First Measurements of Ionospheric TEC and GPS Scintillations from an Unmanned Marine Vehicle

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ABSTRACT

Our ability to monitor the geospace environment from the vast stretches of the open *ocean* remains a technological challenge. This is a problem because oceans cover about 70% of the Earth's surface. Traditional ground-based ionospheric and upper atmospheric monitoring systems (e.g. ionosondes, imagers, interferometers) have been bulky, power intensive and have not been demonstrated to successfully operate from a platform in the open ocean. ASTRA has developed capabilities for integrating small size, weight, and power (SWaP) geospace instruments on unmanned marine vehicles. As part of this effort, we have successfully demonstrated a real-time monitoring capability for ionospheric Total Electron Content (TEC) and scintillation measurements. In this paper we describe a low SWaP dual-frequency GPS receiver called "GPS Autonomous Micro-Monitor at ASTRA" (GAMMA) which can be optimized for operations from an extremely dynamic environment such as the ocean surface. Funded by the Air Force Research Laboratory, ASTRA recently performed a multi-day demonstration of the receiver off the coasts of Hawaii and Lima, Peru. In this paper, we will discuss the GAMMA receiver; describe the operating platform for the receiver; and present measurements of ionospheric TEC and GPS scintillations made while deployed in the ocean. TEC and scintillation measurements from the marine vehicle will be compared against ground observations to provide validation and to assess the impact of the ocean environment on the data quality. We anticipate this capability will open up many new applications for passively monitoring the ionosphere and its perturbations from previously inaccessible regions, such as the ocean, and from moving vehicles.

1. INTRODUCTION

The ionosphere affects radio wave propagation, and thus modern radio-based navigation, communications, and surveillance systems can be affected by ionospheric space weather. Ionospheric weather includes gradients and irregularities that affect trans-ionospheric UHF and L-band line-of-sight propagation (refraction errors and scintillation) and VHF/HF sky-wave and scatter propagation. Ionospheric irregularities at equatorial, auroral, and middle latitudes constitute a major category of space weather effects that need to be better characterized and understood [Kintner et al., 2009]. Associated with these irregularities are scintillations that can cause GPS receivers to lose signal tracking [Humphreys et al., 2004]. Given the recent explosion of GPS-based services in the world's technological infrastructure and the increased reliance of GPS for PNT (Positioning, Navigation, and Timing), there is a growing demand for GPS diagnostic systems allowing end users to identify situations when their technologies are vulnerable.

Characterization, modeling, and imaging of ionospheric dynamics and disturbances suffers from too few ionospheric sensors. Traditional ground-based ionospheric monitoring systems (e.g. ionosondes) have been expensive, bulky, and power intensive and have not permitted coverage of large ocean areas or on-demand theater coverage. Even coverage by smaller, less expensive instruments, such as dual-frequency GPS receivers, remains sparse. This state of affairs is illustrated in Figure 1 [Occhipinti et al., 2008], which shows values of Total Electron Content (TEC) from measurements by dual frequency GPS receivers around the globe. Each colored pixel indicates the availability of a measurement. The measurements come predominantly from the US, Europe, Japan and Australia. The white areas are locations where no data were available – especially Africa, South America, the Middle East and Afghanistan, and the oceans. Much of the low latitude region that is of great importance to the US DoD is not covered, making ionospheric specification and forecasting in mission-critical regions very difficult. Hence, nowcasting the spread of amplitude and phase scintillations is difficult-to-impossible given the receivers that have been available and their distribution. These challenges are even more severe in oceanic regions. In addition, because of the dominant west-to-east drift of the ionosphere, near-term forecasting requires measurements that are several hundred km upstream (i.e. to the west) of the region of interest. For many theaters these locations are in the ocean and are therefore inaccessible.

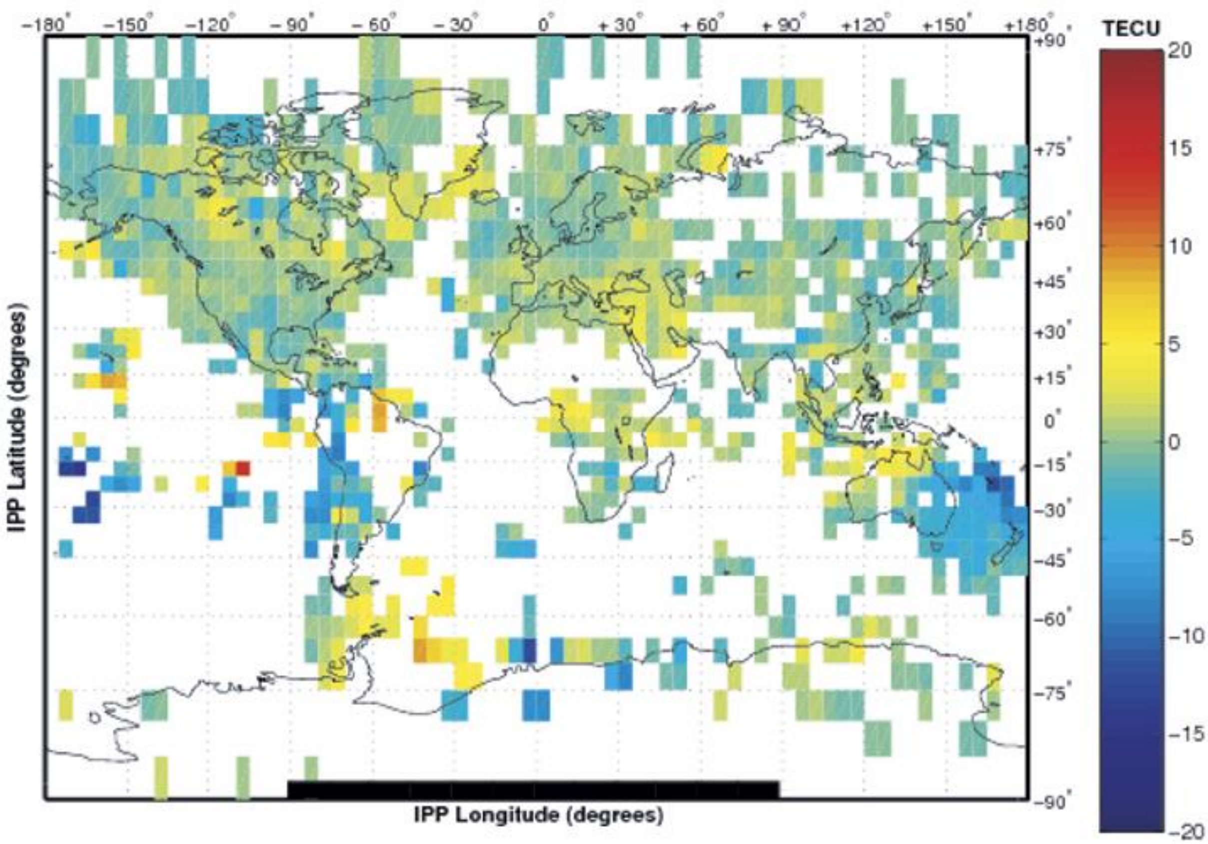

Figure 1. Global Map of the ionospheric Total Electron Content (TEC) showing measurements from ground-based dual-frequency GPS instruments. [Occhipinti et al., 2008].

In this paper we describe a low size, weight, and power (SWaP) robust GPS receiver for ionospheric monitoring that can fill the gaps in measurement coverage. We present results from a field demonstration conducted in January 2015 off the coast of Lima, Peru. The paper is organized as follows: Section 2 briefly describes the new GPS receiver developed for this study and provides an overview of software innovations that enables ionospheric monitoring from a dynamic platform, such as an ocean buoy; Section 3 describes the recent Peruvian field experiment and presents results from the experiment, and Section 4 recapitulates the salient findings of this study.

2. GAMMA GPS Receiver

The GPS Autonomous Micro-Monitor at ASTRA (or 'GAMMA'), funded by the Air Force Research Laboratory (AFRL), is a compact dual-frequency GPS software receiver that tracks L1 and L2 civilian signals (specifically L1 C/A and L2 CL). It provides an unprecedented capability to make accurate TEC and scintillation measurements from a moving platform, such as remote ocean buoys, and to relay these measurements to users in real-time. The GAMMA GPS receiver differs from typical GNSS receivers in two key ways: it has been specially designed to measure TEC and scintillation parameters from moving platforms, such as an ocean buoy or an aircraft, and; (2) its design features include low power consumption and a fully-autonomous system capable of operating from remote locations (supported by ASTRA's Standalone System Support Module) where power and communication infrastructure are not otherwise available. GAMMA is a next-generation design that leverages software and hardware from ASTRA's successful CASES (Connected Autonomous Space Environment Sensor) dual-frequency GPS space weather monitor. Details of the CASES receivers have been discussed previously by Crowley et al. [2011, 2012], O'Hanlon et al. [2011] and Azeem et al. [2013]. Figure 2 shows the OEM version of the GAMMA GPS receiver. The top board in the figure is the RF Front End, the middle board is the interface board which performs all high level functions such as user interface, preparing data packets etc., while the board at the bottom is the DSP board which performs signal acquisition and tracking and other low level functions. Because of the on-board Linux computer housed on the interface board, the GAMMA receiver does not require an external computer, thus reducing the SWaP of the overall system, and with corresponding reductions in cost. Table 1 shows various data streams provided by the GAMMA GPS receiver in real-time. The four columns of Table 1 indicate different data types, their cadence and whether they are configurable on the receiver. In addition to the typical GPS navigation solution (Column 4), the receiver also provides scintillation parameters (Column 3), TEC and other useful parameters (Column 2), and high-rate raw data that can be used for post-processing (Column 1).

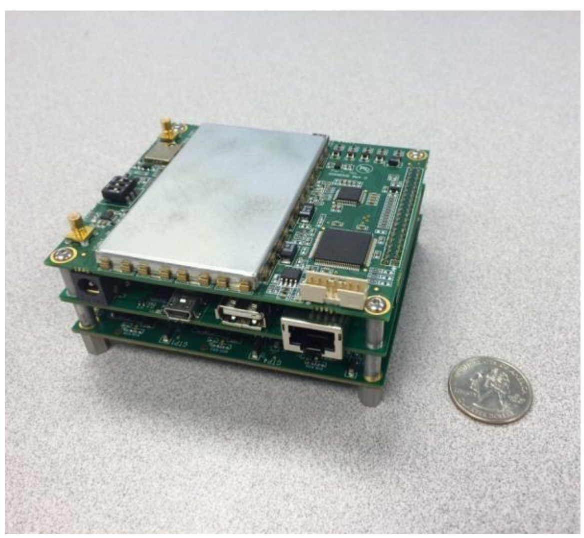

Figure 2. OEM version of the GAMMA GPS receiver showing the RF Front End (top board), the interface board (middle board), and the DSP board (bottom).

Table 1. GAMMA GPS receiver's standard data products.

Data Type	Per Channel High Rate Data	Per Channel Low Rate Data	Per Channel Scintillation Parameters	Navigation Information
Default Data Rate	**100 Hz**	**1 Hz**	**1measurement per 60 second**	**1 Hz**
Configurable Rate?	**Yes, 50 or 100 Hz**	**Yes, <= 1 Hz**	**Yes**	**Yes, <= 1 Hz**
Available Parameters	Integrated Carrier Phase In-Phase Accumulation Quadrature Accumulation GPS Time Receiver Time	**Pseudorange-based TEC** **Phase-based delta TEC** Pseudorange Integrated Carrier Phase GPS Time Receiver Time Doppler Frequency PRN (Azim/Elev/Health) C/N0 Data Validity Flag Cycle Slip Flag Signal Acquisition Status	$\mathbf{S_4}$ $\boldsymbol{\sigma_\Phi}$ $\boldsymbol{\tau_o}$ Scintillation Power Ratio GPS Time Reference Channel Status PRN	Receiver X/Y/Z Position GPS Time Receiver Time Receiver X/Y/Z Velocity Receiver Clock Error Receiver Clock Error Rate Navigation Solution Flag

3. FIELD TEST SETUP

To demonstrate autonomous operation of the GAMMA receiver in an ocean environment, we integrated the receiver onto a robotic unmanned maritime vehicle, called "Wave Glider", built by Liquid Robotics Inc. of Sunnyvale, CA, USA. The Wave Glider, which uses waves to propel itself, provides a new way to achieve ocean-based observations. The Wave Glider in its deployment configuration is shown in Figure 3.

Figure 3. Wave Glider deployed off the coast of Lima, Peru on January 20, 2015. The GAMMA receiver is mounted under the solar panels in a Payload Dry Box. The GPS antenna is located on the top of the mast on the right.

From January 20-27, 2015 we deployed a GAMMA receiver on the Wave Glider about 11 miles off the coast of Lima, Peru (12.04° S, 77.03° W). The Wave Glider provided persistent ocean presence for the duration of the field experiment. We collected ionospheric TEC and scintillation measurements under various vehicle dynamics conditions, which included station keeping, straight-line traverse, and box maneuvers. Stored TEC and scintillation data was transmitted at a 15 minute cadence via an Iridium satellite link. We note here that the data cadence was chosen to reduce communications cost, however, the GAMMA receiver is capable of transmitting TEC and scintillation data in real time via satellite. Continuous surface presence means that data can be delivered as it is collected. For the duration of the test we also deployed two other GAMMA receivers on land approximately 12 miles from the Wave Glider, to provide a stationary reference for comparison and validation of the measurements from the water.

4. RESULTS

4.1 Phase Scintillation Measurements

Phase scintillation is the high frequency (<30 second period) change in the integrated carrier phase from the GPS receiver. Phase scintillation is reported with a parameter denoted by σ_φ, which is the standard deviation of the carrier phase in radians. Ionospheric variability is usually the cause of these high frequency oscillations, but as the integrated carrier phase is essentially just a measure of the change in distance between the receiver and satellite versus time, any high frequency movement of the receiver's antenna will lead to similar changes in the integrated carrier phase, and will arbitrarily raise the measured σ_φ.

GAMMA has a phase scintillation noise floor of approximately 0.02 radians (0.5 cm). This means that any antenna motion with an amplitude of more than 0.5 cm and a period less than approximately 30 seconds will show up in the calculated phase scintillation index (σ_φ). Strong ionospheric scintillation is associated with a σ_φ value of about 0.8 or higher, which is equivalent to 16 cm of antenna movement. When the buoy is on the water, the antenna undergoes periodic motion due to the Wave Glider's dynamics with a period of just a few seconds and an amplitude in excess of 20 cm. This raises the measured σ_φ well above what would normally be considered strong ionospheric scintillation, even when the ionosphere is quiet, rendering the measurement useless (Figure 4a). Because the change in the integrated carrier phase as the antenna moves is well correlated for each satellite—a function of the direction of antenna movement and the geometry of the satellite constellation -- the integrated carrier phase from all satellites can be used to precisely calculate the antenna's movement over the scintillation time window. That information can then be used to subtract the antenna's movement from the observations to allow a motionless calculation of σ_φ for all satellites (see Figure 4b).

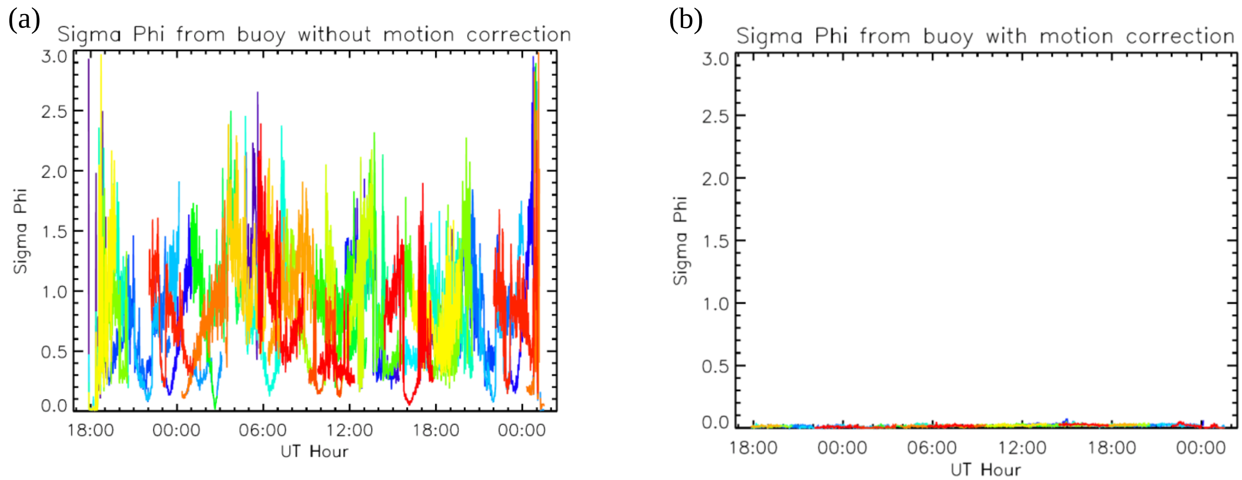

Figure 4. (a) Calculated phase scintillation index (sigma phi) without compensating for antenna motion on the Wave Glider. Note that strong ionospheric scintillations are often associated with a σ_φ of around 0.8 cycles; (b) Same as (a) but now but now compensating for antenna motion.

Figure 5 shows the GAMMA phase scintillation index data for January 21, 2015. The right panel shows the measured σ_φ from a GAMMA GPS receiver located on shore in Lima, Peru, while the left panel shows the measured σ_φ from GAMMA on the buoy. It is clear from the figure that the scintillation event recorded by GAMMA from 0300 to 0400 UT on Jan 21 coincides well with the σ_φ increase measured by the ground-based GAMMA receiver in Lima at the same time.

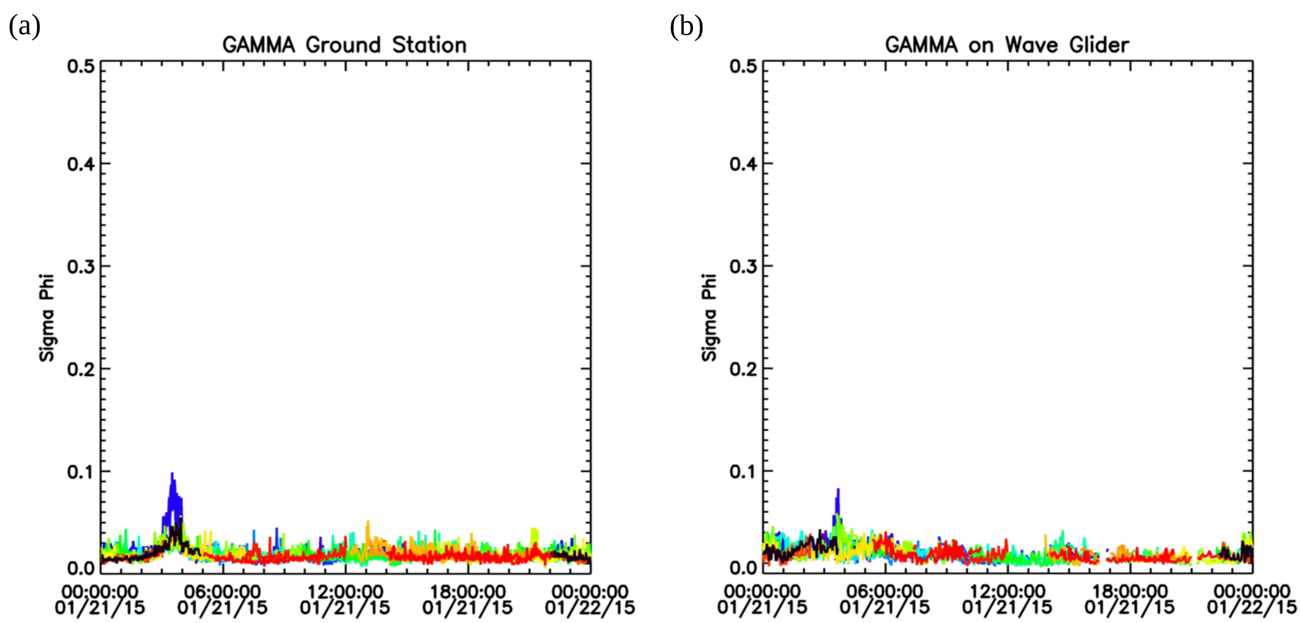

Figure 5. GAMMA σ_φ from (a) a GAMMA receiver on shore in Lima, Peru; (b) the Wave Glider deployed 11 miles off the coast of Lima for a small scintillation event on January 21, 2015.

4.2 TEC Measurements

In addition to scintillation, the GAMMA receiver also measures ionospheric TEC. However, like scintillation, the motion of the buoy causes deterioration in the quality of the TEC measurements unless special processing is applied. ASTRA has developed special processing algorithms that can remove the effects of the motion on the TEC measurements. As a validation of the technique, we compare TEC from the buoy with that from the GAMMA ground-station. Figure 6a shows VTEC from one of the GAMMA receivers deployed in Lima, on dry land. Figure 6b shows VTEC from the receiver on the Wave Glider, using the high rate data collected on-board the receiver. After applying our new processing algorithm, VTEC measurements from the Wave Glider show good agreement with those from the GAMMA receiver in Lima, Peru.

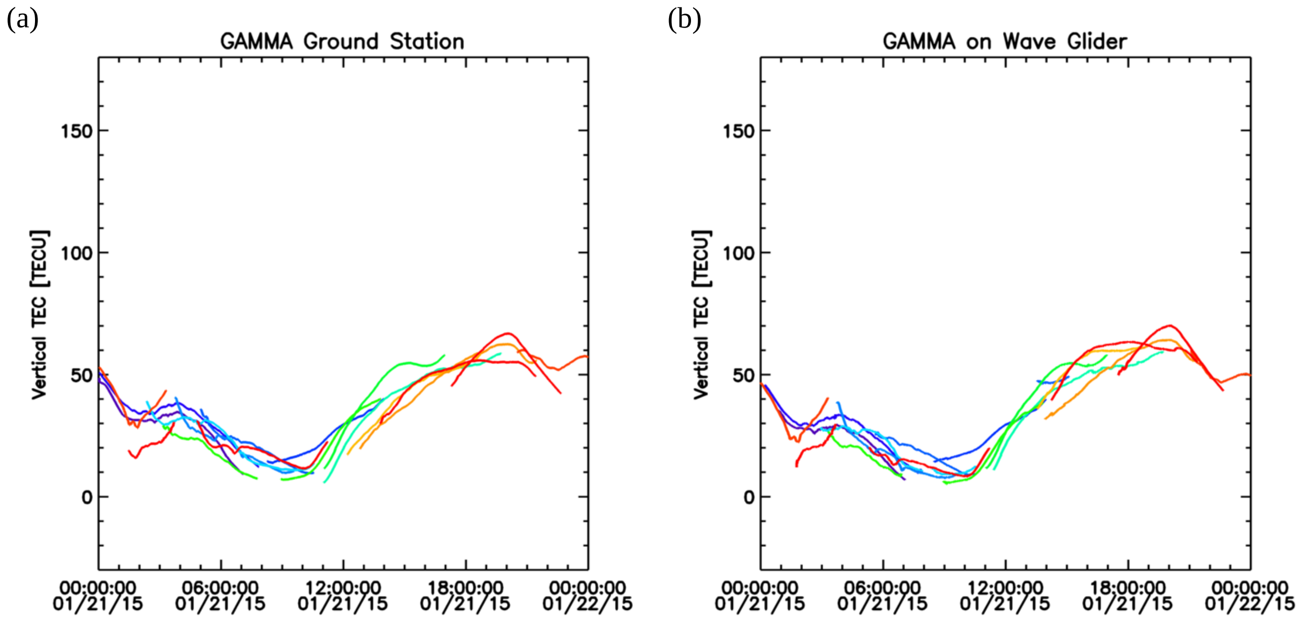

Figure 6. (a) VTEC from a GAMMA GPS receiver located at Lima, Peru (12 miles from the Wave Glider), (b) VTEC from the GAMMA GPS receiver on the Wave Glider while deployed 11 miles off the coast of Lima.

5. CONCLUSIONS

We have developed a small size, weight and power dual-frequency GPS receiver for ionospheric monitoring that is capable of successful operation on moving platforms. The GAMMA receiver uses novel signal processing techniques to remove the effects of platform motion on measurements of phase scintillation, amplitude scintillation, and total electron content. The receiver was deployed on a robotic, unmanned, maritime vehicle for a recent campaign off the coasts of Peru. The field test in Peru demonstrated the full functionality of the GAMMA receivers from a buoy including its autonomous operation and the Iridium communication link back to the shore. In this paper we present phase scintillation and TEC measurement from the GAMMA GPS receiver while deployed on the Wave Glider maritime vehicle. Comparison of scintillation and TEC measurements from the GAMMA receiver on the Wave Glider to the on-shore GAMMA receiver demonstrated the capability of the new GPS receiver to make accurate and real-time ionospheric measurement from an ocean buoy. To our knowledge, this is the first time such measurements have been successfully made from the surface of open water. We anticipate this capability will open up many new applications for passively monitoring the ionosphere and its perturbations from previously inaccessible regions, such as the ocean.

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