Unclassified

SECURITY CLASSIFICATION OF THIS PAGE

②

REPORT DOCUMENTATION PAGE

AD-A264 750

1a. REPORT SECURITY CLASSIFICATION	1b. RESTRICTIVE MARKINGS
2a.	3. DISTRIBUTION/AVAILABILITY OF REPORT
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	Approved for public release; Distribution unlimited

4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S)
	AFOSR-TR- 3 0204

6a. NAME OF PERFORMING ORGANIZATION	6b. OFFICE SYMBOL *(If applicable)*	7a. NAME OF MONITORING ORGANIZATION
Utah State University		AFOSR/NL

6c. ADDRESS *(City, State and ZIP Code)*	7b. ADDRESS *(City, State and ZIP Code)*
CASS, UMC 4405 Logan, Utah 84322-4405	Building 410 Bolling AFB, D.C. 20332

93-10735

8a. NAME OF FUNDING/SPONSORING ORGANIZATION	8b. OFFICE SYMBOL *(If applicable)*	9. PROCUREMENT INSTRUMENT
AFOSR	NC NL	AFOSR-90-0026

8c. ADDRESS *(City, State and ZIP Code)*	10. SOURCE OF FUNDING N
Building 410, 110 Duncan Ave suite 0115 Bolling AFB, D.C. 20332-0001	

PROGRAM ELEMENT NO.	PROJECT NO.	NO.	NO.
61103D	3484	HS	

11. TITLE *(Include Security Classification)* USU Center of Excellence in Theory & Analysis of the Geoplasma Environment

12. PERSONAL AUTHOR(S)
Schunk, Robert Walter

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT *(Yr., Mo., Day)*	15. PAGE COUNT
Final	FROM 89/10/01 TO 92/09/30	1993 February 17	27

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*
FIELD	GROUP	SUB. GR.	Modelling, Theory; Analysis; Ionosphere; Magnetosphere; Thermosphere; Densities; Temperatures; Velocities; Instabilities

19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

A team of ten Ph.D. scientists and several graduate students was assembled at USU to work in close collaboration with scientists at the Air Force Geophysics Laboratory on a number of problems that are relevant to Air Force systems, including OTH radars, communications, and orbiting space structures. The overall goal of the research was to obtain a better understanding of the basic chemical and physical processes operating in the geoplasma environment, including the ionosphere, thermosphere, and magnetosphere. Some of the specific tasks included the following: (1) Studies of ionospheric structure and irregularities; (2) Study the feasibility of developing better operational ionospheric models; (3) Conduct model/data comparisons in order to validate the ionospheric models; (4) Study plasma electrodynamics in the high latitude ionosphere; (5) Study magnetosphere-ionosphere coupling problems; (6) Continue the development of a thermospheric circulation model; (7) Study plasmasphere refilling problems; (8) Study OTH ray tracing problems at high latitudes; and (9) Study certain spacecraft-environment interaction problems, including those related to high-voltage power sources, spacecraft outgassing, artificial plasma cloud expansion, and spacecraft charging at LEO altitudes.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT	21. ABSTRACT SECURITY CLASSIFICATION
UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☒ DTIC USERS ☐	Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE NUMBER *(Include Area Code)*	22c. OFFICE SYMBOL
Lt. Col. J. Stobie	(202) 767-4960	

DD FORM 1473, 83 APR EDITION OF 1 JAN 73 IS OBSOLETE. Unclassified

SECURITY CLASSIFICATION OF THIS PAGE

Final Technical Report

USU Center of Excellence in Theory and
Analysis of the Geo-Plasma Environment

By: R.W. Schunk
           Center for Atmospheric and Space Sciences
           Utah State University
           Logan, Utah 84322-4405

For: Department of the Air Force
           AFOSR/NC
           Directorate of Chemical and Atmospheric Sciences
           Bolling Air Force Base
           D.C. 20332-6448

Attention: Lt. Col. Stobie

Grant: AFOSR-90-0026

1. INTRODUCTION

A team of ten Ph.D. scientists and several graduate students was assembled at USU in order to establish a 'Center of Excellence in Theory and Analysis of the Geo-Plasma Environment.' The USU scientists worked in close collaboration with colleagues at the Air Force Phillips Laboratory in Bedford, Massachusetts, on a number of problems that were relevant to Air Force systems, including OTH radars, communications, and orbiting space structures. The overall goal of the research was to obtain a better understanding of the basic chemical and physical processes operating in the geoplasma environment, including the ionosphere, thermosphere, and magnetosphere. Some of the more specific goals were as follows:

1. Study the production, transport and decay of ionospheric density structures. This included studies of the main electron density trough, sun-aligned arcs, and plasma blobs.

2. Assist in the development of better operational ionospheric models for the Air Force. This included running our numerical model of the global ionosphere for numerous geophysical cases so that the results could be incorporated into the AWS *Ionospheric Specification Model.*

3. Conduct model/data comparisons in order to validate the ionospheric models.

4. Develop a ray tracing code for our global ionospheric model so that we could support AFPL's OTH radar compaigns.

5. Explore methods of incorporating the AFPL particle precipitation energy index in both magnetospheric convection and particle precipitation models, which are inputs to the ionospheric and thermospheric specification models.

6. Study plasma convection characteristics at high latitudes with the emphasis on northward interplanetary magnetic field (IMF) conditions.

7. Study magnetosphere-ionosphere coupling problems, including wave excitation associated with the polar wind and energetic ion outflows. We also studied the electrical coupling and currents in the magnetosphere-ionosphere system.

8. Continue the development of a high-resolution multi-species thermospheric circulation model. This is relevant to AWS's interest in developing a real-time *Thermospheric Specification Model.*

9. Study plasmasphere refilling characteristics associated with magnetic storms and substorms.

10. Study certain spacecraft-environment interaction problems, particularly those related to solar cell changing, high-voltage power sources, artificial plasma cloud expansion, and outgassing from large structures orbiting at ionospheric altitudes.

2. USU-PHILLIPS LABORATORY COLLABORATIVE EFFORTS

We have had on-going collaborative projects with several scientists at the Phillips Laboratory in Bedford, Massachusetts. The names of the PL scientists and their branches, together with a brief description of the research, are given in the following paragraphs.

2.1 D. Anderson (LIS)

We helped D. Anderson develop a *High Latitude Ionospheric Specification Model* for Air Weather Services. Our original effort involved running our numerical ionospheric model for both the northern and southern hemispheres for a range of solar cycle, seasonal, magnetic activity, and IMF conditions. A total of 108 ionospheric simulations were run. R. Daniell of Computational Physics Incorporated (CPI) 'fit' our calculated density distributions as a function of altitude, latitude, longitude, season, solar cycle, magnetic activity, and universal time using relatively simple functions. These background density distributions were then incorporated into his Parameterized Real-Time Ionospheric Specification Model (PRISM). During the last year, D. Anderson requested that we determine the accuracy of the fitting procedure and D. Crain in our group undertook this effort. D. Crain found that the parameterized model developed by R. Daniell reproduced the original density distributions very well and that the parameterized version of our numerical ionospheric model was much more representative of the high-latitude ionosphere than existing models.

At the request of D. Anderson, J. Sojka spearheaded an inter-model comparison of the noon sector mid-latitude F region. This inter-model comparison, PRIMO, is a CEDAR activity, but is, to a large extent, the outgrowth of USU-PL interactions in ionospheric model and data comparisons. The problem being focussed on in this research area is the difficulty during solar *maximum conditions of reproducing the observed* N_mF_2 values. The models are generally too low. A presentation of these results was made at the CEDAR 1991 and 1992 meetings.

2.2. S. Basu (LIS)

In collaboration with S. Basu and C. Valladares (Boston College) we studied the properties of sun-aligned arcs. In one effort, the emphasis was on the ionospheric modification caused by a typical sun-aligned polar cap arc. The radar, optical, and satellite data pertaining to these arcs that were available at Phillips Laboratory were used to define the arc features and our ionospheric model was then run using these parameters to elucidate the ionospheric response to the arc. A paper describing this work has been published (paper 39).

2.3 J. Buchau (LIS)

In support of J. Buchau's OTH radar work, Captain P. Citrone interfaced our time-dependent, high-resolution ionospheric model with the *Jones and Stephenson* [1975] ray-tracing program to examine the effects of 3-D electron density gradients on ray propagation. We carried out initial validation tests of the ray paths through this ionosphere. These tests indicated an azimuthal position bias as the ray paths are bent by horizontal electron density gradients. Work was underway to simulate ionospheric conditions for a PL-OTH campaign. The potential value of this physical model is that it can generate physically realistic ionospheric conditions, which can be used as a reference for ray-tracing simulations on a specific day, time, and location. *In situ* data can then be used to modify or add fine structure as appropriate. Or, in the absence of data, sensitivity studies can readily be carried out. For his M.S. thesis, P. Citrone studied the effects of the trough-auroral boundary on the propagation and bending of HF radio waves.

2.4. *H. Carlson* (LIS)

Previously, we conducted a number of simulations of the high latitude ionosphere for H. Carlson so that we could study trough formation mechanisms. The study was motivated by EISCAT incoherent scatter radar data, which showed the rapid formation of a plasma density trough. D. Crain in our group is comparing the preliminary model simulations with the EISCAT data to determine if additional simulations are needed.

H. Carlson emphasized the need to understand the electrodynamics of a sun-aligned polar cap arc. He was interested in understanding how the system self-consistently evolves from a fairly uniform ionosphere to a polar cap arc situation. He was also interested in determining what contribution the F region ionization makes to the overall conductivity of the sun-aligned arc. In response to these interests, L. Zhu initiated the development of a time-dependent model of a sun-aligned arc in which the electrodynamics are treated self-consistently in the frame of the magnetosphere-ionosphere system. The model development was completed during the last year and the model is currently being used to study the temporal development and evolution of an arc driven by magnetospheric processes (paper 40).

2.5 *D. Cooke* (PHK)

We studied a range of spacecraft-environment interaction problems that are relevant to D. Cooke's interest. These included outgassing from the Space Shuttle, the expansion of artificial plasma clouds, solar cell charging processes, and high-voltage spheres in the ionosphere. Several papers were written on these topics and these are briefly described in the next section and listed in the URI Publications section

2.6 *W. Denig* (PHG)

The very strong geomagnetic storm of 13 March 1989 was the focus of a close collaboration with Dr. W. Denig. The first draft of the publication was completed. The extensive DMSP data base for this March, 1989, period was interpreted by W. Denig and used both as an input data set to our global ionospheric model, and as an *in situ* plasma density reference data set to compare against the model results. The pre-storm observation and model agreement was good. During the storm phase, the comparisons were very good. Both DMSP and TEC data were used for the comparisons.

2.7. *S. Gussenhoven* (PHP)

T. Frooninckx, an AFIT student, followed up S. Gussenhoven's DMSP spacecraft charging work by using DMSP charging data and ambient plasma densities from the TDIM to study the solar cycle dependence of spacecraft charging. This work produced an M.S. thesis for Captain T. Frooninckx and two publications (papers 29 and 34).

2.8. *D. Hardy* (PHP)

The particle precipitation data obtained by D. Hardy from instruments on the DMSP satellites are crucial to real-time ionospheric and thermospheric specification models. We worked with D. Hardy to explore ways of using his improved particle precipitation energy (PPE) index in the specification models so as to obtain more reliable predictions for the ionospheric and thermospheric parameters.

2.9. *J. Klobuchar* (LIS)

In conjunction with J. Klobuchar at Phillips Laboratory and P. Doherty at Boston College, we began a study of the TEC variation observed at various high-latitude stations compared to those predicted by our ionospheric model. Specifically, TEC values predicted by our time-dependent ionospheric model were compared with the diurnal variations of TEC measured at the Goose Bay, Hamilton Bay, and Poker Flat observing sites and, in general, very good agreement between model and data was achieved. A paper on this comparison has been written (paper 38).

2.10. *N. Maynard* (PHG)

We had a collaborative effort with N. Maynard concerning the shape of the plasma convection pattern for northward IMF, when the flow in the polar cap can be sunward. L. Zhu in our group calculated the field-aligned current signature associated with a distorted 2-cell convection pattern so that it could be compared with that obtained from a multi-cell convection pattern. Both signatures were compared with magnetometer data to determine whether the distorted 2-cell or multi-cell convection pattern is more appropriate for northward IMF. Two papers were published on this subject (papers 23 and 33).

2.11. *E. Weber* (LIS)

We used E. Weber's rocket data to see if we could deduce the electric field and particle precipitation features associated with sun-aligned arcs in the polar cap. Eventually, we wanted to conduct ionospheric simulations including sun-aligned arcs. However, before this could be done, we needed to calculate the electron heating and ion production rates due to energetic electron precipitation in the arc. One of our AFIT students, D. Payne, therefore, initiated the development of an auroral electron deposition code. This code was then used in a parameter study of the ion production rates in sun-aligned arcs for a wide range of geophysical conditions. This work produced an M.S. thesis for Captain Payne.

2.12. *J. Whalen* (LIS)

J. Sojka met with J. Whalen during his July 19, 1991, visit to Hanscom Air Force Base. They discussed J. Whalen's recent work on the extensive IGY ionosonde data base, which covers both the northern and southern hemispheres. They discussed, at some length, his equinox data, which show the same K_p dependence for the afternoon sector troughs in the northern and southern hemispheres. The conjugacy is remarkably strong considering the various shortcomings in global coverage and available days in the equinox periods during IGY. They discussed a joint follow-up to this work using the USU northern and southern hemisphere computer simulations that were run for D. Anderson (the 108 simulations).

J. Whalen has also been looking at the stations in the polar cap which, during winter conditions, see a peak density at magnetic noon rather than geographic (solar) noon. This maximum is a convection feature. He had data from up to 5 stations at different longitudes but at the same magnetic latitude (~75°) in the southern hemisphere. Each had a distinctly different solar-magnetic noon offset and each showed the magnetic noon peaking. These data relate to the phenomenon referred to as the "tongue of ionization." This work was at an early stage, but we were interested in following up with an ionospheric model study and a subsequent comparison with his data to see if our ionospheric model properly describes the 'tongue' feature. Unfortunately, this work was not completed.

3. AWS PERSONNEL

Four Air Force personnel from Air Weather Services completed their M.S. theses during the last three years. Their names, theses titles, major professors, and completion years are listed below.

1. Gary R. Huffines
   Title: Using the USU Ionospheric Model to Predict Radio
   Propagation Through a Simulated Ionosphere
   Date: 1990
   Major Professor: Jan J. Sojka

2. Thomas B. Frooninckx
   Title: High-latitude Spacecraft Charging in Low-Earth Polar Orbit
   Date: 1991
   Major Professor: Jan J. Sojka

3. David R. Payne
   Title: Electron Heating and Ion Production Rates in Auroral and
   Sun-Aligned Arcs
   Date: 1991
   Major Professor: Robert W. Schunk

4. Peter J. Citrone
   Title: The Effect of Electron-Density Gradients on Propagation
   of Radio Waves in the Mid-Latitude Trough
   Date: 1991
   Major Professor: Jan J. Sojka

In addition, two new Air Force students, W. Cade and M. Loveless, recently joined our group and began working on research topics for their M.S. theses.

4. SCIENTIFIC ACCOMPLISHMENTS

In addition to the USU-PL collaborative efforts that were discussed in Section 2, we also conducted additional studies as part of our University Research Initiative (URI) program. In total, *42 scientific papers* have been written, *4 M.S. theses* have been completed, and *56 presentations* have been given at both national and international meetings during the last three years of our URI program. In addition, there have been several trips to PL in Boston, Massachusetts, and AWS in Colorado Springs, Colorado, in order to coordinate joint activities. Our URI publications, presentations, and a travel summary are included in this report.

Because of the large number of publications, we cannot discuss all of the research that we conducted with partial support from our URI grant. Therefore, in the subsections that follow, we briefly highlight *some* of the scientific accomplishments.

4.1. *Ionosphere Structure Modelling*

Large-scale density structures are a common feature in the high latitude ionosphere. They have been observed in the dayside cusp, polar cap, and nocturnal auroral region over a range of altitudes, including the E-region, F-region, and topside ionosphere. Relative to background densities, the perturbations associated with large-scale density structures vary from about 10% to a factor of 100. These structures can be created by a variety of mechanisms, including particle precipitation in the dayside cusp, in sun-aligned polar cap arcs and in the nocturnal auroral oval; by structured electric fields; and by the break-up of convection patterns. Because of the effect of plasma density structures on OTH radars and communications, we had an on-going program to study such features. Our most recent emphasis was on the ionospheric modifications associated with sun-aligned polar cap arcs (paper 39).

Our 3-dimensional ionospheric model was used in a comprehensive parametric study of the ionospheric modifications associated with sun-aligned polar cap arcs (paper 39). The key arc parameters were systematically varied, including the width, the electric field structure, and the precipitation energy flux and characteristic energy. The main conclusions of our study are that the ionospheric response to arcs is nonlinear, with the largest modifications occurring for intermediate arc widths and electric field strengths, and that the E and F region responses are very different. Additionally, we found that as the ionospheric plasma drifts into, across, and then out of a sun-aligned arc, it is modified in a nonuniform manner in response to the production and heating in the arc. The ionospheric modification is characterized by enhanced E-region densities within the precipitation region, enhanced F-region densities due to production from the soft component of precipitation and to upward diffusion from the lower ionosphere, and enhanced topside densities due to increased scale heights associated with the ion and electron heating in the arc. As the flux tube convects out of the arc, the E-region densities decrease rapidly due to the fast recombination of the molecular ions. However, the F-region density actually increases as the flux tube first leaves the arc due to downward diffusion from the topside ionosphere, which is in response to the decrease in T_e and T_i. Subsequently, the F-region density decays slowly due to the relatively slow O^+ recombination rate. This produces the distinctive '*candle flame in the wind*' in a contour plot of N_e, with cross arc convection corresponding to the wind.

4.2. *Operational Ionospheric Models*

Because the Air Weather Service is interested in improving its operational ionospheric models, we devoted a significant effort toward studying both numerical and empirical models of the ionosphere. We tried to develop hybrid models, whereby empirical and numerical approaches are blended to obtain a reliable but efficient ionospheric model. This research has led to three publications (papers 5, 6, and 10). We helped in the development of a semi-empirical model of the

high latitude ionosphere called HLISM (paper 5). HLISM consists of a set of semi-empirical regional models (trough, auroral oval, and polar cap) coupled with a parameterized version of output from the USU numerical model of the high latitude ionosphere. HLISM is intended to be driven by real-time data so that it can better describe high latitude features, such as the main trough, the polar cap, and the auroral oval, in real time. Since HLISM was restricted to the northern polar region, it was subsequently extended to both low latitudes and the southern polar region (paper 6). These model developments will be incorporated into a global version of the Ionospheric Conductivity and Electron Density (GLOBAL ICED) model that will be used by the Air Weather Service at the new Space Forecast Center. In another study (paper 10), we used a different empirical approach in an effort to develop a computationally fast model of the northern high latitude ionosphere.

4.3. Model/Data Comparisons

Typically, we devoted an appreciable amount of time in conducting model-data comparisons in order to validate our global ionospheric model. We completed two model-data comparisons (papers 3 and 13). The first study was concerned with the 'main' or 'mid-latitude' electron density trough, while the second study involved the 'polar hole.' The main trough study was motivated by work done by J. Whalen at PL. He studied a large database of IGY ionosonde data and showed that the F-region trough exhibits both a strong magnetic activity dependence and a strong longitudinal dependence. We conducted a series of model studies and showed that the strong longitudinal dependence is connected with the offset of the geomagnetic axis from the geographic axis, while the magnetic activity dependency is associated with the westward plasma convection in the afternoon sector (further details are given in paper 3). The polar hole is also a region of low electron density, but this region appears in the polar cap and is not always present. Recently, W. Hoegy of NASA Goddard Space Flight Center successfully combined plasma density data from a variety of satellites spanning more than a solar cycle and then described the resulting density morphology via an empirical model. Contained in this empirical model was information on the polar hole and its variation with season, hemisphere, universal time, and IMF By component. We conducted a series of ionospheric model simulations and verified that the polar hole dependencies seen in the data are properly described by our numerical model (see paper 13).

4.4. OTH Radar Campaign

Radio waves propagating through the ionosphere, a medium of inhomogeneous refractive index, are severely perturbed in both amplitude and direction. The description of the refractive index requires knowledge, not only of the plasma density, but also its spatial gradients. Empirical models based on simple profile geometries do not have realistic horizontal spatial gradients. However, the TDIM model has the potential to simulate these gradients if the magnetospheric precipitation and convection electric field patterns are available. Hence, we pursued research to test this hypothesis.

As a first step in this direction, a 3-D ray tracing program was coupled to the TDIM model. This initial phase verified the role of spatial density gradients in determining the ray path through the ionosphere. We then engaged in reconstructing the ionospheric trough density gradients associated with a series of PL-OTH campaign data sets. Data from DMSP, PL auroral observatory aircraft, ground-based digisondes, magnetometers, and incoherent scatter radars were analyzed. These were then compared with climatological level TDIM runs to determine how to introduce the detailed structure (weather) into the TDIM simulation, the result of which was a combined TDIM-ray tracing program to simulate the PL-OTH campaign ray paths.

4.5. *Magnetosphere-Ionosphere Coupling via Electric Fields*

It is well known that the electric fields, particle precipitation, auroral conductivity enhancements, and Birkeland currents that couple the magnetosphere-ionosphere system are strongly dependent upon the direction of the IMF. When the IMF is southward, the Birkeland (or field-aligned) currents flow in the Region 1 and 2 current sheets, the F region plasma convection exhibits a 2-cell structure with antisunward flow over the polar cap, the conductivity enhancements are confined to the statistical auroral oval, and the auroral electron precipitation is also confined to the classical oval. However, when the IMF is northward, the situation is considerably more complicated and less clear. In this case, an additional field-aligned current system occurs in the polar cap called the NBZ currents; plasma convection can be sunward in the polar cap and the pattern can assume multi-cell, severely distorted two-cell or turbulent characteristics; and particle precipitation occurs in the polar cap that can be uniform, in the form of multiple sun-aligned arcs, or in a θ-aurora configuration.

We conducted several theoretical studies in an effort to elucidate the ionosphere-magnetosphere coupling processes during northward IMF. One of our efforts involved the use of our electrodynamic model to investigate the 'large-scale' field-aligned currents that exist in the polar cap during northward IMF (papers 23 and 33). With our electrodynamic model, we solve Ohm's law and the current continuity equation so as to obtain self-consistency between the ionospheric conductivity, field-aligned current, horizontal E-region current, and convection electric field. In one effort, we used the USU conductivity model and conducted a systematic study of the influence of the ionospheric conductance on the form of the field-aligned current associated with the Heppner-Maynard 'distorted two-cell' convection pattern (paper 23). Our modelling results indicated that, contrary to previous claims, the NBZ current can be associated with the distorted two-cell convection pattern for most of the ionospheric conductivity conditions. We found that the seasonal and auroral activity conditions significantly affect the ionospheric conductivity and that the conductivity variations can influence the basic features of the NBZ current system associated with the distorted two-cell convection pattern. Based on these results, we suggested that the field-aligned current system observed by the MAGSAT satellite might imply a distorted two-cell convection patterns, and that a four-cell pattern is more likely to occur when the IMF is due north or very close to the north.

4.6. *Magnetosphere-Ionosphere Coupling via Ion Outflow*

The outflow of thermal plasma from the topside ionosphere at high latitudes (i.e., the polar wind) is very important because the escaping thermal plasma drains the ionosphere and mass-loads the magnetosphere. However, it is difficult to model the outflow because the polar wind is collision-dominated at low altitudes, passes through a transition region, and then becomes collisionless at high altitudes. Over the years, various mathematicals have been used to describe the outflow (hydrodynamic, collisionless kinetic, generalized transport, etc.), but the different models have limitations, particularly in the transition region from collision-dominated to collisionless flow. In an effort to better understand the strengths and limitations of the various models, we used different mathematical models for the same polar wind conditions so that a direct comparison of results could be made.

We completed three papers dealing with the validity of the various mathematical models of the polar wind and related flows (papers 19, 24, and 31). In one study (paper 24), we compared, in as consistent a manner as possible, solutions to the bi-Maxwellian-based 16-moment set of transport equations with those obtained from a semikinetic model, assuming boundary conditions characteristic of both supersonic and subsonic flows in the terrestrial polar wind as well as supersonic flow in the solar wind. For each case in which transport and semikinetic solutions were compared, three separate semikinetic solutions were generated. These three semikinetic solutions assumed the particle distribution function at the baropause to be an isotropic Maxwellian,

a bi-Maxwellian, and a bi-Maxwellian-based 16-moment expansion with zero stress, respectively. Our study demonstrated several important points: (1) For supersonic "collisionless" flows, the 16-moment transport theory and the semikinetic model assuming a 16-moment distribution at the baropause are almost identical in their predictions, even for the higher-order moments (parallel and perpendicular heat flows). This is true for both polar and solar wind conditions. (2) The semikinetic solutions assuming either a Maxwellian or a pure bi-Maxwellian at the baropause also show extremely close agreement with the transport results for the lower-order moments (density, drift velocity, and parallel and perpendicular temperatures), but are less accurate in their heat flow predictions. (3) The nearly precise agreement between the 16-moment transport solutions and the semikinetic solutions with a 16-moment distribution at the boundary, which implicitly contain the full hierarchy of moment equations, indicates that moments higher than heat flow (flow of parallel and perpendicular thermal energy) are not needed to describe the steady-state polar and solar wind cases considered in this study. (4) Because of its underlying assumptions, the semikinetic model is unable to properly describe subsonic H^+ flows. Therefore, a comparison of semikinetic and transport models for subsonic flow conditions must await future advances in the kinetic theory. (5) Collisions are clearly of importance in determining the thermal and heat flow structure of the solar wind. The 16-moment transport model, which incorporates the effects of Coulomb collisions, yields temperature anisotropie at 1 AU that are in agreement with measurements, while the semikinetic model, which is collisionless, does not.

Another important aspect of the polar wind concerns the 'stability' of the flow. As the horizontally convecting ionosphere moves through the dayside cusp region, energetic ions are created at low altitudes, and subsequently, they overtake and penetrate the polar wind at high altitudes. These energetic ion beams passing through the polar wind could destabilize the flow, which would then affect the mass, momentum, and energy coupling between the ionosphere and magnetosphere. In an effort to address this issue, we conducted a systematic study of the effect of O^+ beams on the stability of the polar wind. The cases we considered covered a wide range of electron-to-background ion temperature ratios (0.1, 1, 10) and beam-to-background ion density ratios (0.1, 0.5, 0.9). We found that the polar wind is indeed unstable for a range of conditions. It tends to be more unstable for high electron temperatures and for nearly equal beam and background densities. Further details are given in paper 8.

4.7. *Plasmasphere Dynamics*

With support from our previous AFOSR contract, we constructed the first 3-dimensional, time-dependent model of the plasmasphere. The model is based on a numerical solution of the nonlinear continuity and momentum equations for H^+ ions and electrons, and includes field-aligned flow, cross-L drifts , and corotational electric fields. During this grant period, our 3-dimensional plasmasphere model was extended to include O^+ dynamics and the ion energy equations. This allowed us to get improved predictions for plasmasphere refilling rates after geomagnetic storms as well as to model the thermal structure of the plasmasphere.

4.8. *Spacecraft Charging*

Spacecraft charging of Air Force satellites can lead to serious operational anomalies and, hence, this area of research has direct and practical applications. Most of the charging occurs along geosynchronous orbits as the satellites encounter the energetic particles in the radiation belts, but recent experimental evidence has shown that satellites in low-earth-orbit can also charge to significant potentials. In particular, experimental evidence clearly indicates that Defense Meteorological Satellite Program (DMSP) polar orbiting spacecraft at 840 km can develop electric potentials as severe as -1430 V while at high magnetic latitudes. To explore this charging region, an analysis of DMSP F6, F7, F8, and F9 satellite precipitating particle and ambient plasma measurements taken during periods of high, medium, and low solar flux was performed (papers 29 and 34). One hundred eighty-four charging events ranging from -46 to -1430 V were

identified and an extreme solar cycle dependence was found, as charging is most frequent and severe during solar minimum. Satellite measurements and time-dependent ionospheric model (TDIM) output were used to determine the cause of the solar cycle dependence and to characterize the environments which both generate and inhibit these potentials. The electron precipitation associated with various DMSP charging levels was analyzed; it was suggested that precipitating electrons as low as 2 to 3 keV may contribute to charging, although higher-energy electrons make greater contributions. Secondary electron production due to incident electrons below 1 keV was shown to inhibit charging. The energetic electron fluxes shown to generate charging did not vary significantly over the solar cycle. Instead, DMSP ambient plasma data and TDIM generated results indicated that a variation in the thermal plasma density of over 1 or more orders of magnitude was the cause of the solar cycle dependence, and an ambient plasma density of less than 10^4 cm^{-3} was found necessary for significant negative charging (≥ 100 V) to occur.

4.9. *Solar Cell Operation*

We published six papers dealing with the interaction of solar cell modules with the ionospheric plasma (papers 2, 4, 11, 15, 26, and 35). For future space missions, elevated voltages of hundreds of volts are necessary to minimize mass requirements and resistive losses of solar arrays in orbit. However, these voltages could lead to hazardous conditions, such as anomalous current surges, arcing, and continuous power drains. The actual operating conditions are controlled by the electric field structure at critical locations (i.e., solar cell edges or interconnector-cover glass regions). The electric fields are able to accelerate plasma particles to high energies, which leads to secondary electron emission from the solar cell material by the impacting particles. We used both laboratory measurements and theoretical modelling results to elucidate some of the basic interaction processes associated with high-voltage solar cells. We also considered both positive and negative solar cells, different voltage turn-on times, and different solar cell materials. One of the more important results we found was that arcing can occur on the edges of solar cells not just at the interconnector-dielectric interface.

4.10. *High-Voltage Spheres*

Four of our papers were concerned with the interaction of a high-voltage sphere with the LEO plasma environment (papers 12, 20, 22, and 25). This work was motivated by the fact that high-voltage power sources are being considered for both military and commercial space stations, and the direct interaction of a high-voltage system with the ionospheric plasma could lead to arcing and severe power losses.

In one study (paper 20), we concentrated on the initial interaction of a biased sphere with a magnetized, partially-ionized plasma that had characteristics similar to those found at shuttle altitudes. Positive potentials were suddenly applied to the sphere and the subsequent response of the plasma was modelled via a numerical solution of the time-dependent, three-dimensional, nonlinear fluid equations for the ions and electrons and the Poisson equation. The main goal of the study was to determine the effect of impact ionization and collisions on the sphere-plasma interaction in the presence of outgassed or released neutrals from the Space Shuttle. Simulations were conducted for different neutral species, a range of neutral densities, as well as different magnetic field strengths. The main conclusions of the study are as follows: (1) When a high-voltage sphere is embedded in a magnetized, partially-ionized plasma, an electron density torus tends to form around the sphere in the equatorial plane at early times. The torus rotates about the sphere in the **ExB** direction. If the background neutral gas density is sufficiently high, the electrons accelerated by the strong electric fields associated with the sphere can ionize the gas by impact. At a critical ionization rate, a discharge or breakdown occurs. Collisions, on the other hand, act to decelerate the electrons and modify the space charge configuration (i.e., modify the toroidal shape); (2) For low neutral densities ($\leq 5 \times 10^{11}$ cm^{-3}), collisions and impact ionization are not important; (3) For neutral densities of the order of 10^{12} cm^{-3}, ionization occurs in the

toroidal region where the electron density is elevated, but this impact ionization does not appreciably affect the current collection. In this case, a toroidal density configuration can be maintained without a discharge and the effect of collisions is to broaden the torus; (4) For neutral densities of the order of 10^{13} cm^{-3}, the major ionization still occurs in a toroidal region. However, the ionization causes the plasma density and current collection to increase rapidly. A toroidal discharge is expected in this case; (5) For neutral densities of the order of 10^{14} cm^{-3}, impact ionization occurs all around the sphere in an explosive manner. The discharge is likely to be spherical in this case; (6) The above results are for a magnetic field of 3 gauss. If the magnetic field is reduced and the other parameters are held fixed, the ionization that occurs tends to be more spherical. The current collection also tends to be higher; and (7) Different molecules have different ionization energies, and collision and ionization cross-sections. Of the four species studied, Ar, N_2, and O have very similar properties, and hence, the features discussed above for Ar also apply quantitatively for N_2 and O. However, barium behaves very differently. It has a larger collision cross-section and lower ionization energy. Therefore, for the same conditions, ionization and discharge processes are much easier to trigger in a Ba plasma. Also, compared to Ar, O and N_2, the density distribution, as well as the discharge, tend to be more spherical.

Two papers (22 and 25) involved high-voltage spheres embedded in *unmagnetized* plasmas. In one study, a high 'positive' voltage was applied to the sphere and the effect of different potential rise times was investigated as was the long-term evolution of the sphere-plasma interaction. In the other paper, 'negative' voltages were applied to the sphere and the subsequent sphere-plasma interaction was modelled.

From our simulations we found that after the positive voltage is applied to the sphere, the electrons are accelerated toward the sphere in a few plasma periods and an overshoot oscillation usually follows. The acceleration and the density build-up of the electrons around the sphere produce a high current collection by the sphere. This high current level usually lasts a few hundred plasma periods or a few ion plasma periods. Then the ion motion becomes significant. The ions are accelerated away from the sphere and an ion density shell forms and propagates away from the sphere. The ion density shell blocks the electron flow and reduces the current. The deceleration of the electrons by the ion shell leads to an electron density enhancement so that a double layer structure forms. The double layer propagates outwards and eventually slows down and disappears. This process lasts a few thousand plasma periods. During this time, the current first decreases to a minimum and then slowly reaches a constant level. Low frequency oscillations (lower than the ion plasma frequency) may appear due to the overshoot of the ion density configuration about its equilibrium position. However, a steady state is eventually reached.

In the steady state, the ion density satisfies the Boltzmann relation. In some regions near the sphere, the ions are completely depleted and only electrons are present. There is also a region where the ion and electron densities are unequal. The region with a net space charge is the sheath region. This region can be comparable to or larger than the sphere radius, depending on the applied voltage. The sheath thickness estimated from the electron and ion density profiles agrees with the Langmuir-Blodgett theory. Far away from the sphere, the plasma is unperturbed. Between the sheath region and unperturbed plasma is the presheath, where there is no net space charge, but both the electron and ion densities differ from the unperturbed value. The thickness of the presheath increases with higher applied voltages. The current density from the simulation is 2 to 5 times higher than that from the simple Langmuir-Blodgett theory.

The method of applying the voltage on the sphere affects the temporal evolution. If the voltage is applied according to an exponential law with a rise time τ, only the electron motion at very early times is affected if $\hat{\tau} \leq 1$. For $\hat{\tau} = 0.1$, the result is almost identical to the result for $\hat{\tau} = 0$ (a step function application of the voltage). For $\hat{\tau} = 1.0$, the electron density and velocity near the sphere are lower than those for $\hat{\tau} = 0$ or 0.1 before five plasma periods, and so is the current.

Afterwards, the results are the same. For $\hat{\tau} = 10$, there are several differences. The acceleration of the electrons is much lower. The overshoot oscillation at early times does not occur. The ion motion is affected. The formation of the density shell is delayed. For different $\hat{\tau}$'s, the system reaches the steady state in slightly different ways. For a small $\hat{\tau}$, the ion density configuration may pass the final equilibrium location and oscillate about it. For a large $\hat{\tau}$, such an overshoot oscillation is more unlikely.

In our paper dealing with high 'negative' voltage spheres, simulations were conducted for a range of voltages (-10 to -10,000 V) and for plasma densities from 10^4 to 10^6 cm^{-3}. The temporal evolution of the plasma was followed all the way to the steady state. In all simulations, there were certain qualitative similarities in the plasma response. At very early times, the rapid electron motion away from the sphere resulted in an electron overshoot oscillation (ringing). The frequency of this oscillation was a fraction of the electron plasma frequency and increased slowly with the magnitude of the voltage on the sphere. For high plasma densities, the oscillation was damped as the initial ion current surge to the sphere developed. Subsequently, the ion current reached a peak, decreased, and then attained a steady-state level. The final sheath and presheath sizes for negative-voltage spheres were similar to positive-voltage spheres with the same potential magnitude, although the temporal evolution of the plasma was different for positive and negative spheres. In the steady state and for a given plasma density, the ion density structure in the sheath varied with the applied voltage on the sphere. As the voltage increased, an ion density hole developed around the sphere in the sheath region. Near the sphere the ion density was relatively high, but the ion density decreased with distance, reached a minimum, and then increased to the background value. For a -10,000 V sphere, the ion density near the sphere was also four times larger than the background plasma density.

4.11. *Artificial Plasma Cloud Expansion*

We conducted three-dimensional simulations of the expansion of artificial plasma clouds in the ionosphere at low-earth-orbit (LEO) altitudes (paper 30). Such clouds can be created by spacecraft outgassing followed by ionization or by the direct injection of a neutral gas into the ionosphere. In the study, a 3-dimensional, time-dependent fluid model was used to study the ionization and plasma expansion characteristics of barium clouds. Neutral gas clouds with a total mass of 1 kg were released with a spherical Gaussian density distribution and the subsequent photoionization by solar UV radiation and ion cloud expansion were modelled. Three cases were considered: A cloud without a directional velocity; a cloud with an initial velocity of 5 km/s across the $\vec{B}$ field; and a cloud with initial velocity components of 2 km/s both along and across the $\vec{B}$ field. For the cloud without a directional velocity, the ionization occurs in a spherical volume. The resulting Ba$^+$ cloud expands along the $\vec{B}$ field and the Ba$^+$ density distribution gradually becomes ellipsoidal from the inner to the outer parts of the Ba$^+$ cloud. The electrostatic snowplow effect associated with the expanding Ba$^+$ cloud creates a hole in the O$^+$ background at the center of the Ba$^+$ cloud and creates two O$^+$ density bumps on the two sides of the Ba$^+$ cloud. For the neutral gas release with an initial velocity across the $\vec{B}$ field, the resulting Ba$^+$ cloud has a comet-like density distribution at early times. Eventually, because of the expansion along the $\vec{B}$ field, the Ba$^+$ cloud becomes sheet-like. Again, there are two O$^+$ density enhanced regions and one O$^+$ density depletion region in the background ionosphere. For these two cases, although there are O$^+$ density depletions, there are no electron density (total plasma) depletions. When the neutral gas cloud has initial velocity components both along and across the $\vec{B}$ field, the situation is quite different. The resulting Ba$^+$ cloud has a complicated density distribution. The Ba$^+$ snowplow effect creates an O$^+$ density hole on one side and an O$^+$ density bump on the other side of the expanding Ba$^+$ cloud. There is a net plasma depletion on the side opposite to the Ba$^+$ cloud motion along the $\vec{B}$ field.

URI Personnel

Ph.D. Scientists
R. W. Schunk - P.I.

J. J. Sojka

A. R. Barakat

D. J. Crain

H. G. Demars

T.-Z. Ma

W. J. Raitt

H. Thiemann

W.-H. Yang

L. Zhu

Graduate Students
I. Barghouthi

P.-L. Blelly

A. Khoyloo

L. Zhou

W. Cade - AWS

P. Citrone - AWS [Completed Degree Requirement]

G. Huffines - AWS [Completed Degree Requirement]

M. Loveless - AWS

T. Frooninckx - AWS [Completed Degree Requirement]

D. Payne - AWS [Completed Degree Requirement]

Programmers
M. Bowline

E. Kluzek

Administrative Support
J. Folsom

S. Johnson

L. Twede

URI Publications

1. H. G. Demars and R. W. Schunk, Solutions to bi-Maxwellian transport equations for radial solar wind beyond 28 R_s, *Planet. Space Sci., 39*, 435-451, 1991.

2. H. Thiemann, R. W. Schunk, and L. Gerlach, Solar arrays in the LEO-plasma environment: A model for leakage current phenomena deduced from experimental and theoretical studies, *Proc. European Space Power Conf., ESA SP-294*, 809-813, 1989.

3. J. J. Sojka, R. W. Schunk, and J. A. Whalen, The longitude dependence of the dayside *F* region trough: A detailed model-observation comparison, *J. Geophys. Res., 95*, 15,275-15,280, 1990.

4. H. Thiemann, R. W. Schunk, and K. Bogus, Where do negatively biased solar arrays arc? *J. Rockets & Spacecraft, 27*, 563-565, 1990.

5. R. E. Daniell, L. D. Brown, D. N. Anderson, J. A. Whalen, J. J. Sojka, and R. W. Schunk, A high latitude ionospheric specification model, *Proc. of the STP Symposium in Australia*, 1990.

6. R. E. Daniell, D. T. Decker, D. N. Anderson, J. R. Jasperse, J. J. Sojka, and R. W. Schunk, A global ionospheric conductivity and electron density (ICED) model, *Proc. of the Ionospheric Effects Symposium*, 1990.

7. R. W. Schunk and E. P. Szuszczewicz, Plasma expansion characteristics of ionized clouds in the ionosphere: Macroscopic formulation, *J. Geophys. Res., 96*, 1337-1349, 1991.

8. A. R. Barakat and R. W. Schunk, Effect of O^+ beams on the stability of the polar wind, *J. Geophys. Res.*, submitted, 1990.

9. W.-H. Yang and R. W. Schunk, Latitudinal dynamics of steady solar wind flows, *Ap. J., 372*, 703-709, 1991.

10. L. Bossy, S. Pallaschke, K. Rawer, R. W. Schunk, J. J. Sojka, and H. Thiemann, High-latitude ionospheric model, *Adv. Space Res., 11*, 11-14, 1991.

11. H. Thiemann and R. W. Schunk, Field formation around negatively biased solar arrays in the LEO-plasma, *Adv. Space Res., 12*, 143-146, 1992.

12. H. Thiemann, T.-Z. Ma, and R. W. Schunk, High voltage spheres in an unmagnetized plasma: Fluid and PIC simulations, *Adv. Space Res., 12*, 57-60, 1992.

13. J. J. Sojka, R. W. Schunk, W. R. Hoegy, and J. M. Grebowsky, Model and observation comparison of the universal time and IMF B_y dependence of the ionospheric polar hole, *Adv. Space Res., 11*, 39-42, 1991.

14. R. W. Schunk, Model studies of ionosphere/thermosphere coupling phenomena on both large and small spatial scales and from high to low altitudes, *J. Geomag. and Geoelect., 43*, 501-512, 1991.

15. H. Thiemann and R. W. Schunk, Advanced model of solar array-plasma interactions, *Proc. of the ESA Space Environmental Analysis Workshop*, ESA WPP-23, 9 pages, 1990.

16. A. R. Barakat, R. W. Schunk, I. A. Barghouthi, and J. Lemaire, A Monte Carlo study of the transition from collision-dominated to collisionless polar wind flow, *SPI Conf. Proc. and Reprint Series, 10*, 431-437, 1991.

17. W.-H. Yang, Expansion of solar-terrestrial low-β plasmoid, *Ap. J.*, in press, 1990.

18. R. W. Schunk and J. J. Sojka, Approaches to ionospheric modelling, simulation and prediction, *Adv. Space Res., 12*, 317-326, 1992.

19. H. G. Demars and R. W. Schunk, Comparison of semikinetic and generalized transport models of the polar wind, *Geophys. Res. Lett., 18*, 713-716, 1991.

20. T.-Z. Ma and R. W. Schunk, Ionization in the magnetized ionosphere surrounding a high voltage sphere, *Planet. Space Sci., 39*, 1325-1342, 1991.

21. J. J. Sojka, R. W. Schunk, D. Rees, T.-J. Fuller-Rowell, R. J. Moffett, and S. Quegan, Comparison of the USU ionospheric model with the UCL-Sheffield coupled thermospheric-ionospheric model, *Adv. Space Res., 12*, 89-92, 1992.

22. T.-Z. Ma and R. W. Schunk, High voltage spheres in an unmagnetized plasma: Long term evolution and rise time effects, *Plasma Phys. & Cont. Fusion, 34*, 767-782, 1992.

23. L. Zhu, R. W. Schunk, and J. J. Sojka, Field-aligned current associated with a distorted two-cell convection pattern during northward IMF, *J. Geophys. Res., 96*, 19,397-19,408, 1991.

24. H. G. Demars and R. W. Schunk, Semi-kinetic and generalized transport models of the polar and solar winds, *J. Geophys. Res., 97*, 1581-1595, 1992.

25. T.-Z. Ma and R. W. Schunk, High negative voltage spheres in an unmagnetized plasma: Fluid simulation, *Plasma Phys. & Cont. Fusion, 34*, 783-799, 1992.

26. H. Thiemann and R. W. Schunk, Arc discharges at negatively biased solar arrays, *Proc. of the ESA Space Power Conference, ESA SP-320*, 589-595, 1991.

27. J. J. Sojka, Ionospheric physics, *Rev. of Geophys.*, 1166-1186, 1991.

28. E. Szuszczewicz et al., Modelling and measurement of global scale ionospheric behavior under solar minimum, equinoctial conditions, *Adv. Space Res., 12*, 105-115, 1992.

29. J. J. Sojka, T. B. Frooninckx, and R. W. Schunk, Ionospheric control of a unique solar cycle dependence of DMSP spacecraft charging, *Geophys. Res. Lett.*, submitted, 1991.

30. T.-Z. Ma and R. W. Schunk, Ionization and expansion of barium clouds in the ionosphere, *J. Geophys. Res., 98*, 323-336, 1993.

31. H. G. Demars, A. R. Barakat, and R. W. Schunk, Comparison of generalized transport and Monte Carlo models of the escape of a minor species, *J. Atmos. Terr. Phys.*, in press, 1992.

32. W.-H. Yang, Self-similar evolution of magnetized plasmas, 1. Quasi-static solution, *Ap. J., 392*, 465-469, 1992.

33. L. Zhu, R. W. Schunk, and J. J. Sojka, Field-aligned currents, conductivity enhancements, and distorted two-cell convection for northward IMF, *J. Atmos. Terr. Phys.*, in press, 1992.

34. T. B. Frooninckx and J. J. Sojka, Solar cycle dependence of spacecraft charging in low earth orbit, *J. Geophys. Res.*, in press, 1992.

35. H. Thiemann and R. W. Schunk, Computer experiments on arcing processes as observed in ground tests, *J. Spacecraft & Rockets*, submitted, 1992.

36. P.-L. Blelly, A. R. Barakat, J. Fontanari, D. Alcaydé, M. Blanc, J. Wu, and C. Lathuillere, Observations of the structure and vertical transport of the polar upper ionosphere with the EISCAT VHF Radar. 1. Is EISCAT able to determine O^+ and H^+ polar wind characteristics? A simulation study, *Ann. Geophysicae, 10*, 367-374, 1992.

37. J. Wu, M. Blanc, D. Alcaydé, A. R. Barakat, J. Fontanari, P.-L. Blelly, and W. Kofman, Observations and vertical structure of the polar upper ionosphere with the EISCAT VHF Radar. 2. First investigations of the topside O^+ and H^+ vertical ion flows, *Ann. Geophysicae, 10*, 375-393, 1992.

38. D. J. Crain, J. J. Sojka, R. W. Schunk, P. H. Doherty, and J. A. Klobuchar, A first-principle derivation of the high latitude TEC distribution, *Radio Sci.*, in press.

39. D. J. Crain, J. J. Sojka, R. W. Schunk, and L. Zhu, Parameterized study of the ionospheric modifications associated with sun-aligned polar cap arcs, *J. Geophys. Res.*, in press.

40. L. Zhu, J. J. Sojka, R. W. Schunk, and D. J. Crain, A time-dependent model of polar cap arcs, *J. Geophys. Res.*, in press.

41. J. J. Sojka, Driving ionospheric models in real time, *Proceedings of the Solar Terrestrial Predictions Workshop*, in press.

42. J. J. Sojka, Magnetospheric shortcomings in ionospheric-magnetospheric coupling: An ionospheric perspective, *Proceedings of the Solar Terrestrial Predictions Workshop*, in press.

URI Presentations

1. *W.-H. Yang* and R. W. Schunk, On the source-surface model, AGU Fall Meeting, San Francisco, California; *EOS, 70*, 1254, 1989.

2. *H. G. Demars* and R. W. Schunk, Solar wind proton velocity distributions: Comparison of bi-Maxwellian-based 16-moment theory with observations, AGU Fall Meeting, San Francisco, California; *EOS, 70*, 1263, 1989.

3. *R. W. Schunk*, Modelling the dynamic ionosphere, *Invited Review*, Presented at AGU Fall Meeting, San Francisco, California; *EOS, 70*, 1237, 1989.

4. *T.-Z. Ma* and R. W. Schunk, Expansion of a three-dimensional plasma cloud in the ionosphere, AGU Fall Meeting, San Francisco, California; *EOS, 70*, 1240, 1989.

5. *R. J. Sica*, R. W. Schunk, S. J. Cariglia, M. Buonsanto, J. Holt, and D. Sipler, How well do we really understand the quiet-time mid-latitude ionosphere?, AGU Fall Meeting, San Francisco, California; *EOS, 70*, 1247, 1989.

6. *C. E. Rasmussen*, J. J. Sojka and R. W. Schunk, Modeling of annual variations in plasmaspheric density, AGU Fall Meeting, San Francisco, California; *EOS, 70*, 1247, 1989.

7. *J. J. Sojka*, R. W. Schunk and J. A. Whalen, The longitude dependence of the dayside *F*-region trough: A detailed model-observation comparison, AGU Fall Meeting, San Francisco, California; *EOS, 70*, 1248, 1989.

8. *M. D. Bowline*, J. J. Sojka, R. W. Schunk, J. D. Craven, L. A. Frank, J. Sharber, J. D. Winningham and J. P. Heppner, Dynamics Explorer 1 and 2 data-TDIM study for 22 November 1981, AGU Fall Meeting, San Francisco, California; *EOS, 70*, 1248, 1989.

9. *H. Thiemann* and R. W. Schunk, Simulations of solar array-LEO plasma interactions, AGU Fall Meeting, San Francisco, California; *EOS, 70*, 1249, 1989.

10. *R. W. Schunk* and J. J. Sojka, Temporal variations of the polar wind, AGU Fall Meeting, San Francisco, California; *EOS, 70*, 1249, 1989.

11. *R. E. Daniell*, L. D. Brown, W. G. Whartenby, D. N. Anderson, J. J. Sojka and R. W. Schunk, A parameterized version of the USU high latitude ionospheric model, AGU Fall Meeting, San Francisco, California; *EOS, 70*, 1248, 1989.

12. *D. N. Anderson*, J. A. Whalen, S. Basu, R. E. Daniell, L. D. Brown, W. G. Whartenby, J. J. Sojka and R. W. Schunk, A high latitude ionospheric specification model (HLISM), National Radio Science Meeting, 3-5 January 1990; Boulder, Colorado.

13. *J. J. Sojka* and R. W. Schunk, Ionospheric dependence and sensitivity on the solar EUV flux, Presented at the Quarterly Space Model Development Review Meeting, Peterson Air Force Base, 29 January 1990; Colorado Springs, Colorado.

14. *R. W. Schunk* and J. J. Sojka, Ionospheric variations, *Invited Review*; Presented at the SUNDIAL Workshop, 9-12 April 1990; New Orleans, Louisiana.

15. *R. W. Schunk* and J. J. Sojka, Ionospheric forecast model, Presented at the Ionospheric Specification Model Quarterly Review, 14 May 1990; Boston, Massachusetts.

16. *R. W. Schunk*, Model studies of ionosphere-thermosphere coupling phenomena on both large and small spatial scales and from high to low altitudes, *Invited Review*, Presented at the Seventh International Symposium on Solar Terrestrial Physics, 25-30 June 1990; The Hague, The Netherlands.

17. *R. W. Schunk* and J. J. Sojka, Coupled modelling of the ionosphere and thermosphere, *Invited Review*, 28th COSPAR Meeting, 25 June-6 July, 1990; The Hague, The Netherlands.

18. *R. W. Schunk* and J. J. Sojka, Approaches to ionospheric modelling, simulation, and prediction, *Invited Review*, 28th COSPAR Meeting, 25 June-6 July, 1990; The Hague, The Netherlands.

19. *J. J. Sojka*, R. W. Schunk, D. Rees, T. Fuller-Rowell and R. J. Moffett, Comparison of the USU ionospheric model with the UCL self-consistent ionospheric-thermospheric model, 28th COSPAR Meeting, 25 June-6 July, 1990; The Hague, The Netherlands.

20. *E. P. Szuszczewicz*, P. Wilkinson, M. A. Abdu, R. W. Schunk, R. Sica, R. Hanbaba, M. Sands, T. Kikuchi, R. Burnside, J. Joselyn, M. Lester, R. Leitinger, G. O. Walker, B. M. Reddy and J. Sobral, Modelling and measurement of global-scale ionospheric behavior under solar minimum, equinoctial conditions, *Invited Talk*, 28th COSPAR Meeting, 25 June-6 July, 1990; The Hague, The Netherlands.

21. L. Bossy, S. Pallaschke, R. Rawer, R. W. Schunk, J. J. Sojka, and *H. Thiemann*, Combined ionospheric model derived from CCIR and USA data, 28th COSPAR Meeting, 25 June-6 July, 1990; The Hague, The Netherlands.

22. *J. J. Sojka*, R. W. Schunk, W. R. Hoegy, and J. M. Grebowsky, Model and observation comparison of the universal time and IMF dependence of the ionospheric polar hole, 28th COSPAR Meeting, 25 June-6 July, 1990; The Hague, The Netherlands.

23. T.-Z. Ma, R. W. Schunk and *H. Thiemann*, PIC-simulation for the high voltage sphere problem, 28th COSPAR Meeting, 25 June-6 July, 1990; The Hague, The Netherlands.

24. *H. Thiemann* and R. W. Schunk, Electric field formation around negatively biased solar arrays in the LEO plasma, 28th COSPAR Meeting, 25 June-6 July, 1990; The Hague, The Netherlands.

25. *A. R. Barakat* and R. W. Schunk, Polar wind instability due to H^+ and O^+ beams, Presented at the 1990 Cambridge Workshop in Theoretical Geoplasma Physics on 'Magnetic Fluctuations, Diffusion and Transport in Geoplasmas,' 16-20 July 1990; Cambridge, Massachusetts.

26. *A. R. Barakat*, R. W. Schunk and I. Barghouthi, A Monte Carlo study of the transition layer between the collision-dominated and the collisionless regions in the polar wind; Presented at the 1990 Cambridge Workshop in Theoretical Geoplasma Physics on 'Magnetic Fluctuations, Diffusion and Transport in Geoplasmas,' 16-20 July 1990; Cambridge, Massachusetts.

27. *R. W. Schunk*, Recent advances in modelling the coupled ionosphere-polar wind system, *Invited Talk*, presented at the 1990 Gordon Research Conference on 'Modeling in Solar Terrestrial Physics', 30 July-3 August, 1990; Plymouth, New Hampshire.

28. *H. Thiemann* and R. W. Schunk, Advanced model of solar array-plasma interactions, ESA Space Environment Analysis Workshop, 9-12 October, 1990; ESTEC, Noordwijk, The Netherlands.

29. *R. W. Schunk* and J. J. Sojka, Simulations of the high-latitude ionosphere for a wide range of conditions, AGU Fall Meeting, San Francisco, California; *EOS, 71*, 1502, 1990.

30. *H. Thiemann* and R. W. Schunk, Electric field formation at solar cell edge regions, AGU Fall Meeting, San Francisco, California; *EOS, 71*, 1506, 1990.

31. *W.-H. Yang* and R. W. Schunk, What the magnetic clouds at 1 AU infer, AGU Fall Meeting, San Francisco, California; *EOS, 71*, 1519, 1990.

32. *H. G. Demars* and R. W. Schunk, Comparison of generalized transport and kinetic models of the polar wind, AGU Fall Meeting, San Francisco, California; *EOS, 71*, 1493, 1990.

33. *T.-Z. Ma* and R. W. Schunk, Evolution of three-dimensional plasma clouds in the ionosphere, AGU Fall Meeting, San Francisco, California; *EOS, 71*, 1506, 1990.

34. *J. J. Sojka* and R. W. Schunk, F-region's dependence on temporal and spectral structure in the solar EUV flux, AGU Fall Meeting, San Francisc , California; *EOS, 71*, 1482, 1990.

35. *A. Khoyloo*, A. R. Barakat, and R. W. Schunk, Ion plasma flow in the outer plasmasphere: A semi-kinetic model, AGU Fall Meeting, San Francisco, California; *EOS, 71*, 1523, 1990.

36. *I. A. Barghouthi*, A. R. Barakat, J. Lemaire, and R. W. Schunk, H$^+$ outflow in the polar wind: A Monte Carlo study, AGU Fall Meeting, San Francisco, California; *EOS, 71*, 1493, 1990.

37. R. W. Schunk and *J. J. Sojka*, High-latitude ionospheric simulations for a wide range of conditions, presented at the First Annual Conference on Prediction and Forecasting of Radio Propagation at High-Latitudes for C^3 Systems, 12-14 February, 1991; Monterey, California.

38. *R. E. Daniell*, L. D. Brown, D. N. Anderson, J. A. Whalen, J. J. Sojka, and R. W. Schunk, High-latitude ionospheric specification model (HLISM), First Annual Conference on Prediction and Forecasting of Radio Propagation at High-Latitudes for C^3 Systems, 12-14 February, 1991; Monterey, California.

39. J. J. Sojka, P. Citrone, and *R. W. Schunk*, Simulation of radio wave propagation through a realistically structured ionosphere, First Annual Conference on Prediction and Forecasting of Radio Propagation at High-Latitudes for C^3 Systems, 12-14 February, 1991; Monterey, California.

40. *D. J. Crain*, J. J. Sojka, R. W. Schunk, and P. H. Doherty, A first-principle derivation of the high latitude TEC distribution, AGU Spring Meeting, Baltimore, Maryland; *EOS, 72*, 213, 1991.

41. R. W. Schunk and J. J. Sojka, Dynamic changes in the ionosphere/thermosphere system during major magnetic disturbances, presented on our behalf by *D. J. Crain* at the 20th General Assembly of the IUGG, 11-24 August, 1991; Vienna, Austria.

42. *L. Zhu*, R. W. Schunk, and J. J. Sojka, Influence of the ionospheric conductance on the feature of the field-aligned current associated with a distorted two-cell convection during northward IMF, presented at the 20th General Assembly of the IUGG, 11-24 August, 1991; Vienna, Austria.

43. *A. R. Barakat* and R. W. Schunk, A collisional semi-kinetic model for the polar wind, presented at the 20th General Assembly of the IUGG, 11-24 August, 1991; Vienna, Austria.

44. *T.-Z. Ma* and R. W. Schunk, Ionization in the magnetized ionosphere surrounding a high voltage sphere, presented at the 20th General Assembly of the IUGG, 11-24 August, 1991; Vienna, Austria.

45. A. Khoyloo, *A. R. Barakat*, and R. W. Schunk, On the discontinuity of the semi-kinetic model for plasma flows along geomagnetic field lines, presented at the 20th General Assembly of the IUGG, 11-24 August, 1991; Vienna, Austria.

46. *H. G. Demars* and R. W. Schunk, Comparison of semikinetic and generalized transport models of the solar and polar winds, presented at the 20th General Assembly of the IUGG, 11-24 August, 1991; Vienna, Austria.

47. *H. G. Demars*, A. R. Barakat, and R. W. Schunk, Comparison between 16-moment and Monte Carlo models for outflows in space, presented at the 20th General Assembly of the IUGG, 11-24 August, 1991; Vienna, Austria.

48. *V. B. Wickwar*, J. J. Sojka, and R. W. Schunk, Comparison of observed and modeled electron densities from different regions of the globe, presented at the 20th General Assembly of the IUGG, 11-24 August, 1991; Vienna, Austria.

49. *D. J. Crain*, J. J. Sojka, R. W. Schunk, and L. Zhu, A parameterized study of polar cap arcs, AGU Fall Meeting, San Francisco, California; *EOS, 72*, 365, 1991.

50. *T.-Z. Ma* and R. W. Schunk, Barium plasma clouds from high-speed gas releases in the ionosphere: A 3-D simulation, AGU Fall Meeting, San Francisco, California; *EOS, 72*, 366, 1991.

51. R. W. Schunk and *J. J. Sojka*, Ionosphere-magnetosphere coupling processes at high latitudes, AGU Fall Meeting, San Francisco, California; *EOS, 72*, 363, 1991.

52. *L. Zhu*, J. J. Sojka, R. W. Schunk, and D. J. Crain, A time-dependent model of polar cap arcs, AGU Fall Meeting, San Francisco, California; *EOS, 72*, 356, 1991.

53. *R. W. Schunk* and J. J. Sojka, Ionosphere-magnetosphere coupling processes at high latitudes, *Invited Talk*, AGU Chapman Conference on 'Micro and Meso Scale Phenomena in Space Plasmas', February 17-22, 1992; Kauai, Hawaii.

54. *H. G. Demars*, R. W. Schunk, and A. R. Barakat, Comparing semi-kinetic, generalized transport and Monte Carlo predictions for steady state flows of interest in space science, presented at the 18th Rarefied Gas Dynamics Symposium, July 27-31, 1992; Vancouver, British Columbia, Canada.

55. *V. B. Wickwar*, J. J. Sojka, and R. W. Schunk, Review of N_e and T_e discrepancies between observations and model calculations in the F region, presented at the 29th Plenary Meeting of COSPAR, 1 September, 1992; Washington, D. C.

56. D. J. Della-Rose, *V. B. Wickwar*, J. J. Sojka, and R. W. Schunk, F-region electron temperatures, electron heating rates, and electron heat fluxes, presented at the 29th Plenary Meeting of COSPAR, 1 September, 1992; Washington, D. C.

URI Travel Summary

1. American Geophysical Union Fall Meeting
   San Francisco, California
   12/4 - 12/8/89
   R. W. Schunk, J. J. Sojka, W.-H. Yang, H. Demars, T.-Z. Ma, C. E Rasmussen, and
   H. Thiemann attended meeting and 13 papers were presented.

2. Space Model Development Review Meeting
   Peterson Air Force Base, Colorado Springs, Colorado
   1/29/90
   R. W. Schunk and J. J. Sojka attended meeting and a joint paper was presented.

3. AFGL Meeting
   Boston, Massachusetts
   3/12 - 3/13/90
   R. W. Schunk and J. J. Sojka attended meeting to discuss collaborative projects with D.
   Anderson, F. Marcos and N. Maynard.

4. SUNDIAL Meeting
   New Orleans, Louisiana
   4/9 - 4/12/90
   R. W. Schunk attended meeting and presented an invited paper.

5. Ionospheric Specification Model Quarterly Review
   AFGL; Boston, Massachusetts
   5/14/90
   R. W. Schunk and J. J. Sojka presented talks.

6. CEDAR Workshop
   Boulder, Colorado
   6/15/90
   J. J. Sojka was a panel member involving High Latitude Plasma Structures.

7. Solar-Terrestrial Physics Symposium
   The Hague, The Netherlands
   6/25 - 6/30/90
   R. W. Schunk presented an invited review talk.

8. COSPAR International Meeting
   The Hague, The Netherlands
   7/2 - 7/6/90
   R. W. Schunk, J. J. Sojka and H. Thiemann attended and 8 papers were presented.

9. Cambridge Workshop on Transport in Geoplasmas
   Cambridge, Massachusetts
   7/16 - 7/20/90
   A. Barakat attended and presented 2 papers.

10. Gordon Research Conference
    Plymouth, New Hampshire
    7/30 - 8/3/90
    R. W. Schunk presented an invited talk.

11. AFOSR Supported Research
    Boulder, Colorado
    8/30 - 9/1/90
    D. Payne visited NCAR to discuss the development of an auroral deposition code with
    Dirk Lummerzheim.

12. AFGL Meeting
    Boston, Massachusetts
    9/3 - 9/6/90
    R. W. Schunk and J. J. Sojka discussed collaborative efforts with H. Carlson, W. Denig, R.
    Daniell, D. Hardy, S. Gussenhoven, and J. Whalen.

13. Ionospheric Specification Model Quarterly Review
    Scott Air Force Base, Illinois
    9/17 - 9/18/90
    J. J. Sojka attended meeting and presented talk.

14. Pierre-Louis Blelly visit to USU
    Logan, Utah
    October 1990
    To work on a project with R. W. Schunk.

15. AFOSR Supported Research
    Boulder, Colorado
    11/13 - 11/16/90
    D. Payne visited NCAR to compare auroral deposition codes with Dirk Lummerzheim.

16. H. Thiemann visit to USU
    Logan, Utah
    November - December 1990
    To work on several projects with R. W. Schunk.

17. American Geophysical Union Fall Meeting
    San Francisco, California
    12/2 - 12/7/90
    H. Demars, A. Khoyloo, T.-Z. Ma, H. Thiemann, and W.-H. Yang attended meeting and
    presented papers.

18. AFOSR Supported Research
    Hanscom Air Force Base, Massachusetts
    12/11 - 12/19/90
    P. Citrone visited the Geophysics Laboratory to collect data and discuss research.

19. Conference on C^3 Systems
    Monterey, California
    2/9 - 2/17/91
    R. W. Schunk attended meeting and presented two papers.

20. Ionospheric Specification Model Quarterly Review
    Colorado Springs, Colorado
    3/4 - 3/7/91
    J. J. Sojka attended meeting.

21. PRIMO Workshop
    Boulder, Colorado
    6/20 - 6/21/91
    R. W. Schunk and J. J. Sojka attended this workshop which was organized by D. Anderson
    of Phillips Laboratory.

22. AFOSR Supported Research
    Boston, Massachusetts
    7/18 - 7/20/91
    J. J. Sojka visited the Geophysics Laboratory to discuss collaborative research projects.

23. IUGG General Scientific Assembly
    Vienna, Austria
    8/16 - 8/22/91
    H. G. Demars attended meeting and presented paper.

24. AFOSR Supported Research
    Fairbanks, Alaska
    9/17 - 9/19/91
    L. Zhu visited Joe Kan at the University of Alaska to discuss collaborative research projects.

25. AFOSR Supported Research
    Dallas, Texas
    10/3/91 - 10/14/91
    David Crain visited colleagues at University of Texas, Dallas to discuss collaborative research
    projects.

26. AFOSR Supported Research
    Boston, Massachusetts
    10/31 - 11/8/91
    Jan Sojka visited colleagues at Phillips Laboratory, Hanscom Air Force Base, to discuss
    collaborative research projects.

27. American Geophysical Union Fall Meeting
    San Francisco, California
    12/9 - 12/13/91
    Abdallah Barakat, David Crain, Ti-Ze Ma, and Jan Sojka attended the AGU Meeting and
    presented four papers.

28. AFOSR Supported Research
    Boston, Massachusetts
    2/2 - 2/7, 1992
    David Crain to visit co-authors at Phillips Laboratory, Hanscom Air Force Base to discuss
    collaborative research paper.

29. AFOSR Supported Research
    Kauai, Hawaii
    2/17 - 2/22/92
    R. W. Schunk presented an invited paper at the AGU Chapman Conference.

30. CEDAR and HLPS Meetings
    Boulder, Colorado
    6/17 - 6/22/92
    David Crain, Lie Zhu, and Jan Sojka attended CEDAR and HLPS Meetings.

31. AFOSR Supported Research
    Vancouver, Canada
    7/27 - 7/31/1992
    H. G. Demars presented an invited review paper.