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HIGH-LATITUDE INCOHERENT-SCATTER RADAR MEASUREMENTS FOR THE ISTP PROGRAM

SRI Project 1431

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Over the course of this contract, the ISTP mission became a reality and proved to be one of NASA's success stories. SRI and the NSF-sponsored Sondrestrom radar contributed significantly to the success. We provided dedicated radar experiment time with operation modes specifically designed to complement the ISTP spacecraft. Data collected during coronal mass ejection events indicated that at times significant energy is fed from the ionosphere to the magnetosphere. A model of global conductance is emerging from combined POLAR and Sondrestrom data sets. We initiated a study to investigate the behavior of the global energy budget during the evolution of magnetospheric storms and substorms using a number of ground-based and satellite data sets.

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1 INTRODUCTION

A primary use of the Sondrestrom radar is to extend ISTP (International Solar Terrestrial Physics) spacecraft capability by providing coordinated, simultaneous measurements of ionospheric parameters (such as electron density, plasma temperature, plasma velocity, ion-neutral collision frequency, electric field and currents, conductivity, etc.).[1] These measurements are especially important to the ISTP goals because they improve the evaluation of spacecraft measurements by broadening their interpretation to include the ionospheric effects of geospace storms. Beyond this traditional task, the Sondrestrom radar provides the most comprehensive measurement of the high-latitude ionosphere within the ISTP program.

The unique location and steerability of the radar provide regular access to a number of poorly understood magnetospheric regimes from the central plasma sheet to the lobe. Observations are possible during both day and night and are insensitive to environmental conditions (such as, lunar illumination, cloud cover, and lack of ionospheric irregularities) that can restrict other optical and radio wave techniques.

General research using the Sondrestrom radar has resulted in over 200 refereed publications, including recent submissions to Geophysical Research Letters (GRL) concerning Global Geospace Science (GGS) events. In addition, several ISTP-specific studies are under way or under design.

[1] J.D. Kelly, C.J. Heinselman, J.F. Vickrey, and R.R. Vondrak, "The Sondrestrom radar and accompanying ground-based instrumentation," *Space Sci. Rev.*, Vol. 71, Nos. 1-4, pp. 797-813, 1995.

2 ACCOMPLISHMENTS

The importance of the ISTP ground-based measurements have been most recently exemplified by coronal mass ejection (CME) events, such as the one that occurred on 10 January 1997. During this event the Sondrestrom radar observed large electric fields and ion temperatures, and periods of enhanced joule heating where the ionosphere feeds significant energy to the magnetosphere.[2] Subsequent CMEs have been observed and are the basis for ongoing research involving the entire ISTP community.

A novel ISTP initiative commenced on 1996 to compare auroral energy flux (F_e) estimates as derived form POLAR satellite UVI images with Sondrestrom incoherent-scatter (IS) radar E-region electron density altitude profiles. This study showed good agreement in both energy flux magnitude and its time history for the 20 May 1996 POLAR apogee period.

A global POLAR and Sondrestrom radar conductance model naturally follows from improved radar and satellite estimates of precipitation energetic. This model, in development, merges high-precision radar conductivity measurements with POLAR ultraviolet imager (UVI) conductance estimates in a hypercube parameterized on solar and geomagnetic activity, latitude and local time, and season of the year. The goal of this study is to derive a new global conductance model based on this high-resolution data set.

Ionospheric measurements of currents and joule heating are an important aspect of the ISTP program in revealing how electromagnetic energy is transferred within the magnetosphere–ionosphere (M–I) system. Sondrestrom radar measurements and analysis permit the local assessment of the height-resolved and height-integrated currents and joule heating rate in the high-latitude E-region that included neutral wind effects.

An additional Sondrestrom–ISTP initiative uses a number of ground-based and satellite diagnostics to investigate the behavior of the global energy budget during the evolution of magnetospheric storms and substorms. The goal of this study is a rigorous test of various models for magnetospheric substorm initiation and growth through an analysis of the partition of energy input into the global auroral ionosphere. This initiative also includes a quantification of the effectiveness of ion upflow mechanisms.

[2] E.R. Sánchez, J.P. Thayer, J.D. Kelly, and R.A. Doe, " Energy transfer between the ionosphere and magnetosphere during the January 1997 CME event," *Geophys. Res. Lett.*, 25, 2597, 1998.

3 SONDRESTROM RADAR OPERATIONS AND RECENT ACTIVITIES

From 1 September 1997 through August 1998, there were 371 hours of Sondrestrom IS radar operations in 49 experiments designed to study the physics of the low-latitude boundary layer, the cusp, the nightside M–I coupling of substorms, and the effectiveness of ion upflow mechanisms.

There were 241 radar operations designed to study the physics of the ionospheric impact of CME-induced storms. The radar experiments were performed for the storms of 6–11 January 1997, 30 September–2 October 1997, 6–8 November 1997, 10–19 March 1998, and 4–5 May 1998.

All of the data have been processed and Key Parameters were submitted to the Central Data Handling Facility within 48 hours of the end of all the experiments.

September 1997. There were two experiments coordinated with ISTP satellites to investigate the physics of M–I coupling during substorm expansions. The intervals selected were

08–09 September	21–05 UT
24–25 September	20–05 UT

There were also three experiments coordinated with ISTP satellites to study the cusp and boundary layers. The intervals selected were

03 September	16–24 UT
14–15 September	21–12 UT
24 September	12–20 UT

We initiated the preparation of two manuscripts discussing the ionospheric response to the January storm that was caused by a CME. These manuscripts were submitted to a special GRL issue on ISTP measurements and modeling of storms.

October 1997. There were three experiments coordinated with ISTP satellites to investigate the physics of M–I coupling during substorm expansions. The intervals selected were

05 October	00–04 UT
07 October	00–05 UT
31 October–01 November	22–08 UT

There were also two experiments coordinated with ISTP satellites to study the boundary layers. The intervals selected were

10 October	02–08 UT
27 October	05–10 UT

Two manuscripts discussing the ionospheric response to the January storm that was caused by a CME were submitted to a special GRL issue on ISTP measurements and modeling of storms.

November 1997. There were three experiments coordinated with ISTP satellites to investigate the physics of M–I coupling during substorm expansions in November 1997. The intervals selected were

31 October–01 November	22–06 UT
10–11 November	22–05 UT
21–22 November	22–05 UT

We participated in the ISTP Science Workshop held at Goddard Space Flight Center 4–6 November 1997. Data analysis of correlative studies of ionospheric impact of CMEs was presented. A collaboration with the modeling group at the University of Maryland was initiated to combine a magnetohydrodynamic (MHD) model of the magnetosphere with ionospheric measurements to elucidate how the energy exchange between the ionosphere and the magnetosphere is distributed during the January storm.

December 1997. There were three experiments coordinated with ISTP satellites to investigate the physics of M–I coupling during substorm expansions. The intervals selected were

01–02 December	22–06 UT
06–07 December	23–08 UT
17–18 December	23–08 UT

The following invited paper was presented at the Fall AGU meeting in San Francisco: "Multi-Point Observations of Resonances Near Substorm Onset," by E. R. Sánchez and J. D. Kelly. Research efforts continued toward elucidating the phenomenological and theoretical framework of the energy transfer between the ionosphere and the magnetosphere and the coherence of the global response of the magnetosphere to solar input. Intercalibration between POLAR UVI and Sondrestrom measurements of energy flux, mean energy, and conductivity also continued. The above mentioned activities involved collaboration with the MHD Modeling Group at the University of Maryland, the Ionosphere Modeling Group at the University of Alaska, the University of Washington POLAR UVI Group, the University of Iowa POLAR VIS Group, the Johns Hopkins University, Applied Physics Laboratory (JHU/APL) SuperDarn Group, and CANOPUS.

January 1998. There were four experiments coordinated with ISTP satellites to investigate the physics of M–I coupling during substorm expansions. The intervals selected were

02–03 January	22–05 UT
08–09 January	23–08 UT
13–14 January	23–05 UT
28–29 January	20–05 UT

We continued research collaborations with the MHD Modeling Group at the University of Maryland, the Ionosphere Modeling Group at the University of Alaska, the University of Washington POLAR UVI Group, the University of Iowa POLAR VIS Group, the JHU/APL SuperDarn Group, and CANOPUS.

In early January we received the reviewer comments from GRL concerning the paper titled "Energy Transfer Between the Ionosphere and Magnetosphere During the January 1997 CME Event," by Sánchez et al. The paper was revised in accordance to the comments and was resubmitted in February.

February 1998. There were seven 7-hour experiments coordinated with ISTP and IMP-8 satellites to determine the physics of the lower-latitude boundary layer. The intervals selected were

03–04 February	22–05 UT
08–09 February	21–04 UT
09–10 February	22–05 UT
14–15 February	22–05 UT
19–20 February	22–05 UT
20–21 February	22–05 UT
25–26 February	22–05 UT

We continued research collaborations with the MHD Modeling Group at the University of Maryland, the Ionosphere Modeling Group at the University of Alaska, the University of Washington POLAR UVI Group, the University of Iowa POLAR VIS Group, the JHU/APL SuperDarn Group, and CANOPUS.

The revised paper, titled " Energy Transfer Between the Ionosphere and Magnetosphere During the January 1997 CME Event," by Sánchez et al. was resubmitted on 9 February and accepted on 13 February. This paper would be included in the GLR ISTP special issue.

March 1998. There were three 7-hour experiments coordinated with ISTP satellites to investigate the physics of M–I coupling during substorm expansions. The intervals selected were

02–03 March	22–05 UT
12–13 March	22–05 UT
18–19 March	22–05 UT

Software development of time-frequency analysis (Fourier and wavelet) to elucidate the timing and coherence of the response of the M–I system to storm and substorm excitation was begun.

Collaboration with the University of Washington for time-frequency analysis of auroral dynamics using Sondrestrom radar and Polar UVI measurements was also started.

We continued collaboration with University of Alaska and University of Iowa to intercalibrate Polar UVI, VIS, and Sondrestrom measurements of ionospheric conductivities.

April 1998. There were three runs totaling 25 hours of experiments coordinated with ISTP satellites to investigate the physics of M–I coupling during substorm expansions. The intervals selected were

08–09 April	23–08 UT
23–24 April	20–05 UT
29–30 April	23–06 UT

Dr. Ennio Sánchez attended the ISTP science workshop at Goddard Space Flight Center 7–9 April. He presented ground-based and spacecraft coordinated measurements of cusp and results of analysis of observations of storm M–I coupling. He also coordinated a collaboration with spacecraft principal investigators (PIs) and the Maryland simulation group to carry out model data comparison of M–I coupling.

We continued software development of time-frequency analysis (Fourier and wavelet) of spacecraft and ground-based measurements for the investigation of the response of the M–I system to storm and substorm excitation.

We continued collaboration with the University of Washington for time-frequency analysis of auroral dynamics using Sondrestrom radar and Polar UVI measurements and with the University of Alaska and University of Iowa to intercalibrate Polar UVI, VIS, and Sondrestrom measurements of ionospheric conductivities.

May 1998. There were three runs totaling 33 hours of experiments coordinated with ISTP satellites to investigate the physics of M–I coupling during substorm expansions. The intervals selected were

04–05 May	18–05 UT
20–21 May	23–10 UT
30–31 May	18–05 UT

Two talks and one poster were presented at the Spring AGU Meeting in Boston, Massachusetts, during the week of 26–29 May.

The first talk was "On the Relationship Between Ionospheric and Magnetospheric Convection During the Passage of Solar Wind Disturbances," by E.R. Sánchez, J.D. Kelly, K.B. Baker, J. Borovsky. M. Thomsen, T. Mukai, and Y. Saito.

The second talk (invited) was "Radio Sensing of the Ionosphere: New Findings and Challenges," by E.R. Sánchez.

The poster (invited) was "Coordinated ISTP and GEM Substorm Campaign, January 1 and 2, 1997," by N.J. Fox, M. Brittnacher, L.A. Frank, K. Liou, A.T. Lui, H.J. Opgenoorth, J.M. Ruohoniemi, E.R. Sánchez, J.B. Sigwarth, and J.A. Slavin.

We continued software development of time-frequency analysis (Fourier and wavelet) of spacecraft and ground-based measurements for the investigation of the response of the M–I system to storm and substorm excitation.

We continued collaborations with the University of Washington for time series analysis of nightside auroral properties using Sondrestrom radar and Polar UVI measurements and with the University of Alaska and University of Iowa to intercalibrate Polar UVI, VIS, and Sondrestrom measurements of ionospheric conductivities.

June 1998. There were three Sondrestrom radar experiments totaling 33 hours of radar time coordinated with ISTP and IMP-8 satellites to determine the physics of the lower-latitude boundary layer. The intervals selected were

10–11 June	22–10 UT
15–16 June	22–08 UT
20–21 June	20–05 UT

Dr. Sánchez attended the Geospace Environment Modeling (GEM) Workshop in Snowmass, Colorado, 15–19 June. Dr. Sánchez presented results of the collaboration among SRI and other ISTP PIs concerning substorm expansion phase measurements and interpretation.

We continued software development of time-frequency analysis (Fourier and wavelet) of spacecraft and ground-based measurements for the investigation of the response of the M–I system to storm and substorm excitation.

We continued collaborations with the University of Washington for time-series analysis of nightside auroral properties using Sondrestrom radar and Polar UVI measurements. Collaborations with the University of Alaska and University of Iowa to intercalibrate Polar UVI, VIS, and Sondrestrom measurements of ionospheric conductivities also continued.

July 1998. There were two experiments totaling 28 hours coordinated with ISTP and IMP-8 satellites to determine the physics of the lower-latitude boundary layer. The intervals selected were

06–07 July	22–09 UT
11–12 July	22–08 UT
16–17 July	22–05 UT

We continued software development of time-frequency analysis (Fourier and wavelet) of spacecraft and ground-based measurements for the investigation of the response of the M–I system to storm and substorm excitation.

We continued collaborations with the University of Washington for time-series analysis of nightside auroral properties using Sondrestrom radar and Polar UVI measurements and with the University of Alaska and University of Iowa to intercalibrate Polar UVI, VIS, and Sondrestrom measurements of ionospheric conductivities.

August 1998. There were two experiments totaling 17 hours coordinated with ISTP and IMP-8 satellites to determine the physics of the lower-latitude boundary layer and the substorm M–I coupling. The intervals selected were

06–07 August	2200–0815 UT
11–12 August	2200–0500 UT

There were five experiments totaling 10 hours coordinated with FAST and AKEBONO satellites to measure the strength of mechanisms that contribute to the flow of ionospheric ions into the magnetosphere. The intervals selected were

06 August	2000–2200 UT
07 August	0815–1015 UT
08 August	0800–1000 UT
09 August	0800–1000 UT
10 August	0730–0930 UT

We continued software development of time-frequency analysis (Fourier and wavelet) of spacecraft and ground-based measurements for the investigation of the response of the M–I system to storm and substorm excitation.

We continued collaborations with the University of Washington for time-series analysis of nightside auroral properties using Sondrestrom radar and Polar UVI measurements and with the University of Alaska and University of Iowa to intercalibrate Polar UVI, VIS, and Sondrestrom measurements of ionospheric conductivities.

4 Summary

Over the course of this contract, the IST mission became a reality and proved to be one of NASA's success stories. SRI and the NSF-sponsored Sondrestrom radar contributed significantly to the success. We provided dedicated radar experiment time with operation modes specifically designed to complement the ISTP spacecraft. Data collected during coronal mass ejection events indicated that at times significant energy is fed from the ionosphere to the magnetosphere. A model of global conductance is emerging from combined POLAR and Sondrestrom data sets. We initiated a study to investigate the behavior of the global energy budget during the evolution of magnetospheric storms and substorms using a number of ground-based and satellite data sets.

This project provided the resources for the following publications:

Doe, R.A., J.D. Kelly, D. Lummerzheim, G.K. Parks, G.A. Germany, and J. Spann, Initial comparison of POLAR UVI and Sondrestrom IS radar estimates for auroral energy flux, *Geophys. Res. Lett.*, 24, 999, 1997.

Kozyra, J.U., M.-C. Fok, E.R. Sánchez, D.S. Evans, D.C. Hamilton, and A.F. Nagy, "The role of precipitation losses in producing the rapid early recovery phase of the Great Magnetic Storm of February 1986," *J. Geophys. Res.*, 103, 6801, 1998.

Sánchez, E.R., "What kind of constraints does the problem of global geospace circulation impose on the specification of a spacecraft constellation?," *Science. Closure and Enabling Technologies for Constellation Class Missions,* 10, 1998.

Sánchez, E.R., J.D. Kelly, V. Angelopoulos, T. Hughes, and H. Singer, "Alfvén modulation of the substorm magnetotail transport," *Geophys. Res. Lett.*, 24, 979, 1997.

Sánchez, E.R., J.P. Thayer, J.D. Kelly, and R.A. Doe, " Energy transfer between the ionosphere and magnetosphere during the January 1997 CME event," *Geophys. Res. Lett.*, 25, 2597, 1998.

Sánchez, E.R., M. Thomsen, A.T.Y. Lui, M. Ruohoniemi, T. Mukai, Y. Saito, T. Nagai, V. Angelopoulos, K. Liou, and J. Sigwarth, "How does solar wind pressure control the onset and evolution of substorms?," *J. Geophys. Res.,* submitted 1999.

Sánchez, E.R., A.T.Y. Lui, M. Ruohoniemi, T. Mukai, Y. Saito, T. Nagai, V. Angelopoulos, K. Liou, and J. Sigwarth, "Multipoint observations of reconnection in the magnetotail: When does lobe reconnection start?," *J. Geophys. Res.,* submitted 1999.

Our collaboration with ISTP PIs continues under NASA contract number NAS5-99173.

14 September 1999

Ms. Loren Kruger
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Goddard Space Flight Center
Greenbelt Road
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Reference: Contract NAS5-31185
(SRI Project P01431)

Dear Ms. Kruger:

SRI International is pleased to submit our Final Report entitled "High-Latitude Incoherent-Scatter Radar Measurements for the ISTP Program." This report has been prepared in accordance with the requirements of the referenced contract.

Technical questions concerning this report should be addressed to Dr. John D. Kelly at (650) 859-3749; all other matters should be addressed to me at (650) 859-4424.

Sincerely,

Margaret Baxter
Senior Contract Administrator

Cc: Dr. Steve Curtis, Code 695

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