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Article

Ionospheric Corrections for Space Domain Awareness using HF Line-of-Sight Radar

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Highlights

What are the main findings?

- High frequency radars are a non-traditional class of sensor capable of the surveillance of space. However, the measurements are subject to biases due to ionospheric refraction.
- A method was developed to correct the ionospheric errors to high frequency radar observations of resident space objects using numerical ray tracing through a climatological model ionosphere.

What are the implications of the main findings?

- At solar minimum the method provided a significant improvement in the accuracy of radar range measurements; however, the ionospheric corrections to the measured angle of arrival and radial velocity were small.
- This method can provide improvements to orbital determination accuracy for space domain awareness during any ionospheric conditions.

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) radar operating in line-of-sight (LOS) mode, as their large surveillance field-of-view enables simultaneous tracking of several objects. HF signals are, however, subject to ray bending and group retardation when propagating through the ionosphere. This paper demonstrates the development and implementation of a method for calculating the ionospheric correction for HF LOS satellite observations, using three-dimensional numerical ray tracing through a climatological model ionosphere. Defence Science and Technology Group's experimental HF LOS radar was deployed during a SpaceFest trial in late 2020, and recorded observations of resident space objects (RSOs). The ionospheric correction is applied to these observations and compared to propagations obtained from the reported two line elements (TLEs) of the RSOs to assess the correction performance. The results demonstrate that, even during weak ionospheric conditions, ray tracing through a climatological model ionosphere produces a significant improvement in the residuals between the range measurements and TLEs.

Keywords: HF radar; space domain awareness; ionosphere; space surveillance; ionospheric modelling

1. Introduction

As of 2025, the number of resident space objects (RSOs) with size greater than 10 cm exceeds 64,000, with 57,000 of those located in low Earth orbit (LEO). Objects in LEO (below 2000 km) travel at speeds upwards of 7 km/s, can manoeuvre frequently, and vary in size from a 10 cm³ CubeSat to the 109 m long International Space Station. The increasingly congested LEO environment has resulted

in a surge in interest in the detection, tracking, and cataloguing of RSOs, known as space domain awareness (SDA) [1].

A Space Surveillance Network (SSN), known as project SPACE-TRACK, was established by the United States National Space Surveillance Control Center (NSSCC) in 1960 to monitor and catalogue RSOs [2]. The compilation of orbital parameters of known RSOs is now performed by United States Space Command, and distributed by SpaceTrack (<https://www.space-track.org>), for both military and civilian/scientific applications. The SSN consists of mechanical radars, phased-array radars, ground-based optical telescopes and satellite-borne optical sensors [3,4]. Australia is host to electro-optical SDA facilities at Mt Stromlo, near Canberra, and Learmonth, in Western Australia [5]. A dedicated C-band (4 - 8 GHz) SDA radar is located at Exmouth, Western Australia [6] and two S-band (2 - 4 GHz) phased array radar systems are located at Bunbury, Western Australia [7].

SSN radar systems operating in the UHF band and above provide high sensitivity (which is crucial for tracking small objects) and high tracking precision [8], due to their large size relative to their operating wavelength. However, they typically have a narrow tracking field-of-view (FOV) [9], and can be prohibitively expensive to deploy and operate. Additionally, RSO signal-to-noise ratio (SNR) measurements are subject to significant variation due to the radar cross section (RCS) of the RSOs varying with orientation with respect to the radar. Optical sensors offer even higher tracking precision, but even narrower surveillance volumes, ground-based systems can be disabled by cloud cover [5], and some are only able to operate in the hours following dusk and preceding dawn when RSOs are not covered by Earth's shadow [6,10].

Alternative sensors have been explored for SDA, such as HF radars [10–18], VHF radars [3,6,19] and radio telescopes such as the Murchison Widefield Array [9,20]. HF systems offer several advantages over conventional SDA sensors, including significantly lower cost, and ease of deployment and operation in remote locations [21]. Longer wavelengths allow a large antenna capture area to be achieved with a smaller number of antennas and channels [10]. The reduced computational processing load that comes with using a repetitive chirp waveform means an HF space surveillance system can easily surveil large volumes of space in real time [17], providing cueing for instruments with a smaller FOV. Lower waveform bandwidths and chirprates reduce the data-volume flow-rate through the radar processing chain which enables the use of advanced signal processing algorithms [22]. This allows comparatively smaller and cheaper HF systems to achieve similar performance to much larger traditional microwave systems for large targets [17]. However, it is difficult for HF systems to detect targets smaller than approximately 1 m^3 due to the small radar cross-section of these targets at HF.

Due to the refractive properties of the ionosphere, HF radio waves are bent back towards the surface of the Earth. However, above the critical frequency of the ionosphere HF radio waves are capable of penetrating into space. When operating at frequencies around 30 MHz, the signals transmitted by HF radars are capable of penetrating the ionosphere at most elevation angles, and thus HF radars, when operating at these frequencies, can observe objects in space in a LOS mode. However, a non-insignificant amount of ionospheric refraction still occurs and this introduces errors in the measurement of both the position and speed of the observed RSO [23], degrading the accuracy of the observation and impacting orbital determination (OD) efforts.

This paper describes a method of calculating the ionospheric correction for RSO observations made using an HF LOS radar system with a 2-D receive antenna array. The corrections to the range, elevation, azimuth, and radial velocity (Doppler) are calculated and applied to the RSO observations, which are compared to 'truth' data from associated two-line elements (TLEs), obtained from SpaceTrack and propagated using a simplified generalised perturbation (SGP4) propagator. Section 2 describes the HF LOS system and details the software and models used to propagate the RSO TLEs and perform the ionospheric correction to the RSO observations. Section 3 describes the methods used to calculate the ionospheric correction to the RSO observations. Section 4 presents the results of the ionospheric corrections and the comparison to the truth data obtained from the associated TLEs. An analysis of the results is presented in Section 5, followed by conclusions.

2. Instrumentation

An experimental 2-dimensional HF LOS radar was deployed by Defence Science and Technology Group during the “SpaceFest” event in November and December 2020 [24]. SpaceFest is a series of space surveillance capability demonstrations and equipment trials, run in some form by Australian Defence since 2018 [10]. Shown in Figure 1, the HF LOS radar was located near Coondambo (31.04°S, 135.87°E) in South Australia, approximately 520 km North-North-West of Adelaide.

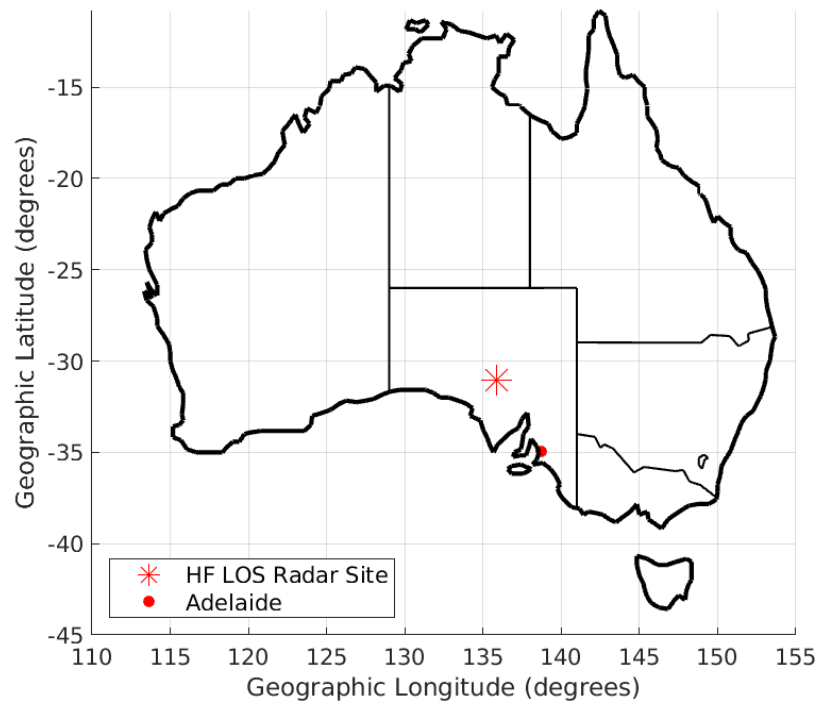


Figure 1. Location of the Coondambo HF LOS radar site in rural South Australia, with the location of Adelaide shown for reference.

The transmit array consisted of 4 vertically directed log-periodic dipole antennas (LPDAs), shown in Figure 2. Its operating frequency was 32.55 MHz, at which the beamwidth was $\sim 45^\circ$. The transmit power was 16 kW (4 kW per antenna) with the transmitted waveform being frequency modulated continuous wave (FMCW). The waveform repetition frequency (WRF) was 100 Hz and the bandwidth 10 kHz, giving a range resolution of 15 km.

The receive array was a hexagonal unit cell array of 30 vertically directed LPDAs, shown in Figure 3. It was located at a separate site ~ 2 km away from the transmit array. The angular resolution is approximately 3° . However, this value degrades at lower elevation angles as the array aperture decreases, exceeding 5° for elevation angles below approximately 55° . Typically, RSOs were visible above elevation angles of 60° ; however, larger RSOs such as the International Space Station were visible at elevation angles as low as 45° . This allows continuous observation of some RSOs for over 2 minutes, enhancing tracking capability and improving potential OD performance. Range, Doppler, elevation angle, and azimuth angle information were recorded.

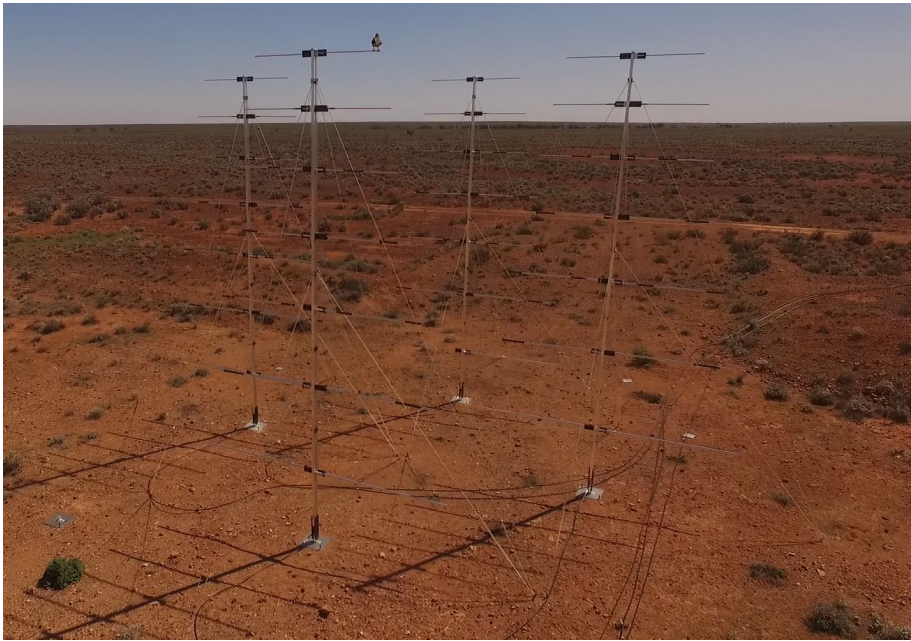


Figure 2. Transmit array of the experimental 2-dimensional HF LOS radar operated by DST Group at Coondambo, Australia.

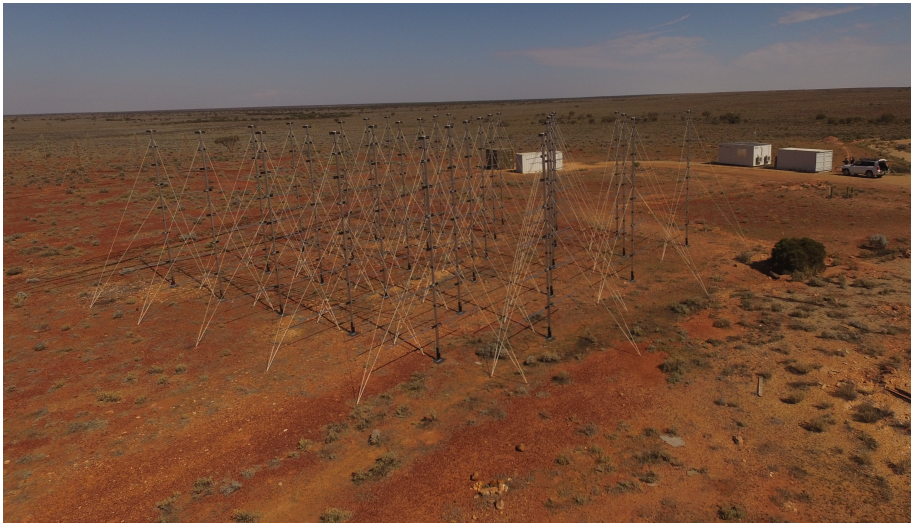


Figure 3. Receive array of the experimental 2-dimensional HF LOS radar operated by DST Group at Coondambo, Australia.

The radar operated in 6 blocks over a 7 day period, which are outlined in Table 1. During this period a total of 637 RSOs were identified.

Table 1. Radar operating blocks.

Block	Start (UT)	End (UT)	Duration
Block 1	2020-11-28 21:37	2020-11-29 01:05	3h 28min
Block 2	2020-11-29 20:13	2020-11-30 05:07	8h 54min
Block 3	2020-11-30 23:17	2020-12-01 03:25	4h 08min
Block 4	2020-12-02 06:58	2020-12-02 13:03	6h 05min
Block 5	2020-12-03 05:55	2020-12-03 12:19	6h 24min
Block 6	2020-12-04 07:59	2020-12-04 12:29	4h 30min

Truth data for the position of the RSOs observed by the HF LOS radar were obtained from published two-line elements (TLEs). SpaceTrack publishes catalogues of TLEs containing the orbital

parameters of all observed RSOs with a size greater than 10 cm, including operational satellites, de-orbiting rocket modules, and larger pieces of space debris. At the time that the TLE is generated from the SSN observations (referred to as the epoch), TLEs have a nominal error of 1 km [25]. The set of models known as Simplified General Perturbations (SGP4) propagate the position of the RSO body forward or backward in its orbit to predict its state vector of position and velocity at any point in time. The SGP4 models predict the effect of perturbations to the RSO orbit caused by the Earth's shape, radiation, and gravitational effects from the sun and moon [26]; however, they are known to inadequately handle atmospheric drag and are incapable of predicting manoeuvring objects [27]. As a result, the error of TLEs increase by approximately 1-3 km per day after the epoch [25]. The MATLAB package OrbProp [28], which contains the SGP4 propagator [29], was used to search the catalogue of known RSOs for those which would be present within the HF LOS radar's observing sector during the operating times.

The calculations for the ionospheric correction were performed using three-dimensional numerical ray tracing through a climatological model ionosphere with the MATLAB ray tracing package PHaRLAP [30]. The model ionosphere was generated using the 2020 International Reference Ionosphere (IRI) [31] for each day of the campaign.

3. Method

Errors in the observation of RSOs by an HF LOS system are introduced by interaction of the HF radio-wave signal with the ionosphere. The inhomogeneous, anisotropic nature of the ionosphere leads to three effects which impact the orbit determination of an RSO: retardation of the group velocity, increase of the phase velocity, and refraction of the radio waves [32]. These three effects result in an observed RSO appearing to have a larger measured range, decreased magnitude of measured radial velocity, and higher measured elevation angle. The magnitude of the effect of the ionosphere on the range will increase as the measured range increases, due to the longer path through the ionosphere causing the radio wave to experience greater group retardation. The magnitude of the effect of the ionosphere on the angular measurement of the RSO will increase at lower elevations, as a radio wave transiting the ionosphere at a greater angle of incidence will experience greater refraction; however, at 32.55 MHz this effect will be small.

While the increase in phase speed of the radio signal due to the ionosphere shortens the phase path, P , the ionospheric effect on the radial velocity, V_R , is due to the variation in the Doppler shift caused by the rate of change of the phase path. The measured Doppler shift, δf , is [33]:

$$\delta f = -2 \frac{f}{c} \frac{dP}{dt}, \quad (1)$$

where f is the radar operating frequency and c is the speed of light in vacuo. Note, we have introduced a factor of 2 to account for propagation from the radar to the RSO and back to the radar. As radial velocity is related to the Doppler shift by $-c \frac{\delta f}{2f}$ we have the following equation for the measured radial velocity:

$$V_{R,m} = \frac{dP}{dt}. \quad (2)$$

At the point of closest approach, while the radio-wave phase path, P , is less than the actual range of the RSO (due to the effect of the ionosphere), the radar measured radial velocity and the actual radial velocity of the RSO are the same, and equal to zero. This is due to the rate of change of slant range and the rate of change of phase path, $\frac{dP}{dt}$, both being zero at the point of closest approach. As the RSO recedes from the point of closest approach, both the actual range and phase path increase. However, the increasing amount of ionosphere traversed by the radio waves as the RSO range increases means the effect of the ionosphere on the phase path increases, i.e. the phase path increases more slowly than the actual range of the RSO. Thus the effect of the ionosphere on the RSO radial velocity measured by the radar is to reduce the magnitude and this effect is greater the further the RSO is from the point of closest approach.

The anisotropic nature of the ionosphere (caused by the geomagnetic field) means it is birefringent with respect to radio waves [32]. This causes linearly polarized radio wave signals to split into left and right-handed elliptical polarizations which experience different amounts of ray bending, group retardation and phase speeds [32]. For the case of HF signals of high enough frequency that they penetrate the ionosphere, the difference in the ray path is negligible. However, their different times of arrival at the radar receiver mean that they interfere to reproduce a linearly polarized wave with its plane of polarisation rotated with respect to the original transmitted signal; a well known effect called Faraday rotation. As the RSO travels in its orbit the phase path length between it and the radar changes and consequently so too does the rotation angle of the plane of polarisation of the received signal. This causes the received signal power to periodically fade, a process known as Faraday fading. As the difference between the ray paths for the two polarizations is negligible (indeed, the HF LOS radar is unable to resolve them in either range or angle-of-arrival) we ignore this effect and calculate the correction to the range, range rate, elevation and azimuth of the observed RSOs using three-dimensional ray tracing with the geomagnetic field excluded.

A unique match with an associated 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 [16]. Range-Doppler coupling occurs for FMCW signals and refers to the range offset (or bias) in the measured range to the target due to the Doppler shift imposed on the signal due to the target’s radial velocity. Details regarding the beam-forming and signal processing techniques used for detecting the RSOs are provided by [21] and [10] respectively. They are not discussed further here for brevity.

The ionospheric correction method applied to the observations of the RSOs produces a correction to the range, elevation, azimuth, and radial velocity (Doppler) measured by the HF LOS radar.

3.1. Measured RSO Position Correction

The position of the detected RSO is corrected first, using the process illustrated in Figure 4. At each step along the RSO’s path, the measured elevation and azimuth are used as the starting angles for an HF radio-wave ray path modelled by PHaRLAP. This ray is numerically traced through the model ionosphere until the modelled group range matches the measured range from the radar, at which point the ray tracing is terminated. The modelled ray accounts for both group retardation and ray bending, and the location of the termination point of the ray is the modelled true position of the RSO. This is then converted into a corrected (i.e., line-of-sight) range, elevation, and azimuth.

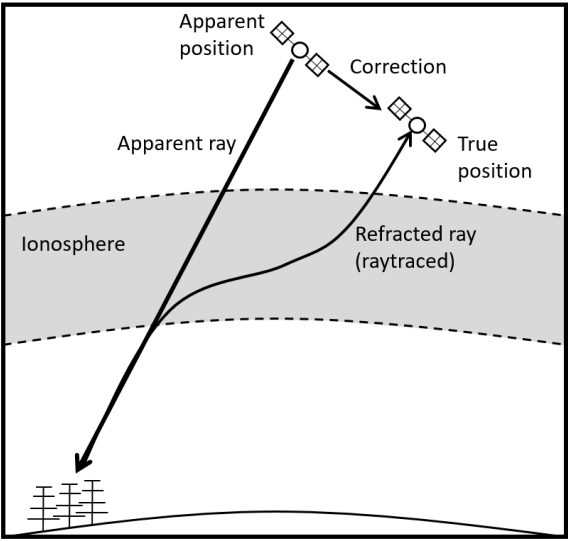


Figure 4. Illustration of the process for calculating the ionospheric correction to the position of an RSO for an HF LOS radar measurement. At 32.55 MHz, the amount of ray bending is small. Here it is exaggerated for illustrative purposes.

3.2. Radial Velocity Correction

Two different methods were considered for the range rate correction. The first, which we refer to as the *Raytracing Method*, calculates the corrected radial velocity by taking the numerical derivative of the corrected range calculated in Section 3.1:

$$V_{R,c} = \frac{dR_c}{dt}, \quad (3)$$

where R_c is the corrected range.

However, this method is sensitive to any uncertainties or random errors in the range measurements. As the calculation of the corrected range in PHaRLAP is dependent on terminating the ray tracing when the calculated group range matches the measured range, any errors in the measured range will be reproduced in the corrected range calculation. The numerical differentiation of the corrected range can then result in small uncertainties becoming large, which is unsuitable for a reliable ionospheric correction to the radial velocity. For example, with a range resolution of 15 km and sampling frequency of 2 Hz, uncertainties in a numerical differentiation of the measured range can reach 30,000 m/s - three orders of magnitude larger than the expected range rate correction.

A second method of calculating the radial velocity correction, which we refer to as the *Phase-Path Correction Method*, was developed which seeks to avoid the effects of uncertainties in the range measurements. Consider the difference between the corrected range and the phase path: $\delta P = R_c - P$. As both R_c and P are calculated using PHaRLAP as described in Section 3.1, any random errors in the corrected range are also replicated in the phase path. Therefore, taking the difference between the phase path and corrected range effectively 'subtracts' the random errors, and only leaves numerical uncertainties from the ray tracing. We can differentiate this expression to give:

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

Substituting in the expressions from Equations 2 and 3 gives:

$$V_{R,c} = V_{R,m} + \frac{d(\delta P)}{dt}. \quad (5)$$

Since $\frac{d(\delta P)}{dt}$ can be calculated independently of the radar measured value of $V_{R,m}$ by taking the numerical derivatives of R_c and P , calculated by PHaRLAP, Equation 5 provides a second method for calculating the corrected radial velocity. As Doppler is measured to a much higher precision than range, incorporating the radial velocity into this method makes it suitable for use in the presence of noisy range measurements.

3.3. Validity of the Phase-Path Correction Method Assumptions

The advantage of the Phase-Path Correction method over the Raytracing method is that it is not subject to the large random errors of the latter. However, before we can use the Phase-Path Correction method, we must demonstrate that it reliably reproduces the results of the Raytracing method under a variety of ionospheric conditions and geometries. To demonstrate this, simulated RSO data were generated over two hypothetical radar receivers. One is located in the mid-latitude region (similar to the ionospheric conditions at the HF LOS radar), where ionospheric gradients are negligibly small. The other is located in the low-latitude region, under the large meridional ionospheric gradient of the southern edge of the equatorial ionisation anomaly. Figure 5 shows the location of the two hypothetical radars: one located at 32°S, 130°E, and the other at 15°S, 130°E, under simulated ionospheres during both solar minimum and solar maximum conditions. The solar minimum ionosphere was generated for local mid-morning of December 1, 2020, and the solar maximum ionosphere was generated for local mid-morning of August 1, 2024. Both simulated RSOs follow polar orbits, passing directly over the receiver at an altitude of 500 km. Kepler's Third Law and assumed circular orbits were used to

generate realistic orbital speeds. Ray tracing was used to determine the phase path from the receiver to the synthetic RSO, to generate a realistic ‘measured’ radial velocity (see Equation 2).

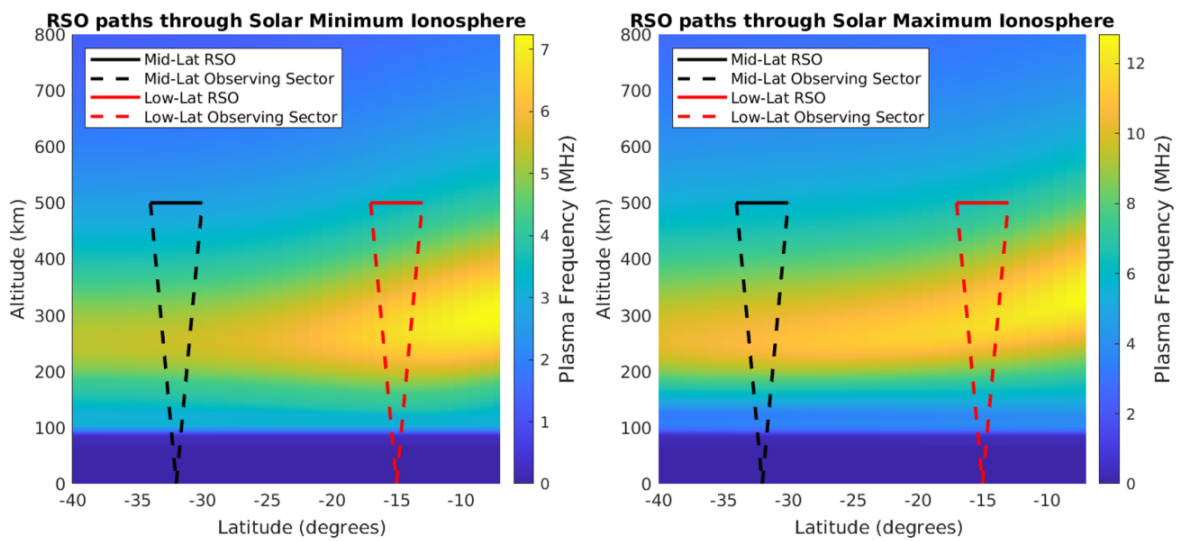


Figure 5. Latitude-altitude cross-section of a modelled ionosphere, showing the paths of two simulated RSOs passing two hypothetical observer locations, one in the mid-latitude region and one in the low-latitude region for solar minimum conditions (left) and solar maximum conditions (right). Note the differing colour scales.

Table 2 shows the RMS radial velocity correction for both methods in both locations. The differences between the two methods indicate there may be some uncertainty in the Phase-Path Correction method compared to the Raytracing method under different ionospheric conditions. However, these uncertainties are small compared to the radial velocity corrections and so we are able to use the Phase-Path Correction method to remove the effect of the ionosphere on the RSO radial velocity measurements.

Table 2. Results of the two methods of calculating the radial velocity correction for mid-latitude and low-latitude locations.

	RMS Correction, Raytracing Method	RMS Correction, Phase-Path Correction Method	RMS Difference Between Methods ¹
Mid-Latitude, Solar Minimum	19.8 m/s	19.8 m/s	0.07 m/s
Low-Latitude, Solar Minimum	39.5 m/s	39.7 m/s	0.8 m/s
Mid-Latitude, Solar Maximum	56.8 m/s	56.5 m/s	0.3 m/s
Low-Latitude, Solar Maximum	72.0 m/s	72.1 m/s	0.3 m/s

¹ This column is the RMS of the difference between the two correction methods at each point along the synthetic RSO’s path. This is not equal to the difference between the RMS corrections of the two methods (i.e., the difference between the middle two columns) due to the non-linear nature of the radial velocity corrections, especially in the presence of ionospheric gradients.

4. Results

Figure 6 shows an example of the ionospheric correction applied to radar observations, alongside corresponding TLE propagations, for the satellite Starlink-1202. The left panel shows a range-time plot, and demonstrates that the radar measurements are positively biased compared to the TLE propagation, which is removed by the ionospheric correction. The centre panel displays radial velocity as a function of time, and shows that the radar observations have a small negative bias compared to the TLE propagation. However, the effect of the ionospheric correction in this case is to increase the magnitude

of the radial velocity. This is highlighted in the two inset graphs: there is a small degradation in the agreement between radar and TLE in the first half of the observation (negative radial velocity), but a small improvement in the agreement in the second half (positive radial velocity). In this case, the effect of the ionospheric correction in increasing the magnitude of the radial velocity measurements produces no improvement in the agreement between the radar measurements and TLE propagation. The right panel is an elevation-azimuth graph on polar axes, which shows overall good agreement between the radar measurements and TLE propagation, which is not improved by the small ionospheric correction.

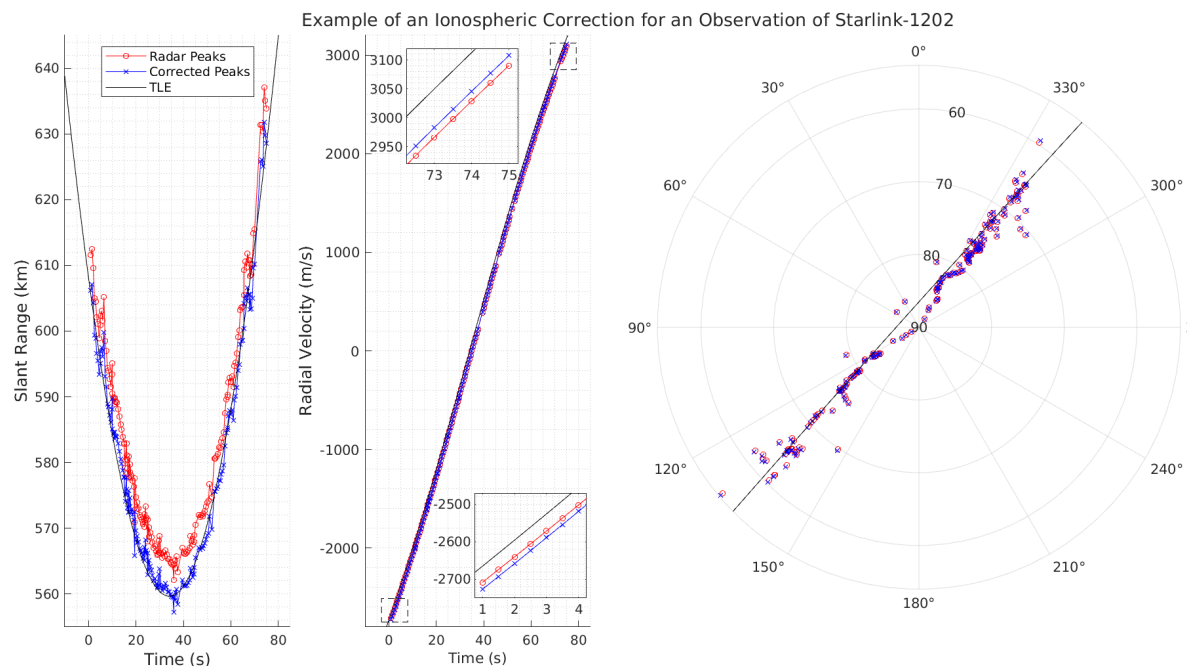


Figure 6. Example of an ionospheric correction performed on an observation of the satellite Starlink-1202, showing the range (left), radial velocity (centre), and angular (right) measurements. The inset graphs in the centre panel show a zoom-in of the first four and last three seconds of the radial velocity observations.

Figure 7 shows another example of an ionospheric correction applied to radar observations, alongside corresponding TLE propagations, for the satellite Landsat-7. The left panel again demonstrates a positive bias in the radar range measurements compared to the TLE propagation, which is significantly improved by the ionospheric correction. The centre panel for this case shows that the radar radial velocity measurements are positively biased compared to the TLE propagation. The ionospheric correction again has the effect of increasing the magnitude of the radial velocity observations (see inset graphs), which does not improve the overall agreement between the radar observations and the TLE propagation. The right panel shows the elevation-azimuth polar plot, and again the agreement between the radar measurements and the TLE propagation is not improved by the ionospheric correction.

These two examples demonstrate the effects of the ionospheric correction in the expected manner, i.e. to reduce the measured range and increase the magnitude of the measured radial velocity. Regarding the former, the corrected range is close to that expected from the TLE. However, regarding the radial velocity, there appears to be an additional bias in either the TLE truth (expected as per [25]), observations, or both. This bias is unrelated to the ionospheric correction, and further, it is greater than the effect of the ionosphere. The effect of the ionospheric correction on the angular measurements is, as expected, negligible. However, there is an appreciable difference between the observations and TLE near the zenith in both examples. The difference does not present as a bias and is possibly due to large scale travelling ionospheric disturbances (TIDs) which may cause angular deviations in the ray path.

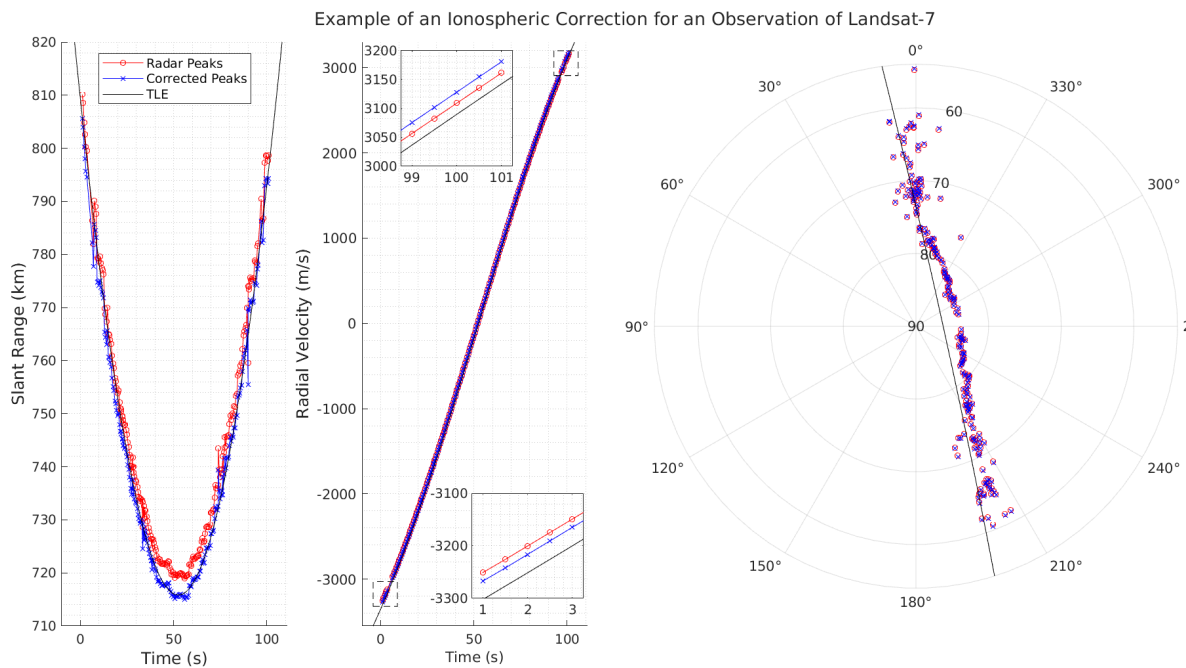


Figure 7. Example of an ionospheric correction performed on an observation of the satellite Landsat-7, showing the range (left), radial velocity (centre) and angular (right) measurements. The inset graphs in the centre panel show a zoom-in of the first and last three seconds of the radial velocity measurements.

While instructive, these examples do not provide a statistical assessment of how well the radar measurements agree with TLE propagations before and after the ionospheric correction. Uncertainties in the TLEs [25], the resolution of the instrument, and the use of a climatological ionospheric model which is not able to reproduce TIDs or day-to-day variations in the ionosphere are all expected to impact the assessment. Therefore, to properly assess the accuracy of the ionospheric corrections, the comparisons between each individual radar measurements of the 362 observed RSOs and their corresponding TLE propagations, both before and after the application of the ionospheric correction, were analysed over the whole dataset.

Figure 8 shows histograms of the range residuals between the radar measurements and TLE propagations, prior to and following the application of the ionospheric correction, with a normal distribution fitted to each. It shows an improvement in the mean range residual from 4.66 km to 0.98 km, which is within the nominal TLE positional uncertainty of 1 km. No significant improvement to the spread of the residuals is noted. Figure 9 shows the same residuals, this time in a 2-dimensional histogram, as a function of the measured range. A total linear regression trend line [34] is plotted on top of each histogram, along with a mean and standard deviation for each 50 km bin along the measured range axis. The trend line in the left panel shows that prior to the ionospheric correction, the range residual between the measured range and TLE propagation increased as a function of the measured range, at a rate of 6.8 m/km. The trend line in the right panel shows that following the ionospheric correction, this rate was reduced to 3.3 m/km. These figures indicate that the ionospheric correction has significantly improved the agreement between the radar range measurements and the TLE propagations.

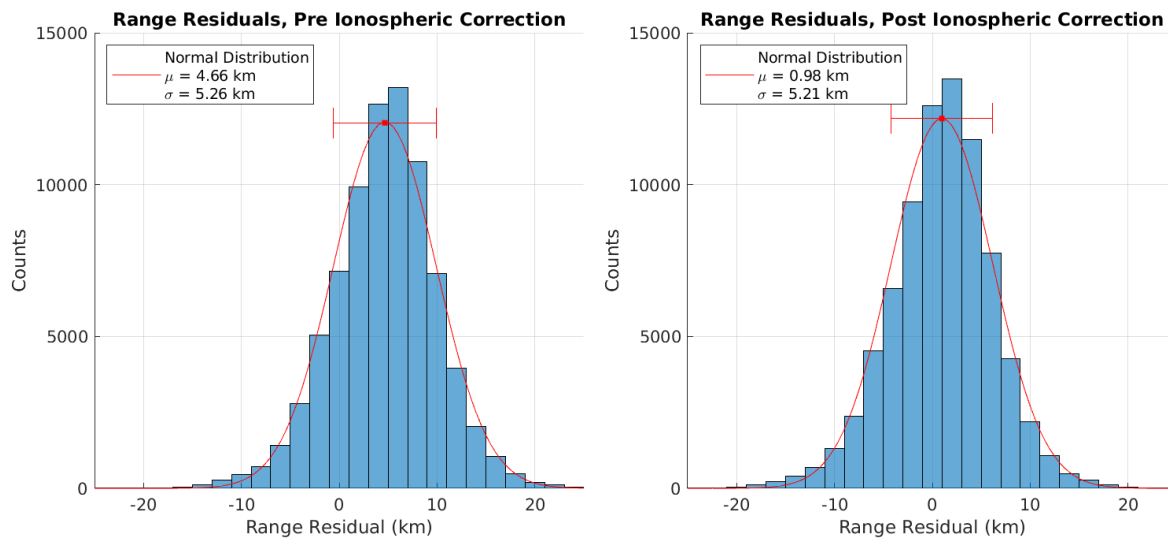


Figure 8. Histograms of range residuals between the radar measurements and TLE propagations prior to (left) and following ionospheric correction (right). A normal distribution is fitted to each histogram, with mean and standard deviation listed.

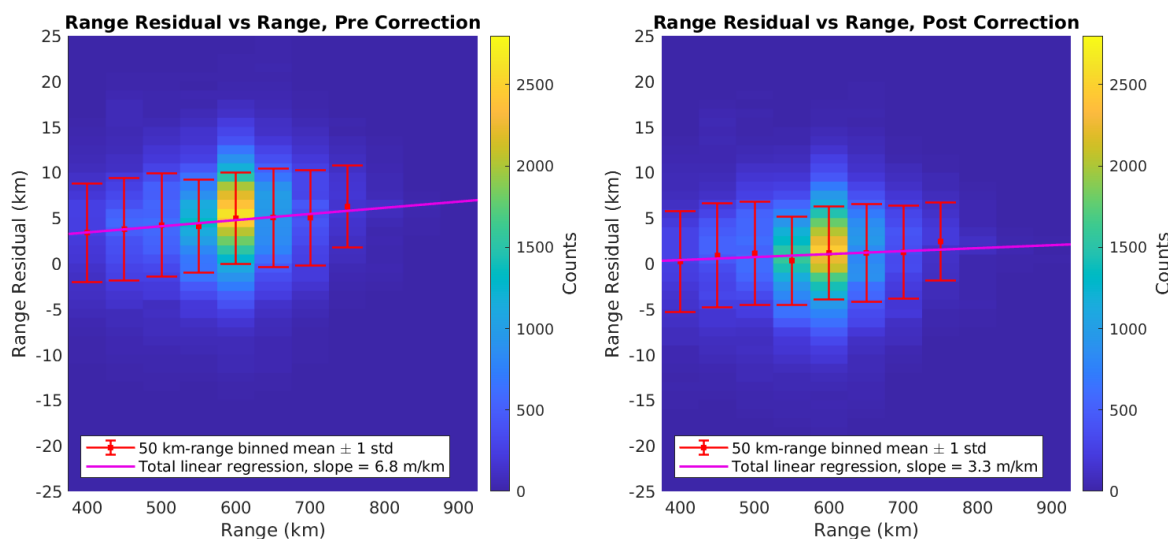


Figure 9. 2-dimensional histograms of range residuals between the radar measurements and TLE propagations prior to (left) and following ionospheric correction (right), as a function of measured range in bins of 50 km. The mean and standard deviation are plotted in red for each 50 km range-bin, with a total linear regression trend line plotted in magenta.

Figure 10 shows a 2-dimensional histogram of the ionospheric correction to the range measurements, as a function of measured range. A 90% confidence error ellipse is fitted to the data, which shows a high degree of spread in the corrections. The eigenvectors of the error ellipse and a total regression trend line both indicate the range correction is highly dependent on the measured range, which is expected as radio waves which take a longer path through the ionosphere experience greater group retardation. Care must be exercised when interpreting the fitted total regression line; e.g. the trend line implies no ionospheric correction at a measured range of 380 km and a positive correction at shorter ranges. That is clearly unphysical as the radio waves still traverse the ionosphere and consequently experience group retardation.

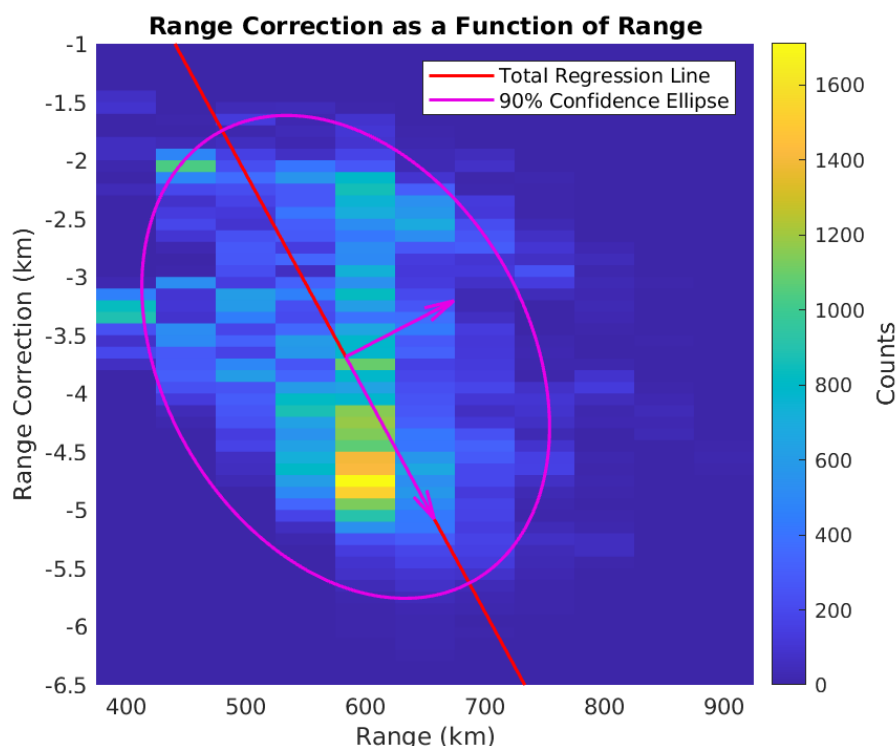


Figure 10. 2-dimensional histogram of the ionospheric correction to the range measurements, as a function of measured range. A total linear regression trend line is plotted in red and a 90% confidence error ellipse and corresponding eigenvectors are plotted in magenta.

The large spread in the range corrections displayed in Figure 10 is due to two factors. First, the magnitude of the ionospheric range correction is dependent on the strength of the ionosphere. The observation periods shown in Table 1 occur during both local night and local day time conditions, leading to a large variation in the strength of the ionosphere. Second, a radio wave which transits the ionosphere at a lower elevation angle, in comparison to a radio wave which transits the ionosphere at 90° elevation, but to the same measured range, will experience greater group retardation due to the longer path through the ionosphere. As a result, the elevation angle of the RSO also impacts the ionospheric range correction.

Figure 11 shows histograms of the radial velocity residuals between the radar measurements and the TLE propagations, prior to and following the application of the ionospheric correction (Phase-Path Correction method), with a normal distribution fitted to each. The mean radial velocity residual increases from 3.47 m/s to 7.01 m/s. However, this is small compared to the spread of the residuals. The standard deviation remained the same at 135 m/s. A two-sided t-test rejects the null hypothesis that the distributions of pre- and post-ionospheric correction radial velocity residuals arise from distributions of equal mean at a 99.99% confidence level, indicating that while small, the radial velocity correction is statistically significant. Never-the-less, at low solar cycle conditions this figure indicates that, as shown in the centre panels of Figures 6 and 7, the ionospheric radial velocity correction is small compared to other errors which may be present in the radar measurements and the TLE propagations.

Figure 12 shows a 2-dimensional histogram of the ionospheric correction to the radial velocity measurements, as a function of measured radial velocity. A 90% confidence error ellipse shows a much lower degree of spread compared to the range corrections in Figure 10. The spread is at a minimum around the origin; however, it does increase as a function of the magnitude of the radial velocity. This is as expected from the discussion at the start of Section 3. A positive correlation between measured radial velocity and the radial velocity correction is demonstrated by the total regression trend line, which passes through the origin. This supports the observations from the example ionospheric corrections in

Figures 6 and 7 that any bias in the measured radial velocity is not due to ionospheric refraction and consequently will not be corrected.

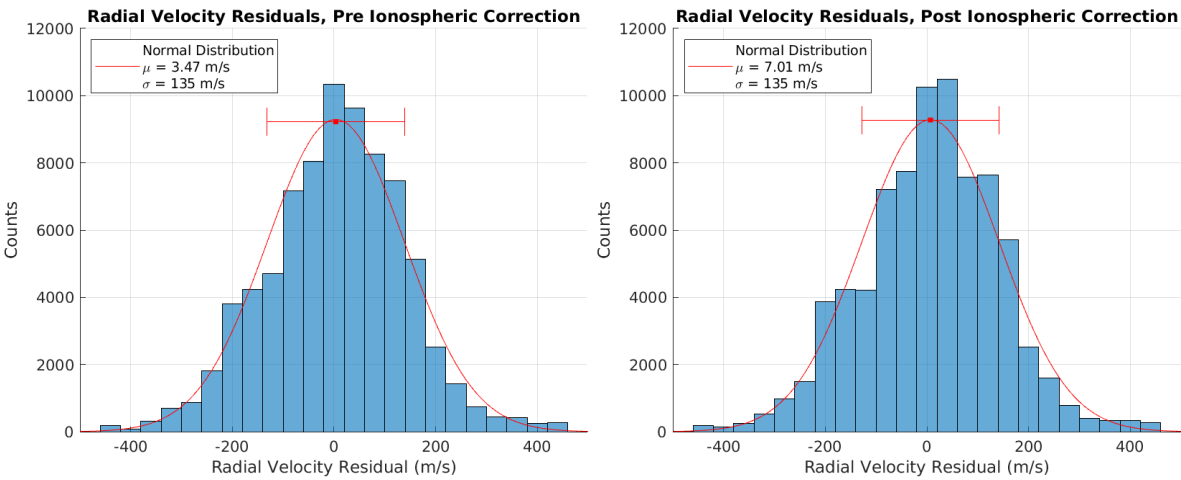


Figure 11. Histograms of radial velocity residuals between the radar measurements and TLE propagations prior to (left) and following ionospheric correction (right). A normal distribution is fitted to each histogram, with mean and standard deviation listed.

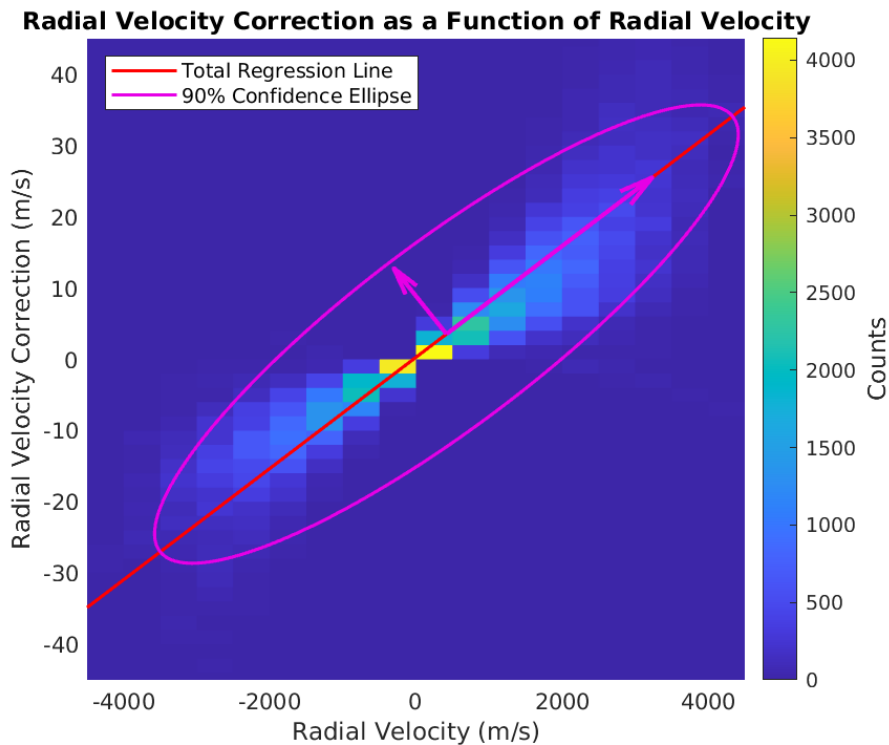


Figure 12. 2-dimensional histogram of the ionospheric correction to the radial velocity measurements, as a function of measured radial velocity. A total linear regression trend line is plotted in red and a 90% confidence error ellipse and corresponding eigenvectors are plotted in magenta.

Figure 13 shows histograms of the angular residuals between the radar measurements and the TLE propagations, prior to and following the ionospheric correction. The angular residuals were produced by calculating the angle between the vector pointing from the radar receiver to each radar observation of the RSO along its path, and the vector pointing from the radar receiver to each corresponding point in the TLE propagation. A log-normal distribution is fitted to each histogram. The mean and standard deviations of each distribution are presented, showing the mean increased slightly from $\ln(2.15^\circ)$

to $\ln(2.19^\circ)$, and the standard deviation remained the same at $\ln(2.25^\circ)$ following the ionospheric correction. We performed a two-sample Kolmogorov-Smirnov test and rejected the null hypothesis that the distributions are the same at a 0.2% significance level (p-value 0.001) confirming that, while the effect of the ionosphere on the angular measurement of the RSOs for weak ionospheric conditions is small compared to the uncertainty in the measurements, it is statistically significant.

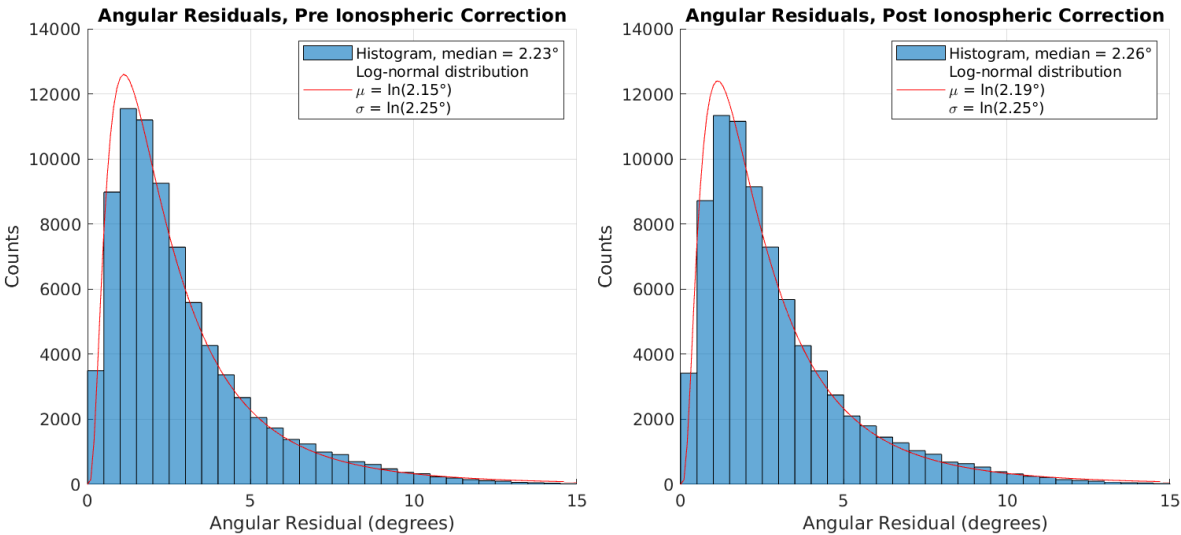


Figure 13. Histograms of angular residuals between the radar measurements and the TLE propagations prior to (left) and following ionospheric correction (right). A log-normal distribution is fitted to each histogram, with mean and standard deviation listed.

Figure 14 shows 2-dimensional histograms of the angular residuals between the radar measurements and TLE propagations prior to and following the ionospheric correction as a function of measured elevation in bins of 4 degrees. The median and inter-quartile range (IQR) of each bin are plotted, and they show a clear variation of the angular residuals with elevation, although there is no change after the application of the ionospheric correction. The angular residuals appear to have local maxima around elevation angles of 52° and 72° , and local minima around 64° and 80° . A third local maximum may be present around 88° ; however, the low number of samples between 86° and 90° means that this is not certain. The cause of this variation in angular residuals is likely to be due to variations in the sensitivity of the beam pattern of the receive array.

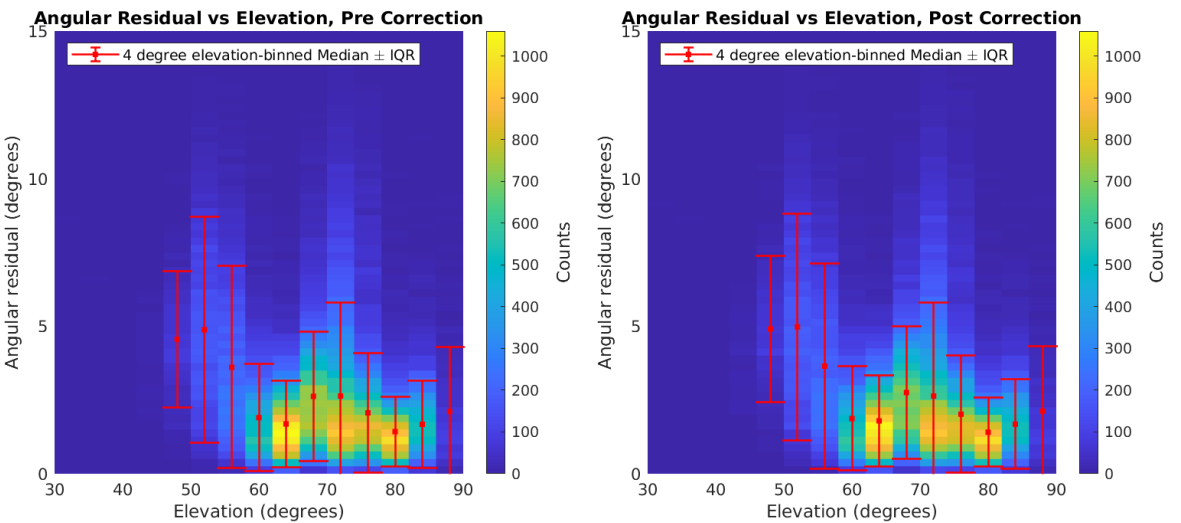


Figure 14. 2-dimensional histogram of the angular residuals between the radar measurements and TLE propagations prior to (left) and following ionospheric correction (right), as a function of measured elevation in bins of 4 degrees. The median and inter-quartile range (IQR) are plotted in red for each 4 degree elevation-bin.

Figure 15 shows 2-dimensional histograms of the angular residuals, similar to Figure 14, this time as a function of azimuth, in bins of 30 degrees. The median and IQR of each bin are also plotted, and reveal no azimuthal dependence in the angular residuals, prior to or following the application of the ionospheric correction.

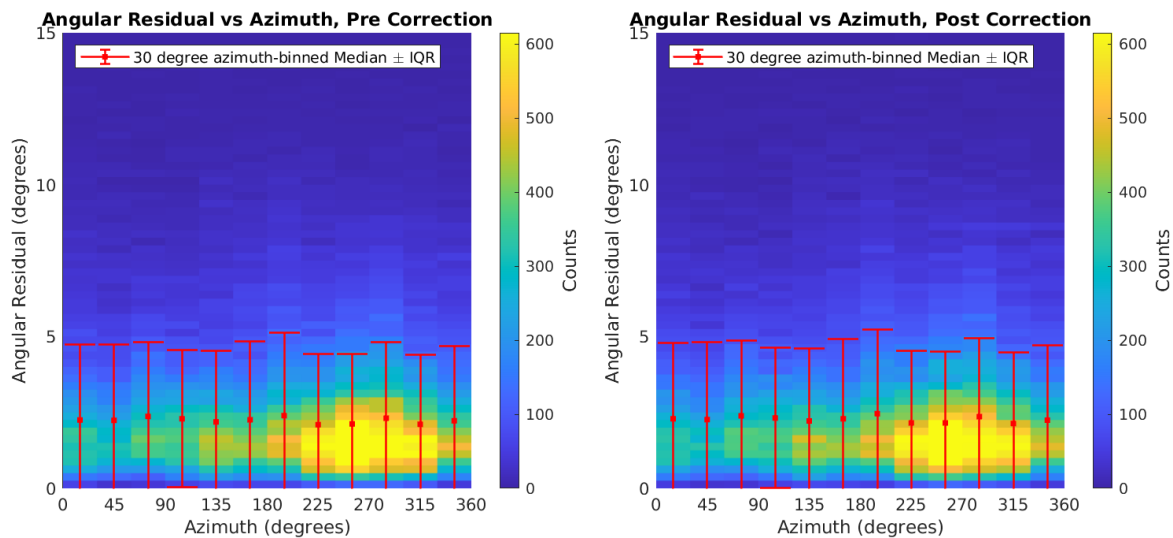


Figure 15. 2-dimensional histogram of the angular residuals between the radar measurements and TLE propagations prior to (left) and following ionospheric correction (right), as a function of measured azimuth in bins of 30 degrees. The median and inter-quartile range (IQR) are plotted in red for each 30 degree azimuth-bin.

Figure 16 shows a 2-dimensional histogram of the ionospheric correction to the angular measurements, plotted as a function of measured elevation. A total regression trendline, as well as the median and IQR of each elevation bin reveal a clear dependence on elevation angle. This is expected as vertically propagating radio waves experience very little ray bending (zero ray bending for the case of no ionospheric gradients and ignoring the geomagnetic field), with the degree of ray bending increasing with off-zenith angle (lower elevation angles). The magnitude of the angular correction; however, is small at all observed elevation angles, with the median angular correction for elevation angles between 46° and 50° (the lowest elevation-bin with sufficient samples for statistical significance) being $\sim 0.3^\circ$.

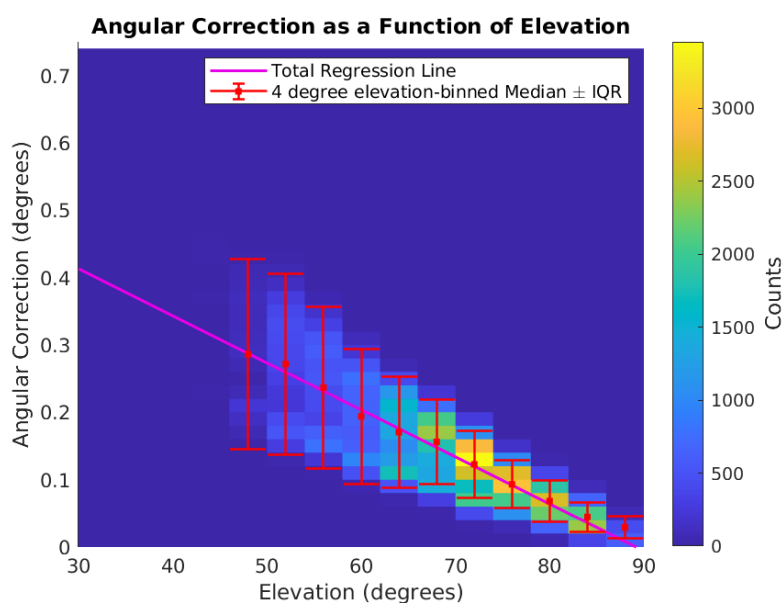


Figure 16. 2-dimensional histogram of the ionospheric correction to the angular measurements, as a function of the measured elevation in bins of 4 degrees. A total linear regression trend line is plotted in magenta, and the median and inter-quartile range (IQR) are plotted in red for each 4 degree elevation-bin.

Figure 17 shows a 2-dimensional histogram of the ionospheric correction to the angular measurements as a function of measured azimuth. The median and IQR of the 30° azimuth-bins appear to show an increase in the ionospheric angular correction around the 240°-270° and 270°-300° bins. This is likely to be the result of a sampling bias towards more RSO observations at lower elevation angles in that azimuth sector. There is no corresponding peak in ionospheric correction in the opposite direction (60°-120°).

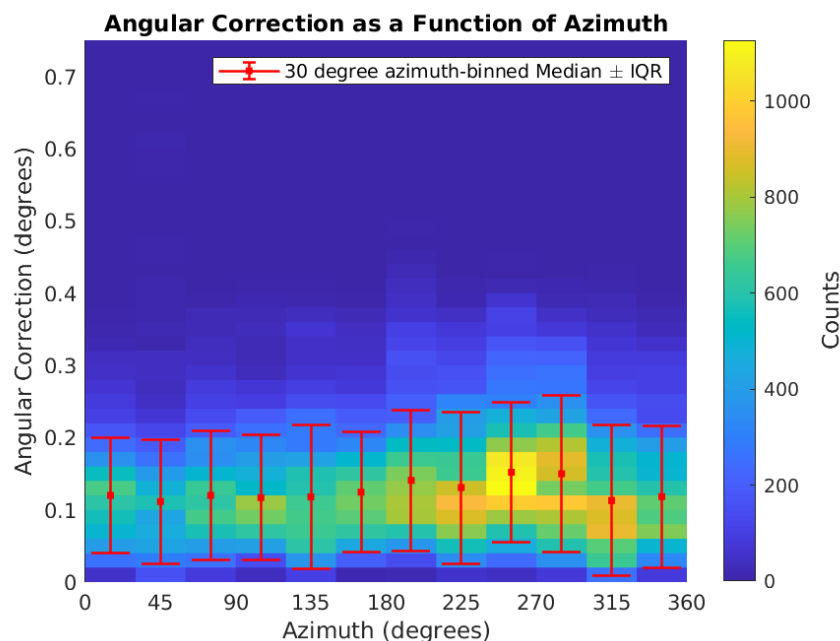


Figure 17. 2-dimensional histogram of the ionospheric correction to the angular measurements, as a function of the measured azimuth in bins of 30°. The median and inter-quartile range (IQR) are plotted for each 30° azimuth-bin.

5. Discussion

The results presented in this paper illustrate that it is possible to improve the accuracy of an RSO observation from an HF LOS radar by calculating and correcting for the error introduced by ionospheric refraction. The results presented in this paper were recorded during a range of local times (see Table 1) representing a range of ionospheric conditions, during which the magnitude of the ionospheric correction varied. This section presents a discussion of the results, the limitations of the method and its reliance on ionospheric modelling, and future directions for improving the accuracy of the corrections.

The magnitude of the ionospheric radial velocity corrections shown in Figure 12, relative to the large spread in the magnitude of the radial velocity residuals shown in Figure 11, indicates that the effect of the ionosphere is not the only source of error between the radar measurements and TLE propagations of the radial velocity. It is likely that uncertainties in the TLEs (nominally 1 km at TLE epoch [25]) are the main contributor to the observed difference between the radar observations and TLE propagations. It is also possible that uncertainties in the de-aliasing of the radial velocity and the correction for range-Doppler coupling introduced biases into the radial velocity measurements. This uncertainty would introduce a systematic uncertainty at the level of individual RSO passes, but would be randomly distributed across the whole dataset. This uncertainty arises from the necessity of determining the RSO's point of closest approach when de-aliasing the radial velocity. Further determination of the sources of error in the radial velocity are to be the subject of future work in this area.

The ionospheric angular corrections presented in Figures 16 and 17 show the magnitude of the ionospheric ray bending present in the RSO observations is small. These corrections are consistent with expectations that, at an operating frequency of 32.55 MHz, there would be a minimal amount of

ray bending at low elevation angles, negligible ray bending near the zenith, and no dependence of the ray bending on the azimuth angle.

The results in this paper only investigate ionospheric corrections for RSO observations made in a limited variety of ionospheric conditions, specifically at solar minimum. To investigate the expected ionospheric correction over a broad range of ionospheric conditions, we modelled synthetic RSO observations at night-time solar minimum and day-time solar maximum conditions.

Figure 18 shows maps of ionospheric plasma frequency at an altitude of 270 km over Australia for two hypothetical ionospheres modelled using IRI2020. The left panel shows an ionosphere generated during local night time (1600 UT), southern hemisphere summer (December 1), in solar minimum conditions (year 2019) with a smoothed sunspot number (R12 version 1.0) of 1. The right panel shows an ionosphere generated during local day time (0300 UT), southern hemisphere winter (August 1), in solar maximum conditions (year 2024) with a smoothed sunspot number of 130. These ionospheres are intended to represent the range of potential ionospheric conditions, presenting a (a) very weak ionosphere, and (b) very strong ionosphere; enabling a demonstration of the range of magnitudes of ionospheric corrections which could be necessary for an HF LOS radar operating in an SDA mode.

In both panels of Figure 18, a red dot denotes a hypothetical HF LOS radar receiver (located in the same place as the HF LOS radar used in this paper), able to observe RSOs at elevation angles above 30 degrees at an operating frequency of 32.55 MHz. Synthetic RSO tracks were generated for polar orbits with orbital heights ranging between 200 km and 1260 km for an orbit passing directly over the receiver. The dashed line in each panel shows the ground track traced by an RSO orbiting at 1260 km within the observer sector of the receiver. Kepler's Third Law and assumed circular orbits were used to generate realistic orbital velocities, such that ionospheric corrections could be applied to the synthetic range, elevation, azimuth, and radial velocity tracks.

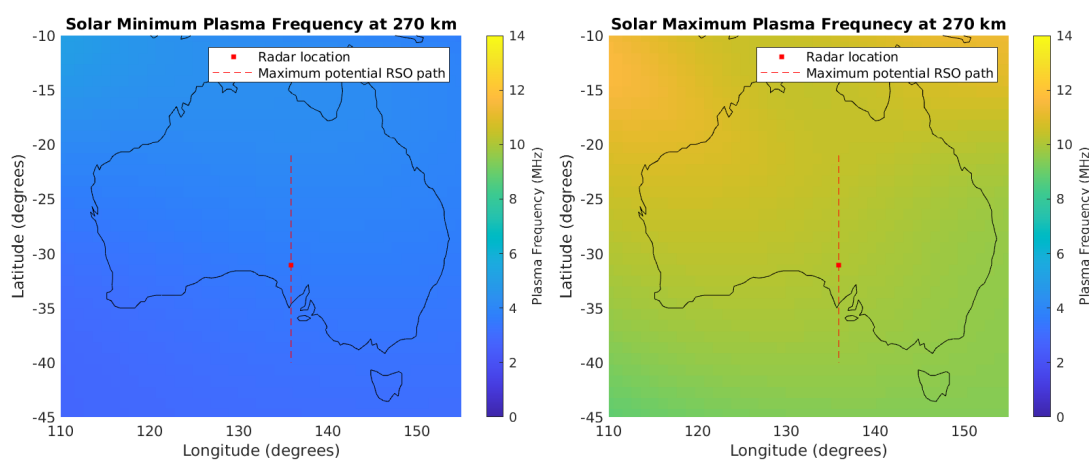


Figure 18. The two test ionospheres generated by IRI2020 used to demonstrate the potential range in magnitude for ionospheric corrections for an HF LOS radar operating at 32.55 MHz. The left panel shows the plasma frequency at an altitude of 270 km for local night time, summer conditions with $R12 = 1$. The right panel shows the plasma frequency at an altitude of 270 km for local day time, winter conditions for $R12 = 130$. The location of the observing radar is shown by a red dot, and the ground track of the synthetic RSO at an altitude of 1260 km above the minimum observable elevation angle of 30° is indicated by the dashed red line.

Figure 19 shows the magnitude of the ionospheric range correction as a function of geometric elevation angle and range from the hypothetical radar receiver for each of the simulated ionospheres from Figure 18. A pair of dashed lines on each panel shows the path of two reference RSOs in circular orbits at altitudes of 410 km and 700 km. In the left panel, the ionospheric range correction for the weak ionospheric conditions has magnitudes of up to 3 km for ranges over 900 km and elevation angles under 45 degrees. In the right panel, the magnitude of the ionospheric range correction during the strong ionospheric conditions exceeds 25 km for ranges over 900 km and elevation angles under 45 degrees. In both cases, RSOs orbiting at any altitude above 410 km would experience large ionospheric

range corrections at low elevation angles. This also demonstrates that even during weak ionospheric conditions, the ionospheric error introduced to range measurements can be large enough to impact orbital determination (OD) accuracy, and during stronger conditions the effect will be much greater.

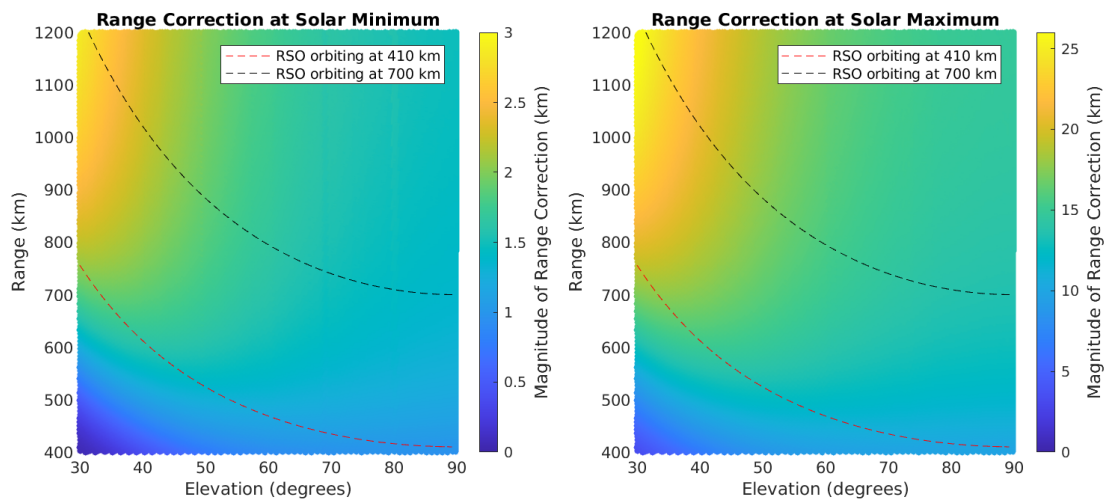


Figure 19. Magnitude of the correction to observed range measurements as a function of elevation and range for ionospheres simulated for summer, solar minimum, local night time conditions (left), and winter, solar maximum, local day time conditions (right). The paths of hypothetical RSOs orbiting at 410 km (red) and 700 km (black) are shown by dashed lines.

Figure 20 shows the magnitude of the ionospheric angular correction as a function of geometric elevation angle and range from the hypothetical radar receiver for each of the simulated ionospheres from Figure 18. During weak ionospheric conditions the ionospheric angular correction reaches up to 0.2 degrees for ranges above 550 km and elevation angles below 40 degrees. Above 60 degrees, the angular correction is below 0.05 degrees at all ranges. During strong ionospheric conditions, the angular correction exceeds 2 degrees for ranges above 550 km and elevation angles below 40 degrees, and is below 0.5 degrees for elevation angles above 60 degrees. This supports the results in Figures 13, 14, and 15, that showed during solar minimum the ionospheric angular correction would be negligible. However, during solar maximum, at low elevation angles the ionospheric angular correction can become large enough to impact OD accuracy.

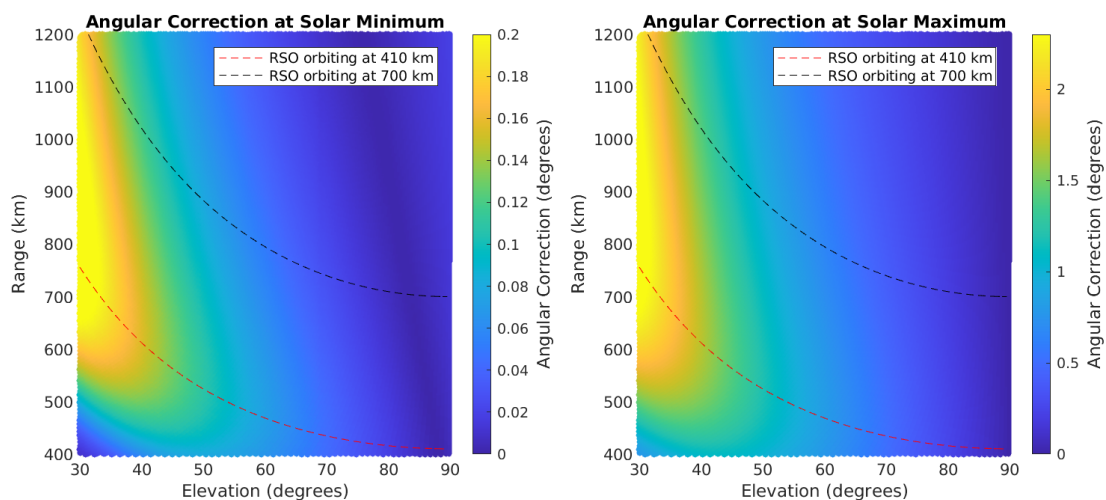


Figure 20. Magnitude of the correction to observed angular measurements as a function of elevation and range for ionospheres simulated for summer, solar minimum, local night time conditions (left), and winter, solar maximum, local day time conditions (right). The paths of hypothetical RSOs orbiting at 410 km (red) and 700 km (black) are shown by dashed lines.

Figure 21 shows the magnitude of the ionospheric radial velocity correction as a function of geometric elevation angle and range from the hypothetical radar receiver for each of the simulated ionospheres from Figure 18. During weak ionospheric conditions the ionospheric radial velocity correction reaches up to 20 m/s at low elevations for ranges which would encompass RSOs orbiting at any altitude in LEO or higher. The correction decreases to 0 m/s at the zenith for all ranges. This is in agreement with the distribution of radial velocity corrections reported in Figure 12. During strong ionospheric conditions, the right panel of Figure 21 shows that the radial velocity correction reaches up to 150 m/s at low elevations for ranges which would encompass RSOs orbiting in LEO or higher. As RSOs in LEO typically have radial velocities of around ± 4500 m/s at low elevation angles, the ionospheric correction could account for up to 3% of the total measurement, in comparison to approximately 0.5% during weak ionospheric conditions. Therefore, during strong ionospheric conditions the ionospheric radial velocity correction is likely to produce a noticeable improvement between HF LOS radar observations and TLE propagations, and consequently will be critical for obtaining accurate OD for SDA purposes.

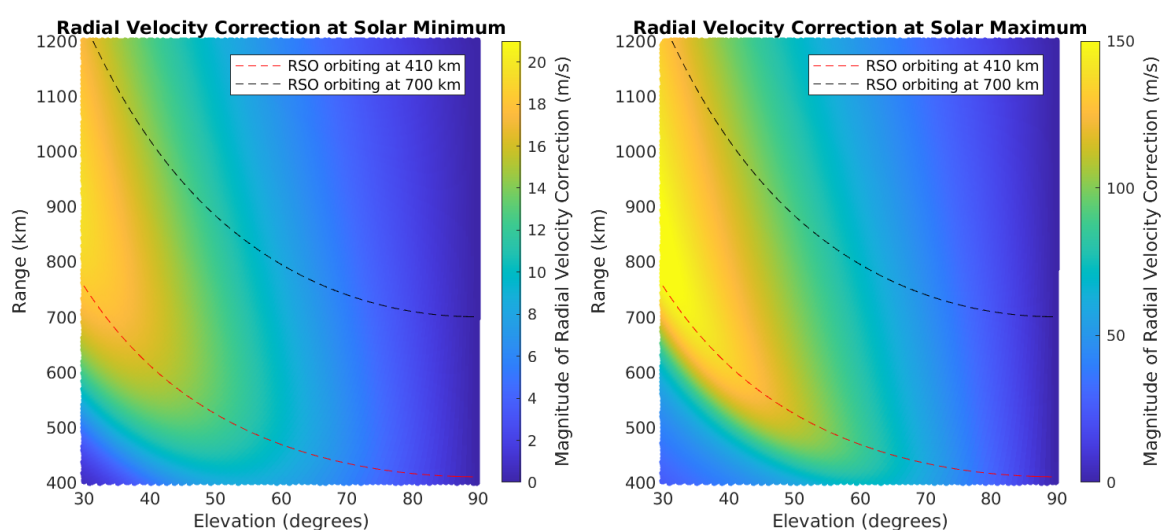


Figure 21. Magnitude of the correction to observed radial velocity measurements as a function of elevation and range for ionospheres simulated for summer, solar minimum, local night time conditions (left), and winter, solar maximum, local day time conditions (right). The paths of hypothetical RSOs orbiting at 410 km (red) and 700 km (black) are shown by dashed lines.

Previous studies have suggested that it is not possible to perform ionospheric corrections for HF LOS RSO observations using ray tracing due to the dependence on climatological ionospheric models which are not sufficiently accurate for SDA, especially at frequencies below 30 MHz where ionospheric errors are much larger [15]. However, the current study has shown that the ionospheric corrections derived by ray tracing through a climatological model ionosphere produce a significant improvement in the agreement between radar observations and TLE propagations. This method has also been shown to be sufficient for accurate OD of RSOs over multiple passes, and subsequent cueing of narrow field-of-view sensors; discussed in [10].

The method of calculating the ionospheric correction for HF LOS RSO observations described in this paper does, however, have limitations. Firstly, it requires elevation measurements in order to perform the raytracing. This limits the method to use with 2-dimensional HF LOS arrays, as 1-dimensional arrays do not resolve elevation and azimuth angles separately. Instead, the elevation and azimuth angles are conflated into a single measured angle, known as the “coning angle” [12]. Secondly, the method currently relies on the accuracy of a climatological ionospheric model, which does not capture day-to-day variability and fine-scale structure such as travelling ionospheric disturbances. This could be improved by the operation of a collocated vertically incident ionospheric sounder (VIS). This sounder would provide real-time information on the local height and strength of the ionosphere,

which can be used as inputs to IRI, improving its accuracy. Furthermore, if a network of ionospheric sounders was available, a real-time ionospheric model could be developed and used to improve the accuracy of the corrections.

6. Conclusions

In this paper, we have described a method which can account and correct for the effects of ionospheric refraction on the position and velocity of RSO observations by an HF LOS radar using three-dimensional numerical ray tracing through a climatological model ionosphere. The method was applied to RSO observations from Defence Science and Technology Group's experimental HF LOS radar during a SpaceFest trial in late 2020. It produced a significant improvement in the agreement between the HF LOS observations and the associated TLE tracks in the range measurements, reducing the mean range error to within 1 km. However, it was demonstrated that the angular and radial velocity corrections were too small to produce a significant improvement in the agreement between HF LOS observations and the associated TLE tracks. The method was further applied to synthetic RSO observations through a model ionosphere during day-time solar maximum conditions. This showed that during solar maximum, the ionospheric correction to range, angular, and radial velocity measurements are all significant. Future work will include applying this method with an ionospheric sounder collocated with an HF LOS radar to allow real-time ionospheric modelling, and using the method with orbital determination algorithms.

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