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SERENE SPACE ENVIRONMENT

Plasma structures in the ionosphere inferred from LOFAR observations of A-team radio sources

Alan Wood[1], Gareth Dorrian[1], Ben Boyde[1] and Richard Fallows[2]

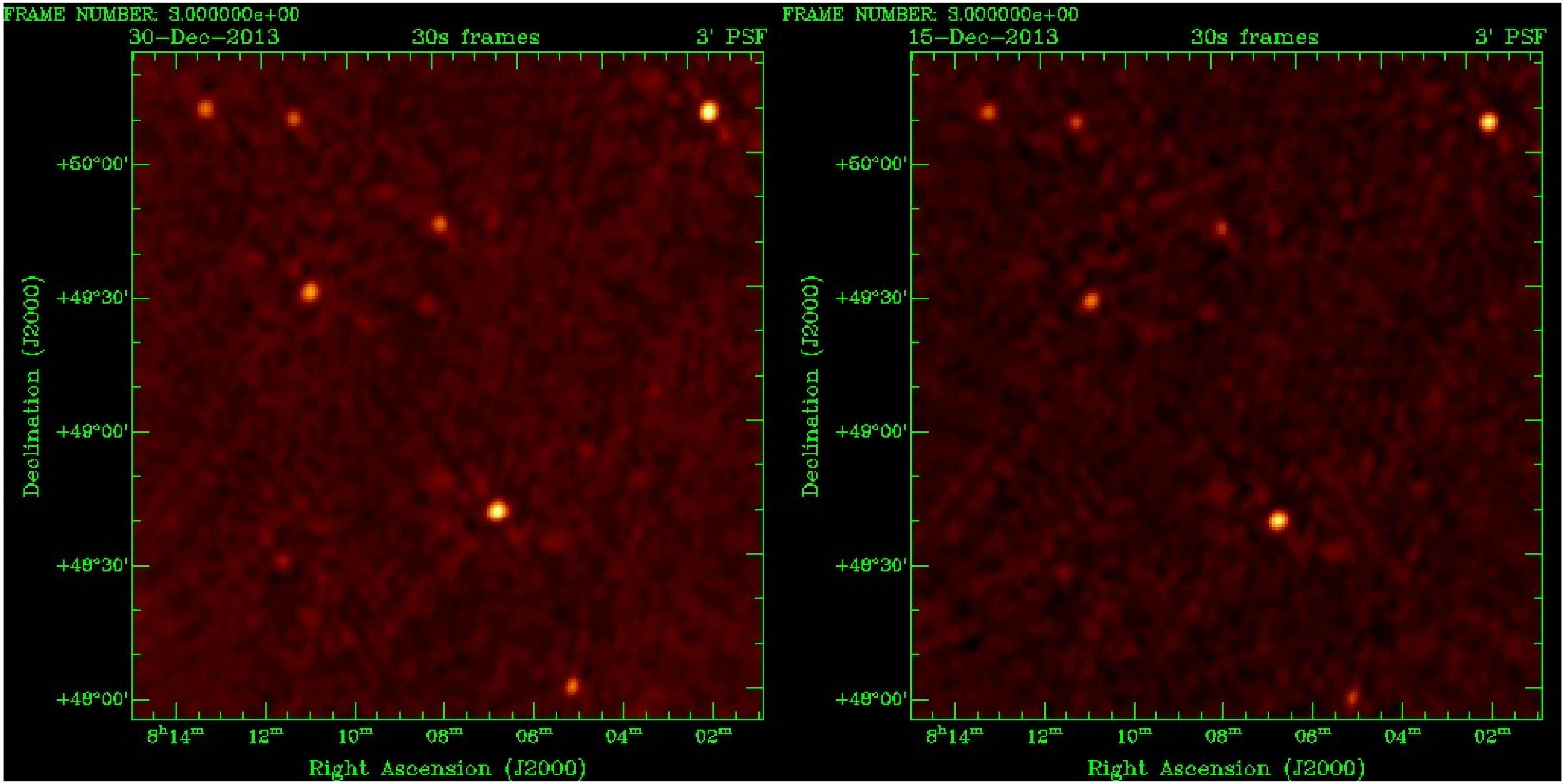
[1] Space Environment and Radio Engineering (SERENE) group, University of Birmingham, UK
[2] Rutherford Appleton Laboratory, UK

A four year research programme supported by the Leverhulme Trust (RPG-2020-140)

LEVERHULME TRUST

Plasma Structures in the Mid-Latitude Ionosphere

Observations of natural radio sources



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SERENE SPACE ENVIRONMENT

Image Credit: Gre de Bruyn, Astron

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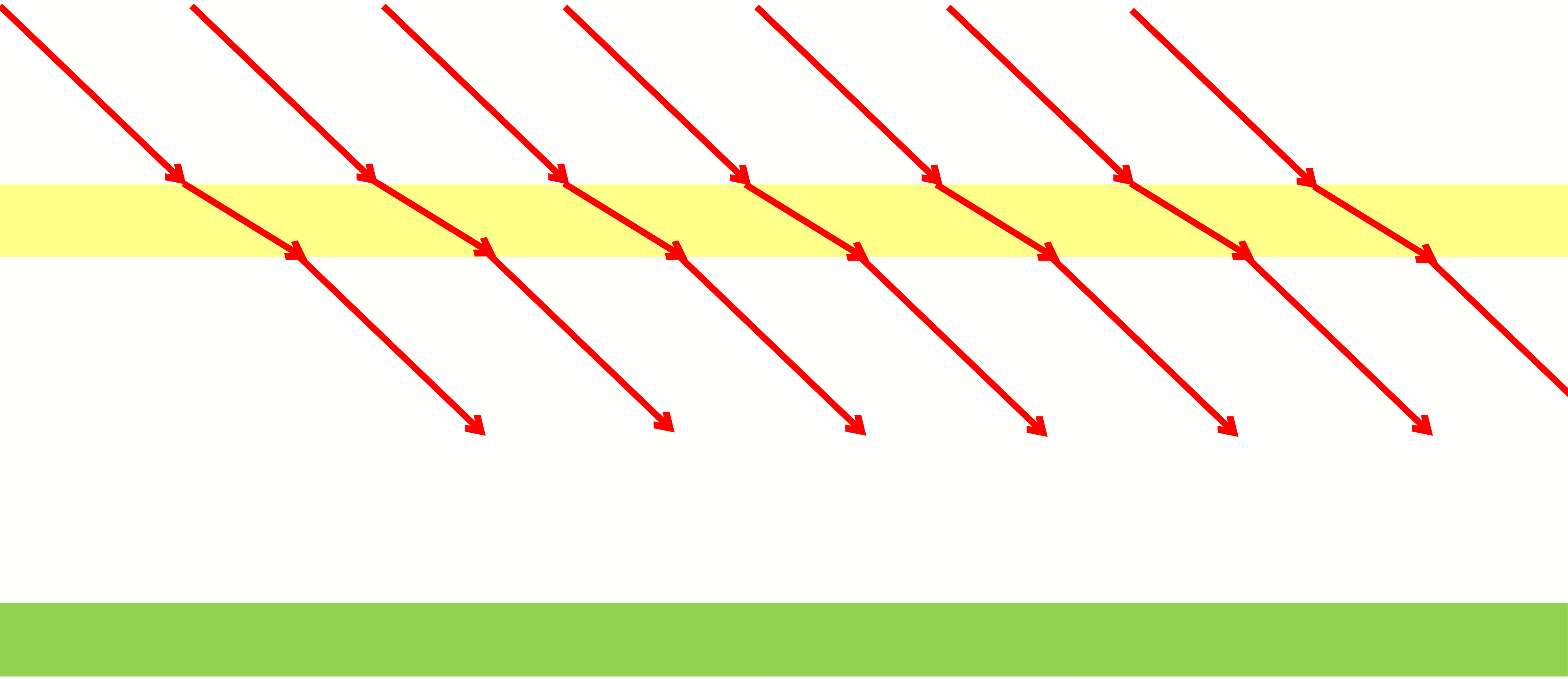
Uniform Plasma Density: Refraction



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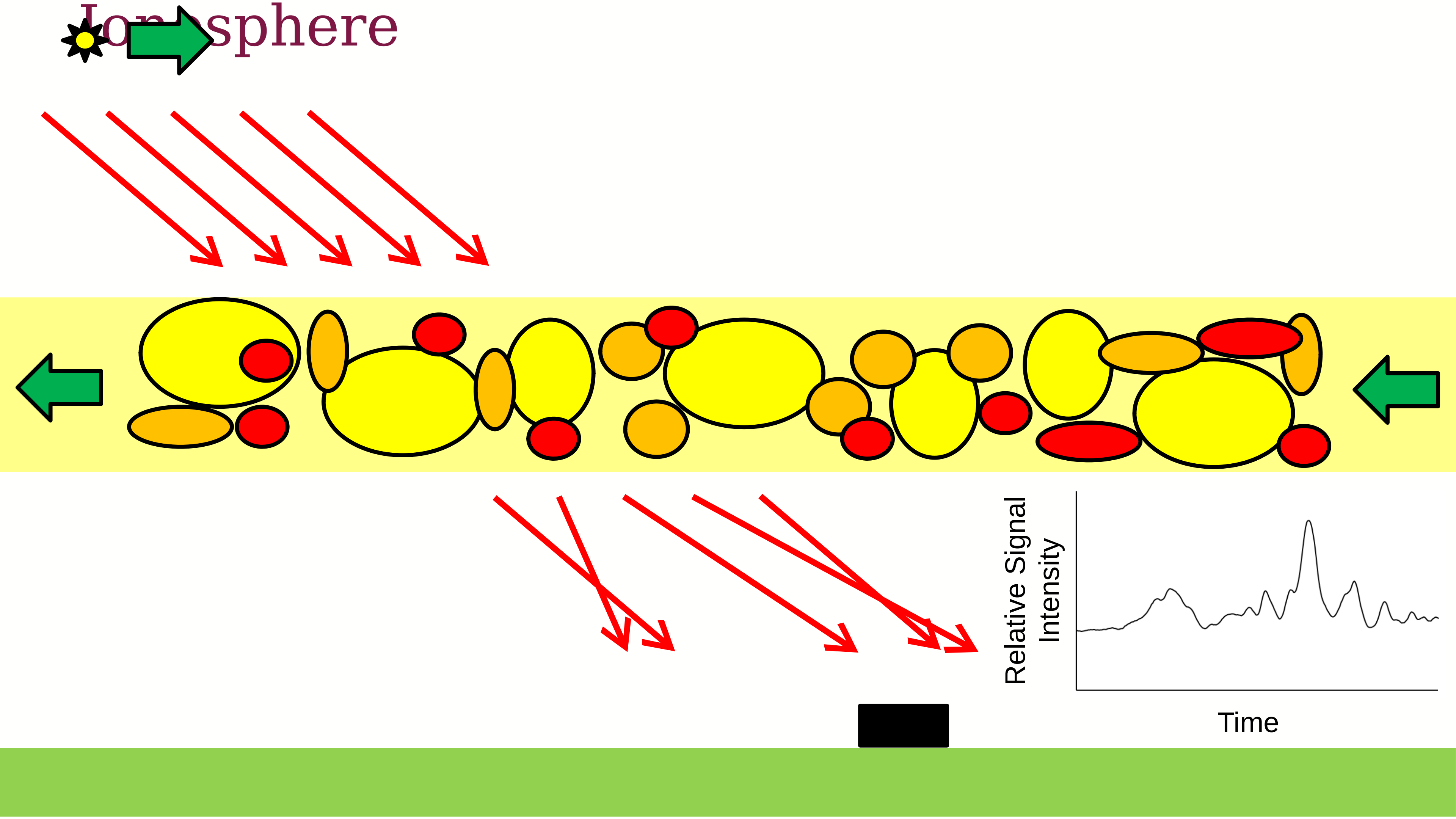
Plasma Structures in the Mid-Latitude Ionosphere



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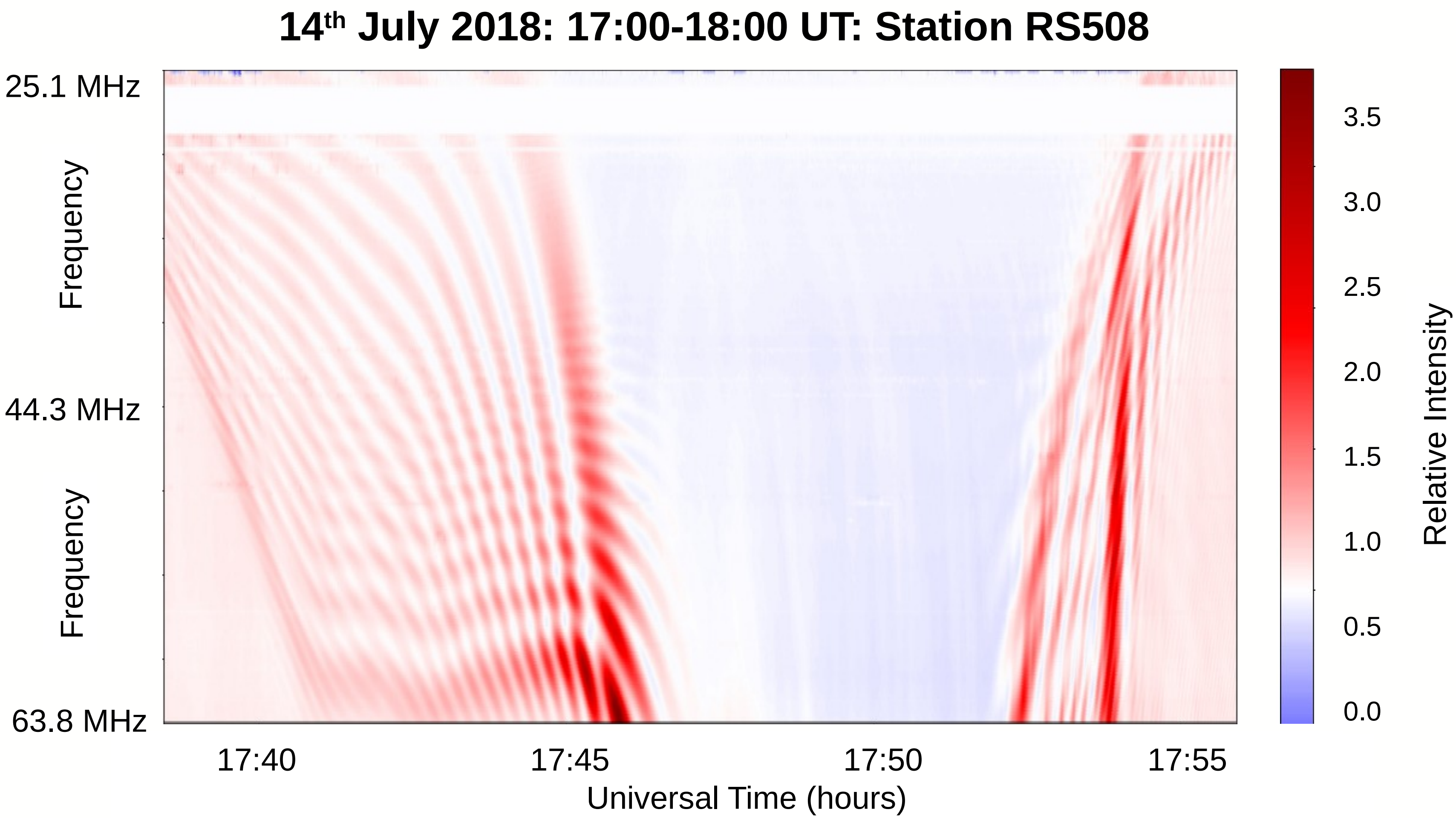
14th July 2018: Cygnus A: LOFAR



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Plasma Structures in the Mid-Latitude Ionosphere

Observations inferred from LOFAR at 10-80 MHz & 110-250 MHz

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SERENE SPACE ENVIRONMENT

Image Credit: Astron

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Cygnus A: 14th July 2018

A sporadic-E layer in the ionosphere

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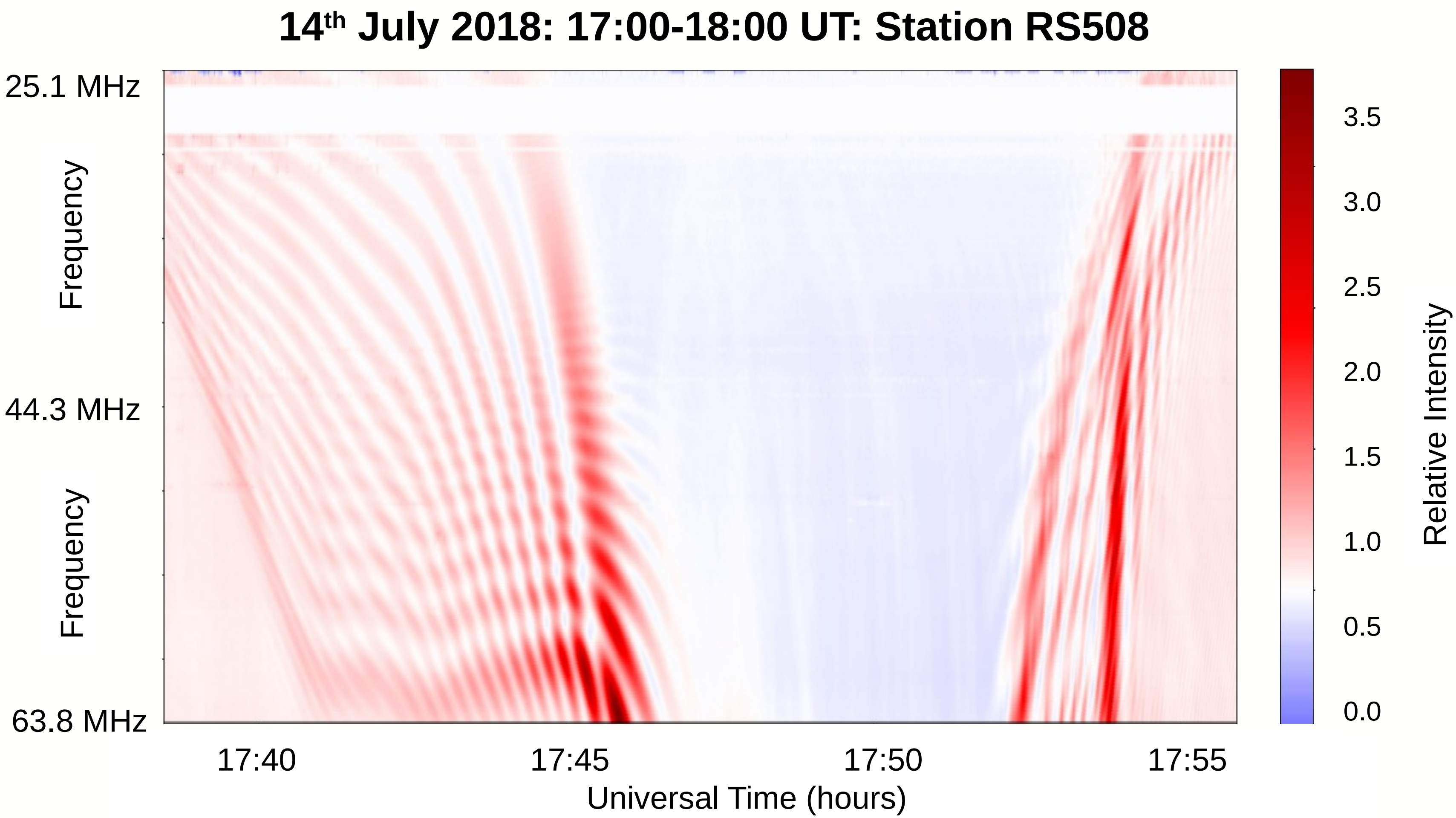
SERENE SPACE ENVIRONMENT

14th July 2018: Cygnus A: LOFAR



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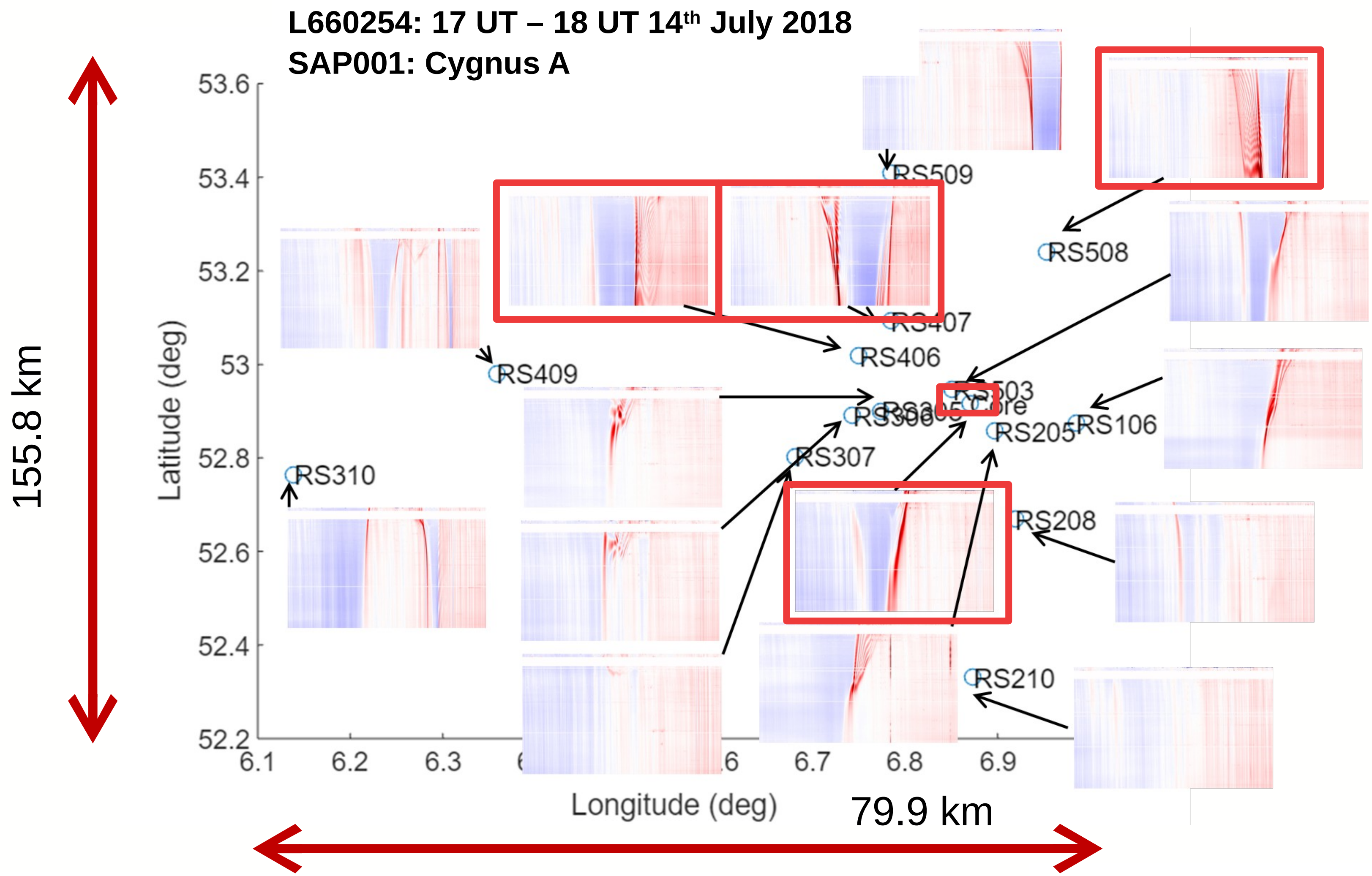
Cygnus A: LOFAR Observations

Source Az: 69° El: 37°

North east of stations



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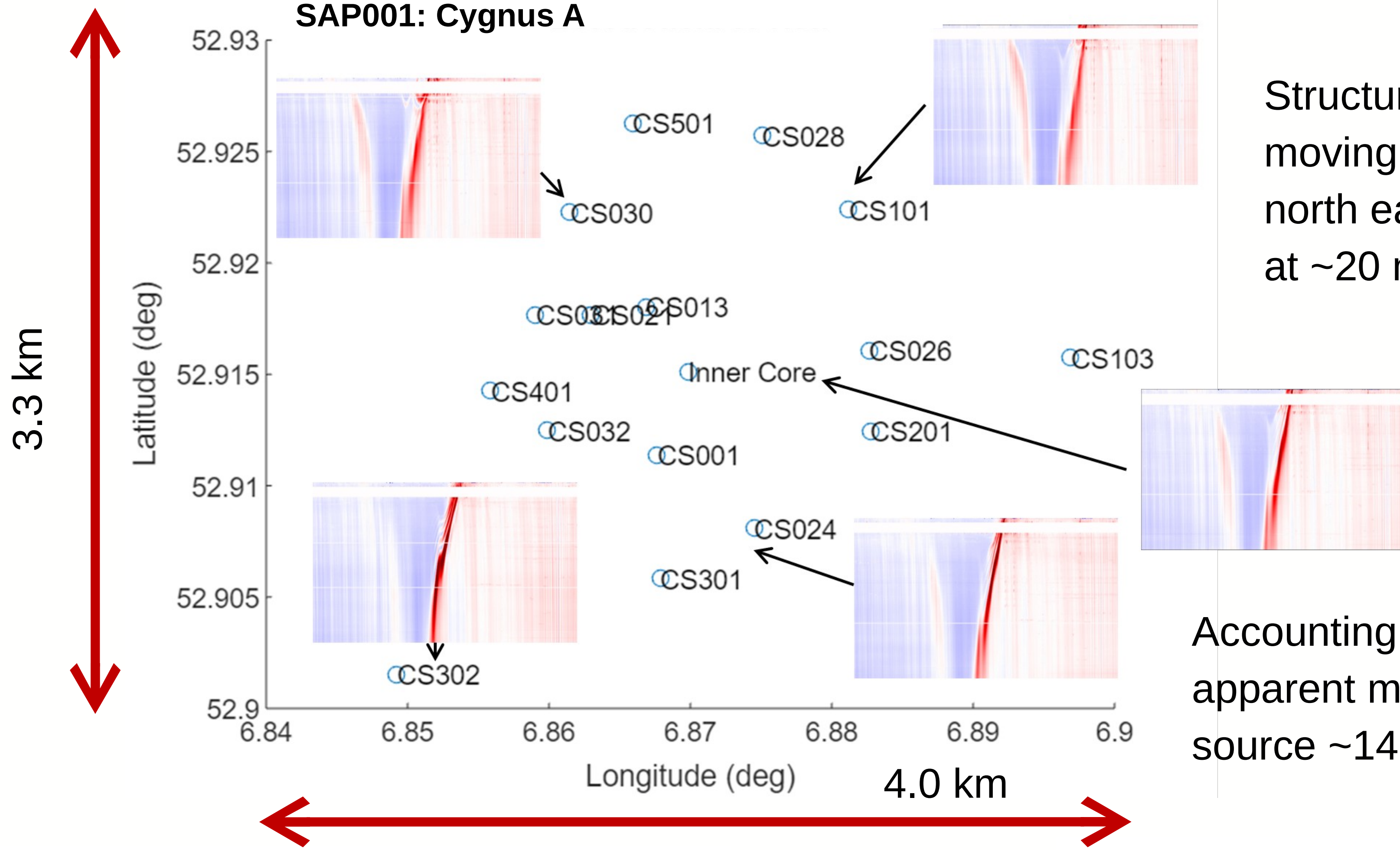
Cygnus A: LOFAR Core

Source Az: 69° El: 37°

North east of station

L660254: 17 UT – 18 UT 14th July 2018
SAP001: Cygnus A



Structure is moving north east at ~20 m s^{-1}

Accounting for apparent motion of source ~14 m s^{-1}

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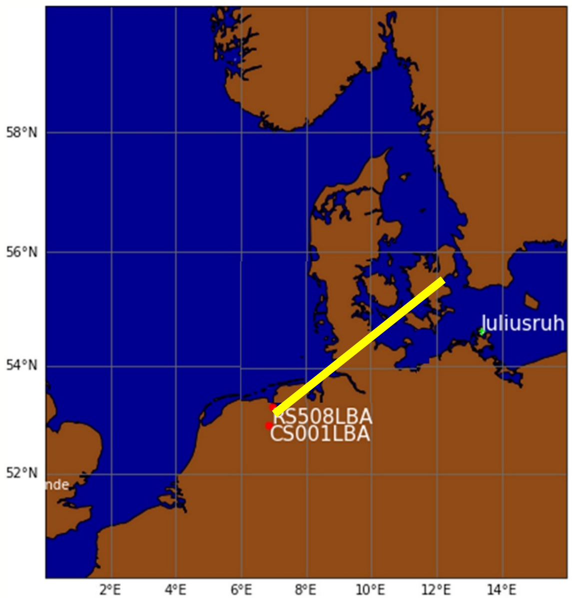
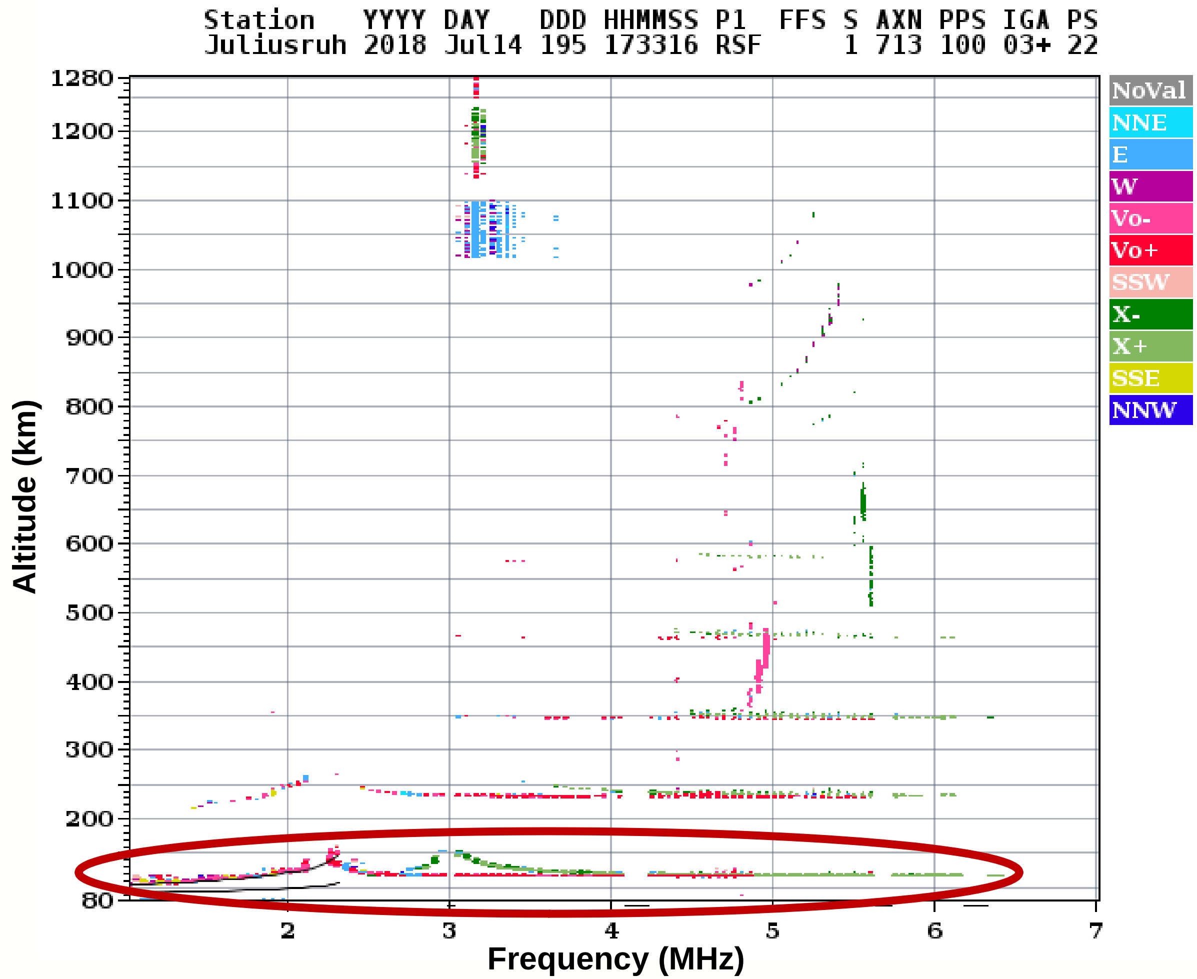
Juliusruh Ionosonde





Observe plasma density enhancement between 17 UT and 18 UT

Interpret as Sporadic-E

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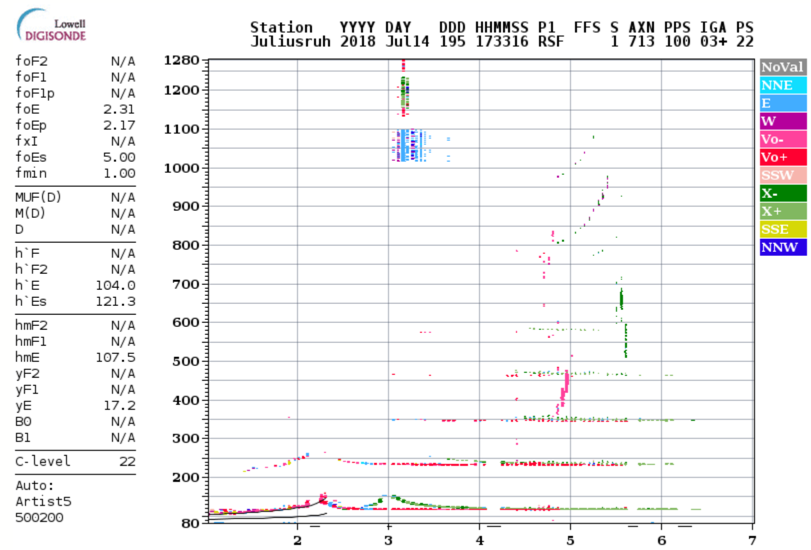
Juliusruh Ionosonde

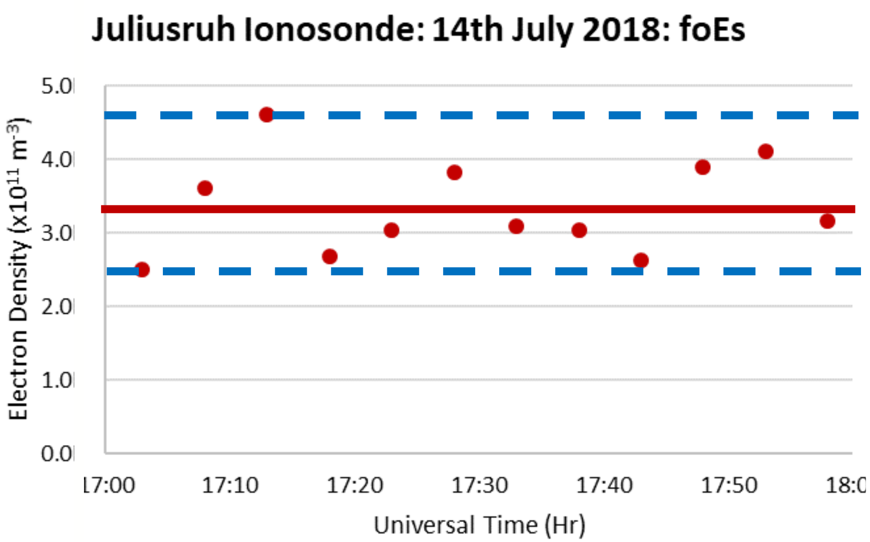
Sporadic-E

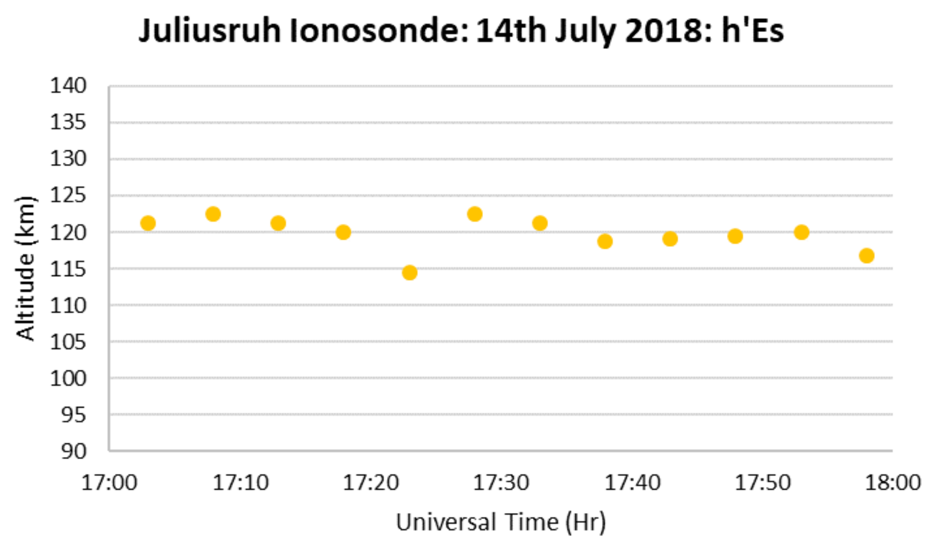
Height: ~120 km

Density: ~3.3×10^{11} m^{-3}

(Min: 2.5×10^{11} m^{-3}; Max: 4.6×10^{11} m^{-3})







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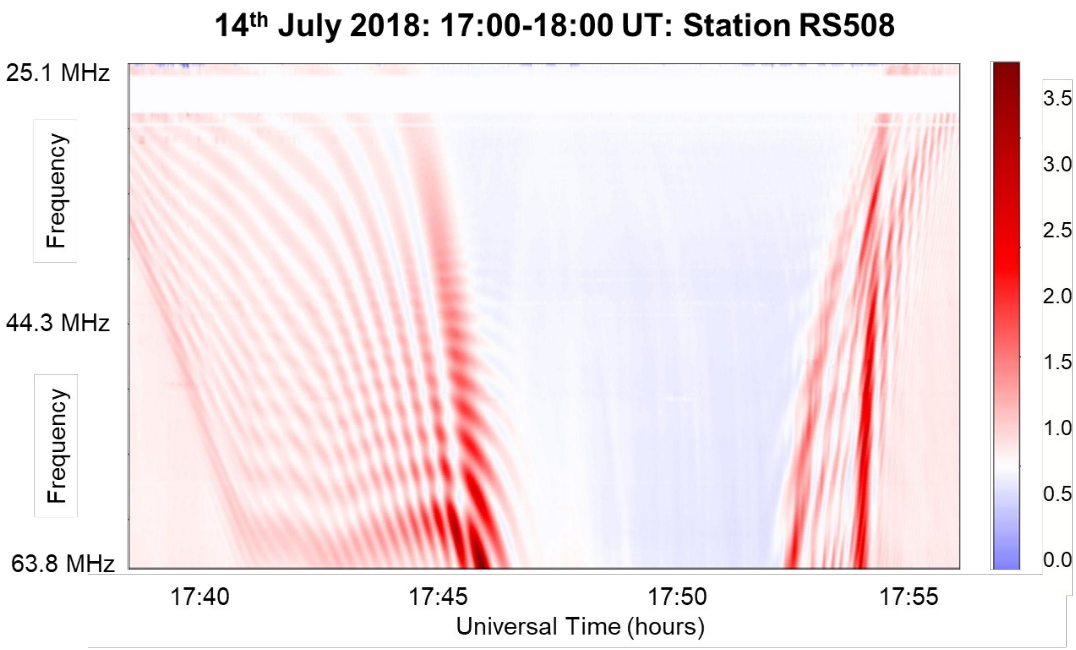
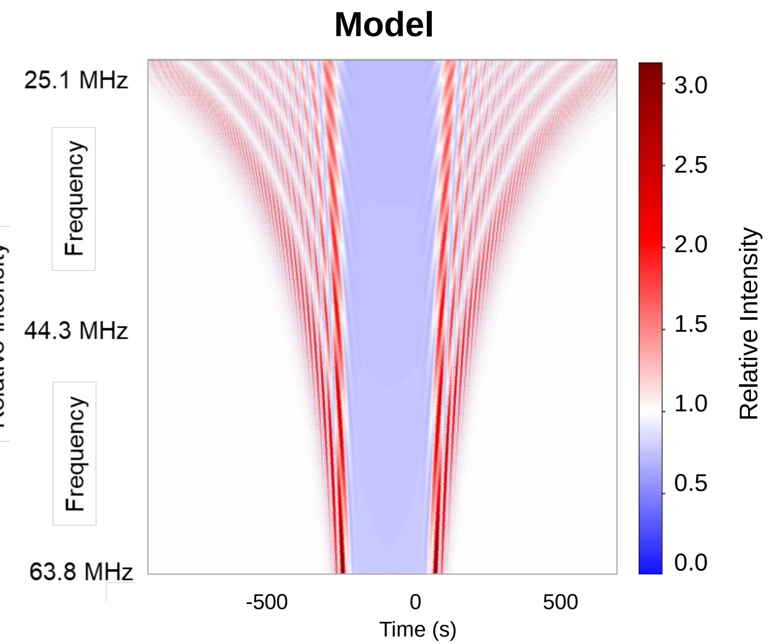
Modelling: 14th July 2018





Use a Gaussian to model a density variation of ~2×10^{11} m^{-3} in a layer ~10 km thick

1. Amplitude of Gaussian in terms of phase change, 1.7×10^{9} rad Hz
2. Standard deviation of Gaussian, 1 km
3. Altitude, 120 km
4. Elevation of source, 37 degrees
5. Velocity of plasma, 20 m/s

Model assumes that the path to the source is perpendicular to the phase screen

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Cygnus A: 15th September 2018

A Small-Scale Travelling Ionospheric Disturbance (SSTID)

Work by Ben Boyde

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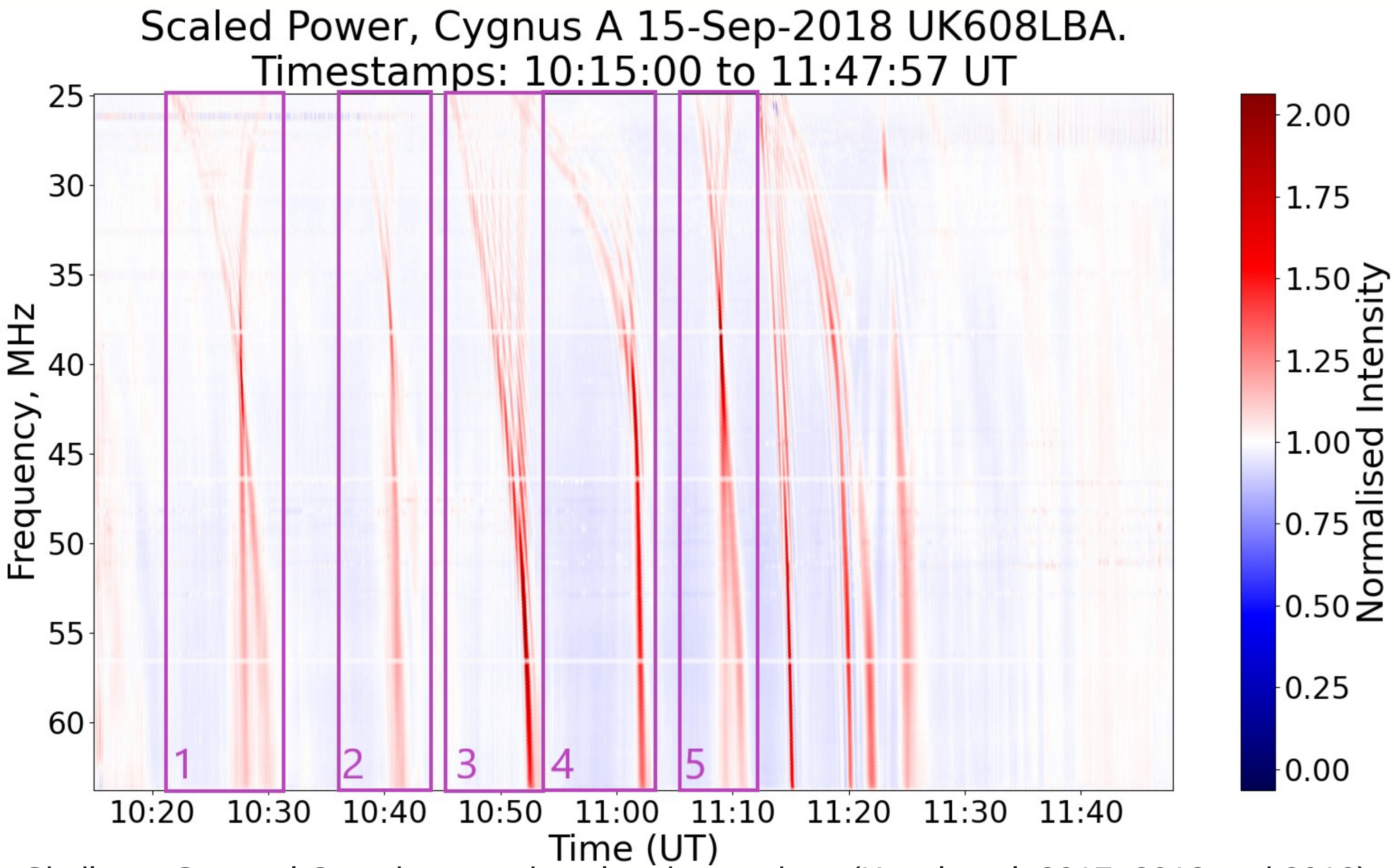
Small Scale (λ<30km) TID



Similar to Spectral Caustics seen in solar observations (Koval et al. 2017, 2018 and 2019)

Boyde, B., et al., J. Sp. Weather Sp. Clim. 12, 34, 2022. doi.org/10.1051/swsc/2022030

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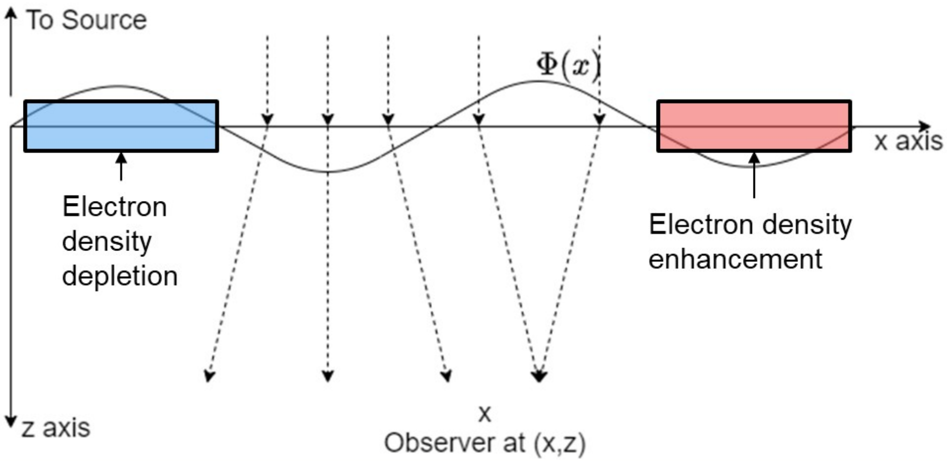
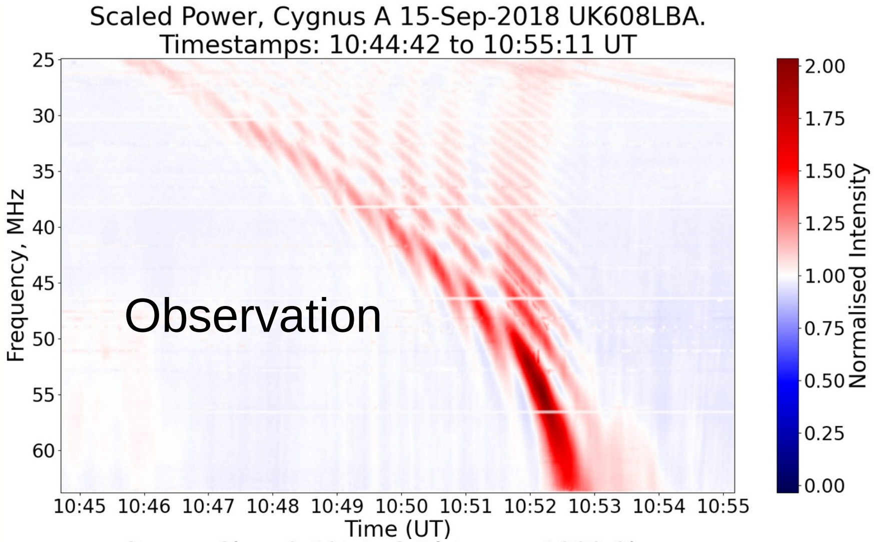
A Simple Phase Screen Model

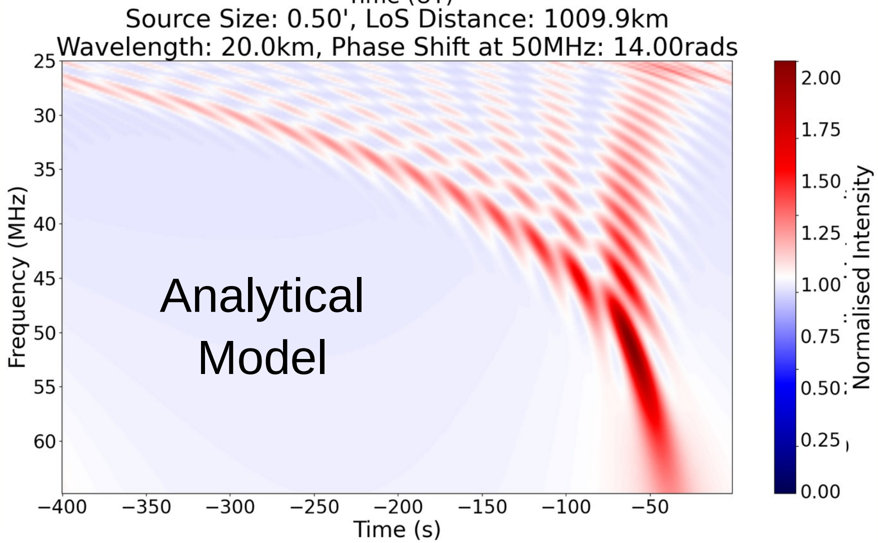
Treat the ionosphere as a thin phase screen containing sinusoidal variation, representing a Travelling Ionospheric Disturbance (TID)



Meyer-Vernet, N. (1980). On a day-time ionospheric effect on some radio intensity measurements and interferometry. *Astronomy and Astrophysics*, *84*, 142-147.

Comparing Model and Observations





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A Simple Phase Screen Model

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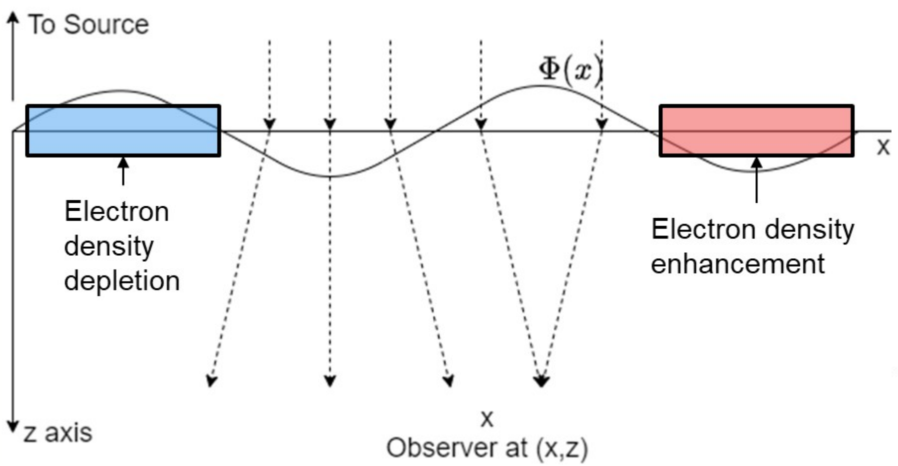
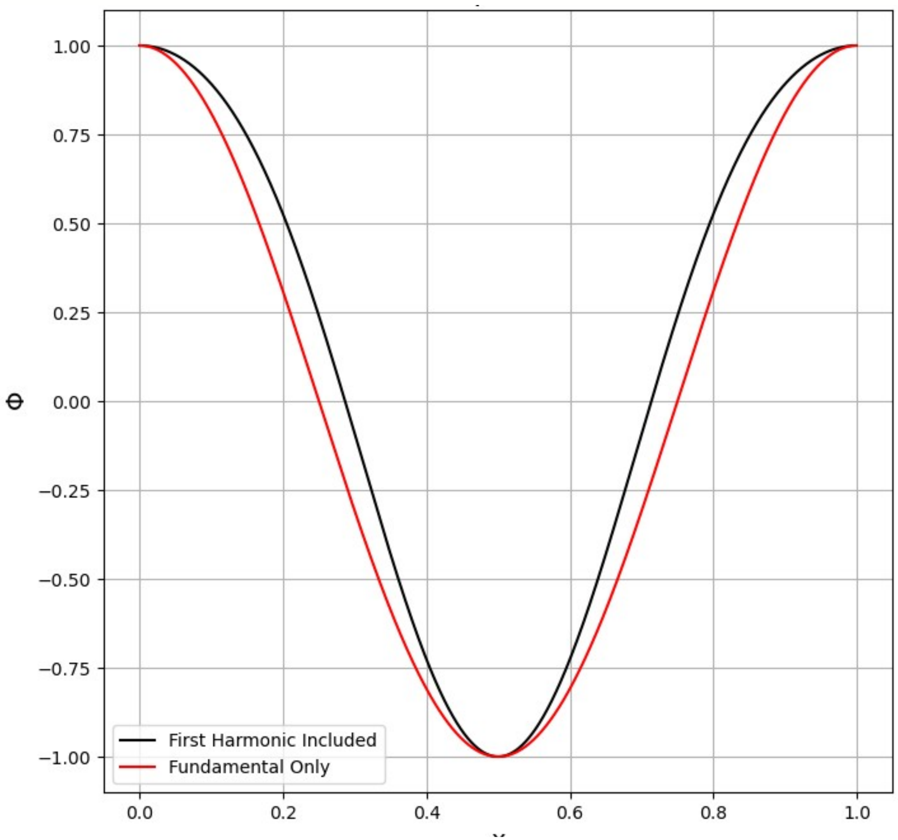


Meyer-Vernet, N. (1980). On a day-time ionospheric effect on some radio intensity measurements and interferometry. *Astronomy and Astrophysics*, *84*, 142 147.



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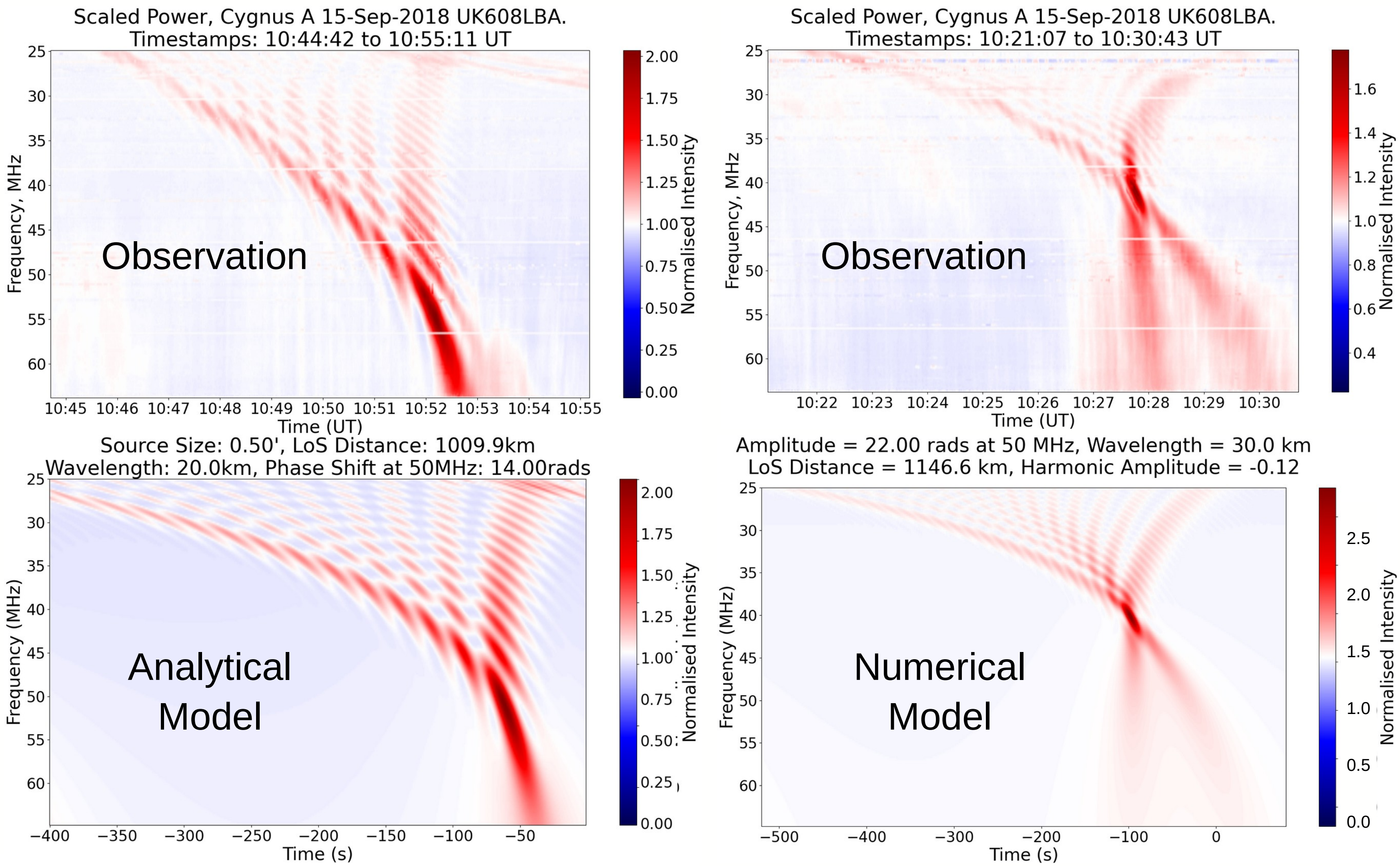
Comparing Model and Observations



Boyde, B., et al., J. Sp. Weather Sp. Clim. 12, 34, 2022. doi.org/10.1051/swsc/2022030

J. Space Weather Space Clim. 2022, 12, 34

https://doi.org/10.1051/swsc/2022030

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Research Article

Open Access

Lensing from small-scale travelling ionospheric disturbances observed using LOFAR

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[2] ASTRON – The Netherlands Institute for Radio Astronomy, Oude Hoogeveensedijk 4, 7991 PD Dwingeloo, The Netherlands
[3] Leibniz Institute of Atmospheric Physics at the University of Rostock, 18556 Juliusruh, Germany
[4] Space Radio-Diagnostics Research Centre, University of Warmia and Mazury, ul. Romana Prawocheskiego 9, 10-719 Olsztyn, Poland
[5] Leibniz-Institut für Astrophysik Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany
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Received 5 July 2022 / Accepted 28 August 2022

Abstract – Observations made using the LOw-Frequency ARray (LOFAR) between 10:15 and 11:48 UT on the 15th of September 2018 over a bandwidth of approximately 25–65 MHz contain discrete pseudo-periodic features of ionospheric origin. These features occur within a period of approximately 10 min and collectively last roughly an hour. They are strongly frequency dependent, broadening significantly in time towards the lower frequencies, and show an overlaid pattern of diffraction fringes. By modelling the ionosphere as a thin phase screen containing a wave-like disturbance, we are able to replicate the observations, suggesting that they are associated with small-scale travelling ionospheric disturbances (TIDs). This modelling indicates that the features observed here require a compact radio source at a low elevation and that the TID or TIDs in question have a wavelength <~30 km. Several features suggest the presence of deviations from an idealised sinusoidal wave form. These results demonstrate LOFAR's capability to identify and characterise small-scale ionospheric structures.

Keywords: Small-scale travelling ionospheric disturbance / phase screen / ionospheric physics

Cygnus A & Cassiopeia

Observational Campaign LT16_002

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Statistics from LT16_002

LT16_002: 1092 hours observing Cygnus A, September 2021 – November 2022

Event: Relative signal intensity at 44.5 MHz rises to 20 % above the median value

Shows the percentage of events in this category *(comparison to top row of table)*

UT	Sample		Events	
	Count	Proportion	Count	Proportion
All	1092	100%	251	100%
20-02 UT (night)	394	36%	124	49%
02-08 UT (dawn)	310	28%	53	21%
08-14 UT (day)	130	12%	22	9%
14-20 UT (dusk)	258	24%	52	21%

Season	Sample		Events	
	Count	Proportion	Count	Proportion
All	1092	100%	251	100%
Nov-Jan	461	42%	30	12%
Feb-Apr	424	39%	29	12%
May-Jul	309	28%	139	55%
Aug-Oct	171	16%	53	21%

F10.7 cm Solar Flux	Sample		Events	
	Count	Proportion	Count	Proportion
All	1092	100%	251	100%
Low (F10.7 <120)	638	58%	120	48%
Medium (120 <=F10.7	365	33%	81	32%
High (F10.7 >150)	89	8%	50	20%

Kp	Sample		Events	
	Count	Proportion	Count	Proportion
All	1092	100%	251	100%
Low (Kp <=2)	648	59%	198	79%
Medium (2 <Kp <=4)	393	36%	106	42%
High (Kp >4)	51	5%	10	4%

Effects of structures most commonly seen at night and in summer

Next: Develop a climatology and compare to climatologies of other features (sporadic-E, MSTIDs etc.)

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Calibration Solutions: dTEC

Work by Ben Boyde

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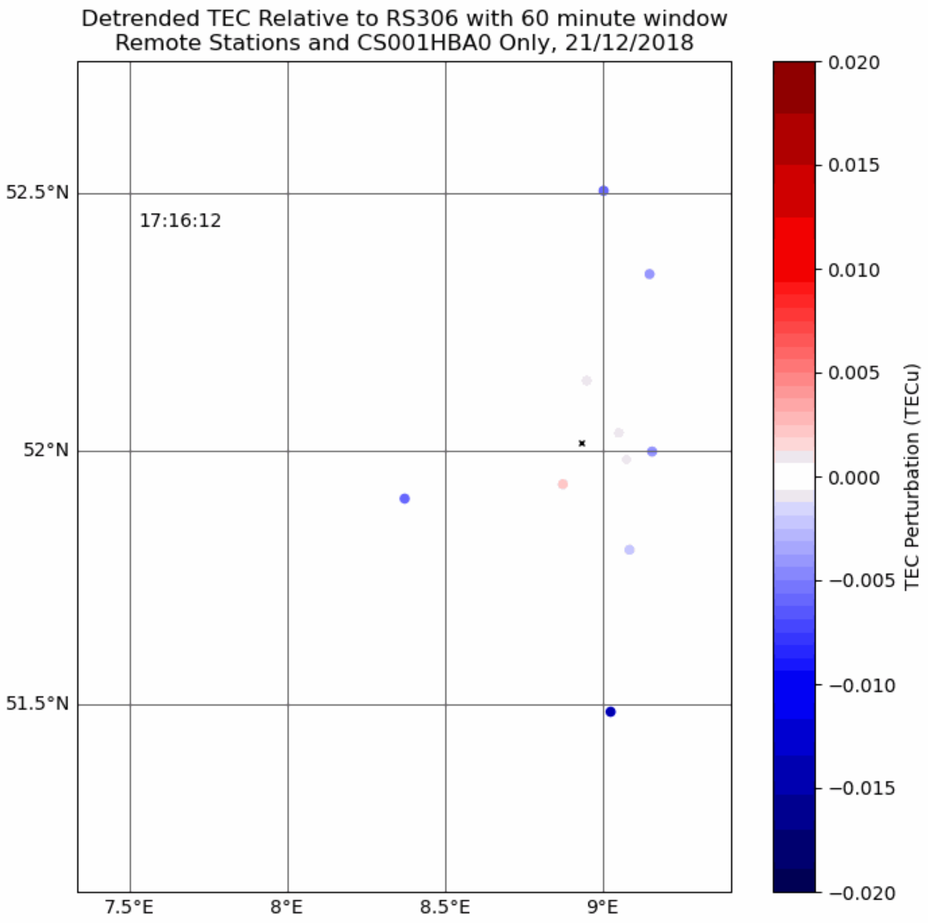
Calibration Solutions: dTEC

Waves in the ionosphere

Using dTEC from calibration solutions

Over 1,000 hrs of data from LBA survey

Case study, statistical study to follow



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Interstellar and Ionospheric Scintillation Arcs

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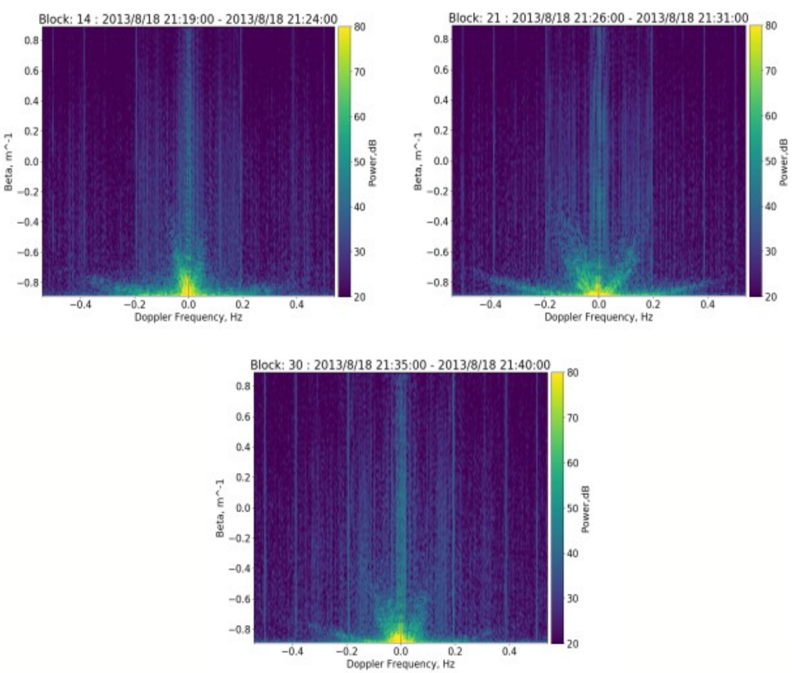
Scintillation Arcs: Secondary (Delay-Doppler) Spectra

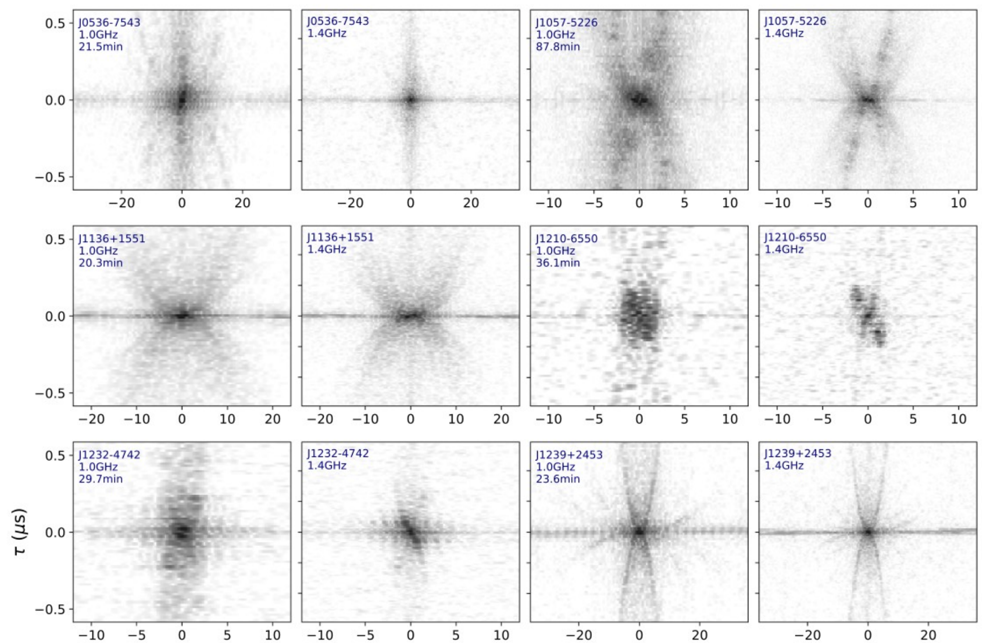
The Ionosphere



Variations on timescales of minutes, spatial scales of 10s – 100s of km

Fallows, R. A. et al., J. Sp. Weather Sp. Clim. 10, 16, 2020. doi.org/10.1051/swsc/2020010

The Interstellar Medium



Variations on timescales of months, spatial scales of 10s – 1000s of AU

Main, R. A. et al., MNRAS, 218, 1086-1097, 2023

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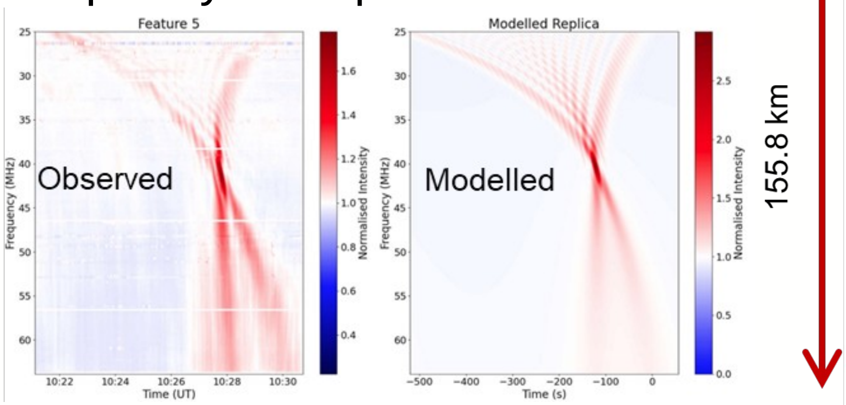
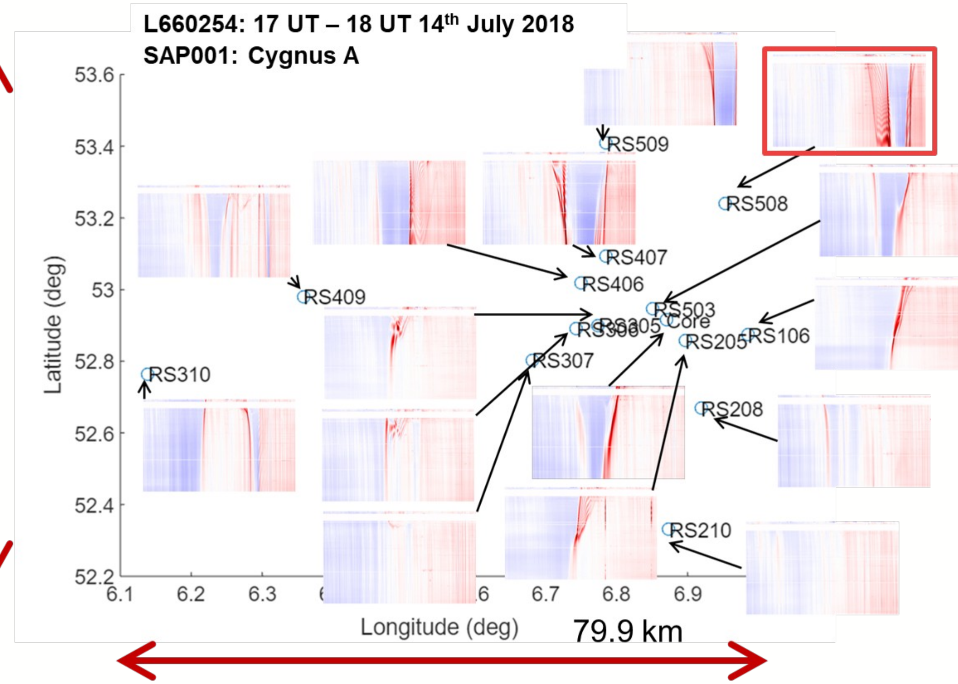
Summary

LOFAR can observe ionospheric structures at high temporal, frequency and spatial resolution





Dynamics and drivers of the terrestrial atmosphere can be inferred

Calibration solutions give differential Total Electron Content (dTEC): Observe waves

Fallows, R. A. et al., J. Sp. Weather Sp. Clim. 10, 16, 2020. doi.org/10.1051/swsc/2020010

Boyde, B., et al., J. Sp. Weather Sp. Clim. 12, 34, 2022. doi.org/10.1051/swsc/2022030

Dorrian, G. et al., Space Weather, 21, e2022SW003198, 2023. doi.org/10.1029/2022SW003198

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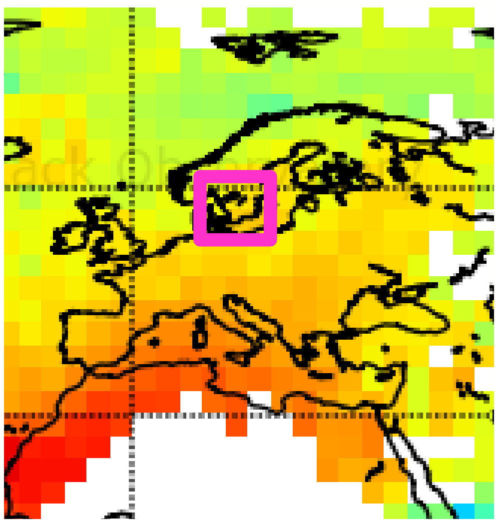
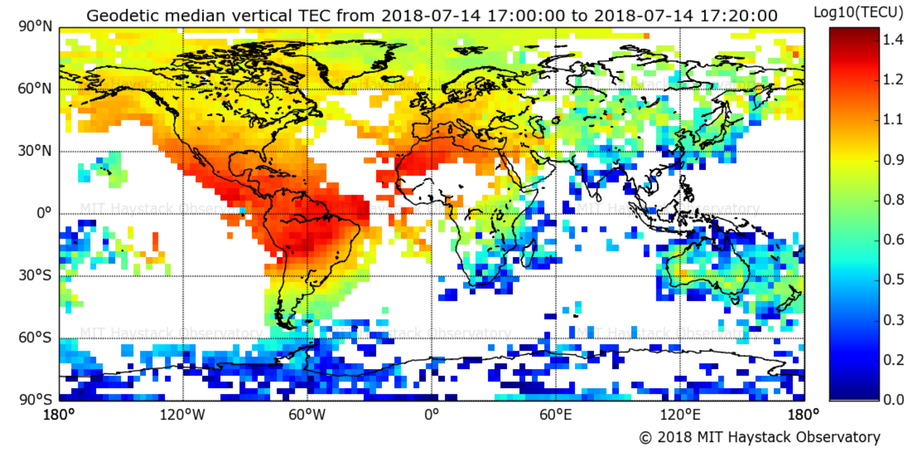
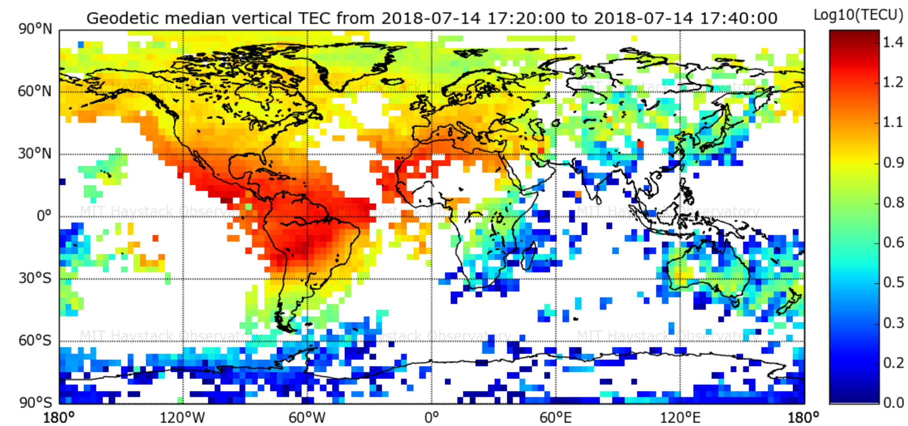
GNSS TEC Maps

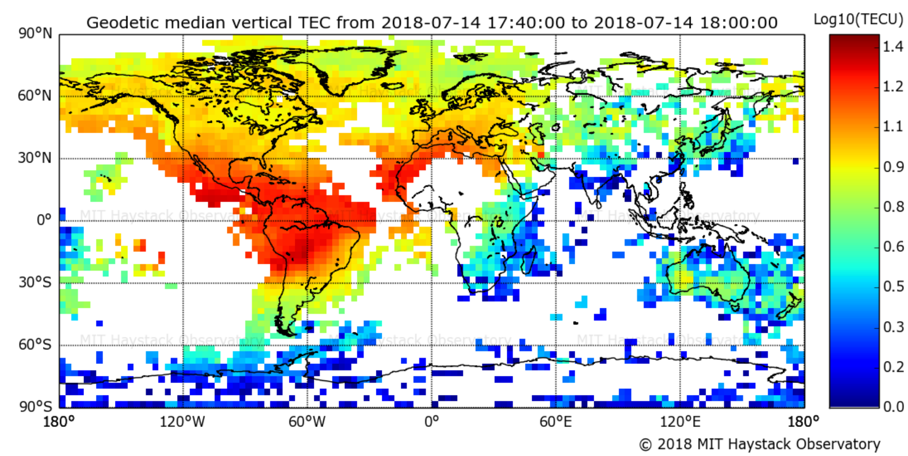
GNSS TEC

Does not show structure









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SERENE SPACE ENVIRONMENT

Cassiopeia A: 18th – 19th August 2013

Secondary Spectra: Two distinct arcs

1.75

L distance from observer to scattering screen

1.5

C curvature of arc

1.25

v velocity

1.0

Cross-correlation analysis using different stations gives velocity

0.75

Then determine altitude

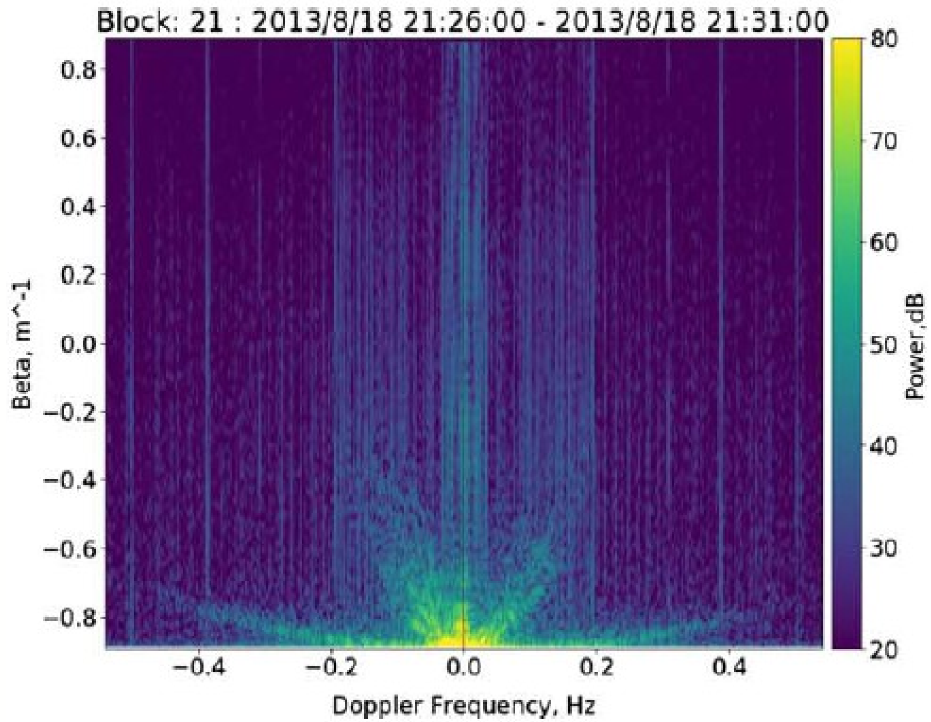
0.5

Two scattering screens

0.25

Two Travelling Ionospheric Disturbances, with different wavelengths and directions

0.0



The 2D FFT of the dynamic spectrum. β, the conjugate of wavelength, is used on the y-axis as it resamples in equal wavelength bins

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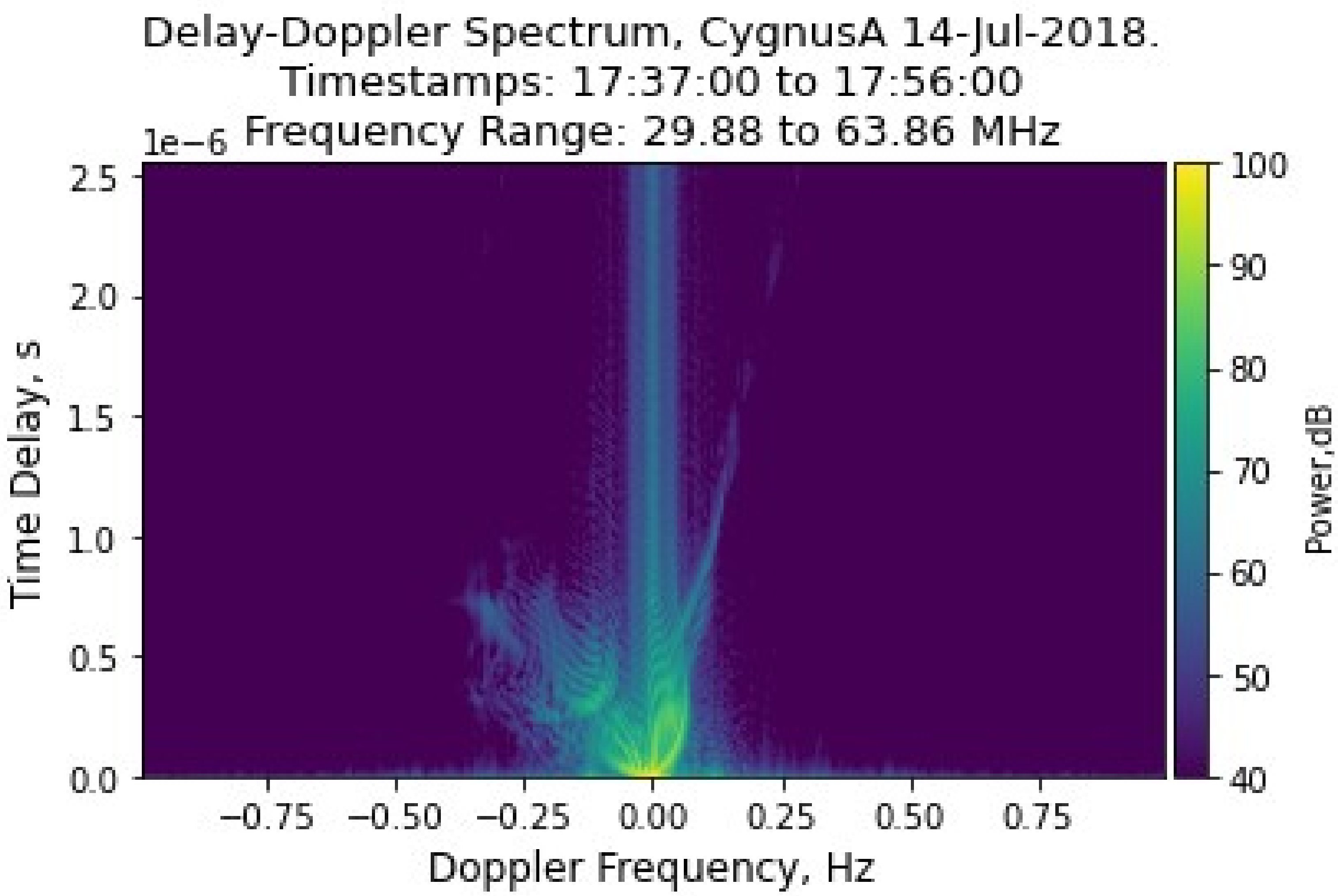
Delay-Doppler Spectra: RS508, Whole Feature



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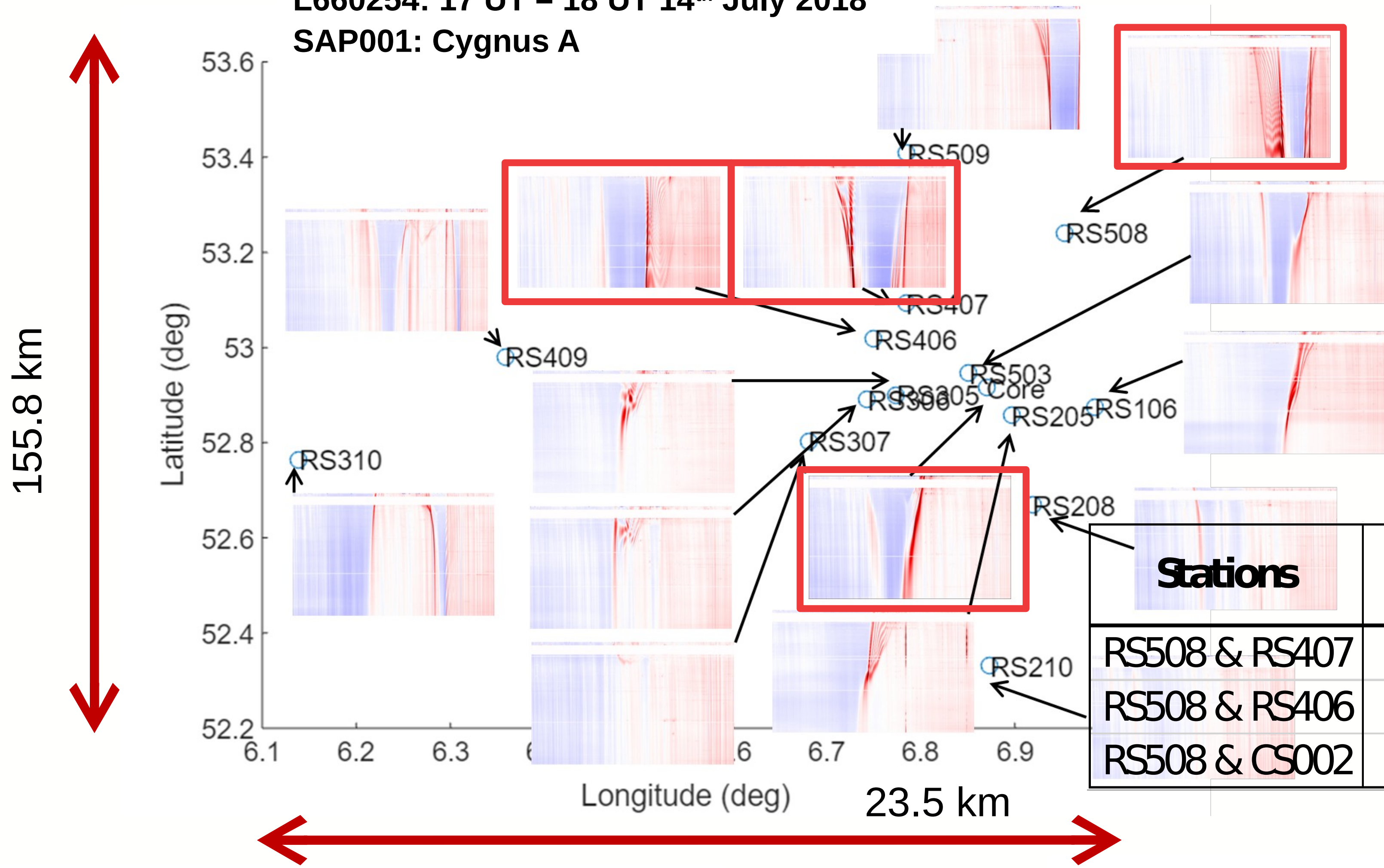
Cygnus A: LOFAR Observations

Source Az: 69° El: 37°

North east of stations

L660254: 17 UT – 18 UT 14th July 2018

SAP001: Cygnus A



Stations	Speed (m/s)
RS508 & RS407	15
RS508 & RS406	30
RS508 & CS002	27

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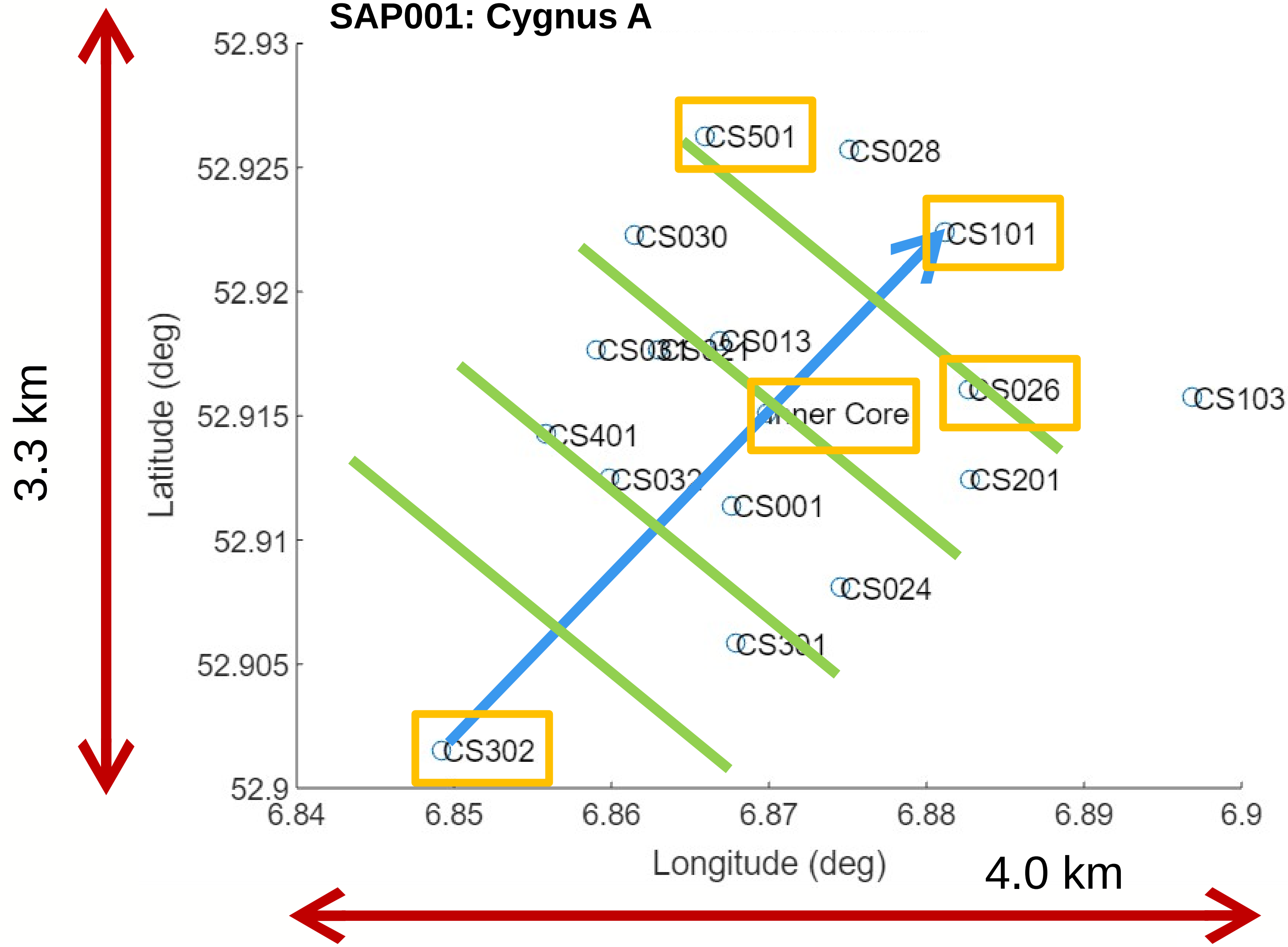
Velocity of Structure

Source Az: 69° El: 37°

North east of station

L660254: 17 UT – 18 UT 14th July 2018
SAP001: Cygnus A



Interested in the cross-correlations which imply the lowest velocities

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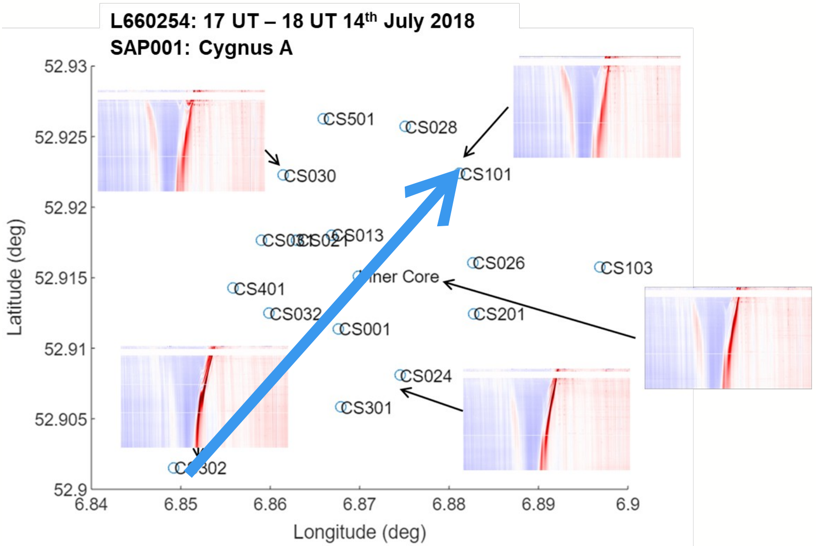
Velocity of Structure

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

Interested in the cross-correlations which imply the lowest velocities



Structure is moving northeast at ~ 20 m s^{-1}

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Context

Heliogeophysical conditions: Quiet

Geomagnetic: Kp: 1 aa: 2 nT Dst: -3 nT

Solar Activity: $F_{10.7}$cm solar radio flux: 72 sfu

No significant solar flares

Solar wind: IMF Bt: ~4 nT Velocity: 420 km s^{-1}

Data from: www.ukssdc.ac.uk, http://isgi.unistra.fr, https://data.nas.nasa.gov/helio/portals/solarflares, https://cdaw.gsfc.nasa.gov/CME_list/radio/waves_type2.html and https://cdaweb.gsfc.nasa.gov/index.html

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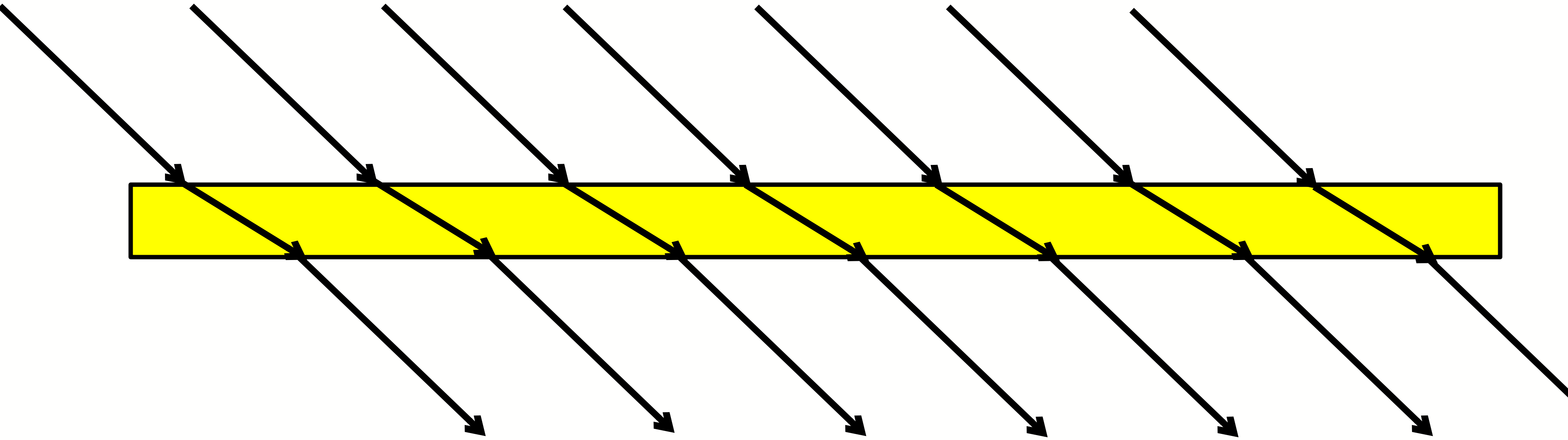
SERENE SPACE ENVIRONMENT

LEVERHULME TRUST

Asymmetry

Need to access for the elevation of the source



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LEVERHULME TRUST

Asymmetry

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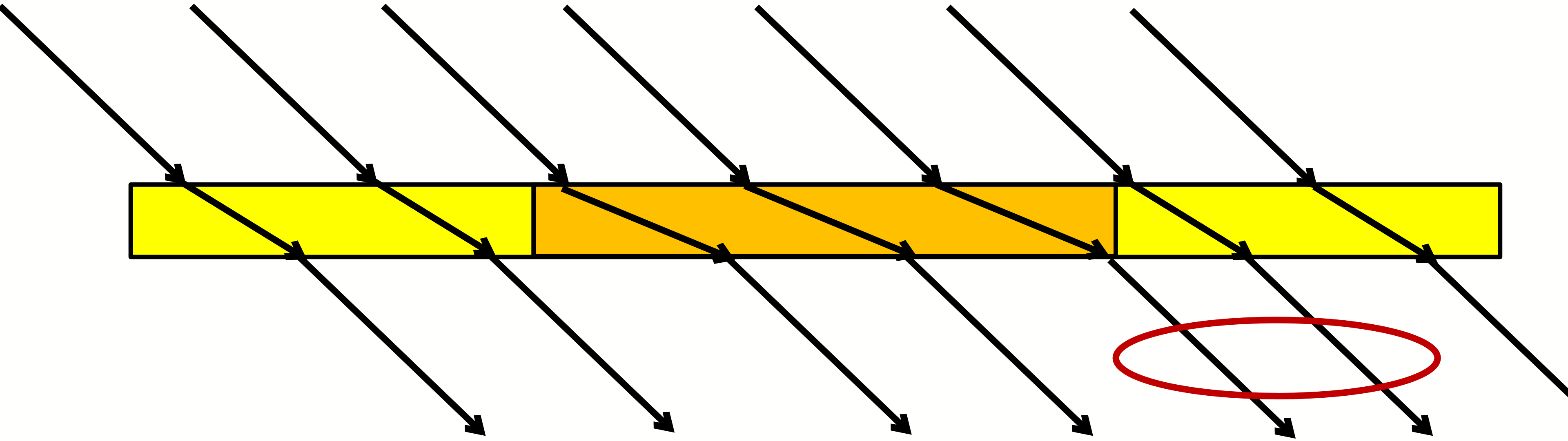

Get an enhancement of the signal intensity on the trailing edge of the feature

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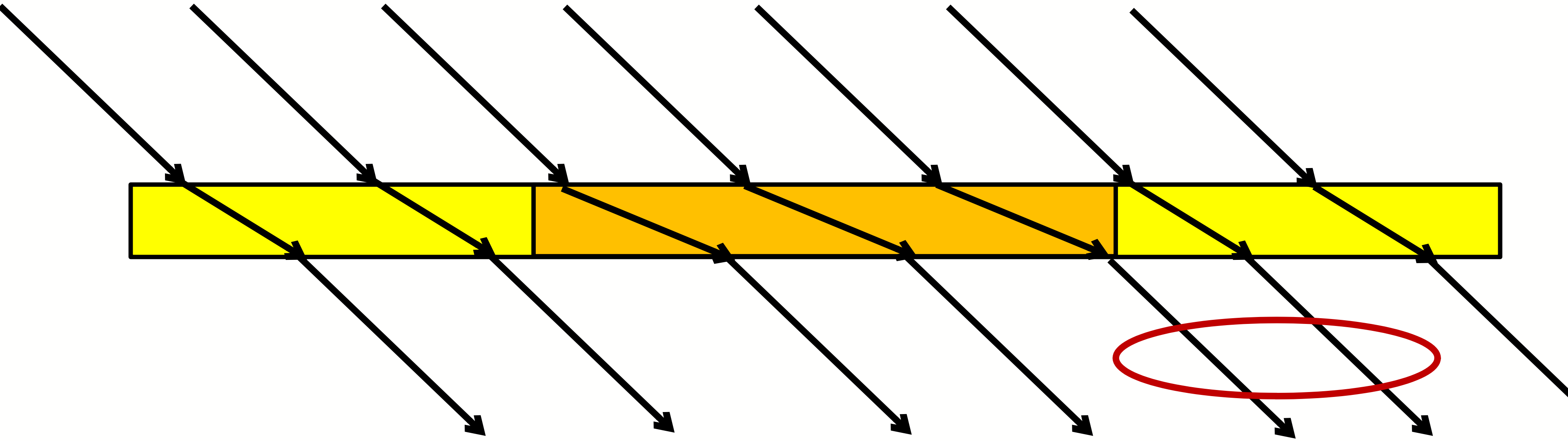
Asymmetry

Need to account for the elevation of the source



Get an enhancement of the signal intensity on the trailing edge of the feature

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