Ionospheric Impacts on UHF Space Surveillance

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CONFERENCE PAPER

Earth's atmosphere contains regions of ionized plasma caused by the interaction of highly energetic solar radiation. This region of ionization is called the ionosphere and varies significantly with altitude, latitude, local solar time, season, and solar cycle. Significant ionization begins at about 100 km (E layer) with a peak in the ionization at about 350 km (F2 layer). Above the F2 layer, the atmosphere is mostly ionized but the ion and electron densities are low due to the unavailability of neutral molecules for ionization so the electron density decreases exponentially with height to well over 1000 km. The gradients of these variations in the ionosphere play a significant role in radio wave propagation. These gradients induce variations in the index of refraction and cause some radio waves to refract. The amount of refraction depends on the magnitude and direction of the electron density gradient and the frequency of the radio wave. The refraction is significant at HF frequencies (3-30 MHz) with decreasing effects toward the UHF (300-3000 MHz) range. UHF is commonly used for tracking of space objects in low Earth orbit (LEO). While ionospheric refraction is small for UHF frequencies, it can cause errors in range, azimuth angle, and elevation angle estimation by ground-based radars tracking space objects. These errors can cause significant uncertainty in precise orbit determinations. For radio waves transiting the ionosphere, it is important to understand and account for these effects. Using a sophisticated radio wave propagation tool suite and an empirical ionospheric model, we calculate the errors induced by the ionosphere in a simulation of a notional space surveillance radar tracking objects in LEO. These errors are analyzed to determine correlations with ionospheric variability. Corrections to surveillance radar measurements can be adapted from our simulation capability.

1. INTRODUCTION

Earth's atmosphere contains regions of ionized plasma caused by the interaction of highly energetic solar radiation. This region of ionization is called the ionosphere and varies significantly with altitude, latitude, local solar time, season, and solar cycle. Significant ionization begins at about 100 km (E layer) with a peak in the ionization at about 350 km (F2 layer). Above the F2 layer, the atmosphere is mostly ionized but the ion and electron densities are low due to the unavailability of neutral molecules for ionization so the electron density decreases exponentially with height to well over 1000 km. The gradients of these variations in the ionosphere play a significant role in radio wave propagation. These gradients induce variations in the index of refraction and cause some radio waves to refract. The amount of refraction depends on the magnitude and direction of the electron density gradient and the frequency of the radio wave. The refraction is significant at HF frequencies (3-30 MHz) with decreasing effects toward the UHF (300-3000 MHz) range. UHF is commonly used for tracking of space objects in low Earth orbit (LEO). While ionospheric refraction is small for UHF frequencies, it can cause errors in range, azimuth angle, and elevation angle estimation by ground-based radars tracking space objects. These errors can cause significant uncertainty in precise orbit determinations which can reduce the accuracy of conjunction analysis efforts. This uncertainty can lead owner/operators of satellites to make misinformed decisions on actions taken to deconflict collisions. This can lead to increased risk of collisions of satellites with potentially catastrophic results.

Northrop Grumman, through internal research and development efforts, has created a sophisticated radio wave propagation tool suite. The core of this tool suite is a ray tracing algorithm using the recursive acronym NINJART Is Not Just Another Ray Tracer (NINJART). The proprietary tool suite combines the output of fifteen environmental model types to account for the influences of radio waves propagating through the natural environment. The core of NINJART is a highly accurate and fast ray tracing system. A UHF ray tracer needs to be accurate in order to reduce the accumulated error which can come from other sources such as the ionospheric electron density model and the vector model of the antenna. A ray tracer must also be fast; slow ray tracing speeds would make the use of applications impractical. NINJART consists of an embarrassingly parallel algorithm rigorously solving the 3-D Hasselgrove equations with a Runge-Kutta adaptive step quadrature rule to accurately ray trace high frequency (HF) to ultra-high frequency (UHF) radio waves. Among other uses, it is capable of simulating propagation of space surveillance radars. It can use a variety of ionospheric models to include operational data assimilative or empirical models depending on the needs of the user. Though the effects are small at UHF, it can use magnetic field models such as the International Geomagnetic Reference Field (IGRF) [1] model to account for the effects of magneto-ionic splitting. NINJART utilizes the CUDA programming language to take advantage of the raw computing power of general purpose graphical processing units (GPUs). This allows tracing of thousands of rays concurrently. NINJART achieves additional processing savings, without sacrificing accuracy, by use of an adaptive step size algorithm which uses smaller steps when the direction of the ray is rapidly changing and larger steps when it's relatively straight. NINJART accounts for all the significant processes a radio wave undergoes while traversing the ionosphere for the purpose of space surveillance. Using NINJART, we conducted a modeling and simulation experiment to characterize the impacts of ionospheric refraction on a notional UHF space surveillance radar.

2. METHODOLOGY

Using NINJART as the core of our radar simulation, we modeled a notional UHF (435 MHz) radar near the center of the continental United States. While this is not an actual radar site, the results of our simulation will provide an accurate estimate of ionospheric impacts that could be experienced by any UHF radar. NINJART can easily be configured to simulate specific radars, but for the sake of demonstration we chose to use a notional radar located in Omaha, Nebraska. The electron density model used during the simulation was the International Reference Ionosphere (IRI) 2012 [2]. The IRI is an empirical model based on most of the available and reliable data sources for the ionospheric plasma. NINJART can use other electron density models, such as data assimilative models, since the model input is modular. Even though magneto-ionic splitting is a very small contribution to propagation at UHF, we have included the IGRF model in our simulation. From the simulated radar location, radar signals were propagated in a 360-degree azimuth and from 1 to 85 degrees in elevation. All the rays were propagated to an altitude of 850 km representative of a Low Earth Orbit (LEO) satellite requiring each ray to transit the F2 layer. These rays were simulated through an ionosphere with no electron density and one with a fully representative ionosphere at one-hour increments for each month using the 15th day of each month to represent all days in the month. This process was repeated on 4 years of data, 2010 – 2013. Data to drive the IRI (Ap, SSN, and F10.7) were collected from the National Centers for Environmental Information (NCEI) [3]. The end points of the rays from the "no ionosphere" and the "normal ionosphere" cases were compared and the differences were broken into their respective range, azimuth, and elevation components. The analysis of these statistics is shown in the next section.

3. RESULTS

The impact of ionospheric refraction was examined in terms of error in range, azimuth angle, and elevation angle. Range errors along the ray path are a result of primarily vertical ionospheric electron density gradients as the radar ray transits the ionosphere toward the simulated satellite at 850km. The range errors are interrelated to the apparent elevation angle change due to the refraction caused by vertical electron density gradients. The refraction is in the direction toward the Earth resulting in a longer path to the 850 km point. The extra distance traveled is measured in time by the radar resulting in a ranging error. Figure 1 shows a histogram of range errors for all elevation and azimuth angles and all times during the 4-year period we simulated.

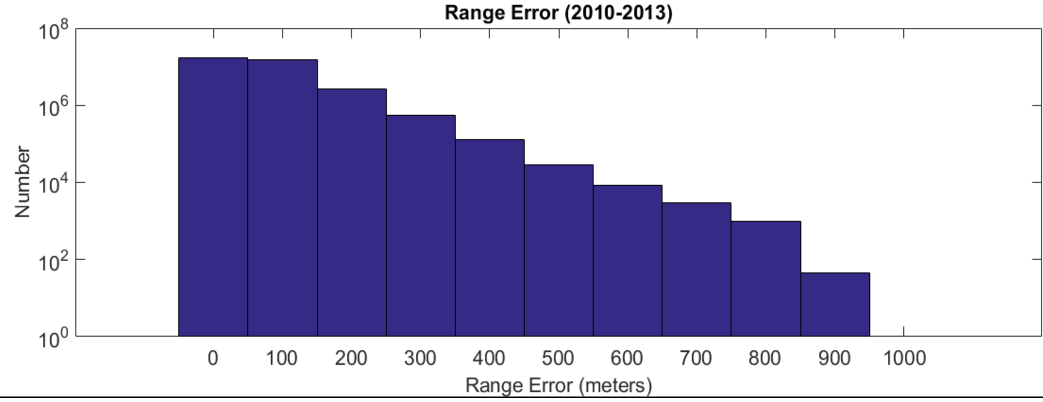

Figure 1. Histogram of Range Error induced by the ionosphere for the years 2010-2013.
The y-axis is a log scale to assist the reader with viewing the higher valued errors.

The predominant errors are in the 0 to 150 meter range. However, many comparisons result in errors in excess of this range. We further investigate the relationship of error magnitudes to the variations in the ionosphere in the following sections.

In Figure 2, the mean range errors are shown as a function of time of day. The times listed are universal coordinated time (UTC) and the offset to the local time at the radar is -6 hours. The plot shows that errors are minimized in the pre-sunrise time range and begin to increase to a maximum in the afternoon hours. This is consistent with the ionization of the ionosphere caused by solar radiation. The chart shows a 9-hour rise time of errors from the nighttime min to daytime max. The decay time is about 15 hours. This is consistent with the behavior of the ionosphere as well. As the sun rises in the morning, there is a rapid ionization of the F2 region due to the abundance of photons interacting with the neutral molecules at ~ 350 km altitude. As the sun sets over a region of the Earth, the local ionosphere no longer has a significant source for ionization and begins to recombine. The mean free path for electrons at these high altitudes is quite long which allows the free electrons to persist for quite some time. In fact, the F2 layer is a persistent feature even at night. The electron density decreases by at least an order of magnitude or two, but it is present even in nighttime regions. To first order the ionospheric F2 region can be treated as a collisionless plasma [4] .

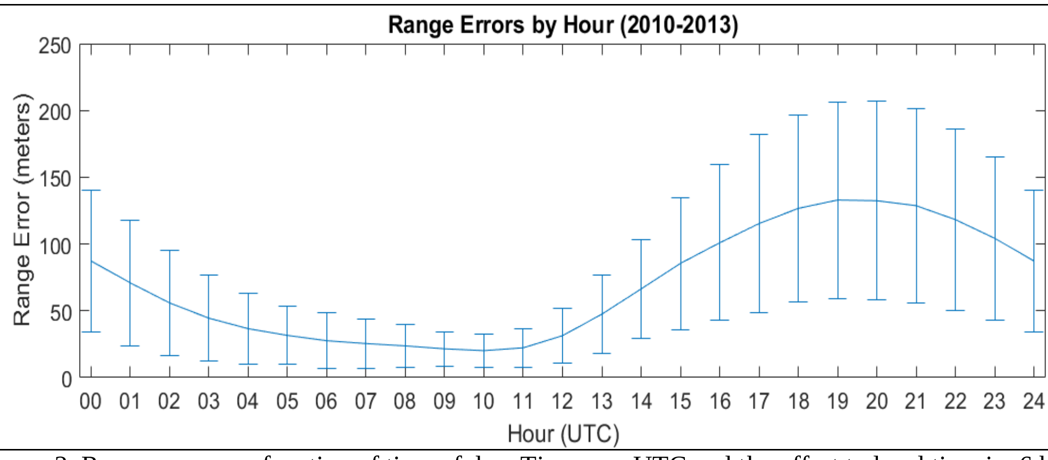

Figure 2. Range error as a function of time of day. Times are UTC and the offset to local time is -6 hours.

The variability of the errors also changes throughout the day. The majority of this variability is associated with the assorted azimuth and elevation angles used in the simulation at each specific time. The various ray geometries allow inspection of different parts of the ionosphere around the radar site. Figure 3a and 3b show the variability in range error as a function of elevation angle at times representative of the minimum and maximum range errors (1100Z and

2000Z respectively). The figures clearly show an increase in error variability, particularly at low elevation angles, simply due to the intensity of the ionosphere at different times of day. It is important to note that the variability shown in Figure 2 is only shown for one standard deviation while the data in Figure 3 show all data points.

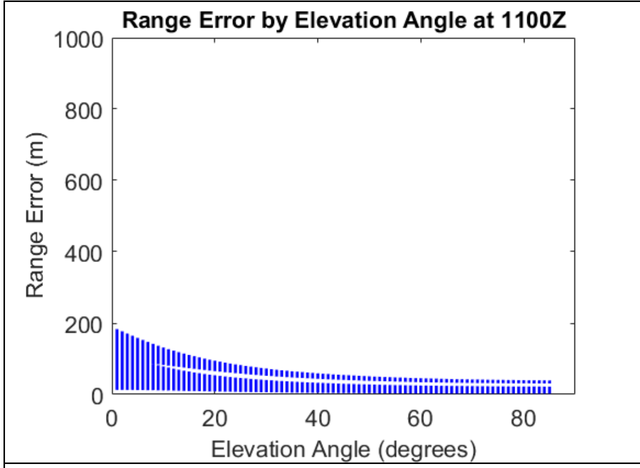

Fig 3a. Radar Range Error by Elev. Angle (morning)

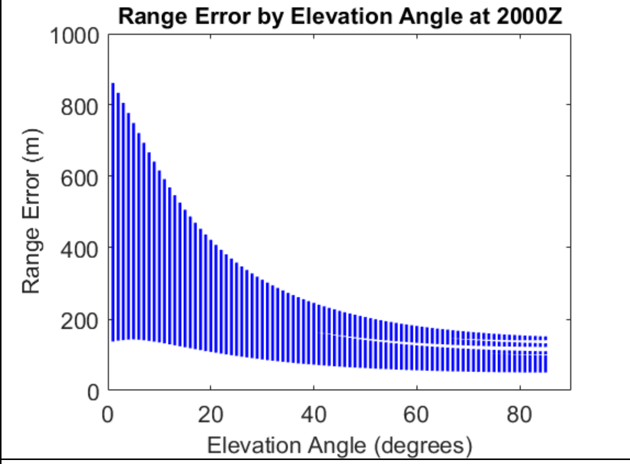

Fig 3b. Radar Range Error by Elev. Angle (afternoon)

Figure 4a and 4b show the variability in range error as a function of azimuth angle at times representative of the minimum and maximum range errors (1100Z and 2000Z respectively). The data clearly show the difference in error caused by viewing angle of the radar. The polar ionosphere, which would be viewed at azimuth angles from 300 to 50 degrees, causes much less error and error variability than does the lower latitude ionosphere from 150 to 250 degrees.

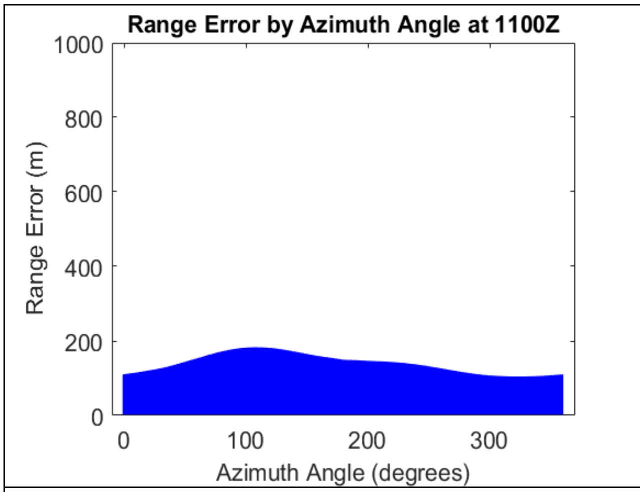

Fig 4a. Radar Range Error by Az. Angle (morning)

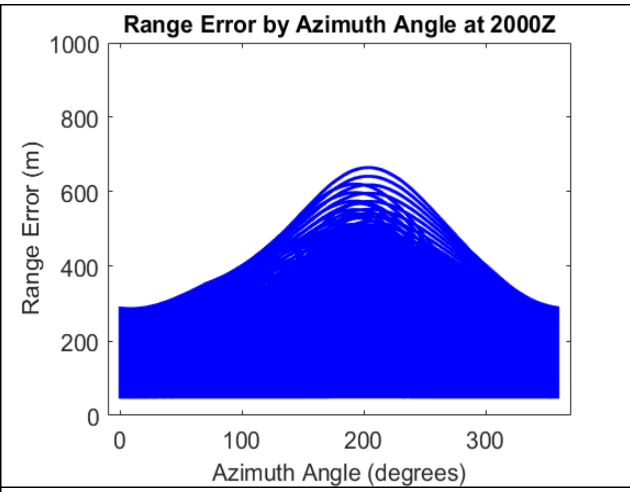

Fig 4b. Radar Range Error by Az. Angle (afternoon)

Since range errors are so closely correlated to elevation angle errors, it is prudent to examine those errors in more detail. Figure 5 shows a histogram of the elevation angle errors from our simulation. The figure shows errors for all elevation and azimuth angles and all times during the 4-year period we simulated.

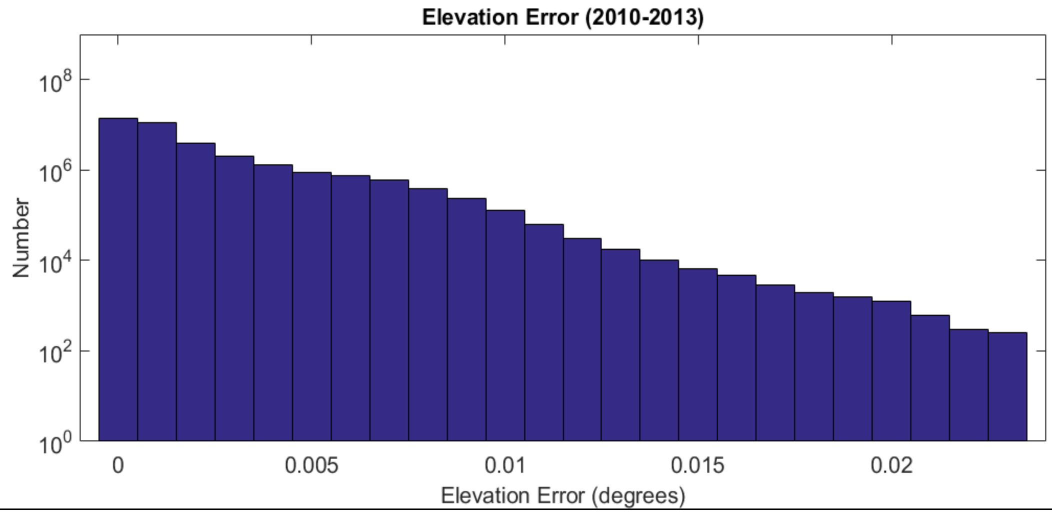

Figure 5. Histogram of Elevation Angle Errors induced by the ionosphere for the years 2010-2013.

The figure shows most of the elevation angle errors are near zero but can range upward to nearly .025 degrees. The larger errors are directly related to the low elevation angle propagation paths and are a result of the duration of time the ray spends under the influence of the strong ionospheric F2 layer vertical gradient. Figure 6 shows the elevation angle errors as a function of elevation angle.

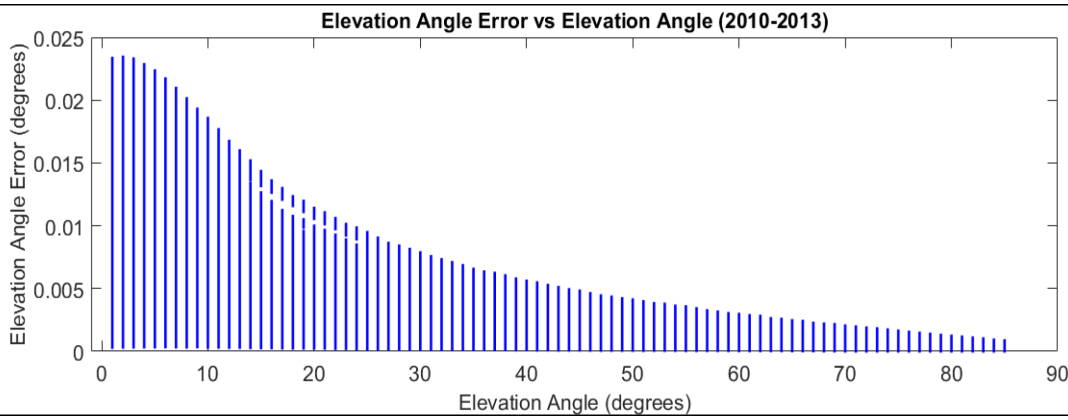

Figure 6. Elevation Angle Errors as a function of elevation angle for the years 2010-2013

The data show that the bulk of the errors are associated with low elevation angles. The variance of the errors at these low elevation angles is also quite large. This is consistent with the observations made in the range error data.

Elevation angle errors are also strongly related to the direction of the propagation path relative to the global ionosphere. This can be seen in Figure 7, which shows elevation angle errors by azimuth.

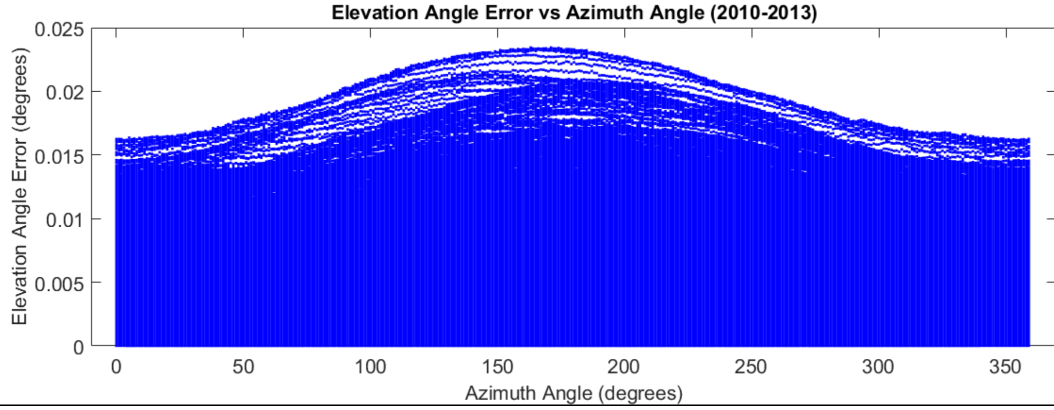

Figure 7. Elevation angle errors as a function of azimuth angle for the years 2010-2013

The data show a slight increase in the elevation errors in the direction of the lower latitude ionosphere and smaller errors in the direction of the polar ionosphere as was seen in the range error data.

Elevation angle errors are also strongly related to the time of day. Figure 8 shows the elevation angle errors as a function of time of day. Much like the range errors, the elevation angle errors show larger values during the daytime and smaller values at night. Additionally, the variance of these errors is also strongly dependent on the time of day with the larger errors during the daytime when the ionospheric plasma is dense. The rise and decay time of the errors and variances are similar to the range error results.

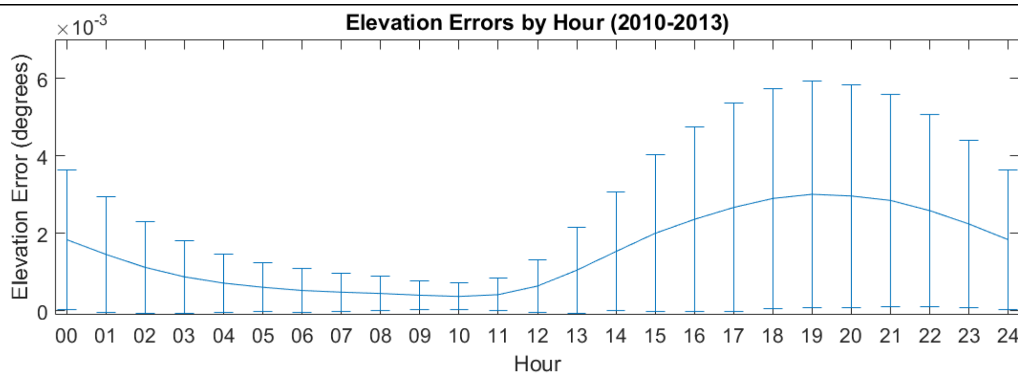

Figure 8. Elevation Angle errors as a function of time of day for the years 2010-2013

Another way to look at the impact of the ionosphere on UHF radio waves is by examining the influence of horizontal electron density gradients. The azimuthal component of the ionospheric-induced error was computed in a similar manner as the range and elevation errors. The histogram of the data is shown in Figure 9. These apparent errors are solely induced by horizontal gradients of electron density. These gradients result in a change in the index of refraction causing the radio waves to bend toward lower values of electron density. Stronger gradients result in more refraction of the radio waves and thus produce larger azimuthal errors. Strong ionospheric gradients exist on a global scale depending on time of day, season, solar conditions, and the solar cycle.

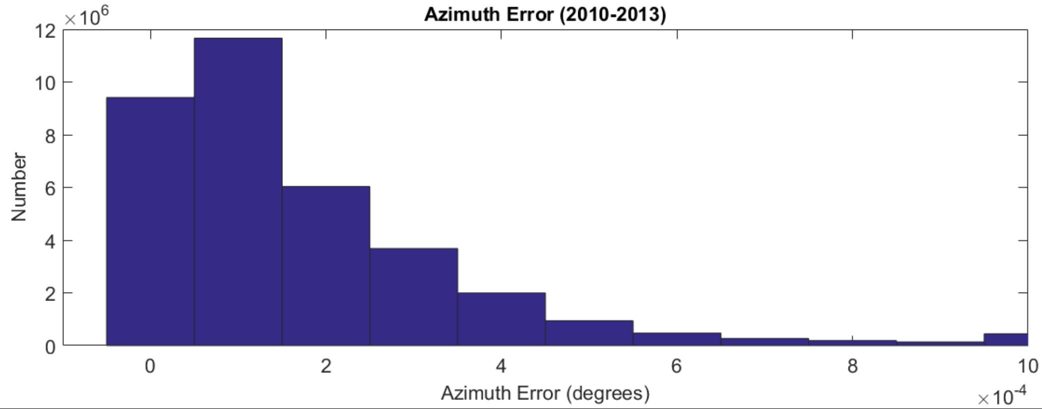

Figure 9. Histogram of Azimuth angle error induced by the ionosphere for the years 2010-2013

This effect can be verified by looking at the azimuthal errors by time of day. During the sunlit portion of the day the ionosphere becomes much more ionized. This creates large gradients emanating from the solar subpoint toward the nighttime areas. The largest gradients exist in the mid-latitudes along the edges of the Appleton anomaly, the most ionized region in the ionosphere located near and following the solar subpoint. Large gradients are evident at local sunrise and to a slightly lesser extent after sunset. The impact of these phenomena can be seen in Figure 10. The azimuthal errors and associated variability begin to increase just after 1100 UTC which would be sunrise at this radar site. The errors and variability remain high until sunset (2400 UTC) and gradually decrease to the minimum just before sunrise.

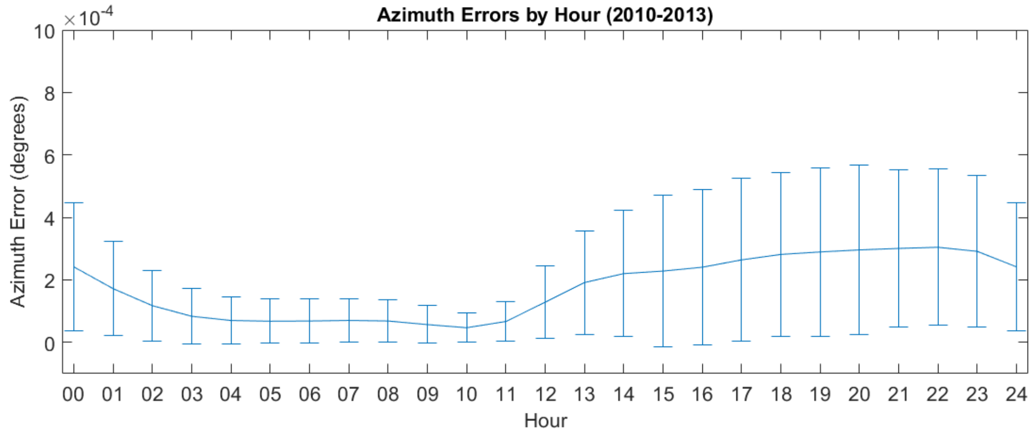

Figure 10. Azimuthal errors as a function of time of day. Times are UTC and the offset to local time is -6 hours.

Figure 11 shows the azimuth errors as a function of azimuth to show the impacts of radio wave propagation direction relative to the large ionospheric gradients. To orient the reader, 0 degrees would be in the direction of North, 90 degrees would be East, 180 degrees would be South, and 270 degrees would be West.

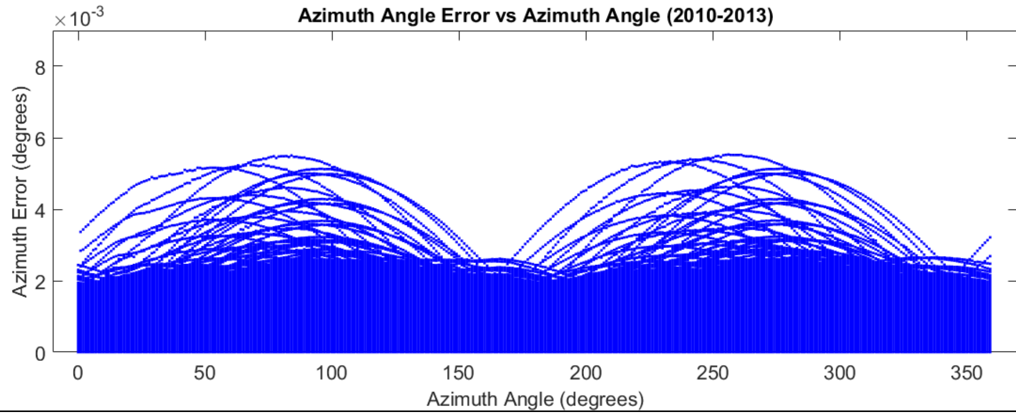

Figure 11. Azimuthal errors as a function of Azimuth. 0 is North and 180 is South.

The figure clearly shows long ray paths in the Eastward and Westward directions undergo the maximum refraction to the large global ionospheric gradient between the equatorial and polar ionospheres. While these angles are quite small the resultant displacement at long range can be quite large resulting in significant errors in the placement of objects under surveillance.

SUMMARY

The ionosphere can have significant impacts on the propagation of radio waves in the UHF band. The impacts are greatest at the lower end of the band (~300 MHz) and decrease as the frequency is increased. We have developed a method of simulating radio waves propagating through a modeled ionosphere to compute the error induced by ionospheric gradients. We showed errors in radar range measurements can be as large as 900 meters while tracking objects at 850 km LEO orbits with elevation angle errors on the order of 10^{-3} degrees and azimuthal errors on the order of 10^{-4} degrees. Range and elevation angle errors can be attributed to vertical ionospheric gradients while azimuthal angle errors can be attributed to horizontal ionospheric gradients. Each error component (range, elevation, and azimuth) varied by time of day in a similar manner. The errors and the error variances were smallest just before sunrise and reach their maximum during the afternoon. Errors were also sensitive to the look angle of the radar. When aimed at the lower latitude ionosphere range and elevation angle errors were larger than look angles toward the polar ionosphere. Azimuthal errors were significantly larger when transmitting perpendicular to the strong global ionospheric gradients. Depending on the precision needed, UHF observations may need to account for variations in the ionosphere due to its refractive properties in this band. With an accurate ionospheric model and ray tracing tool suite, our methodology can be used to correct the range, azimuth angle, and elevation angle errors in radar measurements. A fast and accurate radio wave propagation tool suite is fundamental to accounting for these errors. Additionally, a good method of calculating the errors and providing a correction factor in terms familiar to the radar is fundamental to removing the ionospheric artifacts from the data.

4. ABBREVIATION AND ACRONYMS

DoD - Department of Defense
GPS - Global Positioning System
HF – High Frequency (3 – 30 MHz)
IGRF – International Geomagnetic Reference Field
IRI – International Reference Ionosphere
LEO – Low Earth Orbit
MHz – Megahertz
NINJART - NINJART Is Not Just Another Ray Tracer
SATCOM - Satellite Communications
UHF - Ultra High Frequency (300 – 3000 MHz)
UTC – Universal Coordinated Time from the French Temps Universel Coordonné
VHF - Very High Frequency (30 – 300 MHz)

REFERENCES

1. *The International Reference Ionosphere Today and In the Future.* **Bilitza, Dieter, et al., et ald.** 2010, Journal of Geodesy, Vol. 85, pp. 905-020.
2. *The International Geomagnetic Reference Field: the 12th Generation.* **Thébault, Erwan, et al., et al.** 2015, Earth, Planets, and Space, pp. 67-79.
3. **National Centers for Environmental Information (NCEI).** Space Weather and Solar Events. [Online] 2016. https://www.ngdc.noaa.gov/stp/spaceweather.html.
4. **Air Force Geophysical Laboratory.** Ch 9. Ionospheric Physics. *Handbook of Geophysics and the Space Environment.* s.l. : United States Air Force, 1985.