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Quasi-stationary substructure within a sporadic E layer observed by the Low-Frequency Array (LOFAR)

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Abstract—Observations made with the Low-Frequency Array (LOFAR) have been used to infer the presence of variations in a sporadic E layer on a spatial scale of several kilometres and a temporal scale of ~10 min. LOFAR stations across the Netherlands observed Cygnus A between 17 UT and 18 UT on 14th July 2018 at frequencies between 24.9 MHz and 64.0 MHz. Variations in the relative signal intensity, together with the consideration of geometric optics, were used to infer the presence of a plasma structure. Spatial variations between the stations and the dispersive nature of the observations suggested that this plasma structure was located within the ionosphere. Independent confirmation of the presence of a sporadic E layer, and variation within it, was obtained from observations made by the Juliusruh ionosonde (54.6° N, 13.4° E), which observed reflection of radio waves at an altitude of ~120 km and from frequencies of up to ~6 MHz. The large number (38) of LOFAR stations across the Netherlands, together with the sub-second temporal resolution and broadband frequency coverage of the observations, enabled the fine details of the spatial variation and the evolution of the structure to be determined. The structure was quasi-stationary, moving at ~12 m s⁻¹, and it exhibited significant variation on spatial scales of a few kilometres. The observations were consistent with the steepening of a plasma density gradient at the edge of the feature over time due to an instability process. A 1-D numerical model showed that the observations were consistent with an electron density enhancement in the sporadic E layer with a density change of $2 \times 10^{11} \text{ m}^{-3}$ and a spatial scale of several kilometres. Collectively, these results show the ability of LOFAR to observe substructure within sporadic E layers and how this substructure varies with time. They also show the potential value of such datasets to constrain models of instability processes, or to discriminate between competing models.

Keywords: Sporadic E / Small scale variations / Radio wave propagation / Mid latitude ionosphere / Observations

1 Introduction

Jansky (1932) surveyed the sky at a frequency of 20.5 MHz and determined that a subset of the emissions at this frequency was of extra-terrestrial origin. It was initially thought that these emissions originated from the Sun, but it was later shown that the source appeared to be at the centre of the Milky Way (Jansky, 1933). Such signals are affected by any plasma through which they pass and one such plasma is the terrestrial ionosphere. The ionosphere is the part of the Earth's atmosphere

comprised of ions and electrons (reviewed by Hargreaves, 1992), which typically has a maximum electron density at an altitude of several hundred kilometres. Prior to the space age, the only practical way to study the region above this maxima, i.e. the topside ionosphere, was to observe the effect of this plasma on trans-ionospheric radio signals of extra-terrestrial origin (Payne-Scott & McCready, 1948) or of terrestrial origin and subsequently reflected by the moon (Kerr et al., 1949). Little & Lovell (1950) observed Cygnus A and Cassiopeia A with radio telescopes located at Cambridge (52.2°N; 0.1°E) and Jodrell Bank (53.2°N; 2.3°W), which were separated by some 200 km. Variations in the intensity of the received signal were

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not correlated, which meant that these variations were not due to changes in the radio source. Observations on multiple baselines were used to infer that the scale size of the plasma structure causing these variations was several kilometres. Based on this scale size, it was suggested that the plasma structures were located in the ionosphere, as opposed to the interstellar medium. Observations of Cassiopeia A at radio frequencies at low elevation from Ithaca (42°N; 77°W) led to the suggestion that the ionospheric plasma structures were in the E-region, as the ionospheric pierce point (IPP) for these observations in the F-region was close to the polar cap where photoionisation was insubstantial at the times of these observations (Dueño, 1956). Although it is now known that dense patches of plasma can be transported throughout the polar cap at F-region altitudes (Weber et al., 1986) throughout the year (Buchau & Reinisch, 1991), Dueño (1956) remains the first to suggest that the plasma structures affecting trans-ionospheric radio signals were in the E-region.

In the early part of the present century, there was renewed interest in radio astronomy at low frequencies. This was, in part, driven by the desire to observe the 21-cm hydrogen line in the distant (early) universe, where the redshift results in this line being observed at frequencies below 250 MHz (e.g. Yatawatta et al., 2013). The new generation of radio telescopes, of which the Low-Frequency Array (LOFAR; van Haarlem et al., 2013) is one, enables the terrestrial effects on trans-ionospheric radio waves to be observed in an unprecedented level of detail. Fallows et al. (2014) demonstrated that this instrumentation, which is also used by the Kilpisjärvi Atmospheric Imaging Receiver Array (KAIRA) in northern Finland (McKay-Bukowski et al., 2014), could observe ionospheric effects through variations in the intensity of the received signal when observing Cygnus A at frequencies between 30 and 250 MHz. The capability of LOFAR to observe such effects in the mid-latitude region over Europe was demonstrated by Fallows et al. (2016). Fallows et al. (2020) summarised the tools and techniques that can be applied to LOFAR data in order to infer the properties of ionospheric structures from variations in the intensity of the received signal. These authors presented a case study which showed the simultaneous observation of two Travelling Ionospheric Disturbances (TIDs), which each had a different altitude, velocity and propagation direction. Boyde et al. (2022) used a simple model which treated the ionosphere as a 1-D thin phase screen to show that observed variations in the signal intensity of Cygnus A were caused by a small-scale TID. Dorian et al. (2023) used LOFAR to observe the substructure within a TID.

Koval et al. (2017) used the Nançay Decametric Array (NDA) to observe the Sun at frequencies within the range of 10–80 MHz. Variations in the intensity of the received signal due to the effect of the ionosphere were observed. Subsequent modelling (Koval et al., 2018) and observations (Koval et al., 2019) showed that these effects were associated with medium-scale TIDs. Waszewski et al. (2022) conducted observations of multiple radio sources beyond the solar system at 154 MHz using the Murchison Widefield Array. The ionospheric phase variance was compared to that inferred from previous measurements of refractive shifts, and it was shown that these terms were correlated with a Pearson correlation coefficient of 0.71.

The delay-Doppler spectrum, also known as the scattering function, generalised power spectrum or secondary spectrum,

is the 2D Fourier transform of the dynamic spectrum and is a useful tool for investigating variations in the relative intensity of the received signal. It is referred to as the delay-Doppler spectrum because the Fourier conjugate variables on the axes correspond to the differential time delay f_v and differential Doppler shift f_f between pairs of interfering waves (Cordes et al. 2006). Electron density structures which cause variations in the relative signal intensity in the dynamic spectrum can also result in parabolic arcs in the delay-Doppler spectrum. Parabolic arcs in a secondary spectrum were first identified by Stinebring et al. (2001) and the origin of their shape was explained by Walker et al. (2004). These have been used to determine the morphology of structures in the interstellar medium (Briskin et al., 2010) and in the ionosphere (Fallows et al., 2014, 2020). In the ionospheric case, a sinusoidal variation in the electron density resulted in a parabolic arc in the delay-Doppler spectrum, which could then be used to infer the altitude and velocity of the scattering screen.

It is assumed that the radio waves from an extraterrestrial radio source are in phase at the top of the atmosphere, although the phase itself is unknown. As the radio waves pass through the ionosphere, they experience phase changes in proportion to the Total Electron Content (TEC, the integral of electron density along the line of sight), with different phase changes at different frequencies. The absolute TEC along any given path cannot be established using observations of the received phase alone, as the phase of the radio wave at the top of the atmosphere is unknown. However, the difference in TEC (dTEC) on different ray paths can be established. Mevius et al. (2016) used LOFAR to infer dTEC on numerous pairs of ray paths with different separations in order to determine the amount of structuring in the ionosphere on different spatial scales. The slope of the resulting power spectra was steeper than that expected for pure Kolmogorov turbulence for baselines between 1 and 80 km. TIDs will appear in dTEC measurements as waves. Beser et al. (2022) used such observations to identify variations in dominant wave direction over the course of several hours. Boyde et al. (2024) developed a method to determine both the wavelength and propagation direction of such waves and demonstrated that this method can be used to observe waves with an amplitude an order of magnitude below those which can be inferred from Global Navigational Satellite Systems (GNSS) TEC measurements.

The ionosphere is structured on a wide range of temporal and spatial scales. Variations on temporal scales ranging from seconds to more than a solar cycle, and spatial scales from a few meters to thousands of kilometres have been widely reported in the published literature, the underlying physical processes of which have been summarised by Hargreaves (1992). Of particular relevance to the present study is a phenomenon known as sporadic E. This is a dense, thin layer of plasma at an altitude of around 90–130 km. It was first identified during studies conducted in the 1930s which were summarised in Appleton's Nobel Prize lecture (Appleton, 1947), with more detailed reviews given by Appleton & Naismith (1947) and Thomas & Smith (1959). The occurrence of these layers varies with both local time and season. They can be caused by the presence of a variation in the wind speed at different altitudes which, in the presence of the geomagnetic field, acts to create regions of enhanced plasma density as reviewed by Whitehead (1970). At mid-latitudes, sporadic E layers are strongly

influenced by the action of the diurnal and semidiurnal tides (Pancheva et al., 2003) and they are more common in summer and during the day (Wu et al., 2005).

As well as using signals from natural radio sources to study variability in the ionosphere, artificial satellites can also generate such signals. Maruyama (1991) used observations of signals transmitted from the Engineering Test Satellite (ETS) 2 which was in a geostationary orbit transmitting at 136 MHz. The signal was received by the Wakkanai ground station (45.4°N; 141.7°E) in Japan and used to study the midlatitude ionosphere. The effects of plasma structures were observed, and the climatology of these structures showed similarities to the climatology of sporadic E layers. Subsequent numerical modelling work to determine the shape of the plasma structures suggested that some of these were due to linear irregularities that are elongated perpendicular to the drift direction, while others were due to disk-shaped irregularities (Maruyama, 1995).

The purpose of this paper is to present observations of a quasi-stationary substructure in a sporadic E layer observed by LOFAR, and the evolution of this substructure. The paper is arranged as follows. Section 2 details the instrumentation and observing modes, the observations and associated modelling work are presented in Section 3 and in Section 4 the results are discussed and conclusions are drawn.

2 Instrumentation and observational campaign

LOFAR (van Haarlem et al., 2013) is a radio telescope that operates at HF/VHF frequencies from 10–250 MHz, with a gap between 90–110 MHz for the FM band which is used by commercial and publicly-owned broadcasters. At the time of writing, LOFAR has 52 stations, 38 of which are located in the Netherlands and the remaining 14 are located across central and western Europe. The 38 stations in the Netherlands are divided into 24 core stations (labelled ‘CS’), concentrated within a 4 km × 4 km area, and 14 remote stations (labelled ‘RS’, which are more widely spaced but still within 100 km of the core). There are two antenna types. The Low Band Antennas (LBA) are used to observe in the frequency range 10–90 MHz while the High Band Antennas (HBA) are used to observe in the frequency range 110–250 MHz. The radio astronomical observations conducted include both beam-formed observations in the time domain and radio interferometry. The effects of the ionosphere on radio interferometry observations were discussed in detail by de Gasperin et al. (2018).

The present study used single-station beam-formed observations made using both the core and remote stations in the Netherlands between 17:00:00 UT and 17:59:59 UT on 14th July 2018 at a temporal resolution of 10.5 ms. The LBA was used across a frequency range of 24.9–64.0 MHz. This range was divided into 200 frequency bands, each with a bandwidth of 195.3 kHz. The radio source observed was Cygnus A (RA: 299.87°; Dec: 40.73°), which has been characterised using LOFAR at these frequencies by de Gasperin et al. (2020). At the frequencies considered in this study, Cygnus A is one of the most intense radio sources in the sky outside of the solar system. Points contaminated by Radio Frequency Interference (RFI) were identified by applying a median filter to the data

using a window of 976.9 kHz × 0.51 s which flattened out the scintillation pattern and then applied a threshold of five sigma above the average value to identify the RFI. The extent of this window, in both time and frequency, was much smaller than the features which were to be studied. For subsequent analysis, the RFI data points are replaced by an interpolation from nearby data, using the Python Astropy (Astropy Collaboration et al., 2013; Price-Whelan et al., 2018) library routine, “interpolate_replace_nans”; this method was outlined in Fallows et al. (2020). The observations were made at a temporal resolution of 10.5 ms, but these data were then downsampled to a temporal resolution of 0.50 s to reduce the noise. There was no subsequent subtraction of background noise.

An ionosonde transmits radio waves at a range of frequencies and the reflection of these radio waves enables both the altitude and the density of the ionosphere to be determined up to the altitude at which the peak electron density occurs. Ionograms from the Juliusruh ionosonde (54.63°N; 13.37°E; Weiß, 2016) were also used in this study. This instrument is owned by the Leibniz Institute of Atmospheric Physics, Kuehlungsborn and the data were accessed through the Global Ionospheric Radio Observatory (GIRO; Reinisch & Galkin, 2011).

Proxies for the heliogeophysical conditions were also used. The geomagnetic indices Kp, aa and Dst, were used as proxies for geomagnetic activity. The F10.7 cm solar radio flux was used as a proxy for solar activity (Tapping, 2013). The presence or absence of solar flares was determined using the x-ray Geostationary Operational Environmental Satellite (GOES) archive data (Gopalswamy et al., 2019). The presence or absence of CMEs was established using the NASA catalogue based on Wind and STEREO (Solar Terrestrial Relations Observatory) observations. The Interplanetary Magnetic Field (IMF) and the solar wind velocity were taken from the Operating Missions as Nodes on the Internet (OMNI) database (Papitashvili & King, 2020).

3 Observations and modelling

3.1 Observations in the time domain

On the 14th of July 2018, LOFAR stations across the Netherlands observed Cygnus A between 17:00:00 UT and 17:59:59 UT. The dynamic spectrum showing the relative signal intensity as a function of time and frequency is shown in Figure 1. The figure shows a subset of these data, from station RS508 between 17:33 UT and 17:58 UT. The data for each channel have been normalised by dividing the observed signal intensity by the median value of the intensity observed for this channel. This removed the frequency-dependent variations in both the intensity of the source and gain variations which resulted from the varying sensitivity of the receiving antenna array. The normalisation enables comparisons between different frequencies. A relative intensity of zero would indicate that no signal was received. At ~17:50 UT station RS508 (53.2°N 7.0°E) observed a deep fade in the intensity of the received signal, lasting ~7.5 min. At 17:50 UT the azimuth and elevation of the radio source, calculated from the right ascension and declination, were ~65° and ~34° respectively. Immediately before and after this deep fade, rapid variations of signal strength were observed, with rippling in these

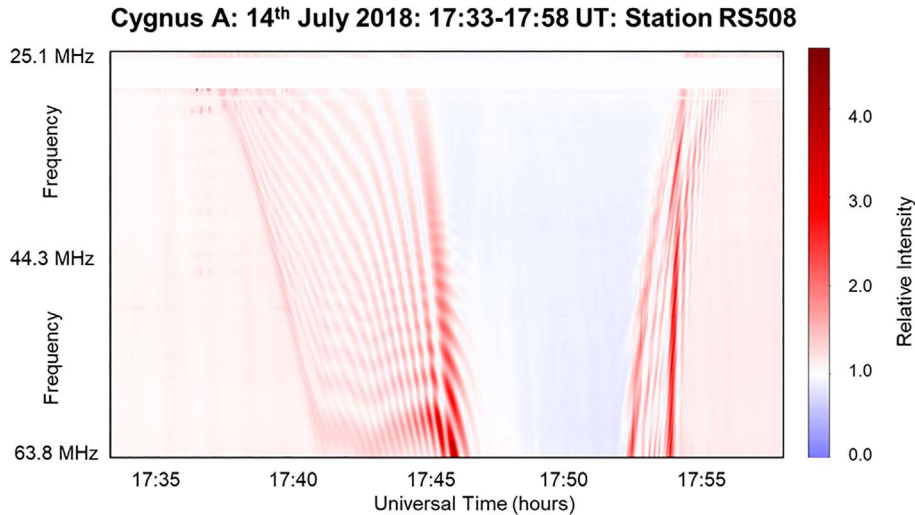


Figure 1. The dynamic spectrum showing the relative signal intensity as a function of time and of frequency for an observation of Cygnus A made by LOFAR station RS508 (located at 53.24°N; 6.95°E) on 14th July 2018 between 17:33 UT and 17:58 UT, and between 24.9 MHz and 64.0 MHz. The lowest frequencies are shown at the top of the plot. Horizontal white regions correspond to frequency channels removed due to significant radio frequency interference.

enhancements. This rippling effect varied with frequency and occurred at greater time intervals from the mid-point of depletion at lower frequencies. The effect was asymmetric, spread out over a greater range of times at the start of the feature.

The heliogeophysical conditions at the time of this observation were quiet. The values of the geomagnetic indices Kp, aa and Dst, which are proxies for geomagnetic activity, were all relatively low indicating geomagnetically quiet conditions. The values of Kp and aa, for 15 UT–18 UT, were 0+ and 5 nT respectively. The value of Dst for 17 UT–18 UT was −4 nT. The F10.7 cm solar radio flux, which is a proxy for solar activity, took a relatively low value of 72 sfu. There were no flares observed at class B or above on this day listed in the x-ray GOES archive. There were no CMEs impacting the Earth on this day listed in the NASA catalogue, based upon Wind and STEREO observations. The solar wind data were taken from the OMNI database where spacecraft observations are time-shifted to the Earth's bow shock. The mean value of the IMF between 15:00 UT and 18:00 UT was (3.6 ± 0.2) nT, the mean value of the z-component of the IMF was (-2.8 ± 0.5) nT and the mean value of the solar wind bulk velocity was (416 ± 3) km s^{−1}, with the uncertainties given by the standard deviation of the observations. These values are consistent with the slow solar wind.

It is tempting to use a statistic to represent the variations in the relative signal intensity shown in Figure 1. The amplitude scintillation index S_4 has been calculated for these data. The resulting values of S_4 , together with the challenges associated with using this statistic in this context, are shown in [Supplementary material 1](#).

Observations from LOFAR stations across the Netherlands can be used to determine the spatial extent, morphology and time evolution of the feature. Figure 2 shows the dynamic spectra for all of the remote stations in the LOFAR network across the Netherlands, and also core station CS002, between 17:00 UT and 18:00 UT. CS002 was chosen as it is the closest

station to the centre of the core, with the location of the centre of the core estimated from the average latitude and longitude of all core stations. The colour scale for Figure 2 has a lower maximum value than Figure 1, to ensure that the weaker variations towards the south and west of the network are clearly shown. The network shows that the feature evolved significantly on a spatial scale of tens to hundreds of km and a temporal scale of tens of minutes.

These spatial and temporal scales give confidence that the effect is ionospheric in origin. If it were in the interstellar medium then the scale sizes involved would result in the dynamic spectra at each station being very similar (Little & Lovell, 1950). The same arguments hold for the interplanetary medium. Water vapour in the troposphere can also affect the propagation of trans-atmospheric radio signals at these frequencies (van Velthoven, 1990). However, such an effect is non-dispersive, so is not the primary mechanism responsible for the variations observed in this case.

Several stations, of which RS307 is a particularly good example, show a gentle increase in the intensity of the received signal during the observation. During this interval, the elevation of Cygnus A increased from 27° to 35°. At higher elevations, the LBA has an increased sensitivity and the shorter path through the atmosphere results in an increase in the intensity of the received signal. This variation can typically be removed by fitting a third-order polynomial (e.g. Fallows et al., 2020). Such an approach was not used in the current study as the third-order polynomial fits the largest variations in intensity across the observation which, in this case, is the transient feature identified in Figure 1 and not the background. None of the observations are completely free of this transient feature so none of them can be used to produce a background profile which can be guaranteed to be free of artefacts from the fitting process. As the current study is primarily interested in the structure of the transient feature, rather than the precise intensity values, this issue is not considered further.

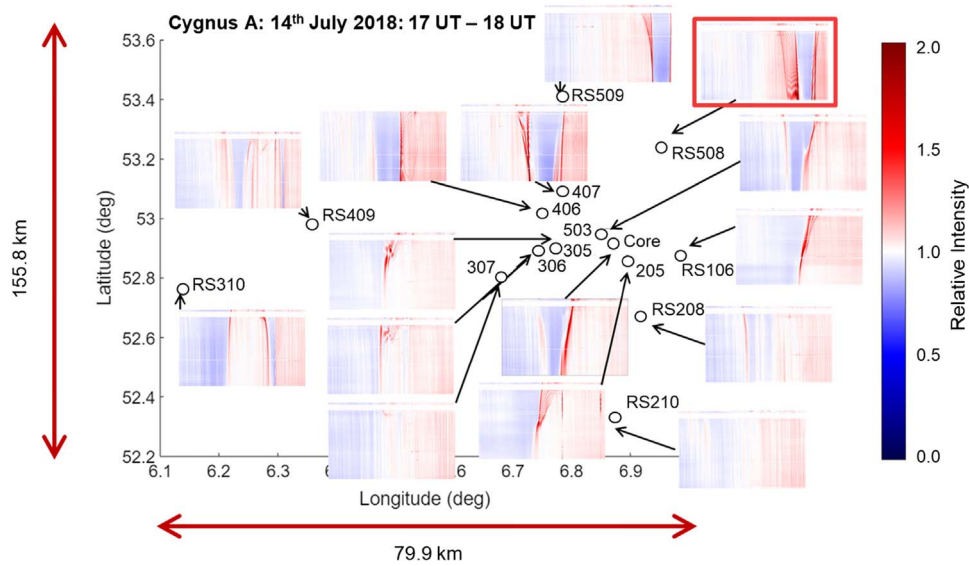


Figure 2. The dynamic spectra showing the relative signal intensity as a function of time and frequency for an observation of Cygnus A made by the LOFAR remote stations across the Netherlands on 14th July 2018 between 17:00 UT and 18:00 UT. The 24 closely spaced stations comprising the LOFAR core, some with separations as small as ~ 100 m, are labelled as ‘Core’ and the dynamic spectrum for CS002 is shown. To enhance the clarity of this figure, both the intensity scale and time axes differ from Figure 1 and the prefix RS is removed from selected stations. The relative signal intensity is shown on a scale between 0 and 2, with white representing a relative signal intensity of 1.0 and the duration of the time axis is one hour.

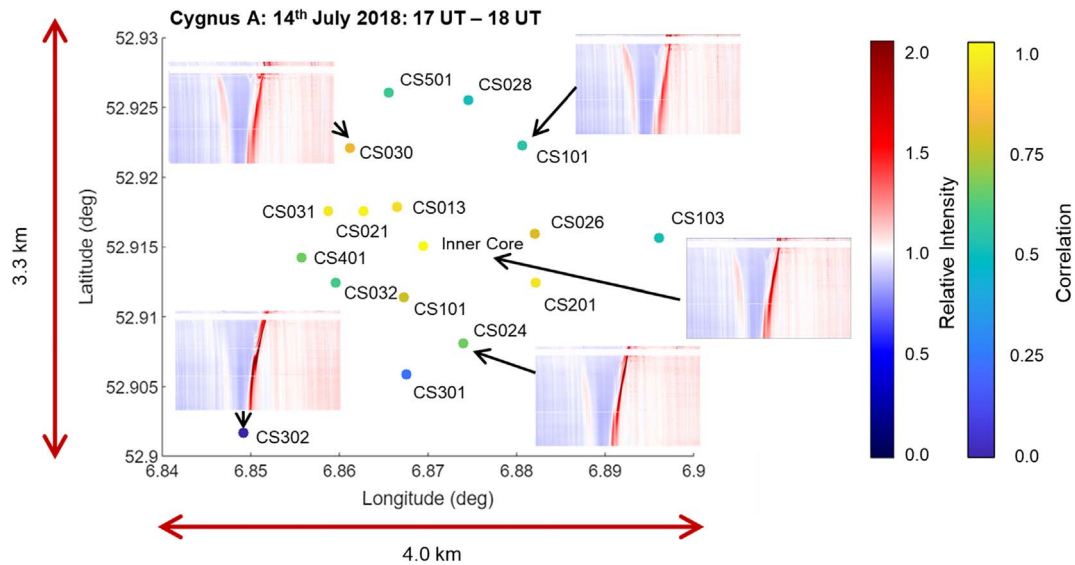


Figure 3. The dynamic spectra showing the relative signal intensity as a function of time and frequency for an observation of Cygnus A made by selected LOFAR core stations across the Netherlands on 14th July 2018 between 17:00 UT and 18:00 UT. Nine closely spaced stations (CS001, CS002, CS003, CS004, CS005, CS006, CS007, CS011 and CS017), some with separations as small as ~ 100 m, are labelled as ‘Inner Core’ and the dynamic spectrum for CS002 is shown. The colour scale for the relative signal intensity and the time axis are the same as in Figure 2. The station locations for all core stations are colour-coded to show the correlation at zero lag between each station and CS002 at a frequency of 44.5 MHz. The correlation for the Inner Core is the mean value of the correlations at zero lag of CS002 with each of the other seven inner core stations.

The LOFAR core is a dense network of 24 stations located within a few km of each other. This network is shown in Figure 3 together with five dynamic spectra for the observation of Cygnus on 14th July 2018 between 17:00 UT and 18:00 UT. The colour scale is identical to Figure 2. Strong similarities are readily apparent in all 24 dynamic spectra, but in the interests of

clarity, only five are shown in Figure 3, with the stations selected to cover the centre of the network and locations towards the northeast, southeast, southwest and northwest of this array.

In order to investigate the morphology of the structure on the spatial scale of the LOFAR core, a cross-correlation analysis

Table 1. The cross-correlation of the relative signal intensity at 44.5 MHz between LOFAR station CS002 and other stations across the LOFAR core for a time interval of 17:00–18:00 UT. The lag compared to station CS002 is shown, with positive values indicating that the structure was observed at this location after CS002. The correlation at this lag and the correlation at zero lag are shown. The velocity has been calculated assuming that the direction of propagation of the structure is parallel to a straight line between stations from which the lag is calculated. The stations with the positive and negative velocities closest to zero are shown in bold type.

Station	Lag compared to CS002 (s)	Correlation at this lag	Correlation at zero lag	Distance (km)	Velocity (m/s)
CS001	24.2	0.97	0.77	0.44	18.2
CS002	–	1.00	1.00	0.00	–
CS003	–1.5	1.00	1.00	0.12	–81.4
CS004	4.0	0.99	0.98	0.12	30.8
CS005	3.0	0.99	1.00	0.13	41.8
CS006	0.0	0.99	0.99	0.13	–
CS007	–2.5	0.99	0.99	0.09	–36.3
CS011	0.0	0.99	0.99	0.29	–
CS013	–7.5	0.94	0.92	0.38	–50.3
CS017	–12.1	0.97	0.91	0.49	–40.9
CS021	–1.5	0.96	0.97	0.54	–358.1
CS024	26.2	0.96	0.68	0.84	32.3
CS026	–21.6	0.94	0.79	0.87	–40.1
CS028	–47.8	0.84	0.55	1.23	–25.7
CS030	–24.2	0.93	0.81	0.97	–40.3
CS031	3.0	0.94	0.94	0.78	258.0
CS032	35.2	0.96	0.63	0.73	20.7
CS101	–45.3	0.88	0.58	1.11	–24.6
CS103	–46.3	0.93	0.55	1.82	–39.2
CS201	–5.5	0.95	0.94	0.92	–165.5
CS301	49.8	0.93	0.31	1.04	20.9
CS302	125.8	0.82	0.09	2.05	16.3
CS401	33.7	0.95	0.67	0.94	27.9
CS501	–42.8	0.86	0.61	1.27	–29.6

was undertaken and the results are shown in Table 1. This analysis initially used the full hour of observations. There were 200 frequency channels in this observation and the 100th channel was at a frequency of 44.5 MHz. The relative signal intensity at this frequency was selected. The correlation between the relative signal intensity observed at this frequency at station CS002 and each of the other core stations in turn was calculated. The correlation at zero lag, from which the spatial variability of the structure can be inferred, is shown in Table 1 and these values are plotted in Figure 3. Nine stations, CS001, CS002, CS003, CS004, CS005, CS006, CS007, CS011 and CS017 are closely spaced, with separations as small as ~100 m. In the interests of clarity, these are marked in Figure 3 as ‘Inner Core’ and the correlation shown in Figure 3 is the mean value of the correlations at zero lag of CS002 with each of the other seven stations. It is clear from the correlations shown in Figure 3 that there is significant variability in the feature on a horizontal spatial scale of a few kilometres, and that the feature is anisotropic, with the largest similarities observed in a direction which is approximately aligned with the geomagnetic east-west axis.

This cross-correlation analysis was used to determine the lag at which the maximum correlation occurred and the correlation at this lag, with positive values of the lag indicating that the structure was observed at this location after CS002. The correlations at zero lag for stations CS101 and CS302 were 0.58 and 0.09 respectively, indicating that the structure varied significantly on a spatial scale of a few km. The correlation at the peak lag for these stations was 0.88 and 0.82 respectively, which indicated that the structure evolved as it moved or that the

different stations sampled different parts of the structure. A rough estimate of the velocity could also be made, assuming that the direction of propagation of the structure was parallel to a straight line between stations from which the lag was calculated. If the structure is propagating as a plane wave, then the positive and negative velocities closest to zero indicate the approximate velocity of the structure. The stations for which this condition was fulfilled are CS101 and CS302, which are shown in bold type in Table 1. The location of these stations relative to CS002 indicates that the structure was moving in a north-easterly direction at approximately 20 m s^{-1} . However, this is only a very rough estimate with most of the available information not used in this calculation. The cross-correlation analysis was repeated using just the times around the structure (17:10 UT–17:40 UT). The changes for the lag compared to CS002, the correlation at this lag and the correlation at zero lag were small and did not exceed 5.0 s, [0.03] and [0.05] respectively. The velocity estimated between stations CS101 and CS002 was reduced by 1.3 m s^{-1} and it was unchanged between stations CS302 and CS002.

The velocity can be calculated in a more rigorous manner using the method discussed by Fallows et al. (2020), which makes use of all possible baselines within the LOFAR core and all available frequencies. The intensities are averaged over the frequency band 29.8–64.0 MHz at each station. The auto- and cross- power spectra were calculated using the relative signal intensities from every station pair within the LOFAR core for 17:10–17:40 UT. A low pass filter with a cut-off of 0.5 Hz was used to remove high-frequency noise. The velocity was

found to be $(22 \pm 3) \text{ m s}^{-1}$ and to have an azimuth of 39° , which is in agreement with the simple analysis based on the results shown in Table 1. As the LOFAR observations are dispersive, this method was repeated using just the frequency channels at 55 MHz and above as the dispersive effects are minimised at these higher frequencies. This gave a velocity of $(30 \pm 4) \text{ m s}^{-1}$ at an azimuth of 39° . The method of Fallows et al. (2020) had only been used previously with wavelike structures. In the present paper, this method was applied to a discrete structure. The velocity found using this method is in agreement with the velocity obtained from the simple cross-correlation analysis.

The observed velocity for a point source is due to both the motion of the plasma structure and the apparent motion of the radio source, which are related to each other by the simple expression:

$$v_{\text{observed}} = v_{\text{plasma}} - v_{\text{source}} \quad (1)$$

where v_{observed} is the observed velocity (specifically the velocity of the variations in the signal intensity), v_{source} is the velocity of the IPP of the line of sight between the radio source and the observer and v_{plasma} is the velocity of the plasma structure. The velocity of the IPP depends upon the altitude of the plasma structure, which needs to be independently determined.

Cygnus A was at an azimuth of 57.5° and an elevation of 27.2° at 17:00 UT, and an azimuth of 67.0° and an elevation of 35.2° at 18:00 UT on 14th July 2018, as observed by LOFAR station RS508. The line of sight path to Cygnus A is directed to the northeast of the observing stations. Figure 4 shows the range of possible IPPs for altitudes between 0 km and 350 km at 17:50 UT, and these are relatively close to the Juliusruh ionosonde (54.63°N ; 13.37°E).

An ionosonde transmits radio waves upwards at a range of frequencies which can be reflected in the ionosphere and then received at ground level. Figure 5 shows ionograms from the Juliusruh ionosonde at 15-min intervals between 17:00 UT and 18:00 UT on 14th July 2018. Each of these ionograms shows a quasi-horizontal line at an altitude of ~ 120 km and at frequencies up to ~ 6 MHz, characteristic of a sporadic E layer. Additional echoes at multiples of this altitude are due to multi-hop propagation, where the transmitted wave completes multiple circuits of the ground-ionosphere-ground path prior to reception. Each of these ionograms also shows some indication of echoes above 250 km, where the frequency increases with altitude, characteristic of the F-region. Collectively, these observations imply that a sporadic E layer was present and that this layer did not completely reflect radio waves at these frequencies, possibly due to variations within this layer. These observations of a sporadic E layer are close to, but not co-located with, the IPPs of the LOFAR observations from station RS508.

Ionograms from the Juliusruh ionosonde were observed at 5-min intervals (see Supplementary material 2), which showed the same general patterns as those presented in Figure 5. These data are available from the GIRO (Reinisch & Galkin, 2011); however, manual scaling has been conducted by one of the authors to extract various parameters from each ionogram. The maximum frequency which is reflected by the sporadic E layer (foE_s ; in MHz), the blanketing frequency of the sporadic E layer and the virtual height at which this electron density occurred ($h'E_s$; in km) was estimated. The electron density,

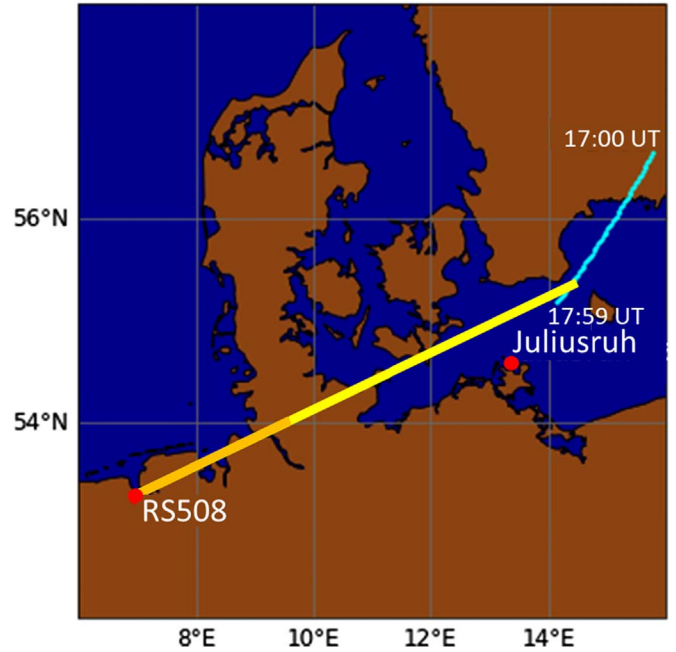


Figure 4. A map showing the approximate viewing geometry from LOFAR station RS508 towards Cygnus A on 14th July 2018 at 17:50 UT. Cygnus A was at an azimuth of 65° and an elevation of 34° . The eastward end of the yellow line corresponds to an ionospheric pierce point at an altitude of 350 km and the eastward end of the orange part of this line corresponds to an ionospheric pierce point at an altitude of 120 km. The blue line indicates the position of the ionospheric pierce point at an altitude of 350 km between 17:00 UT and 17:59 UT.

N_e (in m^{-3}), of the sporadic E layer could then be calculated (Hargreaves, 1992):

$$N_e = \left(\frac{foE_s}{8.98 \times 10^6} \right)^2. \quad (2)$$

Figure 6 shows the maximum electron density of the sporadic E layer, the electron density of the blanketing sporadic E layer and the virtual height at which this electron density occurred at 5-min intervals. The altitude of the sporadic E layer was relatively stable, with maximum and minimum values of 125.9 km and 117.3 km respectively. The mean value was 122.6 km and the standard deviation was 2.2 km. Variations in the electron density of this layer are readily apparent. The maximum frequency reflected by the sporadic E layer varied, with maximum and minimum values of 6.22 MHz and 5.09 MHz respectively. The corresponding electron densities, calculated from equation (1) were $4.80 \times 10^{11} \text{ m}^{-3}$ and $3.21 \times 10^{11} \text{ m}^{-3}$ respectively. The mean value was $4.04 \times 10^{11} \text{ m}^{-3}$ and the standard deviation was $5.21 \times 10^{10} \text{ m}^{-3}$. The ionosonde observes a region centred vertically above the instrument in all cases, although the field of view can extend to as much as 30° from the vertical. At an altitude of 120 km, this corresponds to a distance of ~ 70 km in all directions. LOFAR observations from multiple stations (Fig. 2) also show variations on a horizontal spatial scale of tens of kilometres, which would imply variations in the plasma observed by the ionosonde within the field of view of the instrument. In order to investigate this,

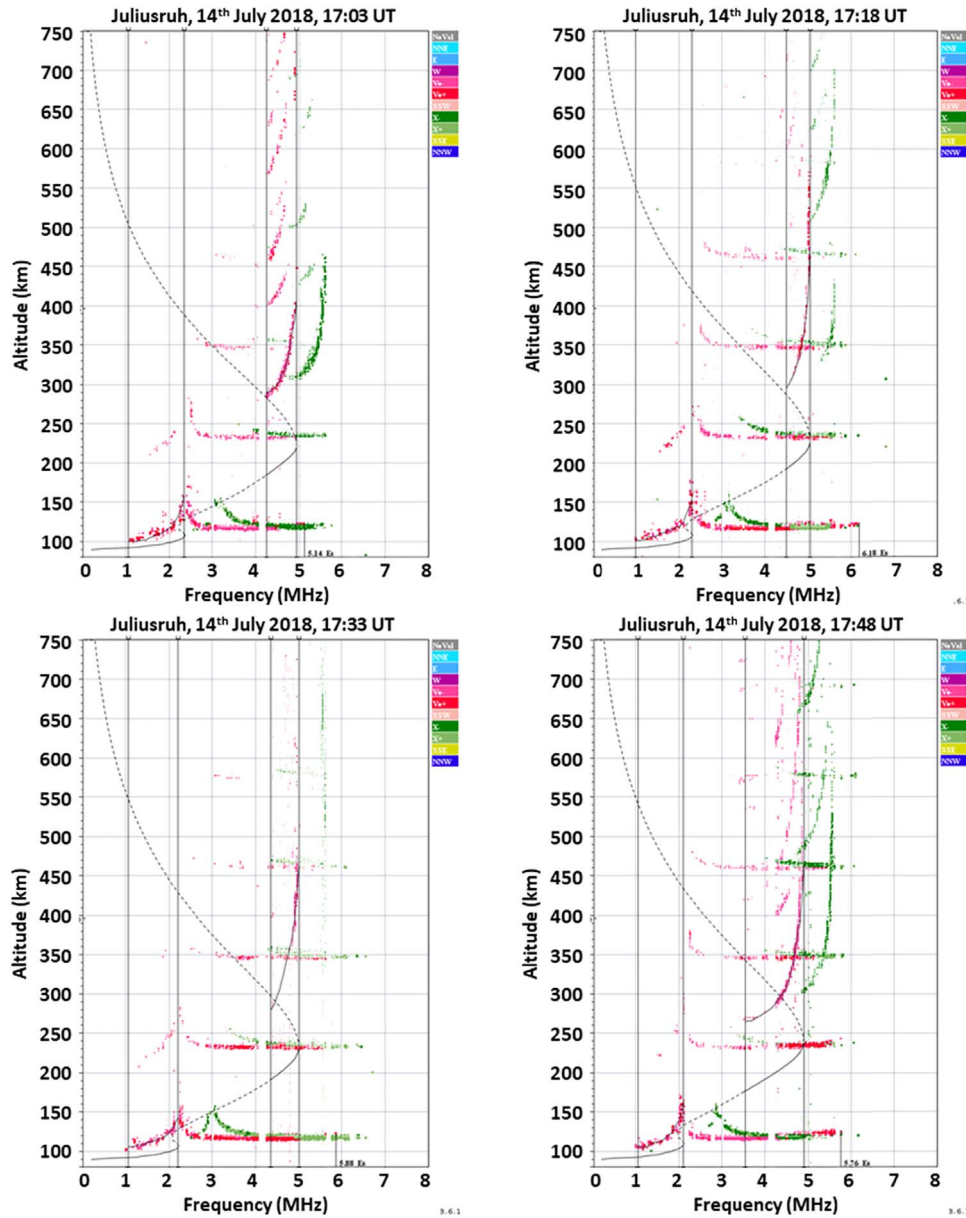


Figure 5. Ionograms from the Juliusruh ionosonde (54.63°N; 13.37°E) at 15-min intervals on 14th July 2018. The ionograms shown are at timestamps of 17:03 UT (top left panel), 17:18 UT (top right panel), 17:33 UT (bottom left panel) and 17:48 UT (bottom right panel). Pink and green colours represent the ordinary and extraordinary wave modes respectively.

the difference between the maximum electron density of the sporadic E layer and the blanketing electron density of the sporadic E layer was calculated. This ranged between zero (no change) and $3.3 \times 10^{11} \text{ m}^{-3}$, indicating significant variations in the density of the sporadic E layer on a horizontal spatial scale of tens of kilometres.

An individual LOFAR station is not directed at the same point in the atmosphere throughout the observation window due to the motion of the radio source relative to the observer. As the ionosonde observed changes to the sporadic E layer over time, this showed that there are temporal changes in the plasma observed at a given geographic location, therefore the variations observed by LOFAR cannot be explained purely by the apparent motion of Cygnus A.

If the altitude of the structure is assumed to be 120 km, then the velocity of the IPP is approximately $\sim 17 \text{ m s}^{-1}$ in a south-westerly direction at an azimuth of 200° . The component of the motion of the IPP which is parallel to the velocity of the variations in the signal intensity can be used in equation (1) to find that the velocity of the plasma was $\sim 12 \text{ m s}^{-1}$ in a north-easterly direction at an azimuth of $\sim 38^\circ$.

3.2 Simulation

In order to determine whether it is feasible for the variations in the relative signal intensity observed by LOFAR to be due to variations in a sporadic E layer, a simple model was applied in which the ionosphere was modelled as a 1-D phase screen.

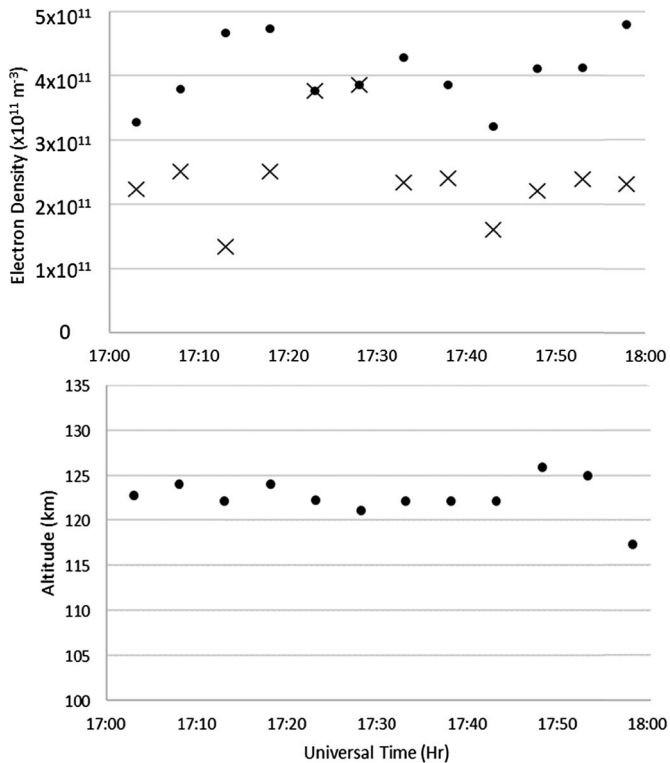


Figure 6. The maximum electron density of a sporadic E layer (top panel, dots), the blanketing density of a sporadic E layer (top panel, crosses) and the altitude at which this electron density occurred (bottom panel) inferred from observations made by the Juliusruh ionosonde (54.63°N; 13.37°E) at 5-min intervals on 14th July 2018 between 17:00 UT and 18:00 UT.

The phase screen approach is a common simplification used in analytic (e.g. Meyer-Vernet, 1980) and numerical (e.g. Hocke & Igarashi, 2003; Carrano et al., 2020) studies of ionospheric radio propagation. It was first used alongside ionospheric observations from LOFAR by Boyde et al. (2022), who extended the model of Meyer-Vernet (1980) to include intensity corrections for background sky emission and to allow a wider range of perturbations to be studied.

In the present study, a one-dimensional Gaussian-shaped enhancement in the electron density was introduced as a perturbation to the thin phase screen. There were two reasons for this choice. Firstly, the structure observed by LOFAR appeared to be due to a discrete feature, so it seemed reasonable to trial an enhancement which is also a discrete feature. Secondly, the observed variations in the received signal intensity of the geostationary satellite ETS 2 at 136 MHz using a midlatitude receiving station in Japan, reported by Maruyama (1995), have a similar form to what would be seen if a time series at a single frequency was taken from Figure 1 of the present study. Maruyama (1995) modelled the structure which caused these variations by assuming that the spatial variation of the electron density in the irregularities had a Gaussian shape. They also reported that they trialled other functional forms of the spatial variation, but that these did not yield any significant differences in the model output. Therefore, a one-dimensional Gaussian function in a horizontal plane was used as the starting point

in the present paper. The amplitude and standard deviation of the Gaussian function, the line of sight distance to the scattering screen and the observed velocity of the plasma structure are all free parameters in the model and appropriate estimates of these are needed.

The amplitude of the Gaussian function in terms of the phase change used within the model was 1.7×10^9 rad Hz, which is equivalent to a density variation of $2 \times 10^{11} \text{ m}^{-3}$ in a layer 10 km thick. Such a phase change may also be expressed in terms of TEC as 0.2 TECu ($1 \text{ TECu} = 10^{16} \text{ m}^{-2}$). The density variation was based on the variability in the electron density observed by the ionosonde. Sporadic E layers have been observed at a range of thicknesses, for example, Tsai et al. (2018) used observations from the FormoSat-3/COSMIC GPS radio occultation experiment to show that the thickness of these layers ranged from 0.1 to 10 km. It is appreciated that, in the present paper, the model starts by using the upper boundary of this range, but a reduction in this value is discussed later in this section. Initially, the standard deviation of the Gaussian was taken to be 1 km, as the observations from the LOFAR core (Fig. 3) showed variations on a spatial scale of a kilometre. The velocity required in the model is the velocity of the plasma structure relative to the line of sight (v_{observed} in Eq. (1)), not the real velocity of the plasma structure (v_{plasma} in Eq. (1)). The velocity of the scattering screen was 22 m s^{-1} as determined by the cross-correlation analysis. The line of sight distance to the scattering screen was calculated from the elevation of the radio source and the altitude of this screen. The elevation of the source was taken to be 34° . The altitude was estimated to be 120 km based on observations from the Juliusruh ionosonde (Fig. 6). These observations are of the virtual height, which is a little greater than the true height (Hargreaves, 1992), however, the difference between the virtual height and the true height in the E-region is usually small.

The model output using these values is shown in Figure 7a. A depletion in relative signal intensity was observed, surrounded by enhancements in relative signal intensity. The rippling effect observed on either side of this depletion was due to the interference of refracted radio waves. This basic pattern is consistent with the observations from station RS508 (Fig. 1). Frequency-dependent behaviour was also observed in the model, although the amount of dispersion is greater in the model than in the observations. The asymmetries seen in the observations were not present in the model, and the reasons for this are discussed later in this section.

The estimates of the parameters used as inputs to the model contain substantial uncertainties, so it is sensible to determine how robust the model is to variations in these values. Figures 7b and 7c show the effect of halving or doubling the phase change, where halving the phase change corresponds to either halving the thickness of the sporadic E layer or halving the density perturbation of this layer. Figures 7d and 7e show the effect of halving or doubling the standard deviation of the Gaussian. Halving or doubling the velocity changed the scale on the time axis but did not result in any other alterations. This is shown in Figures 7f and 7g. In all cases, the basic pattern of a depletion in relative signal intensity, surrounded by an enhancement in relative signal intensity, is shown. In all cases the effect is dispersive, and some form of rippling is observed, due to the interference of the refracted radio waves. This interference was not observed at higher frequencies in Figures 7b and 7d as the

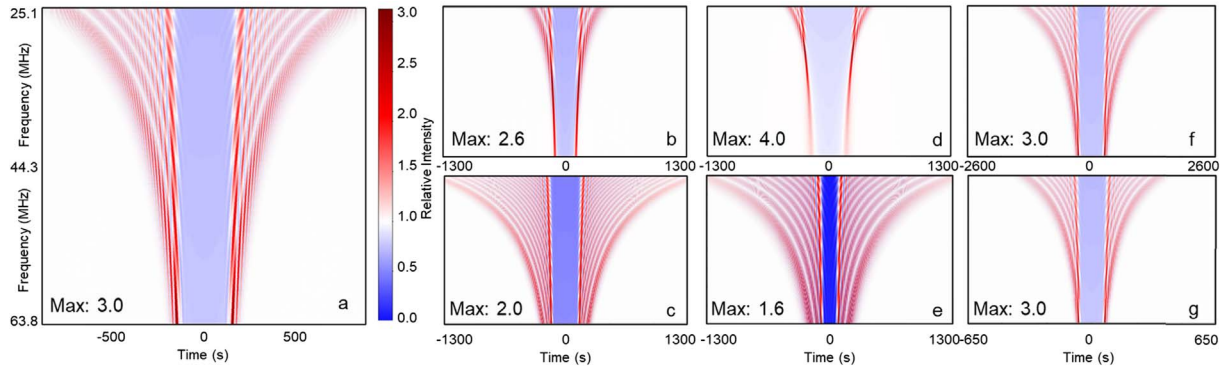


Figure 7. Modelled dynamic spectra showing the relative signal intensity as a function of time and frequency for comparison with the observation of Cygnus A presented in Figure 1. Panel a shows the variations resulting from a Gaussian-shaped enhancement in the electron density with a maximum phase change of 1.7×10^9 rad Hz (corresponding to an enhancement of $2 \times 10^{11} \text{ m}^{-3}$ across an altitude range of 10 km) and a standard deviation of 1 km. The scattering screen was assumed to be at an altitude of 120 km, moving with a velocity of 22 m s^{-1} and the radio source was assumed to be at an elevation of 34° . Panels b–g show the effects of varying some of these assumptions by changing one parameter from those used for panel a in each plot. The phase change was halved to 8.4×10^8 rad Hz in panel b and doubled to 3.4×10^9 rad Hz in panel c. The standard deviation of the Gaussian was doubled to 2 km in panel d and halved to 500 m in panel e. The velocity of the scattering screen was halved to 11 m s^{-1} in panel f and doubled to 44 m s^{-1} in panel g. The timescale and the intensity scale vary between panels. The maximum intensity is indicated in the bottom left of each panel. White represents a relative intensity of 1.0 in every panel.

path length between the scattering screen and the observer was too short for interference to occur at these frequencies based upon the amount of refraction. Collectively, the model output showed that it is plausible that the observations from station RS508 shown in Figure 1 are due to variations within a sporadic E layer, although, if it is assumed that the variations in electron density can be represented by a Gaussian function, then the thickness of this layer must be towards the upper end of the range of plausible values. It is possible that using a different function in the model, particularly one which contained a steeper gradient in the electron density, would enable the observations to be replicated with a thinner sporadic E layer. However, it did not seem sensible to add an additional free parameter (the choice of function) to the model without clear observational evidence to support this decision. The purpose of this model is not to exactly replicate the observations, but to show whether it is plausible that variations in a sporadic E layer could result in the observed variations in the relative signal intensity.

Clegg et al. (1998) presented the geometrical optics for refraction by a Gaussian plasma lens with a specific application for astrophysical plasmas, such as plasma structures in the interstellar medium. The same approach can be applied at smaller scale sizes for the ionosphere. Clegg et al. (1998) showed that phase changes of the radio wave as it passed through a Gaussian plasma lens resulted in regions of focussing, defocussing and regions where the interference of the refracted radio waves caused strong variations in the signal intensity, bounded by the inner and outer caustics (Fig. 8). The distance between the lens and the focusing points depends upon the characteristic size of the lens, the total electron content along the ray path and the wavelength of the incident radio wave. The dynamic spectrum for the observation of Cygnus A by LOFAR station RS508 shown in Figure 1 and the modelled dynamic spectrum in Figure 7a are largely consistent with what would be expected from geometrical optics if the distance between the lens and the observer is greater than the distance between the lens and the focussing region (Fig. 8). Clegg et al. (1998) also showed

the characteristic size of the lens, which is twice the standard deviation of the Gaussian, can be estimated as $\Delta x'_i/4.3$ where $\Delta x'_i$ is the distance between the pair of inner caustics. The observation of Cygnus A by station RS508 shows that the time between the inner caustics is ~ 7.5 min. at a frequency of 44.5 MHz (Fig. 1). If the lens is moving at a velocity of 22 m s^{-1} , then this corresponds to a distance of ~ 10 km. It follows that the characteristic scale of the lens is 2.3 km and the standard deviation of the Gaussian is 1.2 km, consistent with the estimate used within the present paper.

It is also interesting to note that, when the phase change was reduced (Fig. 7b) or the standard deviation of the Gaussian was increased (Fig. 7d) then the modelled dynamic spectra showed markedly less rippling and more closely resembled those observed in the LOFAR core (Fig. 3). The dynamic spectra from the core stations are more consistent with what would be expected from geometrical optics if the distance between the lens and the observer is less than the distance between the lens and the focussing region (Fig. 8). Clegg et al. (1998) showed that this could be a result of a reduction in the distance between the lens and the observer, an increase in the total electron content along the ray path or a decrease in the characteristic scale of the lens. In the present study, the reduction in the phase change could correspond to a reduction in the variation in the electron density (Fig. 7b) or to an increase in the width of the Gaussian (Fig. 7d). Another possible explanation is that this could also be explained by replacing the Gaussian lens with another function which has a lower curvature. The minimum in the relative signal intensity at station CS002 was at $\sim 17:25$ UT, some 25 min. prior to the minimum in relative signal intensity observed at station RS508. During this time interval, as the plasma density structure moved in a northeasterly direction the plasma density gradient at the edge of the feature would be expected to steepen due to an instability process. A suitable candidate mechanism is the Perkins instability (Perkins, 1973), for which a physical explanation was given by Zhou & Mathews (2006) and which was shown to be

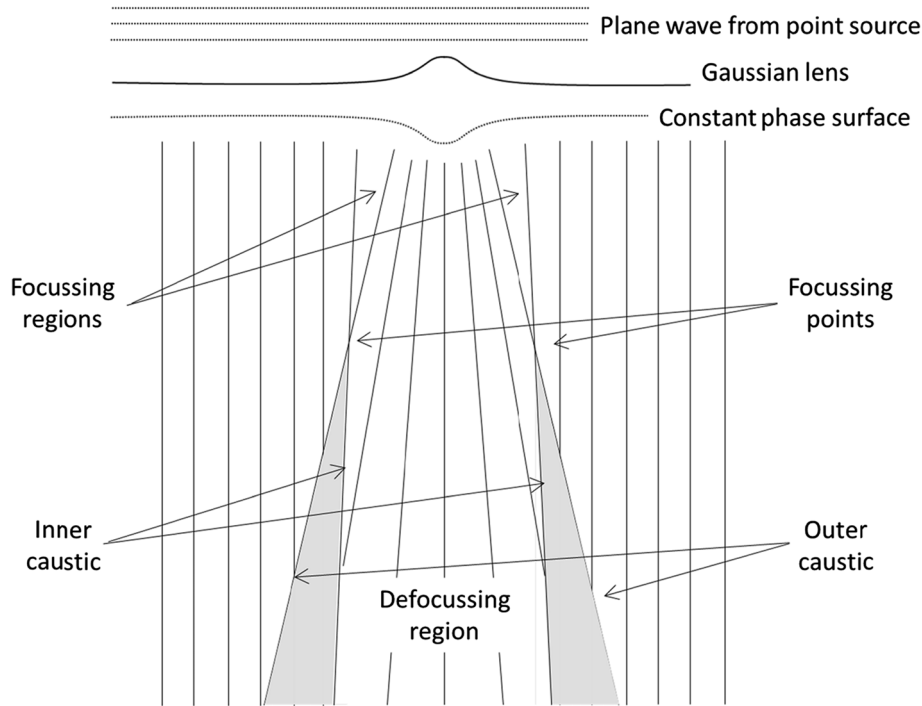


Figure 8. Schematic diagram of refraction by a Gaussian plasma lens (after Clegg et al., 1998). The dashed lines show lines of constant phase before and after a plane wave passes through a Gaussian lens. The lens is shown by a thick solid line. The representation of this lens is purely schematic, as it is assumed to have a negligible and uniform width along the line of sight. The thin solid lines represent ray paths which are normal to the phase front after the wave has passed through the Gaussian lens. Focussing occurs at the focussing points. The interference of the refracted waves causes variations in the signal intensity on relatively small spatial scales in the grey-shaded region, which is bounded by the inner and outer caustics.

relevant to a sporadic E layer by Cosgrove et al. (2004). Unfortunately, it is not practical to calculate the growth rate of such an instability using the observational data available in the present paper due to the absence of some key information, such as the scale height of the neutral atmosphere. Nevertheless, these results do show that it is plausible that the electron density gradient at the edge of the feature was steepening over time and show the potential value of LOFAR as a source of observations to constrain analytical or numerical models of instability growth rates, or to discriminate between competing models.

There is one feature which is readily apparent in the observations and which is not captured by the model at all, namely the asymmetry in the observations. This is due to one of the underlying assumptions within the model. The model assumes that the phase screen is perpendicular to the direction of propagation of the radio wave. The source is at an elevation of 34° and the velocity of the variations in the signal intensity (v_{observed} in Eq. (1)) is assumed to be in the horizontal direction, so the phase screen is not perpendicular to the direction of propagation of the radio wave. This asymmetry is dependent on the wavelength of the incoming radio signals, with longer wavelengths undergoing more refraction which, in the dynamic spectra manifests in the greater spread of the ripples in time at lower frequencies. Figure 9 shows a cartoon of a radio wave from an astronomical source passing through the ionosphere, where the ionosphere is represented by the grey slab with the deeper grey shading indicating a region of enhanced plasma density. As the radio wave, indicated by the black lines, enters the ionosphere

the lines are parallel and equally spaced. Refraction of the incoming signal occurs, with greater amounts of refraction associated with regions of greater plasma density. After passing through the ionosphere, the spacing of the black lines on the right-hand edge of the region of enhanced plasma density is smaller than any of the other arrows shown, indicating an enhancement in the signal intensity. In the cartoon, this is shown as a slab containing two different uniform densities, but the same effect would result from a Gaussian superimposed on a gradient in the background electron density. An asymmetry could also be created with a skewed Gaussian. As both of these scenarios could be used to create an asymmetry, it did not seem sensible to develop the model further for this observational paper without additional clear observational evidence to support this decision.

The model contains several other simplifications. If v_{observed} is assumed to be horizontal, then the propagation direction is quasi-parallel to the azimuth of the line of sight, and this effect is not included within the model. The model uses a 1-dimensional Gaussian lens, so only accounts for variations in one plane. Figure 2 indicates that the structure is asymmetric and is elongated in one direction, therefore the use of a one-dimensional lens appears to be reasonable in the present case. The model also assumes that there is no evolution of the structure within the time period considered. Given that the feature evolved significantly in the ~ 25 min. between when it is observed by station CS002 and station RS508, there may also be temporal evolution during the ~ 10 min. when it is observed

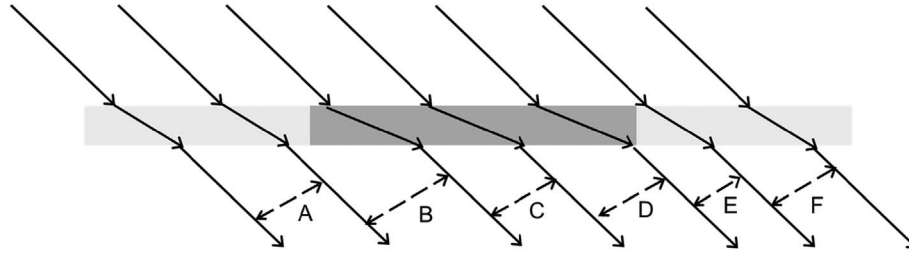


Figure 9. A diagram illustrating the asymmetric variation in signal intensity introduced by a plasma density enhancement in the ionosphere. The black lines represent a radio wave propagating from a distant astronomical source. The ionosphere is illustrated by a grey band, with the deeper grey shading indicating a region of enhanced plasma density.

at an individual station. While there is clearly significant scope for further development of this model in future projects, it does enable a qualitative comparison in the present study.

In summary, the simple phase screen model containing a Gaussian enhancement in the electron density with a standard deviation of 1 km and an amplitude corresponding to an enhancement of $2 \times 10^{11} \text{ m}^{-3}$ across an altitude range of 5 km (Fig. 7b) shows strong similarities to the dynamic spectra observed in the LOFAR core (Fig. 3). The dynamic spectrum observed by station RS508 approximately 25 min. later (Fig. 1) is more consistent with a Gaussian enhancement in the electron density with a standard deviation of 1 km and an amplitude corresponding to an enhancement of $2 \times 10^{11} \text{ m}^{-3}$ across an altitude range of 10 km (Fig. 7a). There are several possible explanations for this behaviour: intrinsic variation of density structure over time, intrinsic variation of the altitude range over time, apparent density variation due to changing viewing angle, and apparent density variation due to lines of sight having ionospheric pierce points in different regions where the Gaussian is probably not completely identical. In the ionosphere, smaller-scale structures can arise from larger-scale structures due to instability processes including the gradient-drift instability (Keskinen & Ossakow, 1983), the Kelvin–Helmholtz instability (Burston et al., 2016) and the Perkins instability (Zhou & Mathews, 2006). Rather than the variations observed between stations CS002 and RS508 being due to changes in the altitude spanned by the sporadic E layer, it is plausible that these changes could also be explained by a steepening of the electron density gradient at the edge of the enhancement due to an instability process. If so, then observations from LOFAR could potentially be used to determine which of several instability processes are acting on ionospheric plasma at a given time.

3.3 Observations in 2-D frequency space

The delay-Doppler spectrum resulting from observations of Cygnus A from station RS508 on 14th July 2018 between 17:37:00 UT and 17:56:00 UT, and between 29.8 MHz and 64.0 MHz, is shown in the top left panel of Figure 10. This is the 2D Fourier transform of the dynamic spectrum. The frequency range is slightly less than the corresponding dynamic spectrum (Fig. 1), with the lowest frequencies removed. The lower frequency channels were highly contaminated by noise, and removing individual channels would have resulted in artefacts in the delay-Doppler spectrum. Therefore, the entire range of channels below 29.8 MHz was removed.

The delay-Doppler spectrum for 17:37–17:56 UT (Fig. 10a) shows a complicated structure. Clear parabolic arcs have been observed in previous studies when the plasma structure is a plane wave, for example Fallows et al. (2020). This is not the case in the present study. The complexity of the delay-Doppler spectra arises, in part, from the superposition of information from the leading and trailing edges of the feature. A simpler structure is observed by plotting subsets of these data. Figure 10b (17:37:00 UT–17:46:33 UT) corresponds to the ripples at the start of the feature shown in the dynamic spectra, Figure 10c (17:47:00 UT–17:52:00 UT) corresponds to the depletion in the signal intensity observed in the dynamic spectra and Figure 10d (17:53:40 UT–17:56:00 UT) corresponds to ripples observed at the end of the feature in the dynamic spectra. There are some small gaps in this time series to ensure that only observations which clearly show the required information (for example, ripples across all frequencies) are included in the delay-Doppler spectra.

A clear asymmetry is shown between the delay-Doppler spectra which correspond to the start and the end of the feature (Figs. 10b and 10d), with a smaller range of Doppler frequencies at the start of the feature due to this occurring across a greater timespan in the dynamic spectrum. The middle of the feature (Fig. 10c) does not show a significant structure. This is expected, given the lack of variation in the dynamic spectrum at this time. It is quite difficult to obtain additional information from the delay-Doppler spectrum of this feature since the traditional analysis rests on the presence of scattering regions that are approximately fixed over time and frequency. In the present study, most of the variation seems to come from a single Gaussian lens, so radio waves are focused from different regions of the Gaussian depending on frequency and time. Furthermore, the lens itself may well evolve during the observations. Nevertheless, it is interesting to note that lens effects, such as the asymmetry of the structure, can be inferred from the delay-Doppler spectrum in the case of an isolated feature.

4 Discussion

The effects of small-scale structures within the ionosphere on the intensity of a trans-ionospheric radio signal have been observed by LOFAR. The observations are consistent with the effects of a plasma structure which exhibits variation in electron density of $\sim 2 \times 10^{11} \text{ m}^{-3}$ in a layer ≤ 10 km thick, with the horizontal spatial scale of the order of kilometres. These scale sizes suggest that the structure is located within the E-region

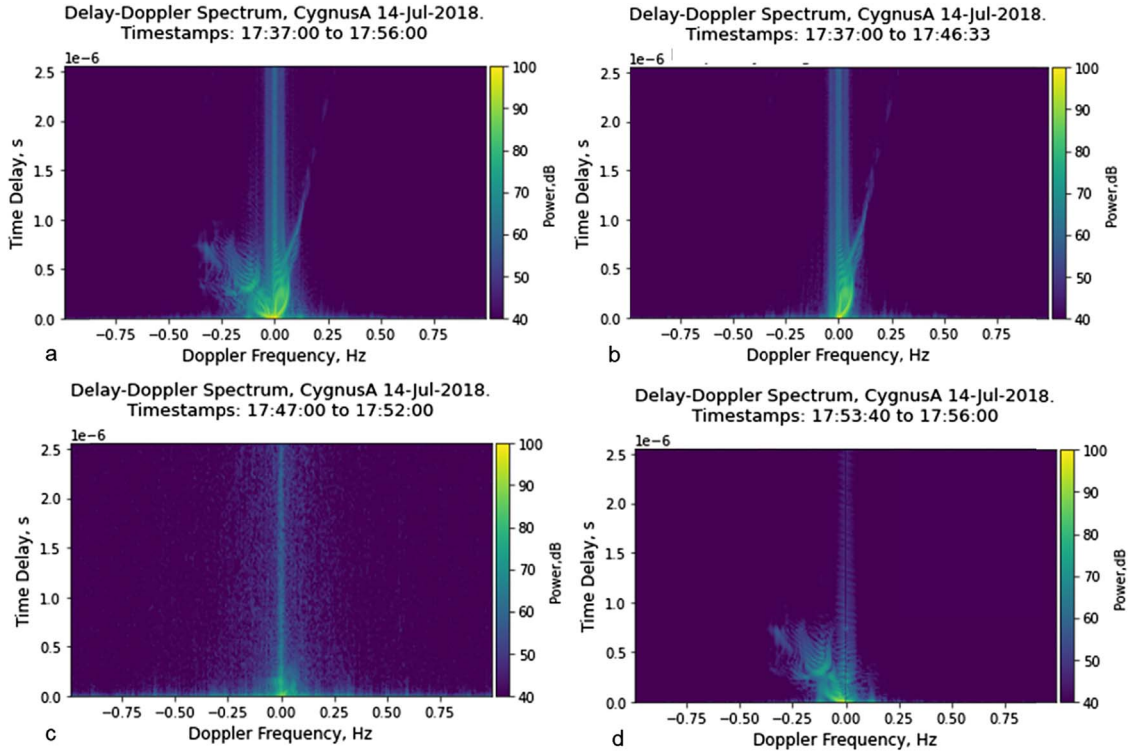


Figure 10. The delay-Doppler spectra of the observation of Cygnus A made by LOFAR station RS508 on 14th July 2018 showing the power as a function of the Doppler frequency and time delay. Panel a shows the delay-Doppler spectrum for observations between 17:37:00 UT and 17:56:00 UT, whereas the other panels show spectra for subsets of these times. Panel b shows observations between 17:37:00 UT and 17:46:33 UT, panel c shows observations between 17:47:00 UT and 17:52:00 UT and panel d shows observations between 17:53:40 UT and 17:56:00 UT. All panels show frequencies between 29.8 MHz and 64.0 MHz.

and is consistent with variations within a sporadic E layer. Observations from a nearby, but not co-located, ionosonde show the presence of such a layer. When the properties of the sporadic E layer observed by the ionosonde are used to drive a phase screen model, then the main features of the observations are reproduced. The possibility that the ionospheric structure was located in the F-region cannot be definitively excluded. However, the spatial scales of the plasma structure were not consistent with those commonly observed in the F-region (Hargreaves, 1992).

The structure was slowly moving, with a velocity of $\sim 12 \text{ m s}^{-1}$. It was of an irregular shape. Differences in the dynamic spectra were observed at different receiving stations at different times, showing that the structure evolved over time. This evolution was consistent with a steepening of the plasma density gradient at the edge of the structure, possibly due to an instability process. While modelling such a process is beyond the scope of the present paper, it does show the potential value of LOFAR as a source of observations to constrain analytical or numerical models.

The variations in the signal intensity observed using station RS508 (Fig. 1) bear a striking resemblance to observations of plasma blobs in a sporadic E layer at mid-latitudes made at a single frequency (136 MHz) using transmission from a geostationary satellite observed at a single location (Maruyama, 1991), and the subsequent numerical modelling work to determine the shape of the plasma structure (Maruyama, 1995). The present study presents a number of advancements upon this earlier

work. Firstly, the broadband nature of the LOFAR observations allows the effect to be shown to be dispersive, and so it can be categorically stated that this is an ionospheric, rather than a tropospheric, effect. Secondly, and most importantly, the large number of LOFAR stations allows the spatial variability and the temporal evolution of the structure to be directly observed. These observations show variations in the morphology and evolution of the plasma structure that cannot be captured from a single station. Thirdly, Maruyama (1991) compared the climatology of observations of variations in the radio waves from the geostationary satellite with the climatology of observations of sporadic E layers from an ionosonde. The approach in the present paper uses complementary observations from the ionosonde at a coincident time, which is distinct from, but complementary to, that used by Maruyama (1991).

The origin of the variations in the sporadic E layer is more difficult to determine. While it is well known that plasma structures can propagate through this region originating at auroral (e.g. Tsugawa et al., 2004) or equatorial (e.g. Chemiak & Zakharenkova, 2016) latitudes, this feature is quasi-stationary, which implies a local source. Upward propagating Atmospheric Gravity Waves (AGWs; Hines, 1960) can perturb the ionosphere and result in a sporadic E layer (Didebulidze et al., 2015), but such perturbations would be expected to be periodic rather than the isolated feature observed here. Sources of upward propagating AGWs can include flow over variable topography (i.e. mountains) or strong convection associated with thunderstorms (as reviewed by Hocke & Schlegel,

1996). As there is no such elevated topography in the region of interest, this mechanism does not appear to be appropriate in this case. Large terrestrial storms can be inferred from the temperature of the cloud tops observed by Meteosat Satellite Images (<https://weather.us/satellite/europe/top-alert-15min/20180714-2300z.html>). These data do not show any indication of large terrestrial thunderstorms within 100 km of the IPP for LOFAR station RS508 for these observations at an altitude of 120 km. There were no lightning strikes in this region during the time of the LOFAR observations as inferred by the UK Met Office's Arrival Time Difference Network (ATDnet) lightning location system. Lightning is generally visible in the LOFAR observations themselves as sharp, broadband RFI features in the dynamic spectra. No such features were observed in this observation. Meteors can also provide a source of ionisation in the E-region which can become compressed into a thin layer by wind shear. There is an ongoing flux of meteors impacting the upper atmosphere, which peaks at $\sim 2\text{--}3$ LT and this flux is also enhanced during meteor showers. The timing of this ionospheric event was $\sim 18\text{--}19$ LT and did not coincide with any peak in known meteor showers. Although we are not aware of any reports in the literature of a large, individual meteor causing ionospheric effects similar to those reported in this paper, the NASA database of fireballs was checked (<https://cneos.jpl.nasa.gov/fireballs/>) and it did not indicate any suitable candidate event. The geomagnetic conditions at the time of the observation were quiet, as were the solar conditions. These quiet conditions, coupled with the implication of a local source, suggest that this structure is not a consequence of space weather driven by solar activity. In the future, additional studies using LOFAR observations during times when effects such as thunderstorms or meteor impact were known to occur would be useful to determine the impact of such features on trans-ionospheric radio signals.

5 Summary

The Low Frequency Array (LOFAR) is one of the most advanced radio telescopes in the world. When radio waves from a distant astronomical source traverse the ionosphere, structures in this plasma affect the signal. The high temporal resolution available (~ 10 ms), the large range of frequencies observed (10–90 MHz & 110–250 MHz) and the large number of receiving stations (currently 52 across Europe) mean that LOFAR can also observe the effects of the midlatitude ionosphere in an unprecedented level of detail.

On the 14th of July 2018 LOFAR stations across the Netherlands observed Cygnus A between 17:00 UT and 18:00 UT between 24.9 MHz and 64.0 MHz. At approximately 17:50 UT, station RS508 (53.24°N; 6.95°E) recorded a deep fade in the intensity of the received signal, lasting less than 10 min. Immediately before and after this deep fade, rapid variations of signal strength were observed. This feature was also observed using other LOFAR stations across the Netherlands, albeit at slightly different times and with a slightly different structure. Spatial variations between the stations and the dispersive nature of the effect suggested that this plasma structure was located in the ionosphere. Independent confirmation of the presence of a sporadic E layer, and variations within it, was

observed by the Juliusruh ionosonde. A 1-D numerical model and consideration of geometrical optics were used to show that the LOFAR observations were consistent with an electron density enhancement in the sporadic E layer with a density change of $2 \times 10^{11} \text{ m}^{-3}$ and a spatial scale of several kilometres. The LOFAR observations across multiple stations showed that the structure was quasi-stationary, with a velocity of $\sim 12 \text{ m s}^{-1}$ and that it exhibited significant variation on temporal scales of a few kilometres. The slow velocity and the small scale of the structure imply a local source. The observations were consistent with the steepening of a plasma density gradient at the edge of the feature with time due to an instability process. The geomagnetic conditions at the time of the observation were quiet, as were the solar conditions, which implies that this event is not a consequence of space weather driven by solar activity. Collectively, these observations show the ability of LOFAR to observe substructures within sporadic E layers and also the evolution of such structures.

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(IMF) and the solar wind velocity were taken from the OMNI database at <https://spdf.gsfc.nasa.gov/pub/data/omni/> and the work of the Space Physics Data Facility (SPDF) in preparing the OMNI database is gratefully acknowledged. The UK Met Office's Arrival Time Difference Network (ATDnet) lightning location data was provided by the UK Met Office and is available on request. The assistance of Katherine Wood with the compilation of the bibliography and the proofreading of the manuscript is gratefully acknowledged. The editor thanks two anonymous reviewers for their assistance in evaluating this paper.

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Supplementary material

The supplementary materials of this article are available at <https://www.swsc-journal.org/10.1051/swsc/2024024/olm>.

Supplementary material 1: The amplitude scintillation index S_4 as a function of time, frequency and the interval over which it was calculated for an observation of Cygnus A made by LOFAR station RS508 on 14th July 2018 between 17:05 UT and 17:55 UT.

Supplementary material 2: Ionograms from the Juliusruh ionosonde (54.63°N; 13.37°E) at 5-minute intervals on 14th July 2018 between 17:03 UT and 17:58 UT.

References

- Appleton E. 1947. *The ionosphere, Nobel Lecture*. Available at <https://www.nobelprize.org/uploads/2017/01/appleton-lecture-new.pdf> (accessed: 22nd September 2023).
- Appleton E, Naismith R. 1947. The radio detection of meteor trails and allied phenomena. *Proc Phys Soc* **59**: 461. <https://doi.org/10.1088/0959-5309/59/3/313>.
- Collaboration Astropy, Robitaille TP, Tollerud EJ, Greenfield P, Droettboom M, et al. 2013. Astropy: a community Python package for astronomy. *A&A* **558**: A33. <https://doi.org/10.1051/0004-6361/201322068>.
- Beser K, Mevius M, Grzesiak M, Rothkaehl H. 2022. Detection of periodic disturbances in LOFAR calibration solutions. *Remote Sens* **14**(7): 1719. <https://doi.org/10.3390/rs14071719>.
- Boyde B, Wood A, Dorrian G, Fallows RA, Themens D, et al. 2022. Lensing from small-scale travelling ionospheric disturbances observed using LOFAR. *J Space Weather Space Clim* **12**: 34. <https://doi.org/10.1051/swsc/2022030>.
- Boyde B, Wood AG, Dorrian GD, de Gasperin F, Sweijen F, Mevius M, Beser K, Themens D. 2024. Wavelet analysis of differential TEC measurements obtained using LOFAR. *Radio Sci* **59**: e2023RS007871. <https://doi.org/10.1029/2023RS007871>.
- Briskin WF, Macquart J-P, Gao JJ, Rickett BJ, Coles WA, Deller AT, Tingay SJ, West CJ. 2010. 100 μ s resolution VLBI imaging of anisotropic interstellar scattering toward pulsar B0834+06. *Astrophys J* **708**: 232–243. <https://doi.org/0004-637X/708/1/232>.
- Buchau J, Reinisch BW. 1991. Electron density structures in the polar F region. *Adv Space Res* **11**(10): 29–37. [https://doi.org/10.1016/0273-1177\(91\)90317-D](https://doi.org/10.1016/0273-1177(91)90317-D).
- Burston R, Mitchell C, Astin I. 2016. Polar cap plasma patch primary linear instability growth rates compared. *J Geophys Res Space Phys* **121**: 3439–3451. <https://doi.org/10.1002/2015JA021895>.
- Carrano C, Retterer J, Groves K, Crowley G, Duly T, Hunton D. 2020. Wave-optics analysis of HF propagation through traveling ionospheric disturbances and developing plasma bubbles. In: XXXIIIrd General Assembly and Scientific Symposium of the International Union of Radio Science, Rome, Italy, 29 August–05 September <https://doi.org/10.23919/URSIGASS49373.2020.9232348>.
- Cherniak I, Zakharenkova I. 2016. First observations of super plasma bubbles in Europe. *Geophys Res Lett* **43**(21): 11–137. <https://doi.org/10.1002/2016GL071421>.
- Clegg AW, Fey AL, Lazio TJW. 1998. The Gaussian plasma lens in astrophysics: refraction. *Astrophys J* **496**: 253–266. <https://doi.org/10.1086/305344>.
- Cordes JM, Rickett BJ, Stinebring DR, Coles WA. 2006. Theory of parabolic arcs in interstellar scintillation spectra. *Astrophys J* **637**: 346. <https://doi.org/10.1086/498332>.
- Cosgrove RB, Tsunoda RT, Fukao S, Yamamoto M. 2004. Coupling of the Perkins instability and the sporadic E layer instability derived from physical arguments. *J Geophys Res* **109**: A06301. <https://doi.org/10.1029/2003JA010295>.
- de Gasperin F, Mevius M, Rafferty DA, Intema HT, Fallows RA. 2018. The effect of the ionosphere on ultra-low-frequency radio-interferometric observations. *A&A* **615**: A179. <https://doi.org/10.1051/0004-6361/201833012>.
- de Gasperin F, Vink J, McKean JP, Asgekar A, Avruch I, et al. 2020. Cassiopeia A, Cygnus A, Taurus A, and Virgo A at ultra-low radio frequencies. *A&A* **635**. <https://doi.org/10.1051/0004-6361/201936844>.
- Didebulidze GG, Dalakishvili G, Lomidze L, Matiasvili G. 2015. Formation of sporadic-E (Es) layers under the influence of AGWs evolving in a horizontal shear flow. *J Atmos Sol-Terr Phys* **136**: 163–173. <https://doi.org/10.1016/j.jastp.2015.09.012>.
- Dorrian G, Fallows RA, Wood A, Themens DR, Boyde B, Krankowski A, Bisi M, Dańbrowski B, Vocks C. 2023. LOFAR observations of substructure within a traveling ionospheric disturbance at mid-latitude. *Space Weather* **21**: e2022SW003198. <https://doi.org/10.1029/2022SW003198>.
- Dueño B. 1956. Low-angle fluctuations of the radio-star Cassiopeia as observed at Ithaca, N.Y., and its relation to the incidence of sporadic-E. *J Geophys Res* **61**(3): 535–540. <https://doi.org/10.1029/JZ061i003p00535>.
- Fallows RA, Bisi MM, Forte B, Ulich T, Konovalenko AA, Mann G, Vocks C. 2016. Separating nightside interplanetary and ionospheric scintillation with LOFAR. *Astrophys J Lett* **828**: L7. <https://doi.org/10.3847/2041-8205/828/1/L7>.
- Fallows RA, Coles WA, McKay-Bukowski D, Vierinen J, Virtanen II, et al. 2014. Broadband meter-wavelength observations of ionospheric scintillation. *J Geophys Res Space Phys* **119**: 10544–10560. <https://doi.org/10.1002/2014JA020406>.
- Fallows RA, Forte B, Astin I, Allbrook T, Arnold A, et al. 2020. A LOFAR observation of ionospheric scintillation from simultaneous medium- and large-scale travelling ionospheric disturbances. *J Space Weather Space Clim* **10**: 10. <https://doi.org/10.1051/swsc/2020010>.
- Gopalswamy N, Mäkelä P, Yashiro S. 2019. A catalog of type II radio bursts observed by Wind/WAVES and their statistical properties. *Sun Geosphere* **14**: 111–121. <https://doi.org/10.31401/SunGeo.2019.02.03>.
- Hargreaves JK. 1992. The solar-terrestrial environment, Cambridge atmospheric and space science series. Cambridge University Press, Cambridge. <https://doi.org/10.1017/CBO9780511628924>.
- Hines CO. 1960. Internal gravity wave and ionospheric heights. *Can J Phys* **38**: 1441–1481. <https://doi.org/10.1139/p60-150>.
- Hocke K, Igarashi K. 2003. Wave-optical simulation of the oblique HF radio field. *Radio Sci* **38**: 1039. <https://doi.org/10.1029/2002RS002691>.
- Hocke K, Schlegel K. 1996. A review of atmospheric gravity waves and travelling ionospheric disturbances: 1982–1995. *Ann Geophys* **14**: 917–940. <https://doi.org/10.1007/s00585-996-0917-6>.
- Jansky KG. 1932. Directional studies of atmospherics at high frequencies. In: *Classics in radio astronomy. Studies in the history*

- of modern science, Sullivan WT (Ed.), Springer, Dordrecht, pp. 10–22. https://doi.org/10.1007/978-94-009-7752-5_1.
- Jansky KG. 1933. *New radio waves traced to centre of the Milky Way; mysterious static*, New York Times, 5th May 1933, p. 1. Available at <https://www.nytimes.com/1933/05/05/archives/new-radio-waves-traced-to-centre-of-the-milky-way-mysterious-static.html?searchResultPosition=2>.
- Kerr F, Shain C, Higgins C. 1949. Moon echoes and penetration of the ionosphere. *Nature* **163**: 310–313. <https://doi.org/10.1038/163310a0>.
- Keskinen MJ, Ossakow SL. 1983. Theories of high-latitude ionospheric irregularities: a review. *Radio Sci* **18**(6): 1077–1091. <https://doi.org/10.1029/RS018i006p01077>.
- Koval A, Chen Y, Stanislavsky A, Kashcheyev A, Zhang QH. 2018. Simulation of focusing effect of traveling ionospheric disturbances on meter-decameter solar dynamic spectra. *J Geophys Res: Space Phys* **123**: 8940–8950. <https://doi.org/10.1029/2018JA025584>.
- Koval A, Chen Y, Stanislavsky A, Zhang QH. 2017. Traveling ionospheric disturbances as huge natural lenses: solar radio emission focusing effect. *J Geophys Res Space Phys* **122**: 9092–9101. <https://doi.org/10.1002/2017JA024080>.
- Koval A, Chen Y, Tsugawa T, Otsuka Y, Shinbori A, et al. 2019. Direct observations of traveling ionospheric disturbances as focusers of solar radiation: spectral caustics. *Astrophys J* **877**: 98. <https://doi.org/10.3847/1538-4357/ab1b52>.
- Little C, Lovell A. 1950. Origin of the fluctuations in the intensity of radio waves from galactic sources: Jodrell Bank observations. *Nature* **165**: 423–424. <https://doi.org/10.1038/165423a0>.
- Maruyama T. 1991. Observations of quasi-periodic scintillations and their possible relation to the dynamics of Es plasma blobs. *Radio Sci* **26**(3): 691–700. <https://doi.org/10.1029/91RS00357>.
- Maruyama T. 1995. Shapes of irregularities in the sporadic E layer producing quasi-periodic scintillations. *Radio Sci* **30**(3): 581–590. <https://doi.org/10.1029/95RS00830>.
- McKay-Bukowski D, Vierinen J, Virtanen I, Fallows RA, Postila M, et al. 2014. KAIRA: The Kilpisjärvi Atmospheric Imaging Receiver Array – System overview and first results. *IEEE Trans Geosci Remote Sens* **53**(3): 1440–1451. <http://doi.org/10.1109/TGRS.2014.2342252>.
- Mevius M, van der Tol S, Pandey VN, Vedantham HK, Brentjens MA, et al. 2016. Probing ionospheric structures using the LOFAR radio telescope. *Radio Sci* **51**: 927–941. <https://doi.org/10.1002/2016RS006028>.
- Meyer-Vernet N. 1980. On a day-time ionospheric effect on some radio intensity measurements and interferometry. *A&A* **84**: 142–147. Available at <https://articles.adsabs.harvard.edu/pdf/1980A%26A....84..142M>.
- Pancheva D, Haldoupis C, Meek CE, Manson AH, Mitchell NG. 2003. Evidence of a role for modulated atmospheric tides in the dependence of sporadic E layers on planetary waves. *J Geophys Res* **108**: 1176. <https://doi.org/10.1029/2002JA009788>.
- Papitashvili NE, King JH. 2020. “OMNI 5-min Data” [Data set], NASA Space Physics Data Facility. Available at <https://doi.org/10.48322/gbpg-5r77> (accessed on 10th July 2023).
- Payne-Scott R, McCready LL. 1948. Ionospheric effects noted during dawn observations on solar noise. *Terr Magn Atmos Electr* **53**(4): 429–432. <https://doi.org/10.1029/TE053i004p00429>.
- Perkins F. 1973. Spread F and ionospheric currents. *J Geophys Res* **78**(1): 218–226. <https://doi.org/10.1029/JA078i001p00218>.
- Price-Whelan AM, Sipőcz BM, Günther HM, Lim PL, Crawford SM, et al. 2018. The astropy project: building an open-science project and status of the v2.0 core package. *Astron J* **156**: 123. <https://doi.org/10.3847/1538-3881/aabc4f>.
- Reinisch BW, Galkin IA. 2011. Global ionospheric radio observatory (GIRO). *Earth Planets Space* **63**(4): 377–381. <https://doi.org/10.5047/eps.2011.03.001>.
- Stinebring DR, McLaughlin MA, Cordes JM, Becker KM, Espinoza Goodman JE, Kramer MA, Sheckard JL, Smith CT. 2001. Faint scattering around pulsars: probing the interstellar medium on solar system size scales. *Astrophys J* **549**(1): 97. <http://doi.org/10.1086/319133>.
- Tapping KF. 2013. The 10.7 cm solar radio flux (F10.7). *Space Weather* **11**: 394–406. <https://doi.org/10.1002/swe.20064>.
- Thomas JA, Smith EK. 1959. A survey of the present knowledge of sporadic-E ionization. *J Atmos Sol-Terr Phys* **13**: 295–314.
- Tsai LC, Shin-Yi S, Chao-Han L, Harald S, Wichert J, Mahdi Alizadeh M. 2018. Global morphology of ionospheric sporadic E layer from the FornoSat-3/COSMIC GPS radio occultation experiment. *GPS Solut* **22**: 118. <https://doi.org/10.1007/s1029-018-0782-2>.
- Tsugawa T, Saito A, Otsuka Y. 2004. A statistical study of large-scale traveling ionospheric disturbances using the GPS network in Japan. *J Geophys Res* **109**: A06302. <https://doi.org/10.1029/2003JA010302>.
- van Haarlem MP, Wise MW, Gunst A, Heald G, McKean JP, et al. 2013. LOFAR: the low-frequency array. *A&A* **556**: A2. <https://doi.org/10.1051/0004-6361/201220873>.
- van Velthoven PFJ. 1990. Medium scale irregularities in the ionospheric electron content, *PhD thesis*, Eindhoven University, The Netherlands.
- Walker MA, Melrose DB, Stinebring DR, Zhang CM. 2004. Interpretation of parabolic arcs in pulsar secondary spectra. *Mon Not R Astron Soc* **354**: 43–54. <https://doi.org/10.1111/j.1365-2966.2004.08159.x>.
- Waszewski A, Morgan J, Jordan CH. 2022. A measurement of small-scale features using ionospheric scintillation. Comparison with refractive shift measurements. *Publ Astron Soc Aust* **39**: e036. <https://doi.org/10.1017/pasa.2022.33>.
- Weber EJ, Klobuchar JA, Buchau J, Carlson HC Jr., Livingston RC, de la Beaujardiere O, McCready M, Moore JG, Bishop GJ. 1986. Polar cap F layer patches: structure and dynamics. *J Geophys Res* **91**: 12121–12129. <https://doi.org/10.1029/JA091iA11p12121>.
- Weiβ J. 2016. History of the Juliusruh ionospheric observatory on Rügen. *Hist Geo Space Sci* **7**: 1–22. <https://doi.org/10.5194/hgss-7-1-2016>.
- Whitehead JD. 1970. Production and prediction of sporadic E. *Rev Geophys* **8**: 65–144. <https://doi.org/10.1029/RG008i001p00065>.
- Wu DL, Ao CO, Hajj GA, de La Torre Juarez M, Mannucci AJ. 2005. Sporadic E morphology from GPS-CHAMP radio occultation. *J Geophys Res Space Phys* **110**: A01306. <https://doi.org/10.1029/2004JA010701>.
- Yatawatta S, de Bruyn AG, Brentjens MA, Labropoulos P, Pandey VN, et al. 2013. Initial deep LOFAR observations of epoch of reionization windows – I. The north celestial pole. *A&A* **550**: A136. <https://doi.org/10.1051/0004-6361/201220874>.
- Zhou Q, Mathews JD. 2006. On the physical explanation of the Perkins instability. *J Geophys Res* **111**: A12309. <https://doi.org/10.1029/2006JA011696>.