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Ionospheric Corrections for HF Line-of-Sight Satellite Observations at Solar Minimum

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Abstract

As the near-Earth space domain becomes increasingly congested, the field of space domain awareness (SDA) has risen in importance and motivated the use of non-traditional sensors. One such class of sensor is high frequency (HF) radars operating in line-of-sight (LOS) mode. HF signals are, however, subject to ray bending and group retardation when propagating through the ionosphere. We have demonstrated a method for performing ionospheric corrections for HF LOS satellite observations, allowing for improved measurements of satellite position and speed, which can assist with improving the accuracy of object tracking.

1. Introduction

Objects in low Earth orbit (LEO) can be small, orbit at high speeds, and can manoeuvre frequently, which makes the tracking of such objects crucial for SDA. As of 2025, the number of resident space objects (RSOs) with size greater than 10 cm exceeds 64,000, with over 57,000 of those in LEO. HF radars present several advantages over traditional SDA sensors due to their low cost, ease of deployment in remote locations, and wide field-of-view [1].

HF radars are typically deployed as over-the-horizon sensors, utilising the refractive properties of the ionosphere to bend radio waves back towards the surface of the Earth [2]. When operated at around 30 MHz; however, the radio waves are capable of penetrating the ionosphere at most elevation angles, allowing the LOS observation of RSOs. The radio waves are subject to refraction by the ionosphere which can change the apparent position and speed of the observed RSOs, degrading the accuracy of the observation.

This paper describes a method of calculating the ionospheric correction for RSO observations made using an HF LOS radar with a 2D receive antenna array. The corrections to the range, elevation, azimuth, and range rate (Doppler) are calculated and compared to the simplified generalised perturbation (SGP4) propagation of two-line elements (TLEs) which parameterise the RSO's orbits. TLEs are compiled by United States Space Command and issued by SpaceTrack (https://www.space-track.org).

2. Instrumentation

An experimental 2-dimensional HF radar was deployed by Defence Science and Technology Group (DSTG) during the "SpaceFest" event in November and December 2020, near Coondambo (31.04°S, 135.87°E) in South Australia, approximately 520 km North-North-West of Adelaide. The transmit array consisted of 4 vertically directed log-periodic dipole antennas (LPDA). Its operating frequency was 32.55 MHz, transmit power was 16 kW, and it utilised a frequency modulated continuous wave (FMCW) waveform with a bandwidth of 10 kHz, range resolution of 15 km, waveform repetition frequency of 100 Hz, and beamwidth of ~45°. The receiver array was a hexagonal unit cell array of 30 vertically directed LPDAs.

The radar operated for 6 blocks over a 7 day period during local night time. During this period a total of 637 objects were identified within the radar detections.

Catalogues of all published TLEs on the days of interest were obtained from SpaceTrack. TLEs contain position and velocity data for a given epoch for a single RSO, which can be propagated forward or backward in time by an SGP4 propagator. The MATLAB package OrbProp [3] was used, which contains the SGP4 propagator [4].

The calculations for the ionospheric correction were performed using 3-dimensional magneto-ionic numerical ray tracing through a climatological model ionosphere with the MATLAB ray tracing package PHaRLAP [5]. The model ionosphere was generated using the International Reference Ionosphere (IRI) 2020 [6].

3. Method

A unique match with a corresponding TLE was found for 362 of the 637 RSOs observed by the radar. The detection of each object was isolated from noise and interference, and corrected for range-Doppler coupling.

The ionospheric correction method produces a correction to the range, elevation, azimuth, and range rate measured by the HF LOS radar. The position of the detected RSO is corrected first, using the process illustrated in Figure 1. At each point along the object's path, the measured elevation and azimuth are used as the starting angles for a ray modelled by PHaRLAP. This ray is traced through the model ionosphere until the modelled group range matches the measured range, at which point the ray tracing is terminated. The modelled ray accounts for group retardation and ray bending, and the location of the end point of this ray is the modelled true position of the object, assuming the model ionosphere is accurate. This is then converted to a corrected range, elevation, and azimuth.

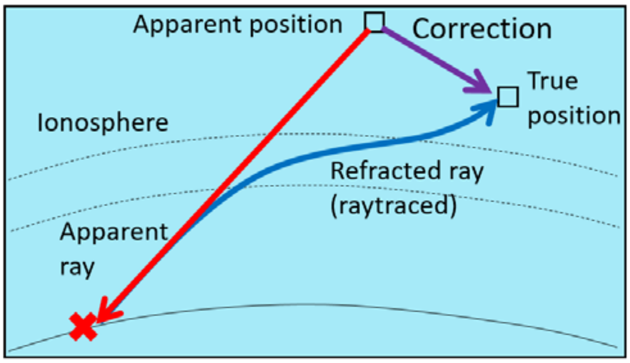

Figure 1. Illustration of the process for calculating the ionospheric correction to the position of an RSO for a HF LOS radar measurement. At 32.55 MHz, the amount of ray-bending is small. Here it is exaggerated for illustrative purposes.

Two different methods were used to calculate the range rate correction. The first, which we refer to as the *Raytracing method*, calculates the corrected range rate by taking the numerical derivative of the corrected range, calculated above:

$$RR_c = \frac{dR_c}{dt}, \tag{1}$$

Where RR_c is the corrected range rate and R_c is the raytraced corrected range.

However, this method for calculating the corrected range rate is sensitive to uncertainties or errors in the range measurements. Since the calculation of the corrected range by PHaRLAP is dependent on the measured range, small uncertainties in the measured range can become large due to the numerical differentiation of the corrected range.

The second method, which we refer to as the *Phase-Path Correction method*, was developed to mitigate this. Consider the measured Doppler shift, δf [7]:

$$\delta f = -2\frac{f}{c}\frac{dP}{dt}. \tag{2}$$

where f is the radio wave frequency, c is the speed of light in vacuo, P is the phase path and the factor of 2 accounts for propagation both from the radar to the RSO and back. As range rate is related to Doppler shift by $-c\delta f/2f$ we have the following equation for the measured range rate:

$$RR_m = \frac{dP}{dt}. \tag{3}$$

Since the phase path is also calculated by PHaRLAP during the raytracing process, the phase path correction, $\delta P = R_c - P$ can be calculated independently of the range rate measurement. In this expression, taking the difference between R_c and P effectively subtracts any errors which were replicated from the measured range. We can now take the derivative:

$$\frac{d(\delta P)}{dt} = \frac{dR_c}{dt} - \frac{dP}{dt}. \tag{4}$$

Substituting in the expressions from Equations 1 and 3, we have a second, independent method of calculating the corrected range rate which is more suitable for use with potentially noisy radar detections:

$$RR_c = RR_m + \frac{d(\delta P)}{dt}. \tag{5}$$

To demonstrate that the methods in Equation 1 and 5 are equivalent, simulated satellite data were generated both with and without the presence of ionospheric gradients during local mid-morning of December 1, 2020. Figure 2 shows two simulated RSO paths: one observed by a hypothetical radar located at 32°S, 130°E, under a flat ionosphere, and the other at 15°S, 130°E, under a meridional gradient. Both RSOs orbit at an altitude of 500 km and are observed by the radars at elevation angles above 60 degrees. Table 1 shows the results of the range rate correction for both methods in both locations. For the mid-latitude location, over the duration of the simulated RSO observation the Raytracing method gives an RMS ionospheric correction of 19.8 m/s, and the Phase-Path Correction method gives an RMS ionospheric correction of 19.8 m/s. The RMS difference between the two methods is 0.07 m/s, and the scale of the corrections in both cases is ~ 1% of the total range rate values. For the low-latitude location, the Raytracing method gives an RMS ionospheric correction of 39.5 m/s, while the Phase-Path Correction method gives an RMS ionospheric correction of 39.7 m/s, with an RMS difference of 0.8 m/s between the two methods. This indicates there may be some uncertainty between the two methods under different ionospheric conditions; however, these uncertainties are small compared to the range rate corrections and measurements.

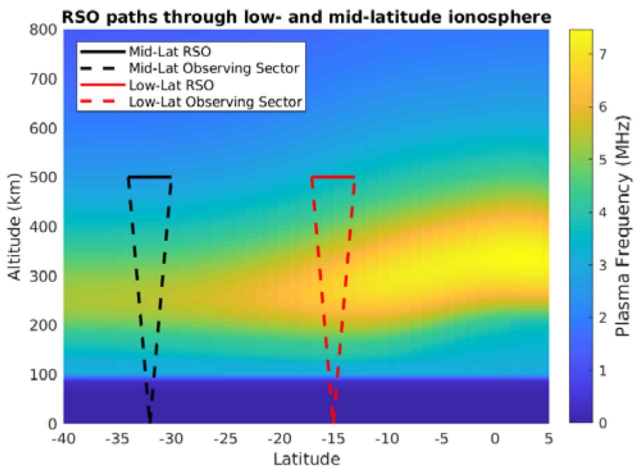

Figure 2. Latitude-Altitude cross-section of the modelled ionosphere, showing the paths of two simulated RSOs passing over hypothetical observer locations, one in the mid-latitudes and one in the low-latitudes.

Table 1. Results of the two methods of calculating the range rate ionospheric correction for mid-latitude and low-latitude locations.

	RMS Correction, Raytracing Method	RMS Correction, Phase-Path Correction Method	RMS Difference between methods
Mid-Latitude	19.8 m/s	19.8 m/s	0.07 m/s
Low-Latitude	39.5 m/s	39.7 m/s	0.8 m/s

4. Results

Figure 3 shows the comparison, in the form of residuals, between the radar RSO observations and the TLE propagations before and after the ionospheric correction for the range (a), elevation (b), azimuth (c), and range rate (d). A Gaussian distribution is fitted to each set of residuals.

Figure 3a shows that the range residuals decrease from a mean of 4.67 km and standard deviation of 5.34 km, to a mean of 0.99 km and standard deviation of 5.29, bringing the mean error within the nominal error of ~1 km at the epoch for TLEs [8]. Figures 3b and 3c; however, show no significant improvement in the elevation and azimuth residuals after the ionospheric correction. This is likely to be because the amount of ray bending is small compared to the angular resolution of the HF LOS radar (~3°). Similarly, the range rate residuals show no significant improvement after the application of the ionospheric correction using the Range Rate method. This is likely to be because the range rate correction is small compared to the uncertainty in the range rate from the TLEs [8].

The ionospheric corrections are small during local night time at solar minimum, especially for the elevation, azimuth, and range rate. However, this algorithm can be also applied to observations taken during any ionospheric conditions. Figure 4 shows the modelled typical magnitude of range correction as a function of observed elevation and range for solar minimum, night time conditions (top) and solar maximum, day time conditions (bottom). Two dashed lines indicate the paths of RSOs, orbiting at 400 km and 900 km altitude respectively. This figure shows that during solar maximum, a typical day time ionosphere can account for up to 17 km of deviation in range observations. At low elevation angles (30° - 45°), a typical day time ionosphere at solar maximum could account for up to 1.5° in deviation for elevation and 200 m/s in range rate. The ionospheric deviation for the azimuth observations remains small (<0.3°) for elevation angles less than 80°; however, it increases for larger elevation angles due to the coordinate singularity at the zenith.

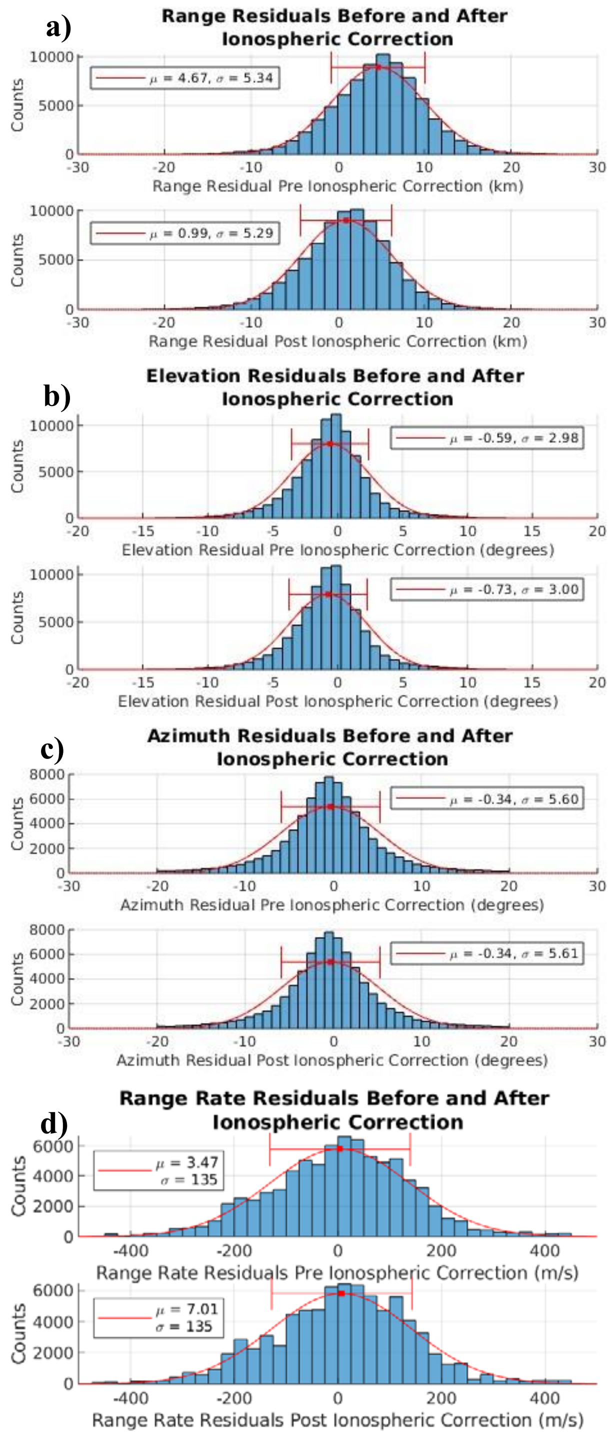

Figure 3. Residuals between the radar observations and corresponding TLE propagations before and after the ionospheric correction for the range (a), elevation (b), azimuth (c), and range rate (d).

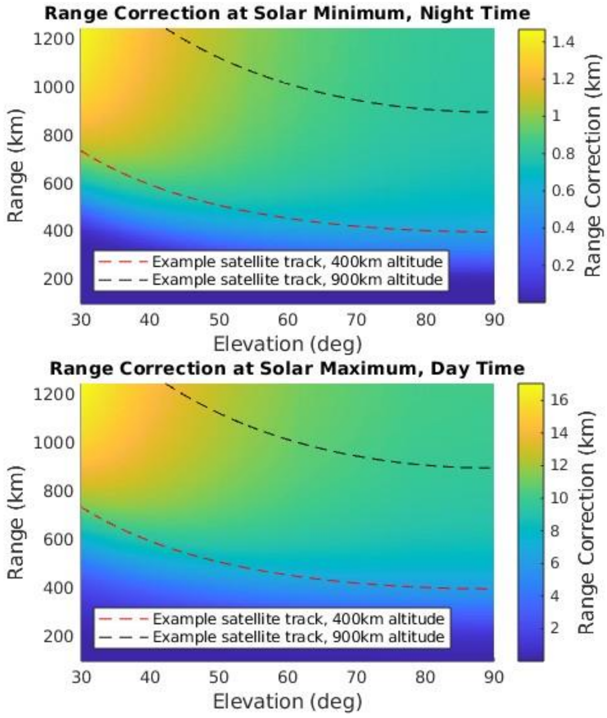

Figure 4. Magnitude of the ionospheric correction to observed range for solar minimum, night time (top), and solar maximum, day time (top), modelled for the HF LOS radar location near Coondambo, SA, as a function of observed elevation and range. Note the different colour scales in each plot.

5. Conclusion

In this paper we have described an algorithm that can account for the effects of ionospheric refraction on the position and velocity of HF LOS observations of RSOs using a climatological model ionosphere. This algorithm was applied to observations of RSOs with an experimental HF LOS radar in late 2020 during solar minimum at local night time. When compared to TLE propagations, the ionospheric correction brought the range measurements to within a mean error of 1 km. Corrections to the elevation, azimuth, and range rate did not result in significant improvements. However, the ionospheric errors introduced to these quantities was small. Future work will include applying this algorithm during stronger ionospheric conditions, with a real-time modelled ionosphere, and in conjunction with an orbital determination algorithm to further improve RSO detection and tracking accuracy.

6. Acknowledgements

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References

[1] G. J. Frazer, C. G. Williams, and H. Yardley, "Energy-budget analysis of a 2-D high-frequency radar incorporating optimum beamforming," in *2016 IEEE Radar Conference (RadarConf)*, 2-6 May 2016 2016, pp. 1-6, doi: 10.1109/RADAR.2016.7485242.

[2] D. A. Holdsworth, K. Mulder, and M. D. E. Turley, "Jindalee Operational Radar Network: New Growth from Old Roots," in *2022 IEEE Radar Conference (RadarConf22)*, 21-25 March 2022 2022, pp. 1-6, doi: 10.1109/RadarConf2248738.2022.9764214.

[3] *OrbProp*. (2018). MATLAB Central File Exchange. Accessed: 20/04/2021.

[4] D. Vallado and P. Crawford, "SGP4 Orbit Determination," in *AIAA/AAS Astrodynamics Specialist Conference and Exhibit*, 2008.

[5] M. A. Cervera and T. J. Harris, "Modeling ionospheric disturbance features in quasi-vertically incident ionograms using 3-D magnetoionic ray tracing and atmospheric gravity waves," *Journal of Geophysical Research: Space Physics,* vol. 119, no. 1, pp. 431-440, 2014, doi: https://doi.org/10.1002/2013JA019247.

[6] D. Bilitza, M. Pezzopane, V. Truhlik, D. Altadill, B. W. Reinisch, and A. Pignalberi, "The International Reference Ionosphere Model: A Review and Description of an Ionospheric Benchmark," *Reviews of Geophysics,* vol. 60, no. 4, p. e2022RG000792, 2022, doi: https://doi.org/10.1029/2022RG000792.

[7] J. A. Bennett, "The calculation of Doppler Shifts due to a changing ionosphere," *Journal of Atmospheric and Terrestrial Physics,* vol. 29, no. 7, pp. 887-891, 1967/07/01/ 1967, doi: https://doi.org/10.1016/0021-9169(67)90055-4.

[8] D. Vallado, P. Crawford, R. Hujsak, and T. S. Kelso, "Revisiting Spacetrack Report #3," in *AIAA/AAS Astrodynamics Specialist Conference and Exhibit*, 2006.