Measurements of the Ionosphere with the CARINA Satellite Flying Between the E- and F-Layers

Paul A. Bernhardt, Carl L. Siefring, Paul Oppenheimer

Plasma Physics Division and Naval Center for Spacecraft Technology

Naval Research Laboratory, Washington, DC 20375

ABSTRACT

An evolutionary step in ionospheric research is the Naval Research Laboratory CARINA mission where multiple spacecraft are put into limited life (45 to 60 day) earth orbits (LLEO) in the 150 to 250 km altitude range. Previous space missions have used either short-duration, sounding rockets in the 0 to 1000 km altitude range or long-duration, low-earth-orbit satellites with average altitudes above 300 km. The NRL CARINA satellites will explore the lower thermosphere with direct, in situ observations and will be able investigate both sporadic-E layers below the satellite and F-region structures above the satellite using radio propagation from ground and space based RF sources. The CARINA satellites look like cylinders with large mass (200 kg) and low drag area (0.05 sq-m). The sensors for the first CARINA mission are the orbiting GPS receiver (OGR), ram Langmuir probe (RLP) and an electric field instrument (EFI) covering the high frequency (2 to 15 MHz) range. The unique measurements with the CARINA satellite include (1) direct fly-through of the regions of the ionosphere modified by high power radio waves, (2) tomographic mapping Sporadic-E layers using ground HF radio beacons, (3) detection of the ionospheric coupling of extreme ocean storms using HF radar surface wave sea scatter to the CARINA receiver, (4) monitoring of traveling ionospheric disturbances in the lower thermosphere by employing in situ plasma probes and orbiting GPS TEC receivers, and (5) detecting electric field transients from terrestrial lightning that can drive space-plasma fluctuations. Subionospheric satellite experiments will expand the knowledge of lower thermospheric science at all latitudes and enhance our understanding of the direct coupling between large scale terrestrial disturbances and bottomside ionosphere.

1. CARINA SPACECRAFT

The CARINIA satellite is 1.75 meters long with a diameter of 0.25 meters (Figure 1). Extending from the back of the aerodynamic structure is a 1.75 meter antenna connected to an internal electric field receiver. The spacecraft is stabilized along the orbit by passive fins and active magnetic torque rods. On the body of are antennas for the dual frequency GPS receiver and the telemetry, tracking and command (TT&C) receiver. Power is provided by primary cell batteries which take up the bulk of the space inside the satellite. The ram face of the satellite is a stainless steel Langmuir probe biased for ion collection. The components of CARINA have been designed by the Naval Center for Space Technology [Figure 2].

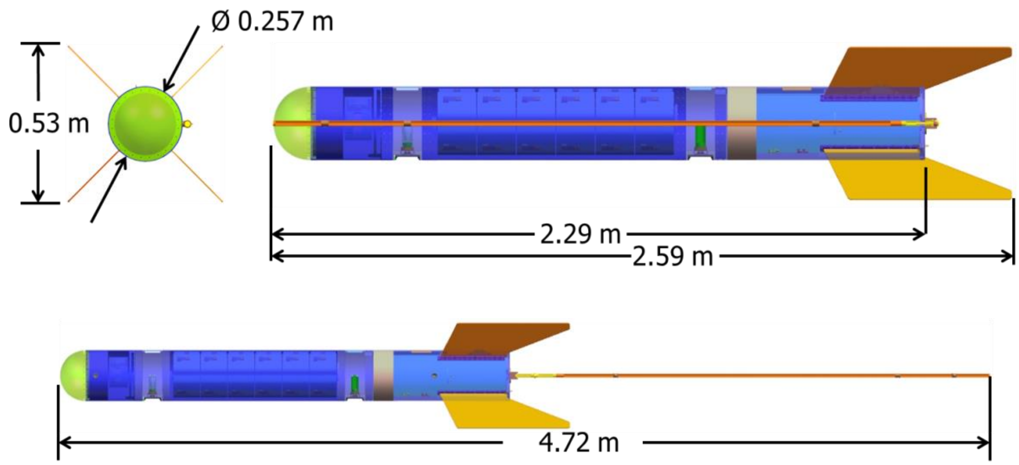

Figure 1. CARINA mechanical configurations before (top) and after (bottom) antenna deployment. The Langmuir Probe (Green) is on the ram face and the electric field antenna (Orange) is deployed in the wake. A dual frequency GPS receiver employs a zenith mounted antenna to measure the total electron content (TEC) in the F-layer above the spacecraft.

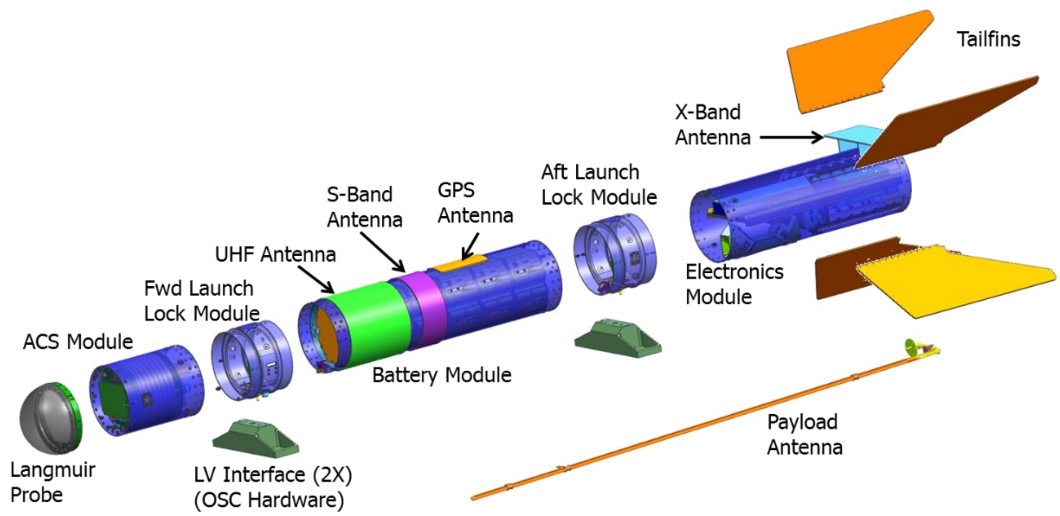

Figure 2. Components of the CARINA spacecraft to ensure long live at low altitude, acquisition of ionospheric data, knowledge of position and attitude, and rapid transmission of large data blocks.

2. CARINA ORBIT

CARINA is launched into low low-earth-orbit (LLEO) by the Antares rocket that carries the Cygnus spacecraft to the International Space Station. In 2015, two CARINA satellites are scheduled to be injected into a 51.6 degree inclination orbit with a final separation distance of 2500 km. The lower thermosphere will be sampled along the rocket trajectory plane with a time separation of about 5 minutes. A representative orbit for the CARINA satellites is given in Figure 2 for a 24 hour period. The orbit apogee will decay over the mission from 270 km to 150 km. No other satellite currently in a low eccentricity orbit is found at the CARINA altitude around 200 km. With this orbit, CARINA can make unprecedented observations of the bottomside ionosphere and lower thermosphere.

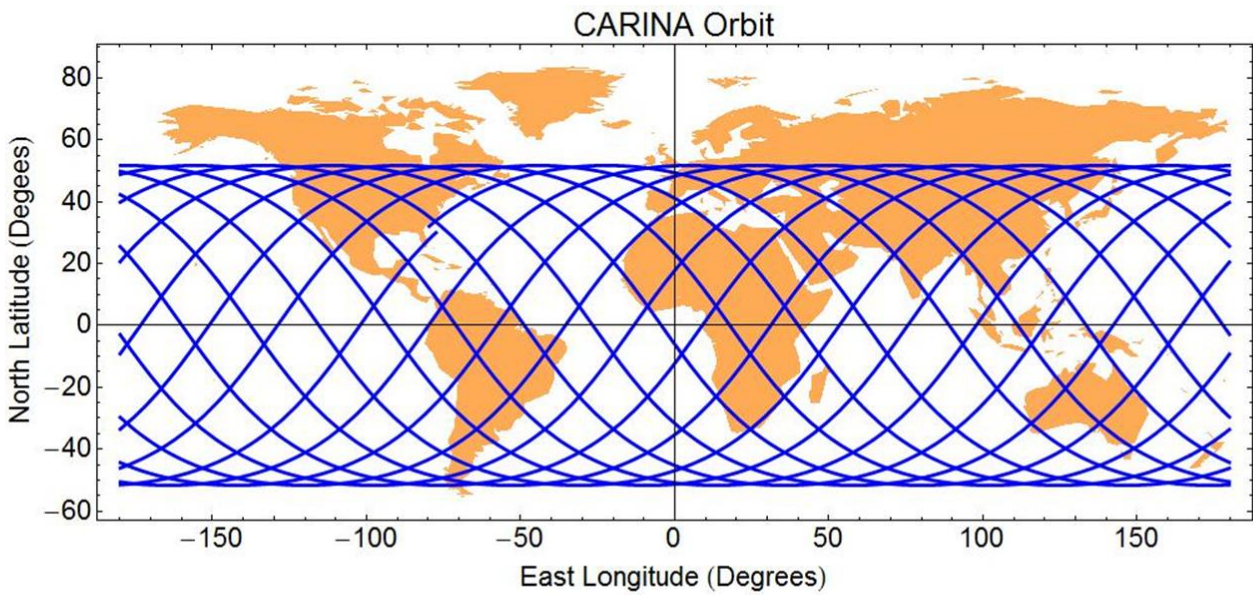

Figure 2. Ground track of the CARINA trajectory over one day. At the low altitude of CARINA, the satellite will be operational for about 45 days before burning up on re-entry.

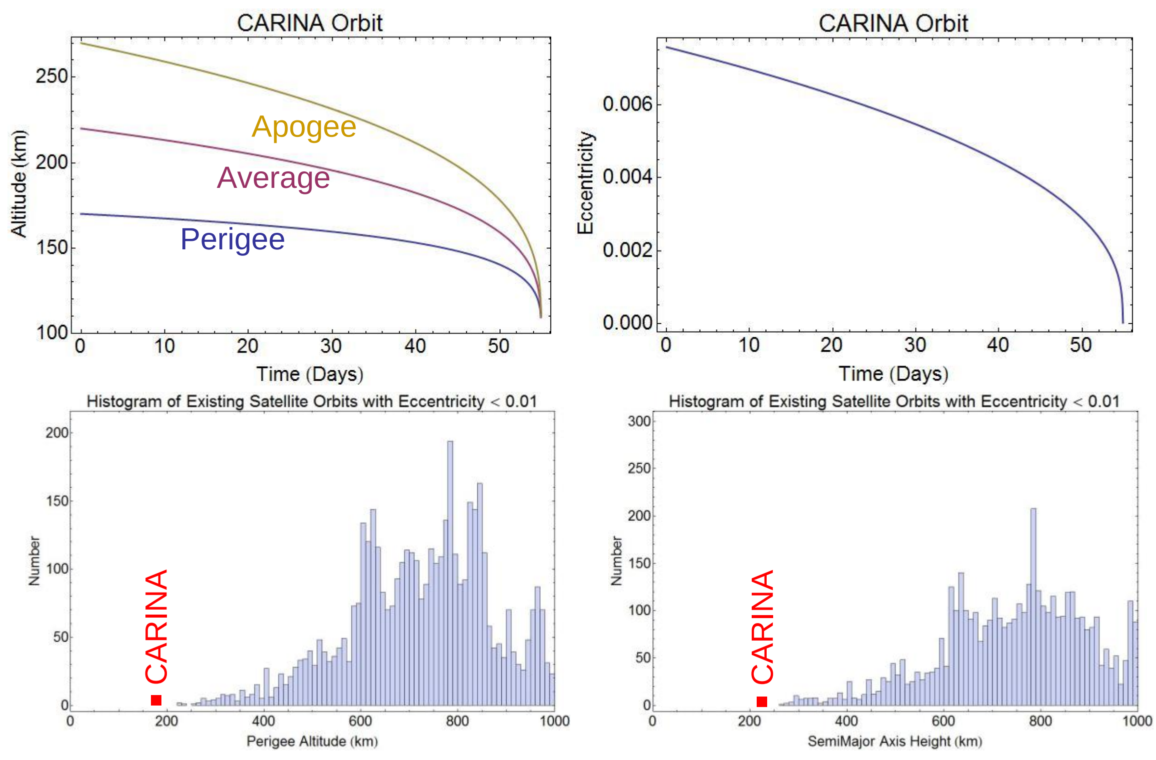

Figure 3. CARINA sustained low altitude orbit. The CARINA will decay of the two month lifetime of the mission ending up with a nearly circular orbit at 150 km altitude. CARINA will fly much lower for longer duration than any satellite currently in orbit.

3. CARINA SCIENCE INSTRUMENTS

Three instruments designed to measure the ionosphere throughout the mission duration are being flown on CARINA. First, an electric field instrument (EFI) connected to the trailing monopole measures electromagnetic and electrostatic waves in the 3 kHz to 13 MHz frequency range. The dynamic range of the EFI is 80 dB with two ranges. The high range detects strong electric fields with maximum strength of 10 V/m. The low range has peak a amplitude of 100 mV/m before saturation. EFI data is limited to collection over a 20 minute period maximum. The design of the EFI has heritage from the radio receiver instrument (RRI) currently operating on the Canadian Enhanced Polar Outflow Probe (ePOP) satellite.

The second instrument on CARINA is a fixed bias Ram Langmuir Probe (RLP) that measures ion densities in the 10^2 to 10^6 cm^{-3} range. This probed will be sampled at 8 kHz to have a spatial resolution of about 1 km. The RLP data can be acquired continuously over one 24 hour period while the EFI is operational. The heritage for the RLP includes several NRL sounding rocket flights as well as collaborations with the AFRL designers of the planar Langmuir probe (PLP) on C/NOFS.

The third instrument is an orbiting GPS receiver (OGR) that uses measurements at L1 and L2 to determine the position of the satellite and the integrated electron density or total electron content (TEC) in the F-Layer above the satellite. Dual frequency measurements of carrier phase and pseudo-range are processed on the satellite to yield continuous measurements of slant TEC and radio scintillations around the globe along the CARINA orbit at a 1 Hz sample rate. Low resolution scintillation data will also come from the spacecraft GPS receiver. The receiver used on CARINA is a Novatel OEM-615 which has flight heritage on CubeSats and other small satellites.

4. CARINA SCIENCE

The CARINA acronym represents the mission science topics with (1) **C**ostal Ocean Wave Remote Sensing where the wave height spectrum derived from HF surface wave scatter, (2) **A**ssimilation Models using GPS TEC and in situ plasma density to updating data driven ionospheric models (GAIM, IDA3D), (3) **R**adio Wave Propagation and Interactions to study the impact of (a) the bottomside ionosphere on HF ray trajectories, (b) ionospheric irregularities on UHF/L-band scintillation and (c) ionospheric modification by high power HF waves, (4) **I**onospheric Structures such as sporadic-E/intermediate layers and TIDs as well as large scale bottomside fluctuations in the f-layer, (5) **N**eutral Drag by tracking the CARINA orbit through reentry modelling of drag coefficients and providing neutral density model updates, and (5) **A**tmospherics and Lightning with direct observations of lightning EM pulses and their impact on ionosphere.

For the ocean wave height spectrum measurements, existing ground transmitters will be monitored by the EFI to observe the direction wave, ionospheric refracted waves, and ocean scattered waves from space (Figure 4). The advantage of CARINA flying below the ionosphere is that the HF ocean scatter can be directly observed over much longer ranges with a full spectrum of observation angles. Similarly, direction of lightning pulses from space in the HF spectrum is possible with CARINA because of its sub-ionospheric orbit trajectory (Figure 5).

CARINA will aid in understanding the effects of irregularities on long range HF propagation. Both ray-trace and full wave techniques have been used to predict the CARINA signal strengths. For a ground HF transmitter, the VTRPE Model developed by Frank J. Ryan [Introduction to the VTRPE Model, 2013] was used to predict the electric field strengths from a ground HF transmitter operating at 10 MHz with a smooth ionosphere (Figure 7). A representation of the CARINA applications to propagation in a structured ionosphere is shown in Figure 8 using 3-D HF raytracing through electron densities derived by radio beacon tomography [Bernhardt et al. 2014].

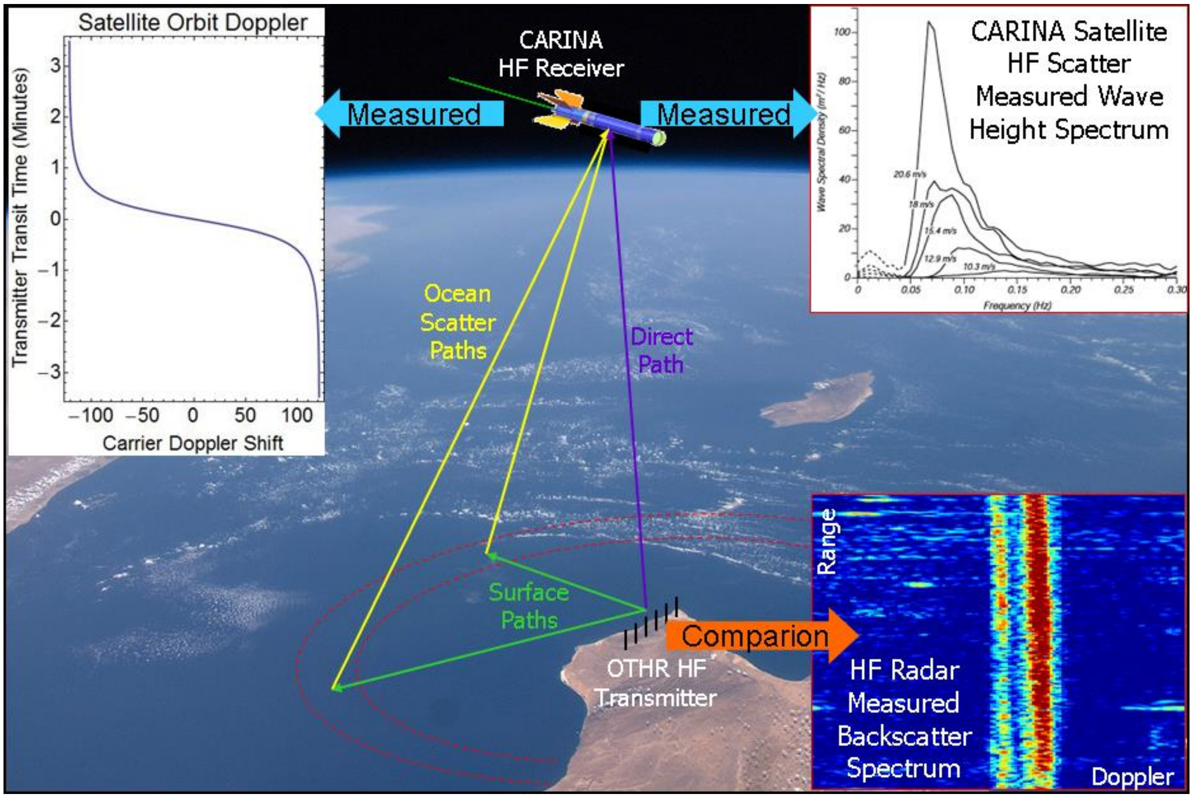

Figure 4. Bistatic HF radar scatter to the CARINA satellite provides ocean sea state conditions and measurements of ionospheric propagation. These can be compared with ground costal ocean radar (CODAR) observations used for remote sensing of wind and current speeds as well as wave height.

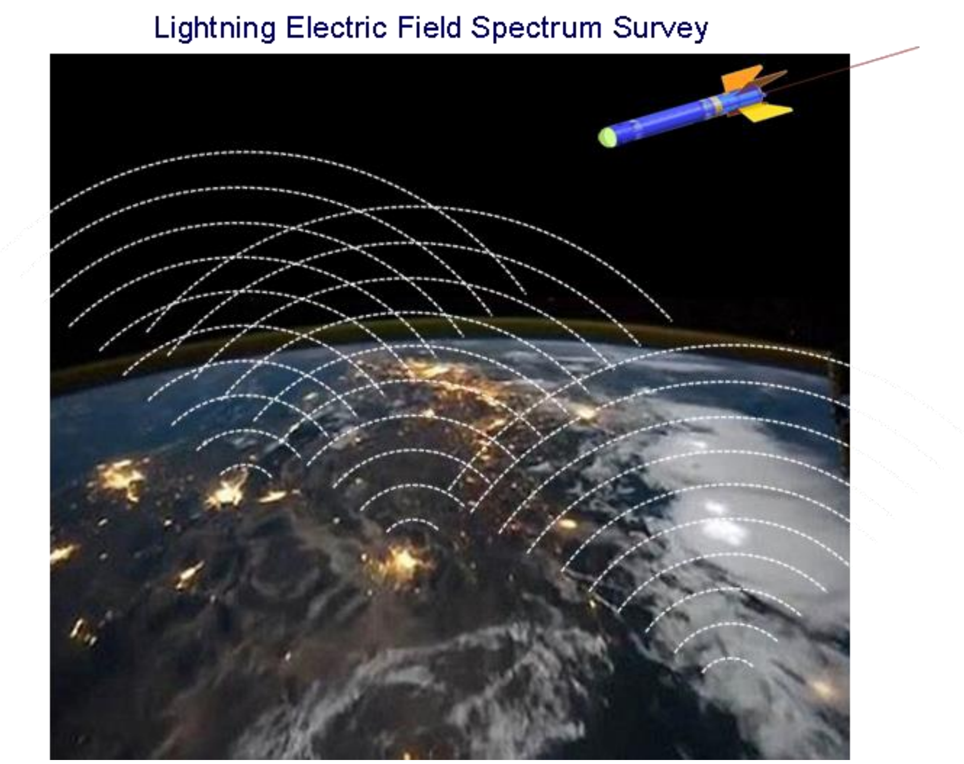

Figure 6. Atmospheric science with lighting as CARINA flies over active storm regions.

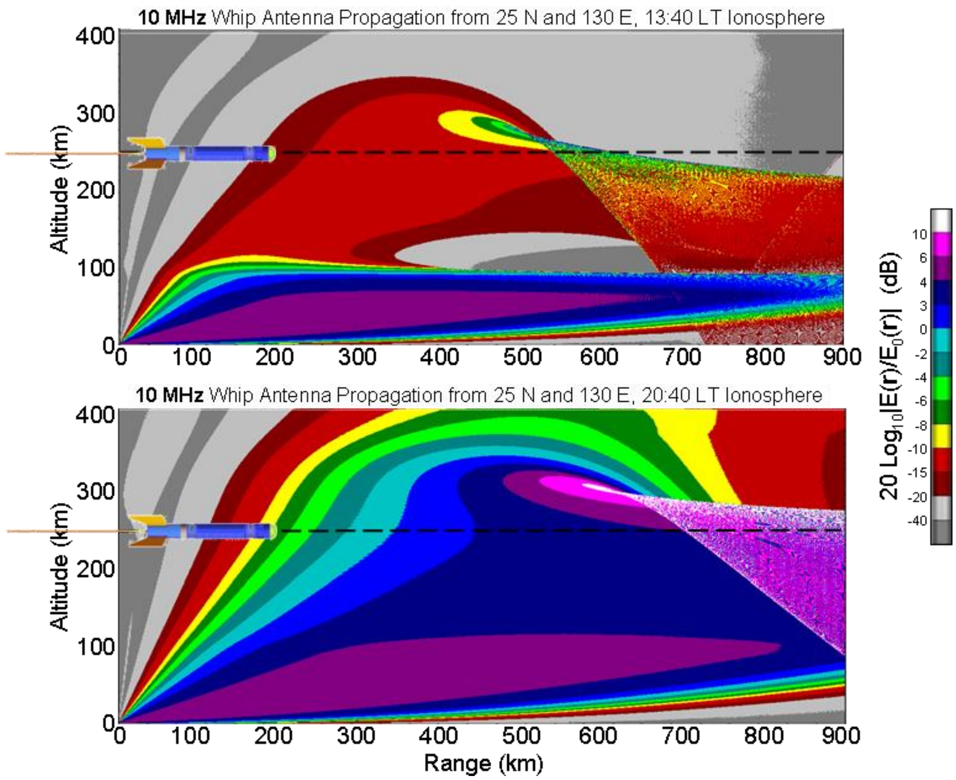

Figure 7. Predictions of HF (10 MHz) propagation from a ¼ - wavelength vertical monopole. The interesting regions are the caustic regions below the F-layer at horizontal ranges of 500 – 700 km where the intense signal strengths are found. At 200-250 km altitude, CARINA should often fly directly through these caustic regions.

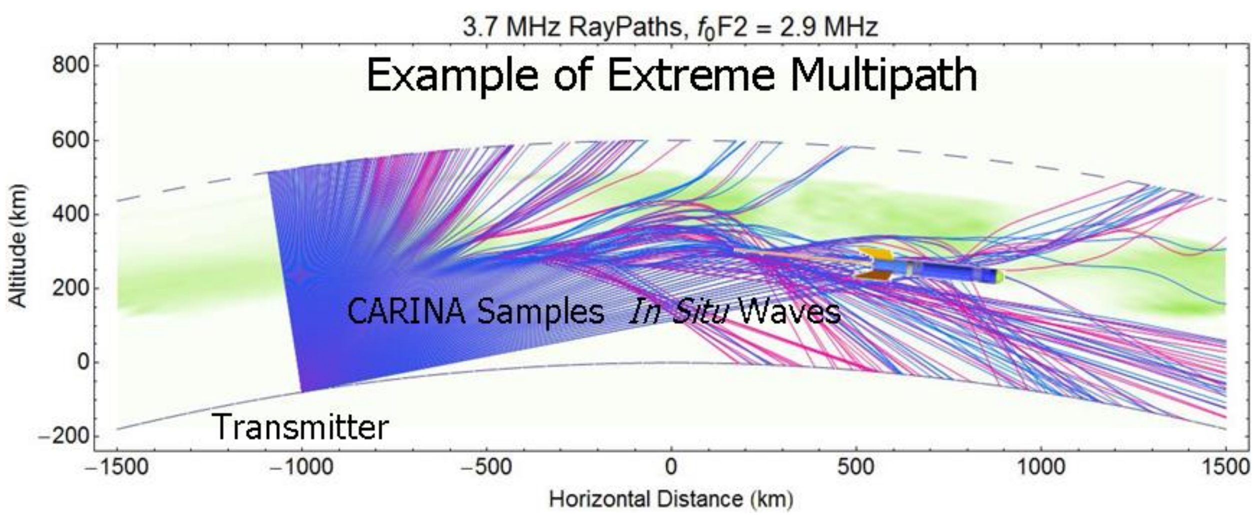

Figure 8. HF Rays (Blue O-mode and Red X-mode) propagating in a structured ionosphere based on tomographic reconstructions from the C/NOFS CERTO beacon. CARINA will measure both the bottom side ionosphere and the effects plasma structures on the waves.

Two types of sites are being set up around the globe for CARINA measurements. First, calibration sites near incoherent scatter radars such as located at the Jicamarca Radio Observatory in Peru, the MU radar in Japan, the Arecibo Observatory in Puerto Rico, and the Haystack Observatory in Massachusetts. These sites will validate the accuracy of the RLP observations of plasma density at the satellite altitude. Second, all locations providing ground radio beacons, including the calibration sites, will be designated as science sites as well as other locations providing ground radio beacons.

N. CONCLUSIONS

The CARINA satellites provide unique geometry for ionospheric research with a long duration flight below the F-layer and above E-layer. The CARINA science will provide in situ probes of HF modified ionosphere, radio probes of sporadic-E layers, global observations of the F-region above satellite orbit. The CARINA satellites have powerful in situ instruments such as the HF receiver with a monopole antenna, the plasma probe and GPS TEC receiver. CARINA addresses HF propagation science objectives with self-consistent checks of the accuracy of F-region electron densities and will provide unique ionospheric measurements for propagation models. CARINA supports studies of both the F-region and E-region densities at low to mid latitudes. Future CARINA science missions will be extended to higher latitude.

ACKNOWLEDGEMENTS
This work was supported by the 6.1 Base Program at NRL.

REFERENCES

Paul A. Bernhardt, Matthew A. Hei, Carl L. Siefring, and Matthew R. Wilkens, Predictions of HF system performance for propagation through disturbed ionospheres measured using low-Earth-orbit satellite radio beacon tomography, Radio Science, 49, 506-517, 2014.

Frank J. Ryan (2013), User’s Guide for the Variable Terrain Radiowave Parabolic Equation (VTRPE) Electromagnetic Wave Propagation Model Applied Technology, Inc., San Diego, CA