hammer-Aitoff map of SMEI orbit 3523. The horizontal indicates the ecliptic. The equator is also shown. The eastern hemisphere is toward the left of the Sun.

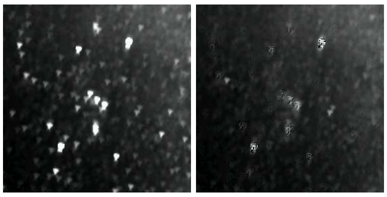

Figure 3: Subtraction of stars brighter than 6^{th} magnitude in the constellation of Orion.

The unresolved sidereal background (including the Milky Way) is removed by subtracting a background skymap build from SMEI observations themselves (Figure 4).

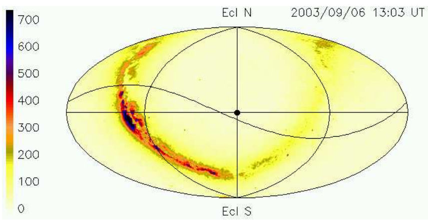

Figure 4: Sidereal background map constructed from SMEI data. This map is subtracted after stars brighter than 6^{th} magnitude have been removed individually.

Another diffuse signal observed by SMEI is zodiacal light (sun light reflected from the zodiacal dust cloud). This is modeled (Figure 5) from the SMEI data and is removed from the sky maps, leaving the heliospheric signal free from large changes in the background. The zodiacal dust model also provides a measure of the asymmetry of the dust cloud to the ecliptic plane, and the brightness of the Gegenschein.

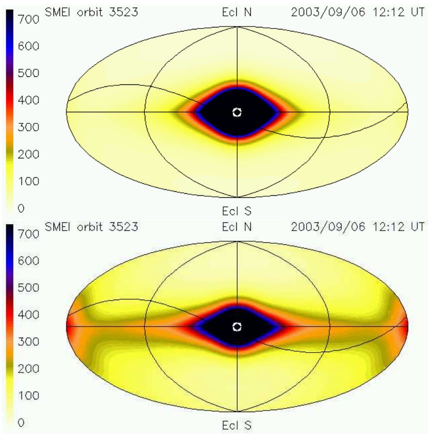

Figure 5: Model of the zodiacal dust cloud derived from the SMEI data. In the bottom map an elongation filter $(\epsilon/45°)^{1.2}$ has been applied to emphasize the zodiacal plane and Gegenschein.

3D Reconstruction of the Solar Wind

Heliospheric remote sensing observations provide one of very few ways for observing structures in the solar wind between the immediate solar environment (observed by coronagraphs), their arrival at 1 AU (observed by near-Earth in-situ instruments), and subsequent movement into the outer heliosphere (observed by deep-space satellites such as Ulysses). Remote sensing data probe the solar wind globally over a large range of solar elongations, extending over the solar poles, which are difficult to access by other means. In situ data provide detailed information about the solar wind plasma at a single location as a function of time. Remote sensing can provide a global view which allows a better understanding of the 3D context of in situ data.

At UCSD we have developed techniques for studying the 3D extent of the solar wind using remote sensing data. Applied to the Thomson scattering observations from SMEI, in combination with IPS velocity data (when available), these tomographic techniques allow us to study the characteristics and evolution of solar disturbances, such as CMEs, and provide the 3D density and radial outflow velocity of these structures as they move out into the heliosphere.

October 2003 halo CME at Earth and at Mars

The halo CME observed by SOHO/LASCO on November 28, 2003, and reaching Earth 2 days later, was also observed by SMEI. Figure 6 shows a reconstruction of the density in the halo CME derived from the SMEI data. The CME shows up as a loop-like structure extending in the north-south direction.

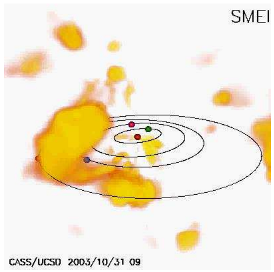

Figure 6: Volume rendering of the density distribution in the October 2003 halo CME on its way to Mars after it has passed Earth.

Figure 7 (left) shows a comparison of the time series of the density near Earth as observed by the ACE spacecraft in comparison with the SMEI reconstruction. At this time Mars is trailing Earth about 23 in ecliptic longitude. The SMEI reconstruction shows that the CME reaches Mars about 1.5 days after it passes Earth. For this period we obtained solar wind ram pressure data from the Mars Orbiter (Crider, private communication). Figure 7 (right) shows a time series of the Mars Orbiter data in comparison with the SMEI reconstruction. The Mars Orbiter data confirm that the CME indeed did hit Mars.

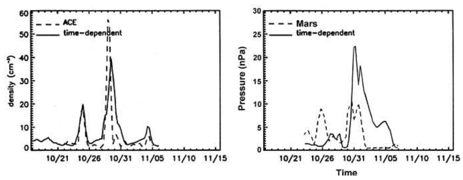

Figure 7: The October 2003 halo CME. (left) SMEI-derived density at Earth in comparison with ACE in situ data. (right) SMEI-derived ram pressure at Mars in comparison with in situ Mars Orbiter data.

References

[1] Eyles, C.J., G.M. Simnett, M.P. Cooke et al., "The Solar Mass Ejection Imager (SMEI)", Solar Phys. 217, 319, 2003.

[2] Jackson, B.V., A. Buffington, P.P. Hick et al., "The Solar Mass Ejection Imager (SMEI) Mission", Solar Phys. 225, 177, 2004.

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