Bistatic Observations of the Ocean Surface with HF Radar, Satellite and Airborne Receivers

Paul A. Bernhardt
Plasma Physics Division
Naval Research Laboratory
Washington, DC USA
paul.bernhardt@nrl.navy.mil

Carl L. Siefring
Plasma Physics Division
Naval Research Laboratory
Washington, DC USA
carl.siefring@nrl.navy.mil

Stanley C. Briczinski
Plasma Physics Division
Naval Research Laboratory
Washington, DC USA
stan.briczinski@nrl.navy.mil

Juha Vierinen
Physics and Technology
University of Tromso
Tromos, Norway
juha-pekka.vierinen@uit.no

Ethan Miller
Applied Physics Lab.
Johns Hopkins Univ.
Laurel, MD USA
Ethan.Miller@jhuapl.edu

Andrew Howarth
Physics and Astronomy
University of Calgary
Calgary, CA
howarth@phys.ucalgary.ca

H. Gordon James
Physics and Astronomy
University of Calgary
Calgary, CA
howarth@phys.ucalgary.ca

Eugene Blincoe
ROTHR
Raytheon IIS
Chesapeake, VA USA
Eugene_Blincoe@raytheon.com

***Abstract*—A new concept has been developed which can view vast regions of the Earth's surface. Ground HF transmissions are reflected by the ionosphere to illuminate the ocean over a few thousand kilometers. HF receivers detect the radio waves scattered by the sea and land surface. Using the theory of radio wave scatter from ocean surfaces, the HF data is then processed to yield the directional wave-height spectrum of the ocean. This technique has several advantages over existing remote sensing methods. A large area of the ocean can be sampled to yield the wave-height characteristics with high, km-scale resolution. The wave height spectrum can be directly compared with temporal frequency spectrum obtained with buoys at specific points in the ocean volume. Furthermore, the technique uses HF waves which penetrate the dense rain found in hurricanes.**

Keywords—HF Ocean Remote Sensing

I. INTRODUCTION

HF waves have been used for decades to provide remote sensing of the ocean by measuring the backscatter and bistatic-scatter of surface waves [1] Barrick, 1972. Recently it was proposed by [2] Bernhardt et al., 2016 that sky-wave illumination of the ocean using HF reflection by the ionosphere could provide measure the ocean wave height spectrum over large regions. Further explorations of this technique are explored in this paper.

High Frequency (HF) sky-wave mapping of the ocean surface uses a four components: (1) the ground HF transmitter radiating from wide or narrow beam antennas, (2) the ionosphere to reflect or refract upward EM waves downward to the ocean, (3) the sea surface to scatter EM waves into all solid angle directions, and (4) an HF receiver and antenna to record the scattered waves for later analysis. The specific geometries for the measurement system greatly vary depending on the location of the receiver on the ground, on a low-flying airplane or on a satellite orbiting above the ionosphere. The ground-to-ground and the ground-to-space geometries are explored in the next sections.

II. GROUND BASED GEOMETRY FOR HF SKY-WAVE ILLUMINATION OF THE OCEAN

The first example of this system uses a transmitter and receiver on the earth's surface to form of an oblique scatter sounder. A few of the ray paths for the HF scatter sounder are illustrated in Figure 1. The single hop ray path between two points on the earth surface are only affected by the bottomside of the ionosphere. Two types of two-hop paths are found. The propagation path with a central mirror (specular) reflection point again only is determined by the ionosphere. The strength of the scatter (non-specular) path is affected by both the ionosphere and the surface properties of the ocean. Knowledge of the ionosphere based on the one-hop and specular two-hop paths may be used to remove the ionospheric effects from the non-specular two-hop paths leaving data on the wave-height spectrum of the ocean.

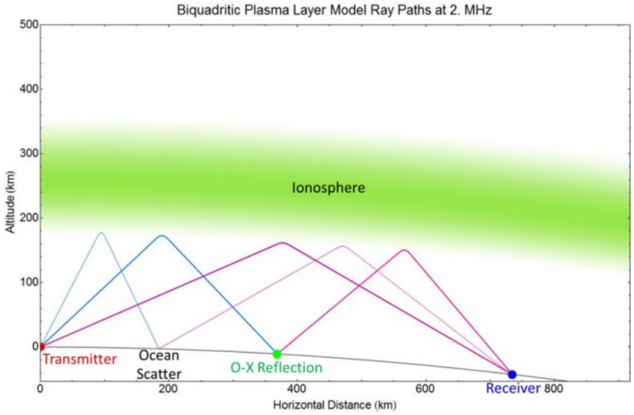

Figure 1. HF rays from a ground transmitter propagating to a single-point receiver using both ionospheric reflection and ground surface reflection and scatter. The non-specular ray paths can be used to measure the roughness properties of the ocean.

This work was sponsored by the NRL 6.1 Base Program.

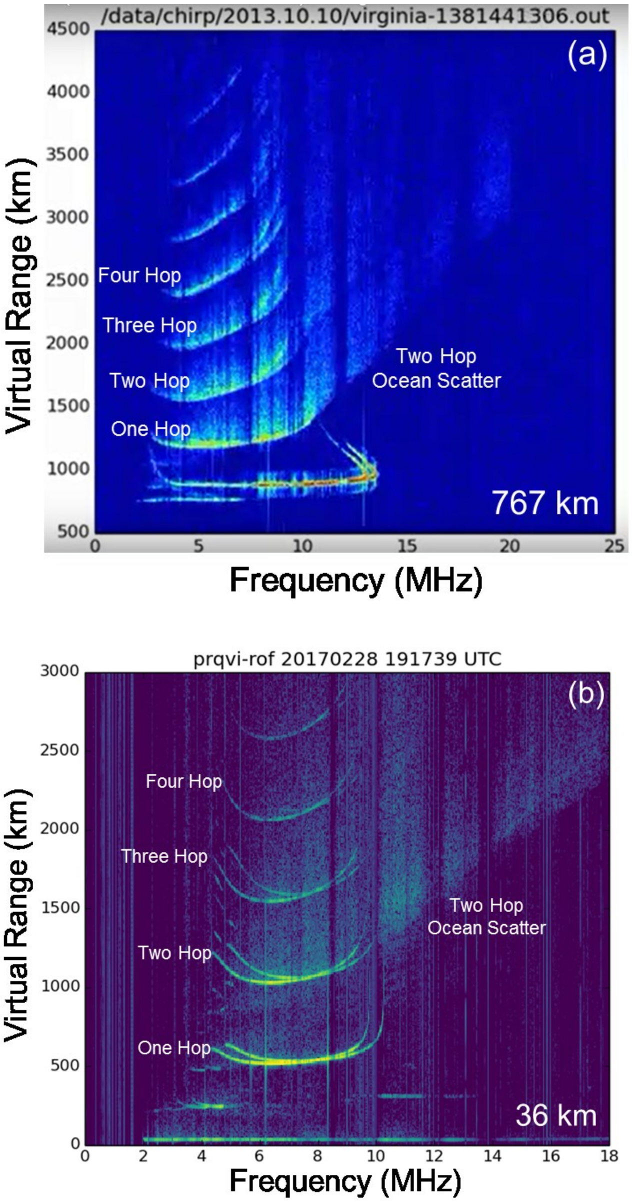

Figure 2. Oblique Ionograms from the 2 to 20 MHz swept transmissions from (a) Chesapeake VA to MIT Haystack MA and (b) Vieques PR to Culebra PR. In both cases, the two hop ocean scatter extends to larger frequencies and ranges because of out-of-plane paths involving low ray elevations. Ocean scatter contributes to the diffuse spread of power in both frequency and range.

An oblique sounder with swept (2 to 20 MHz) signals from a ground site which can be demodulated at a receiver to yield oblique ionogram displays that show also show ocean scatter. The demodulation algorithm and on-line movies of oblique ionograms have been provided by [5] Vierinen, 2013 of the with examples from a digital receiver located at MIT Haystack Observatory in Massachusetts using a swept HF transmitter in Virginia at a distance of 767 km from the transmitter. The sounding data illustrate both the variability of the ionosphere and the strength of ocean scatter at ranges exceeding 1000 km. Recently, a digital receiver system was set up at Culebra Puerto Rico by the Applied Physics Laboratory of the Johns Hopkins Laboratory to give oblique ionograms for separations from the ROTHR transmitter at Vieques, Puerto Rico by 36 km. Data from both sets of measurements show the same key components for the sounding records. The distinct 1st, 2nd, 3rd, 4th, etc. hop data provide information about the electron density profile of the F-layer ionosphere over the ocean between the islands of Culebra and Vieques. The diffuse two-hop scatter lying between the 2nd and 3rd hop ionograms and extending to the right of the 2nd hop maximum may be used to determine the wave height spectrum of the Atlantic Ocean off of Pennsylvania and the Caribbean Sea surrounding the Puerto Rican Islands.

Both the ionosphere and ocean effects are often observed with oblique sounders. Estimation of the received radio wave power uses raytracing to the ionosphere and back down to the ground for the range of elevation angles and azimuths from the transmitter. The scattered rays from the ocean are traced using a homing algorithm to the receiver along paths reflected by the ionosphere. Bernhardt et al., 2016 [2] have developed a computer model for simulating the sky-wave illumination of the ocean and computing the scatter as a function of incident and scatter angle. For the two-hop oblique scatter geometry in Figure 1, the multi-hop oblique ionograms components of the data were used to determine the ambient ionospheric profile below the F-Layer peak using the quasi-parabolic technique described by Croft and Hoogasian, 1968 [3], and Huang, Reinisch, and Kuklinski,1996 [4]. Once the bottomside plasma profile has been determined, the propagation code described by Bernhardt et al.,2016 [2] was used to predict the 2nd hop component of the ocean scatter.

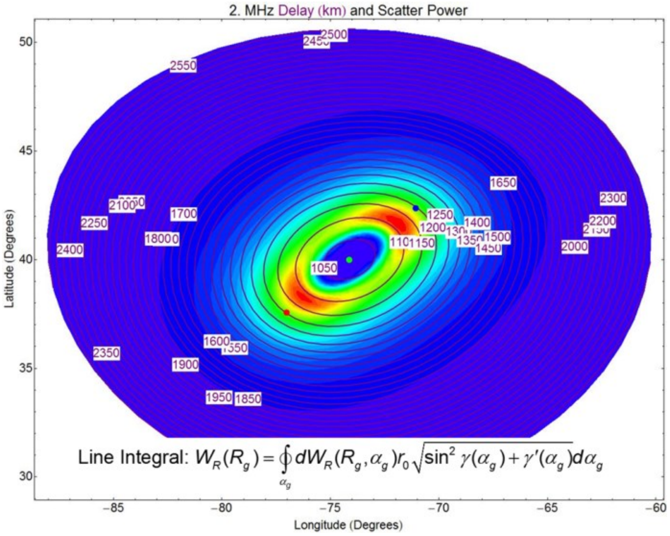

Figure 3. Illumination of the ocean at 2 MHz showing two-hop group delay contours (km) around the specular reflection point (green) on the ocean for propagation from the transmitter (red) to the receiver (blue). The specific geometry for this example is the HF transmitter at Chesapeake Virginia and the receiver at MIT Haystack Massachusetts given in Figure 2a.

At each frequency, the combined ray trace and ocean scatter model is used to compute the power at the receiver for each ray that leaves the transmitter point. An important intermediate step in the ocean scatter is projection of the scatter power to geometric coordinates on the sea surface is shown in Figure 3. The group delay contours are ellipses around minimum group delay point for the specular path. The scatter from the ocean is strongest at two regions on either side of the specular point along a line between the transmitter and receiver. The line integral at fixed range of the scatter power yields the received power at each range. Similar diagrams at each frequency provide the basis for the range versus frequency intensity of the scattered ocean signal.

The received power for simulated ionosphere propagation and ocean scatter over the full range of frequencies is shown in Figure 4. The structure of the ionospheric and ocean scatter closely matches the one and two hop components shown in Figure 2a. The model shows that the scattered power represents the ocean wave height spectrum integrated around a large region of the ocean covering a few thousand kilometers because the transmitter antenna was omnidirectional and it emits HF waves in all direction. If the transmitter antenna were an array to form a narrow beam at a selected azimuth and elevation direction, the received ocean scatter for each HF wave frequency would be from one wave number of the wave height spectrum at a fixed geographic location. To determine the full wave height spectrum at any point on the ocean the measurement system could be enhanced by (1) placing the HF receiver on a moving platform (airplane or satellite), (2) making measurements throughout the flight of the platform, (3) moving an HF beam across the ocean, and (4) sweeping the HF frequency in time. Such enhancements are discussed in the next section.

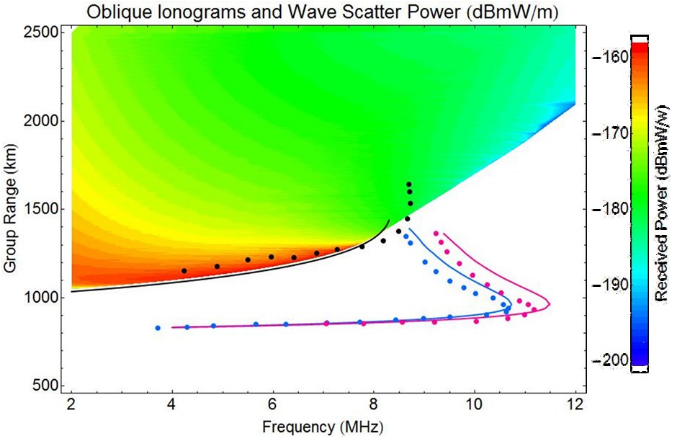

Figure 4. 1-hop and 2-hop oblique ionograms overlaid with ocean scatter power. The points are scaled from the oblique ionograms in Figure 2a. A vertical slice of the oblique ionogram at a fixed frequency represents the average wave height spectrum with range mapping to a line integral of ocean wave number.

III. SPACE-BASED RECEPTION OF HF OCEAN SCATTER

The ocean scatter measurements move from fixed ground receivers to orbiting receivers with a technique called HF Ground-Ionosphere-Ocean-Space (GIOS). GIOS can view vast regions of the Earth's surface using currently available assets. Ground HF transmissions are reflected by the ionosphere to illuminate the ocean over a few thousand kilometers. HF receivers on low-earth-orbit satellites detect the radio waves scattered by the sea and land surface. Using the theory of radio wave scatter from ocean surfaces, the GIOS data is then processed to yield the directional wave-height spectrum of the ocean. The GIOS technique has several advantages over existing remote sensing methods. First, a large area of the ocean can be sampled to yield the wave-height characteristics with high, km-scale resolution. This measurement scale matches the grid size used in physics-based oceanographic models. The wave height spectrum can be directly compared with temporal frequency spectrum obtained with buoys at specific points in the ocean volume. Furthermore, the GIOS technique uses HF waves which penetrate the dense rain found in hurricanes. Microwave attenuation inside strong sea storms blocks mapping of the sea surface.

To test the GIOS concept, ground HF transmissions from over-the-horizon radars were employed to scatter sky wave signals from the ocean to radio receivers in low-earth-orbit. The HF receiver (RRI) on the Canadian ePOP/CASSIOPE satellite has collected radio signals scattered from the ocean illuminated by ground transmitters in the US, Australia and Northern Europe. This satellite has two dipole antennas in a crossed configuration to measure HF waves below 18 MHz. Right and left hand circular polarization is synthesized from the data from the in phase (I) and quadrature (Q) data provided by the RRI digital instrument. For the ground HF transmission source, the Relocatable Over the Horizon Radar (ROTHR) system in Chesapeake Virginia was used to illuminate the ocean extending from coast of Florida to south of Jamaica. Range and Doppler processing of the radar waveforms yields an ocean scatter map at each time in the ePOP orbit.

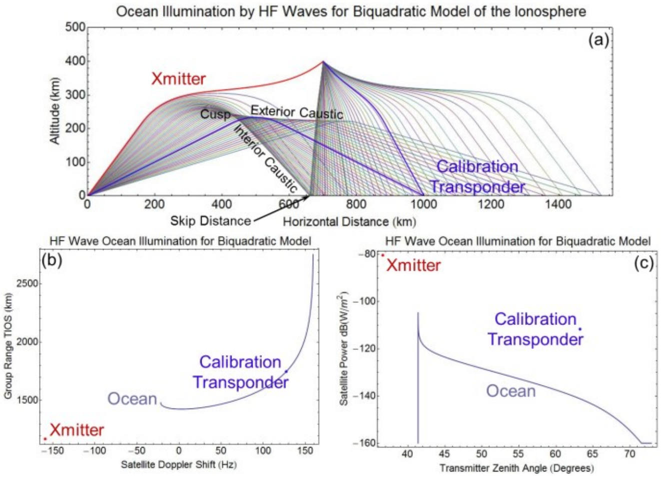

Figure 5. Computations of (a) ray paths, (b) received frequency shifts and group path delays and (c) signal strength for single azimuth HF radio beams refracting from the ionosphere and scattering form the ocean for reception at a satellite. The flat-earth simulation was made with 10 MHz transmissions from the axis origin using a 4th order (biquadratic model) of the ionosphere with an 8 MHz critical frequency and layer peak height of 310 km.

The Geometry for the GIOS experiments is shown in Figure 5 with simulations of a narrow azimuth beam from a ground transmitter at a fixed frequency. The satellite in orbit at an altitude of 400 km and ground range of 700 km is moving at 7.7 km/s producing a wide range of Doppler frequency shifts depending on the direction of the HF wave. The received signal power varies by a several orders of magnitude depending on the incident and scatter angles from the ocean. All the computations were made with the HF radio beam and satellite orbit in the same plane. The Frequency-Range curve

(Figure 2b) for the ocean scatter maps to a line on the ocean surface. The received power for each transmitter launch angle (Figure 2c) represents ocean scatter power at the incident and scatter angles. An HF transponder may be used to check the accuracy of conversion from the measured frequency shift and range delays to a latitude and longitude point on the ocean's surface.

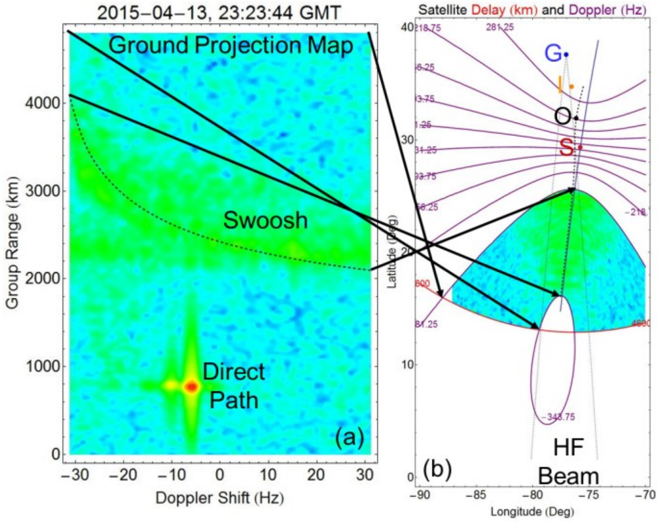

Figure 6. HF scatter data projected to the ocean surface for measurements made on 13 April 2015 at 23:23:44 GMT

Using the ROTHR transmitter to illuminate the Atlantic and Caribbean Oceans south of Chesapeake Virginia, data were collected on the ePOP satellite at 17.5 MHz. The ROTHR transmissions were demodulated to give the range-frequency display shown in Figure 6a. The red "Direct Path" dot at a range of 700 km and a frequency shift of -6 Hz is the direct reception of the HF transmissions corresponds to the red line in Figure 5a. The curved green feature, labeled as "swoosh" in Figure 6a, corresponds to the ocean scatter curve in Figure 5b. Using raytracing through a model ionosphere, a ground projection is made to transfer the Range-Frequency measurements to a scatter power map on the ocean surface (Figure 6b). This projection coincides with the HF beam lines for the HF transmitter.

IV. DATA COLLECTIONS AND FUTURE ANALYSIS

Ground scatter power projections obtained at multiple points in the satellite orbit can be used to determine the ocean wave height spectrum using synthetic aperture radar (SAR) techniques. High latitude measurements with GIOS were conducted using HF receivers on the Canadian ePOP satellite and on a Twin Otter Aircraft flying over the Arctic Ocean north of Barrow Alaska. The HF illumination source for the ePOP data collections was the HAARP transmitter in Alaska operating at 4.5 MHz with a 10 degree x 10 degree beam launched with an elevation angle of 30 degrees and a 200 Hz repeating chirp with a band width of 20 kHz (Figure 7). This HF beam can be swept in azimuth over Arctic Ocean to provide a wide area for measurements of sea ice and ocean wave conditions.

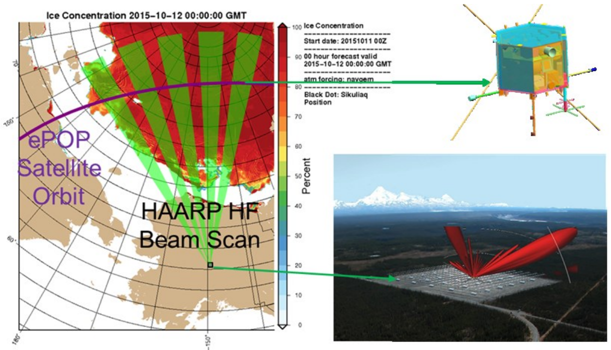

Figure 7. Components of the Arctic Ocean illumination tests with the Radio Receiver Instrument (RRI) on the Canadian ePOP satellite using the narrow HF beam from the HAARP transmitter in Alaska.

The de-chirp analysis for RRI data acquired in February 2017 is designed to measure the boundary between ice, ocean and broken ice as well as the ice thickness. Subsequent HF tests in March used the SuperDARN radars in Adak and Kodiak at 11.467 and 11.567 MHz, respectively. During the period of 13 to 18 March 2017, a Twin Otter airplane with NRL HF receiver system was flown from Barrow Alaska to observe the sky wave signals propagating via the ionosphere to the Arctic Ocean. Ice and ocean observations during these tests will be compared with buoy and airplane measurements at the same locations and times. In May 2017, tests of the GIOS technique are scheduled with the NRL Surface Wave Radar located at Cape May, New Jersey scatter up from the ocean to the ePOP satellite and the NRL Airborne HF Sensors. The Twin Otter will be flown east and south of Wallops Island Virginia while the ePOP is passing overhead. The airplane component provides a calibration point over the ocean to aid in the range-Doppler analysis of the HF data from the satellite receiver. All of these experiments will be summarized in future papers using both ocean scatter data and ray trace simulations illustrated here.

V. SUMMARY

The concept of sky-wave illumination of the ocean by high frequency waves has been explored to measure the ocean wave height spectrum using bistatic Bragg scatter. At HF frequencies, the primary scatter comes from wind driven swells with wavelengths on the order of 100 meters. The HF scatter power can be received with either ground, airborne or satellite receivers. Satellite receivers provide large area coverage of the ocean with analysis complications arising from propagation refraction between the scatter point on the earth's surface and the reception point above the ionosphere on the satellite. Ionospheric knowledge is essential for interpretation of the scatter HF waves to yield ocean surface parameters. Both direct paths from the transmitter to the satellite and HF transponders at known ground points can provide validation signals for the height profiles of the ionosphere.

A coupled ray-trace and ocean scatter model has been developed to demonstrate the capabilities of the GIOS technique for ocean remote sensing. Ground based oblique sounding (OS) in the 2 to 20 MHz HF frequency range has long been used to provide information on the ionosphere for many years. For the first time, model simulations have shown that the diffuse range scatter in the HF OS display can be attributed to non-specular scatter from the ocean surface. The ocean-scattered wave power at a remote ground receiver is primarily from second hop paths that extend a few hundred kilometers from the ground transmitter and receiver locations.

Collection of HF scattered signals with space-based and airborne HF receivers has occurred during several campaigns at high and mid latitudes. The data have yet to be analyzed to give maps of the wave height spectra over the ocean. This analysis is complicated by a number of factors including (1) projection of the range-frequency observations to the earth's surface, (2) removal of ionospheric absorption and refraction effects on the received power, and (3) optimizing the HF beam geometry relative to the satellite position along orbit trajectory. The results from such analysis will be reported in the future.

ACKNOWLEDGMENT

The ROTHR Program Office and the ePOP Spacecraft Operations Center provided invaluable support for the HF radar measurements.

REFERENCES

[1] Barrick, D. E., “Remote sensing of sea state by radar” in Remote Sensing of the Troposphere, V. E. Derr, ed., Chapter 12, 1972.

[2] P. A. Bernhardt et al., "Large area sea mapping with Ground-Ionosphere-Ocean-Space (GIOS)," OCEANS 2016 MTS/IEEE Monterey, Monterey, CA, 2016, pp. 1-10. doi: 10.1109/OCEANS.2016.7761503.

[3] Croft, T. A. and H. Hoogasian, Exact ray calculations in a quasi-parabolic ionosphere with no magnetic field, Radio Sci., 3, 1, pp. 69-74 (1968).

[4] X. Huang, B.W. Reinisch, W.S. Kulinski, Mid-point electron density profiles from oblique ionograms, Annali Di Geofisica, Vol. XXXIX, 4, August 1996.

[5] Juha Vierinen, Ionospheric sounders (or over the horizon radars) in Virginia and Puerto Rico, 10 October 2013, https://www.youtube.com/watch?v=GJQV6eIkokA); and GNU Chirp Sounder, Sodankylä Geophysical Observatory at the University of Oulu Finland, http://www.sgo.fi/~j/gnu_chirp_sounder/.