Inter-Hemispheric Studies of Ionospheric Irregularities

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LONG-TERM GOALS

Various observational tools are available for the study of F-layer irregularities in the equatorial region. These include optical observations of the depletion of electron density (groundbased and spacebased), GPS phase fluctuations, C/NOFS, DMSP and ROCSAT *in situ* observations of ion density depletions, radar observations of coherent backscatter from equatorial irregularities, and ionospheric soundings. Each makes contributions to observational studies and each has its limitations. Our long term goal, using a full set of these measurements, is to study the physics of the equatorial regions, particularly during periods of irregularity development. Subsequent coupling of high latitude observations and equatorial observations will lead to forecasting where and when intense irregularities occur in various world areas and how they affect transmissions from satellites.

OBJECTIVES

Equatorial ionospheric irregularities, particularly in the region 10^{o} to 20^{o} north and south of the magnetic equator, are the cause of radio communications fades of up to 20 dB in episodic occurrence patterns. This latitude region includes regions of DoD/Navy operations in the Middle East, Africa, Indian and Pacific Oceans, and Latin American. Some receivers can deal with fades of this type while others cannot. Field program users of satellite-to-ground or to ocean-based reception links need to know that problems are of natural causation rather than equipment malfunctions. Methods of dealing with the fading can only be designed using knowledge of the geophysical and environmental characteristics of these irregularities (e.g., size and velocity).

APPROACH

Our approach to studying geophysical disturbances as the cause of communications disruptions involves the use of unique (in house) regional data sets funded by ONR, and state-of-the-art models (both empirical and computer simulation codes), in conjunction with global satellite observations available via the internet. Our own optical measurements involve all-sky camera observations of ionospheric structures taken at two sites near the Equatorial Ionization Anomaly (EIA) region in the southern hemisphere, i.e., from our ONR-sponsored observing systems at the El Leoncito and Mercedes Observatories in Argentina. To assess communications links, we study GPS signal phase fluctuations using an online network of over 60 ground stations throughout the EIA latitude band in

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14. ABSTRACT
Various observational tools are available for the study of F-layer irregularities in the equatorial region. These include optical observations of the depletion of electron density (groundbased and spacebased), GPS phase fluctuations, C/NOFS, DMSP and ROCSAT in situ observations of ion density depletions, radar observations of coherent backscatter from equatorial irregularities, and ionospheric soundings. Each makes contributions to observational studies and each has its limitations. Our long term goal, using a full set of these measurements, is to study the physics of the equatorial regions, particularly during periods of irregularity development. Subsequent coupling of high latitude observations and equatorial observations will lead to forecasting where and when intense irregularities occur in various world areas and how they affect transmissions from satellites.

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both hemispheres. To understand the types of ionospheric structure disturbance responsible for the GPS effects, we use the sensors onboard the C/NOFS, DMSP and ROCSAT satellites that give direct ionospheric ion density measurements along each orbit.

The optical all sky measurements also allow us to identify unusual patterns of drift that occur during large-scale, solar-terrestrial disturbances known as geomagnetic storms. Our approach has been to study a number of individual storms and to search for characteristics that are common to all and thus capable of being forecast. Under this grant, a new avenue of research will be to study how individual substorm events (typically lasting a few hours as opposed to days) instigate (or suppress) the formation of equatorial irregularities.

Key individuals participating in this work are:

(a) Michael Mendillo, Professor of Astronomy, serves as PI and directs the overall analysis consistent with current-day theory in space physics.

(b) Jeffrey Baumgardner, Senior Research Associate in the Center for Space Physics, designs, constructs and repairs all instrumentation; he participates in data analysis and interpretation.

(c) Joei Wroten, Senior Staff Researcher, is in charge of data analysis and archiving; she maintains our website, conducts image processing, and works with the PI on ionospheric effects associated with sub-storms.

(d) Carlos Martinis (Post-doctoral Research Associate) conducts the analysis and interpretation of the imaging data from El Leoncito and Mercedes, Argentina.

(e) Undergraduate research assistant Paul Zablowski works with Ms. Wroten and Dr. Martinis on data analysis tasks for coordinated ground-based/space-based case studies.

WORK COMPLETED

The major accomplishment during the first year of this grant was the creation of a three-station, bi-hemispheric observational program for the study of how ionospheric irregularities map along geomagnetic field lines in the American longitude sector. This was accomplished by the previous award of an ONR-sponsored DURIP grant for the fabrication of two new imaging systems for the new Boston University Observing Station in Mercedes, Argentina. The first phase of this work (installation of the all-sky imager at Mercedes) is now in operational mode. This now allows us to have a fully operational network linking observations made at Arecibo (Puerto Rico) to those made at the El Leoncito and Mercedes Observatories in Argentina, thereby providing the first comprehensive approach to the specification, prediction and scientific analysis of ionospheric irregularities spanning the Earth's geomagnetic equator.

RESULTS

Background: Boston University's initial ONR-sponsored imager is at the El Leoncito Observatory in the western Andes of Argentina (31.8 S, 69.3 W). This site has relatively high geographic latitude for its location under the southern crest of the equatorial EIA region (18 S magnetic latitude). Thus, this location fosters the study of how physical processes originating at the magnetic equator propagate into lower mid-latitudes. Such low-to-high latitude coupling is a frontier area of research in the ionospheric physics community, and our past ONR-sponsored efforts offered leadership science in that area (Mendillo et al., 2005, 2006; Martinis et al., 2005, 2006; Martinis and Mendillo, 2007). The imager at El Leoncito records four types of strongly variable phenomena: (1) highly-structured airglow depletions associated with the Rayleigh-Taylor instability [responsible for equatorial spread-F (ESF)]; (2) brightness waves (BW) associated with the midnight temperature maximum (MTM) reported on under previous ONR grants; (3) strong airglow enhancements associated with the positive phase (also called storm-enhanced-density, SED) aspects of TEC during geomagnetic storms, and (4) simple (non-structured) bands of alternating dark and bright airglow emission (called medium scale traveling ionospheric disturbances, MSTIDs); these have characteristics probably related to a coupled Es-layer/F-layer plasma instability. Disturbance types (1) and (4) are the ones most able to cause radiowave scintillations and GPS disruptions, and thus we concentrate on those effects under this grant. As a secondary goal, we study all aspects of solar-terrestrial disturbances, as related to topic (3).

New Results:

(1) Implementation of new DURIP observational capabilities. The central question that is at the focal point of all of our studies is “Do the optical signatures of a structured ionosphere map consistently from one hemisphere to the other?” As explained in our previous reports, to explore this concept in detail we use images taken at the Arecibo Observatory in the northern hemisphere (Puerto Rico) and map each of the pixels along the Earth’s geomagnetic field lines to their corresponding locations in the ionosphere of the southern hemisphere. This “conjugate point” mapping is a complex process in this particular region of the globe because the Earth’s magnetic field is highly distorted near South America (the so-called South Atlantic Anomaly (SAA) in the terrestrial magnetic field). Arecibo’s conjugate point is near, but not coincident with, our optical field-of-view (FOV) from El Leoncito, and the need to have more coherent data sets led to the DURIP proposal and award for new instrumentation at Mercedes, Argentina. Figure 1 gives an example of the overall relationship between the three sites. There are several items to notice in this figure: (1) the circular FOV from Arecibo maps to a distinctly oval-shaped FOV in the southern hemisphere due to the SAA geometry, (2) this southern FOV includes a small portion of that from our imager at El Leoncito, so partial validation of effects can be obtained from the over-lapping area, and they do indeed agree, and (3) a vastly improved set of conjugate point studies can now be achieved by use of the second imager at Mercedes. The additional benefit of an all-sky imager at Mercedes is that longitude patterns can be mapped over the full region covered by the joint Mercedes-El Leoncito cameras, a two-FOV system that can test temporal prediction methods for these longitudinally-moving structures.

A significant amount of effort during 2009 was devoted to the fabrication of two new optical systems for Mercedes (an all-sky camera and a wide-angle imaging spectrograph). Simultaneously, we worked on the creation of a permanent housing facility for these instruments. Using funds provided by Boston University’s Center for Space Physics to promote studies in equatorial aeronomy, a small “Airglow Observatory” building was added to the existing facilities at Mercedes. The new DURIP all-sky imaging system was completed first and was installed there in early 2009. Additional space (with a second dome to view the sky) has been set aside for the DURIP companion wide-field imaging spectrograph. Space also exists for additional, collaborating instruments to be added in the future.

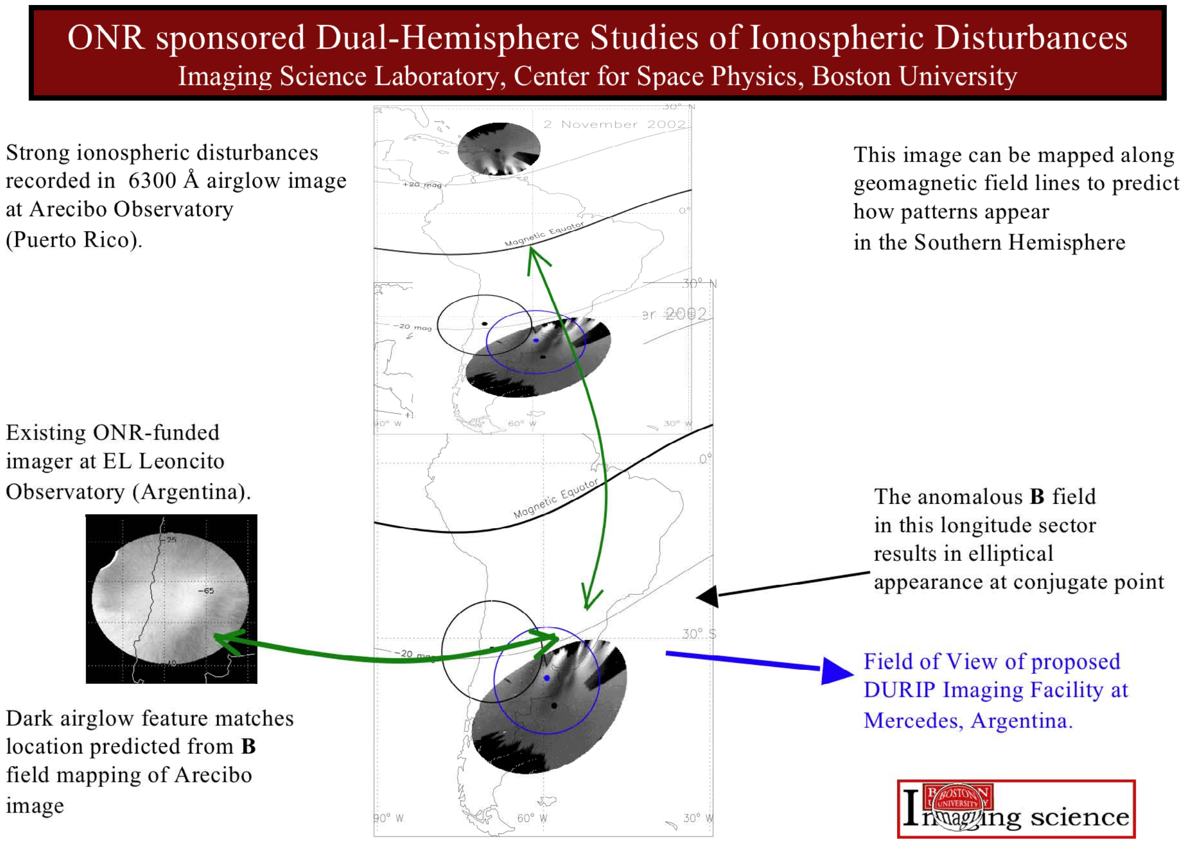

Figure 1. A summary of how airglow images can be mapped along geomagnetic field lines from one hemisphere to another. In this particular example, the validation comes from the ONR sponsored imager at El Leoncito that covers only a small portion of the image mapped from Arecibo. The new instrument location proposed to DURIP is shown with the blue field-of-view, one that covers a far more complete portion of the mapped Arecibo image, thereby allowing for more successful tests of portraying and predicting inter-hemispheric ionospheric disturbances.

(2) Approach to Case Studies. Images are collected during the moon-down periods of each month (approximately 15-18 days per month, called a 'lunation' period). Our undergraduate research assistant (Paul Zablowski) was trained to conduct the preliminary survey and cataloging of these data from both sites in Argentina, identifying nights with clear skies and which types of disturbance patterns were observed (ESF, MSTIDs, BWs, no structures). The same is done (using NSF support) for our all-sky imager at Arecibo. Our current approach is to search for nights when clear skies occurred at Arecibo and one (and hopefully two) of the ONR imaging sites in Argentina, and that structures are seen at one of these sites. In addition, we then search for satellite passes in the region, and in particular for those of the new C/NOFS satellite in the Caribbean area for in situ data at equatorial latitudes, i.e., between our hemispheric imaging sites. At the time of preparing this report, with approximately 6 months of data analyzed, we have selected a few sets of promising case studies. As noted throughout the solar-terrestrial physics community, the prolonged period of solar minimum still in effect has offered a wonderful opportunity to study base-line disturbances, i.e., low solar activity does not lead to the absence of ESF, MSTIDs, BW and ionospheric storms, nor of their potential impact upon technological systems.

(3) Modeling. A key component of our research program is to collaborate with state-of-the-art modeling groups on the simulation and interpretation of our optical observations. During the past year, Dr. Martinis worked closely with colleagues at the Naval Research Laboratory on a study of an optical airglow depletion that evolved into a bright feature during the course of a few hours. This is a very unusual occurrence pattern of ESF morphology, and therefore one that sheds light on the complex electrodynamics that couple regions of the lower and upper ionosphere during plasma instability events. The paper appears as Krall et al. (2009) in the references below.

IMPACT/APPLICATIONS

Much of current understanding of the morphology patterns of communications-disruptive ionospheric irregularities comes from data taken at sites at or near the magnetic equator, such as Huancayo and Jicamarca (Peru) and Manila (Philippines). However, the very strongest amplitude and phase fluctuations of GPS signals come from stations in the Equatorial Ionization Anomaly (EIA) region, a latitude band in each hemisphere located between about 10^o to 20^o from the geomagnetic equator. In these regions, amplitude fluctuations to 20 dB have been noted, even at the high frequencies of GPS. Forecasting the timing and extent of communications dropouts due to ionospheric disturbances are the central applications products of the studies we are conducting.

TRANSITIONS

In order to move towards the goal of forecasting the effects of ionospheric irregularities on communication systems, we must understand the patterns of occurrence during both quiet and disturbed periods. The former is well in hand for ESF-related effects (“airglow depletions”) in that the seasonal-longitude patterns already determined are essentially regional forecasts of *ionospheric disruptive climate*. The day-to-day variability during those seasons remains the elusive topic. This type of *ionospheric weather* is under active study, and forecast techniques are within reach. Progress has been made on the major challenge of understanding *the regional role* of geomagnetic storms in enhancing or inhibiting the occurrence of equatorial and low-latitude irregularities (Martinis et al., 2005). That aspect of our study dealt with the determination of effects caused by *severe ionospheric weather*, and at a very localized level within several world regions. The analogy to tropospheric disturbances would be to tornadoes, i.e., very severe and highly localized micro-climate.

The more demanding problem is day-to-day disturbances, and their consistency in both hemispheres within specific longitude sectors. While we have taken a major first step in understanding this topic under this grant, it is not ready for a transition to operational, reliable use. Similarly, the separate type of “airglow bands” and the irregularities associated with them have not been studied sufficiently (during both quiet and storm conditions) to warrant realistic transitions to operational use. Our prior studies of the ionosphere’s total electron content (TEC) storm effects, on the other hand, have achieved a level of closure between observations, theory and modeling, and forecasting methods are within operational reach (Mendillo et al., 2006). Similarly, the prediction of rocket exhaust depletions of the ionosphere were validated using GPS methods under our previous ONR grant and reliable forecasts can be made if prior knowledge is available of launch time and vehicle characteristics (Mendillo et al., 2008).

RELATED PROJECTS

The ONR-sponsored all-sky camera at the El Leoncito Observatory takes data at multiple wavelengths. Images at 6300 A are the ones used for our thermosphere-ionosphere studies that are the central focus of this grant. Images are also taken at wavelengths associated with processes in the mesosphere to study atmospheric gravity waves. Dr. Steven Smith, Senior Research Associate in the Boston University Center for Space Physics, uses these data in his research on mesospheric dynamics (see Publications section below).

A third use of our imager at El Leoncito comes from the sodium (Na) filter (one of the emissions used for mesospheric studies) to study the extended sodium tail of our Moon. Each month, on the days near new Moon, the Sun's radiation pressure results in the tenuous coma of lunar Na atoms to be pushed towards Earth. The travel time to the terrestrial environment is about two days, and the gravity of Earth then partially focuses the Na atoms into a type of beam streaming away from Earth. When viewed by an all-sky camera on the nightside of the Earth, this tail feature appears as a "sodium spot" a few degrees in size (i.e., easily seen in an all-sky imager). The systematic study of this effect using two years of data from El Leoncito was published by BU graduate student Ms. Majd Matta (see Publications section below).

The use of our ONR sponsored research instruments to support these diverse investigations of space science processes is a true enrichment aspect of our program, for which we express our gratitude to the Office of Naval Research.

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