AFRL-RV-HA-TR-2010-1025

Innovative Technologies to Model, Analyze and Monitor Space Effects on Air Force Space-Based Systems

Patricia Doherty
Thomas Kuchar
David Webb
Dale Levandier
Carl Henney
Ernest Holeman
Kevin Martin

Boston College
Institute for Scientific Research
140 Commonwealth Avenue
Chestnut Hill, MA 02467

Final Report

20 March 2010

AIR FORCE RESEARCH LABORATORY
AIR FORCE MATERIEL COMMAND
Space Vehicles Directorate
29 Randolph Rd.
Hanscom AFB, MA 01731-3010

AFRL- RV-HA-TR-2010-1025

This technical report has been reviewed and is approved for publication.

/ signed /

Alan D. Rebello
Contract Manager

/ signed /

Dwight T. Decker, Chief
Space Weather Center of Excellence

REPORT DOCUMENTATION PAGE [example]

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
03/20/2010	Scientific Report - Final	02-02-2006 to 01-31-2010

4. TITLE AND SUBTITLE
Innovative Techniques to Model, Analyze and Monitor Space Effects on Air Force Systems

5a. CONTRACT NUMBER
FA8718-06-C-0015

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
62601F

6. AUTHOR(S)
P. Doherty, T. Kuchar, D. Webb, D. Levandier, C. Henney, E. Holeman and K. Martin

5d. PROJECT NUMBER
5021

5e. TASK NUMBER
RS

5f. WORK UNIT NUMBER
A1

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Boston College
Institute for Scientific Research
140 Commonwealth Avenue
Chestnut Hill, MA 02467

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory
29 Randolph Rd.
Hanscom AFB, MA 01731-3010

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL/RVBX

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-RV-HA-TR-2010-1025

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for Public Release; Distribution Unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Our innovative research and analysis techniques have increased the knowledge of space effects on Air Force Systems. Our efforts have included numerous studies that address space effects on Air Force systems such as solar and Interplanetary (IP) disturbances and their coupling to geomagnetic storms; improving solar disturbance predictions; basic research in experimental chemical physics that impact space-based systems; DMSP database development and maintenance; DMSP sensor calibration; utilizing DMSP measurements for auroral research and the development of hemispheric power indices; and in developing the next-generation trapped electron and proton models for satellite design, AE-9 and AP-9. Finally, our efforts have included the upgrading of existing AFRL programs that are relevant to space weather studies and forecasting such as AF-GEOspace; support of the Air Force Space Weather Forecasting Laboratory (SWFL) and maintenance of relevant databases.

15. SUBJECT TERMS
Space Weather, Coronal Mass Ejection, Solar Mass Ejection Imager, Heliosphere

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Alan Rebello
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR	29	**19b. TELEPHONE NUMBER** *(include area code)*

Table of Contents

1. Introduction 1

2. Interplanetary (IP) Propagation of Solar Disturbances 1

    2.1. Solar Mass Ejection Imager (SMEI) Data Acquisition and Analysis 1

    2.2. SMEI Observations of Earthward-Directed CMEs and Space Weather 2

    2.3. SMEI Observations of CMEs in the Heliosphere 3

    2.4. Evolution Characteristics of CMEs 3

    2.5. Interplanetary Origin of Multiple-dip Geomagnetic Storms 3

    2.6. V Arc Interplanetary CMEs Observed by SMEI 4

    2.7. Evolution of Comets in the Heliosphere as Observed by SMEI 4

    2.8. Zodiacal Light Observations and Modeling 5

    2.9. Space Weather Forecasting Lab (SWFL) Support 5

    2.10. The Whole Heliosphere Interval (WHI) Campaign 6

    2.11. Next Generation Heliospheric Imager 7

3. Improving Solar Disturbance Predictions 7

4. AF-GEOSpace 8

    4.1. AF-GEOSpace Version 3 8

    4.2. Heliospace 9

5. Space Chemistry Research 9

    5.1. Space Weather Nanosensors 9

    5.2. Colloid Thrusters 10

    5.3. Hall Thrusters 10

    5.4. Extreme Environments 11

5.5. Other Work 11

6. DMSP Database Support and Research 11

6.1. Database Development and Management 12

6.2. Data Archive 14

6.3. DMSP SSJ4/SSJ5 Calibration 15

6.4. The Hardy Project 15

6.5 Hemispheric Power Index 15

7. Next Generation Trapped Electron and Proton Model 15

7.1. Coordinate Systems for Flux Mapping 16

7.2. Spectral Inversion 16

7.3. Angular Flux Distribution and Effects 17

References 20

Bibliography 22

1. INTRODUCTION

Under this contract, our innovative research and analysis techniques have increased the knowledge of space effects on Air Force Systems. Our efforts have included numerous studies that address space effects on Air Force systems such as solar and Interplanetary (IP) disturbances and their coupling to geomagnetic storms; improving solar disturbance predictions; basic research in experimental chemical physics that impact space-based systems; DMSP database development and maintenance; DMSP sensor calibration; utilizing DMSP measurements for auroral research and the development of hemispheric power indices; and in developing the next-generation trapped electron and proton models for satellite design, AE-9 and AP-9. Finally, our efforts have included the upgrading of existing AFRL programs that are relevant to space weather studies and forecasting such as AF-GEOspace; support of the Air Force Space Weather Forecasting Laboratory (SWFL) and maintenance of relevant databases.

Our research personnel have utilized their expertise to provide scientific and technical support in all programs of interest to space effects on Air Force Systems. This has resulted in numerous presentations at national and international conferences and 25 publications in peer reviewed scientific journals.

This report includes a summary of our major research efforts conducted under this contract. Each section includes the overall objectives and conclusions of each project.

2. INTERPLANETARY PROPAGATION (IP) OF SOLAR DISTURBANCES

The objective of this part of the contract is to understand the origins and interplanetary (IP) propagation of disturbances that affect the geosphere, and to develop, support and analyze the data from the Solar Mass Ejection Imager (SMEI) spacecraft experiment, designed to provide early warning and measurement of space hazards. The research studies involved collecting and analyzing satellite and ground-based data sets of pertinent solar, IP and geomagnetic phenomena to address topics that include: (1) The solar eruptive phenomena which lead to sporadic geomagnetic storms; (2) IP shocks and other signatures of solar ejecta; and (3) The characteristics of IP disturbances which produce geomagnetic storms. The most important goal of the studies is to utilize data sets related to solar ejecta and their IP manifestations to define the origins and propagation characteristics of geoeffective disturbances. The work also involves the support of the SMEI spacecraft experiment and analysis of the data returned. SMEI is a proof-of-principle experiment for providing an early warning of 1-3 days of the arrival at Earth of a coronal mass ejection (CME), and measurements of crucial geoeffective parameters of the CME. Finally, our efforts include support of AFRL's Space Weather Forecasting Lab (SWFL) and developmental design of the Next Generation Heliospheric Imager.

2.1. Solar Mass Ejection Imager (SMEI) Data Acquisition and Analysis

The Solar Mass Ejection Imager (SMEI) is an all sky heliospheric imager that was launched into a Sun-synchronous orbit in January 2003 by the U.S. Air Force. Its primary mission was to detect and track Coronal Mass Ejections (CMEs) en route to Earth and to design and test technology that would enable forecast capability for ensuing geomagnetic storms. During the course of this contract, BC researchers have produced processing and analysis software for the SMEI data. This included maintaining the processing pipeline, software support, monitoring SMEI images for CMEs, providing tracks and predictions of CMEs when available and contributing to original research of this most intense solar eruptive phenomenon and its effects on Earth-based systems. In addition, BC researchers have participate as SMEI team members by actively engaging in weekly telecons, attending team meetings, writing papers and delivering numerous presentations on SMEI analysis and research. During this time, SMEI also became part of the AFRL Space Weather Forecasting Lab (SWFL). SWFL is a collaboration of many disciples to evaluate and improve all aspects of space weather forecasting. SMEIs contributions are twofold: provide a mid-course correction for CME propagation models and give advance warning for potential geo-effective solar storms caused by CMEs. In addition to on-going support for the SMEI/SWFL mission, BC contributed to three major projects (two of which are on-going). These are described below.

2.2. SMEI Observations of Earthward-Directed CMEs and Space Weather

CMEs are a primary cause of severe space weather at Earth because they drive shocks and trigger geomagnetic storms that damage space and ground-based assets. The Solar Mass Ejection Imager (SMEI) experiment with the ability to track ICMEs in white light from near the Sun to Earth and beyond, thus providing an extended observational range for forecasting storms. SMEI has detected ICMEs at elongations of 20^o -30^o, or distances as far as 2/3 of the distance from the Earth to the Sun. Depending on the speed of the CME front, these distances correspond to advance-warning times of 10 hours to 2 days.

Our research has included several studies of SMEI's capability to detect and track geoeffective CMEs and, therefore, its capability as a forecasting tool. In one case, we separately examined the sources of moderate (peak $Dst < -60$nT) and intense (peak $Dst < -100$nT) geomagnetic storms during a 2-year interval. SMEI observed associated Earthward-directed CMEs for 85% (39 of 46) and 83% (10 of 12) of these storms, respectively. For the intense storms, the mean lags between the first SMEI observation of the CME and 1) Earth arrival of the associated shock and 2) onset of the storm were 18.6 and 29.25 hours, respectively. In another study, we used distance-time plots of LASCO halo CMEs that were associated both with SMEI transients and ACE shocks at 1 AU to compare the predicted and actual arrival times. The mean range between these values was 10.6 hours, representing an approximate 30% improvement in the accuracy of predicting CME arrival times compared to published results using LASCO data only. Our main conclusion was that SMEI could detect the CMEs causing most major geomagnetic storms. In addition, we have concluded that a SMEI-type instrument could provide improved early warning of storms.

2.3. SMEI Observations of CMEs in the Heliosphere

BC college researchers participated in an effort to statistically summarize CMEs observed by SMEI. These statistics were based on the white light images of nearly the full sky every 102 minutes for three years beginning with the first SMEI images in 2003. The statistical results of the analysis of the SMEI observations of coronal mass ejections (CMEs) traveling through the inner heliosphere showed 139 CMEs observed during the first 1.5 years of operations. At least 30 of these CMEs were observed during by SMEI to propagate out to 1 Astronomical Unit (AU) and beyond and were associated with major geomagnetic storms at Earth. Most of these were observed as frontside halo events by the SOHO LASCO coronagraphs. The results of these statistics were reported in *Webb, et al. 2006.*

2.4. Evolution Characteristics of CMEs

We have investigated the geometric and kinematic characteristics of interplanetary coronal mass ejections (ICMEs) using data obtained by the Large Angle Spectroscopic Coronograph (LASCO), the Solar Mass Ejection Imager (SMEI), and the SECCHI Heliospheric Imaging (HI) experiments on each of the STEREO spacecraft. The early evolution of CMEs can be tracked by the LASCO C2 and C3 and SECCHI COR1 and COR2 coronagraphs, and the HI and SMEI instruments can track their ICME counterparts through the inner heliosphere. The HI fields of view (4 – 90°) overlap with the SMEI field of view (> 20° to all sky) and, thus, both instrument sets can observe the same ICME. In this research, we focused on ICMEs observed on 24 – 29 January 2007, when the STEREO spacecraft were still near Earth so that both the SMEI and STEREO views of large ICMEs in the inner heliosphere coincided. These results included measurements of the structural and kinematic evolution of two ICMEs and comparisons with drive/drag kinematics, 3D tomographic reconstruction, the HAFv2 kinematic, and the ENLIL MHD models. We found encouraging that the four model runs generally were in agreement on both the kinematic evolution and appearance of the events. Results of these efforts have been presented in several meetings including the American Geophysical Union and Space Weather Workshop meetings in 2007 and 2008.

2.5. Interplanetary Origin of Multiple-dip Geomagnetic Storms

In this research, we contributed to research that systematically investigated the interplanetary drivers of major dips during intense ($Dst \leq -100$ nT) geomagnetic storms in 1996–2006. A major dip is defined as a temporary decrease in Dst index with amplitude larger that 14.5 nT. Our initial investigation identified that 90 intense storms occurred during this period. Multiple dips result in a storm if regions of geoeffective solar wind with strong southward magnetic fields are separated by less geoeffective solar wind. Among these 90 intense storms, we found that only 34% (31 events) showed a classical “one-dip” profile, while 49% (44 events) had two dips. Another 17% (15 events) had triple or more dips. We found that of a total of 165 major dips associated with the 90 storms, about 45% (74 dips) were caused by interplanetary coronal mass ejections (ICMEs), or ejecta, and 30% (49 dips) were caused by sheaths (SHs) that lie between shocks driven by ICMEs and leading edges of the ICMEs. About 7% (11 dips) were caused by a shock driven by an ICME running into a preceding ICME and intensifying its magnetic field. About 11% (18 dips) were due to corotating interaction regions (CIRs) formed by the interaction of high-speed solar wind from coronal holes with the preceding slower solar wind. Another 7% (12 dips) were caused by various solar wind structures prior the onset of the storm. Among these different types of drivers, the largest storms dips on average were produced by shocks propagating through preceding ICMEs. One frequent cause of a two-dip storm is that the first dip is produced by the upstream sheath and the second dip is produced by the driving ICME. Another common cause of a two-dip or multiple-dip storm is the presence of multiple subregions of southward magnetic field within a complex solar wind flow, resulting from two successive, closely spaced ICMEs.

2.6. V Arc Interplanetary CMEs Observed with SMEI

In this study, BC researchers contributed to research that included SMEI observations of interplanetary coronal mass ejections (ICMEs) at solar elongation angles near 20°. The ICMEs generally appeared as loops or arcs in the sky, but five showed distinct outward concave shapes called V arcs. Our observations showed some V arcs, formed by trailing edges of ICME flux ropes or by leading ICME edges sheared by solar wind (SW) speed gradients at the heliospheric current sheet. We characterized the properties of these V arcs and compared them with average properties of all SMEI ICMEs. The typical V arc speeds argue against a slow MHD shock interpretation for their structures. We estimated the V arc solar source locations and their opening angle dynamics as tests for SW shearing. The first test contradicted but the second supported the SW shearing explanation. Our studies further considered the implications of the small number of V arcs observed with SMEI. These results together with the point P approximation used to determine the V arc locations and inferred solar source regions is reported in *Kahler and Webb (2007).*

2.7. Evolution of Comets in the Heliosphere as Observed by SMEI

Comet observations have been used as in situ probes of the heliospheric environment since they were used to confirm the existence of the solar wind. Changes in a comet tail's appearance are attributed to changes in the solar wind flow. Large scale tail disruptions are usually associated with boundary crossings of the current sheet or, more rarely, impacts from coronal mass ejections. The Solar Mass Ejection Imager (SMEI) observed three bright comets during April-May 2004: Bradfield (C/2004 F4), LINEAR (C/2002 T7), and NEAT (C/2001 Q4). Investigation of the entire period further reveals that these two comets showed continual changes in their plasma tails. These changes are characterized by a "smokestack-like" billowing effect punctuated by the disconnections. Bradfield however was remarkably quiescent during this entire period. Work performed by BC researchers illustrates these observations and provided analysis for the cause and of the similarities and disparities of these data. Our efforts included the development of a more robust background removal algorithm that not only aided the comet analysis but also other investigations of SMEI-observed CMEs. This research resulted in two publications and a presentation at the 2007 American Geophysical Union Fall Meeting.

2.8. Zodiacal Light Observations and Modeling

One of the backgrounds removed from SMEI imagery is the scattered zodiacal light from solar system dust. The zodiacal light has been characterized by space based instruments but primarily in the infrared. Visible measurements are routinely ground-based and thus suffer from those observation limitations. SMEI is the only space-based instrument that has been able to routinely observe the zodiacal light in the visible. It has also observed the annual variations for many years and thus represents a unique data set for analysis. One of the first results from this analysis was the enhanced backscatter of light from the anti-solar position known as the "gegenschein" that has not been previously observed. The analysis of five years of SMEI gegenschein observations was published. Analysis of the full 7 years of SMEI zodiacal data has been under analysis and will be the subject of a forth coming paper. The paper will include the geometric characteristics (dust scattering properties, scattering function, cloud size and extent, inclination, etc) of the dust cloud and an analysis of the residual, narrow dust bands seen after the bulk of dust cloud has been modeled.

2.9. Space Weather Forecast Lab (SWFL) Support

Part of the mission of SWFL (of which SMEI is a part) is to support the Air Force Weather Agency (AFWA) forecasting requirement. The SMEI data was imported to AFWA for forecasting purposes as well for use in validating their space weather forecasting models. To facilitate AFWA in this, BC researchers were tasked into creating point-and-click measurement software with a graphical interface for AFWA to use with the SMEI data. BC has since provided two software updates after feedback from the end users. BC has also provided training for the forecasters and continues to support updates as needed.

Observations of coronal mass ejections (CMEs) from heliospheric imagers such as the Solar Mass Ejection Imager (SMEI) can lead to significant improvements in operational space weather forecasting. We have worked with the Air Force Weather Agency (AFWA) to ingest SMEI all-sky imagery with appropriate tools to help forecasters improve their operational space weather forecasts. We describe two approaches: 1) Near-real time analysis of propagating CMEs from SMEI images alone combined with near-Sun observations of CME onsets and, 2) Using these calculations of speed as a mid-course correction to the HAFv2 solar wind model forecasts. HAFv2 became operational at AFWA in late 2006. The objective is to determine a set of practical procedures that the duty forecaster can use to update or correct a solar wind forecast using heliospheric imager data.

SMEI observations can be used inclusively to make storm forecasts, as recently discussed in Webb et al. (Space Weather, in press, 2008). We have developed a point-and-click analysis tool for use with SMEI images and are working with AFWA to ensure that timely SMEI images are available for analyses. When a frontside solar eruption occurs, especially if within ~45° of Sun center, a forecaster checks for an associated CME observed by a coronagraph within an appropriate time window. If found, especially if the

CME is a halo type, the forecaster checks SMEI observations about a day later, depending on the apparent initial CME speed, for possibly associated CMEs. If one is found, then the leading edge is measured over several successive frames and an elongation- time plot constructed. A minimum of three data points, i.e., over 3-4 orbits or ~6 hours, are necessary for such a plot. Using the solar source location and onset time of the CME from, e.g., SOHO observations, and assuming radial propagation, a distance-time relation is calculated and extrapolated to the 1 AU distance. As shown by Webb et al., the storm onset time is then expected to be ~3 hours after this 1 AU arrival time (AT). The prediction program is updated as more SMEI data become available.

Currently when an appropriate solar event occurs, AFWA routinely runs the HAFv2 model to make a forecast of the shock and ejecta arrival times at Earth. SMEI data can be used to improve this prediction. The HAFv2 model can produce synthetic sky maps of predicted CME brightness for comparison with SMEI images. The forecaster uses SMEI imagery to observe and track the CME. The forecaster then measures the CME location and speed using the SMEI imagery and the HAFv2 synthetic sky maps. After comparing the SMEI and HAFv2 results, the forecaster can adjust a key input to HAFv2, such as the initial speed of the disturbance at the Sun or the mid-course speed. The forecaster then iteratively runs HAFv2 until the observed and forecast sky maps match. The final HAFv2 solution becomes the new forecast. When the CME/shock arrives at (or does not reach) Earth, the forecaster verifies the forecast and updates the forecast skill statistics.

In our most recent efforts, a more automated version of this procedure was developed and implemented at AFWA.

2.10. The Whole Heliosphere Interval (WHI) Campaign

BC researchers have actively participated in the Whole Heliosphere Interval campaign, an international coordinated observing and modeling campaign to characterize the 3-D interconnected solar-heliospheric-planetary system near solar minimum. The heart of the WHI campaign is the study of the interconnected global 3-D heliophysical domain, from the interior of the Sun, to the Earth, outer planets, and into interstellar space. The WHI observing campaign focused on the 3-D solar structure from solar Carrington Rotation 2068, which ran from March 20 – April 16, 2008.

WHI occurred during this extended solar minimum, which optimizes our ability to characterize the 3-D heliosphere and trace the structure to the outer limits of the heliosphere. Highlights include the 3-D reconstruction of the solar wind and complex geospace response during this solar minimum, contrasts with the past solar minimum, and the effect of transient activity on the "quiet" heliosphere.

Nearly 200 scientists are participating in WHI data and modeling efforts, ensuring that the WHI integrated observations and models will give us a "new view" of the heliophysical system. A summary of some of the key results from the WHI, were presented at the SOHO 23 workshop held in 2009.

Our efforts for this campaign included using observations of the inner heliosphere from the SMEI image since its launch in early 2003 to measure and map the outward flow of CMEs observed during solar minimum. In this research, we report on observatsion and 3D reconstructions of corotating heliospheric structures and CMEs observed by SMEI during the current solar minimum. In these observations and 3D-reconstructions, these is little evidence of density structures that co-rotate over the long-term (for durations of several weeks). We compare the SMEI evidence we have of corotating density structures with 3D-reconstructions of interplanetary scintillation (IPS) velocity observations from the Solar-Terrestrial Environment Laboratory (STELab), Nagoya University, Japan. From these analyses we extracted both solar wind density and velocity to compare with "ground truth" multi-point, in-situ solar wind measurements from the SOHO, Wind, ACE, and the STEREO spacecraft. If we define corotating heliospheric structures by in-situ measurements or by the 3D velocity analyses, the dense structures preceding and following these regions generally appear discontinuous in radial extent from near the Sun out to 1 AU.

2.11. Next Generation Heliospheric Imager

Boston College researchers have actively participated in discussions relative to the development of the Next Generation Heliospheric Imager. These discussions have resulted in a position paper that was used for AFRL briefing purposes and for advocating a Next Generation Heliospheric Imager. Next Generation Imager discussions were continuing at the completion of this contract.

3. IMPROVING SOLAR DISTURBANCE PREDICTIONS

This area of work addresses improving the Air Force's ability to predict geo-effective events driven by solar disturbances. Understanding the current and future conditions of the space environment near the Earth's magnetosphere is of great interest for predicting severe geomagnetic events. This ability requires continuous measurements, or at least reasonable estimates, of the interplanetary magnetic field (IMF) within the heliosphere. The heliospheric magnetic field is driven by dynamical processes on the solar surface that can be recorded with high-resolution images from ground based instruments like the Air Force's Improved Solar Observing Optical Network (ISOON). In addition, a reliable estimate of the global IMF, derived from line-of-sight solar magnetograms, is needed to forecast variations in the solar wind speed. In support of these requirements, the following was addressed by BC research personnel:

- In Mid 2009, a new project was initiated to incorporate GONG magnetograms and future GONG H-alpha data into the current ISOON data processing pipeline to create new products for AFWA. BC research personnel have provided full science & technical supervision for this task.

- BC researchers visited the ISOON instrument and staff at Sacramento Peak, NM in December 2009 to help improve the current ISOON magnetograms and flats. Our researchers outlined different filter-gram (spectral) sequences for ISOON to minimize Doppler signal (and increase cadence w/ fewer filter-grams), plus take LCP & RCP consecutively and move back & forth across spectral line wings. Also, a local version of the Kuhn-Lin-Toussaint flat fielding code was built for use at Kirtland AFB. Personnel also modified the source code to utilize the ISOON image data. However, a residual limb signal remains in the flat along with a large scale gradient. The limb signal is expected to be minimized by including intensity weighting, whereas the large scale gradient can be minimized with increased image offsets.

- Bundled and documented various ISOON IDL functions, in response to a request by Jack Harvey at NSO, to help GONG produce H-alpha data similar to what is currently processed by the ISOON flare detection pipeline. The functions ranged from data compression and image quality analysis to FITS header keywords and solar ephemeris functions.

- Modified and upgraded the Worden-Harvey (WH) solar magnetic flux transport model to incorporate the ensemble Kalman filter code develop by Josef Koller of Los Alamos National Laboratory (LANL). These efforts included modifications to the WH flux transport code to process data from two additional solar magnetograms sources along with the current data source. BC researchers also created a function to produce flux transport movies of various output parameter frames for temporal feedback while analyzing run-time code development.

4. AF-GEOSPACE

AF-GEOSpace is a user-friendly, graphics-intensive software program that combines a suite of space environment specification models with a windows-driven interface that allows users to visualize data from well-established models in one, two and three dimensions. Its prime purpose is to serve as a platform for scientific model validations, environment specification for spacecraft design, mission planning, frequency and antenna management for radar and HF communications, and post-event anomaly resolution.

During the course of this contract, Boston College researchers performed significant enhancements for AF-GEOSpace. These enhancements resulted in improved performance, graphics and accuracy of the program outputs. Several versions of the program were released. This included versions through 2.5. The final version 3.0 is considered the latest product and is still in development at the end of this contract. This version includes new models and a new framework.

Each new release of the program included two types of distributions for both the PC (Windows) version and the LINUX version. One distribution was developed for public release and the other was developed for U.S. Department of Defense government and contractors only (Distribution D).

AF-GEOSpace is a very successful product for AFRL. The AF-GEOSpace team, including BC researcher Mr. Timothy Hall, received the 3rd Quarter Technology Transfer Achievement Team Award in 2006.

4.1. AF-GEOSpace V3

At the beginning of the second year of this contract, BC researchers initiated enhancements for the interactive capability of AF-GEOSpace Version 3. This version provided a new framework that allows users to develop and install “plug-ins” allowing a more variable product that could be updated for a variety of applications. This effort required the development of a new GUI library that uses OpenGL for its rendering. Much effort was devoted to improving basic functionality with the addition of windows based menus, buttons and sliders that are common to most GUI based applications. Version 3 of AF-GEOSpace also enables users to create interfaces to their plug-in modules. Additional programming support was also applied for new widgets and additional functionality.

4.2. Heliospace

The Heliospace software package is a unique scientific tool that provides enhanced graphical and data visualization of 3-Dimensional (3D), time varying systems. The software was developed as a fundamental graphics module for the Air Force (AF)-GEOSpace space environment program.

The Heliospace package is unique in that it generates 3D block adaptive grids for both Cartesian and spherical datasets. In addition, field lines can be generated from vector data and then rendered into 3D grid space. Graphical options include coordinate slices, grid points, isosurfaces and domains. Once rendered the graphics may then be manipulated by rotating, translating and zooming in and out. Multiple viewports can be created to give different views of a single object or to view multiple data sets simultaneously. In addition, time dependent data sets can be viewed in animation.

The Heliospace package has been delivered to the NASA Space Weather Modeling Community. This included development, delivery and transition support of the Heliospace package. In addition, software updates were made as enhancements are implemented and deemed operational.

At the completion of this contract, Heliospace had been developed for the PC (Windows), LINUX and OSX (Max) platforms.

5. SPACE CHEMISTRY RESEARCH

This section describes work performed by BC in its involvement with the Space Chemistry Laboratory of the Space Weather Center of Excellence at AFRL. This work involves basic research in experimental chemical physics that impacts the Air Force’s efforts to develop, incorporate and operate new technologies in space-based systems. The pertinent areas of work involve efforts towards the development of a novel space weather sensor, integration of new thruster technologies for small/miniature spacecraft, and fundamental research on chemistry in the extreme environment in which spacecraft operate, with particular interest in Space Situational Awareness (SSA). The work described below was conducted by BC personnel at the AFRL Space Chemistry Lab facilities, except where noted otherwise.

5.1. Space Weather Nanosensors

This project involved the study of nano-scale self-assembled monolayers (SAMs) as a prospective charge conversion surface for detecting low-energy neutral atoms (LENA) in space weather applications. Detection of LENA, at energies less than 1000 eV, requires ionization of the atoms which is typically carried out at a charge conversion surface. The purpose of this project was to investigate nanomaterials as potentially more efficient conversion surfaces, to allow the development of smaller sensors for deployment on miniaturized satellites. The project involved modifying an existing ion beam instrument into a fast oxygen atom beam facility for studying charge conversion on silane-based SAMs on silicon substrates. The initial results of the project showed that a SAM such as *n*-octadecyltriethoxysilane on silicon yielded higher charge conversion efficiency than polished tungsten, which is the material of choice in recent instruments such as the LENA detector on IMAGE. The project included the investigation of modifying the electronic properties of the SAM by changing the end group of the SAM precursor, specifically replacing the terminal CH_3 group with NH_2 or Br. The initial results of this work, including a description of the instrument, are currently being prepared for publication (Levandier et al., in preparation a). This project was conducted primarily by BC personnel.

5.2. Colloid Thrusters

The colloid thruster is an electric thruster that is a good candidate for future, high efficiency micro- and nano-thruster applications, particularly where precision positioning and station keeping is required. A good example of such a requirement is the upcoming LISA (laser interferometer space antenna) mission, which involves 3 spacecraft arranged in a triangle of 5 million km sides, with required positioning accuracy of less than a micron. The Space Chemistry Lab has been involved in investigating the underlying physics of the vacuum electrospray process that comprises the colloid thruster. This process involves the emission of ions and charged droplets under the influence of a strong electric field acting on the surface of a conducting fluid at the tip of an “emitter”. The project included early studies on fuels involving solutions of salts in organic solvents (Luedtke et al. 2008; Chiu et al. 2005) and progressed to the use of the new class of compounds known as ionic liquids (Chiu et al. 2007; Chiu et al. 2005). Also, the project has examined the use as emitters of fine capillaries, necessary with the salt solutions, and of fine, externally-wetted wires and ribbons, possible with ionic liquids. The Space Chemistry Lab experiments involved measuring mass spectra and kinetic energy of emitted thruster ions as a function of angle from the thruster centerline. The angle-resolved results are also pertinent to spacecraft integration issues, in which avoiding contamination of surfaces by the thruster are considered. BC involvement in this project resided largely in designing and building the test thruster assembly and experimental set-up.

5.3. Hall Thrusters

The Hall thruster is an electric thruster technology, currently in use, that involves the acceleration of ions formed by ionizing xenon fuel with magnetically confined electrons. The Space Chemistry Lab has conducted guided-ion beam experiments to study the interactions of the ions produced in the thruster with the immediate spacecraft environment. The experiments involve measuring absolute cross sections and product angular distributions for collisions/reactions of Xe^+ and Xe^{2+} with Xe and with ammonia. The Xe collision results (Chiu et al., 2008) were incorporated in spacecraft plume modeling codes to aid in understanding the issue of erosion of spacecraft surfaces in relation to Hall thruster use. The ammonia experiments (Levandier et al. in preparation b) were carried out to support the upcoming FalconSAT5 mission, in which a Hall thruster will be operated during the release of ammonia from the spacecraft. BC personnel conducted the ammonia study in its entirety, and were involved in data acquisition in the Xe collision study.

5.4. Extreme Environment

This section largely relates to fundamental research supporting the understanding spacecraft interactions with the environment in which they operate. The oxygen cation is the main ion species in low Earth orbit and its interactions with gasses emanating from spacecraft (for example by desorption or in engine plumes) can result in light emission that are pertinent to SSA considerations. This was the purpose of the study of O^+ reactions with ammonia (Levandier et al. 2008) which involved determining absolute reaction cross sections using the Space Chemistry Lab guided-ion beam facility. This study was done entirely by BC personnel. The studies of H_2^+ and HD^+ reactions (Tang et al. 2007; Tang et al. 2005) were carried out in collaboration with Prof. Cheuk Ng, currently of UCDavis, at the Berkeley National Lab Advanced Light Source (ALS). This work involved developing new methods for studying in greater detail the ion – molecule processes in the spacecraft environment. The H_2^+ and HD^+ studies are important for the fundamental understanding of ion – molecule processes and were conducted to demonstrate the capabilities of the "pulsed-field ionization photoelectron secondary ion coincidence" methodology resulting from this project and intended for use in future AFRL studies. BC personnel were involved in the design of the instrument modifications at the ALS, and in overseeing and participating in the experiments.

5.5. Other Work

In addition to work on the projects described above, BC personnel were involved in the day to day operation and maintenance of the Space Chemistry Lab. During the time covered by this contract, this included the substantial effort required to bring the Space Chemistry Lab into compliance with the newly applied regulations governing laboratory operations in time for an AF Unit Compliance Inspection.

6. DMSP DATABASE SUPPORT AND RESEARCH

BC researchers and technical programming personnel have assumed responsibility for acquisition, processing, analysis and maintenance of all DMSP J data from 1983 through the present. The data begins with F6 data and continuous through the currently active DMSP satellites (F13, F16 and F17).

The DMSP SSJ4/SSJ5 are charged particle analyzers, manufactured by Amptek, Inc. They use an electrostatic deflection system to sort and analyze ions and electrons encountered in low earth orbit polar flight paths. This instrument is a key component of the Air Force Space Weather (AFWA) program and BC is responsible for the ground calibration and in-flight calibration of each instrument to assure its data is appropriately interpreted as accurately as possible at all times. The SSJ data has been the basis of many scientific studies of auroral particles over the years, all directly or indirectly related to Space Weather.

In this section, we summarize DMSP research and database management performed by BC personnel.

6.1. Database Development and Management

BC maintains a complete archive of all DMSP J data from 1983 through the present, beginning with F6 data and continuous through the currently active DMSP satellites (F13, F16 and F17). This archive is maintained with redundancy on the AFRL Unitree file system with a third and fourth copy on CD. This archive is made available to all AFRL personnel. In addition, several levels of processed summary data files are maintained along with viewing software in support of various AFRL projects. BC personnel use the archive, processed files and software tools to monitor the status of J instruments on currently active DMSP satellites.

The archive process is mostly automated, but requires manual processing whenever network problems interrupt the automation string, which occurs on most weekends and occasionally on weekdays. In addition, log files need random checks to detect the onset of problems, the CD archive is done manually, the processing software requires occasional maintenance, and viewing software is updated as required.

The broad objectives of this task are to continue a Time History Data Base development for the current and future DMSP vehicles and maintain the databases for previously flown vehicles.

Currently, data is being received for DMSP vehicles F13, F15, F16 and F17. Over the lifetime of this contract, it is expected that other vehicles will also be launched. The tasks inherent in database development are described below.

The Air Force Weather Agency Satellite Processing Work Center, Offutt AFB, Nebraska, has redesigned the DMSP mission sensor satellite data files, known as prepfiles, into Raw Sensor Data Record (RSDR) files. This format replaces the 36-bit processed file, containing sensor and file structure specific information, with a standard 32-bit format containing only sensor specific information.

Each RSDR file contains one payload readout of sensor data. Instead of receiving twelve hours of data, a bundled readout is received soon after it is processed. Calculated ephemeris data, time codes, and on-board ephemeris are provided for each second of data rather than for each minute. This time and ephemeris information will be identical for specific DMSP flights. Each 36-bit sensor data word is divided into three, 12-bit words and stored right justified in a 16-bit word. However, the RSDR file does not contain the year and day associated with the sensor data. The year and day must be calculated by the use of a set of subroutines that assume that a given time and its associated ephemeris are accurate and that the day given is the day of data or a day within the past three or four days. Each RSDR file will have a name to uniquely identify the data set. The file name will contain the satellite designation, playback revolution number, the year, day, hour, and minute that the RSDR was created, and the sensor identification.

The new Phase 1 time history database formats contain only 16-bit or 32-bit integer data and 8-bit ASCII characters. Each 9-bit data sensor value is stored right justified in a 16-bit word. Each block of data contains one minute of data.

A detailed presentation of the development plan for this project follows.

DMSP data, stored in RSDR format, is transformed into time-ordered databases on a UNIX workstation. Raw data sets for the SSJ, SSIES, and SSM are acquired, copied, and archived.

- Input data is copied by using Secure File Transfer Protocol (SFTP) between the computer at Offutt AFB and the Amber, a SUN Microsystems UNIX computer. To automate this procedure a script is executed at designated times during the day to acquire these files. For each experiment, for each vehicle, a multi-day period is stored on UniTree on a daily basis and is also backed up on DVD on a monthly basis.

- Computer modules, written in FORTRAN, with the input data in RSDR format, were carefully developed to generate SSJ, SSIES, and SSM time-ordered databases. Data values are stored in raw counts for each second; ephemeris values are stored at each even minute. A common software package that computes geomagnetic parameters is used for each experiment. A subroutine was written to unpack the three, 12-bit "data" words and convert them to four, 9-bit sensor words. Since any one revolution will neither start nor end exactly at the start or end of a day, care must be taken to ensure that the set of files used as input for one day overlap into the preceding and succeeding days.

- To facilitate the creation of a database, script files were written for each experiment that generate a procedure that process multiple days of data that consist of multiple input files. As the script procedure is executed a log file is created that contains processing times and error indications. Directories for each experiment are created. A listing of any directory contains the name, size, and date created of each individual file processed. If the file size for a day of data is not what is expected for a particular experiment, it will be verified that the input data is unavailable or the error will be found and the day processed again. The database for each day is stored on the UniTree. Copies of the SSJ database files are sent on a daily basis via FTP to Three outside agencies. Copies of the SSIES, SSJ and SSM database files are archived on to DVD's on a monthly basis.

RSDR SSIES2 Phase II processing

The Phase II processing system accesses the Phase I time history database. This system is comprised of several software routines coded in FORTRAN and is driven by a UNIX script. This process is only used for F13 and F15.

Telemetry data values from the Driftmeter (DM), Scintillation Monitor (SM), Retarding Potential Analyzer (RPA), Langmuir Probe (LP) and Microprocessor (MP) experiments are converted into geophysical parameters and written to output files at one-minute intervals. The automated processing is done on a daily basis with a crontab job initiating the shell script at a specified time in the morning. The files are archived on the UniTree file system. Copies of the Phase II data base files are sent on a daily basis via FTP to two outside agencies.

RSDR SSIES2 and SSIES3 Phase II EDR Processing

The processing consists of accessing the phase I files, converting the files to RSDR format, then to EDR data files. The EDR files are compressed and then archived to the UniTree file system.

A copy of the compressed file is also transferred to the FTP server (dropbox) so that the Naval Research Laboratory can retrieve the files via FTP and to FTP servers at NGDC and the Aerospace Corporation. The processing is done by a combination of UNIX shell scripts, Perl scripts and FORTRAN programs. The automated processing is done on a daily basis with a crontab job initiating the shell script at a specified time in the morning.

RSDR SSM Phase II MFR Processing

The processing consists of accessing the phase I files, converting the files to RSDR format, then to MFR (ASCII) data files. Another program is run converting the ASCII files to binary, the binary files are compressed then transferred to FTP servers at JHU/APL, NGDC and the Aerospace Corporation. Both types of files are also archived to the Unitree file system. The processing is done by a combination of UNIX shell scripts, Perl scripts and FORTRAN programs. The automated processing is done on a daily basis with a crontab job initiating the shell script at a specified time in the morning.

DMSP3 and SWX Web server survey Plot files (SSIES, SSJ & SSM)

The DMSP3 processing consists of a shell script that accesses input files from Unitree, then runs IDL programs that generate High and Low Latitude data survey plot files. The plots files are copied to the Web server for users to access inside the firewall. The automated processing is done on a daily basis with a crontab job initiating the shell script at a specified time in the morning. The High latitude web plots include SSJ Ion and Electron; SSIES Ni and N [O+], Horizontal and vertical drift of thermal ions, and SSM measured minus model magnetic field survey data. The Low latitude web plots include SSIES Ni/N[O+], Ion Drift meter, Temperature and SM total Ion density survey data. Another script, also initiated by a crontab job is run on SWX that copies the plots files generated on dmsp3 on to the SWX web server with a two day delay for users to access outside of the firewall. The log files and web pages are viewed on a daily basis to check for errors in the processing.

6.2. DMSP Data Archive

BC maintains a complete archive of all DMSP J data from 1983 through the present, beginning with F6 data and continuous through the currently active DMSP satellites (F13, F16 and F17). This archive is maintained with redundancy on the AFRL Unitree file system with a third and fourth copy on CD. This archive is made available to all AFRL personnel. In addition, several levels of processed summary data files are maintained along with viewing software in support of various AFRL projects. BC personnel use the archive, processed files and software tools to monitor the status of J instruments on currently active DMSP satellites.

The archive process is mostly automated, but requires manual processing whenever network problems interrupt the automation string, which occurs on most weekends and occasionally on weekdays. In addition, log files need random checks to detect developing problems, the CD archive is done manually, the processing software requires occasional maintenance, and viewing software is updated as required.

6.3. DMSP SSJ4/SSJ5 Calibration

BC is part of the calibration team that has performed complete calibrations of two SSJ5 instruments under this contract. In the process we have made significant improvements in the ‘art’ of calibration at AFRL and have identified weaknesses in the process that must be addressed in order to meet the higher standards that will be imposed for instruments from the GOES and NPOESS programs that are scheduled to be calibrated in the AFRL facility over the next decade.

6.4. The Hardy Project

This project was the culmination of the one started in the late 70s by Dr. David Hardy to completely characterize the particle precipitation in the auroral region in terms of log-normal probability distributions. With modern computer capabilities we were successful in expanding the study from the two early J4s used by Dr. Hardy to the complete set of DMSP J4 instruments covering the period 1983 through 2007. In doing so, we developed improved noise filters and in-flight calibration techniques that will be used in current and future space weather projects. The scientific study of the results was published in Hardy et a., 2008. The in-flight calibration component is routinely updated to keep the corrections current.

6.5. Hemispheric Power Index

AFRL developed, maintained and made available to the space weather community a hemispheric power index based on SSJ4 / 5 electron spectra. Under this contract BC expanded the index to include ions and applied the improved noise filters with the goal of validating our in-flight calibration from the Hardy Project. The validation was successful for electrons and the HP techniques proved to be far better for ions and are now used for our ion in-flight calibration corrections. This is also routinely updated to keep the corrections current. Results of these efforts are reported in Emery et al., 2008.

7. NEXT GENERATION TRAPPED ELECTRON AND PROTON MODELS

The overall objective of this task is to support AFRL in developing the next-generation trapped electron and proton models for satellite design, AE-9 and AP-9. The primary objectives of the effort are to 1) improve the overall accuracy of the models; 2) provide indicators of the uncertainty in the model due to natural variability and imperfect instruments; 3) cover a broad energy range including hot plasma, relativistic electrons, and highly energetic protons; and 4) provide complete spatial coverage. The project has involved analysis of data from many satellites over a long time period to develop maps of the trapped electron and proton flux in near-Earth space. BC has participated in all levels of this project, including planning; most of the activity has concentrated on three main research topics: developing coordinate systems for flux mapping, spectral inversion and cross-calibration of fluxes, and angular flux distributions and their effects on flux mapping.

7.1. Coordinate Systems for Flux Mapping

Many different magnetic coordinates and coordinate systems have been developed over the years, and all of them have certain advantages in certain circumstances. Our purpose here was to select the coordinate system most appropriate for the AE/AP-9 project. Of particular importance was the ability to incorporate new data from different epochs; the inability to do this was one of the primary drawbacks of the AE/AP-8 models. Inherent in this criterion is the ability to account for the secular variations in the Earth's magnetic field. The systems selected needed to balance several criteria:

- Adiabatic invariance: i.e., the system needs to be based on properties of trapped particle motion that remain approximately constant as long as changes in external forcing factors (such as the magnetic field) vary slowly enough.

- Resolution: The coordinate system selected must provide adequate resolution so that fluxes can be accurately interpolated.

- Computational efficiency: If possible, the coordinates selected should be easy and fast to compute.

We evaluated many different systems and selected two different grids, one for the outer zone and one for the inner zone. These grids are based on the third adiabatic invariant, Φ, and the Kauffman K parameter, which is based on the second adiabatic invariant. Figure 1 shows AE-8 fluxes mapped in the outer zone coordinate system.

7.2. Spectral Inversion

Because the detectors on most of the spacecraft used are simple dosimeter designs, a spectral inversion approach was used to obtain differential fluxes from these instruments. The inversion process is summarized in Figure 2. Crucial to the process is knowledge channel spectral response; response functions are normally obtained from pre-flight calibration with particle accelerators and modeling of the energy deposition using Monte-Carlo codes. The next step is to assume shape for the particle flux vs. energy spectrum. This spectrum is then integrated with the channel response functions to obtain a vector of expected counts in each detector channel; an optimization process is then used to find the "best" spectrum to obtain the vector of counts actually observed in the detector. BC developed procedures in MATLAB to perform this spectral inversion process for the CEASE instrument on the AFRL TSX-5 satellite.

BC also used data from other instruments to cross-calibrate fluxes measured by multiple spacecraft. Figure 3 shows energy spectra from several spacecraft measured during a solar proton event.

7.3. Angular Flux Distributions and Effects

In populating the AE/AP-9 particle maps, the quantity needed is the perpendicular flux j_90, the unidirectional, differential flux of locally-mirroring particles. Science-grade instruments such as PROTEL on CRRES can measure this quantity directly, but much of our data comes from wide-angle or omnidirectional detectors, which sample a fraction of the local omnidirectional flux. BC developed a technique to estimate j_90 based on models of the angular response of the detector and the angular distribution of the particle flux in space.

The particle pitch angle distribution model is based on the CRRESPRO model. BC used the data within CRRESPRO to fit a distribution function of the form

$$j = \begin{cases} j_0 \dfrac{\left(y - y_{LC}\right)^a y^b}{\left(1 - y_{LC}\right)^a}; & y > y_{LC} \\ 0; & y \le y_{LC} \end{cases}$$

where

$y = \sin \alpha_0$ (equatorial pitch angle)

$y_{LC} = \sin \alpha_{LC}$ (equatorial loss cone angle)

a, b, j_0, y_{LC} are fitting parameters

A correction factor ξ was then defined by the following relation:

$$\xi(E) = \frac{j_{90}(E)}{j_{\det}(E)} = \frac{\sum_{i=1}^{N} R_i(E)}{\sum_{i=1}^{N} \int_0^{2\pi} d\varphi \int_0^{\pi} d\theta \sin\theta \, A_i(E;\theta) F(E;\theta,\varphi)}$$

where

$j_{\det}$ = flux from the inversion routine

A_i = channel effective area

$R_i(E) = 2\pi \int_0^{\pi} d\theta \, A_i(E,\theta) \sin\theta$ is the energy-dependent response function

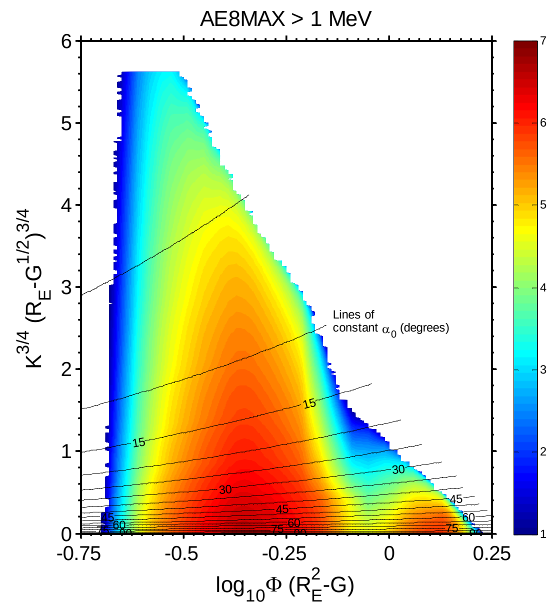

Figure 1. AE-8MAX fluxes plotted in Φ-*K* coordinates selected for the AE/AP-9 outer zone map. Also shown are lines of constant equatorial pitch angle α_0.

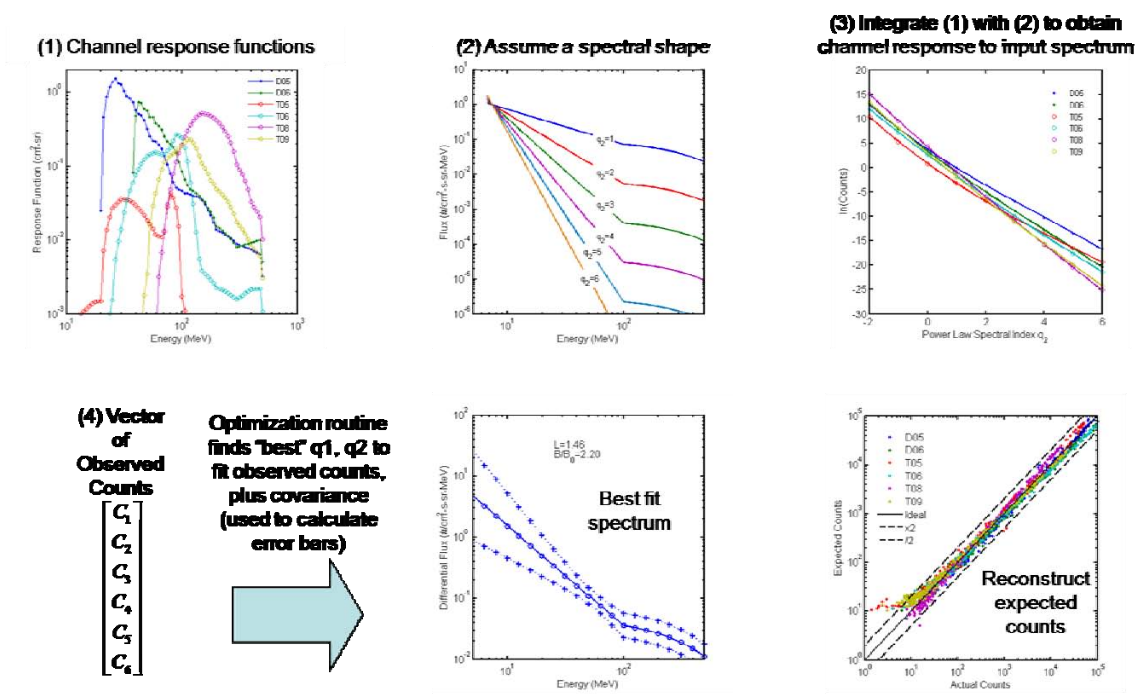

Figure 2. Steps in the spectral inversion procedure.

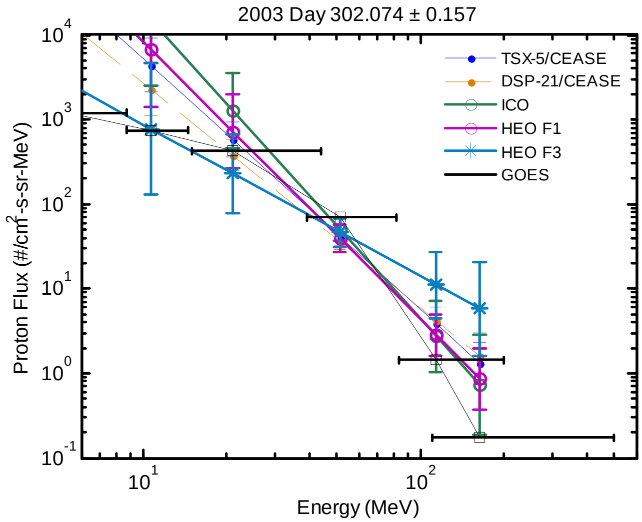

Figure 3. Energy spectra from several spacecraft compared with the spectrum from GOES for the October-November 2003 solar particle event.

REFERENCES

Chiu, Y.-H., Austin, B.L., Dressler, R.A., Levandier, D.J., Murray, P.T., Lozano, P., Sanchez, M.M., Mass spectrometric analysis of colloid thruster ion emission from selected propellants", *Journal of Propulsion and Power,* Vol. 21, 2005, p. 416.

Chiu, Y.-H, Dressler, R.A., Levandier, D.J., Houchins, C., and Ng, C.Y., "Large-angle xenon ion scattering in Xe-propelled electrostatic thrusters: differential cross sections", *Journal of Physics D: Applied Physics*, **2008**, Vol. 21, p. 165503.

Chiu, Y.-H, Gaeta, G., Levandier, D.J., Dressler, R.A., and Boatz, J.A., "Vacuum electrospray ionization study of the ionic liquid [Emim][Im]", *International Journal of Mass Spectrometry*, Vol. 265, p. 146, 2007.

Hardy, D.A., E. G. Holeman, W. J. Burke, L. C. Gentile, and K. H. Bounar (2008), Probability distributions of electron precipitation at high magnetic latitudes, *J. Geophys. Res.*, 113, A06305, doi:10.1029/2007JA012746.

Emery, B.A., V. Coumans, D. S. Evans, G. A. Germany, M. S. Greer, E. Holeman, K. Kadinsky-Cade, F. J. Rich, and W. Xu (2008), Seasonal, Kp, solar wind, and solar flux variations in long-term single-pass satellite estimates of electron and ion auroral hemispheric power, *J. Geophys. Res.*, 113, A06311, doi:10.1029/2007JA012866.

Kahler, S.W. and D. F. Webb (2007), V arc interplanetary coronal mass ejections observed with the Solar Mass Ejection Imager, *J. Geophys. Res.*, 112, A09103, doi:10.1029/2007JA012358.

Levandier, D.J., Chiu, Y.-H, and Dressler, R.A., "A guided-ion beam study of the $O^+(^4S) + NH_3$ system at hyperthermal energies", *Journal of Physical Chemistry A,* 2008, Vol. 112, p. 9601.

Levandier, D.J., Chiu, Y.-H., Dressler, R.A., "A guided-ion beam study of the reactions of Xe^+ and Xe^{2+} with NH_3 at hyperthermal collision energies", *in preparation* (a).

Levandier, D.J., Gruenstein, K., Wu, J., Austin, B., Dressler, R.A., Chiu, Y.-H., "Charge conversion of oxygen atoms in hyperthermal collisions on self-assembled monolayers", *in preparation (b).*

Luedtke, W.D., Landman, U., Chiu, Y.-H, Levandier, D.J., Dressler, R.A., Sok, S., and Gordon, M. S., "Nanojets, electrospray, and field-ion evaporation: Molecular dynamics simulations and laboratory experiments", *Journal of Physical Chemistry A*, 2008, Vol. 112, P. 9628, Feature Article.

Tang, X.N., Houchins, C., Xu, H.F., Ng, C.Y., Chiu, Y., Dressler, R.A. and Levandier, D.J., "An experimental and quasiclassical trajectory study of the rovibrationally state-selected reactions: $HD^+(v=0\text{-}15, j=1) + He \rightarrow HeH^+(HeD^+) + H$", *Journal of Chemical Physics*, Vol. 126, p. 234205, 2007.

Tang, X.N., Xu, N., Zhang, T., Hou, Y., Chang, C., Ng, C.Y., Chiu, Y., Dressler, R.A. and Levandier, D.J., "A pulsed-field ionization photoelectron secondary ion coincidence study of the H_2^+ (X, v^+ = 0-15, N^+ = 1) + He proton transfer reaction", *Journal of Chemical Physics*, Vol. 122, 2005, 164301.

Webb, D. F., Mizuno, D. R., Buffington, A., Cooke, M. P. Eyles, C.J., Fry, C. D., Gentile, L. C., Hick, P. P., Holladay, P. E., Howard, T. A., Hewitt, J. G., Jackson, B. V., Johnston, J. C., Kuchar, T. A., Mozer, J. B., Price, S., Radick, R. R. Simnett, G. M., and Tappin, S. J.: Solar Mass Ejection Imager (SMEI) Observations of CMEs in the Heliosphere, J. Geophys. Res., 111, A12101, doi:10.1029/2006JA011655, 2006.

BIBLIOGRAPHY

Buffington , A., M.M. Bisi, J.M. Clover, P.P. Hick, B.V. Jackson, and T.A. Kuchar, "Analysis of Plasma-Tail Motions for Comets C/2001 Q4 (NEAT) and C/2002 T7 (LINEAR) using Observations from SMEI", *Astrophys. J.,* 677, 798 (2008).

Buffington, A., M. M. Bisi, J.M. Clover, P. P. Hick, B.V. Jackson, T.A. Kuchar, and S. D. Price, "Measurements of the Gegenschein brightness from the Solar Mass Ejection Imager (SMEI)", *Icarus*, 203, 124-133, doi:10.1016/j.icarus.2009.04.007 (2009).

Chiu, Y.-H., Austin, B.L., Dressler, R.A., Levandier, D.J., Murray, P.T., Lozano, P., Sanchez, M.M., Mass spectrometric analysis of colloid thruster ion emission from selected propellants", *Journal of Propulsion and Power,* Vol. 21, 2005, p. 416.

Chiu, Y.-H, Dressler, R.A., Levandier, D.J., Houchins, C., and Ng, C.Y., "Large-angle xenon ion scattering in Xe-propelled electrostatic thrusters: differential cross sections", *Journal of Physics D: Applied Physics*, **2008**, Vol. 21, p. 165503.

Chiu, Y.-H, Gaeta, G., Levandier, D.J., Dressler, R.A., and Boatz, J.A., "Vacuum electrospray ionization study of the ionic liquid [Emim][Im]", *International Journal of Mass Spectrometry,* Vol. 265, p. 146, 2007.

Emery, D.A., V. Coumans, D. S. Evans, G. A. Germany, M. S. Greer, E. Holeman, K. Kadinsky-Cade, F. J. Rich, and W. Xu, Seasonal, Kp, solar wind, and solar flux variations in long-term single-pass satellite estimates of electron and ion auroral hemispheric power, *J. Geophys. Res.*, 113, A06311, doi:10.1029/2007JA012866 (2008).

Ginet , G. P., S. L. Huston , C. Roth, T. P. O'Brien, D. Madden, "The Trapped Proton Environment in Medium Earth Orbit (MEO)," submitted to *IEEE Trans. Nucl. Sci.*, 2010.

Hardy, D.A., E. G. Holeman, W. J. Burke, L. C. Gentile, and K. H. Bounar, Probability distributions of electron precipitation at high magnetic latitudes, *J. Geophys. Res.*, 113, A06305, doi:10.1029/2007JA012746 (2008).

Howard, T. A., C. D. Fry, J. C. Johnston, and D. F. Webb, On the evolution of coronal mass ejections in the interplanetary medium, *Astrophys. J., 667*, 610–625, doi:10.1086/519758 (2007).

Howard, T. A., D. F. Webb, S. J. Tappin, D. R. Mizuno, and J. C. Johnston, Tracking halo coronal mass ejections from 0–1 AU and space weather forecasting using the Solar Mass Ejection Imager (SMEI), *J. Geophys. Res.*, *111*, A04105, doi:10.1029/2005JA011349 (2006).

Johnston, J. C, P.E. Holladay and T.A. Kuchar, "Solar Mass Ejection Imager (SMEI) Mission: Final Report", Air Force Research Laboratory Technical Report, AFRL-RV-HA-TR-2007-1126, 25 October (2007).

Kahler, S. W., and D. F. Webb, V arc interplanetary coronal mass ejections observed with the Solar Mass Ejection Imager, *J. Geophys. Res., 112*, A09103, doi:10.1029/2007JA012358 (2007).

Kuchar, T.A., A. Buffington, C.N. Arge, P.P. Hick, T.A. Howard, B.V. Jackson, J.C. Johnston, D.R. Mizuno, S.J. Tappin, and D.F. Webb, "Observations of a Comet Tail Disconnection Induced by CME Passage", *J. Geophys. Res.*, A04101, doi:10.1029/2007JA012603 (2008).

Levandier, D.J., Chiu, Y.-H, and Dressler, R.A., "A guided-ion beam study of the $O^+(^4S)$ + NH_3 system at hyperthermal energies", *Journal of Physical Chemistry A*, 2008, Vol. 112, p. 9601.

Luedtke, W.D., Landman, U., Chiu, Y.-H, Levandier, D.J., Dressler, R.A., Sok, S., and Gordon, M. S., "Nanojets, electrospray, and field-ion evaporation: Molecular dynamics simulations and laboratory experiments", *Journal of Physical Chemistry A*, 2008, Vol. 112, P. 9628, Feature Article.

Tang, X.N., Houchins, C., Xu, H.F., Ng, C.Y., Chiu, Y., Dressler, R.A. and Levandier, D.J., "An experimental and quasiclassical trajectory study of the rovibrationally state-selected reactions: $HD^+(v=0\text{-}15, j=1) + He \rightarrow HeH^+(HeD^+) + H$", *Journal of Chemical Physics*, Vol. 126, p. 234205, 2007.

Tang, X.N., Xu, N., Zhang, T., Hou, Y., Chang, C., Ng, C.Y., Chiu, Y., Dressler, R.A. and Levandier, D.J., "A pulsed-field ionization photoelectron secondary ion coincidence study of the H_2^+ (X, v^+ = 0-15, N^+ = 1) + He proton transfer reaction", *Journal of Chemical Physics*, Vol. 122, 2005, 164301.

Webb, D. F., T. A. Howard, C. D. Fry, T. A. Kuchar, D. R. Mizuno, J. C. Johnston, and B. V. Jackson, Studying geoeffective interplanetary coronal mass ejections between the Sun and Earth: Space weather implications of Solar Mass Ejection Imager observations, *Space Weather, 7*, S05002, doi:10.1029/2008SW000409 (2009).

Webb, D. F., Howard, T. A., Fry, C. D., Kuchar, T. A., Odstrcil, D., Jackson, B. V., Bisi, M. M., Harrison, R. A., Morrill, J. S., Howard, R. A., and Johnston, J. C.: Study of CME Propagation in the Inner Heliosphere: SMEI and STEREO HI Observations of the January 2007 Events, Solar Physics, STEREO Special Issue, 256, 239, doi:10.1007/s11207-009-9351-8, 2009.

Webb, D. F., T. Howard, J. Johnston, and C. Fry, SMEI observations and space weather forecasting, *Eos. Trans. AGU*, *87*(52), Fall Meet. Suppl., Abstract SH33A-0394 (2006).

Webb, D. F., Mizuno, D. R., Buffington, A., Cooke, M. P. Eyles, C.J., Fry, C. D., Gentile, L. C., Hick, P. P., Holladay, P. E., Howard, T. A., Hewitt, J. G., Jackson, B. V., Johnston, J. C., Kuchar, T. A., Mozer, J. B., Price, S., Radick, R. R. Simnett, G. M., and Tappin, S. J.: Solar Mass Ejection Imager (SMEI) Observations of CMEs in the Heliosphere, J. Geophys. Res., 111, A12101, doi:10.1029/2006JA011655, 2006.

J. Zhang, I. G. Richardson, and D. F. Webb, Interplanetary origin of multiple dip geomagnetic storms, *J. Geophys. Res.*, 113, A00A12, doi:10.1029/2008JA013228 (2008).