Post-sunset Sporadic F propagation: A Sign of Electron Density Isopleth Convergence ?

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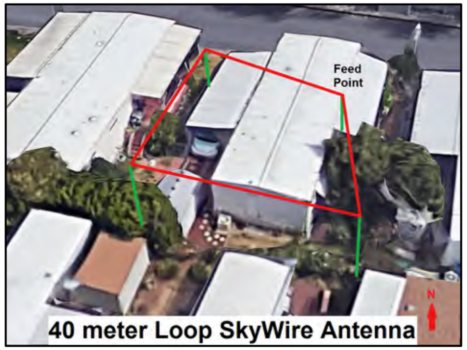
Outline: From Ham WSPR spots *towards* Ionospheric Physics

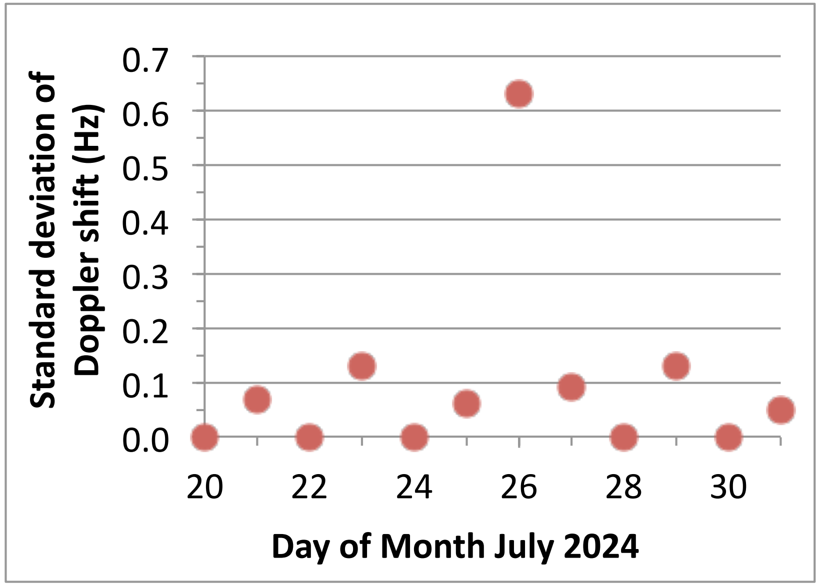
- Hams spotted a post-sunset WSPR 14 MHz opening across continental USA with unusual several Hz variation in Doppler shift.
- Ionospheric Physics: Try and answer *Why?* using HamSCI GRAPE Doppler:
    - Build a picture: What propagation modes were present?
    - Was a TID present? If so, how *does* a TID result in Doppler shift?
    - What is an isopleth?
    - Lets derive estimates of two isopleths from Grape Doppler.
    - How did the post-sunset opening tie-in with estimates of isopleth convergence?

Ham Observations: The *Natural History* of Space Weather



Modest equipment is all it takes to observe *day-to-day* space weather effects on propagation: KiwiSDR with Raspberry Pi4 and a 40 metre loop Sky-Wire antenna at KP4MD.

Such equipment is also capable of observing *outlier* events, triggering the question: What caused *this* event with high Doppler standard deviation?

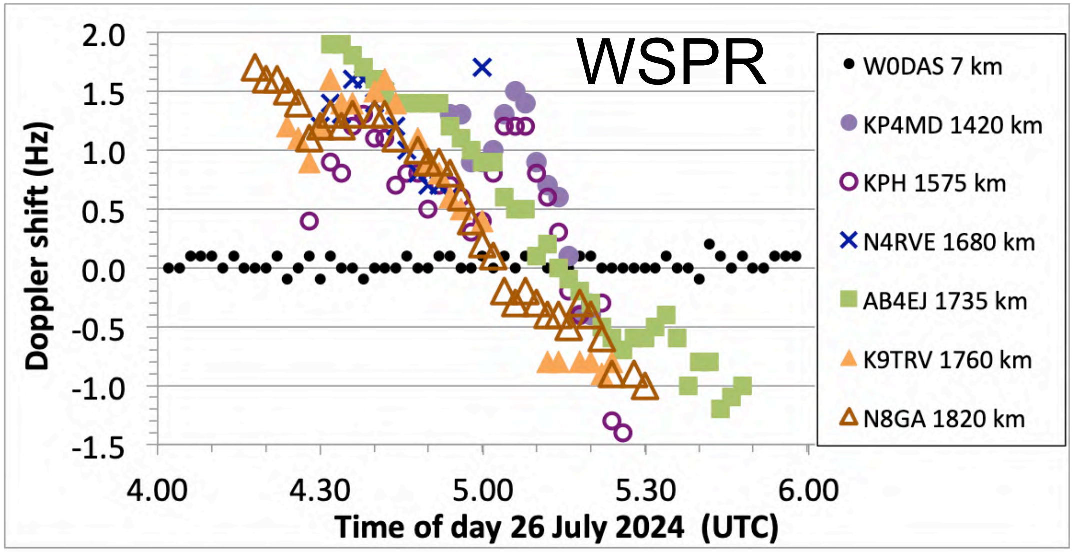


14 MHz WSPR on the 1420 km path WW0WWV Fort Collins to KP4MD Sacramento between 0400 UTC and 0600 UTC each day 20–31 July 2024.

Data and images credit: Carol Milazzo KP4MD

Continent-scale Event Where Doppler Changed ~3 Hz in 1 hr

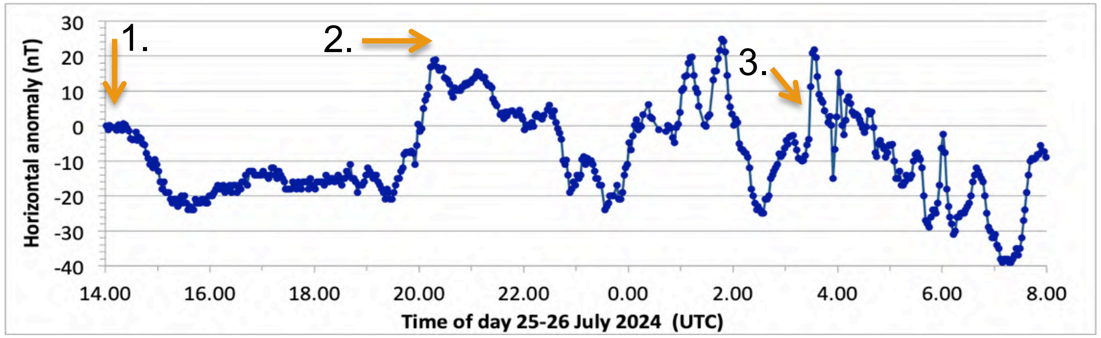
14 MHz opened suddenly, post sunset, on paths over 1400 km from WsprSonde WW0WWV Fort Collins.

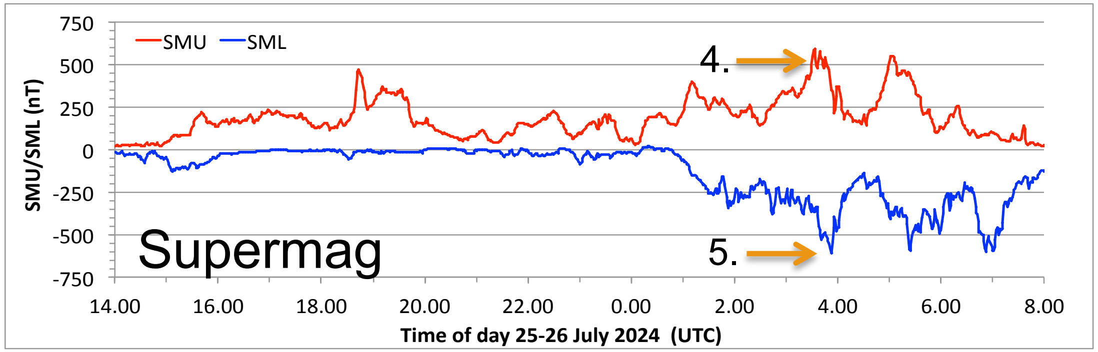


- Line-of-sight monitoring by W0DAS rules out transmitter fault.
- Matched pairs at (KP4MD, KPH) and (K9DZT, N8GA), highly reproducible.
- Staggered times suggest a travelling feature.
- But we only see positive to negative transition. Why?
- Was it higher-than-background electron density that '*opened the band*'? If so, how?

Geomagnetic Conditions on 26 July 2024

N6GN amateur RM3100 magnetometer, Fort Collins

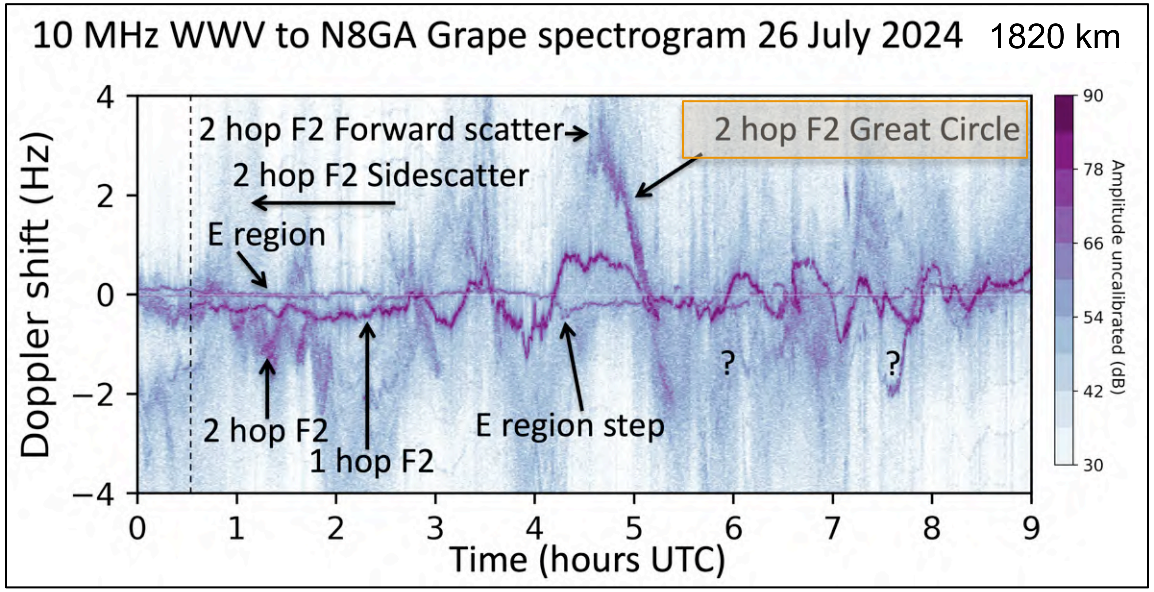




1. CME hit Earth 14:22 UTC 25 July: Little immediate impact.
2. Minor G1 storm as Earth passed through magnetised wake. *Travelling Ionospheric Disturb-ances (TIDs) likely generated.*
3. Sharp step in horizontal anomaly at Fort Collins at 03:28 UTC.
4. +ve Peak in Supermag Eastward (SMU) Auroral Electrojet Index +588 nT at 03:33 UTC.
5. -ve Peak in Supermag Westward (SML) Auroral Electrojet Index -582 nT at 03:51 UTC.

We gratefully acknowledge the SuperMAG collaborators: https://supermag.jhuapl.edu/info/?page=acknowledgement

Observed Propagation Modes: WWV to N8GA at 10 MHz



- Grape Doppler signature strongly suggests two-hop F2 reappears on this path.
- The post-sunset sporadic WSPR reception likely associated with this anomalous return of two-hop.

- Quasi-periodic variations show TID had been triggered.
- E region trace throughout. Thin line, narrow spectral width, near-zero Doppler, but note step.
- One-hop F2 fades *in*, then present throughout.
- Two-hop F2 fades *out* as its skip zone lengthens as evening electron density decreases.
- Two-hop sidescatter present throughout, as wide-bandwidth, fuzzy variations with two-hop Doppler shifts.

Doppler Shift from Rate of Change of Phase Path

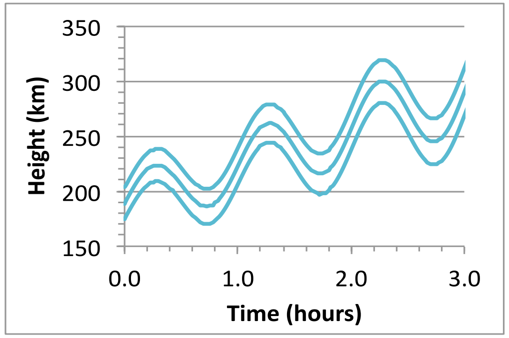
$$\frac{\partial N}{\partial t} = \underbrace{-\nabla N.u_p}_{1} \underbrace{-N(\nabla.u_p)}_{2} + \underbrace{(p-l)}_{3}$$

N	electron (plasma) density	u_p	radial velocity component
p	free electron production	*l*	free electron loss

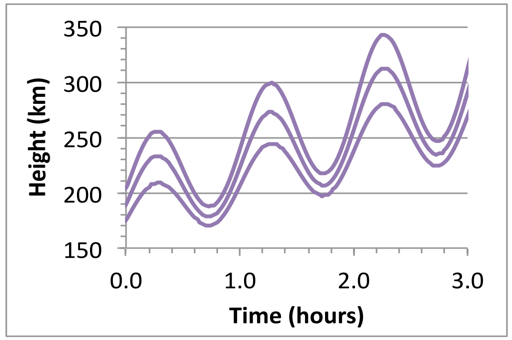
1. **Gradient term:** Advection, radial motion of the reflection region. Commonly vertical motion, e.g. diurnal fall and rise, eclipses, TID.
2. **Divergence term:** Compression/rarefaction, of the plasma, mainly in the reflection region.
3. **Production and Loss**: Imbalance, such as from photoionization during distinct solar flares.

Heights of surfaces of equal electron density after sunset with 'TID'.

Advection: Surfaces track each other. Simple model usually assumed, only term 1.



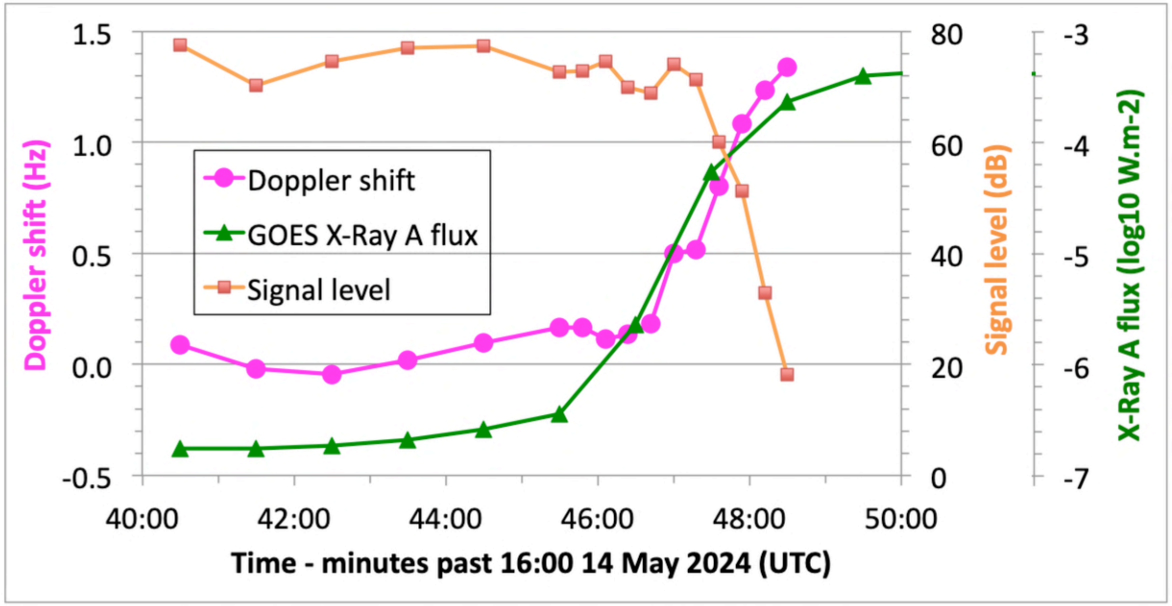
Advection and divergence: Surfaces track, but with compression and rarefaction



Chum, J. et al., 2018. Continuous Doppler sounding of the ionosphere during solar flares. *Earth Planets Space*, 70, pp.1-19.

Doppler Shift from (*p* – *l*) Imbalance: Very easy to spot

- Large spike in free electron production. Example: X8.79 flare on 14 May 2024.
- 15 MHz WWV to Grape receiver at N8GA.
- Doppler spectrum from 60 seconds of digital_RF data.
- Step by 18 seconds during the sharp rise.
- ~1.2 Hz change in Doppler shift until insufficient signal level due to excess absorption induced in D and E regions.



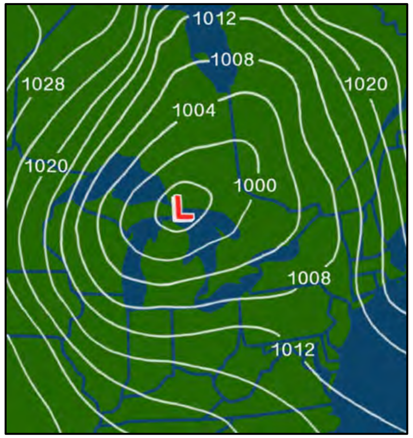
WWV 15 MHz Doppler shift observed at N8GA with signal level and GOES X-Ray A on log scale

GOES data courtesy ESA, NASA, NOAA via https://www.ngdc.noaa.gov/stp/satellite/goes-r.html

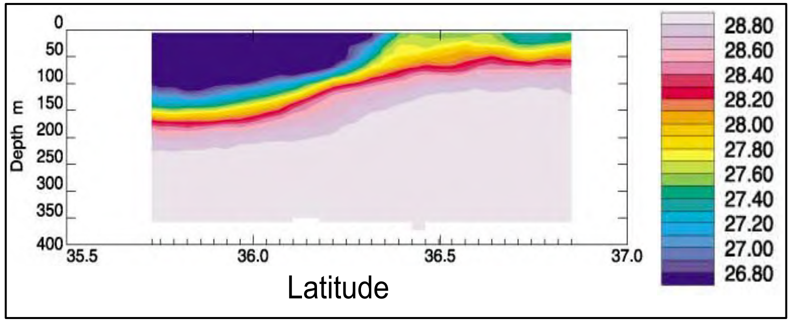
Meet some isopleths showing compression and rarefaction

Plan view Weather Chart Pressure: *Isobars*

Image: CC BY-NC

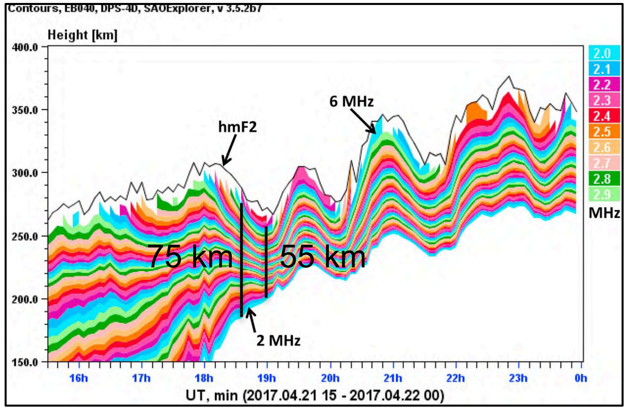


Cross-section upper 400 m in the Mediterranean, Density: *Isopycnals*



Allen et al. (2001).

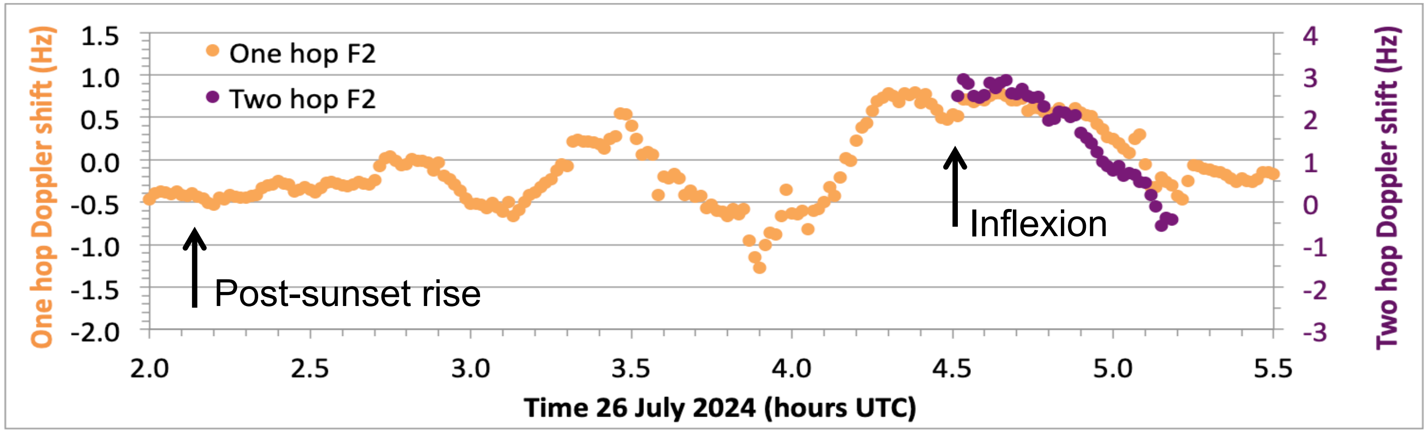
Cross-section 150 km to 400 km in the Ionosphere



Measured post-sunset TID-induced disturbance to plasma frequency isopleths showing compression and rarefaction at the Ebro, Spain ionosonde. Reinisch et al. (2018).

Reinisch, B., et al., 2018. Pilot ionosonde network for identification of traveling ionospheric disturbances. *Rad. Sci.*, *53*(3), pp.365-378.
Allen, J.T., et al., 2001. Mesoscale subduction at the Almeria–Oran front: Part 1: Ageostrophic flow. J. Mar. Sys., 30(3-4), pp.263-285.

Quest for isopleths: A) 10 MHz Doppler Shift WWV to N8GA

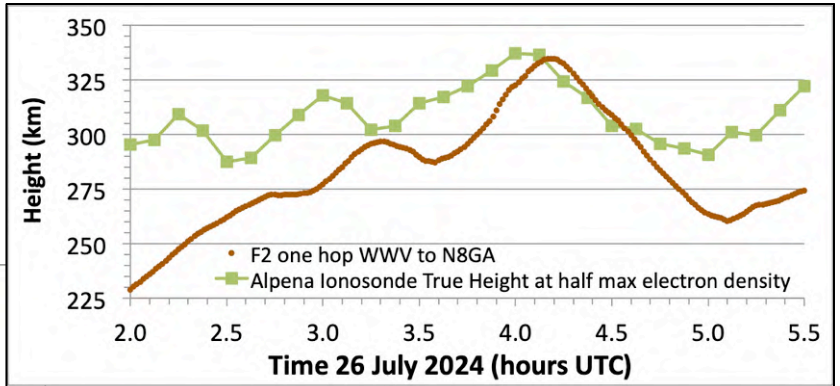


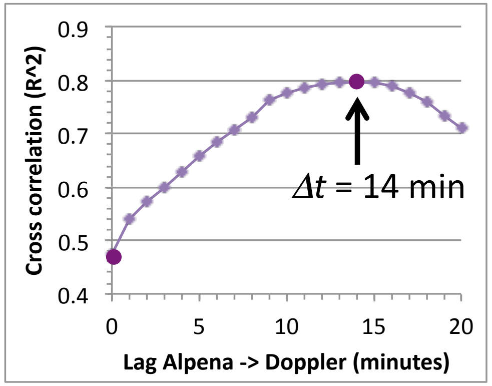
- Doppler time series extracted from digital_RF data files in PSWS database.
- Peaks for two co-propagating modes identified using *scipy* Continuous Wavelet Transform function, Facebook Prophet predictive tracker, then interpolation and manual checks.

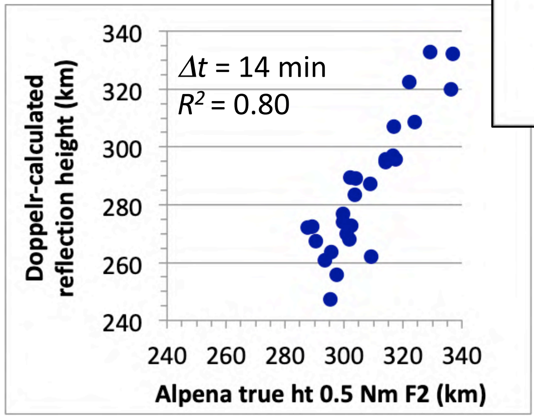
- Critical frequency (electron density) became sufficiently high for two-hop propagation after one-hop Doppler remained positive after a post-peak inflexion at 04:30 UTC.

How to extract Doppler shifts from digital_RF files and identify and allocate peaks are in my HamSCI SCIENCE talk at https://youtu.be/qcM5_IKjvw4?

B) Derive 10 MHz 'Height of Reflection' and Check







- Use PyLap reflection height for 10 MHz at R12=120 at 02:00 UTC as initial constant for Doppler-derived height, ***assume* 100% advection**.
- Cross correlate with Alpena ionosonde true height at half the electron density maximum. Peak R^2 of 0.80 at 14 minutes lag.
- There's an offset (expected) *and* a height scale factor of 1.50.
- **Attribution of 100% Doppler shift to advection *possibly* incorrect.**

Divergence: *A multiplier for Doppler from advection?*

$$f_D = f_{DA} . \frac{\frac{\partial N}{\partial z} + N \frac{2\pi}{c_s T}}{\frac{\partial N}{\partial z}}$$

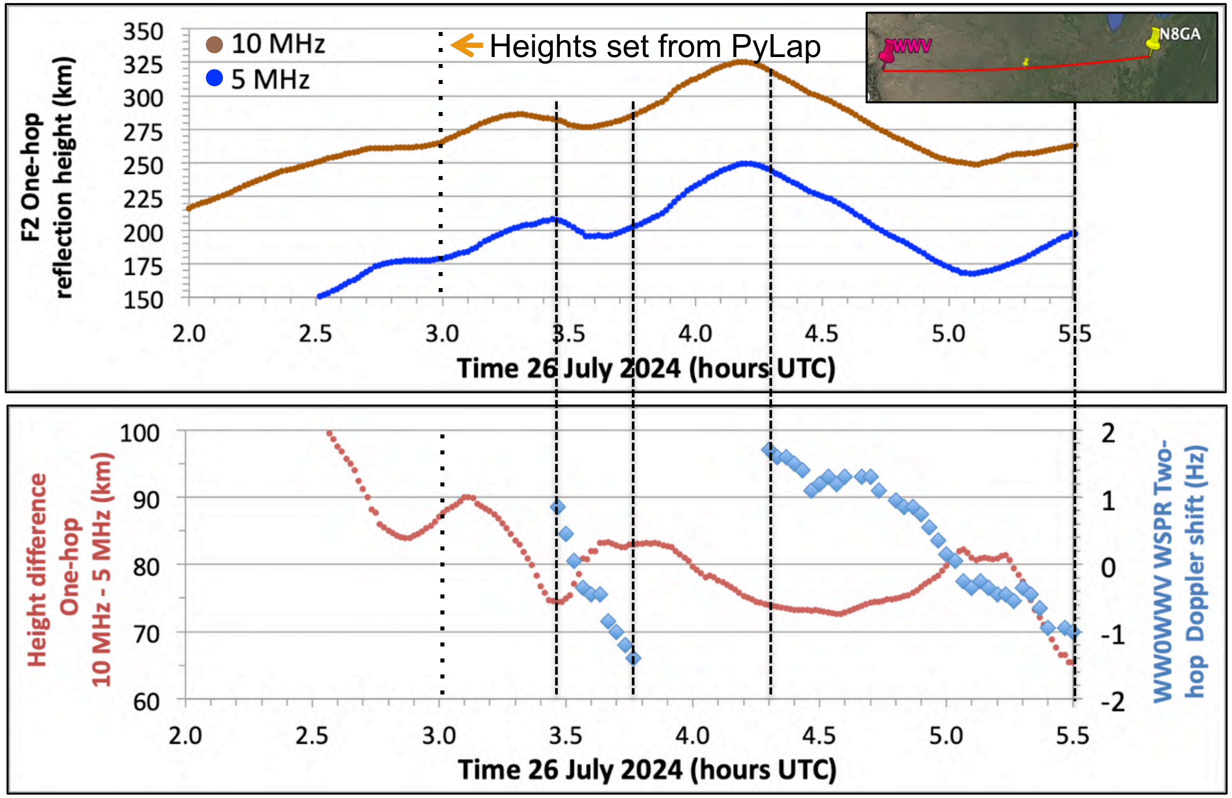
1 2

f_D	Measured Doppler shift
f_{DA}	Doppler shift solely from advection
N	Electron (plasma) density
Z	Height
c_s	*Propagation velocity infrasound wave*
T	*Period of infrasound wave*

- In a study of ionospheric Doppler shifts due to infrasound waves from an earthquake Chum et al. (2012) derived this equation for effect of divergence.
- The second term is a *multiplier* for the true Doppler shift from advection.
- The multiplier is 1 or greater than 1.
- A working hypothesis is that, even though we have a TID and not infrasound as the perturbation, this multiplier could have increased the true height-change Doppler to give the values we measured.

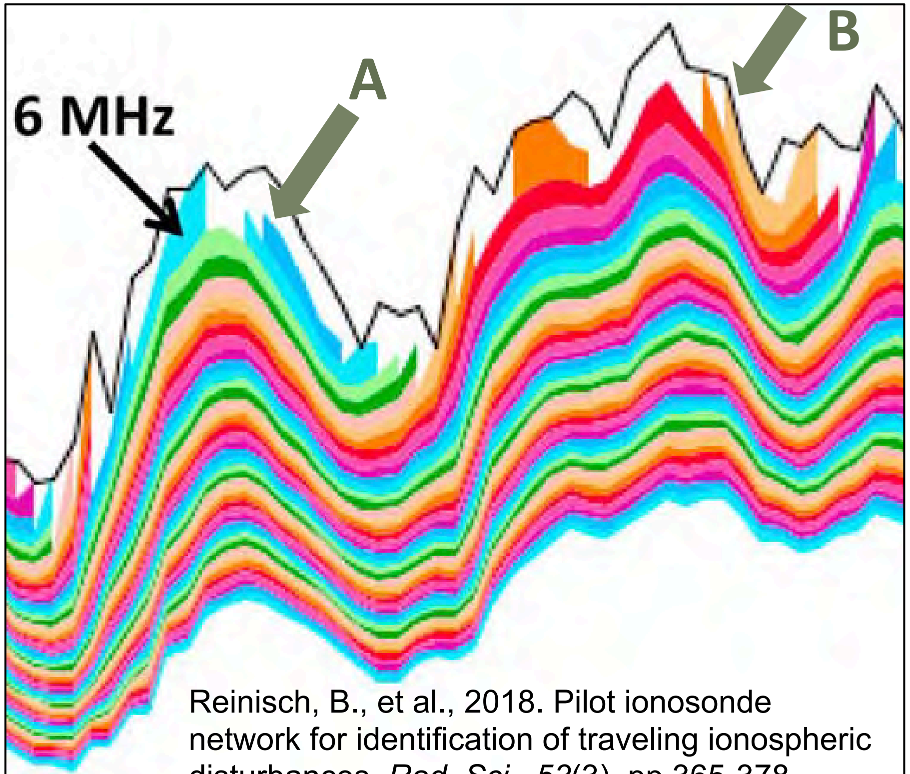
Chum, J. et al., 2012. Ionospheric disturbances (infrasound waves) over the Czech Republic excited by the 2011 Tohoku earthquake. J. Geophys. Res.: Space Phys., 117(A8).

Reflection Heights at 10 MHz and 5 MHz: Isopleth Proxies?



- 03:00 UTC heights set to those from PyLap ray traces.
- These heights may be flawed isopleth proxies.
- Nevertheless, convergence, that is, reduction in isopleth height difference, is seen, especially from just after TID peak to the TID trough.
- Two-hop 14 MHz WSPR propagation reasonably aligned with one-hop isopleth convergence.

Some Support for the Mechanism: Ebro Ionosonde Record



Reinisch, B., et al., 2018. Pilot ionosonde network for identification of traveling ionospheric disturbances. *Rad. Sci.*, *53*(3), pp.365-378.

In the zoomed-in ionosonde critical frequency plot from Reinisch et al. (2018) we see:

- At A, in dark cyan, an isopleth of higher critical frequency emerges after peak height, lasting until the trough.
- At B, in light orange, an isopleth of higher critical frequency emerges after peak height, lasting until just after the trough.

Conclusions

1. Ham WSPR reports great for highlighting propagation anomalies.
2. Multiband GRAPE data may have answered *why* the post-sunset opening occurred, but first :
   a. Reaffirm that Doppler shift comes from convergence as well as advection
   b. Needed to extract Doppler time series for multiple co-propagating modes
3. Showed convergence was likely present:
   a. Inferred height variation greater than from ionosonde
4. WSPR opening start was at greatest convergence, spanning TID peak to trough, prolonged by the extended positive half-cycle of TID Doppler.