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All-sky-imaging capabilities for ionospheric space weather research using geomagnetic conjugate point observing sites

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Abstract

Optical signatures of ionospheric disturbances exist at all latitudes on Earth—the most well known case being visible aurora at high latitudes. Sub-visual emissions occur equatorward of the auroral zones that also indicate periods and locations of severe Space Weather effects. These fall into three magnetic latitude domains in each hemisphere: (1) sub-auroral latitudes ~40–60°, (2) mid-latitudes (20–40°) and (3) equatorial-to-low latitudes (0–20°).

Boston University has established a network of all-sky-imagers (ASIs) with sites at opposite ends of the same geomagnetic field lines in each hemisphere—called *geomagnetic conjugate points*. Our ASIs are autonomous instruments that operate in mini-observatories situated at four conjugate pairs in North and South America, plus one pair linking Europe and South Africa. In this paper, we describe instrument design, data-taking protocols, data transfer and archiving issues, image processing, science objectives and early results for each latitude domain. This unique capability addresses how a single source of disturbance is transformed into similar or different effects based on the unique "receptor" conditions (seasonal effects) found in each hemisphere. Applying optical conjugate point observations to Space Weather problems offers a new diagnostic approach for understanding the global system response functions operating in the Earth's upper atmosphere.

Keywords: All-sky imager; Airglow; Ionospheric perturbations; Magnetic field; Conjugate behavior

1. Introduction

1.1. Overview

An all-sky camera is the term used for a scientific imaging system that employs a fisheye lens to record the scene from horizon-to-horizon at all azimuths. It was developed for use at high latitudes in Europe and North America to record the appearance of visible aurora. A summary of the history and use of all-sky auroral imaging systems can be found in the classic books by Eather (1980) and Akasofu (2003).

The Earth's upper atmosphere ($h > 80$ km) also has emission features within the vast regions equatorward of the visible aurora. While auroral emission patterns appear at middle latitudes during severe geomagnetic storms, they are still auroral processes. In this paper we review the methods of observing and analyzing the low-light-level emissions found at latitudes equatorward of the visible aurora. Such emission patterns are related to the morphology of the Earth's magnetic field (**B**), but at latitudes low enough that the geometry of magnetic field lines are not significantly affected by geomagnetic storms. This magnetic domain from the equator to sub-auroral latitudes encompasses **B**-lines that extend to less than ~4 earth radii ($L < 4$).

We have recently established a network of five paired observing sites at both ends of geomagnetic field lines in three latitude domains in each hemisphere: one pair at

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low latitudes, two pairs at middle latitudes, and two pairs at sub-auroral latitudes. This set of *geomagnetic conjugate point* observatories from L ~ 1 to L ~ 3 provides a new capability for studies of ionospheric disturbances ordered by the geomagnetic field. Under such conditions, a fixed disturbance source encounters different seasonal conditions in each hemisphere. *Conjugate point optical aeronomy* thus offers the opportunity to explore single-source/dual-receptor conditions in ways not previously available to the extent now possible. The disturbances to be discussed in the context of conjugate science are equatorial spread F (ESF) (at low latitudes), medium scale travelling ionospheric disturbances (MSTIDs) (at mid-latitudes), and stable auroral red (SAR) arcs (at sub-auroral latitudes).

We are not the first group to pursue conjugate point optical science. There is a rich history of conjugate studies of the visible aurora at high latitudes. For example, see Frey et al. (1999) for discussion of coordinated space-based/ground-based auroral science. At lower latitudes, conjugate point studies of ionospheric storms appear in Kalita et al. (2016). Studies of SAR arcs from conjugate locations are very few. Reed and Blamont (1974) may have been the first to report on conjugate SAR arcs. They described the brightness values and locations of a SAR arc observed in September 1967 via a combination of ground-based observations in the northern hemisphere and satellite data for the southern hemisphere. Pavlov (1997) used observations made by the OV1-10 satellite during a magnetic storm in February 1967 to compare brightness values in both hemispheres (separated in time by ~25 min) and to probe via modeling the roles of key parameters central to the emission process. Our all-sky-imaging observations of SAR arcs from Millstone Hill (MA) and Rothera (Antarctica) to be described below appear to be the first case of simultaneous ground-based optical data sets from both hemispheres.

Simultaneous conjugate optical observations of MSTIDs were carried out for the first time by Otsuka et al. (2004) who showed MSTIDs during the night of 9 August, 2005 in Japan and Australia. Shiokawa et al. (2005) was able to measure conjugate MSTIDs on several nights during a campaign in May-June 2003 that used all-sky imagers in the Japanese/Australian longitude sector. The mapping of electric fields from one hemisphere to the other was assumed to be the main mechanism to explain the observations. Martinis et al. (2011) presented the first observations of simultaneous measurements of MSTIDs in the American sector using all-sky imaging and GPS data. Their results showing high activity during local winter provided support for the importance of local E and F region coupling, in addition to the inter-hemispheric coupling. A recent study by Burke et al. (2016), using data from C/NOFS satellite and all-sky imagers at El Leoncito and Arecibo, showed that ‘electric field mapping’ occurs by the propagation of Alfven waves generated in the local summer hemisphere.

An early conjugate point study of ESF detected by optical and radio methods was conducted in the Ascension Island longitude sector by combining ground-based and airborne methods (Weber et al., 1983). Their results demonstrated the magnetic field flux-tube coherence of ESF signatures spanning ~3000 km of trans-equatorial distances. Two decades later, much larger-scale studies of ESF onset and evolution using clusters of optical and radio diagnostic instruments were achieved during the Conjugate Point Equatorial Experiments (COPEX) conducted in Brazil in 2002. The all-sky imaging observations from Boa Vista and Campo Grande showed the differences between airglow depletion signatures of large-scale coherence versus small-scale differences, while ionosonde ESF data appeared similar at both sites (Abdu et al., 2009). Sobral et al. (2009) used those optical and radio observations to study plasma dynamics during the same campaign. Examples of ESF depletions reaching conjugate locations at midlatitudes were shown by Martinis and Mendillo (2007) where airglow depletions associated with ESF were observed at the Arecibo Observatory (L ~ 1.4), and also in the southern hemisphere at El Leoncito Observatory.

1.2. Emissions from sub-auroral latitudes to the geomagnetic equator

Airglow is the term for the photons emitted by atmospheric processes involving chemistry (Solomon and Abreu, 1989). The most common mechanism is dissociative recombination of ions and electrons

$$XY^{+} + e^{-} \rightarrow X + Y^{*}, \tag{1}$$

where $*$ indicates an excited state that decays photo-radiatively through

$$Y^{*} \rightarrow Y + \text{photon} \tag{2}$$

This type of emission has relevance to studies of plasma-neutral abundances in the upper atmosphere (~200–500 km).

All such emission effects in the upper atmosphere occur at all hours of local time, and thus Airglow = Dayglow + Nightglow. Dayglow is difficult to detect in the presence of bright sunshine, but observations can be made using specialized optical systems (see review by Chakrabarti, 1998). Nightglow is far easier to detect during the hours after sunset and prior to dawn. This is the emission type we discuss in this paper. For example, 630.0 nm airglow is emitted through the sequence

$$O_2^{+} + e^{-} \rightarrow O + O^{*} \tag{3}$$

with O^{*} representing an oxygen atom in the ^{1}D excited state. Under the right conditions the O^{*} returns to the ground base state by emitting a photon in 630.0 nm:

$$O^{*} \rightarrow O + 630.0\ \text{nm photon} \tag{4}$$

Another emission that is used to study ionospheric processes is 777.4 nm. It results from the radiative recombination of oxygen ions