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14. ABSTRACT

This report results from a contract tasking University of Birmingham as follows: The Grantee will investigate data collected on coronal mass ejections (CME), and attempt to construct images of CMEs as they move towards the earth and predict their arrival. The objective of this research is to create a mathematical model for predicting the arrival and severity of geomagnetic storms resulting from CMEs.

15. SUBJECT TERMS
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Final Report for SPC 05-3059 (Contract FA8655-05-1-3059)

"Coronal Mass Ejection Research Using Solar Mass Ejection Imager (SMEI) Data"

OVERVIEW OF THE OBJECTIVES

The Solar Mass Ejection Imager (SMEI) was largely designed and built at the University of Birmingham, UK, with 55% funding from the USAF (Hanscom) and 45% funding from the University of Birmingham. The principal scientific objective is to demonstrate that such an instrument has the capability of providing an early warning of the arrival at the Earth of fast, dense plasma clouds emitted from the Sun, which via complex physical processes in the magnetosphere may induce damaging conditions in Earth-orbiting spacecraft. In addition, the data will also provide valuable information on the physical processes involved in the emission of fast plasma clouds from the Sun and how they propagate through the interplanetary medium.

SMEI was successfully launched on the Space Test Program Coriolis spacecraft on 6 January, 2003 into a 102-minute polar orbit. Since February 2003 it has been routinely producing all-sky images from its three CCD cameras once an orbit, subject to the customary (minor) interruptions due to spacecraft anomalies, instrumental software changes and CCD camera adjustments. The objectives of the Research Program reported on here were to monitor the state of health of the SMEI instrument; to analyse and interpret the scientific and engineering data from the instrument; to make appropriate changes to the on-board software to optimize the data retrieval; to perform periodic anneals on the CCD cameras to minimise the effects of radiation damage; and to interpret and disseminate the scientific results from the instrument.

EXPERTISE OF THE PERSONNEL

The team at Birmingham is under the leadership of Professor George Simnett and comprises Dr Chris Eyles (SMEI Program Manager at the University of Birmingham), Dr James Tappin (Senior Scientist) and Mr Mark Cooke (On-board software engineer). Simnett and Eyles have been involved in instrumental space programs for 3-4 decades and have published around 200 papers in the scientific literature. Tappin came to Birmingham in 1988 and has considerable expertise in interpreting the CCD camera data as well as in understanding the scientific results from SMEI with respect to Coronal Mass Ejections (CME) from the Sun. In February 2007 Tappin moved from Birmingham to work with the SMEI team at the National Solar Observatory, Sacramento Peak. Cooke developed and wrote all the on-board software for SMEI and has had over ten years' experience in spacecraft software engineering.

ACHIEVEMENTS DURING THE CONTRACT PERIOD

The achievements by the SMEI team at Birmingham have been made in collaboration with our colleagues at Hanscom AFB, Bedford, MA; at Sacramento Peak Observatory, NM; and the University of California, San Diego, CA. The work has been in understanding the CCD camera performance data (Tappin, Eyles), developing software revisions (Cooke); and scientific data analysis (Simnett, Tappin). We report on the first two of these under "Spacecraft Operations" and the last under "Scientific Results". During the contract period we have had weekly teleconferences involving the whole SMEI team.

In February this year SMEI entered its fifth year of operation, which

has significantly exceeded its original design specification. The team at Birmingham has continued to support the successful spacecraft operation by supplying both on-board software revisions and improvements, together with the in-flight masking of the hot pixels in the CCD cameras. The extensive scientific dataset has been analysed to yield a number of interesting results which have been presented at Conferences and published in the refereed scientific literature.

Spacecraft Operations

The Coriolis spacecraft has performed well in orbit, with a few anomalies due to guide star acquisition problems (attitude control) and minor problems with the main instrument (WINDSAT) on the spacecraft. However, the polar orbit means that the instrument encounters high levels of radiation both near the geomagnetic poles and when passing through the South Atlantic magnetic anomaly. Also, there was an error in the thermal design of the instrument, with the result that one of the three cameras is operating at a somewhat higher temperature than ideal. The combination of these factors means that the hottest camera (designated camera 3) develops noisy pixels.

To make efficient use of the spacecraft telemetry the CCD pixels are binned 2x2 on board. This means that if one of the 4 binned pixels is noisy, then that binned pixel is also noisy. We have developed a technique for mitigating this problem by first determining from the weekly calibrations, which are done in engineering mode where the data from each camera is transmitted at full resolution, which pixels are bad. We have then modified the on-board flat-fielding table to eliminate at the pixel level those pixels that are bad. Following this, when the normal mode is resumed with the new flat-field table, a 2x2 bin will simply not contain the bad pixel. This is a complicated task, and Tappin and Cooke have developed the expertise to handle it.

One of the properties of CCD chips is that radiation damage may be reduced by annealing the chip at a high temperature. We had incorporated a heater in each camera specifically for this purpose. Tappin has developed the expertise to address the corrections needed to the SMEI images in order to take into account the gradual increase in the number of hot pixels in the CCD chips. He has continued to refine the software to study the variance of the CCD pixels and the way this changes with the temperature of the individual cameras. It has turned out that the anneals that we had been doing at a temperature of 45 C were only partially successful, and that over the course of a few months the noise levels in the cameras gradually returned to their pre-anneal values. The maximum annealing temperature we can achieve for the sunward-facing camera is around 85 C, but we do not wish to cycle the CCD chip too often at this temperature for fear of damaging the CCD bonding to the camera cold-finger. We have now adopted a sequence of anneals based on Tappin's recommendations which are approximately every 2 months for camera 3 at maximum temperature, and around every 2 months at an 80% duty cycle for cameras 1 and 2. Occasionally we need to perform a high temperature anneal.

Over the last three years a significant reprogramming of the on-board software has been achieved to maintain efficient data retrieval, and this has been carried out by our flight software engineer, Mr Mark Cooke.

In 2006 we experienced a probable failure in the on-board data handling electronics unit that we had been using since launch. The SMEI data handling electronics is fully redundant, and following this problem we successfully changed to the redundant system, and this has

been operating successfully now for over a year. The original SMEI hardware budget was insufficient to provide for the purchase of radiation-hard electronics, which could not really be justified in a program designed to last two years. We designed the electronics such that the redundant unit was not powered, which results in minimal radiation damage while not being used. Thus we have a reasonable chance that SMEI will continue to operate for maybe another year, possibly more. We have continued to participate in weekly teleconferences where the operational issues are fully aired.

In summary, the software efforts have proved to be invaluable to the SMEI team, and Tappin is continuing to develop the diagnostic and end-user software. In February 2007 Tappin moved from Birmingham to the National Solar Observatory to continue his work on SMEI.

Scientific Data Analysis

The SMEI team has been active in publishing the scientific results and reporting on them at professional meetings. A list of these papers resulting from this contract is given in Appendix 1.

It is of considerable interest to determine how solar transients A paper on the way coronal mass ejections move from the Sun, through the SMEI field of view, and on out the the Ulysses spacecraft, which for this study was almost at 5 AU, has been published by Tappin (2006). Howard et al (2006) have shown how SMEI may be used to track CMEs coming towards the Earth, so that this could be useful for space weather forecasting.

The paper on the main results of coronal mass ejections (CME) seen in space from SMEI appeared in the Journal of Geophysical Research last year (Webb et al, 2006). SMEI is the first instrument to have imaged CMEs in the inner heliosphere out to the orbit of Earth, and beyond. One of the surprising results that we first highlighted in 2005 (Simnett, 2005) is the lack of any evidence for 10% or so of the SMEI events in the SOHO/LASCO coronagraphs, which observe the region near the Sun out to 30 solar radii. For comparison, the earth is at around 214 solar radii from the center of the Sun. We are currently preparing a full paper on this topic (Howard and Simnett, 2007) for publication.

SMEI has been able to image some of the major comets that have appeared since launch. For one of them (comet NEAT) SMEI detected the disruption of the comet tail by the passage of a solar transient. A paper on this result (Kuchar et al, 2007) has been submitted to the Journal of Geophysical Research. One surprising result has been the frequent observation of very high altitude aurorae. The observed emissions are from altitudes of 1000km or more, and prior to the SMEI observations (Mizuno et al, 2006) such aurorae were thought to be extremely rare.

Last December we had a Special Scientific Session at the Fall Meeting of the American Geophysical Union (AGU) on the SMEI mission, to publicise the recent scientific results. The papers presented are listed in Appendix 2.

George Simnett

Birmingham

17 October 2007

Appendix 1 Publications resulting from this research

Howard T.A. and Simnett, G.M.: SMEI observations of outward-moving transients in the inner heliosphere which have no signature in LASCO, (paper in preparation, 2007)

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

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

Mizuno, D. R., Buffington, A., Cooke, M. P., Eyles, C. J., Hick, P. P., Holladay, P. E., Jackson, B. V., Johnston, J. C., Kuchar, T. A., Mozer, J. B., Price, S. D., Radick, R. R., Simnett, G. M., Sinclair, D., Tappin, S. J. and Webb, D. F.: Very high altitude aurora observations with the Solar Mass Ejection Imager, *J. Geophys. Res.*, 110, A07230, doi.org/10.1029/2004JA010689 (2005)

Simnett, G.M.: CMEs Observed by SMEI which are not seen by LASCO, Proceedings of the Solar Wind 11 / SOHO 16, "Connecting Sun and Heliosphere" Conference (ESA SP-592). 12 - 17 June 2005 Whistler, Canada. Editors: B. Fleck, T.H. Zurbuchen, H. Lacoste. Published on CDRom., p.157.1 (2005)

Tappin, S. J., The Deceleration of an Interplanetary Transient from the Sun to 5 AU, *Solar Physics*, 233, 233-248 (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)

Appendix 2 SMEI Abstracts for the Fall AGU Meeting, Dec. 11-15, 2006, San Francisco, CA.

J C Johnston, R R Radick, Results from the AFRL Solar Mass Ejection Imager Mission - Four Years of Operation, INVITED SH32A-01

M Tokumaru, M Yamashita, M Kojima, K Fujiki, Propagation of coronal mass ejections in the interplanetary medium, INVITED SH32A-02

A Vourlidas, D F Webb, J S Morril, B V Jackson, CME Brightness at Large Elongations: Application to LASCO and SMEI Observations, INVITED SH32A-03

T A Howard, J C Johnston, D F Webb, Coronal Mass Ejection Evolution in the Inner Heliosphere: Geometry and Speed, SH32A-04

G M Simnett, T A Howard, Interplanetary Transient Events Seen by SMEI Which are not Observed by LASCO: Analysis and Interpretation, INVITED SH32A-05

A Buffington, B V Jackson, P Hick, S D Price, An Empirical Description of Zodiacal Light as Measured by SMEI, SH32A-06

A J Penny, Variable stars with the SMEI instrument, SH32A-07

T Kuchar, A Buffington, T Howard, C N Arge, D Webb, B V Jackson, P P Hick, The Evolution of Comets in the Heliosphere as Observed by SMEI, SH32A-08

D Webb, T Howard, J Johnston, C Fry, SMEI Observations and Space Weather Forecasting,

POSTER SH33A-0394

S E Fry, C D Fry, T A Howard, "Combining HAFv2 Model Simulations With SMEI Images to Improve ICME forecasts and Interpretations of Observations", POSTER SH33A-0395

B V Jackson, P P Hick, A Buffington, "The 20 January 2005 CME Solar Mass Ejection Imager (SMEI) Analyses", POSTER SH33A-0396

E A Jensen, T Mulligan, B V Jackson, M Tokumaru, "3-D Magnetic Field Geometry of the October 28, 2003 ICME: Comparison with SMEI White-Light Observations", POSTER SH33A-0397

A Gonzalez-Esparza, E Andrade, A Carrillo, S Kurtz, S Jeyakumar, R Perez-Enriquez, P Sierra, S Vazquez, P Manoharan, "MEXART. Interplanetary Scintillation Array in Mexico in the 1HY20070", POSTER SH33A-0398

M M Bisi, A R Breen, R A Fallows, G D Dorrian, R A Jones, G Wannberg, P Thomasson, C Jordan, "Off-radial flow of the solar wind from EISCAT and MERLIN IPS observations", POSTER SH33A-0399

G M Simnett, T A Howard, "The Evolution of a Small, Faint Coronal Mass Ejection Into an Interplanetary Transient", SH33A-0400
