AFRL-OSR-VA-TR-2015-0013

North-South America Network of Magnetically Conjugate All-Sky Imagers

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TRUSTEES OF BOSTON UNIVERSITY

01/02/2015
Final Report

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Air Force Research Laboratory
AF Office Of Scientific Research (AFOSR)/ RTB
Arlington, Virginia 22203
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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

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1. REPORT DATE *(DD-MM-YYYY)*
15-12-2014

2. REPORT TYPE
Final

3. DATES COVERED *(From - To)*
30-09-2011 to 29-09-2014

4. TITLE AND SUBTITLE
North-South America Network of Magnetically Conjugate All-Sky Imagers

5a. CONTRACT NUMBER

5b. GRANT NUMBER
FA9550-11-1-0304

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Mendillo, Michael; Baumgardner, Jeffrey; Martinis, Carlos; Wroten, Joei

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Boston University Center for
Space Physics
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Boston, MA 02210

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
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USAF, AFRL
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10. SPONSOR/MONITOR'S ACRONYM(S)
AFOSR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
A: a) Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

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The goal of the original grant has been achieved with high success. Boston University has the only network of optical ASI systems world-wide to study "Space Weather" processes. The science and applications results to emerge from this capability will contribute in fundamental ways to space science and its applications to national needs. The network will enable advanced training for graduate students and post-doctoral associates. We are pleased to express our gratitude to the Air Force Office of Scientific Research for its expression of confidence in our science and technology programs. The DURIP method of providing state-of-the-art improvements to the technical infrastructure on American campuses is an achievement of profound national importance.

15. SUBJECT TERMS
Space Weather, Ionospheric Disturbances, All-Sky-Imaging, Stable Auroral Red Arcs, Medium Scale Traveling Ionospheric Disturbances, Equatorial-Spread-F.

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Heidi Kendig
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**	UU	16	**19b. TELEPHONE NUMBER** *(include area code)* 617-353-7418

BOSTON UNIVERSITY

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NO COST EXTENSION: 30 September 2013 to 29 September 2014

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The goal of this grant was to create a network of low-light-level optical imaging systems to study the behavior of the ionosphere and the types of upper-atmosphere disturbances that lead to disruptions in radio communications and navigation systems used by DoD and civilian communities. The instruments were not purchased, but built at Boston University using commercially available components, with in-house fabrication suitable for installation at selected observatories in the northern and southern hemispheres. The sites selected are linked by common geomagnetic field lines (so-called 'magnetic conjugate point locations')—a requirement for the space science objectives to be enabled by the instruments. Seven all-sky-imagers (ASIs) were fabricated and tested in the Imaging Science Laboratory of the Center for Space Physics at Boston University. Five of the sites selected are taking data (in Massachusetts, Columbia, Peru, Argentina and Antarctica), and two remain to be installed (North Carolina and South Africa). The logistical elements for the non-US sites proved to be complex issues, each unique for that country, and that was the main reason for a no-cost-extension at the end of the initial two-year grant. The final two instruments to be deployed will be accomplished in 2015 using funds made available through the Center for Space Physics.

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PUBLICATIONS

The scientific yield of our DURIP grant is in progress. At each of our sites, background data must be taken to establish baseline conditions from which to measure disturbance scenarios. While there are no publications to report on results achieved with these new instruments; significant results will appear in the leading peer-reviewed journals of space science and technology starting in 2015. Obtaining funding for science yield is our top priority now that the DIRIP instruments are operating as planned.

CHANGES IN RESEARCH OBJECTIVES
None to report

CHANGES IN AFOSR PROGRAM MANAGER

The original Program Manager was Dr. Cassandra Fesen, and the subsequent Program Manager was Dr. Kent Miller. We are pleased to express our gratitude to both Dr. Fesen and Dr. Miller for their encouragement and support during the three-year duration of our DURIP instrumentation-fabrication grant.

NARRATIVE

1. **The Geo-Space Environment.** The Earth's upper atmosphere (heights above 90 km or 50 miles) is a key region within the Solar-Terrestrial System. The thermosphere-ionosphere is the portion of the Earth's atmosphere that absorbs ultraviolet (UV) radiation and X-rays from the Sun. These energetic photons separate electrons from the atoms and molecules present (O, O_2, N_2) to form an ionized gas (or plasma) composed of electrically-charged positive ions (O^+, O_2^+, N_2^+) and negatively-charged electrons (e^-). This region, called the terrestrial ionosphere, has its maximum electron densities (10^5-10^6 e^-/cm^3) at about 300 km. The structure and irregularities of the ionosphere affect the propagation of radio waves that are crucial for communications and navigation conducted for both national defense and commercial/societal needs. Scientifically, the ionosphere is also an active area of basic research because it is the cosmic plasma closest to Earth.

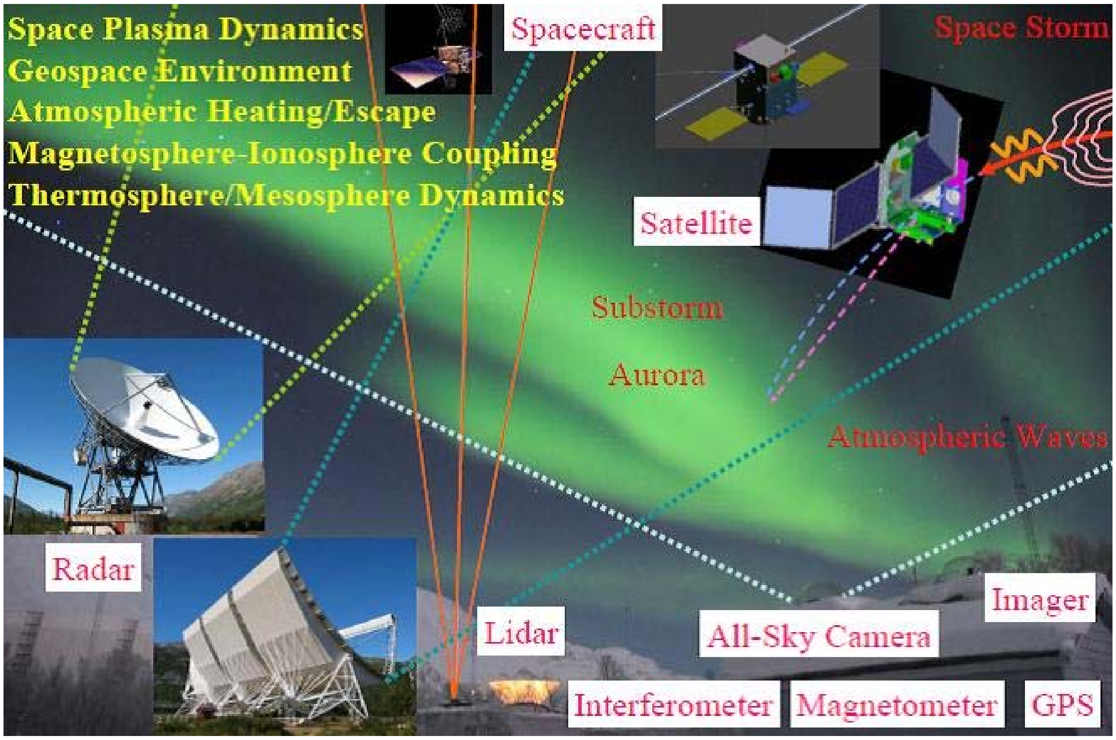


Figure 1. The Earth's upper atmosphere can be observed by a variety of ground-based (radio and optical) systems and via *in-situ* instruments onboard rockets and satellites.

The ionosphere can be observed by a variety of methods: Radars reflect radio waves off the ionosphere, rockets and satellites can make *in-situ* observations, and optical imaging systems can observed emissions coming from the ionosphere. Figure 1 offers a schematic to summarize all of these topics.

This DURIP grant created the first-ever network of optical imaging systems devoted to the systematic study of ionospheric structures and their irregularity patterns—observations made possible by the visible light emissions coming from the upper atmosphere.

2. **Optical Science Methods for Ionospheric Research.** At high latitudes (typically poleward of 65°N and 65°S), the *aurora borealis* and *aurora australis* offer visible evidence of processes in the upper atmosphere that generate light that can be seen by the naked eye. These often spectacular displays are driven by energetic particles that stream down along the magnetic field lines of Earth—visible signs of a terrestrial atmospheric disturbance initiated by solar activity. The variable nature and often dramatic impacts of solar-terrestrial activity are now recognized as an ever-present process called *Space Weather*.

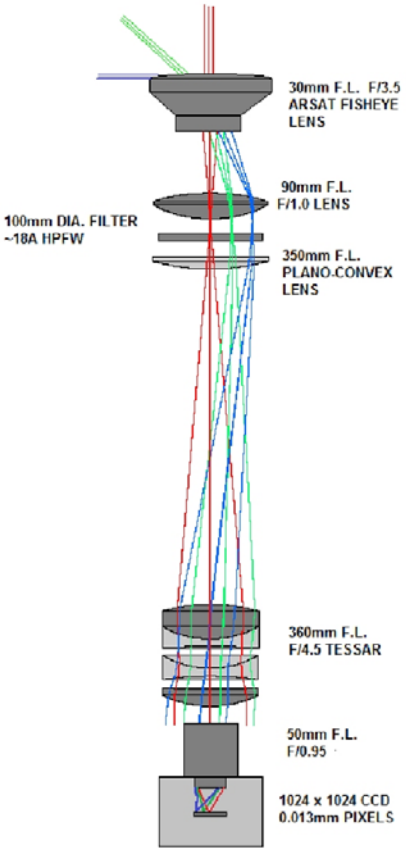


Figure 2 The design characteristics of the Boston University All-Sky-Imager.

Throughout the vast expanse of land and oceans equatorward of the auroral zone, the optical manifestations of Space Weather do not cease. The difference is that they are extremely faint; nevertheless, they are still associated with highly significant ionospheric disturbances. Thus, sophisticated instruments are needed to record the presence and areas of possible impact of Space Weather effects spanning latitudes called *sub-auroral* (45°-65°), *mid-latitude* (20°-45°), and *low & equatorial* (0°-20°). The Imaging Science Laboratory within the Center for Space Physics at Boston University is now the leading research group world-wide in the design and construction of optical imaging systems for sub-visual studies of Space Weather within these three latitude domains. This new capability is due primarily to the Defense University Research Instrumentation Program (DURIP).

From a given site on the surface of the Earth, the maximum amount of sky that can be captured in a single image is the one visible through a fisheye lens, i.e., one with a field-of-view (FOV) of 90° (zenith to horizon) in all directions. Such horizon-to-horizon images at all azimuths (180° FOV) are called "all-sky" images and the optical systems designed for them are called all-sky-imagers (ASIs). The Boston University ASI system developed in-house is depicted schematically in Figure 2; it represents the state-of-the-art system for low-light-level imaging of the upper atmosphere. The key component is the initial fisheye lens that captures light from all directions.

Additional optical elements render the rays nearly parallel to the optical axis. A high-quality, narrow-band filter (typically 12 Å full-width at half-transmission) then isolates specific emissions that come from different regions of the atmosphere.

The BU standard filter wheel has six filters: 6300 Å for atomic oxygen emissions typically from ~200-300 km, 5577 Å for atomic oxygen emissions at ~80 km, 7774 Å atomic oxygen emissions at ~400 km, 5693 Å for sodium emissions at ~90 km, a broadband red filter for emissions at 86 km, and a control filter at 6050 Å for non-atmospheric emissions (i.e., background galactic and scattered light). Figure 3 shows the relationship between wavelengths selected and the specific atmospheric regions such radiation describes.

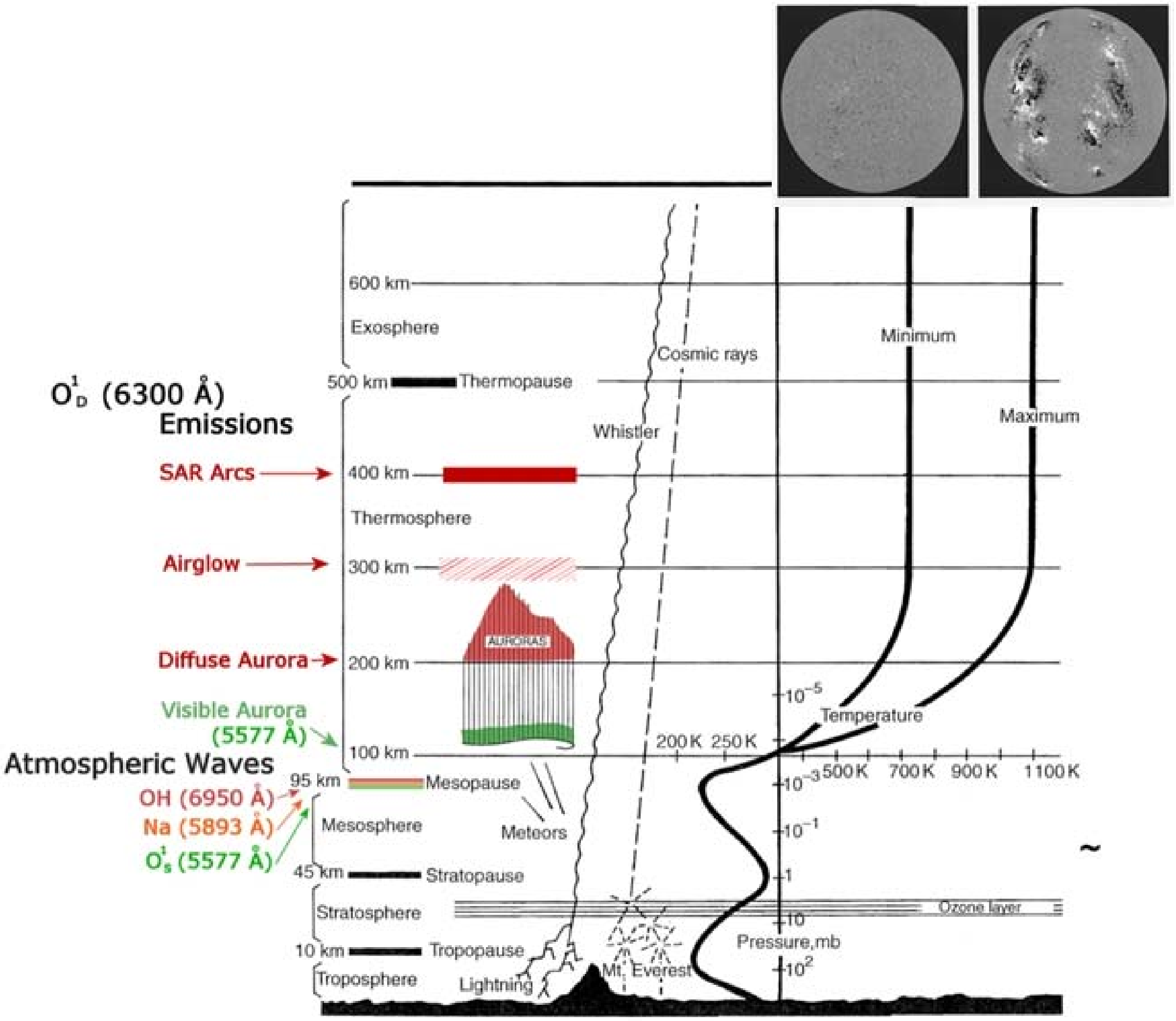


Figure 3. Optical emissions from specific atmospheric regions.

3. Geomagnetic Conjugate Point Science: Context for DURIP Instruments.

3.1. Introduction.

The goal, of course, of a DURIP grant is to obtain state-of-the-art instruments that enable forefront science. The somewhat unusual aspect of our grant is that instruments were not purchased from an existing vendor and immediately placed into laboratory service. In our case, the instruments were fabricated from component parts in our laboratory. Some of the components were purchased (e.g., lenses, filters and detectors)—and these required specifications to multiple vendors and, in some cases, working with vendors to achieve the specific capabilities we needed. When all components are obtained, they have to be tested and integrated into robust overall ASI systems. This required significant use of the Boston University Scientific Instrumentation Facility (SIF) in the Metcalf Science Center on campus. One example of machine shop use is the in-house design and fabrication of all of the filter wheels and their controllers—an activity that truly benefitted from having the SIF on campus (versus working with local "machine shop" companies). This all required significant amounts of time and effort by our Senior Research Scientist Jeffrey Baumgardner.

Once a new ASI instrument was completed, it was then thoroughly tested in the Optical Calibration Facility (OCF) within our Imaging Science Laboratory (ISL) in the Center for Space Physics (CSP). Because these instruments had to operate at remote locations, their robust nature had to be tested—meaning that we operated them continuously, night after night, for several weeks to make sure of their ability for continuous observations.

When a fully-tested system was ready for deployment, a set of logistical issues had to be addressed. Since a number of instruments had to be deployed in other countries, all of the US Export Control rules and documentation had to be addressed. BU provided institutional support for such activities and our Center for Space Physics (CSP) staff and researchers have ample experience in these activities as well. Yet, for each country, there were a number of local/unique issues to address (e.g., modification to an existing building or construction of a new unit to house the BU instrument). Past experience makes us try to house our instruments at existing astronomical observatories since they have solved all of the important infrastructure needs (dark skies, internet service, stable power, thermal control, technical staff for assistance, etc.). In most cases, a Memorandum of Understanding (MOU) between the host institution and our ISL within the CSP had to be negotiated. In many cases (ASIs in Argentina, Colombia, Peru), these MOUs had to be in two languages (English and Spanish), and having Spanish-speaking Research Assistant Professor Carlos Martinis (from Argentina) in our group was a major asset (in addition to his well recognized scientific expertise). Finally, shipping containers had to be purchased, and the instrument and all associated computer systems carefully packed.

Once the instrument arrived at its international location, our hosts had to manage its passage through their local customs office. This involved an entirely different set of documentations and certifications (a unique set of experiences for each country) to show that the unit was not for sale, but rather was part of a multi-year observing program between BU and the host institution.

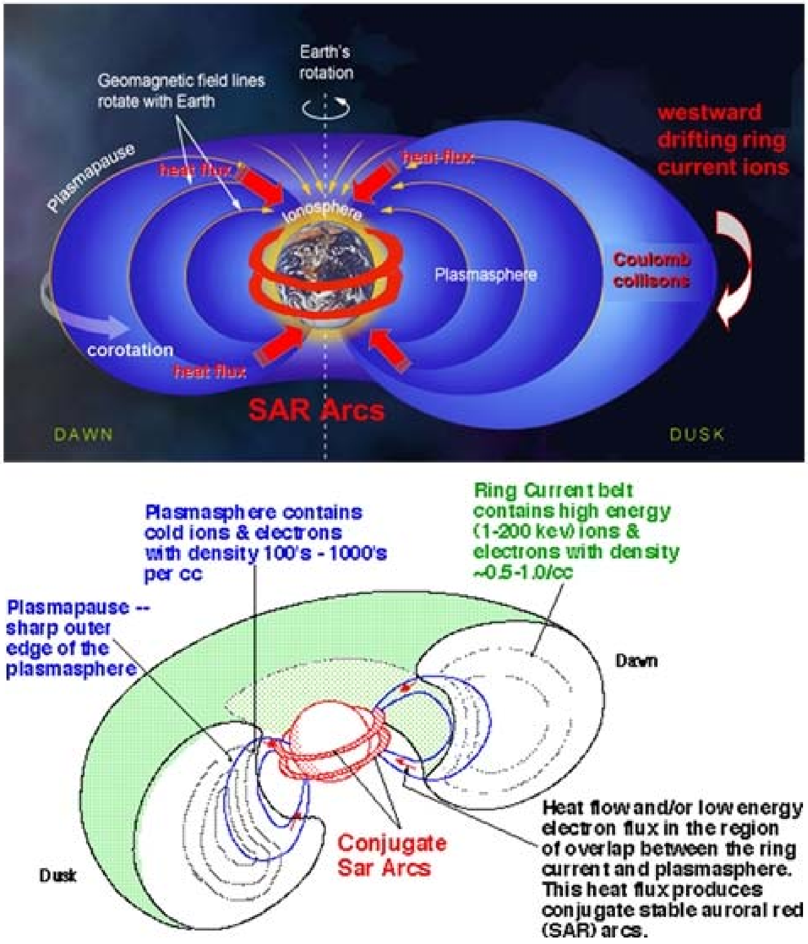
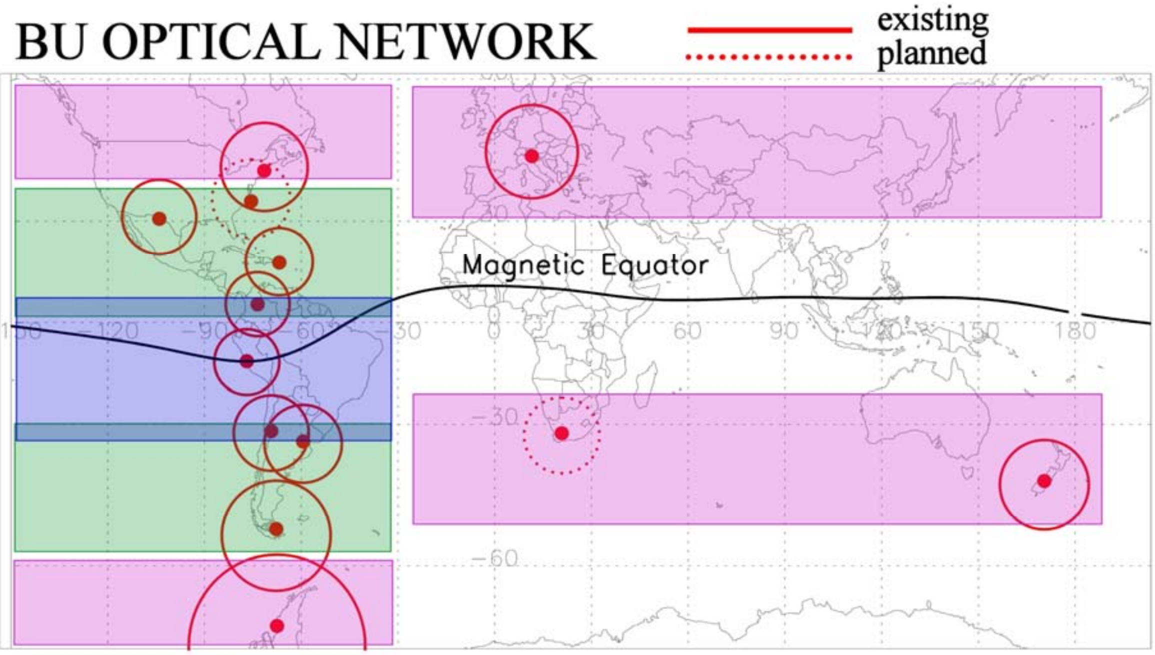


Figure 4. Schematic view of the geomagnetic conjugate point coherence of stable auroral red (SAR) arcs. SAR arcs occur where the plasmapause and inner edge of the magnetospheric ring current interact. Heat conduction into the ionosphere excites atomic oxygen to emit 6300 Å photons.

3.2. Instrumentation from DURIP grant.

Prior to this DURIP grant, Boston University all-sky-imagers had been deployed at a few sites worldwide to study ionospheric structure and dynamics at latitudes ranging from polar to equatorial. Past examples of the science yield from a given site include those from the BU instruments at the Arecibo Observatory in Puerto Rico (Mendillo et al., 1997a), and at the Arequipa Observatory in Peru (Mendillo et al., 1997b). The more recent use of multiple ASI locations to study the same phenomenon (e.g., a stable auroral red (SAR) arc) appeared in our study conducted at three widely-separated longitudes (Europe, North American and New Zealand) in Mendillo et al. (2013). These investigations pointed to a need to study ionospheric disturbances within the context of the site's local geomagnetic field (**B**)—and the extension of those **B**-lines into regions beyond the ionosphere (i.e., into the Earth's inner magnetosphere). The realization that magnetospheric source regions have strong influences upon the ionosphere below via magnetic field line links was then extended to the concept that the ionospheres at *both ends* of the same geomagnetic field line offer a way to study the full system in a comprehensive way. The two locations at the base of a given terrestrial **B**-line (one in the northern hemisphere and one in the southern hemisphere) are called *Geomagnetic Conjugate Points.* Figure 4 (above) gives an example of conjugate points for the sub-auroral field lines associated with the SAR arc phenomenon.

The DURIP enterprise allowed for the first-ever network of geomagnetic conjugate point all-sky-imagers to be established. This was based on the need to study ionospheric disturbances ordered by their geomagnetic latitudes *in each hemisphere.* Due to the tilt of ~12^o of the geomagnetic dipole at Earth, there is a difference between a site's geographic latitude (Φ) and its geomagnetic latitude (Λ). Moreover, this difference varies as a function of longitude. At ~70^{o}W, for example, the dipole tilt is at its maximum in the northern hemisphere. At the Millstone Hill Observatory located in Westford, MA, the geographic latitude is 42.6^{o}N and its geomagnetic latitude is 54^{o}N. Following the magnetic field **B**-line from this location into the southern hemisphere, the same geomagnetic latitude of 54^o S occurs at the geographic latitude of 66^{o}S (located on the Antarctica Peninsular). While any influence of the magnetosphere would be expected to be the same at each site (ordered by their same geomagnetic coordinates), the pre-existing ionospheres produced by solar radiation would be dramatically inconsistent due to their significantly different geographic latitudes. This is for two reasons: (1) the solar zenith angles would be different and thus the effects of solar ionizing radiation, and (2) the neutral atmospheres would be different due to the different seasonal conditions in each hemisphere. Thus, the same geophysical system (e.g., SAR arcs and their disruptive influence) can be studied under local conditions that separate solar control (seasonal effects) from geomagnetic control (disturbance effects). This is the underlying concept of *DURIP-enabled Conjugate Point Science* and similar situations occur for other pairs of stations at middle and low latitudes.



1. Equatorial and low latitude Ionosphere (from magnetic equator to the crests of the Appleton Anomaly). *ESF and MSTIDs, effects on trans-ionospheric radio signals using GPS and optical diagnosis.*

2. Mid latitude Ionosphere (poleward from Anomaly crests to ~ ± 40 mag lat). *Nighttime MSTIDs, E and F region coupling.*

3. Sub-auroral Ionospher (latitudes below auroral ovals). *Stable auroral red (SAR) arcs (magnetic activity effects that transfer magnetospheric ring current energy into the I-T system)*

Figure 5. The Network of Boston University All-Sky-Imagers

Figure 5 shows the Boston University ASI network of stations. The impact of the DURIP systems can readily be seen. At sub-auroral latitudes, the pair Millstone Hill (MA) – Rothera (Antarctica, operated by the British Antarctic Survey) were existing observing locations that had their instruments upgraded via DURIP for conjugate point science. At mid-latitudes, the pair of Cape Hatteras (NC) and Tierra del Fuego (Argentina) comprises a new DURIP location with a new instrument in the north to match an existing one in the south. The low-latitude pair Arecibo (PR) – Mercedes (Argentina) represent exiting observatories with DURIP-supplied instrument upgrades for conjugate point science. The near-equatorial pair of Villa de Leyva (Colombia) and El Leoncito (Argentina) represents a new DURIP site and instrument in the north to match an existing site with instrument in the south. To complete the geomagnetic coverage in the western hemisphere, a new site and new instrument funded by DURIP were established at the geomagnetic equator (Jicamarca, Peru). Finally, for the first-ever conjugate-point ASI studies at European-African longitudes, a new DURIP site and instrument in the south (South

African Large Telescope location) matches an existing site and instrument in the north (Asiago Observatory, Italy).

3.3. Examples of Conjugate Point Observations Achieved by DURIP.

As described in Section 3.1, the purpose of our DURIP grant was to obtain (i.e., to fabricate) new instrumentation for deployment at remote sites that would operate for years to come and enable leadership science. The amount of on-campus efforts for fabrication, testing and deployment—when coupled to those of installations at remote locations—left little or no time for actual scientific use of the new instruments. That is consistent with the very meaning of the word "enable" that is at the core of the DURIP enterprise. Yet, we never lost sight of the true objective, namely, that the new DURIP instrumentation would offer forefront, state-of-the-art capabilities for Space Weather research. To do this, the first requirement was to expand our data archiving system to accommodate the vast amounts of new data from all the new sites. The required upgrades for a comprehensive Data Management System were devised and implemented by Ms. Joei Wroten, Senior Staff Researcher in the Center for Space Physics. The yield of this effort can be found at the Imaging Science Lab's website for data viewing at www.buimaging.com.

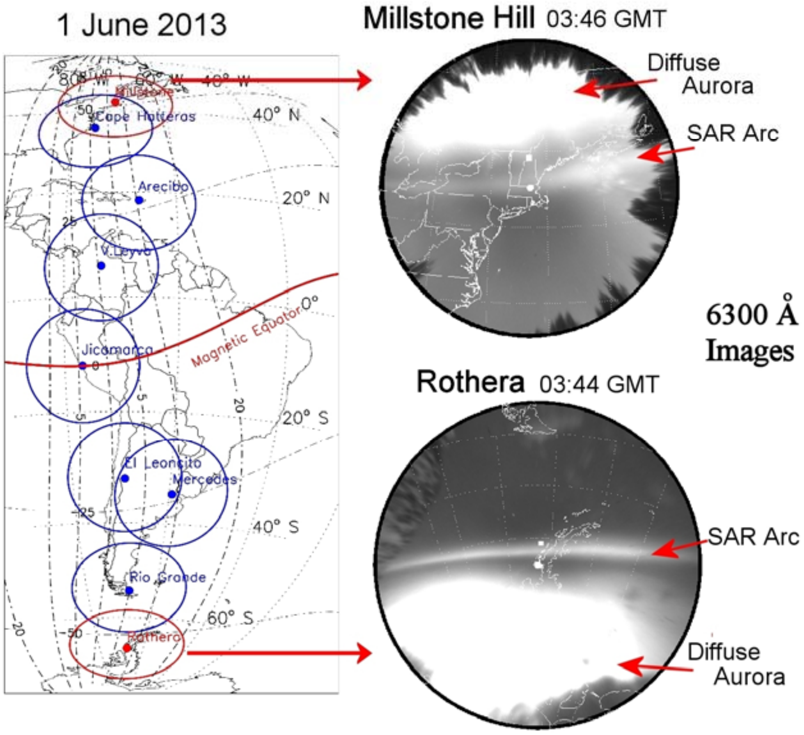
Users of the "BU IMAGING" site find a unique data archive tailored to the goal of comparative-site science. One can select an initial site for a specific night (with specific image wavelengths), and then compare the results found with data taken at its conjugate point location, or at any site within the BU-ASI network. All of the data are shown in "raw data" format—meaning the all-sky mode of zenith in the center of the image, with the geographic cardinal points indicated. The raw data are, in many ways, the most intuitive way to view a geophysical image. Upon request, all such data can be re-formatted (for a specific height of emission) upon a geographical grid in latitude and longitude (with geomagnetic coordinates superposed). Such "unwarped images" are typically used in publications where the spatial relationship between features in the image are compared with other diagnostic information (e.g., radar data, GPS total electron content data; *in-situ* satellite data).

As an illustration of our data for conjugate point science, Figures 6, 7 and 8 show, respectively, examples of SAR arcs captured at the same time at Millstone Hill (MA) and Rothera (Antarctica), medium-scale travelling ionospheric disturbances (MSTIDs) at Arecibo (PR) and Mercedes (Argentina), and equatorial spread-F (ESF) airglow depletion patterns captured at Villa de Leyva (Colombia) and at the El Leoncito Observatory (Argentina). In each case, for each of the nights, one can see a basic coherence in the spatial patterns at both ends of the geomagnetic field lines. These visual data sets confirm in dramatic fashion the fluxtube-physics associated with each of the mechanisms responsible for the effects under study. Moreover, and central to our science agenda, is the fact that there are noteworthy (and perhaps to the eye, subtle) differences seen in each hemisphere. These relate to the background differences of season at each site and their sensitivity to perturbations—details that will illuminate the "hemispheric effectiveness" of both instigating and transmitting disturbances along geomagnetic field lines.

Figures 6, 7 and 8 are spectacular demonstrations of the success of this DURIP grant to the Imaging Science Laboratory within the Center for Space Physics at Boston University. Three continents are involved (North and South American plus Antarctica), three countries (USA and Puerto Rico, Argentina, Colombia), and six robust instruments.

Boston University All-Sky-Imagers

Geomagnetic Conjugate Science Feature: Stable Auroral Red (SAR) Arcs



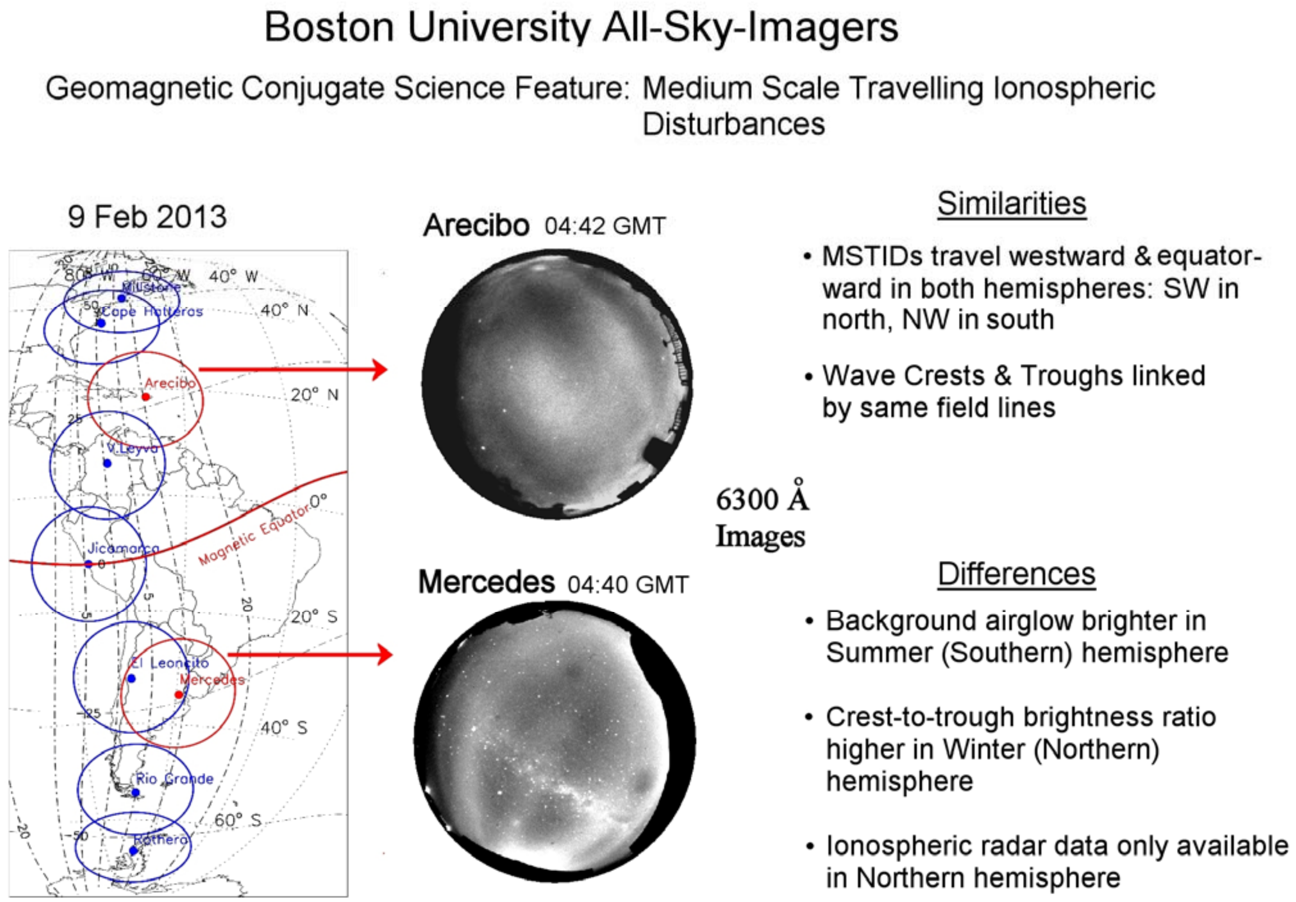
Similarities

- Both SAR Arcs at L= 2.74 R_e
- Same Separations from Diffuse Aurora

Differences

- Small scale structures along arcs
- Brighter in Southern Hemisphere
- Latitude gradients stronger in South

Figure 6. Example of Conjugate SAR Arcs



Boston University All-Sky-Imagers

Geomagnetic Conjugate Science Feature: Medium Scale Travelling Ionospheric Disturbances

9 Feb 2013

Arecibo 04:42 GMT

Mercedes 04:40 GMT

6300 Å Images

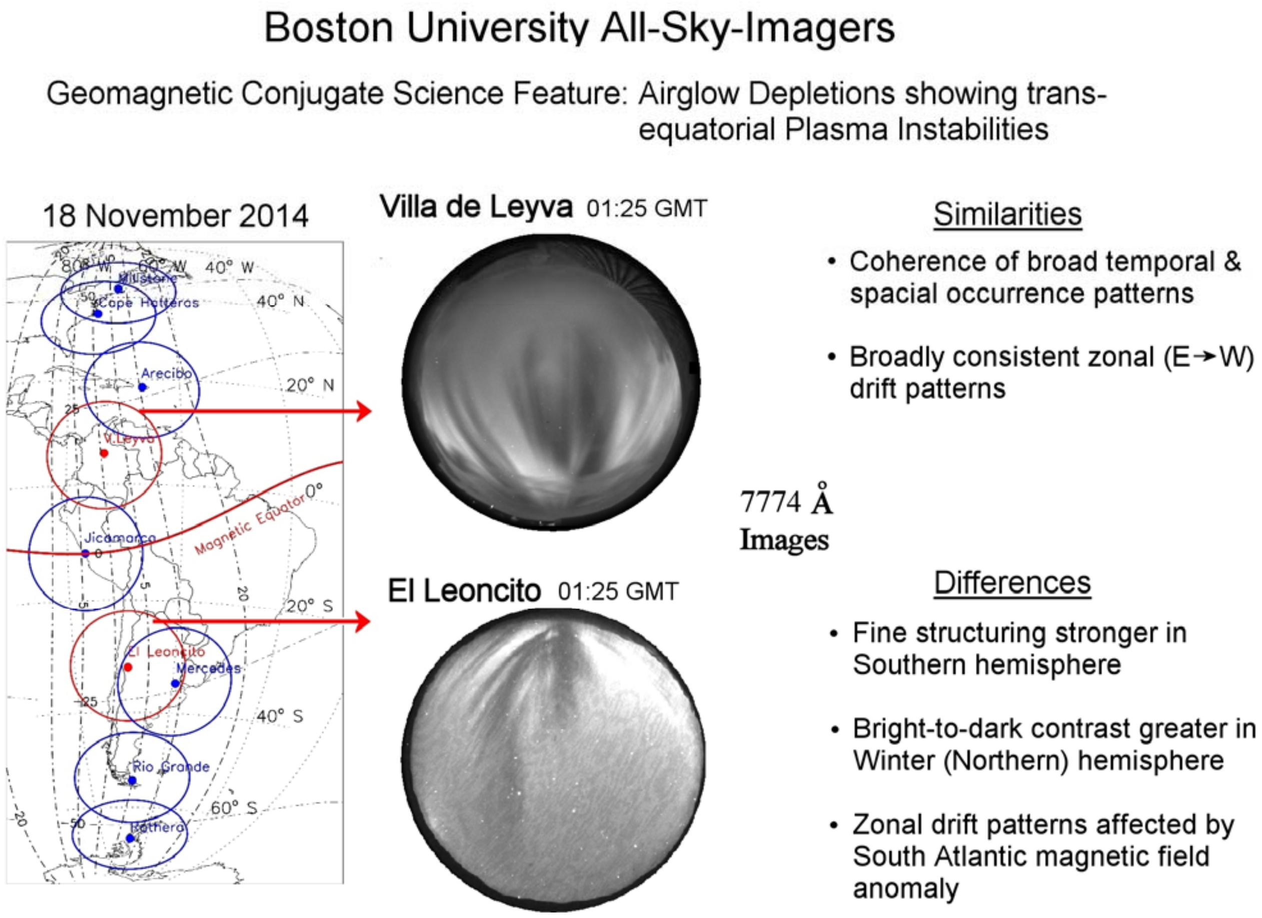
Similarities

- MSTIDs travel westward & equator-ward in both hemispheres: SW in north, NW in south
- Wave Crests & Troughs linked by same field lines

Differences

- Background airglow brighter in Summer (Southern) hemisphere
- Crest-to-trough brightness ratio higher in Winter (Northern) hemisphere
- Ionospheric radar data only available in Northern hemisphere

Figure 7. Example of Conjugate MSTIDs



Boston University All-Sky-Imagers

Geomagnetic Conjugate Science Feature: Airglow Depletions showing trans-equatorial Plasma Instabilities

18 November 2014

Villa de Leyva 01:25 GMT

El Leoncito 01:25 GMT

7774 Å
Images

Similarities

- Coherence of broad temporal & spacial occurrence patterns
- Broadly consistent zonal (E→W) drift patterns

Differences

- Fine structuring stronger in Southern hemisphere
- Bright-to-dark contrast greater in Winter (Northern) hemisphere
- Zonal drift patterns affected by South Atlantic magnetic field anomaly

Figure 8. Example of Airglow Depletions

3.4. Remaining Tasks.

As depicted in Figure 5, there are two DURIP instruments awaiting deployment. Both ASI systems are built and tested, and they remain in our lab pending final plans for installation. These two remaining sites represent both the easiest and most difficult types of observing plans. For the DURIP imager scheduled for deployment at an optical site in North Carolina, the delay has simply been one of convenience. It is an “easy case” due to no international export control issues. This system will be operational by mid-2015 and start its conjugate program in conjunction with the ASI system already in Rio Grande (Tierra del Fuego, Argentina).

The more challenging situation, and final DURIP ASI to get into operation, is the DURIP imager that will be at the conjugate point of the ASI currently operating in Italy. The first-ever BU-ASI-CCD system in western Europe is at the Asiago Observatory in northeastern Italy, a site operated in collaboration with astronomy colleagues at the University of Padua. The Asiago conjugate point is remarkably close to the major astronomical observatory that houses the South African Large Telescope (SALT). The space physics community in South Africa, and its aeronomy program in particular, are eager to house additional instruments at the SALT location. Our contacts and discussions with the South African National Space Agency (SANSA— http://www.sansa.org.za/) have been some of the most encouraging experiences in the overall DURIP experience. There is a marvelous synergy underway, with our request for housing an instrument being used to upgrade local community instruments and facilities to make the SALT location the premier aeronomy observatory in the southern hemisphere. Our DURIP imager at SALT will be the instrument with the most local professional and student interest of all our international locations. Construction is underway and we are confident that the installation trip will be in 2015.

With the DURIP grant formally completed, it is important to state that Boston University funds made available through the Center for Space Physics will cover all costs required to set up the Cape Hatteras and SALT imaging systems.

Acknowledgements: The AFOSR DURIP grant to Boston University’s Center for Space Physics was the largest grant to date for ground-based instrumentation. We are deeply appreciative of the confidence shown in making this award, and we are proud of its accomplishments. Scientific use will, of course, increase during upcoming years. The DURIP instruments will help new graduate students learn optical aeronomy, assist young professional scientists in advancing their careers, and keep senior staff members involved in forefront Space Weather

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