Multiple Characteristics of Ionospheric Variability Patterns

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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, GPS phase fluctuations, DMSP *in situ* observations of ion depletions, radar observations of coherent scatter 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 10o to 20o 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 cities such as Santiago, Bogotá, Cairo, and Singapore. 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 (size, velocity, etc.)

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 a site near the “Anomaly” region in the southern hemisphere, i.e., from our ONR-sponsored observing system at the El Leoncito Observatory in Argentina. To assess communications links, we study GPS signal phase fluctuations using an online network of over 60 ground stations throughout the Anomaly latitude band in both hemispheres. To understand the types of ionospheric structure disturbance responsible for the GPS effects, we use the sensors onboard the DMSP satellites that give direct ionospheric ion density measurements along each orbit.

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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. Results obtained in the South American region are then tested at other longitudes (where we do not have optical data) using the GPS and DMSP satellites. In this way we are able to examine the longitude consistency and robustness of the forecasting techniques.

Key individuals participating in this work are:

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

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

(3) 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 storm studies.

(4) Carlos Martinis (Ph.D. candidate, now post-doctoral Research Associate) conducts the analysis and interpretation of the imaging data from El Leoncito, Argentina.

(5) Megan King (undergraduate research assistant) works with Dr. Martinis on analysis and portrayal of GPS ionospheric data for case study and overall morphology studies.

WORK COMPLETED

There were two major activities and research products achieved during the first year of this grant. One dealt with the large-scale behavior of the ionosphere during geomagnetic storms observed at American longitudes in the northern hemisphere, and the second with the spatial/temporal variability patterns of ionospheric irregularities in the southern hemisphere.

RESULTS

At the ONR co-sponsored "Ionospheric Effects Symposium (IES)" in April 2005, the PI of this grant was invited to give the opening scientific talk on the topic of *Ionospheric Storms*. In recent years, there has been a renewed interest in how the ionospheric total electron content (TEC) changes during storms, and in particular how the storm's positive phase (now called storm-enhanced-densities, SEDs) create large gradients that pose serious impacts upon GPS-based navigation systems. Studies of storm effects based upon GPS-derived observations of TEC are still relatively few in number (less than a dozen in the published literature). Thus, the PI returned to a much larger database of TEC case studies (180 geomagnetic storms) obtained from geostationary satellite radiobeacon observations made during an earlier solar cycle (1967-1976). Each storm was followed over a 4-day period with storm departures (in percent) measured from monthly median control curves at each site. The results were averaged to yield average storm patterns that mapped all key TEC disturbance features seen from auroral to low latitudes. Figure 1 shows these results (Mendillo and Klobuchar, 2006).

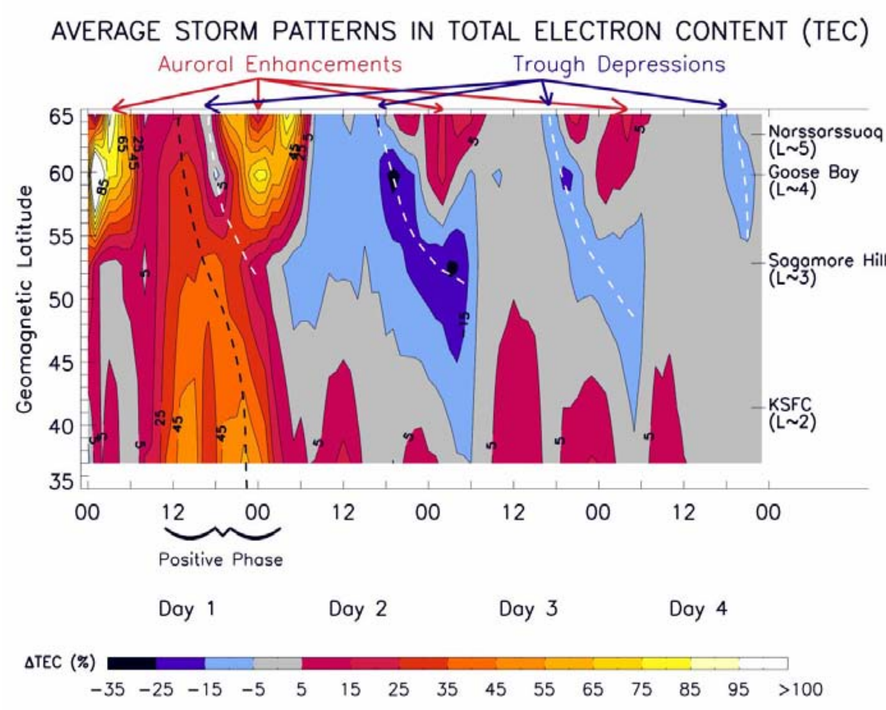

Figure 1: Average storm patterns for total electron content (TEC) using percentage changes from monthly median conditions on a grid of magnetic latitude (left axis) and magnetospheric L-shell values (right axis) versus local time over four days of a geomagnetic storm. The data sets used 70 geomagnetic storms from Narssarssuaq (Greenland), 67 storms from Goose Bay (Labrador), 109 storms from Sagamore Hill (Hamilton, MA), and 70 storms from the Kennedy Space Flight Center (FL). On day-1 of the storm, a strong positive phase begins earlier and is of smaller magnitude at high latitudes, with later and larger storm enhanced densities (SEDs) at lower latitudes. Intrusions of aurora-induced TEC enhancements and depletions due to motions of the trough are seen throughout the storm period. Negative phase effects (daytime TEC depletions) are the major perturbations during subsequent storm days. Taken from Mendillo and Klobuchar (2006).

The key message to come from Figure 1 is that the large-scale ionospheric variations during storms had consistent and systematic characteristic patterns. Thus, while there is considerable variability in ΔTEC(%) in space and time, from event to event, both "now casting" and "forecasting" can be helped by the known morphology patterns shown in Figure 1. Moreover, they helped identify the dominant physical mechanisms (thermospheric dynamics, electrodynamics, and composition changes), and provide the basis for modeling studies needed to more fully achieve successful predictive capabilities for solar-terrestrial ("space weather") disturbances.

The second major study completed during the past year was made possible by the ONR-sponsored imager 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 "Anomaly" 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. This low-to-high latitude coupling is a frontier area of research in the ionospheric physics community, and our effects offer leadership science in that area (Martinis et al., 2006). The BU/ONR imager at El Leoncito has identified 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/SED aspects of TEC during geomagnetic storms (as described above), and (4) simple (non-structured) bands of airglow depletions with characteristics matching a Perkins-like instability. Disturbance types (1) and (4) are the ones most able to cause radiowave scintillations, and thus we concentrated on those effects during the past year. Examples of each type are given in Figure 2. In the top panel, dramatic ESF plumes can be tracked in their eastward motion caused by thermospheric winds via dynamo action with the geomagnetic field. In the bottom panel, the relatively isolated band of airglow depletion that contains irregularities moves in the opposite direction, showing it to be a variability pattern quite distinct from the ESF effects noted above.

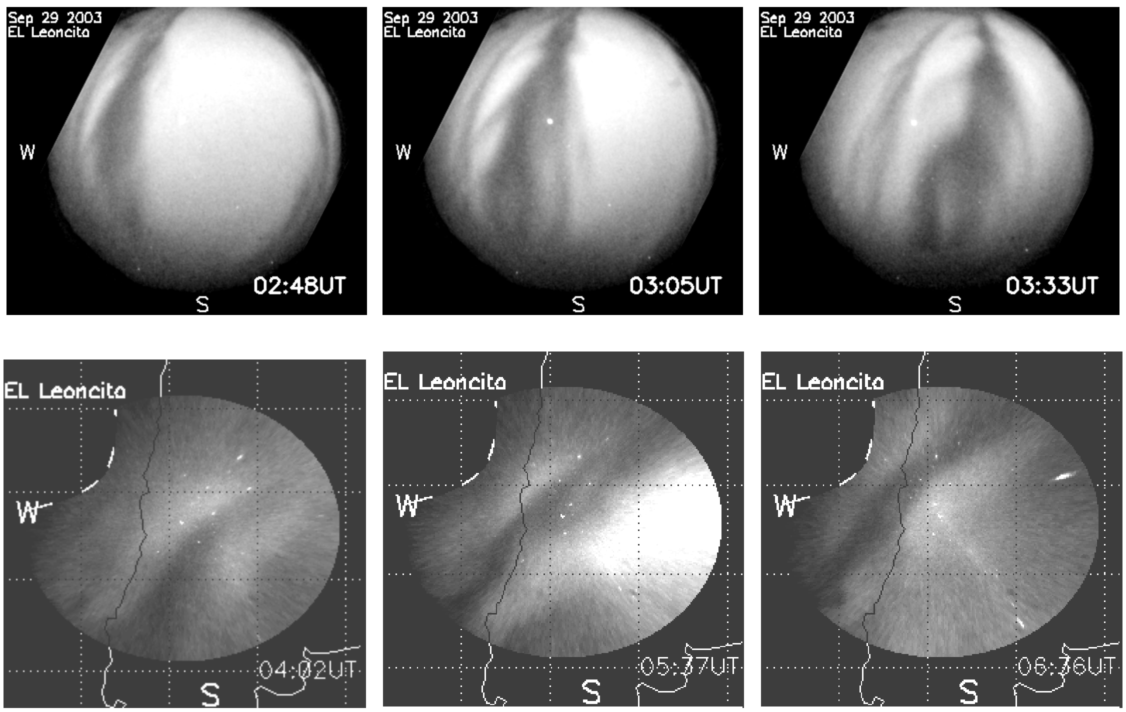

Figure 2: Top panel: raw images showing the eastward motion of very structured airglow depletions. Bottom panel: geographically unwarped images at 300 km showing an airglow band moving towards the north-west. Notice the different orientation and structuring of these two features (taken from Martinis et al., 2006) that both cause radiowave scintillation effects upon GPS signals.

This first set of optical structures from El Leoncito offers major insights into the sources and characteristics of these complex plasma instabilities in the southern hemisphere. Additional work is required to relate them to inter-hemispheric patterns. This will be the major focus of our current work.

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 and FLEETSATCOM signals come from stations in the so-called “Anomaly Region”, a latitude band in each hemisphere located between about 10o to 20o 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. The truly major challenge remaining is a serious one, to understand the regional role of geomagnetic storms in enhancing or inhibiting the occurrence of equatorial and low-latitude irregularities. This aspect of our study amounts to a determination of effects caused by *severe ionospheric weather*, and at a much localized level within several world regions. The analogy to tropospheric disturbances would be to tornadoes, i.e., very severe and much localized micro-climate. While we have taken a major first step in understanding this topic this past year, it is not ready for a transition to operational use. Our ongoing studies aim to do that, but many more storm studies are needed to establish confidence in proposing for realistic, operational forecasting scenarios. 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 studies of 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.

RELATED PROJECTS

None

PUBLICATIONS

Martinis, C., J. Baumgardner, S. M. Smith, M. Colerico, and M. Mendillo, Imaging science at El Leoncito, Argentina, Ann. Geophys., *24*, 1-11, 2006 [published, refereed].

Mendillo, Michael, and John A. Klobuchar, Total electron content: Synthesis of past storm studies and needed future work, Radio Sci., 41, RS5S02, doi:10.1029/2005RS003394, 2006 [published, refereed].