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LOFAR observations of highly defined symmetric quasi-periodic scintillations

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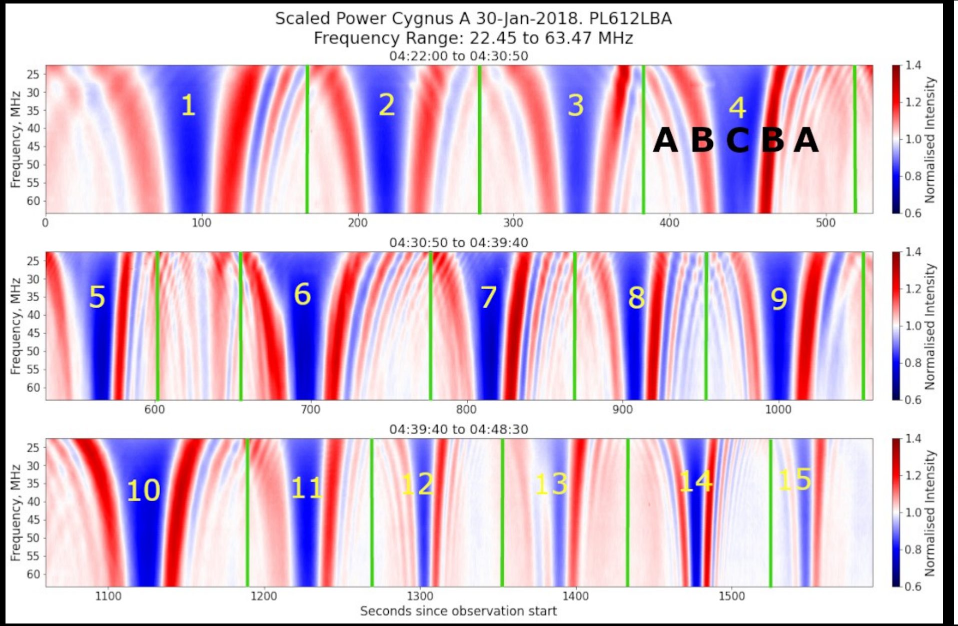
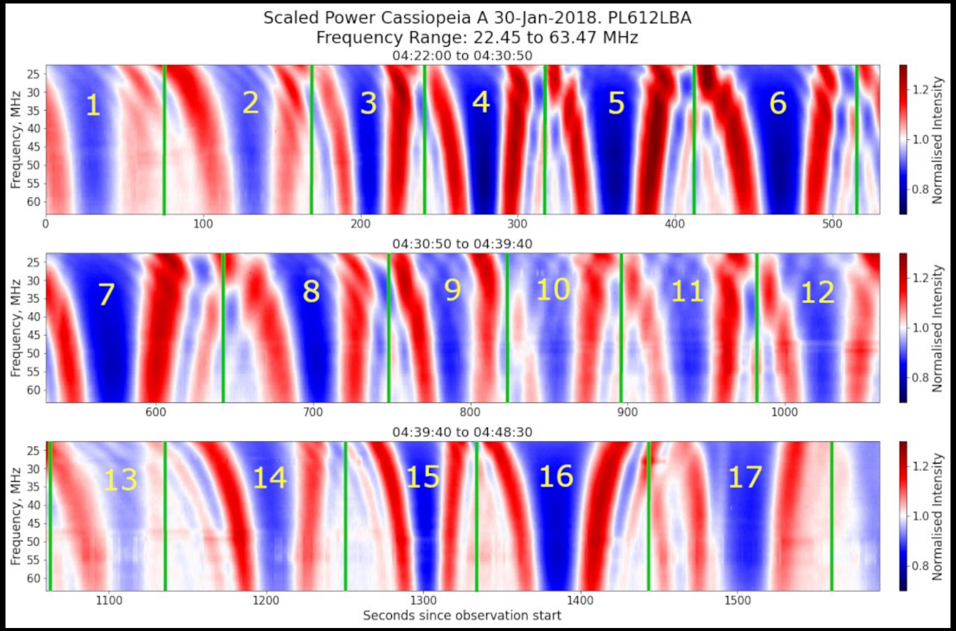
Introduction

- Quasi-periodic scintillations (QPS) are recurrent steady, non-random, trans-ionospheric radio scintillation features.
- Caused by blobs of ionospheric plasma with steep plasma density gradients at their peripheries
- Here we present two LOFAR case studies (pre-sunrise on 30^{th}. Jan 2018, evening on 15^{th}. Dec. 2016) under very quiet geophysical conditions (Kp <= 2+).
- First time features of this kind seen in broadband

Observations 30-Jan-2018

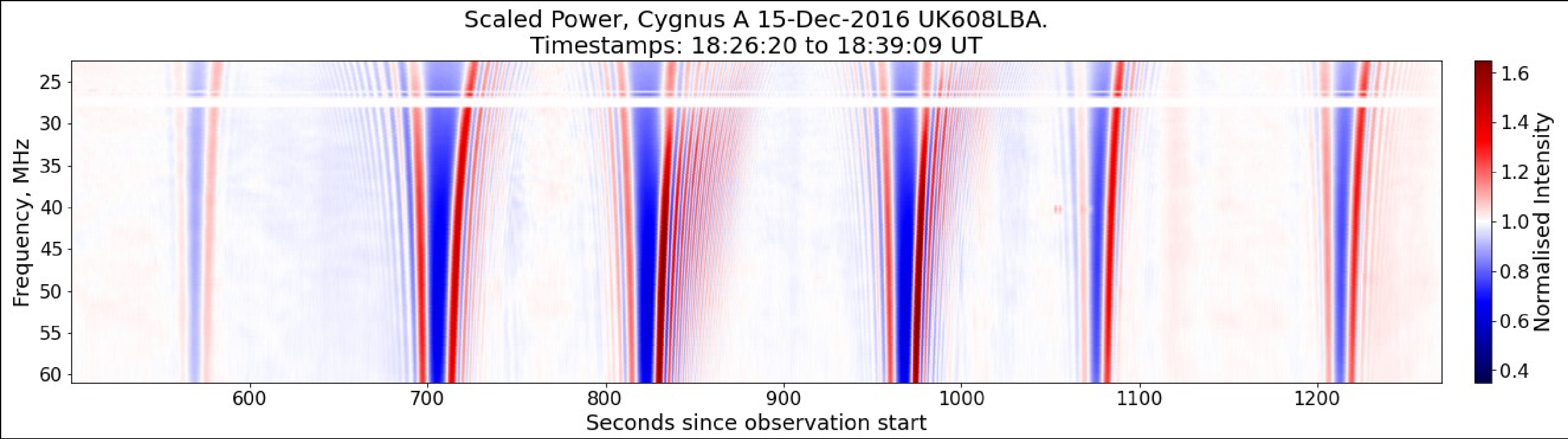




A : 'Ringing Irregularity' pattern
B : Boundary Signal Enhancement
C : Main signal fade / V-shaped fade

~24-minutes of sequential fades on both Cygnus-A & Cass-A

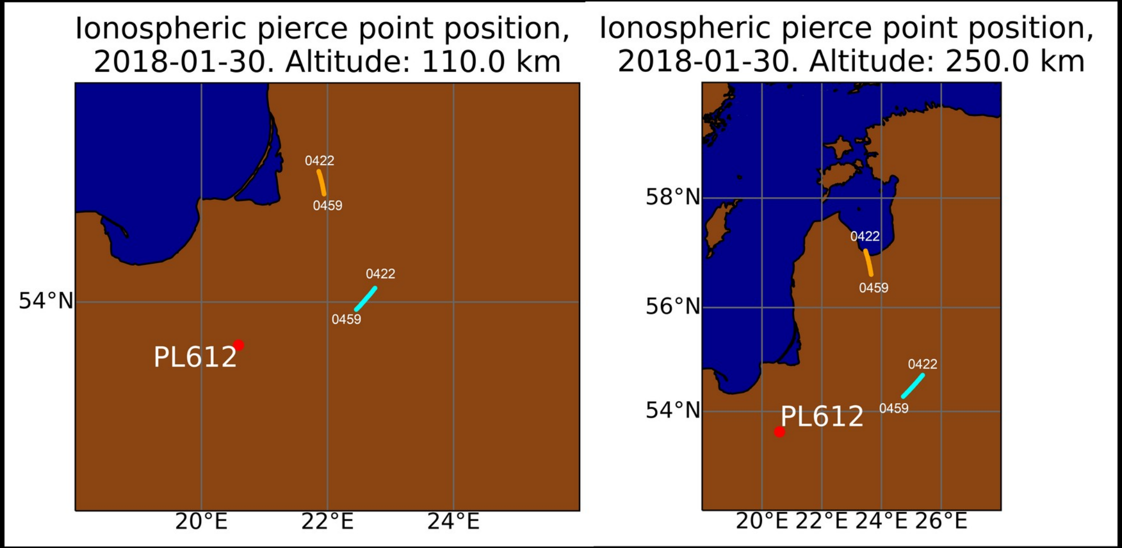
Observations 15-Dec-2016



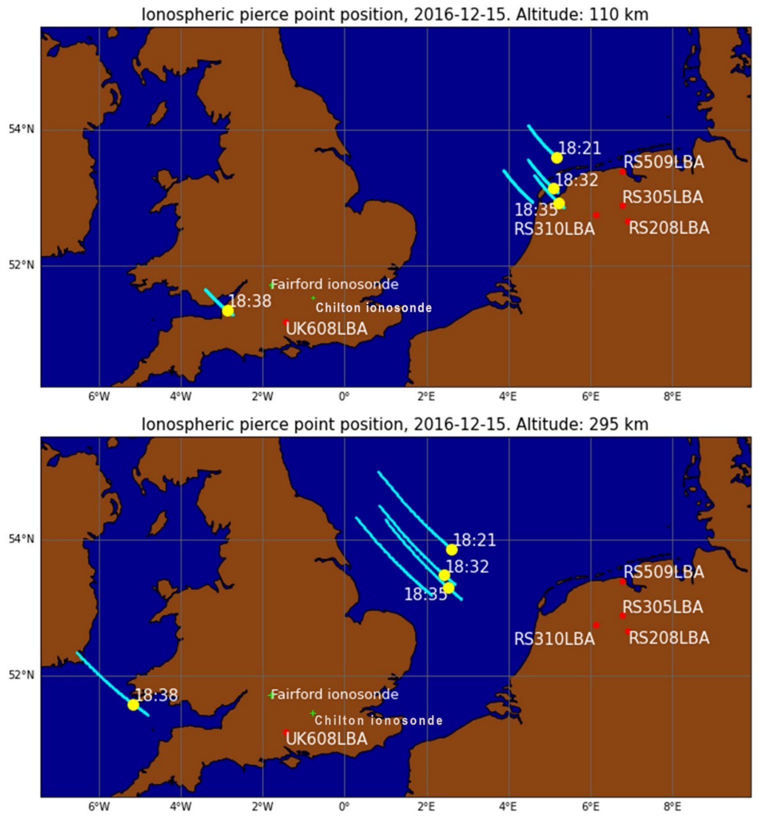
- Narrower main fades
- More highly defined ringing irregularities
- Shorter overall duration ~14 minutes
- Partial / fewer examples detected by few of the remote stations in Netherlands.
- Implies localised generation within a wider regional context

Geographical context

- Ionospheric-pierce-point (IPP) mapping using spherical Earth approximation
- IPP altitudes projected to 110 km & 250 km (E- & F-region of ionosphere)
- Blue arcs for Cyg-A, orange for Cass-A
- All IPPs rotate clockwise along respective arcs



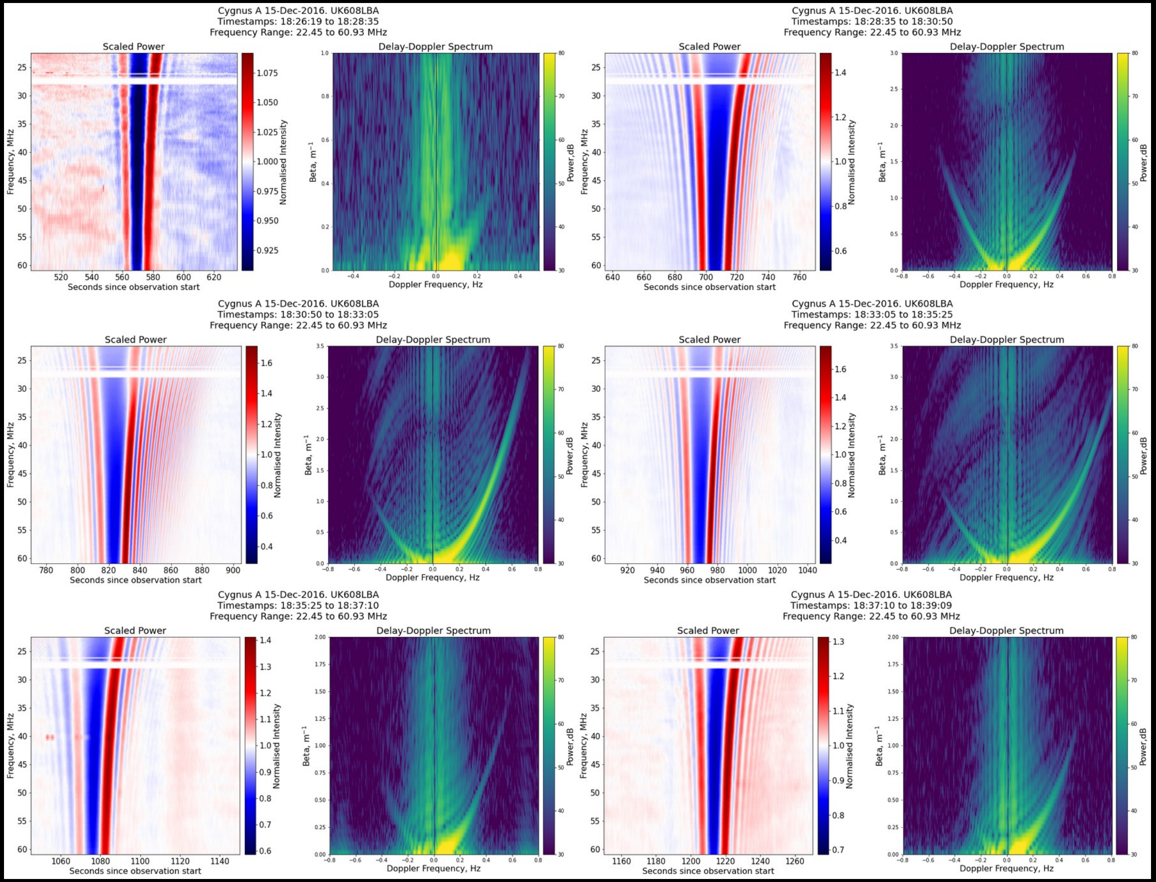
QPS present for full arc length in 2018 observations



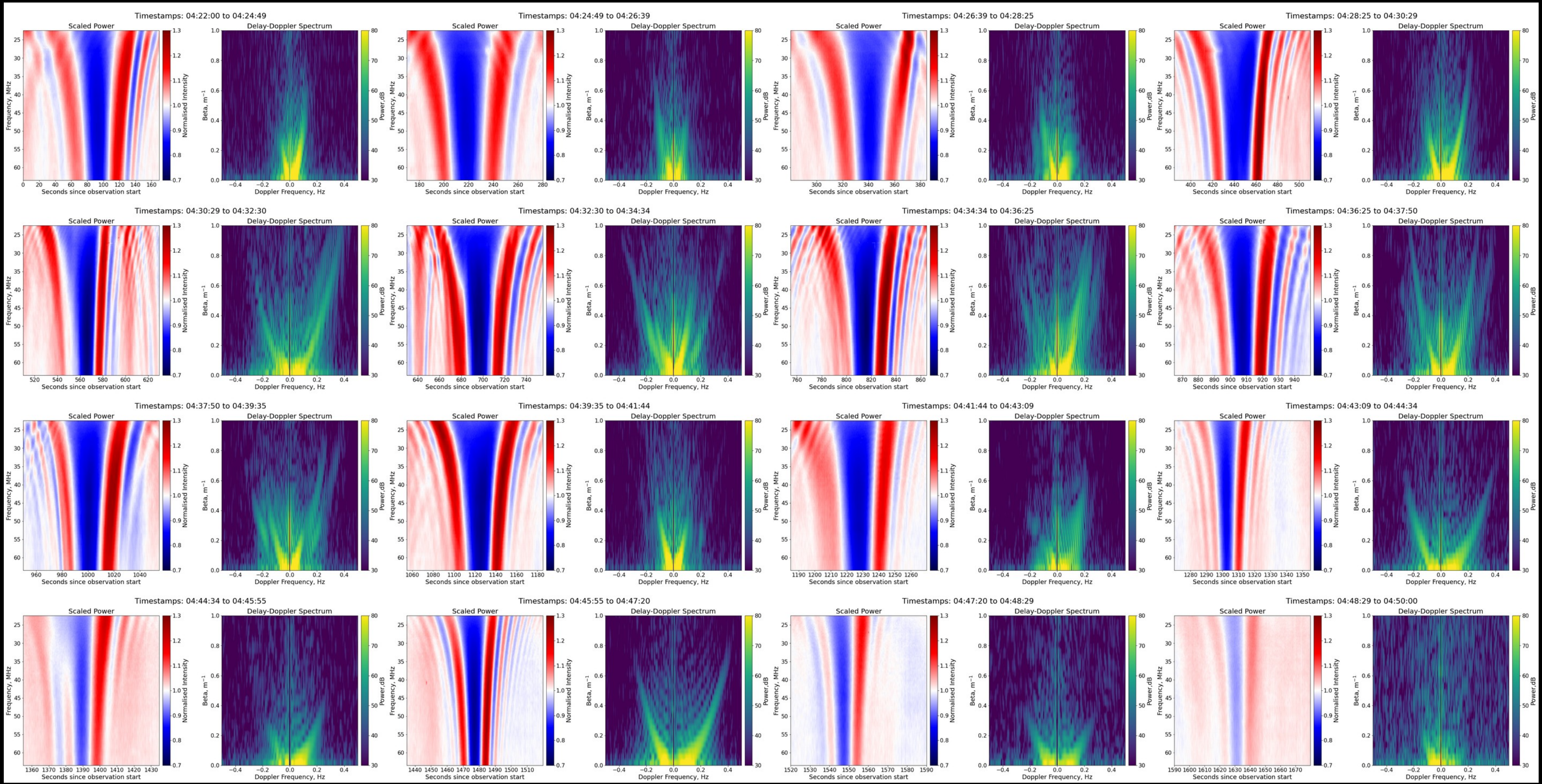
- Yellow spots indicate position and time of QPS detections in 2016 observations
- Green spots show ionosonde positions

Delay-Doppler Spectra Dec-2016

- Delay-Doppler spectrum (DDS) is the 2D Fourier transform of the dynamic spectrum
- Curvature of scintillation arcs is related to velocity of plasma screen and distance from LOFAR station by
  - $L=2CV^2$
- Where:
  - L = Distance to scattering screen
  - C = Arc curvature
  - V = Plasma screen propagation velocity
- Full theory in Cordes et al., (2006)



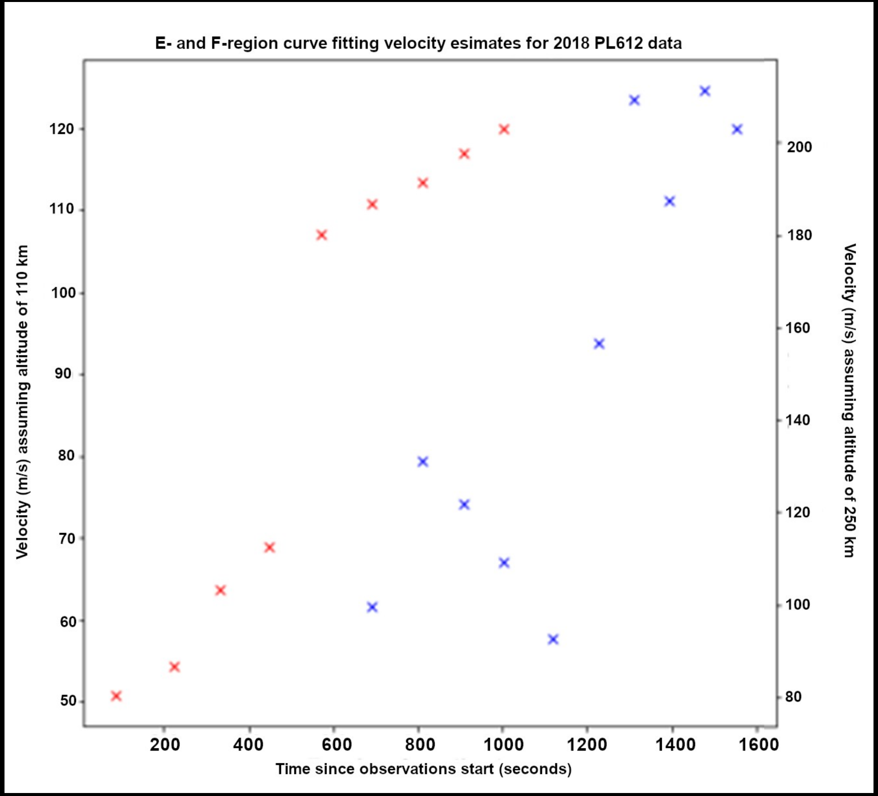
Delay-Doppler Spectra Jan-2018



Velocities estimations

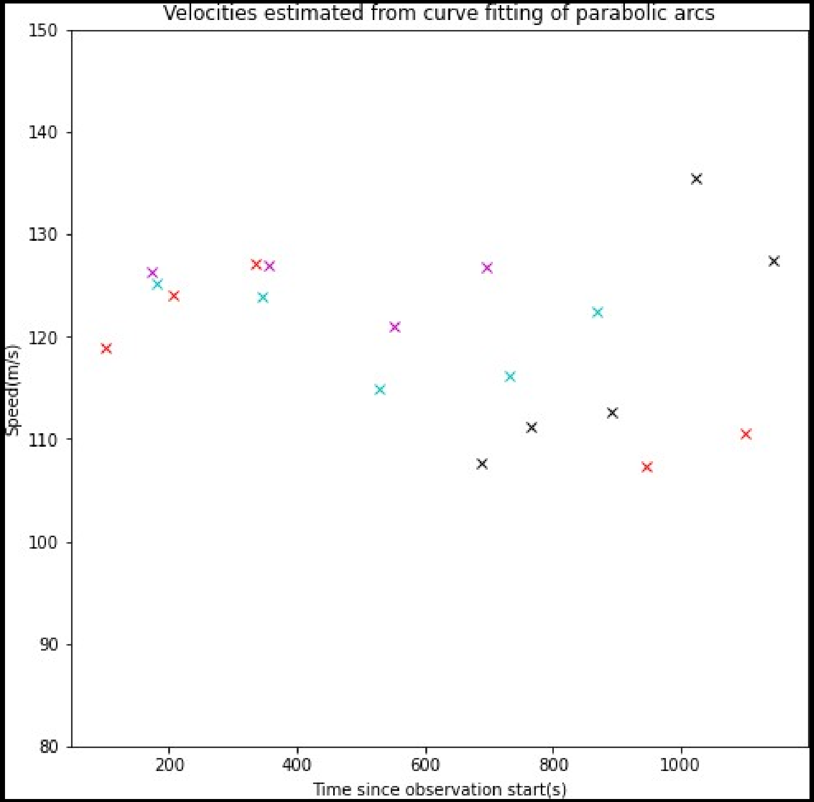
30th. Jan. 2018

Altitudes ambiguous due to absence of cotemporal ionsondes. Assumed either E- or F-region (110 km or 250 km). Shows acceleration.



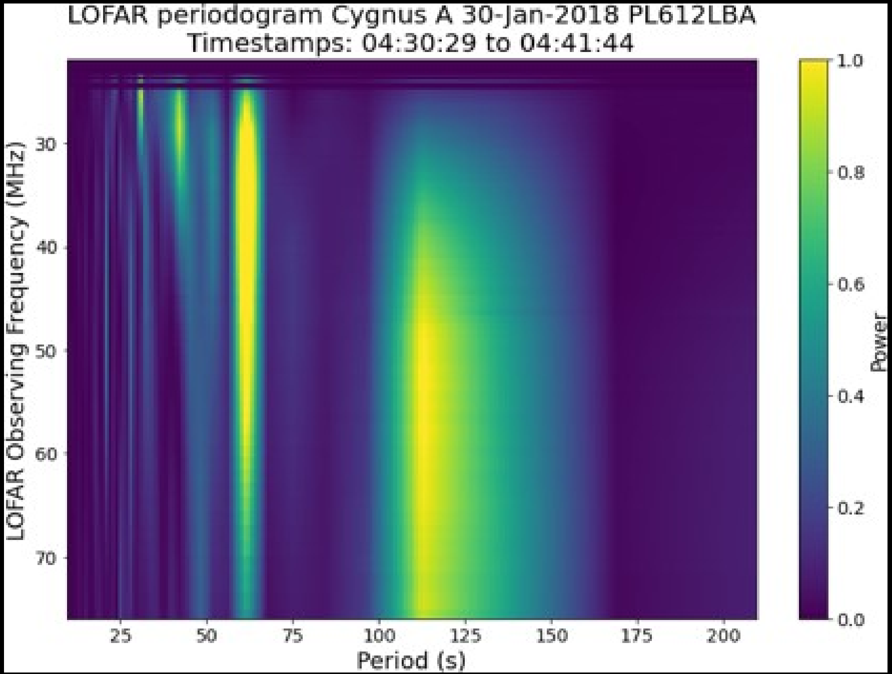
15th. Dec. 2016

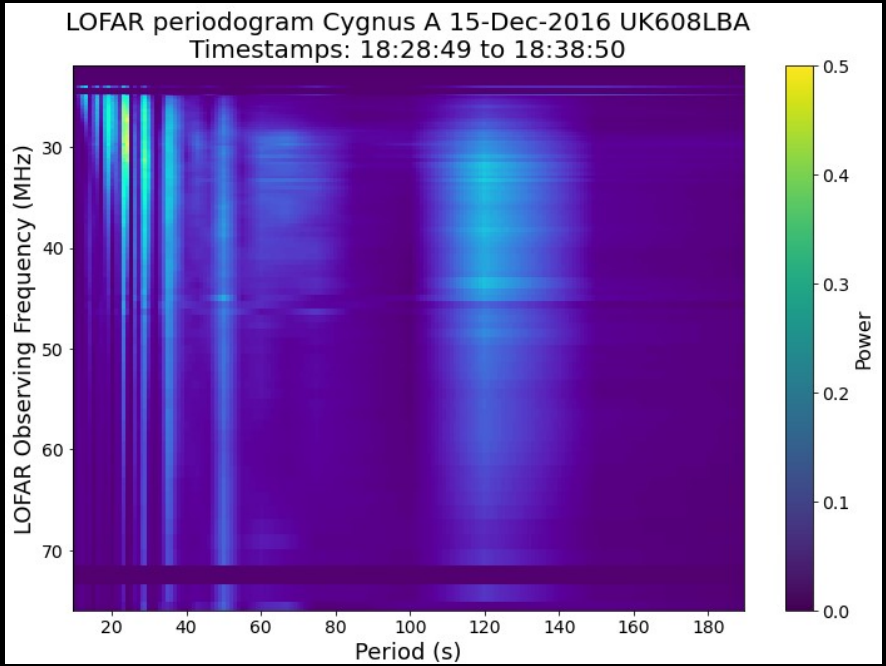
Altitude established from local ionosonde (110 km). Colours indicate different LOFAR stations. Steadier velocity.



Periodograms and size scales

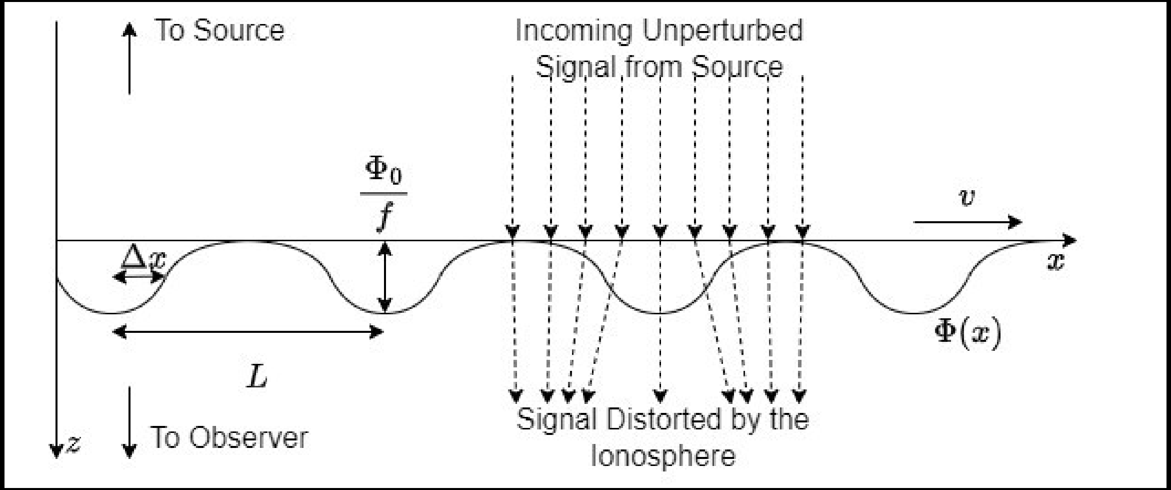
- Both cases exhibit primary periodicities of ~120 sec, with shorter periods corresponding to ringing irregularities
- At velocities estimated (~150 ms^{-1}) corresponds to spacing between main fades (and hence causal plasma blobs) of ~20 km.
- Plasma blobs themselves are, hence, < 20 km in size.





Thin phase screen modelling

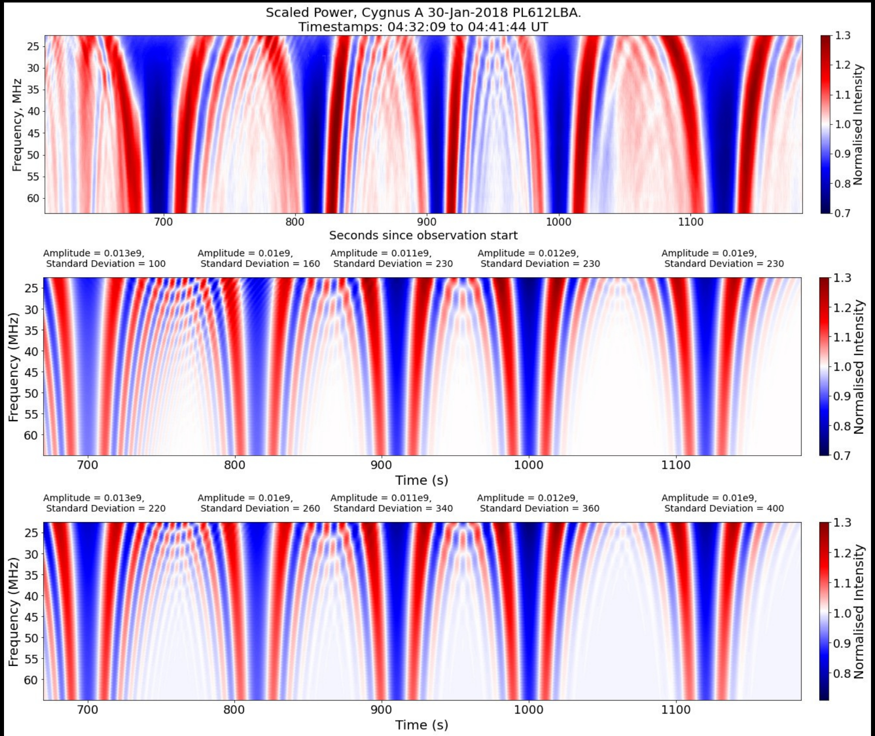
- Uses Gaussian thin-screen phase model to reproduce LOFAR dynamic spectrum
- Based on model developed by Boyde et al., (2022).
- Model can be tuned visually to approximate the original LOFAR dynamic spectrum
- Inputs include propagation velocity of the phase screen (v), observer position (x,z), initial phase (Φ), and observing frequency (f), distance between peaks (L).

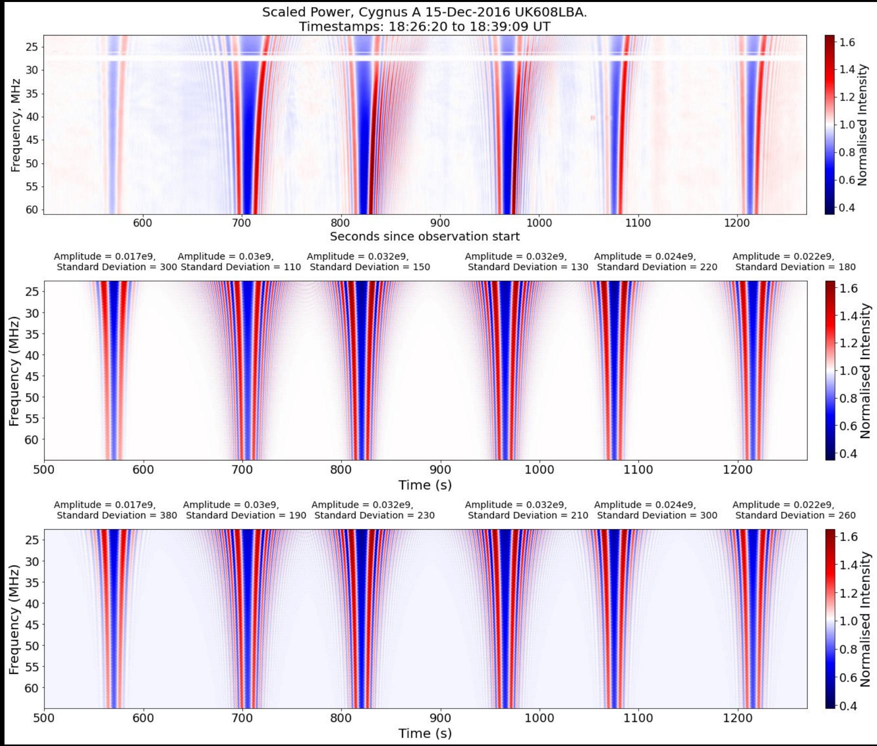


$$\Phi(x,t) = \sum_{i=0}^{n} \frac{\Phi_{0i}}{f} \exp\left(\frac{(x - x_i - vt)^2}{2\Delta x_i^2}\right)$$

Thin phase screen modelling

- Model run for altitudes of 110 km and 250 km in both case studies
- In both cases model well reproduces original LOFAR dynamic spectrum
- Both cases required very small phase distortions equivalent to < 0.01 TECu (very small!)





Conclusions

- LOFAR is highly sensitive to extremely small amplitude phase distortions in the ionosphere (< 0.01 TECu, threshold detectability with GNSS).
- Broadband capabilities and high cadence provide remarkable definition of QPS enabling fundamental physics experiments with ionospheric plasma induced radio scattering.
- Both events occurred during very quiet geophysical conditions (no solar flares, storms, CMEs, etc.). Likely to be terrestrially driven rather than solar wind driven.
- Highly reproducible with thin phase screen modelling.
- First time these features observed in broadband and with such high definition of ringing irregularities.

References

Trigg et al., (2024), Observations of high definition symmetric quasi-periodic scintillations in the mid-latitude ionosphere with LOFAR, *JGR Space Physics*, under review (https://arxiv.org/abs/2312.04387)

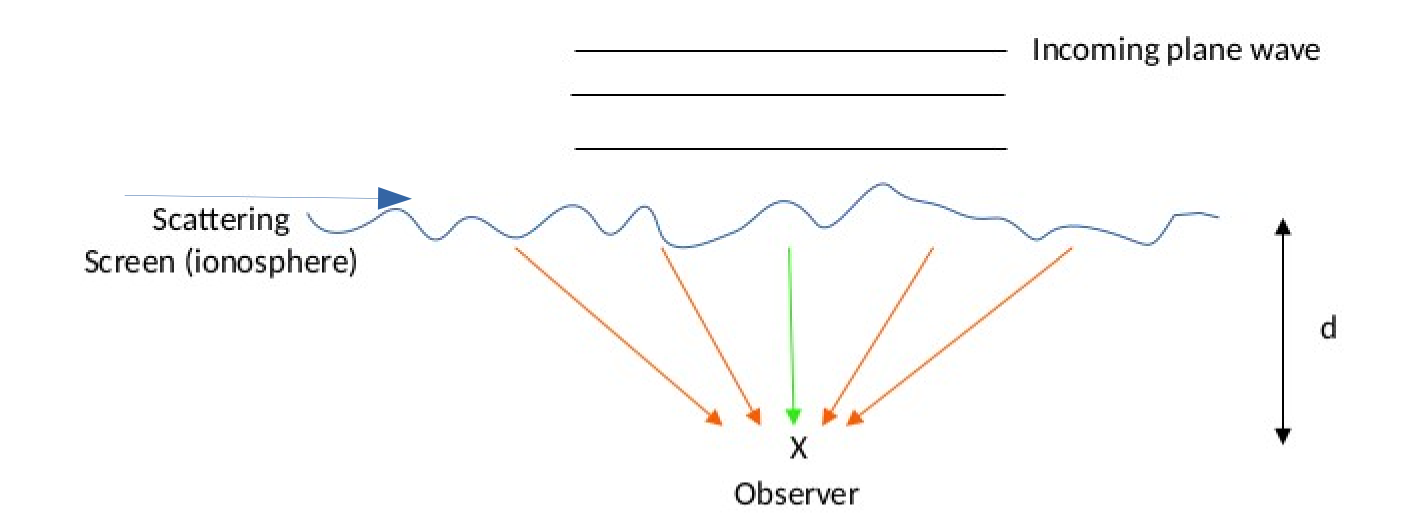
Boyde et al., (2022), Lensing from small-scale travelling ionospheric disturbances observed using LOFAR, *J. Space Weather Space Clim*., 2022, 12, 34, https://doi.org/10.1051/swsc/2022030

Cordes et al., (2006), Theory of parabolic arcs in Interstellar Scintillation Spectra, *ApJ*., 637, doi : 10.1086/498332

Hannah’s paper on arXiv

Appendix – scintillation arc formation

Consequence of Huygens spherical wavelet principle



Inhomogeneous scattering screen in motion generates pair-wise signals (orange arrows) with same delay as seen by observer. Motion adds Doppler effect. Combination thereof creates the arcs. Green arrow shows path of minimal signal delay and Doppler effect.