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

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SUMMARY

This grant provided resources to study (1) ionospheric disturbances that cause severe disruptions of radio communications and navigational systems crucial to Department of Defense programs, and (2) tsunami-generated ionospheric signatures of waves that can be used to study both upward and horizontal ocean-atmosphere coupling. Our primary observational technique is optical—one that provides broad coverage of upper atmosphere structures and disturbances. Using instrumentation provided by the Defense University Research Instrumentation Program (DURIP) we conducted our studies from several sites in North and South America. Each site was equipped with a Boston University state-of-the-art optical instrument called an *All-Sky-magier* (ASI), meaning that it records atmospheric emissions using a 180° field-of-view achieved by a "fish-eye" lens. Moreover, we located these instruments at sites that share a common geomagnetic field line—called conjugate points. For example, the ASI at the Arecibo Radio Observatory in Puerto Rico has its geomagnetic conjugate point in Mercedes (Argentina), while our ASI at the higher latitude Millstone Hill/Haystack Observatory (MA) has its conjugate point covered by an ASI in Rothera (Antartica).

1. **Ionospheric disturbances at low latitudes.**Of particular interest to DoD radio communications and navigational systems are the radio disruptions (*signal amplitude and phase scintillations*) produced by ionospheric irregularities at equatorial and low latitudes from sunset to dawn. These are called Equatorial Spread-F (ESF) scintillations and they are the strongest anywhere on the globe. The optical signatures of such irregularities can be captured by ASI methods that span thousands of kilometers. We use the oxygen 'red line' at 6300 Å to make images of where ionospheric "airglow depletions" exist at times throughout the night. Any radio propagation ray path (e.g., using GPS) through one of these depletions can experience strong scintillation to the point of total signal disruption and therefore the loss of an important navigational tool. Such overall scenarios are called Space Weather events.

Starting in October 2014, the BU ASI network established the first-ever set of three all-sky- imagers spanning latitudes from the geomagnetic equator to low latitudes in each hemisphere. The three ASI observatories are located in three South American countries linked by a common set of geomagnetic field lines: Villa de Leyva (Colombia)-Jicarmarca (Peru)-El Leoncito (Argentina). In Figures 1 and 2, we show how this new resource can be used on a given night (October 30, 2014) to study the latitude-altitude relationship between 6300 Å airglow depletion signatures and the ionospheric irregularities that cause radio disruptions. The key features to note are described in the captions. We stress that using 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. Moreover, the coherence of the perturbations effects can be used to specify space weather environmental impacts in area-denied locations (e.g., information from Argentina can tell if the ionosphere above Columbia is experiencing radio disruptions). This type of research, enabled by this ONR grant, will be conducted by new grant funds.

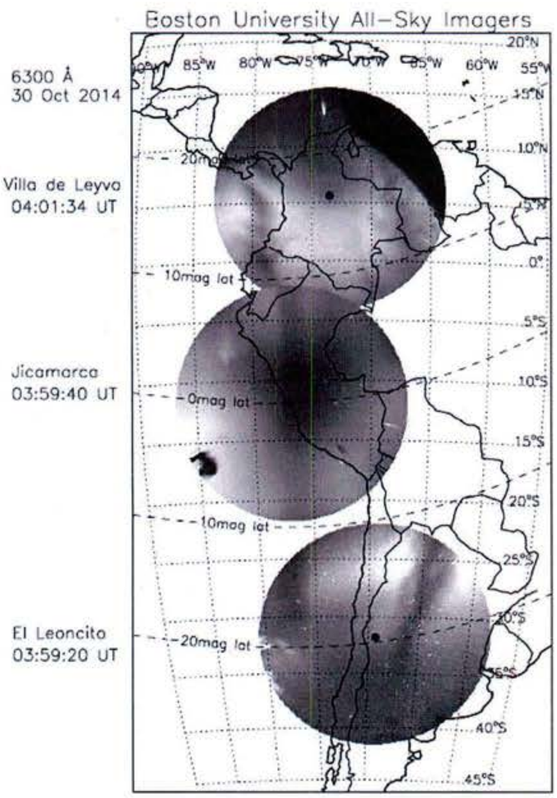

Figure 1. First example of 3-site, all-sky-imager depictions of 6300 Å airglow depletions associated with trans-equatorial plasma instabilities. Two-minute exposure images taken "simultaneously" during the pre-midnight hours of 30 October 2014 were achieved using instruments at Villa de Leyva (Colombia), 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 $\pm 20^{\circ}$ 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.

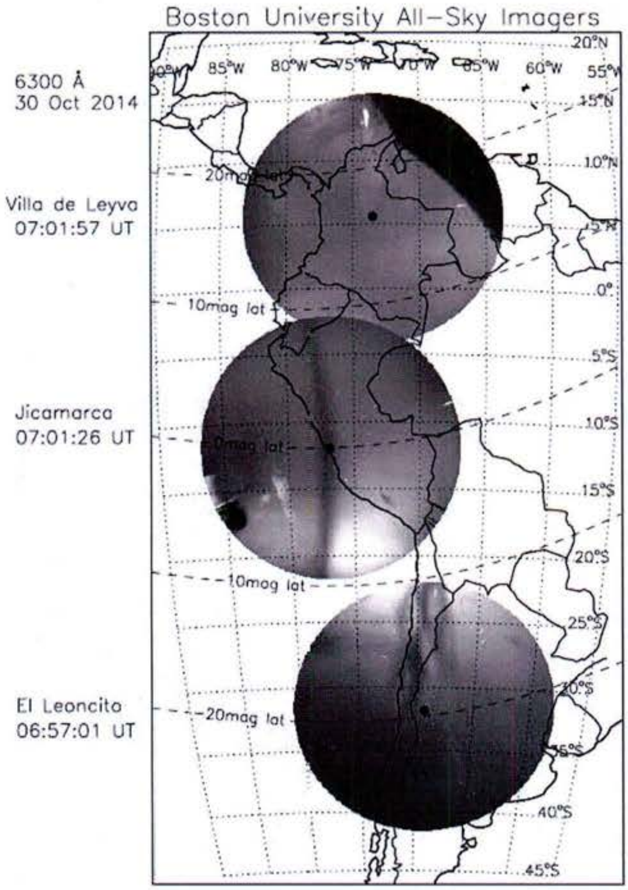

Figure 2. Using the same format as in Figure 1, these three images are for the post-midnight period on the same night of 30 October 2014. A dark airglow depletion spans the image from the equatorial site (Jicarmarca). Ionospheric irregularities "visualized" by their airglow depletions are far less evident 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. Events such as depicted in Figures 1 and 2 are now capable of being analyzed systematically for the first time.

2. Studies 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.

As shown in Figure 1, Boston University operates an ASI at the El Leoncito Observatory in Argentina and Figure 3 displays three red-line images from El Leoncito showing the passage of gravity wave signatures on the night of 12 March 2011. The 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 is17,750 km for airglow layer at 250 km altitude (Figure 4). Using the measured arrival time at El Leoncito and horizontal phase speed of the waves, the estimated "start-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 24hr 8min ±5 min to nearly the opposite side of the globe.

Figure 5 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/]. 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 (Smith et al., 2015).

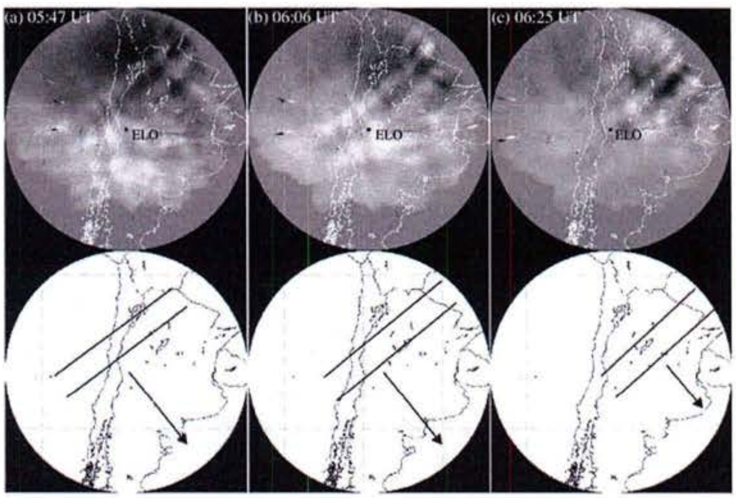

Figure 3. Sequence of three TD all-sky images at the El Leoncito Observatory on 12 March 2011. The unwarped 630.0 nm images show the south-eastward progression of an extensive thermospheric gravity wave event. The schematic tracings in the lower part of each panel highlight the waves more clearly.

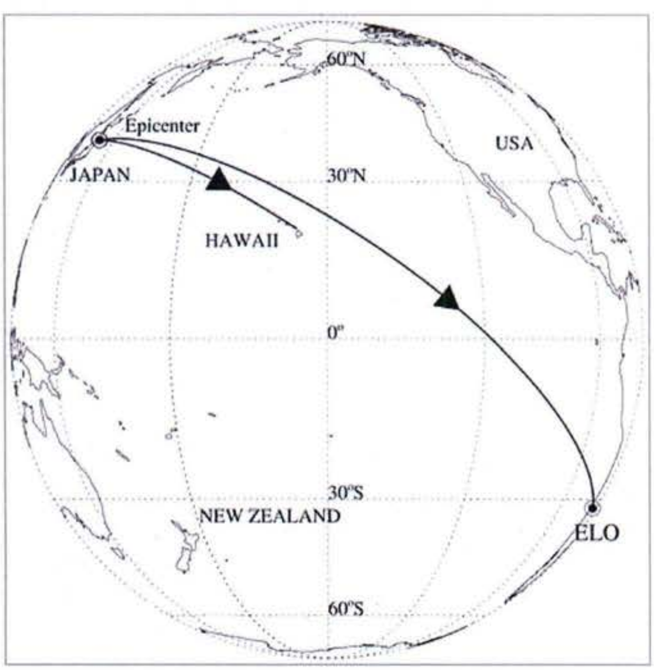

Figure 4. Global map showing the relative locations of the earthquake epicenter and the El Leoncito Observatory (ELO) in Argentina. The propagation path of the tsunami to El Leoncito, a distance of almost 18,000 km, is shown. The propagation path to Hawaii (viz-à-viz Makela et al. (2011)) is also shown for comparison.

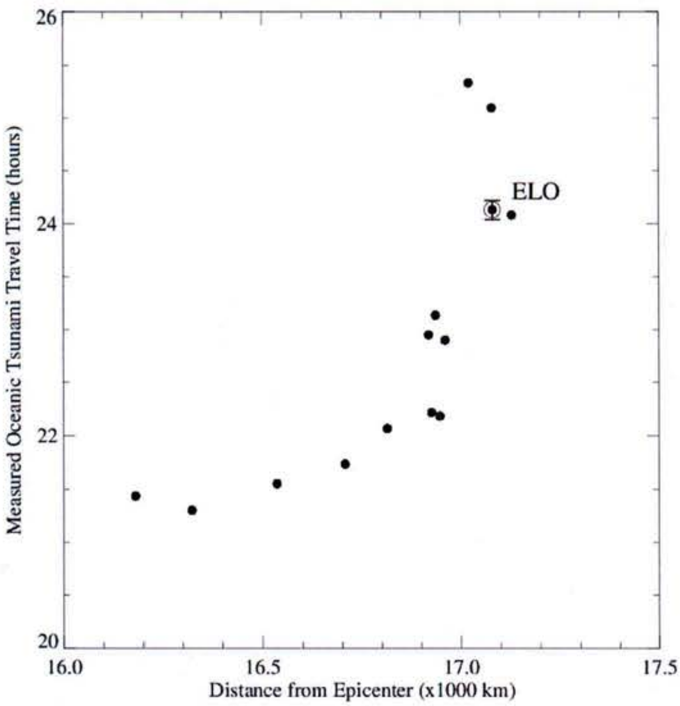

Figure 5. The measured oceanic tsunami travel times to the NOAA Chilean coastal tidal monitoring stations (data from NDGC) with their great circle distances from the earthquake epicenter. The zenith crossing time of the leading 630.0 nm wavefront at El Leoncito (ELO) is also plotted.

Programmatics

The success of this grant was made possible by an existing research infrastructure within the *Imaging Science Laboratory* of the Center for Space Physics at Boston University.

Key Individuals

(a) Michael Mendillo, Professor of Astronomy, served as PI and directed the overall programs of observations and data analysis.
(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, and works with the PI on ionospheric effects associated with solar activity.
(d) Carlos Martinis (Research Assistant Professor) leads the analysis and interpretation of the imaging data from optical imaging systems at equatorial and low latitudes.
(e) Dr. Steven Smith (Senior Research Scientist) leads the analysis and interpretation of wave disturbances in the upper atmosphere.
(f) During the three-year period covered by this grant, several undergraduate research assistants worked with the senior staff members listed above—leaning data analysis methods and developing skills in science and engineering linked to space research.

WORK COMPLETED

We have shown that multi-station observations at conjugate points of the geomagnetic field can be used to characterize the spatial and temporal patterns of ionospheric irregularities that cause communications disruptions. In addition, we have demonstrated that tsunami induced waves in the upper atmosphere are capable of propagation to distances well beyond previous estimates. The question of using such waves to predict tsunami arrival times is one in need of additional research.

IMPACT/APPLICATIONS

We have conducted a pilot study that relates all-sky-imaging in one hemisphere to that in another—with the images showing where ionospheric-disruption effects would occur. We found a broad agreement on the time scale of a night, but a lack of coherence in space and time on time scales of an hour or less. This implies that plasma instabilities may be affected by local conditions more than previously considered.

RELATED PROJECTS: Synergistic Use of Data

At several of the observatories where BU all-sky-imagers operate to gather data about the ionosphere, our background ("control wavelength") data reveal where clouds are located. This is of use to colleagues operating telescopes on the same mountain, or by remote control from home institutions, as a reliable source of "seeing" conditions for their experiments of astronomical targets.

CONCLUSIONS

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 for space weather now-casting and predictions. Our studies also contribute in fundamental ways to the advancement of science related to the broad field geo-space environment. For the training of new scientist and engineers enabled by this grants, we express our gratitude to the Office of Naval Research and its program managers. From an international relations perspective, this ONR/BU program also had a very positive set of interactions with scientific and educational institutions in South America.

Finally, there were no inventions or patents produced from the research supported by this grant.

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