Distinguishing space weather effects from signatures of the January 2022 Tonga volcanic eruption with LOFAR

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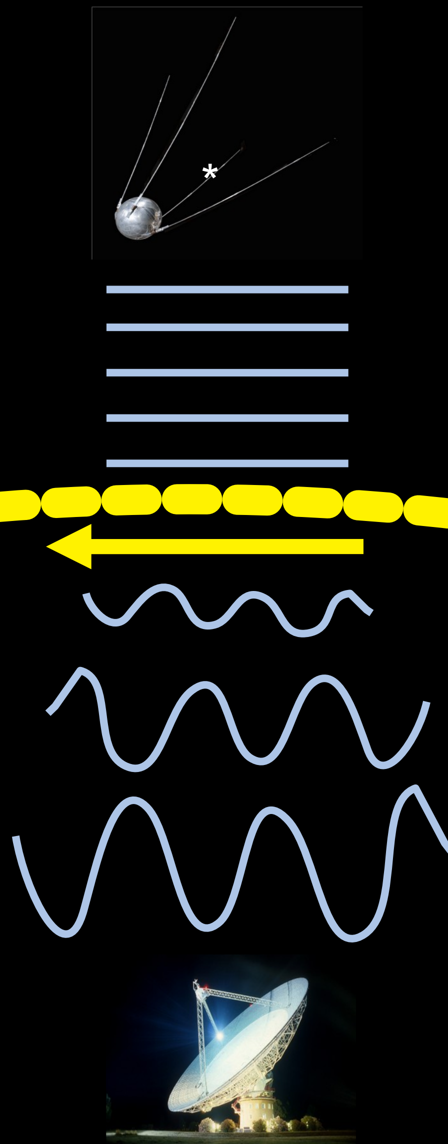
LEVERHULME TRUST

Ionospheric Scintillation (basics)

Coherent radio transmissions from satellites, typically at one or a small number of frequencies, transition through highly structured ionospheric plasma.



Rapid variation in refractive index induces many phase changes along the wavefront, generating interference pattern

If plasma in motion then interference pattern drifts across raypath

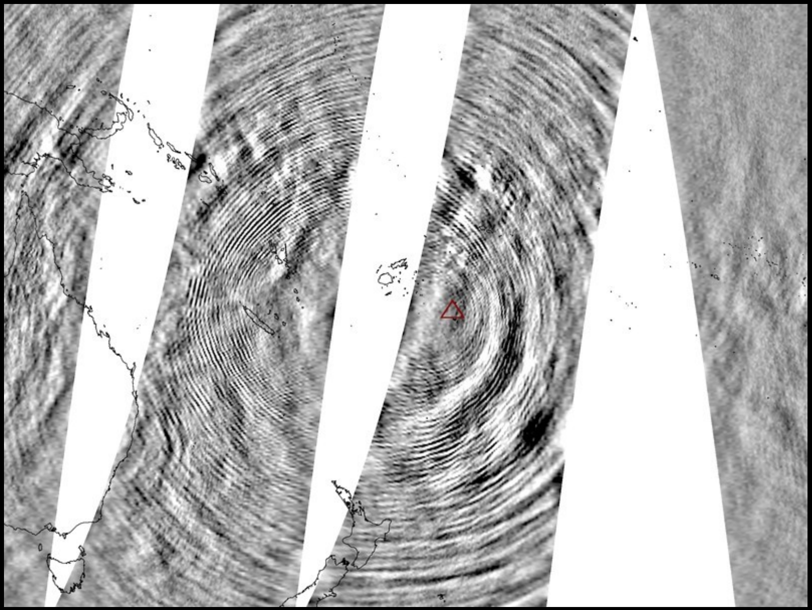
Wavelets constructively and destructively interfere with distance from scattering plasma, resulting in scintillation pattern which varies in time (if scattering plasma is in motion)

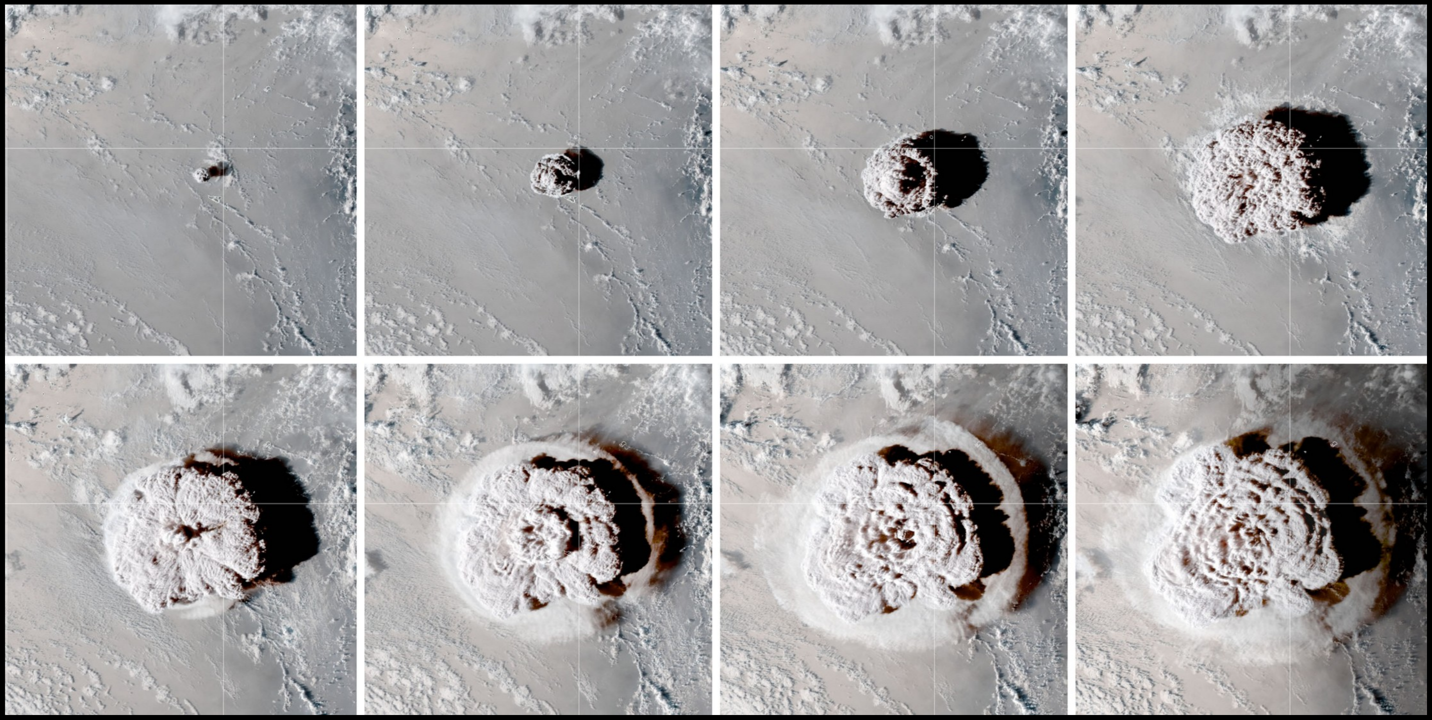
*FYI: Sputnik 1 transmitted on 2-channels: 20 & 40 MHz

The Low Frequency Array (LOFAR)

Tonga Eruption

- Tonga Eruption; largest volcanic eruption of 21st century
- 15th. January 2022, 0415 UT
- Eruption column reached mesosphere ~ 57 km altitude (Highest ever recorded; Proud et al., 2022)
- Distinct AGWs / Lamb Waves generated
- LOFAR data gathered on nights before and after eruption as part of LT16_002





Eruption wave packets

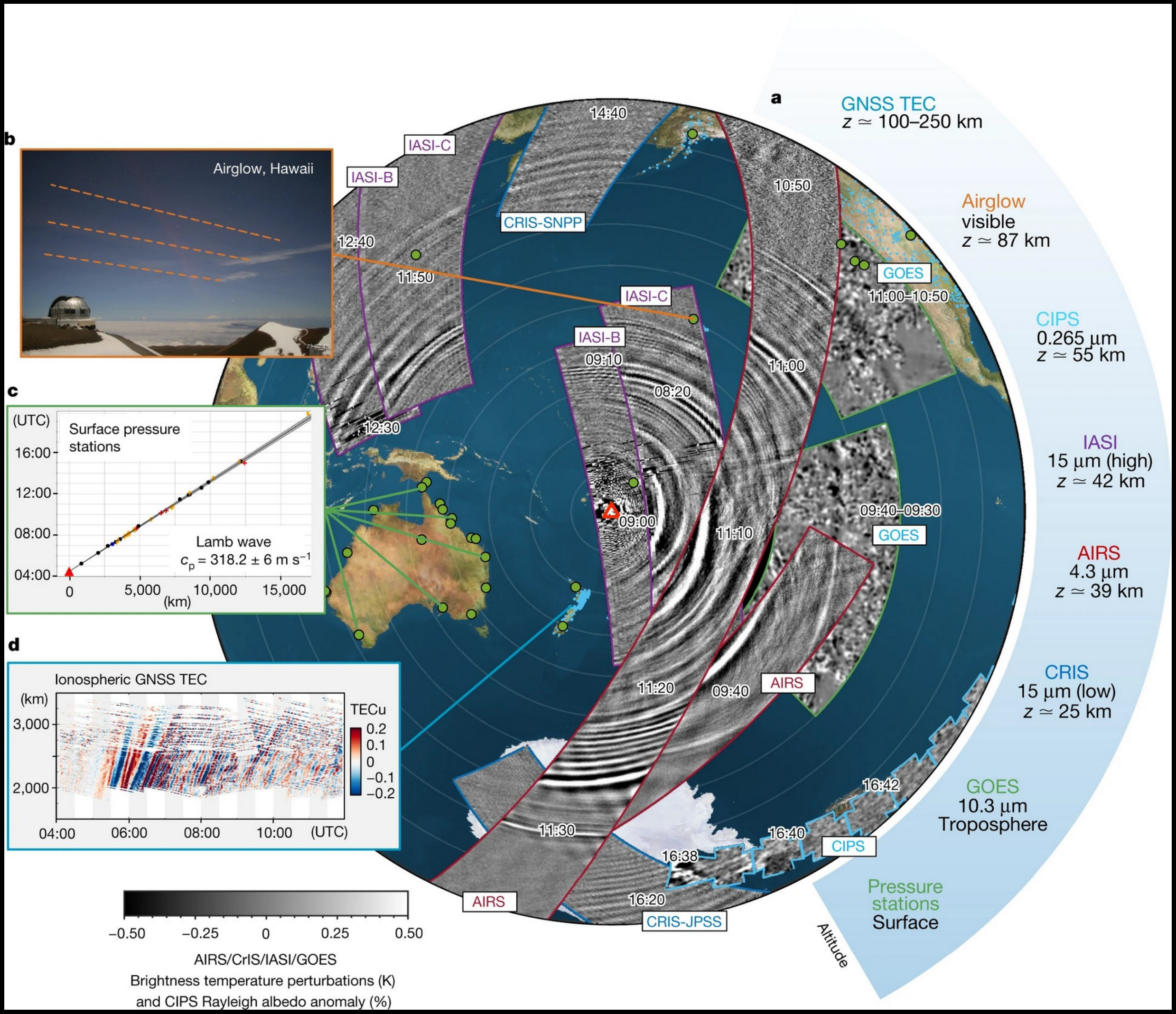


Figure 2 from Wright et al., 2022

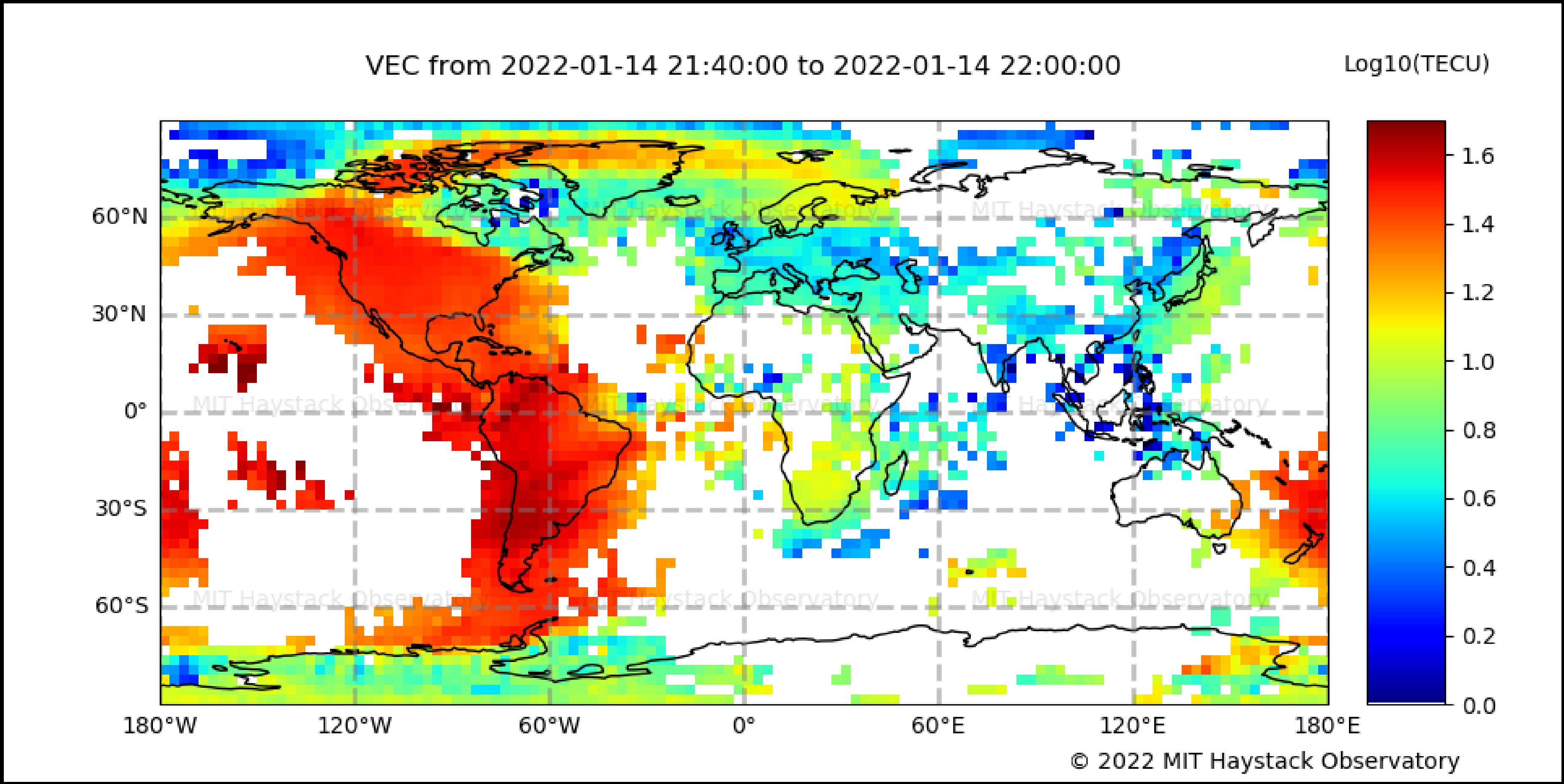
Lamb waves propagating at 318 +/- 6 ms^{-1} at surface level and 308 – 319 ms^{-1} in the upper atmosphere

Followed by internal atmospheric gravity wave packet propagating at speeds between 238 – 269 ms^{-1}.

Heat release from eruption plume continued to generate circular wavefront AGW for > 12 hours after eruption

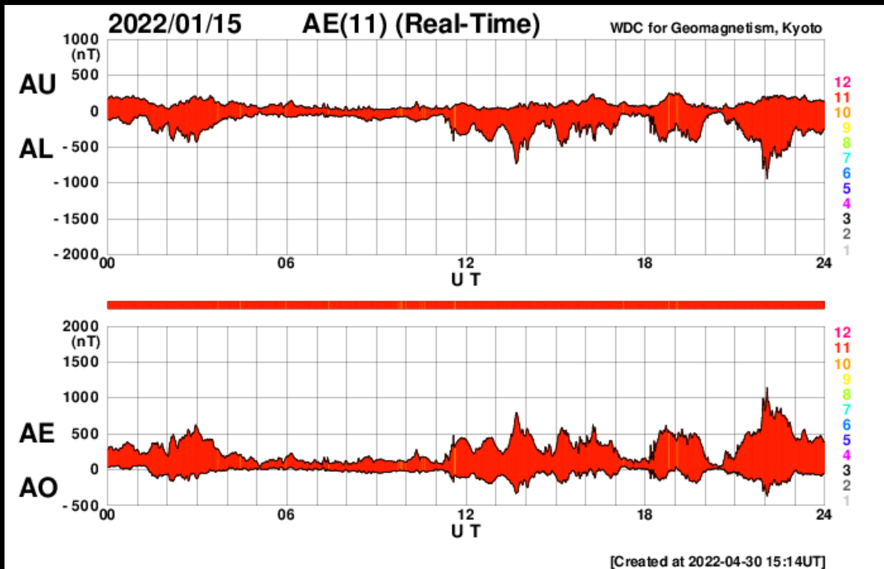
Important as this represents a singular distinct source of AGW; normally hard to localise source

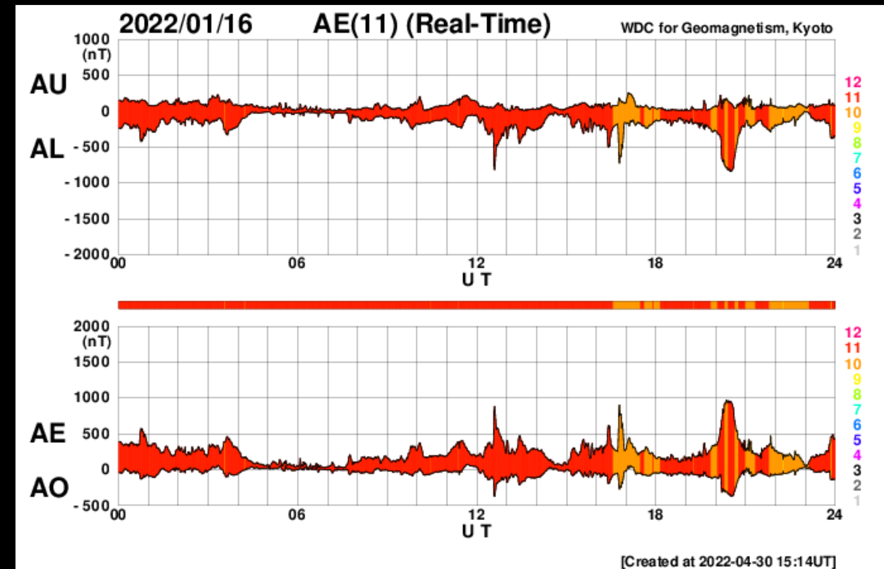
Substorm activity



- Tongue-of-ionisation present the night before the eruption
- Sub-storm activity known to excite AGW/TIDs via Joule heating and Lorenz forces
- Auroral TIDs are often supersonic and propagate equator wards

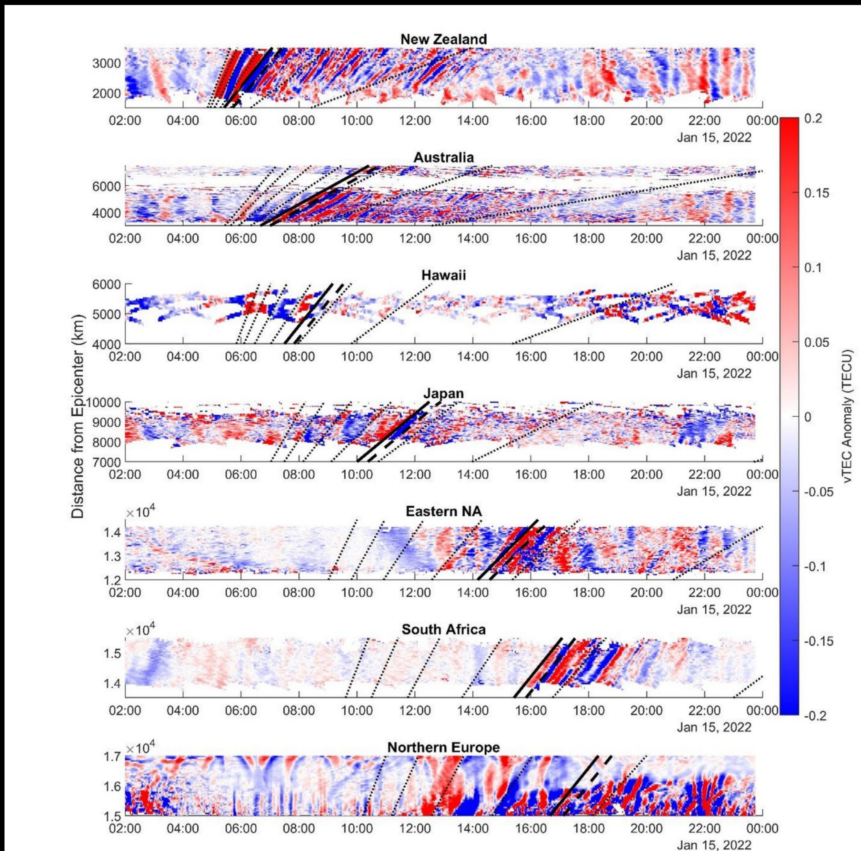
Tonga Eruption & Substorm activity





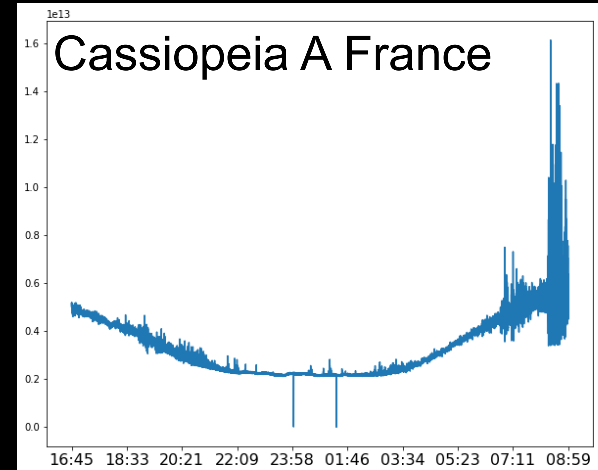
- AE-index shows auroral activity from ~1200 UT on 15th. January to 0400 UT on 16th. January
- Discontinuous, but peak activity at ~2200
- L843074: 0000 14-Jan-2022 to 0825 15-Jan-2022
- L843076: 1645 15-Jan-2022 to 0859 16-Jan-2022
- Modest sub-storm activity complicates eruption related wave identification over Europe

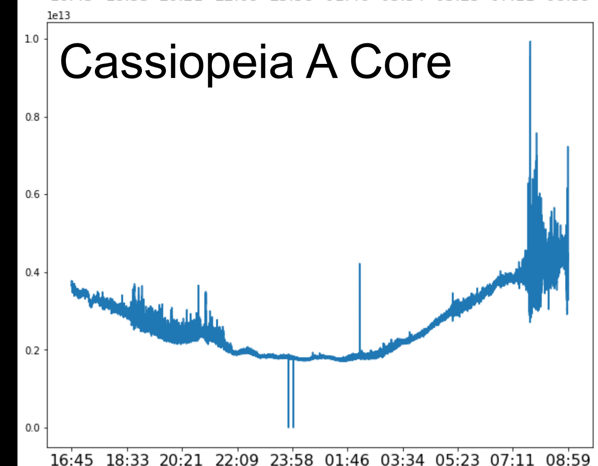
Tonga Eruption & Substorm

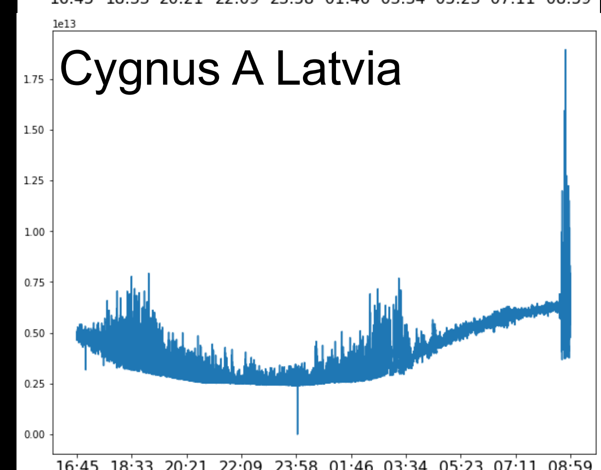


Themens et al. (2022)

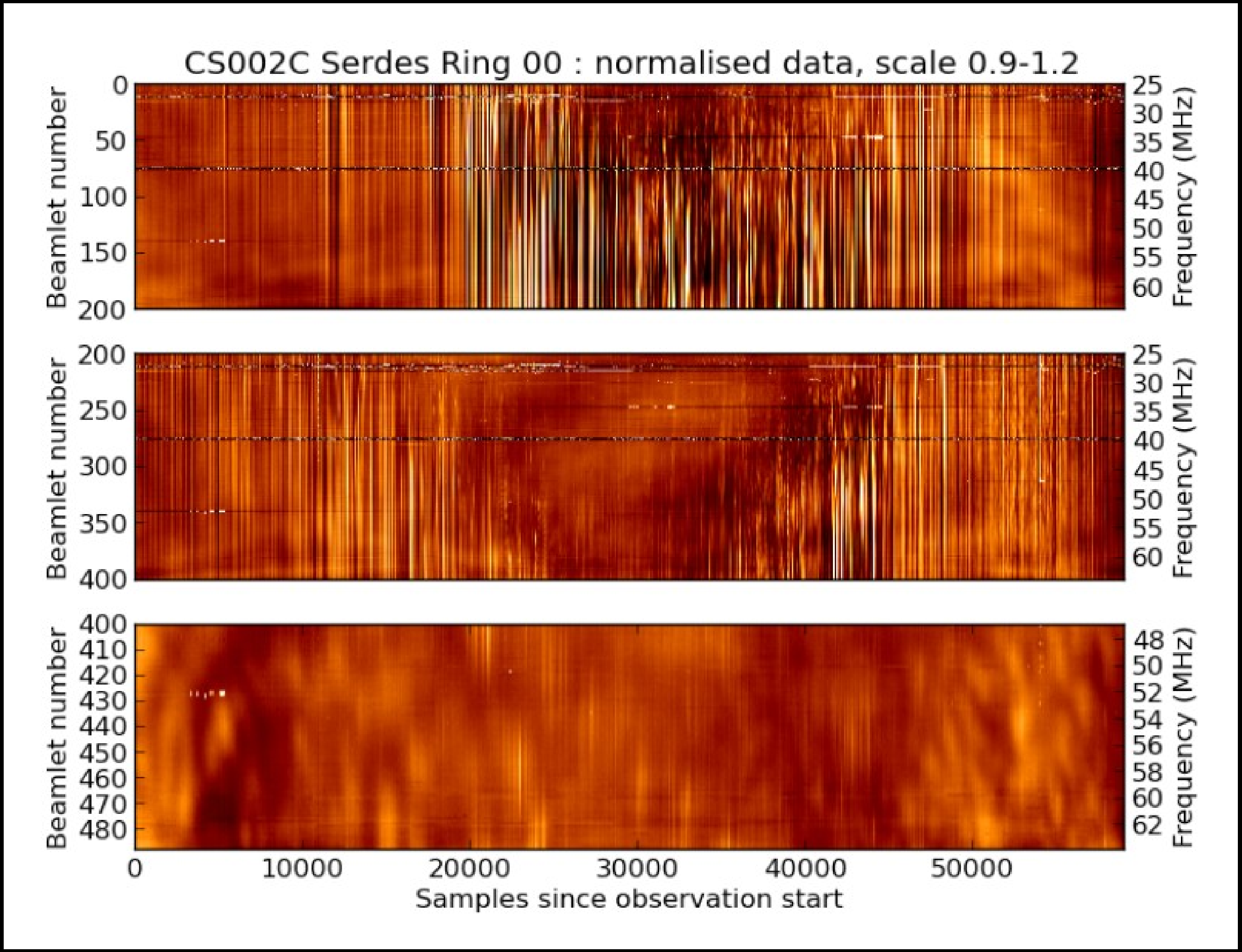
- Strong scintillation detected across Europe
- Occurs between ~0700-0900
- Southern most stations detect it first
- France -> Core -> Latvia
- Second pass of AGWs from antipode







U-shaped features signify sub-storm activity

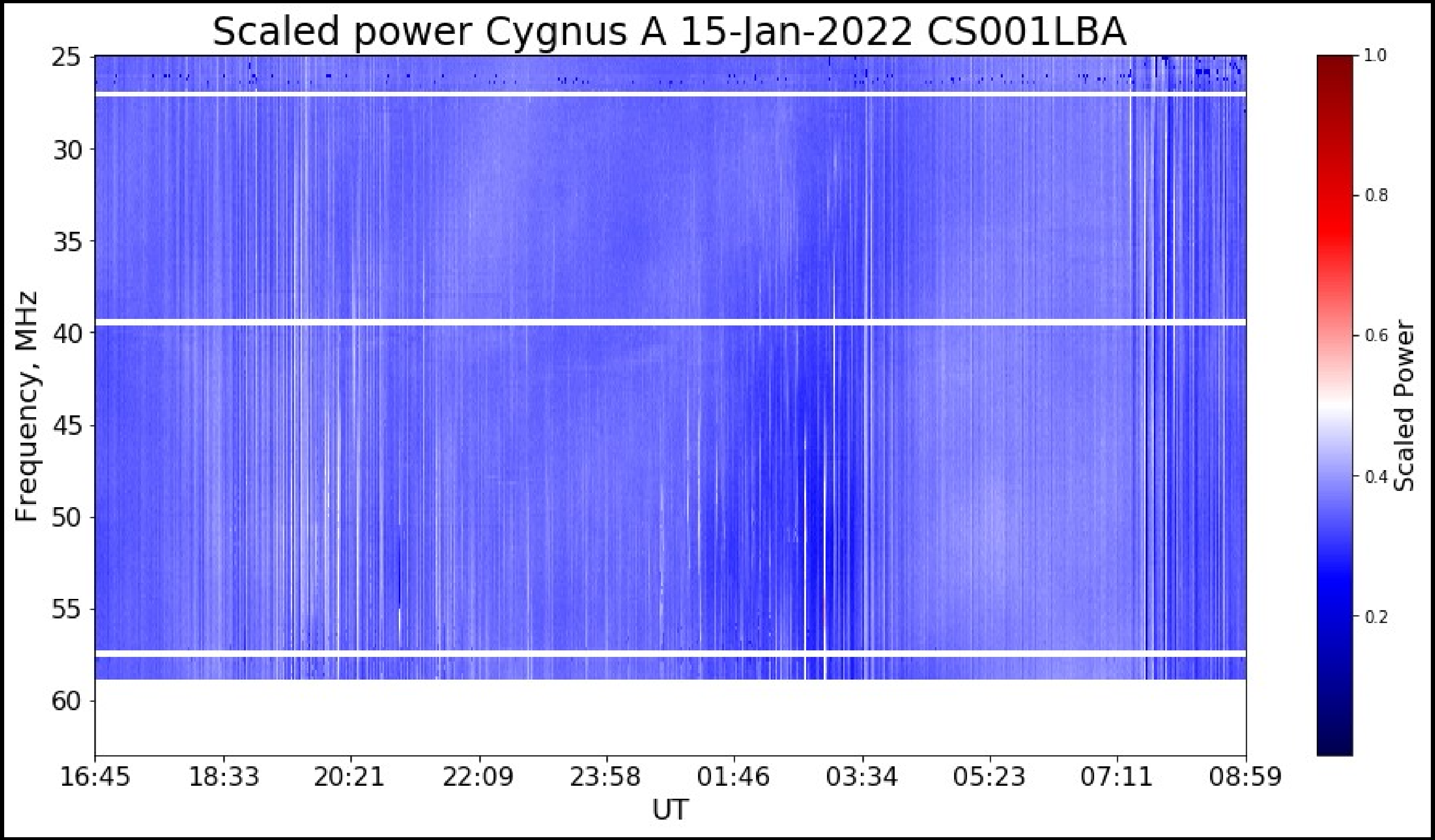


U-shaped features are linked to sub storm activity; seen in all Cyg A observations from this night

Elevation change of source causes raypath to move through the auroral oval

Compares well with time of sub storm activity in AE indice

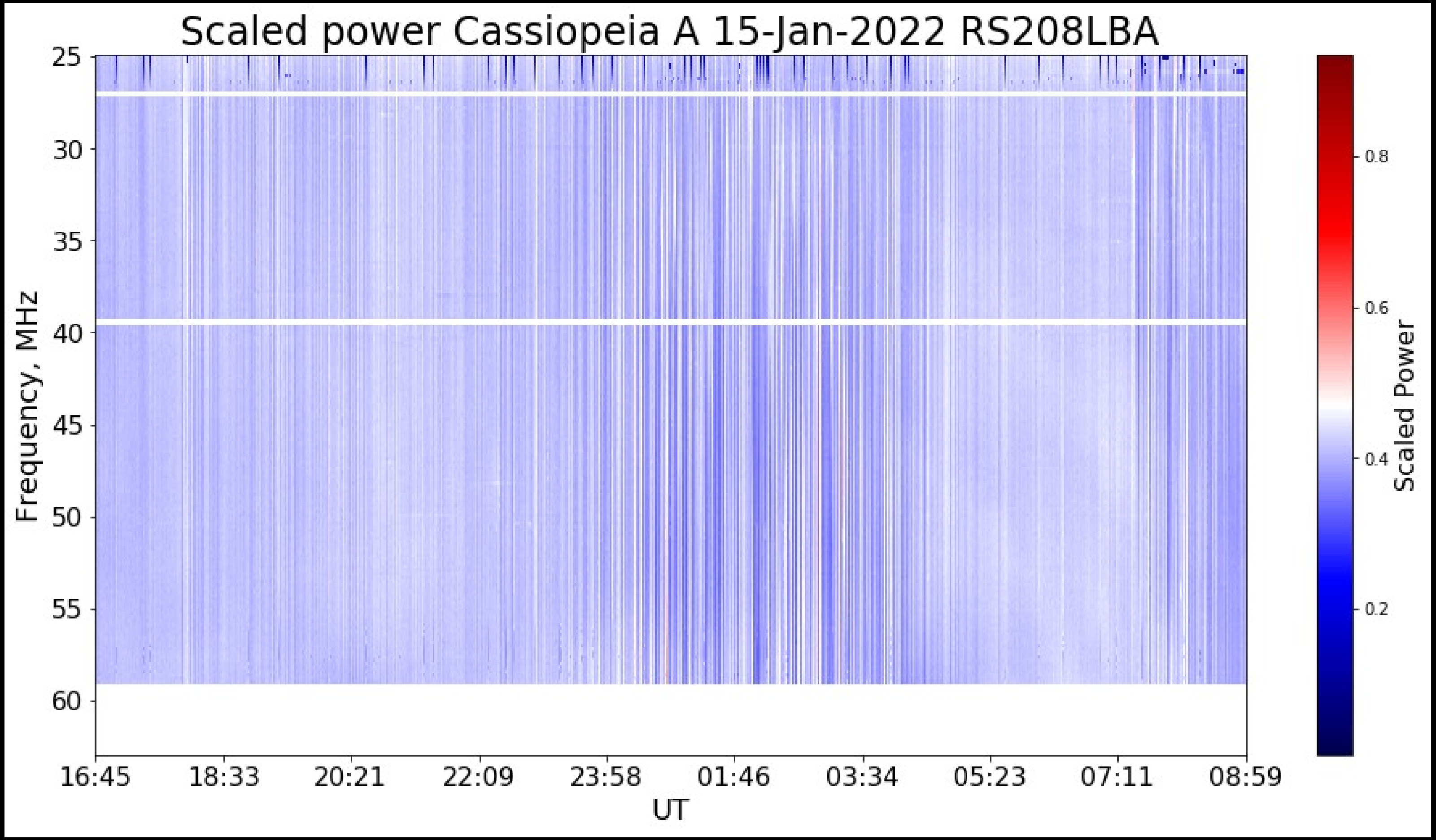
U-shaped features signify sub-storm activity



U-shaped features in Cygnus A during night of eruption caused by line-of-sight passing through the auroral oval.

Volcano signatures may be embedded but hard to distinguish

Cassiopeia A full observing window

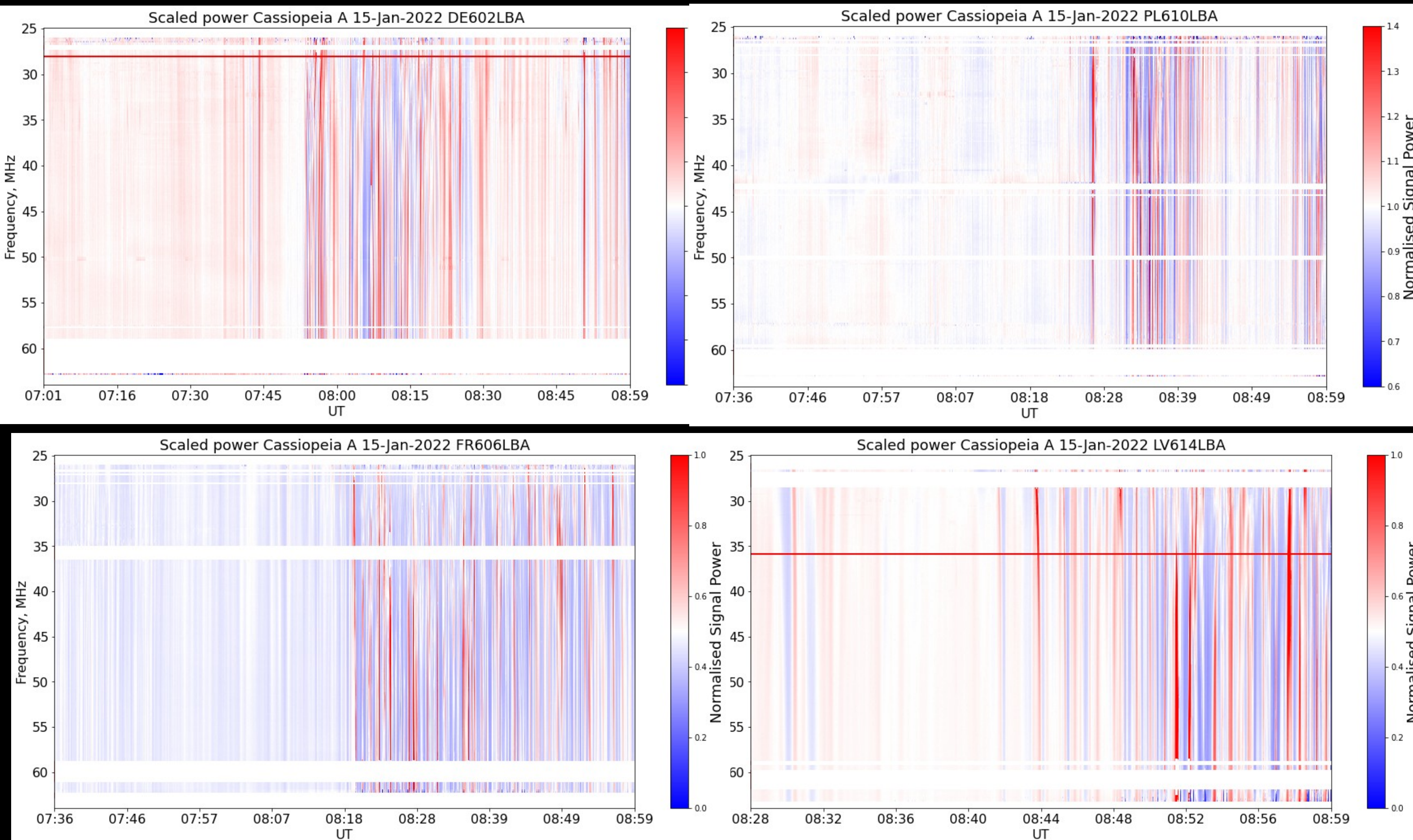


Absence of U-shaped features in Cass A

Line-of-sight further South and higher elevation prevents line-of-sight passing through auroral oval

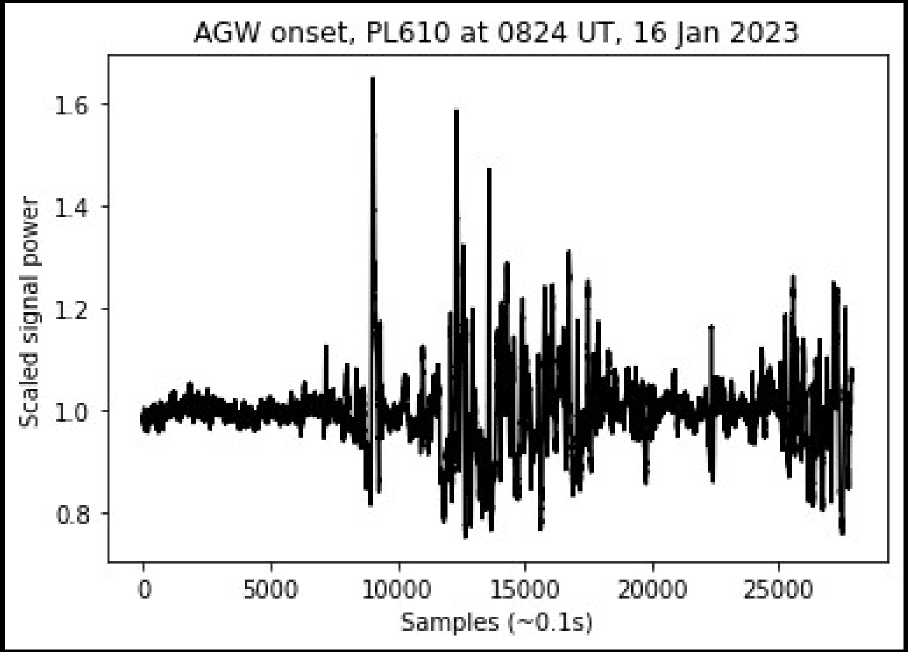
Potentially more useful for identifying volcano signatures

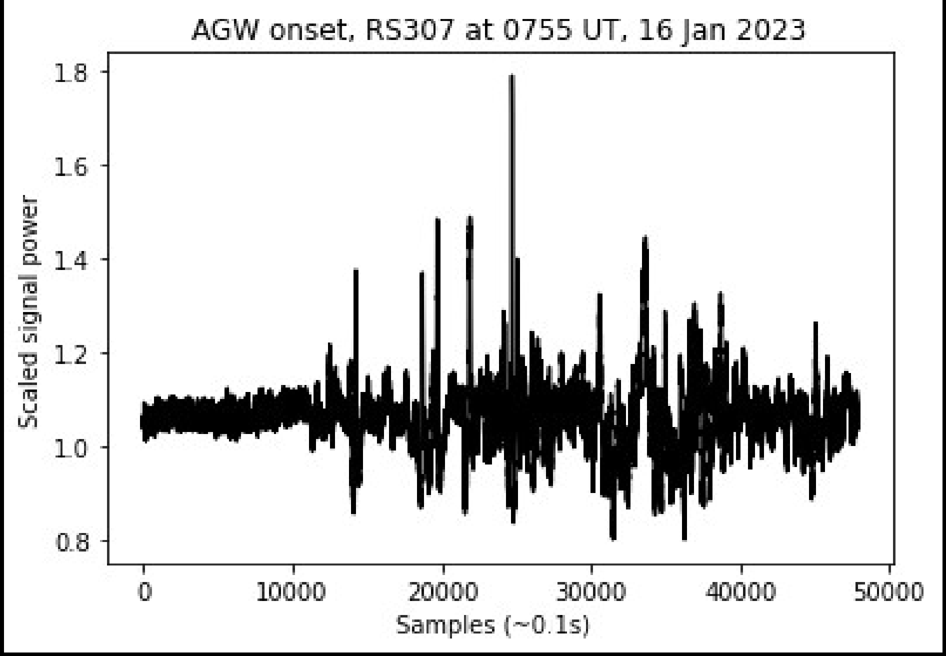
Tonga eruption dynamic spectra

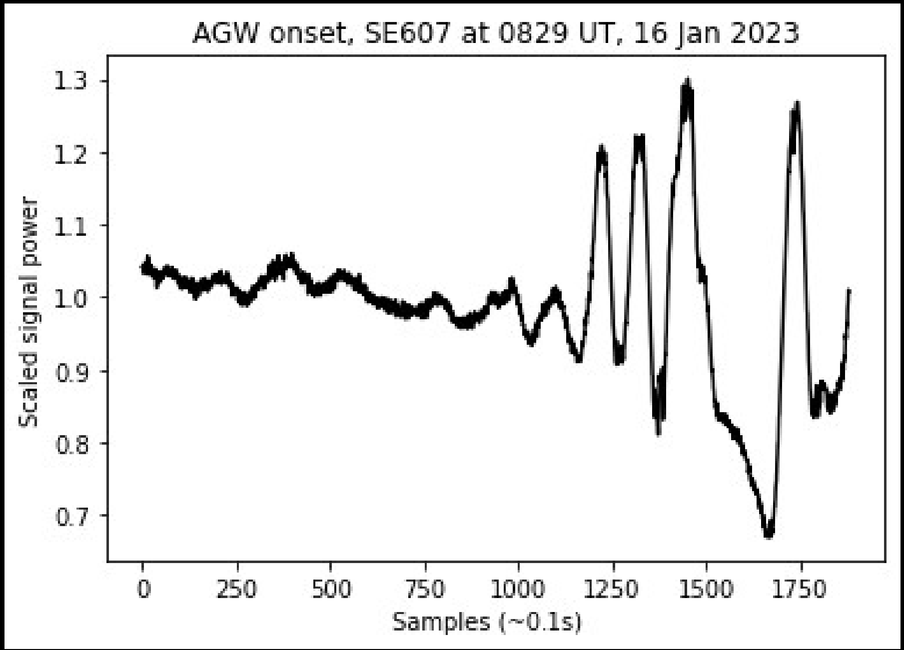


Single channel onsets

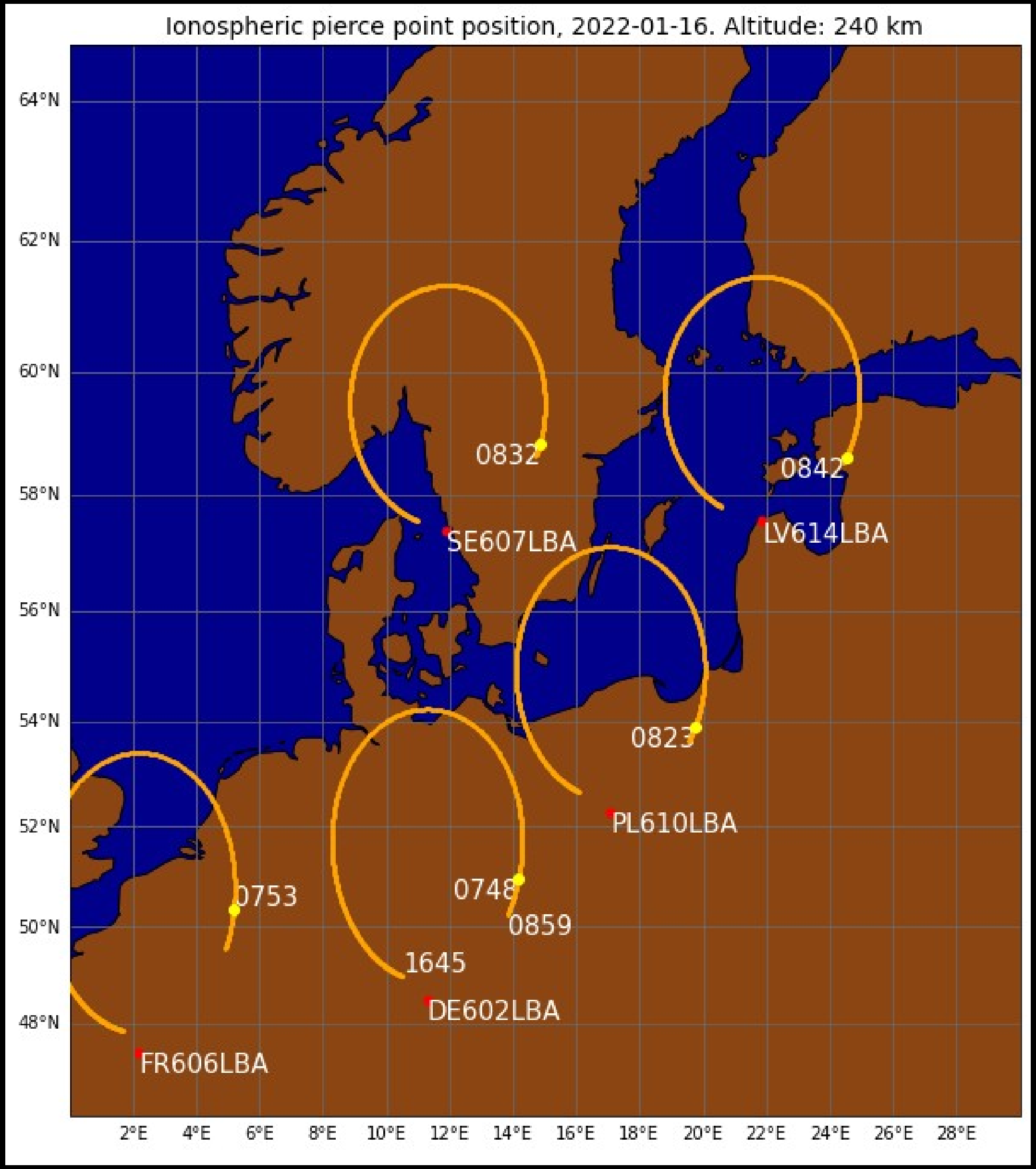
- Rapid onsets clearly visible in single channel samples
- Individual scintilla with life times of order 10 – 20 seconds or less
- Spikes in normalized scintillation power of over 80%





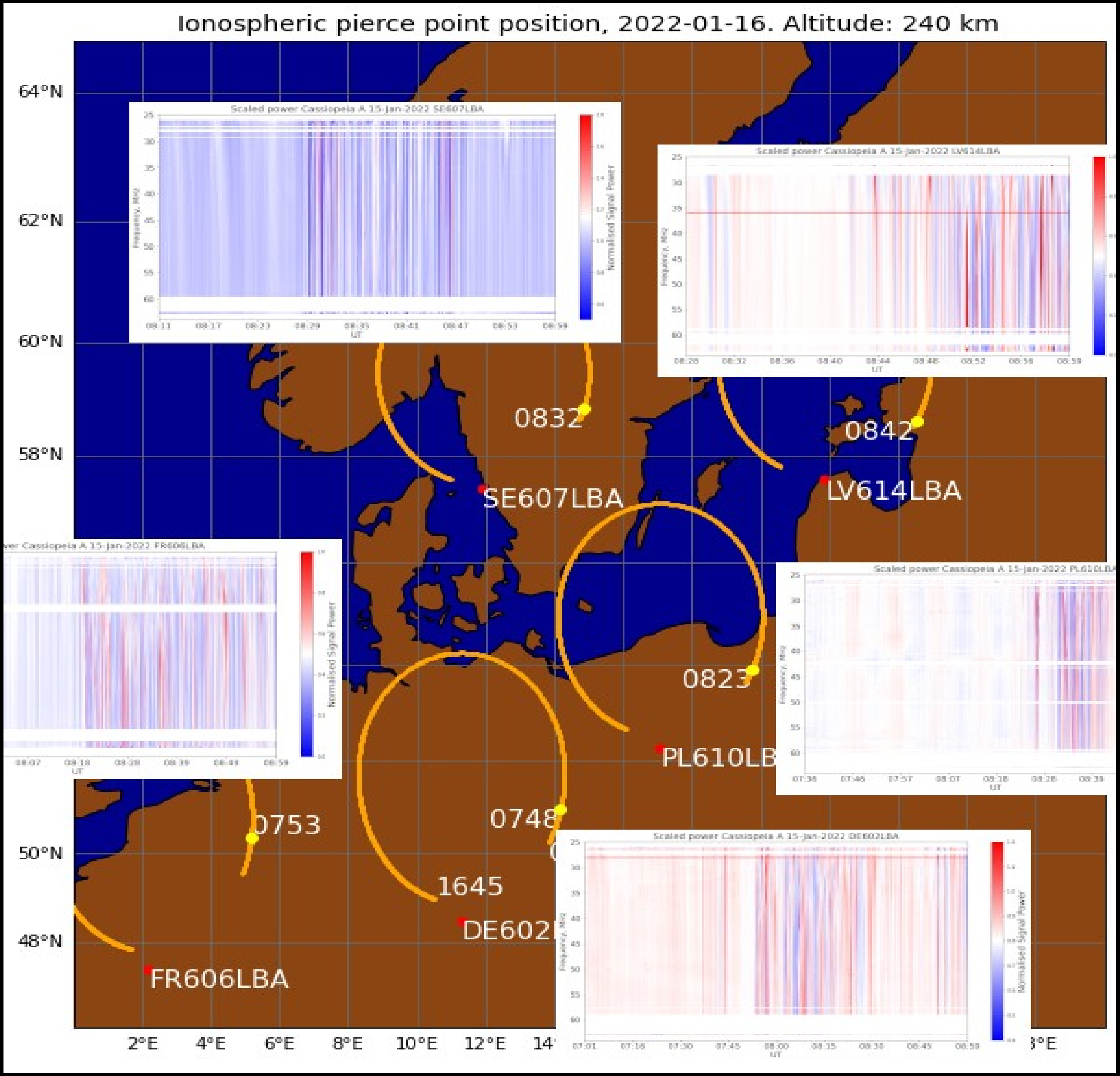


IPP arcs showing feature progression



- IPP (ionospheric pierce point) arcs for Cassiopeia A 15th/16th January
- Projected to 240 km altitude ~F-region
- General progression of sharp-onset features from South to North
- Not consistent with auroral activity or sunrise (e.g. onset at Sweden is before onset at Latvia despite being on same latitude)
- All features in dynamic spectra are sudden onsets with powerful increases in scintillation power

IPP / dynspecs with wave velocities



- Using a wave propagation model with Tonga as source, initiation at 0428 UT on 15 Jan 2022
- All onset times in LOFAR are consistent with AGW propagation velocities from Tonga of between 240 – 245 ms^{-1} on Southern route via Antarctica and the antipode (the 'long way round')
- Known AGW prop. Velocities 238-269 ms^{-1}
- Great circle distance to Tonga is over high Northern Latitude

Conclusions

- Multiple wave signatures seen in LOFAR data 15/16 Jan 2022
- Some clearly identifiable as auroral (mainly in Cygnus A)
- Powerful scintillation event sudden onset near end of observing window
- Northwards propagating with velocities of 240-245 ms^{-1} when modelled using Tonga as source and initiation at time of eruption
- LOFAR likely to be among the most sensitive datasets for Tonga eruption waves (can typically resolve much finer ionospheric structure than other techniques such as GNSS / ionosondes

References

Simon R. Proud et al., (2022). The January 2022 eruption of Hunga Tonga-Hunga Ha’apai volcano reached the mesosphere, Science, 378, 554-557, DOI:10.1126/science.abo4076

LOFAR: The LOw-Frequency ARray, M. P. van Haarlem, et al., (2013) A&A, 556 A2, doi: https://doi.org/10.1051/0004-6361/201220873

Themens et al. (2022). Global propagation of ionospheric disturbances associated with the 2022 Tonga volcanic eruption. Geophysical Research Letters, 49, e2022GL098158. https://doi.org/10.1029/2022GL098158

Wright, C. J., et al., (2022). Surface-to-space atmospheric waves from Hunga Tonga-Hunga Ha’apai eruption, Nature, 609, 741-758, https://doi.org/10.1038/s41586-022-05012-5