Impact of Ionospheric Doppler Perturbations on Space Domain Awareness Observations

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Abstract—As the Low Earth Orbit (LEO) space environment becomes increasingly congested, the need to identify and track space objects has grown. This is currently achieved through a network of ground-based and satellite-mounted sensors. However, these sensors are expensive to produce and maintain which has led to an effort in finding alternative sensors to track satellites. One such alternative is radar operating in the high frequency (HF) and very high frequency (VHF) bands which have been shown to be able to detect space objects. We report on 393 days of satellite observations made by a VHF and HF radar and find evidence of Doppler perturbations across multiple observations in the spectrograms. Two environmental sources of these perturbations were found, with the most numerous being ionospheric plasma instabilities in the 0–0.46 Hz frequency range. The second source was identified as ionospheric plasma waves propagating parallel to the Earth’s surface in a waveguide centred at an altitude of 250 km. To the authors’ best knowledge, this is the first time that radar has been used to observe such waves and a statistical study indicated that, under certain conditions, radar may provide a more sensitive measure of the plasma waves than magnetometers normally used to detect these waves. The results indicate that the Doppler perturbations produced by ionospheric plasma instabilities and waves do not significantly impact the Doppler uncertainty of space domain awareness measurements at HF and VHF frequencies.

Keywords—Space domain awareness, VHF radar, HF radar, plasma waves

I. INTRODUCTION

In the last decade, the number of satellites launched into Earth’s orbit annually has exponentially increased, rising from 120 in 2010 to 2,163 in 2022 [1]. This issue is being compounded by the rapid commercialisation of space with various private corporations attempting to create megaconstellations of satellites, with the SpaceX Starlink program alone planning to deploy 12,000 satellites. Such a sudden influx of satellites would significantly increase the likelihood of a Kessler syndrome event, where debris from satellites colliding leads to a cascade of collisions with other satellites that could render the local space environment inoperable for decades [2]. Consequently, the process of detecting, tracking and cataloguing Resident Space Objects (RSOs) in orbit, known as Space Domain Awareness (SDA), has experienced a surge in interest [3].

There exists a worldwide Space Surveillance Network (SSN) with the purpose of increasing global SDA capability. The SSN is composed of mechanical radars, phased-array radars, space-based optical sensors and the ground-based electro-optical deep space surveillance system [3]. The radars utilised by the SSN operate in the Ultra High Frequency (UHF) (0.3 – 3 GHz) range as that provides high sensitivity against small objects [4]. However, the downside is that at UHF the Radar Cross Section (RCS) of the RSOs varies significantly as their orientation changes with respect to the radar [5]. This makes it difficult to estimate the RSOs’ physical cross section from the RCS. In addition to this, the radars and sensors used in the SSN are expensive to manufacture, maintain and operate which has motivated a search for low-cost alternatives [6].

HF and VHF radars could offer a solution to both issues as they are relatively inexpensive to manufacture and install (the VHF radar used in this paper retail for ~ $1.5 million US [6]), can easily be modified for satellite observations, many currently exist worldwide and have sufficiently low frequencies to enable accurate estimation of an RSO’s RCS.

In order to make reliable satellite observations, a radar needs to be able to accurately measure range and velocity at a high level of precision. The satellite velocity is calculated from its direction of travel and radial Doppler measured by the radar. Thus, any imprecision in the Doppler measurement will lead to a potentially low precision for the calculation of the satellite’s orbital parameters.

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This paper investigates Doppler perturbations in satellite observations made by a HF and VHF radar from 2018-22. The paper is structured as follows. Descriptions of the VHF and HF radars are provided in sections 2 and 3 respectively. Section 4 describes the Doppler perturbations in the satellite observations. Section 5 describes the data analysis method used to extract the spectral and temporal characteristics of the perturbations. Section 6 covers the statistics of the perturbations, including how often they affect the satellites observations and to what degree. Conclusions are given in Section 7.

II. VHF RADAR

The University of Adelaide, in conjunction with ATRAD Pty Ltd, operates the Buckland Park Stratosphere Troposphere (BPST) radar, located ~35 km north of Adelaide, Australia (-34° 37' 36.03", 138° 28' 3.91"). A side view of the radar is shown in Fig. 1. The radar was designed as a wind profiling radar [7] with the capability to measure tropospheric and stratospheric winds (0.5 – 20 km). The radar operates at 55 MHz with a peak transmit power of 48 kW and has an array of 12 x 12 gamma-matched linearly-polarized Yagi antennas used for both transmission and reception. The radar array may be phased to provide 5 beam directions, north, east, south and west, each at an angle of 15° off zenith, and a vertical beam direction. The beamwidths are 6.5°. The radar typically operates in a particular beam direction for 1-2 minutes with 5 seconds of dead time for data transfer [6].

Since 2017, the BPST radar has been used to observe and track RSOs in Low Earth Orbit (LEO) to assist in informing Australia’s SDA capability. The radar measures the range, Doppler, acceleration, elevation and azimuth of orbiting RSOs, and uses these parameters to determine the RSO orbit. Earlier observations with a different antenna configuration are described by [8] and [9]. The HF LOS radar has several advantages over the BPST VHF radar. The first is that the HF system employs a wider transmit beam, such that any RSO stays in the transmit beam longer (up to several minutes instead of tens of seconds). Other advantages are that the HF system can operate continuously and can detect and track multiple RSOs simultaneously. The disadvantage is that it operates at a lower frequency, meaning, as discussed in Section 4, that ionospheric group retardation is more significant.

III. HF RADAR

Defence Science and Technology (DST) Group operates an experimental bistatic high-frequency (HF) line of site (LOS) radar. For the observations described in this paper, the radar was located at Coondambo, Australia (-31° 02' 38", 135° 52' 22"). The DST radar operates at a centre frequency of between 29 MHz and 31 MHz, dependent on local channel availability. This radar is a frequency modulated continuous wave (FMCW) system, and separate arrays are used for transmission and reception, with a separation of ~2 km used for the observations described in this paper. The transmit array is comprised of 4 log-periodic dipole antennas (LPDA) in a 2x2 square arrangement with a total transmit power of 16 kW (4 x 1 kW power amplifiers combined per antenna), while the receiver array is comprised of 30 LPDAs inside a hexagonal unit cell array. The radar waveform is a sawtooth (or chirp) with a typical bandwidth of 10 kHz and waveform repetition frequency (WRF) of 100 Hz. The transmit beam width of the radar is approximately 45°. Fig. 2 shows a photo of the HF LOS radar receive site in Coondambo highlighting the reception array.

Fig. 1. A side view of the BPST VHF radar operated by ATRAD and the University of Adelaide.

Fig. 2. Receive site of the experimental bistatic high-frequency line of site (LOS) radar operated by DST Group at Coondambo, Australia.

The radar measures range, Doppler, acceleration, elevation and azimuth of orbiting RSOs, and uses these parameters to determine the RSO orbit. Earlier observations with a different antenna configuration are described by [8] and [9]. The HF LOS radar has several advantages over the BPST VHF radar. The first is that the HF system employs a wider transmit beam, such that any RSO stays in the transmit beam longer (up to several minutes instead of tens of seconds). Other advantages are that the HF system can operate continuously and can detect and track multiple RSOs simultaneously. The disadvantage is that it operates at a lower frequency, meaning, as discussed in Section 4, that ionospheric group retardation is more significant.

IV. SATELLITE OBSERVATIONS

The DST HF LOS radar operated on a campaign basis during 2018/19, whereas the BPST VHF radar operated on a campaign basis up until November 2021, when it was tasked to observe satellites continuously until December 2022 (excluding the month of February).

For the observations described in this paper, the analysis relies on knowledge of the expected position of the satellite in order to remove its translational motion. The expected position of the satellite is calculated either by propagating orbital Two-Line Elements (TLEs) using the Simplified General Perturbations model Version 4 (SGP4), or through using Special Perturbations (SP) propagations, which numerically integrates the equations of motion for the RSO of interest [6]. TLE propagations require less computational power to calculate the satellite position; however, they are less accurate than SP data. Fig. 3 shows the application of the processing routine, detailed in [3], on a BPST observation of the International Space Station (ISS). This processing routine results in the transformation of the range-Doppler data into range-difference Doppler-difference data.
It can be seen in Fig. 3 that the radar estimated RSO is offset from the TLE predicted range. This range offset is primarily due to the effects of ionospheric group retardation, which is caused by the free electrons in the ionosphere reducing the group velocity of the radio waves. This means that the radar will measure a longer time delay, inferring a larger range than the actual RSO range, as observed in Fig. 3. Note that the ionosphere also imposes an analogous increase in the phase velocity of the radio waves, which means that the radar will measure a smaller phase path than the actual RSO range. This manifests itself as an additional positive slope to the Doppler shift or radial velocity (hereafter referred to as Doppler slope). The ionospheric induced range offset and Doppler slope increase with decreasing radar operating frequency. Additional range offsets and Doppler slopes can result if an RSO maneuvers after the last measurement used to produce the TLE or SP propagations. A further source of range offset for TLE/SGP4 propagations results from upper atmospheric drag which is inadequately handled in SGP4.

The observations described in this paper are produced by applying a peak detection algorithm to the range-difference Doppler-difference data. Spectrograms are then calculated for the range-difference closest to the mean peak range-difference. The majority of the resulting spectrograms exhibit a linear Doppler variation as a function of time, seen in the top spectrogram of Fig. 4. However, on some occasions, short-period Doppler perturbations are observed, an example of which is shown in the bottom spectrogram of Fig. 4. Note that the top example spectrogram shown in Fig. 4 exhibits a small positive Doppler slope due to the aforementioned phase path effects.

Given that the processing method removed the translational effects of the RSO, we attribute the Doppler perturbations observed in Fig. 4 to ionospheric effects. [10] showed that the Doppler shift experienced by radio waves propagating through the Earth’s ionosphere is given by:

\[
\delta f = -\frac{c}{\lambda} \int \frac{\partial \mu}{\partial a} \cos(a) \, ds,
\]

where \(ds\) is the directed segment of the ray path, \(a\) is the angle between the radio wave normal and the ray direction, and \(\mu\) is the refractive index of the ionosphere. It can be seen that as the refractive index changes, which itself is dependent on electron density, a Doppler shift is experienced by the wave [10]. Thus, any temporal variations in electron density along the signal path will impose a perturbation on the observed Doppler frequency. As discussed in this paper, these Doppler perturbations can become significant at HF and VHF frequencies. However, higher operating frequencies experience a refractive index closer to unity [11] which results in a smaller rate of change of refractive index from any ionospheric perturbations. Thus, UHF radar is less susceptible to ionospheric induced Doppler variations.

Of the 166,809 satellite observations made over 382 days by the BPST VHF radar, 35,960 satellite observations had sufficient data points (>50) to undergo further spectral processing.

![Fig. 3. Examples of the application of the processing routine described by [3] on an observation of the International Space Station (ISS) by the BPST VHF radar. The left plot shows the original range-time signal while the right plot shows the range-time signal corrected for the translational motion of the satellite. The white line in both plots shows the position of the satellite as indicated by the TLE propagation. After [3].](image)

![Fig. 4. Spectrograms of two satellite observations taken during 2023. The top spectrogram was created from an observation of a DMSP satellite taken on the 1st of April 2023 by the vertical beam of the BPST VHF radar. The bottom spectrogram was created from an observation of a Starlink satellite, taken on the 2nd of April 2023 by the vertical beam of the BPST VHF radar. The top spectrogram shows evidence of periodic variations in Doppler that reduces the Doppler precision of the observations.](image)

V. DATA ANALYSIS METHOD

This section describes the data analysis method used to extract the spectral and temporal characteristics of the Doppler perturbations observed in Fig. 4. The first step was to extract the Doppler difference of the satellite to produce a Doppler time-series. A cubic spline was applied to the Doppler time-series to add additional data points to produce a regularly sampled time series, as shown in Fig. 5. The next step was to remove any zero Hz bias and Doppler slope caused by TLE or SP propagation errors and ionospheric induced phase path reduction. This was achieved by applying a Fast Fourier Transform (FFT) to the time series followed by a low pass filter to capture the zero Hz bias. An inverse FFT was then applied to the filtered amplitude spectra and the resulting time-series was subtracted from the original time series to completely remove the zero Hz bias and Doppler slope. An FFT with a Hann window was then applied to the filtered time series to calculate the filtered amplitude spectrum, as shown in Fig. 6.

A peak finding algorithm was applied to the filtered amplitude spectra to detect spectral peaks and identify those due to non-physical effects (e.g. caused by spectral leakage and the residual 0 Hz bias). Non-physical peaks are denoted...
by a red circle in Fig. 6, while physical peaks are denoted by green circles. The algorithm was created by adding the parameters of minimum peak prominence, minimum peak height, minimum peak width and minimum peak separation to the `findpeaks` function in MATLAB. A conditional test was implemented that removed the artificial peak induced by the application of the low pass filter (leftmost peak in Fig. 6). The parameter values for the peak finding algorithm were determined and fine-tuned on a small set of training data (100 observations). The algorithm successfully removed all non-physical peaks in the amplitude spectra 95% of the time.

The final step in the method was to convert the frequency values of the peaks in the amplitude spectrum (which is derived from the rate of the radar-satellite path crossing the ionospheric disturbances) to the frequency of the ionospheric disturbances themselves. This is necessary because the satellites’ direction of travel relative to the radar is unique for each satellite and is generally not orthogonal to the direction of the phase front of the ionospheric disturbance. The bearing of the satellite was used to adjust the frequency values of the peaks in the amplitude spectrum.

VI. RESULTS

The analysis found two sources of the ionospheric disturbances. The first and most numerous source of these perturbations was due to plasma irregularities within the 0-0.46 Hz frequency range [12]. The plasma irregularities are signatures of Alfvén waves which have been generated by disruptions in the zonal electric currents in the ionosphere [13]. The second, and from a geophysical perspective, more interesting source of the perturbations, was found to be Electromagnetic Ion Cyclotron (EMIC) waves within the Pc1-2 (0.1 –5 Hz) frequency range.

EMIC waves are generated by plasma temperature anisotropies in the Earth’s magnetosphere ~60,000 km from Earth, and they propagate along geomagnetic field lines as Pc1-2 transverse waves [14]. When the waves reach the ionosphere at below 500 km altitude, they undergo mode conversion into compressional mode plasma waves [14]. The compressional waves then propagate parallel to the Earth’s surface in the ionospheric waveguide centered at an altitude of ~250 km and can be observed across all latitudes [15].

The key characteristic separating plasma irregularities and EMIC waves is their lifetime. EMIC waves can last several hours while plasma irregularities only last several 10s of seconds [13]. Given that the average BPST radar observation lasted several minutes and the HF observations even longer, the EMIC waves can be identified by common wave frequencies across consecutive satellite observations. The data analysis method and algorithm were applied to 382 days of observations made by the VHF radar, and we found that 7,281 RSO observations were affected by plasma irregularities and a further 2,889 were affected by EMIC waves from a total of 1,720 EMIC wave events.

The EMIC waves underwent further investigation because, to the best of the authors’ knowledge, this is the first time such waves have been observed with radar. The frequencies of the 1720 detected EMIC waves were compiled into a histogram which is shown in Fig. 7. The distribution presented in this figure is well within the Pc1-2 frequency range, and the BPST radar distribution is very similar to the distribution observed by [16] using magnetometers.

Ground-based magnetometers measure the change in the geomagnetic field induced by the EMIC waves leaking through the lower boundary of the waveguide, a process known as ‘waveguide leakage’ [17]. Radar, on the other hand, measures the waves directly as they propagate in the ionospheric waveguide. Further work, outside the scope of this paper, has been performed to produce detection statistics for the EMIC waves. These statistics were compared with previous statistical studies on the EMIC waves detected with magnetometers on board satellites. We found that the VHF radar observed more EMIC waves during summer than satellite-mounted magnetometers and this was attributed to some seasonal effect reducing the ability for EMIC waves to be observed through the ionospheric topside boundary by the satellites. This indicates that radar may be more sensitive to the EMIC waves under certain conditions. However, further work with collocated ground-based magnetometers is
perturbations detected in 2,889 of the satellite observations. BPST VHF radar were investigated and the key findings are:

The occurrence statistics of the EMIC waves detected by the waves can be made. merits of using radars and magnetometers to study EMIC frequencies for 1720 EMIC waves. The width of each bin is 0.03 Hz. The red curve is a fitted Nakagami distribution. The parameters of the Nakagami distribution are a size of 1.3701 and a scale of 0.3419. The mode frequency is 0.47 Hz.

necessary before any definitive statements on the relative merits of using radars and magnetometers to study EMIC waves can be made.

The occurrence statistics of the EMIC waves detected by the BPST VHF radar were investigated and the key findings are:

1. The waves occurred mainly during the day with a preference for pre-noon.
2. The occurrence of the waves entered a deep minimum during winter.
3. Measurements taken during 2018/19 accounted for 7% of the total dataset while waves detected in this time accounted for 40% of all wave detections, suggesting an anti-correlation with the 11-year solar cycle.

The analysis was also conducted on 11 days of satellite observations made by the DST HF LOS radar in March of 2019 and November/December of 2020. The analysis found evidence of plasma instabilities and observed 331 EMIC waves. However, statements regarding the seasonal and solar cycle variations in the occurrence rates cannot be made due to the short duration of the HF LOS campaigns.

As discussed earlier, Doppler perturbations were present in 10,170 of the 35,930 BPST satellite observations with enough data points to apply the data analysis method. EMIC waves were found to be the cause of the Doppler perturbations detected in 2,889 of the satellite observations with the remainder (7,281) due to plasma instabilities. Given that the EMIC waves were observed over multiple satellite observations, we can estimate the duration of each wave event by summing the duration of each satellite observation that detected the wave. From this, we estimate that 10,749 minutes of wave activity occurred over the 382 days of satellite observations by the VHF radar.

The operational logs for the VHF radar can be used to determine how often the waves are occurring for the BPST. Unfortunately, these logs were only available from 19th of November, 2021 to 31st of December, 2022 during the 2021/22 observation campaign. During this period, the VHF radar was operational for 486,652 minutes with 5,777 minutes of EMIC wave activity recorded. Therefore, the waves were present over the radar 1.2% of the time from the 19th of November 2021 to the 31st of December, 2022.

Using the available VHF radar operating logs (21 out of the 24 days) for observations taken in 2018/19, we find the radar was operational for 28,366 minutes. During this time, the radar observed 4,843 minutes of wave activity. Therefore, the waves were present over the radar 17.1% of the time during solar minimum. This suggests that the wave activity is higher during solar minimum, which agrees with previous studies (e.g. [18], [19], [20]).

We now examine how often other plasma instabilities affected the BPST radar observations. During 2018/19, 2,468 satellite observations were made and 786 (32%) of these observations showed evidence of Doppler perturbations due to plasma instabilities. However, during 2021/22 33,462 satellite observations were made with 6,495 (19.4%) showing evidence of plasma instability induced Doppler perturbations. Thus, as for the EMIC wave activity, there also appears to be a solar cycle dependence on the occurrence of the plasma instabilities. Consequently, we expect that the occurrence of Doppler perturbations induced by the waves and plasma instabilities will decrease in the build-up of solar cycle 25.

Having determined how often the Doppler perturbations are affecting the radars, we now want to determine what effect these perturbations will have on the accuracy of the satellite Doppler measurements. To do this, we obtained the standard deviation of the VHF BPST Doppler measurements from the period of November 2021 to December 2022, and the 11 days of the DST HF LOS radar. The standard deviation was calculated from the Doppler difference for each satellite measurement as follows. A low order polynomial fit was applied to each satellite measurement during an observation and then subtracted from the Doppler difference. This was done to remove the effect of TLE errors and phase-path induced Doppler slopes from the standard deviation. The standard deviation was then computed on the result. We then separated the standard deviations of the observations into two populations: those with Doppler perturbations (i.e. with plasma instabilities and EMIC waves) and those without, hereafter referred to as ‘affected’ and ‘unaffected’. Histograms of these two populations are displayed in Fig. 8 for the two radars.

As observed in Fig. 8, the affected and unaffected distributions are similar for both radars. The affected and unaffected median standard deviations are 0.39 m/s and 0.30 m/s for the HF radar and 0.40 m/s and 0.30 m/s for the VHF radar. The medians are slightly higher for the affected observations, due to the longer tails. The similarity of the distributions and their low median values compared to the typical radial velocity of LEO satellites (~ 2000 m/s for 15° off-zenith) suggests that the Doppler perturbations caused by plasma instabilities or EMIC waves have little impact on the accuracy of the Doppler measurements of the satellite observations.
In this study we have detailed the motivation for using HF and VHF radars for SDA and the importance of making accurate Doppler measurements. We have shown examples of Doppler perturbations present in satellite observations and, from a statistical analysis, identified two sources for these perturbations. The first and most numerous source is plasma instabilities. The second source was EMIC waves propagating in an ionospheric waveguide parallel to the Earth’s surface. A total of 1,720 EMIC waves were identified, affecting 2,889 satellite observations.

A comparison with previous studies, which investigated the EMIC waves using magnetometers, was conducted. This comparison suggested that, under certain conditions, radar was a more sensitive instrument for detecting these waves. We also found that the occurrence of the sources of the Doppler perturbations (both the EMIC waves and plasma instabilities) decreased in the build-up of solar cycle 25. It was found for satellite observations made by the VHF radar that the Doppler perturbations had very little impact on the accuracy of the observations. Thus, although the Doppler perturbations are often present in the satellite observations, they do not adversely affect the accuracy of the Doppler estimates of satellite observations used in SDA with VHF radar. More observations are required to establish if this is also the case for HF radar.

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Fig. 8. Comparison between the normalised distributions of the radial velocity standard deviations of the affected and unaffected satellite observations for the HF (left) and VHF radar (right).