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Dual-Hemisphere Investigations of Ionospheric Irregularities that Disrupt Radio Communications and Navigation

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LONG-TERM GOALS

Various observational tools are available for the study of ionospheric irregularities that occur from equatorial to auroral latitudes. These include our Boston University optical observations of electron density depletions and associated turbulence, 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 physical causes and operational consequence of ionospheric perturbations, and particularly so during periods of irregularity onset and development. Our primary emphasis is on low latitude effects, and then with their coupling to higher (sub-auroral) latitudes. Such a unified approach will lead to forecasting where and when intense irregularities occur from the equator to mid-latitudes in various world areas, and how they affect transmissions from satellites.

OBJECTIVES

Equatorial ionospheric irregularities, particularly in the region 10° to 20° 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. Ionospheric irregularities (both enhancements and depletions) and the radio scintillations (amplitude "fades" and phase "fluctuations") occur with seasonal patterns (Tsunoda, 1985; Aarons, 1993) are primarily associated with geomagnetic storms—our second foci of investigation (Aarons et al., 1997; Martinis et al., 2005). Some receivers can deal with fades of this type while others cannot. Field program users of satellite-to-ground or ocean-based reception links at all latitudes 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). Our recent studies of ***mid-latitude ionospheric irregularities*** started with the study of wave events known as medium scale travelling ionospheric disturbances (MSTIDs), and their relative signatures at geomagnetic conjugate points in each hemisphere (Martinis et al., 2008). Studies of occasional severe events due to upward coupling (e.g., from earthquakes) also occurred during this final year of investigations (Smith et al., 2015).

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. Boston University All-Sky-Imagers (ASIs) are used to identify optical signatures of ionospheric structures taken at sites near the Equatorial Ionization Anomaly (EIA) region in the southern hemisphere, e.g., from our ONR-sponsored observing systems at the El Leoncito and Mercedes Observatories in Argentina. These include low-latitude 6300 Å airglow depletions that identify where ionospheric irregularities occur due to a process called Equatorial Spread-F (ESF). At lower mid-latitudes, we investigate medium-scale-travelling-ionospheric-disturbances (MSTIDs) that appear as bands of waves propagation westward and equatorward—and these indicate when a different type of ionospheric irregularties occur. 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 both hemispheres. To understand the types of ionospheric structure disturbances 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.

At mid-latitudes (20° - 60° magnetic), different types of ionospheric irregularities occur, but with the same consequences to operational systems. We used our optical network, and in particular the ONR sponsored instrument at the McDonald Observatory in Texas, to identify sub-visual structures (called Stable Auroral Red (SAR) arcs) that appear during even moderate geomagnetic storms that serve to define the northern boundary of the mid-latitude ionosphere (Martinis et al., 2015). SAR arcs are the optical signatures of a boundary of importance, the region in the inner magnetosphere called the plasmapause, that separates equatorial disturbances from auroral disturbances (Mendillo et al., 2013; Mendillo et al., 2015). Mid-latitude ionospheric disturbances are of concern to communications from middle to high latitudes, and for over-the-horizon radars.

The Boston University optical all-sky measurements allow us to identify not only the locations of key boundaries and structure, but also any unusual patterns of drift that occur during geomagnetic storms. Our approach has been to study a number of individual storms each year, and to search for characteristics that are common to all—and thus capable of being forecast.
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 Scientist 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, installs instruments at field sites, and works with the PI on ionospheric effects associated with solar activity.
(d) Carlos Martinis (Assistant Research Professor) conducts the analysis and interpretation of the imaging data from our low and mid-latitude sites.
(e) Steven Smith (Senior Research Scientist) is our expert on mesospheric waves and tsunami effects in the ionosphere-thermosphere system.
(f) Undergraduate research assistants work with Ms. Wroten and Dr. Martinis on data analysis tasks for coordinated ground-based/space-based case studies.

WORK COMPLETED

In Year-3 of this grant we conducted a detailed analysis of a highly unusual upper atmospheric disturbance caused by the Sendai (Japan) earthquake and tsunami of 11 March 2011that was captured in our ONR-sponsored ASI system at the El Leoncito Observatory in Argentina (Smith et al., 2015). In addition we achieved the first-ever observations of equatorial to low-latitude ionospheric irregularities (ESF-type) from three observing sites that shared common geomagnetic field lines from Colombia, Peru and Argentina.

Images of Earthquake and Tsunami-induced Waves in the Ionosphere.

One of the more spectacular uses of all-sky airglow imaging was the recent discovery of waves in the ionospheric airglow layer caused by the great earthquake and tsunami of 11 March 2011 (Makela et al., 2011). They described a large thermospheric gravity wave captured in 6300 Å images that propagated over the Hawaiian archipelago almost five hours after the occurrence of the earthquake. Most interesting, Makela et al. (2011) reported that the airglow wave signatures over Hawaii arrived approximately an hour ahead of the tsunami—thus suggestive of a possible forecast or early-warning capability from ASI observations.

Boston University operates an ASI at the El Leoncito Observatory in Argentina—an instrument constructed and installed via ONR/DURIP funding. Figure 1 displays three red-line images from El Leoncito showing the passage of gravity wave signatures on the night of 12 March 2011. The images are "time-differenced" one, i.e., images resulting from subtracting successive images. This technique retains the dynamic variations in the images, such as due to wave motion, and allows faint brightness variations to be detected more effectively. Analyses of such images yielded a horizontal phase speed of 204 ± 4 m/sec, a wavelength of 200 ± 23 km, and period of 16 ± 2 minutes.

The great circle ground-distance between the El Leoncito Observatory and the earthquake epicenter is 17,080 km, increasing to 17,750 km for airglow layer at 250 km altitude (Figure 2). Using the measured arrival time at El Leoncito and horizontal phase speed of the waves, the estimated time of the tsunami-genic gravity waves in Japan came out to be 05:46:24 UT (±5.5 minutes) on 11 March. This is within 1.5 minutes of the recorded onset time in Japan, well within the uncertainties associated with image processing. The waves detected at El Leoncito thus travelled for 24^{hr} 8^{min} ±5 min to nearly the opposite side of the globe.

Figure 2 shows tsunami arrival time data from a series of tidal monitoring stations located along the Chilean coast, as recorded by the NOAA's National Geophysical Data Center [http://www.ngdc.noaa.gov/hazard/]. The measured arrival time of the airglow waves is shown by the "ELO" symbol—and it can be seen to occupy a position consistent with the ocean data. It is clear from this figure that there is no significant difference in the arrival times of the airglow and ocean signatures of the disturbance. This is in marked contrast to the Makela et al. (2011) results showing the airglow waves over Hawaii arriving about one hour ahead of the tsunami waves. The reason for such differences are unclear, and thus a topic in need of further observational and modeling efforts. One possibility could be that variations in the propagation speed of the tsunami result from variations in ocean depth and/or temperature between vastly different regions of the Pacific Ocean (i.e., between Hawaii in the northern hemisphere and off the coast of Chile in the southern hemisphere). The results of our findings have been submitted for publications, with Dr. Steven Smith as the science lead for this topic (Smith et al., 2015).

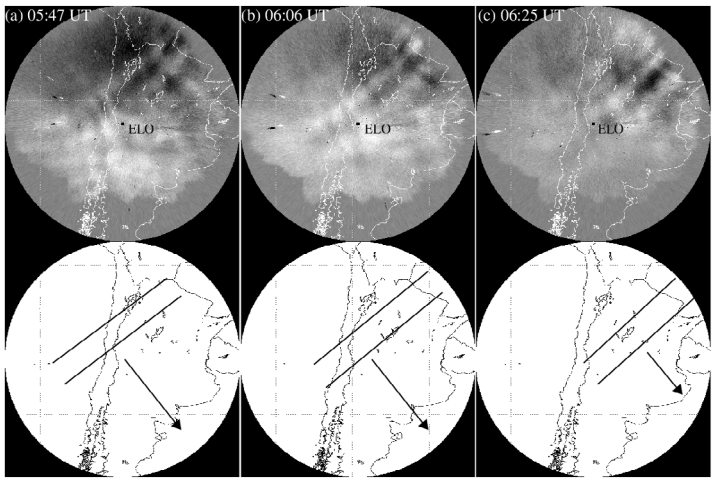

Figure 1. Sequence of three TD all-sky images at the El Leoncito Obs. on 12 March 2011. The unwarped 630.0 nm images show the south-eastward progression of an extensive thermospheric gravity wave event. The schematic tracings in the lower part of each panel highlight the waves more clearly.

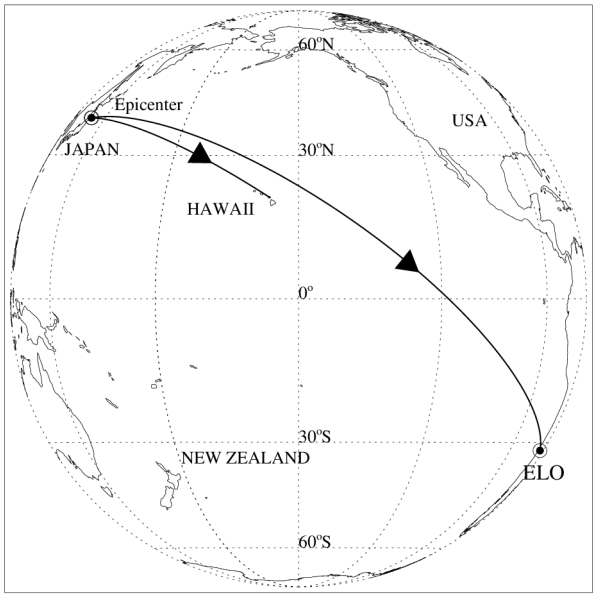

Figure 2. Global map showing the relative locations of the earthquake epicenter and the El Leoncito Observatory (ELO) in Argentina. The propagation path of the tsunami to El Leoncito, a distance of almost 18,000 km, is shown. The propagation path to Hawaii (viz-à-viz Makela et al. (2011)) is also shown for comparison.

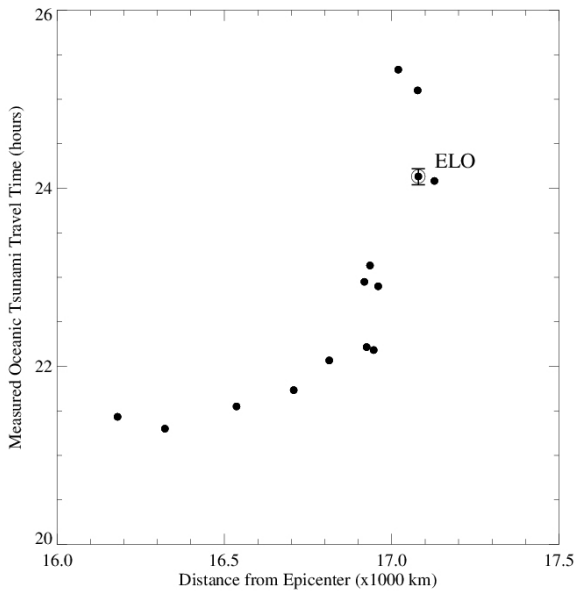

Figure 3. The measured oceanic tsunami travel times to the NOAA Chilean coastal tidal monitoring stations (data from NDGC) with their great circle distances from the earthquake epicenter. The zenith crossing time of the leading 630.0 nm wavefront at El Leoncito (ELO) is also plotted.

Unique Three-Station Imaging Science.

Starting in October 2014, the BU imaging system network established the first-ever set of three all-sky-imagers spanning latitudes from the geomagnetic equator to low latitudes in each hemisphere. The fields of view of Villa de Leyva (Colombia)-Jicarmarca (Peru)-El Leoncito (Argentina) provide the initial results from ground-based observations of the spatial continuity of 6300 Å airglow depletions spanning the geomagnetic equator In Figures 4 and 5, we show how this new resource can be used to study the latitude-altitude relationship between 6300 Å airglow depletion signatures and the ionospheric irregularities that cause radio disruptions.

The ESF events on the night of 30 October 2014 were captured in three ASI systems in South America. In Figure 4, within two minutes of simultaneity, images of pre-midnight ESF patterns were obtained. The key feature to note is that the structured dark areas to the west of zenith at Villa de Leyva essentially connect to the linear central-meridian pattern at Jicamarca, with continuity to the less-structure airglow depletion to the west at El Leoncito. To the east at Villa de Leyva, a second set of tilted and structured airglow depletions are found, with its linear manifestation at Jicamarca beyond the eastern field-of-view. These type of images can be used to explore the heights and latitudes were bifurcations occur, and the difference in their patterns.

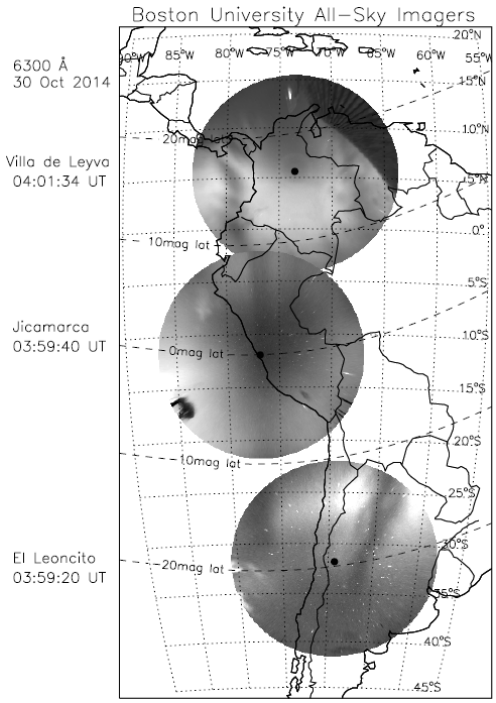

Figure 4. First example of 3-site, all-sky-imager depictions of 6300 Å airglow depletions associated with trans-equatorial plasma instabilities. Two-minute exposure images taken "simultaneously" during the pre-midnight hours of 30 October 2014 were achieved using DURIP instruments at Villa de Leyva (Colombia), Jicamarca (Peru), and El Leoncito (Argentina). In the central image, the N-S aligned airglow depletion through zenith shows where ionospheric irregularities are located in regions close to the geomagnetic equator. This dark feature "connects" to structured airglow depletions at higher latitudes to the north and south, indicating that an entire magnetic meridian experiences irregularities. The magnetic conjugacy is evident with depletions extending to ± 20° magnetic latitudes north and south of the magnetic equator. A similar pair of conjugate airglow depletions are captured to the east, but its equatorial signature falls beyond the field-of-view of the equatorial station. The degree of structuring appears more pronounced in the northern hemisphere.

In Figure 5, taken approximately three hours later, with images all within a minute of simultaneity, there is a marked lack of "connectedness" in the post-midnight patterns observed. The dramatic linear pattern at Jicamarca has no visual spatial continuity with stations to the north and south—indicating a lack of instability growth in height and latitude. Moreover, near the central meridian at El Leoncito, a highly structure pattern is found with no counterpart north of the geomagnetic equator. With single-site images from any one of these three stations, it would be impossible to describe accurately the spatial-temporal evolution of ESF disturbances on this night. Events such as depicted in Figures 4 and 5 are now capable of being analyzed systematically for the first time.

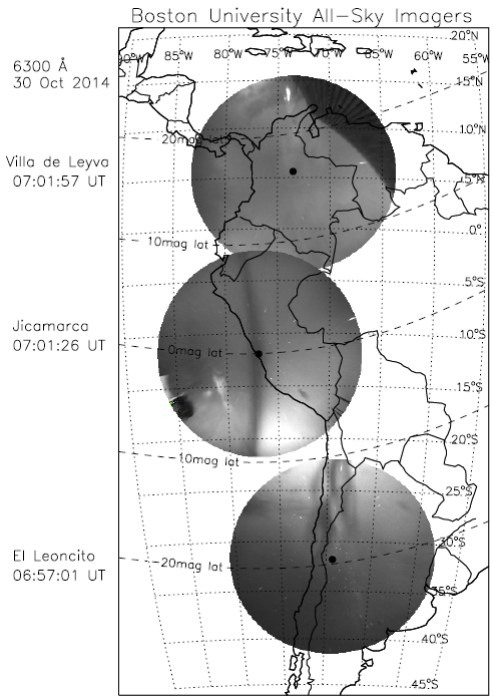

Figure 5. Using the same format as in Figure 4, these three images are for the post-midnight period on the same night of 30 October 2014. A dark airglow depletion spans the image from the equatorial site (Jicarmarca). Ionospheric irregularities "visualized" by their airglow depletions are far less evident at sites north and south of the geomagnetic equator. There is a hint of highly-tilted depletions at the western edge of the FOVs at Villa de Leyva, not seen at El Leoncito. The complex airglow depletions to the east at El Leoncito do not have an easily-identified presence in the images from Villa de Leyva.

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° to 20° 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. ***Our latest studies of the continuity or lack of continuity of atmospheric airglow structures indicative of ionospheric irregularity patterns will allow for systematic investigations of radio disruption upon DoD communications and navigation systems.***

TRANSITIONS

In order to move towards the goal of forecasting the effects of ionospheric irregularities on communication system, 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 problems are how major ionospheric disturbances can be provoked by moderate geomagnetic storms, why day-to-day disturbances are so variable, and how consistent disturbance effects can be in both hemispheres within specific longitude sectors. While we have taken a major first step in understanding these topics, it is not ready for a transition to operational, reliable use. Similarly, the separate type of "airglow bands" (MSTIDs) and the irregularities associated with them have not been studied sufficiently (during both quiet and storm conditions) to warrant realistic transitions to operational use. Based on success of prior studies, we are confident of progress in these areas. For example, our earlier studies of the ionosphere's total electron content (TEC) storm effects 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 optical imaging and 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].

Programmatic Summary

The use of our DURIP and ONR sponsored research instruments to support the highly-focus research goals described in this report represent a state-of-the-art usage of DoD research funds. They have a clear applications avenue and they contribute in fundamental ways to the advance of science related to the geo-space environment. For the training of students, young scientists and engineers enabled by such grants, we express our gratitude to the Office of Naval Research. This program also has a very positive set of interactions with scientific and educational institutions in South America and, in particular, with colleagues in Argentina through the efforts of Professor Carlos Martinis.

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