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14. ABSTRACT

During daylight hours, ultraviolet light from the sun ionizes the neutral gas of the earth's upper atmosphere (70-1500 km altitude), creating a partially ionized plasma. This plasma then gradually decays throughout the night. The atmospheric region associated with this phenomenon is called the ionosphere, and this zone is of great practical importance to the Department of Defense and civilian industries because of its effect on radio waves. Depending on the frequency of a radio wave, the ionosphere will either reflect or transmit its energy; however, when disturbances cause the ionosphere to behave irregularly, it instead distorts reflection and transmission signals, affecting satellite-to-ground and ground-to-ground communications, Global Positioning System (GPS) navigation and correction signals, and space surveillance radars. In order for scientists to understand and accurately model the ionosphere, they must obtain enough data to identify the locations of both current and future disruptions. Using low-light-level imaging equipment to observe the optical emissions, or airglow, produced by reactions in the ionosphere, scientists can now detect and monitor disturbances over wide areas of the earth.

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Optical Imaging Provides a Clear Picture of Ionospheric Disturbances

Deployment of all-sky imagers will help researchers predict space weather disturbances over a wide area.

During daylight hours, ultraviolet light from the sun ionizes the neutral gas of the earth's upper atmosphere (70-1500 km altitude), creating a partially ionized plasma. This plasma then gradually decays throughout the night. The atmospheric region associated with this phenomenon is called the ionosphere, and this zone is of great practical importance to the Department of Defense and civilian industries because of its effect on radio waves. Depending on the frequency of a radio wave, the ionosphere will either reflect or transmit its energy; however, when disturbances cause the ionosphere to behave irregularly, it instead distorts reflection and transmission signals, affecting satellite-to-ground and ground-to-ground communications, Global Positioning System (GPS) navigation and correction signals, and space surveillance radars. In order for scientists to understand and accurately model the ionosphere, they must obtain enough data to identify the locations of both current and future disruptions. Using low-light-level imaging equipment to observe the optical emissions, or airglow, produced by reactions in the ionosphere, scientists can now detect and monitor disturbances over wide areas of the earth. This capability helps scientists provide up to a few hours advance warning of anticipated disturbances; it also allows users who rely increasingly on radio-based systems to optimize those systems and minimize outages and is thus gaining importance for today's battlefield commanders.

AFRL scientists who specialize in identifying and forecasting ionospheric hazards are exploring the use of all-sky optical imagers to detect, track, and predict the motion of equatorial ionospheric plumes. These turbulent plumes have considerable potential to disrupt radio signals essential for satellite communications, GPS navigation, and other critical warfighter capabilities. They originate in tropical regions, where consistently intense sunlight and heating produce plasma-rich atmospheric conditions. The plumes form after sunset, when the ionosphere quickly destabilizes as lighter, less-dense plasma from lower altitudes ascends through the denser, upper-layer plasma, creating the problematic plumes. Ground-based, optical all-sky imagers are one of the instruments researchers are using to detect and forecast communication and navigation outages resulting from these ionospheric plumes.

As depicted in Figure 1, a basic imager consists of a cooled charge-coupled device (CCD) camera; an image intensifier to amplify weak airglow signals; a filter wheel to select emissions from specific atmospheric reactions; a high-speed shutter; various relay optics; and a very-wide-angle, or fish-eye, lens to provide horizon-to-horizon coverage of the sky. Custom data acquisition software running under the Linux[®] operating system controls the imager hardware. The software collects data on a preprogrammed schedule, automatically samples

image brightness, and adjusts both intensifier gain and exposure length in real time to optimize the signal-to-noise ratio. Once deployed, the imaging system is totally autonomous and can operate for months at a time, limited only by hard disk space and maintenance requirements.

The imager's primary observation target is the faint airglow generated by reactions occurring in the ionosphere. Because airglow emits light approximately 100 times dimmer than the faintest light visible to the human eye, imagers perform best when operated away from city lights and after the moon is down. Figure 2 contains a sample image from a system located at the US Air Force (AF) Ascension Island auxiliary airfield; the areas outlined in red represent equatorial ionospheric plumes. Depending on their frequency, radio signals passing through these areas of low-density plasma are susceptible to severe disruption. At solar maximum, the plumes can significantly affect frequencies up through the L-band, while they disrupt systems operating at lower frequencies (250-400 MHz) throughout the solar cycle. The field of view (FOV) of the image displayed in Figure 2 is nearly 1500 km in diameter, or about 15° latitude. To track a plume's path across a wider FOV, scientists can combine successive images to study the plume's motion over a period of time, comparable to observing weather patterns using time-lapse, Doppler radar images.

Once formed--typically within 1-2 hours after sunset--these plumes drift eastward at speeds approximating 100 m/s. Software can map points on the image to geographic latitude and longitude coordinates, allowing scientists to determine the locations of probable communication or navigation outages. They can also reference the same time-lapse sequences used to reveal plume motion to provide short-term, hour-by-hour forecasts of affected locations on the earth's surface.

Figure 3 provides an example of all-sky image data mapped into geographic coordinates that pinpoint an area over the US Navy Support Facility on the Indian Ocean island of Diego Garcia. Centered on the island's geographic coordinates, the image (circled in red) indicates a large, branched plume located directly overhead and extending both north and south of the observation site. Researchers recognize that ionospheric structures larger than a few kilometers tend to map relatively unchanged along the equatorial magnetic field lines, creating symmetrical structures about the magnetic equator. This symmetry implies that the ionosphere over southern Pakistan and northern India will essentially be a mirror image of that observed over Diego Garcia. In addition to doubling the already huge coverage area provided by the all-sky imager, exploitation of this ionospheric symmetry offers another advantage as well. It allows scientists to monitor space weather conditions using instruments situated far from the theater of interest. This feature is particularly useful if the theater is inaccessible to ground instruments due to rugged terrain, a lack of infrastructure, or the presence of unfriendly forces.

However, a number of limitations constrain the use of all-sky imaging as a space weather monitoring technique. First is the requirement for total darkness, a constraint that stems from the weak nature of airglow emissions. Even if scientists employ narrow-band filters to exclude all light except that within 1 nm of the desired emission wavelength, twilight and moonlight adversely affect data quality and can even damage image-intensified systems. Secondly, unless scientists employ data obtained from multiple imaging stations with overlapping FOV, they must also estimate the altitude of optical emissions to accurately map disturbance regions. A third

constraint relates to the size of image data files; these files can be large and slow to transmit, and they may require significant amounts of disk storage space. Finally, weather systems and clouds separating the imager from the ionosphere represent the greatest obstacles interfering with direct operational use of current all-sky imaging systems.

Weather systems and cloud cover are significant barriers to the use of ground-based optical imagers for real-time space weather monitoring because most airglow wavelengths are in the visible range. To address the problem, AFRL researchers recently developed software algorithms that target distinctive qualities of the ionosphere and airglow to distinguish upper atmospheric structures from clouds, which scientists can subsequently remove from processed images. The software algorithm first records a sequence of images and maps each to geographic coordinates based on a predetermined altitude of the airglow layer. It then calculates the plume's two-dimensional (2-D) drift velocity using a Kalman filter to eliminate spurious velocity solutions. The algorithm uses 2-D filtered drift velocity to translate images into a reference frame that moves in accord with ionospheric features. It then statistically combines multiple images of the same features to produce composite images. Assuming the algorithm correctly calculated the drift velocity, (1) the ionospheric features add coherently and are thus greatly enhanced; and (2) stars, clouds, and other extraneous features remain incoherent with respect to the ionospheric reference frame and are thus diminished or completely eliminated by the statistical processing. This technique works particularly well in the equatorial region, where the typically westward trade winds carry clouds in a direction opposite to the normal eastward drift of the nighttime ionosphere. The most recent software version eliminates most cloud effects in conditions comprising up to 50% cloud cover, at which point the algorithm encounters difficulty determining the correct ionospheric drift velocity. The ionospheric velocity derived from this process also allows scientists to make accurate short-term, hour-by-hour forecasts. Figure 4 illustrates sample results of this processing technique.

AFRL's Communication and Navigation Outage Forecasting System (C/NOFS) satellite is also addressing the space weather problem posed by equatorial plumes. A fundamental limitation of the C/NOFS satellite is its 1-D orbital track, which covers only a single latitude/altitude for each longitude. Scientists predicting effects at other latitudes/altitudes must extrapolate from *in situ* data with the aid of plume models or ground-based sensor data. Because of their huge region of coverage, all-sky imagers will give researchers a more comprehensive picture of events occurring in the equatorial ionosphere and should provide key information for validating the C/NOFS instruments and forecast model. With adequate cloud detection/removal processing, all-sky imagers operating from equatorial sites could contribute data directly into C/NOFS models to supplement data from its satellite instruments.

Recent AFRL efforts in the area of ground-based optical observation of ionospheric irregularities have focused on deployable climate-controlled boxes and cloud removal, but other efforts to further improve ground-based imaging are under way as well. Just as cell phone networks rely on intermittently spaced transmitters to provide good coverage, networks of optical imagers with overlapping FOV can provide robust observation of the ionosphere with high accuracy and minimal degradation from tropospheric weather. Because the altitude of ionospheric emissions is so high, ground-based imagers hundreds of kilometers apart are able to observe the same features, from a slightly different angle. Consequently, if one imager is

clouded in, other imagers far away and beneath different weather patterns can still make the observation and use the network to send the data to user displays. Researchers expect distributed imager networks will nearly eliminate problems associated with cloud coverage. Currently, AFRL has two Small Business Innovation Research Phase I contracts under way to develop less-expensive imager hardware, with the goal to create affordable distributed imaging arrays.

Optical all-sky imaging is an emerging tool for observing ionospheric plumes and other space weather disturbances over wide areas. The FOV afforded by these systems allows researchers to detect disturbances and provide limited advance warning of communication and navigation outages for large areas of the earth's surface, increasing the capability, efficiency, and accuracy of the USAF's technology-reliant operations and assets.

*Lt Robert Esposito and Dr. Todd Pedersen, of the Air Force Research Laboratory's **Space Vehicles Directorate**, wrote this article. For more information, contact TECH CONNECT at (800) 203-6451 or place a request at <http://www.afrl.af.mil/techconn/index.htm>. Reference document VS-04-11.*

Figure 1. Low-light all-sky imager

Figure 2. All-sky image taken from Ascension Island in the South Atlantic. The dark areas outlined in red are turbulent plumes of lower-density plasma.

Figure 3. All-sky image (lower right) showing an equatorial plume over Diego Garcia. The same data maps as a mirror image (upper right) reflected about the magnetic equator.

Figure 4. Output of a software algorithm that first converts raw all-sky images (upper left) to geographic coordinates (upper right) to produce a statistical composite image (lower left) and then extrapolates results to generate a short-range forecast (lower right).

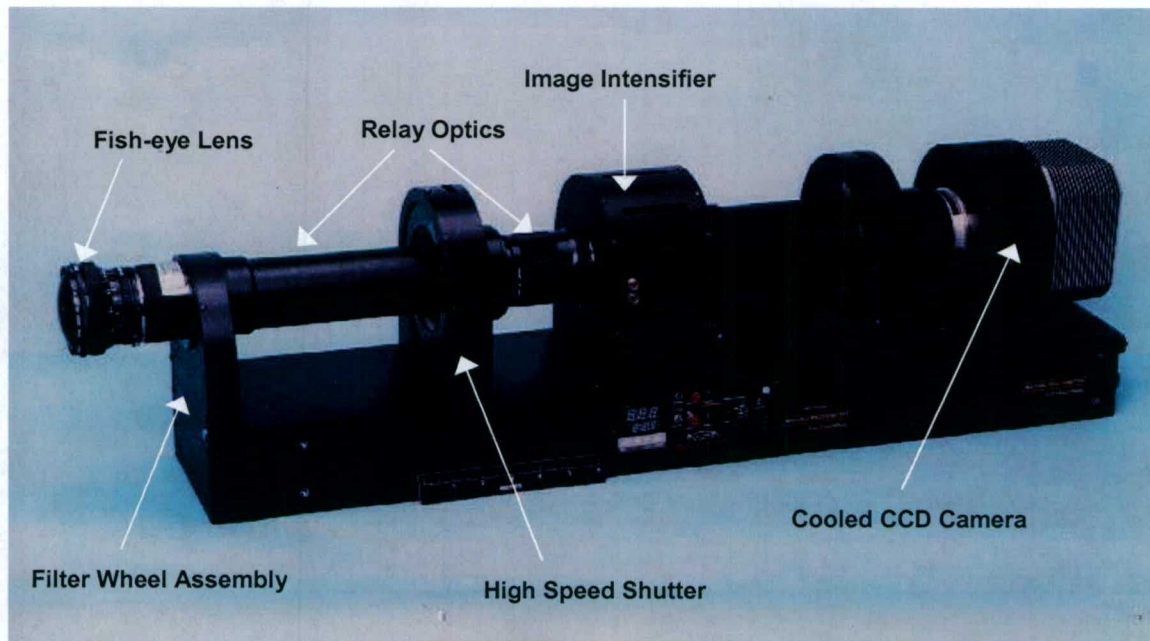


Figure 1. Low-light, all-sky imager

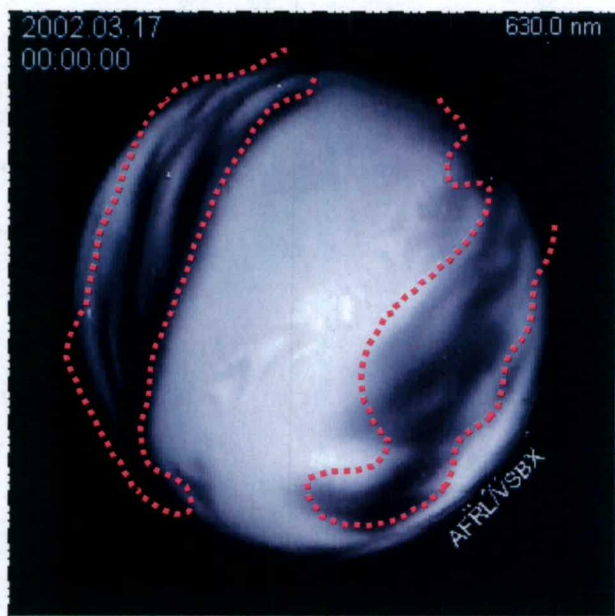


Figure 2. All-sky image taken from Ascension Island in the South Atlantic. The dark areas outlined in red are turbulent plumes of lower-density plasma.

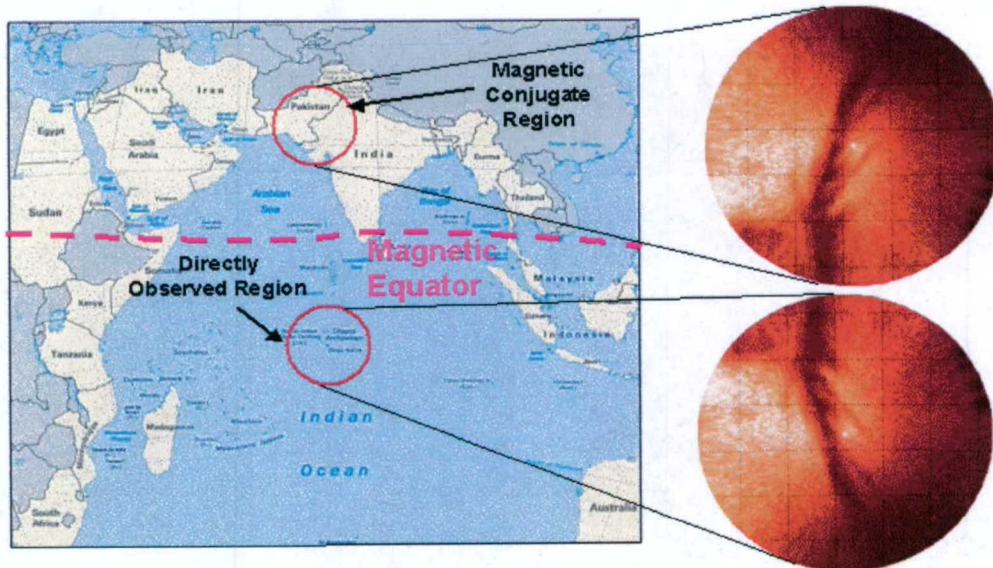


Figure 3. All-sky image (lower right) showing an equatorial plume over Diego Garcia. The same data maps as a mirror image (upper right) reflected about the magnetic equator.

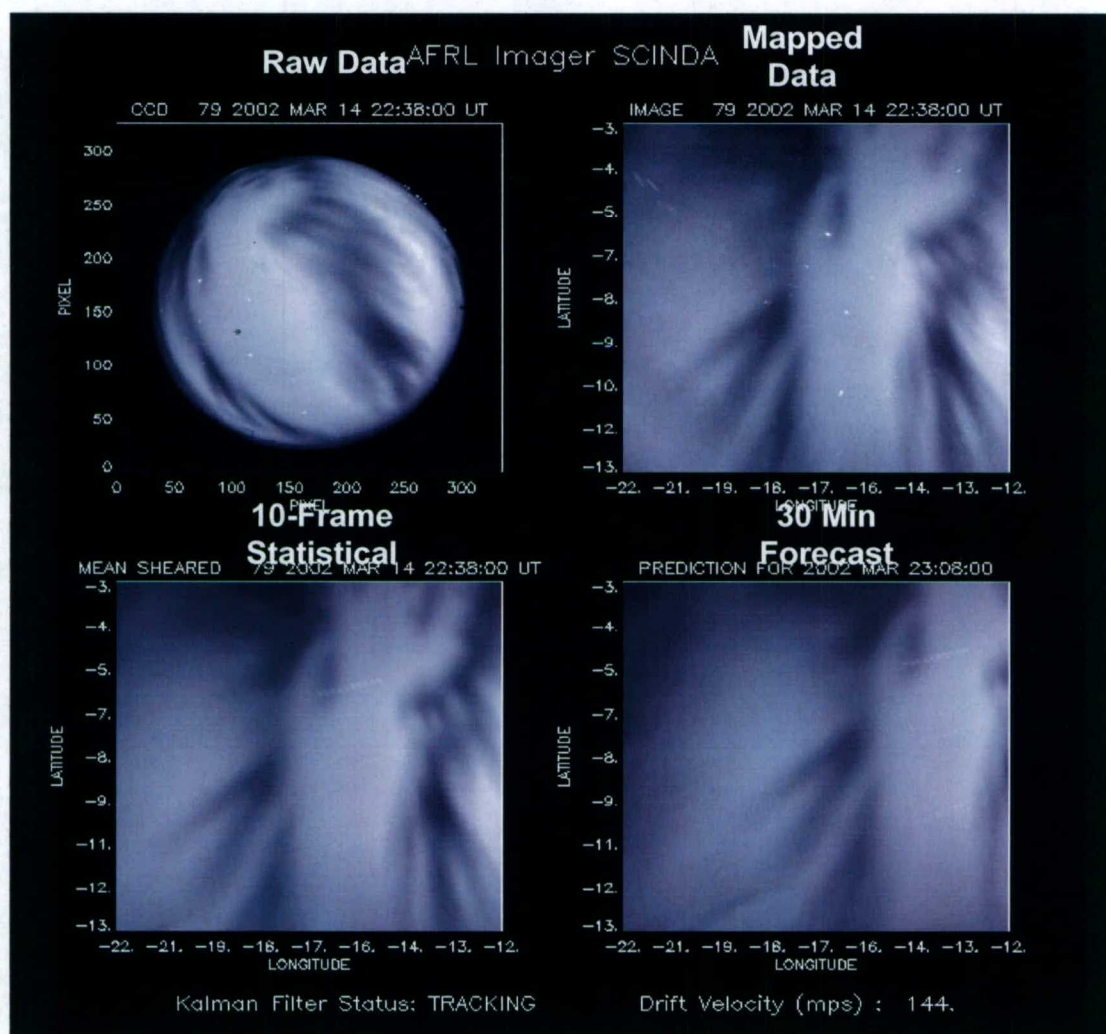


Figure 4. Output of a software algorithm that first converts raw all-sky images (upper left) to geographic coordinates (upper right) to produce a statistical composite image (lower left) and then extrapolates results to generate a short-range forecast (lower right).

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INSET

Tropospheric weather such as rain and snow not only prevents observations, but also limits deployment of all-sky imagers, which require configurations that typically rely on either an observatory infrastructure or an alert operator to protect them from foul weather. By condensing on cooled optical components and corroding or short-circuiting electronic components, atmospheric moisture, including rain and humidity, can ruin images and reduce hardware service life. In polar environments, appropriate safeguards must also be in place to protect hardware and computer system components from temperature extremes and physical damage from snow and ice. To overcome such problems, the AFRL research team built portable climate-controlled shelters to enable deployment of imagers to locations lacking an observatory infrastructure. These insulated and waterproofed boxes house the components necessary for operating an imager anywhere on the globe. Enclosed in the weatherproof container are the imager, computer, required cables and connectors, CCD camera control unit, and combined air conditioning/heating unit. Shock-mounting of all boxed components ensures safe shipping of contents as a portable observatory unit. The completed deployment package requires only electrical power (110 or 220VAC) to operate, although an Internet connection is highly desirable to facilitate real-time data use and remote monitoring of system performance.

