Observing Travelling Ionospheric Disturbances with the LOFAR Radio Telescope

Ben Boyde[1], Alan G. Wood[2*], Gareth Dorrian[2], David Themens[2], Richard A. Fallows[3], Maaijke Mevius[4]

1: Department of Electrical and Electronic Engineering, University of Bath
2: Space Environment and Radio Engineering (SERENE), University of Birmingham
3: STFC Rutherford Appleton Laboratory
4: ASTRON, The Netherlands Institute for Radio Astronomy
* Now at UK Met Office

1: LOFAR: The LOw Frequency ARray

LOFAR (van Haarlem et al., 2013) is a radio telescope centred in the Netherlands, with international stations distributed across Europe from Ireland to Latvia. While primarily intended for radio astronomy, the distortions imposed by the ionosphere on radio signals which pass through it can be used to study structuring in the mid-latitude ionosphere.

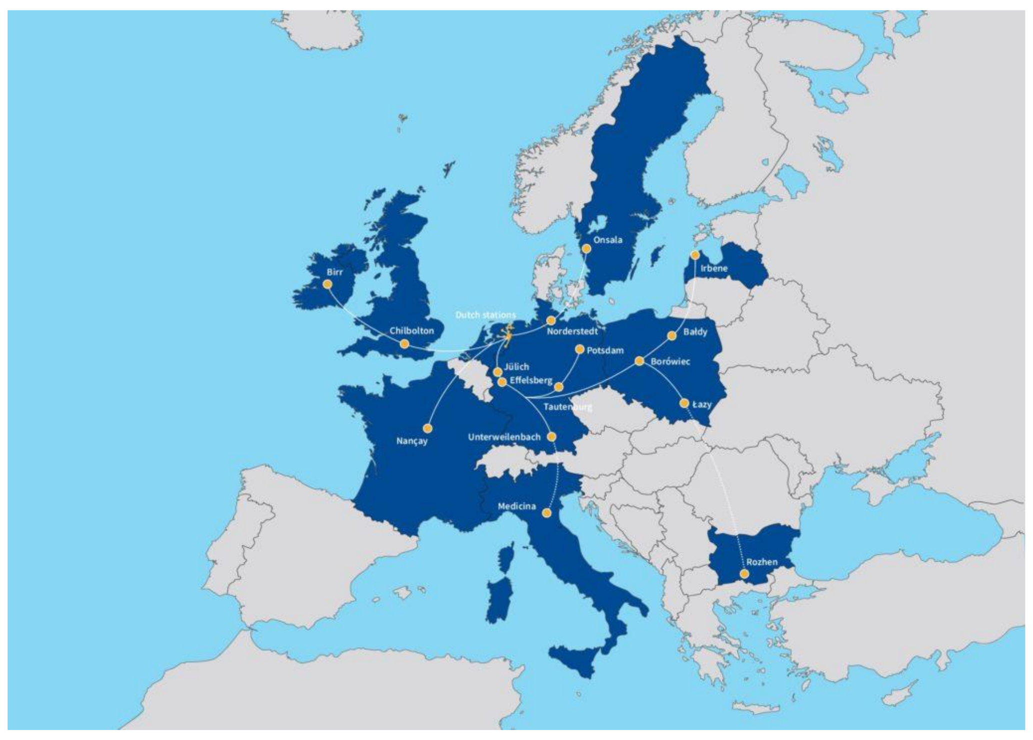

Figure 1: The layout of LOFAR stations, including planned stations in Italy and Bulgaria.

4: Interferometric Calibration Solutions

Although the ionospheric effects observed by LOFAR are extremely useful for studying the ionosphere, for radio astronomy they are an issue which must be corrected for in the calibration process to produce accurate images. This calibration process therefore produces extremely precise measurements of the ionosphere across the LOFAR network, specifically of differential Total Electron Content (dTEC). This is the difference in TEC between the lines of sight for two different LOFAR stations to a given source, and is measured to a precision of ~1 mTECu. A method to identify wave signatures in the calibration solutions and estimate parameters such as wavelength, period and propagation direction has been developed (Boyde et al., 2024).

5: Statistics of Daytime TIDs Observed Using LOFAR

Using the calibration solutions obtained from the LOFAR LBA Survey, a climatology of daytime TIDs observed by LOFAR has been developed (Boyde et al., 2025). Typical wavelengths were ~100-200 km, with the longest detected wavelengths ~500 km. The occurrence rate was found to vary significantly with wave period, with shorter period waves showing a strong preference for winter (Figure 4). The propagation directions also closely match the climatological thermospheric winds provided by the Horizontal Wind Model (HWM14; Drob et al., 2015) on a statistical basis for periods greater than 10 minutes (Figure 5). For shorter periods, there is no relationship between the neutral wind and the observed propagation directions, which suggests that these waves are not associated with AGWs. The lack of AGWs at these periods is likely due to these waves exceeding the typical Brunt-Väisälä frequency in the thermosphere. For periods below 5 minutes, a significant population of waves is identified which show alignment with the geomagnetic field, and the altitudes of alignment indicate that these structures are located in the plasmasphere.

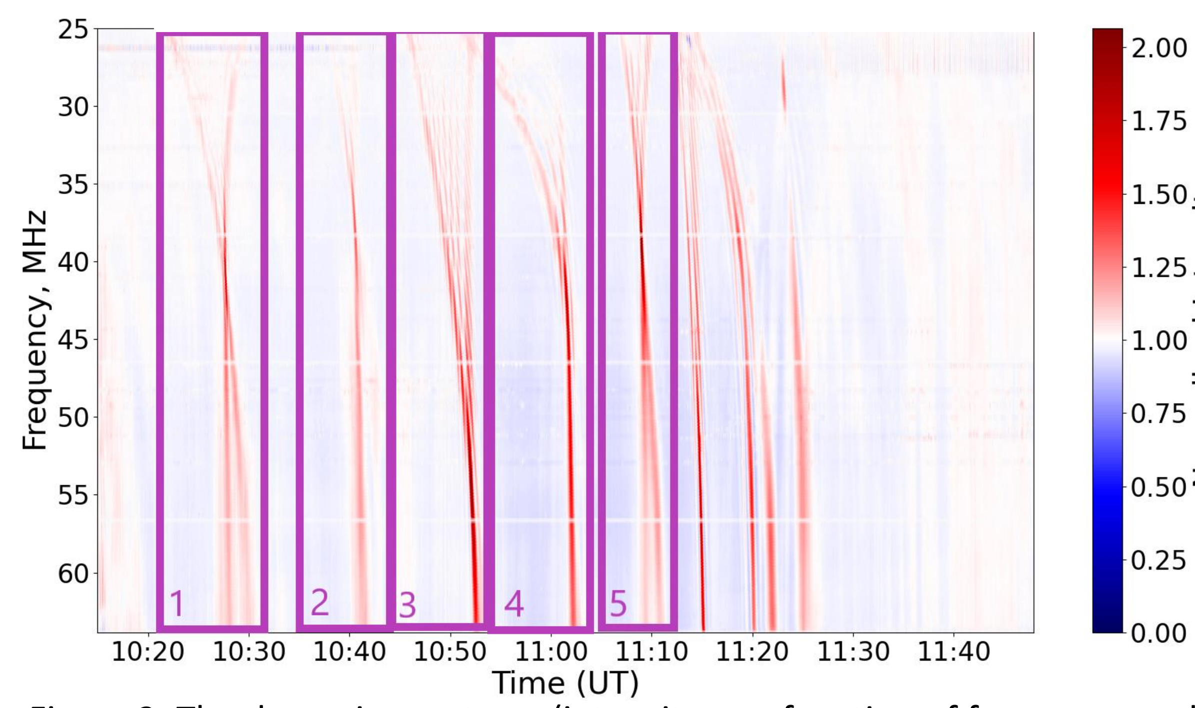

Figure 2: The dynamic spectrum (intensity as a function of frequency and time) of Cygnus A observed from LOFAR station UK608 on 15th September 2018. Note that lower radio frequencies are towards the top of the plot.

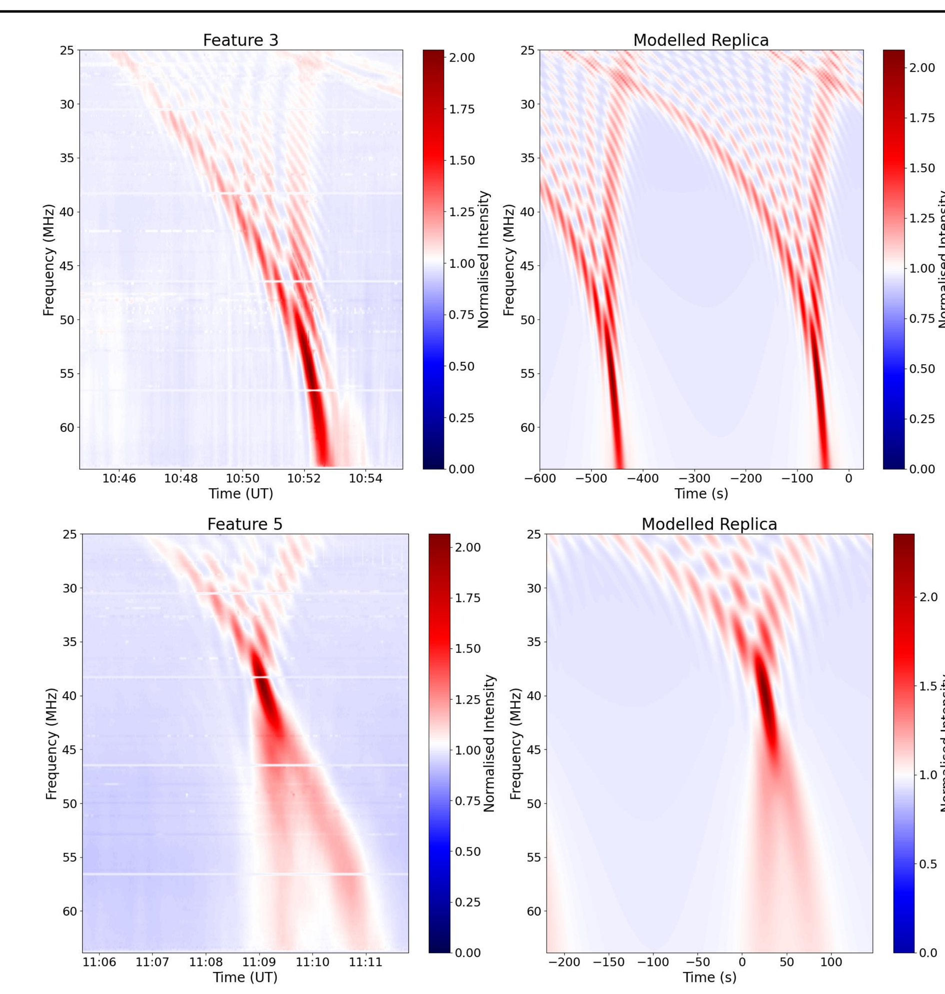

Figure 3: Selected features from Figure 2 (left panels) and their modelled replicas (right panels).

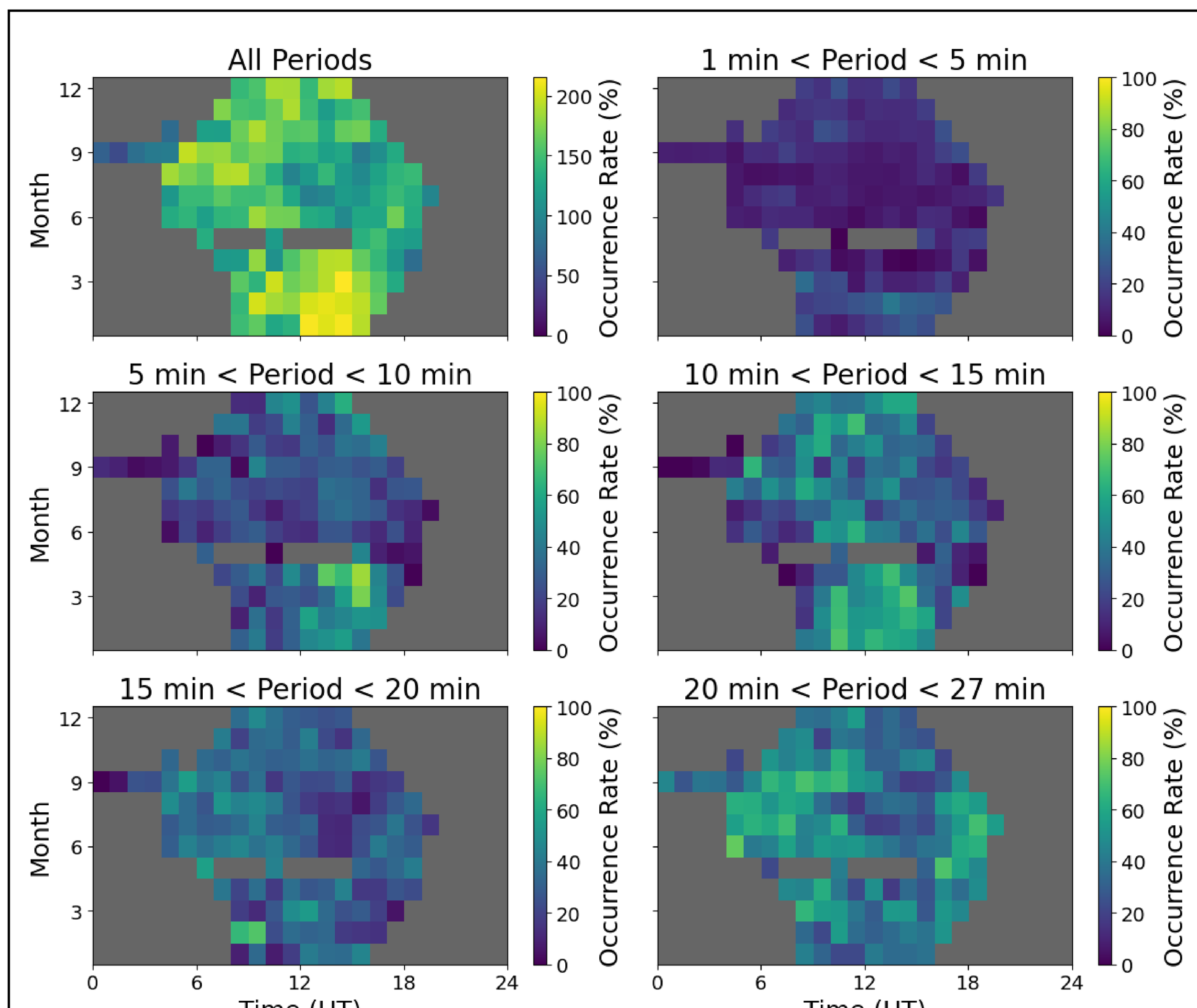

Figure 4: Occurrence rate of waves in LBA Survey observations. Top left panel considers all waves, while the others include only a subset of wave periods. Occurrence rates >100% are possible as occurrence rate is defined by total duration of wave events divided by total observing time, and multiple waves can be simultaneously present at different periods.

2: Travelling Ionospheric Disturbances

Travelling ionospheric disturbances (TIDs) are horizontally propagating waves in the ionosphere. They are typically driven by atmospheric gravity waves (AGWs) propagating in the neutral thermosphere, which can be launched by processes lower in the atmosphere such as fronts and jets as well as wind flow over mountains. TIDs can have significant impact on radio signals used for communications and navigation, and are also frequently studied as a proxy for thermospheric AGWs due to the relative ease of observing the behaviour of the ionosphere compared to the thermosphere.

3: Small-Scale TID Effects on HF/VHF Propagation Observed in Broadband

On 15th September 2018, the UK LOFAR station (UK608: 51.1°N, 1.4°W) observed a quasi-periodic sequence of variations in the intensity of Cygnus A (see Figure 2; Boyde et al., 2022). These show significant frequency dependent behaviour, with a distinct focal frequency within the observing band and interference fringing below this frequency. By comparing the observations to the results obtained from a simple one-dimensional phase screen propagation model, it can be shown that these features can be explained by focusing from a small-scale TID (horizontal wavelength ~ 15-30 km). In some of the features, above the focal frequency there were two distinct maxima of intensity, which indicate that the TID perturbation is not simply a sinusoidal variation of electron density but has a significant additional contribution from the first harmonic.

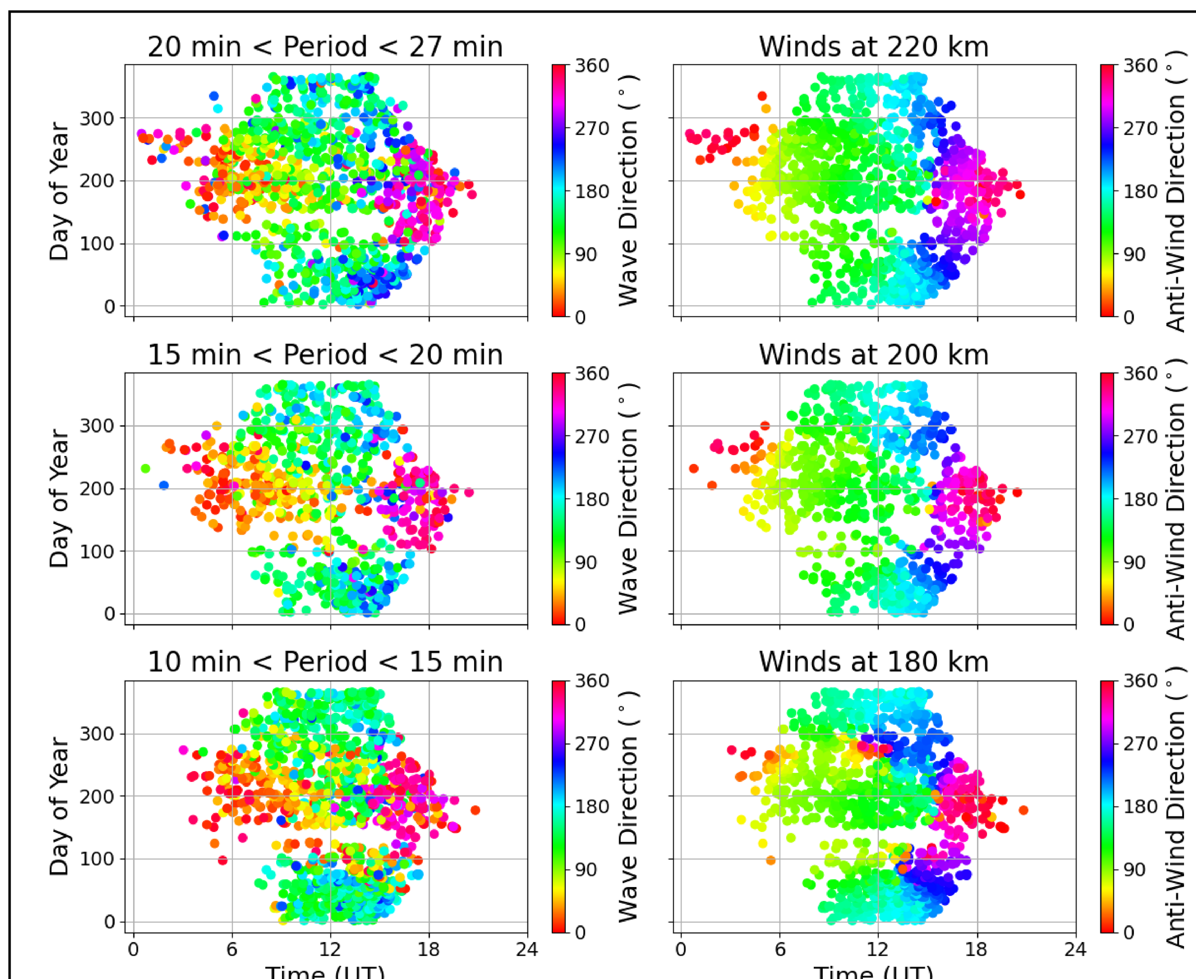

Figure 5: Observed wave propagation directions (left panels) and climatological thermospheric wind directions at the altitude of best match (right panels). Each row shows a different period range.

6: Summary

LOFAR provides a unique, highly sensitive means of studying structure in the mid-latitude ionosphere. The network of stations observing across a broad frequency range at high time resolution enable detailed investigation of the propagation and evolution of these structures, such as the TIDs considered here. The data obtained are useful for both case studies and larger statistical investigations, leveraging the large volume of observations made for astronomical surveys. LOFAR is particularly sensitive to TIDs with wavelengths of tens to a few hundred km, and is able to identify subtle features such as systematic variations of propagation direction with wave period and deviations from idealised sine wave perturbations.

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