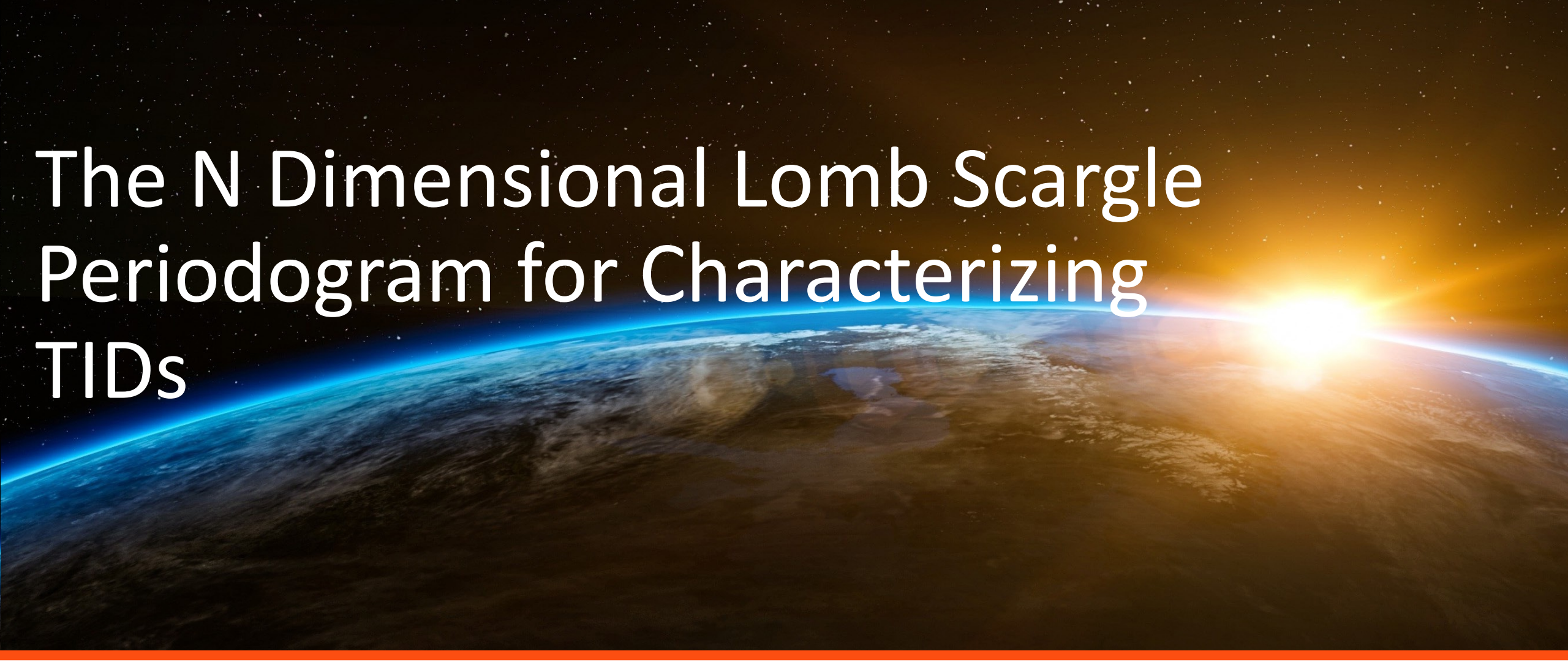
The N Dimensional Lomb Scargle Periodogram for Characterizing TIDs



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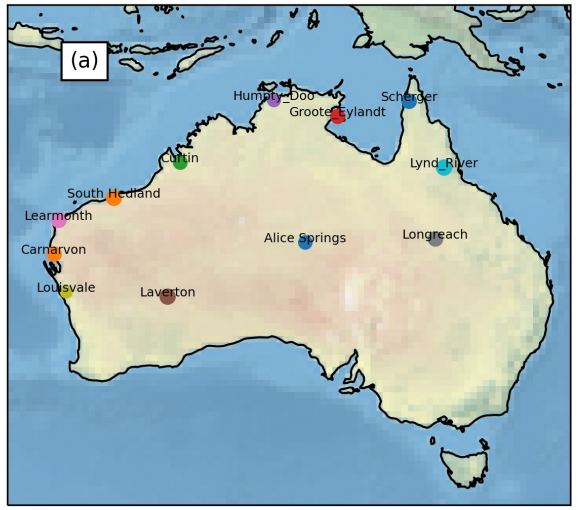
Summary

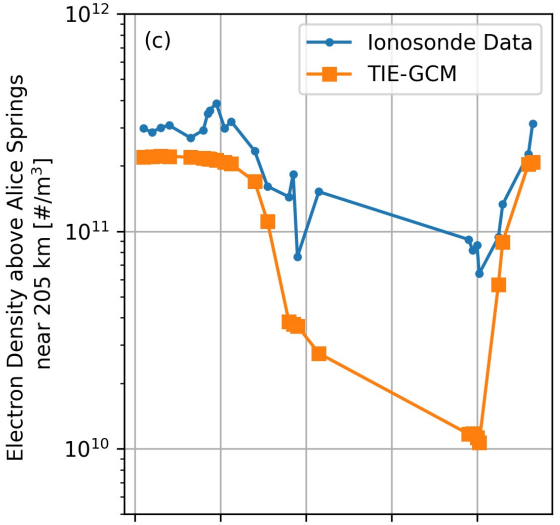
- Traveling Ionospheric Disturbances (TIDs) are a widely-studied phenomena in the ionosphere
- TEC data can be interpolated onto a regular space and time grid and then Fourier Transformed to study the spectra
- We have developed the N Dimensional Lomb-Scargle Periodogram (ND LSP) which removes the need for interpolation
- We demonstrate this method on ionosonde data
- We compare to a TEC analysis and find similar results

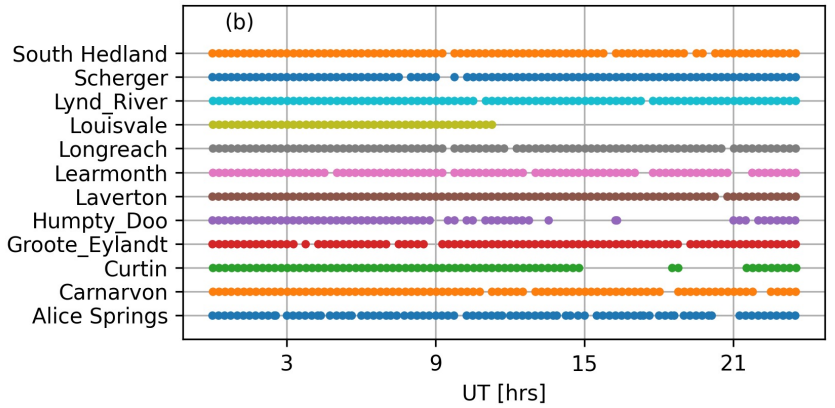
Our Dataset

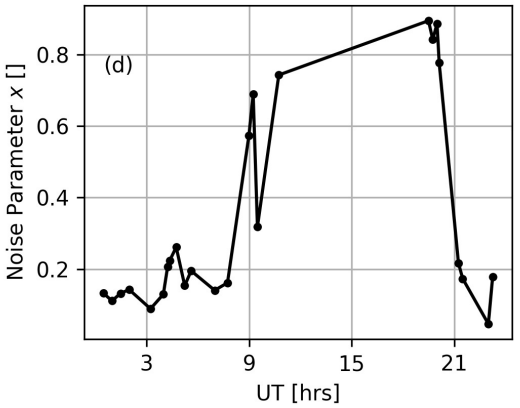
- We used data over Australia on June 29, 2019
- 12 ionosondes each with a nominal 15-minute cadence
- Only use portion of the electron density profile that is directly measured
- Sparse and irregular horizontal coverage
- We use TIE-GCM to estimate a smooth background and measure deviations from this using 'x'

$$x = \log_{10}(N_{eI}) - \log_{10}(N_{eB})$$









Our Method

Input Data

$$t_1, t_2, \cdots, t_n$$
$$\text{lat}_1, \text{lat}_2, \cdots, \text{lat}_n$$
$$\text{lon}_1, \text{lon}_2, \cdots, \text{lon}_n$$
$$\text{alt}_1, \text{alt}_2, \cdots, \text{alt}_n$$
$$x_1, x_2, \cdots, x_n$$

Frequencies to measure

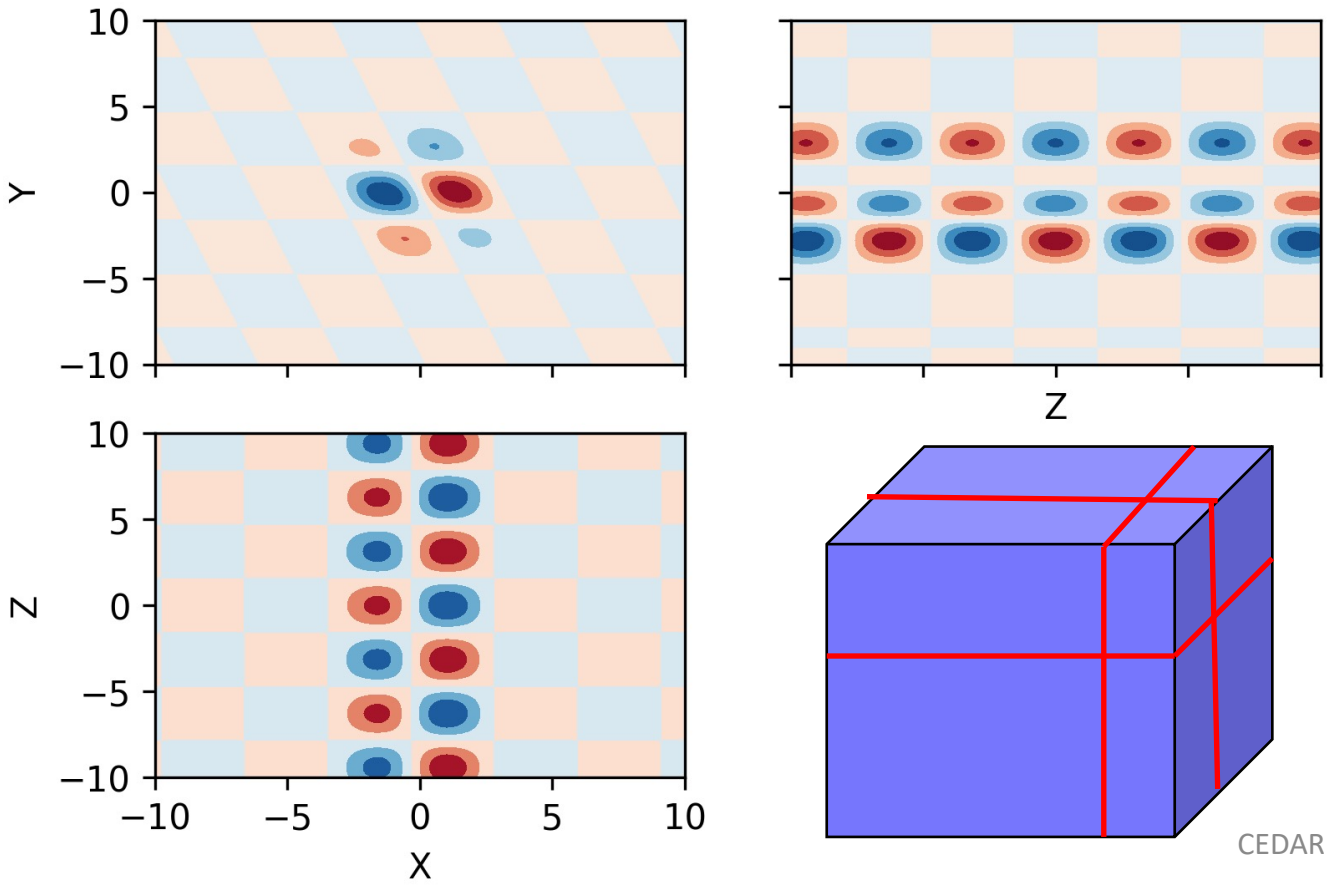
$$f_{t_1}, f_{t_2}, \cdots, f_{t_n}$$
$$f_{\text{lat}_1}, f_{\text{lat}_2}, \cdots, f_{\text{lat}_n}$$
$$f_{\text{lon}_1}, f_{\text{lon}_2}, \cdots, f_{\text{lon}_n}$$
$$f_{\text{alt}_1}, f_{\text{alt}_2}, \cdots, f_{\text{alt}_n}$$

ND LSP

$$A(f_t, f_{\text{lat}}, f_{\text{lon}}, f_{\text{alt}})$$

Visualizing Test Multi-Dimensional Data

$$A = \sin(x + y/3)\cos(y)\cos(z)\exp(-(x^2 + y^2)/10)$$



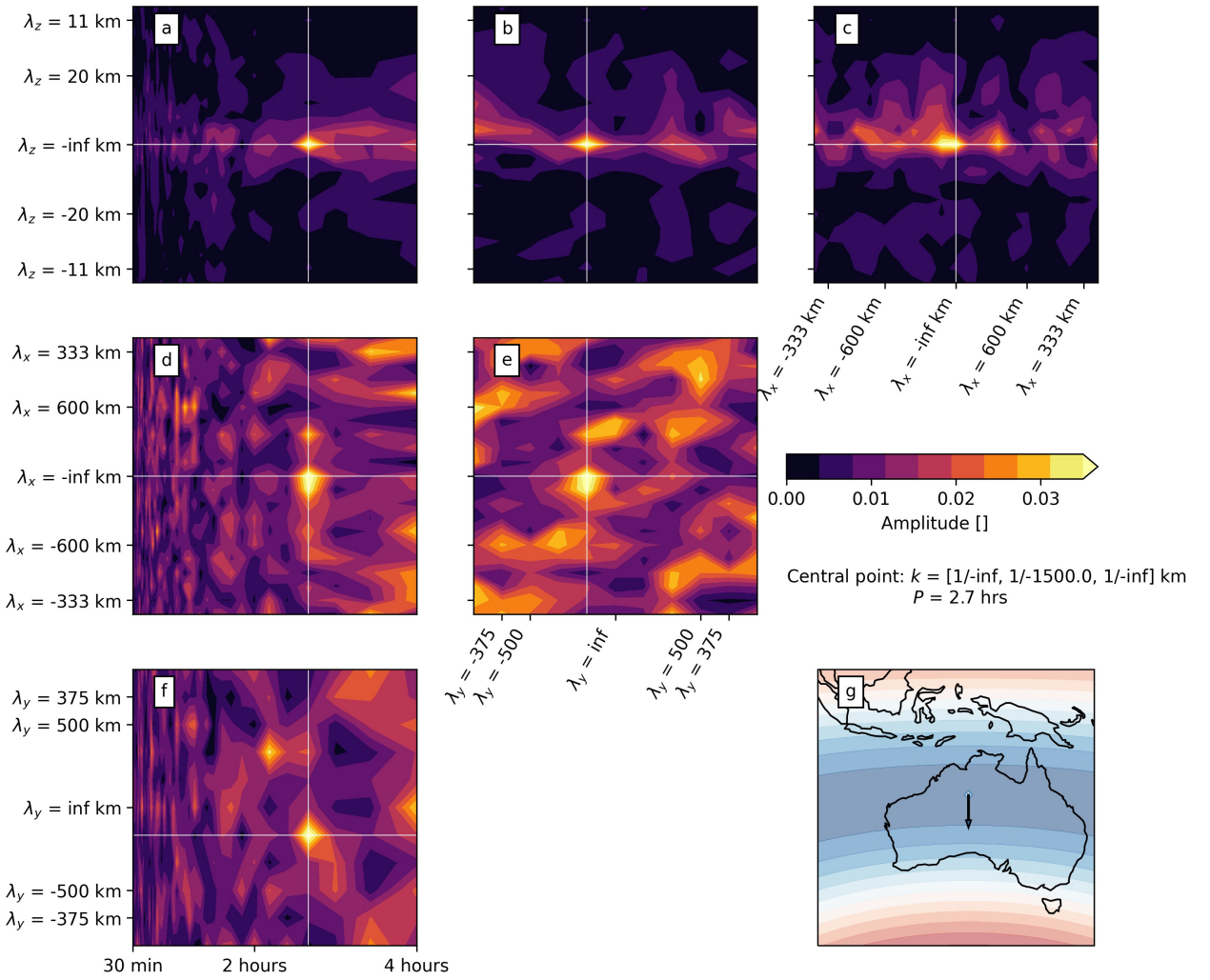
- A three-dimensional function f(x,y,z) can be visualized with three slices through a central point.
- This is shown for the central point of (3, 1, pi)
- We can't see all the data at once

Visualizing Real Data

- Our amplitude is a 4D array – so there are six orthogonal slices through a central point instead of three
- Our central point is a clear peak in all dimensions, and the largest TID in the dataset.
- Traveling due south with speed = 562 km/hr = 156 m/s
- Black arrow in (g) shows the distance the wave moves in an hour

*Assuming waves are ***coherent*** over the whole domain

**Ignoring that we are on a rotating sphere

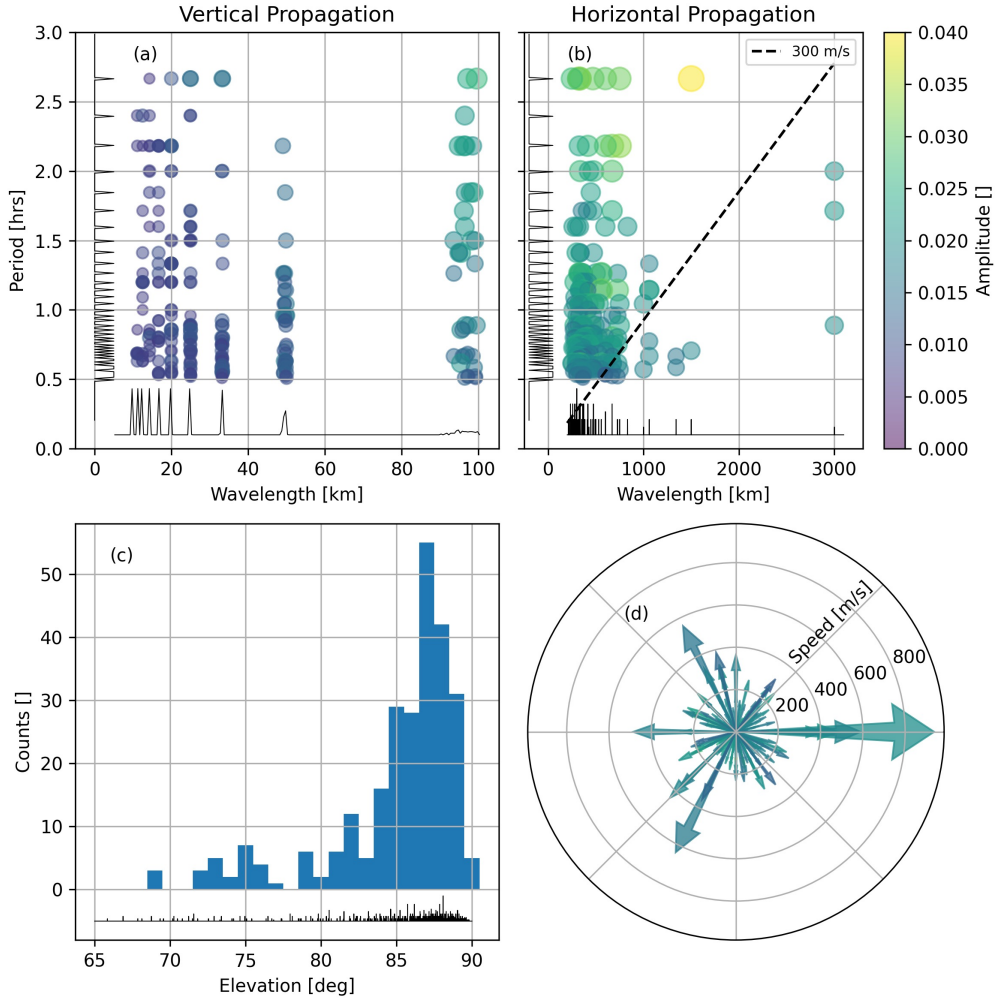


TID Statistics

- Define a TID to be: 1) a local peak 2) significantly higher than the noise floor
- Amplitudes are shown as color. An amplitude of x ~0.04 corresponds to an electron density variation of $10^{0.04} - 1 = \sim 9\%$
- Because of our measurement geometry, we only see horizontal TIDs, or TIDs with elevations over 64°

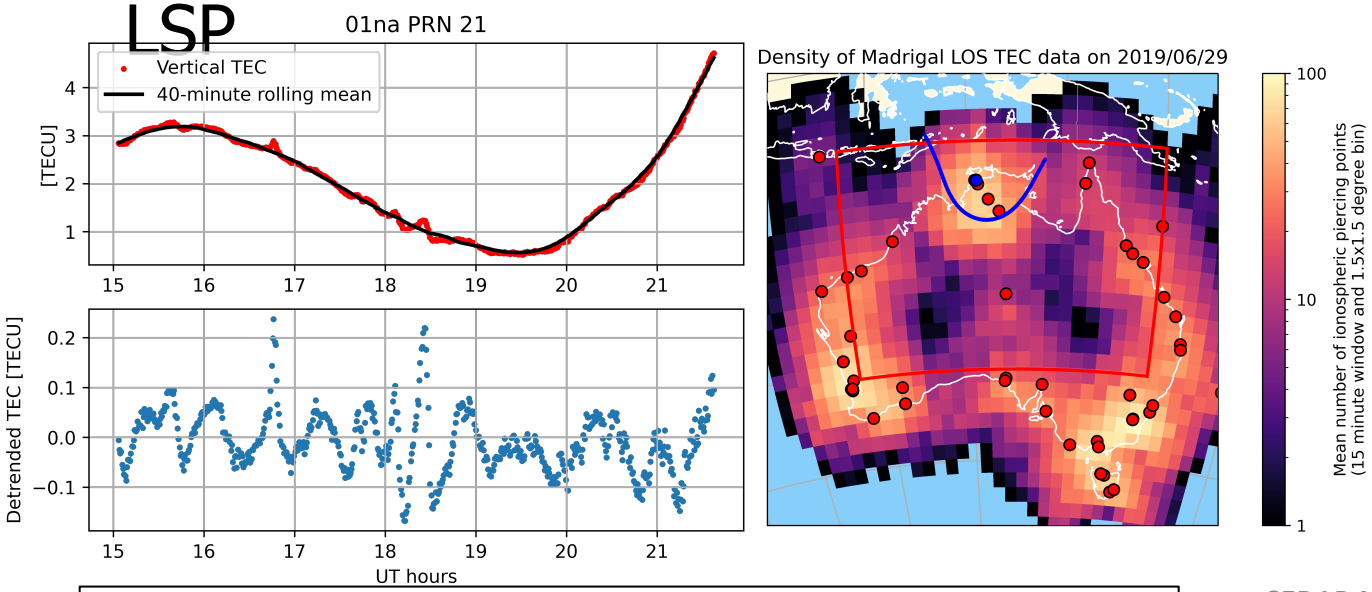
A) This near-vertical population of TIDs are invisible if using only TEC data

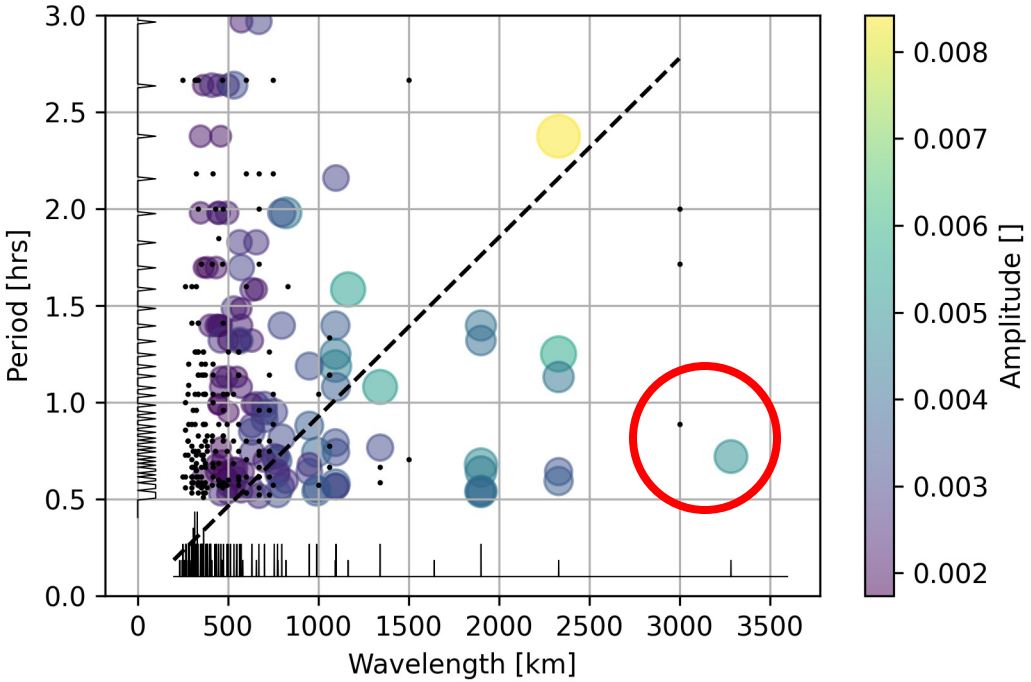
B) Non-vertical TIDs are mischaracterized if using a single ionosonde



Comparison to TEC data

- Used method in Azeem et al., 2018 to calculate wave spectra using TEC and interpolation.
- Large colored dots show waves from TEC and FFT analysis, small black points show waves from Ionosonde and ND LSP





Very similar morphologies despite different resolvable wavelengths and periods!

ND LSP Analysis matches independent analysis and provides new information about the near-vertical TIDs

Anthea Coster, MIT/Haystack Observatory. (2019) Data from the CEDAR Madrigal database. Available from https://w3id.org/cedar?experiment_list=experiments4/2019/gps/29jun19&file_list=gps190629g.002.hdf5

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