Using Digital RF data to derive Doppler Shift and Ionospheric Heights: *Steps Along the Way*

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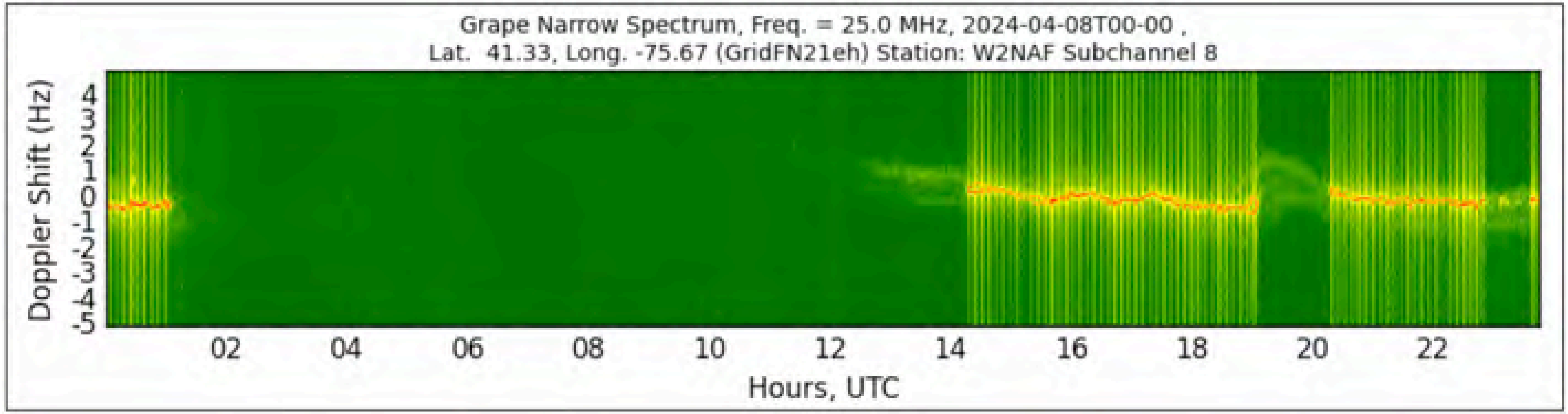
This study could not have been performed without: Grape RX888 WsprDaemon from Phil Karn KA9Q and Rob Robinett AI6VN, PyLap (a wrapper for PHaRLAP, created by Dr Manuel Cervera, Defence Science and Technology Group, Australia that incorporates the International Reference Ionosphere /dat/iri2016/00_iri2012-License.txt) from HamSci and the University of Scranton, PSWS Central Control System from the University of Alabama and HamSci, NIST for WWV, MIT for digital_RF and Nathaniel Frissell W2NAF for his Grape RX888 installation and much more, and finally, but not least to Mary Lou West KC2NMC for posing questions to which some of this presentation may hint at some answers.

Outline Test Case: WWV 25 MHz to W2NAF 8 April 2024

- Reading digital_RF data files
- Doppler shift and spread from autocorrelation in time domain
- Separating propagation modes: One-hop and two-hop sidescatter
- Use Doppler to estimate height of reflection
- *But at times the Doppler is bimodal …*
- Doppler shift of bimodal spectra from frequency domain analysis
- Separating propagation modes: One-hop High and Low rays (*or are they?*)
- Use Doppler to estimate multiple heights of reflection, and
- Compare with PyLap heights of reflection

WWV 25 MHz to W2NAF on 8 April 2024

The Zoomed-out view – Quick-Look PSWS spectrogram

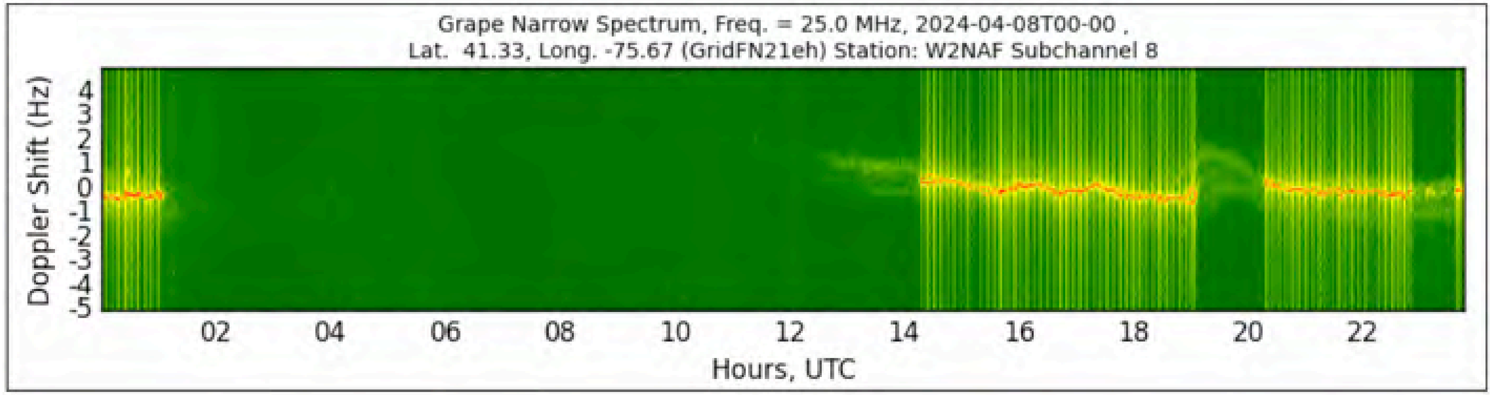


Sit well back from your screen …

This talk will all be about the Doppler trace between 14:00 and 20:00 hours UTC

https://pswsnetwork.caps.ua.edu

WWV 25 MHz to W2NAF on 8 April 2024 - Features



- This segment of spectrogram *appears* amenable to a very simple time domain algorithm to extract values of Doppler shift
  - Overall, it’s a clean, high signal to noise ratio Doppler trace.
  - Some vertical banding, unknown cause, should not be troublesome.
  - Fuzzy, ghostly trace before one-hop path opens, and during eclipse when band closed for one-hop, is two-hop sidescatter. Weak, not troublesome.

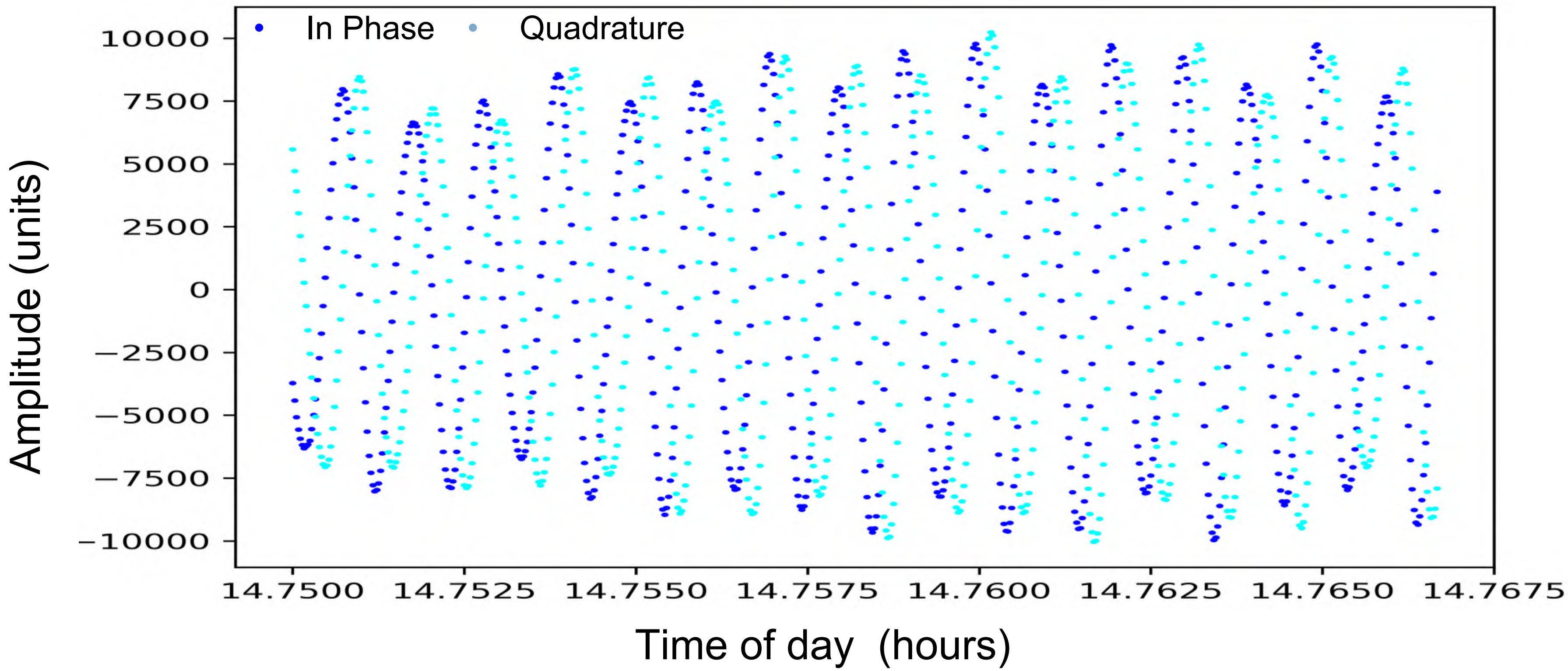
Step 0: Importing digital_rf data into Python

1. On the PSWS website, **Open Filter** in **Observations** to find data set of interest, here: https://pswsnetwork.caps.ua.edu/observations/select_download_range/9604/
2. **Download Observation Data**, unzip, it'll be folder **ch0**, skeleton code follows:

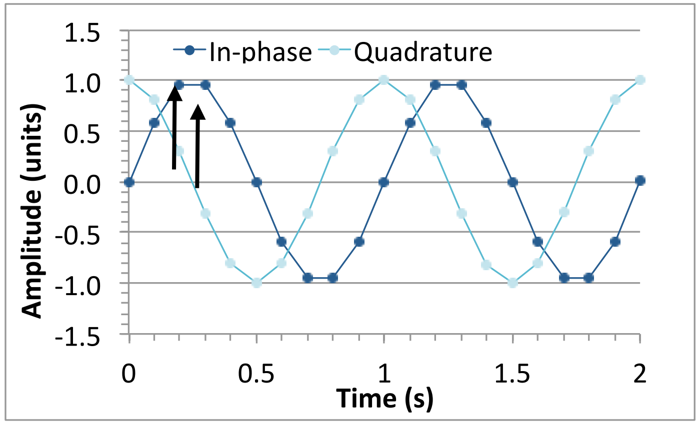
```
import digital_rf as drf
channel='ch0'
frequency=8                        # for RX888 25 MHz with nine time stations WWV & CHU
n_samples=720000                   # at 10 Hz rate to 20:00 if start at 00:00 UTC
do = drf.DigitalRFReader('/users/gxg/desktop/HamSci/grape')   # folder where ch0 folder is found
do.get_channels()
start_time, end_time = do.get_bounds(channel)
input = do.read_vector(start_time, n_samples, channel)
data_25MHz=input[:,frequency]  # just the 25 MHz data as IQ complex numbers
```

Get digital_rf library and full details from https://github.com/MITHaystack/digital_rf

What one minute of IQ at 10 Hz WWV@W2NAF looks like



Step 1: Doppler Estimation via Autocorrelation



Time series of in-phase and quadrature (IQ) in a 1 Hz Grape digital_rf file. Each sample is a complex number.

10 Hz sample rate, that is, *dt* = 0.1 s.

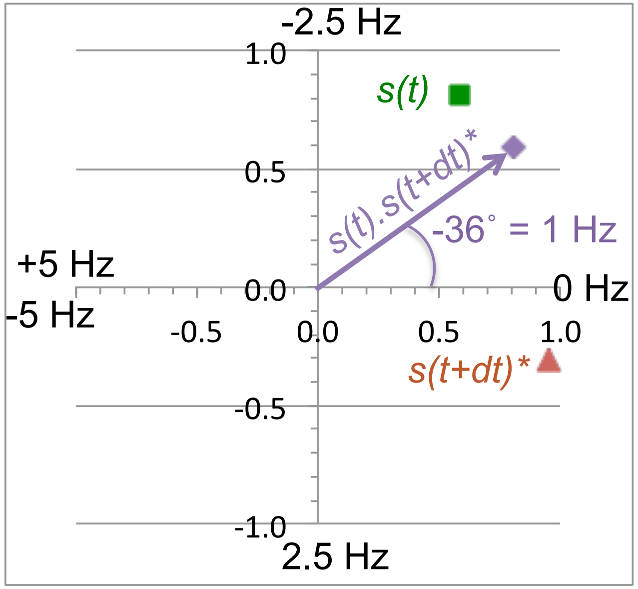
Test signal: 1 Hz Doppler shift

1. Take two adjacent IQ samples *s(t)* and *s(t+dt)*.
2. Form the complex conjugate of the second, *s(t+dt)**, where * denotes conjugate.
3. Multiply, i.e. *s(t).s(t+dt)**
4. Calculate the *argument* (phase angle, ϕ, in degrees) of the resulting complex number. Here it is -36˚.
5. Calculate frequency:

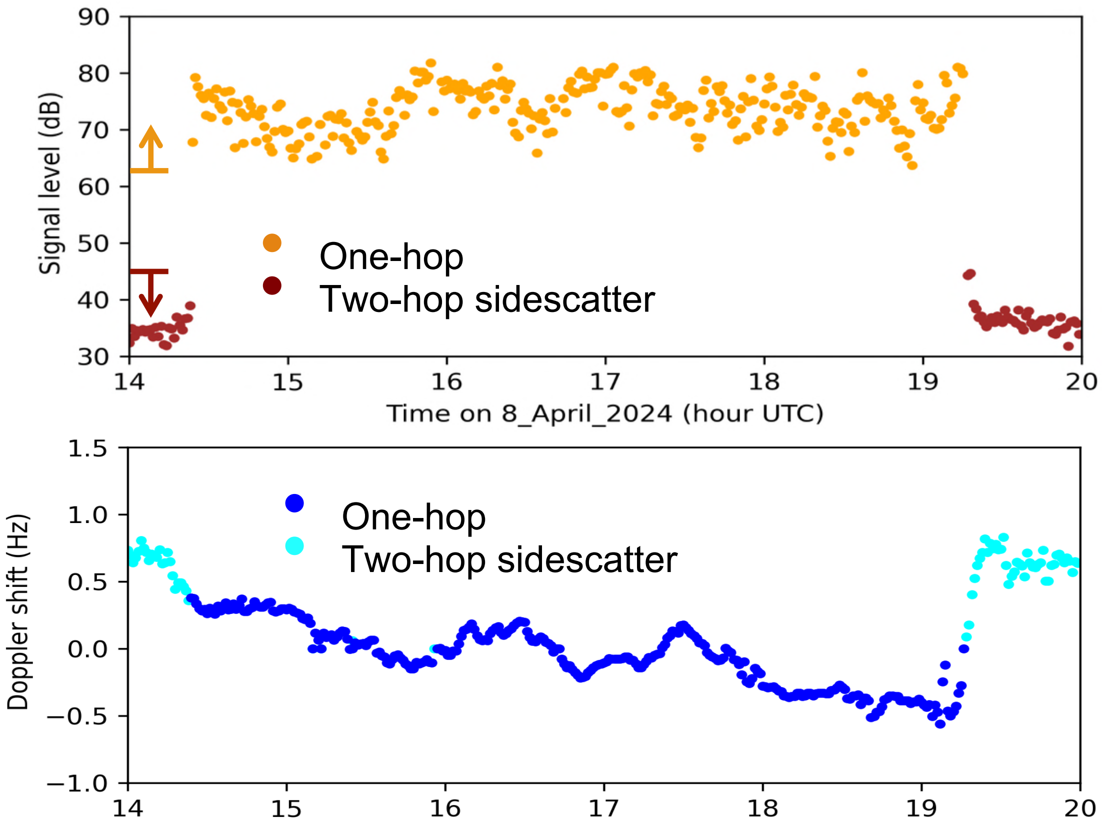
$$f = -(\phi / 360) / dt = 1\ Hz$$

6. In practice, average the correlation function over 600 samples over one minute.

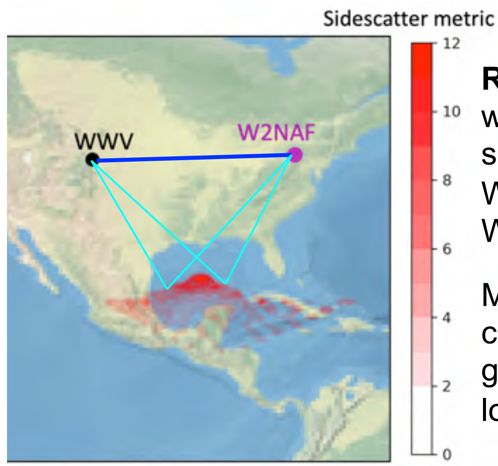
Complex Plane



Step 2: Doppler Results – Identify and Separate Modes



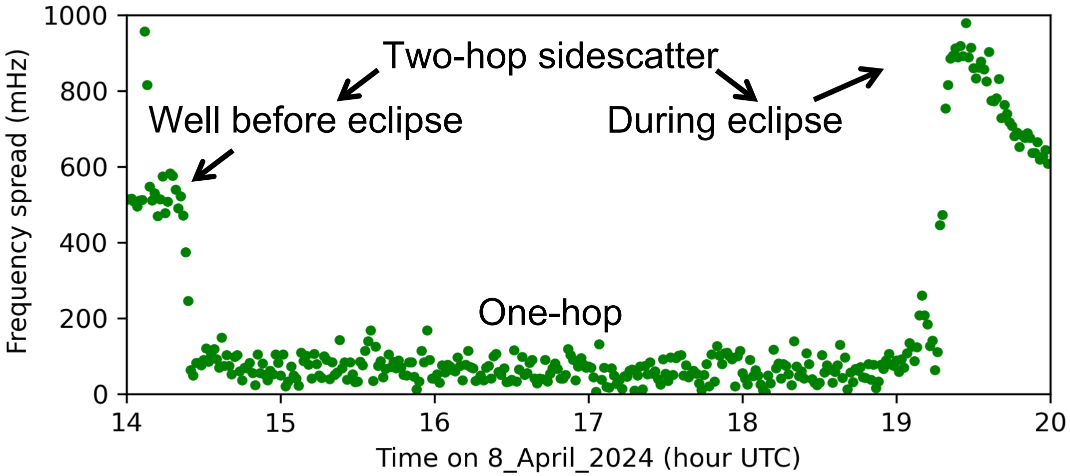
- **Step One:** Simple autocorrelation algorithm gives credible Doppler shift estimates.
- **Step Two:** One-hop and two-hop sidescatter Doppler easily *identified* and *separated* based on amplitude (>63 dB and <45 dB).



Reminder: This is what two-hop side-scatter entails for WWV 25 MHz to W2NAF 19:00 UTC.

Multiple paths and central limit theorem give signal level with low variability.

Step 2: Identify and Separate using Frequency Spread



Time domain autocorrelation algorithm to estimate frequency spread is based on the *magnitude* of the correlation function. Qualitatively, the greater the frequency spread the lower the magnitude of the correlation function cf. a pure sine wave.

$$w_{?} = \frac{\sqrt{2}}{2\pi\Delta t} \cdot \sqrt{\left| \ln\left(\frac{\hat{R}(0) - N}{\left|\hat{R}(\Delta t)\right|} \right) \right|}$$

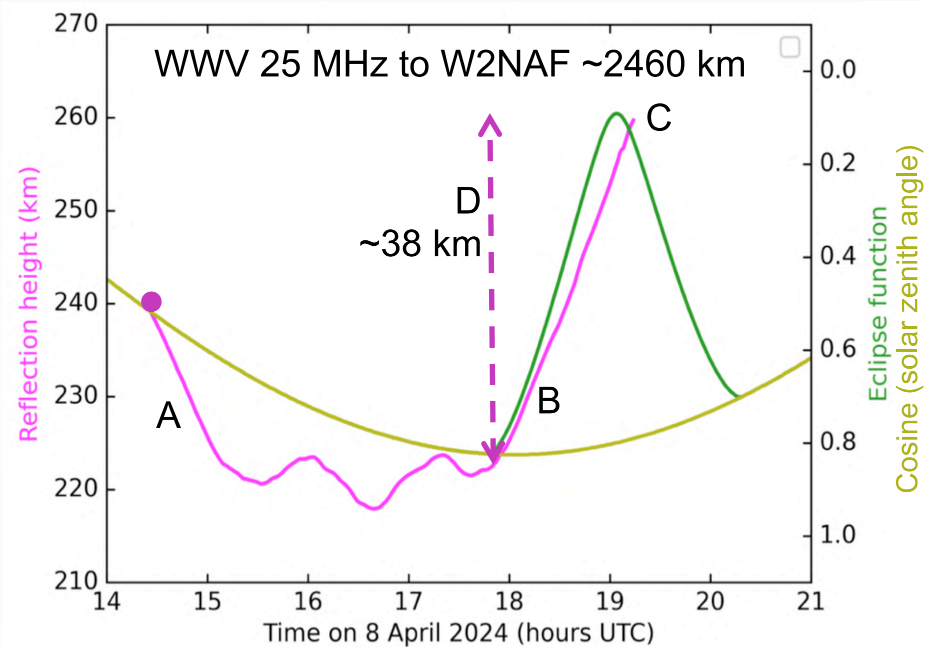
where N is the noise power, which I am taking as zero for now as SNR is high, and $\hat{R}(\cdot)$ signifies the autocorrelation function.

I can't find a definition of what this width represents in % of signal power, 50% 90%, x?

I'll only use as a qualitative estimate, not quantitative.

Warde, D.A. and Torres, S.M., 2013. The autocorrelation spectral density for Doppler-weather-radar signal analysis. *IEEE Trans. Geosci. Rem. Sens.*, 52(1), pp.508-518. https://www.nssl.noaa.gov/projects/mparsup/publications/2014.Warde.TGRS.pdf

Step 3: Reflection Height from Autocorrelation Doppler Shift

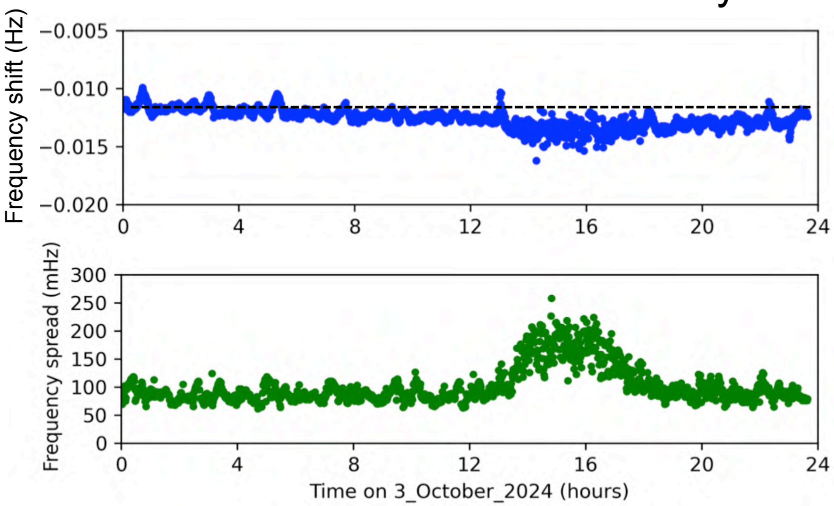


- **Method:** Well described in Collins et al. (2023), with simplified one-hop version in Griffiths (2024). Initial height from PyLap ray tracing (R12=170! to get path to open 14:20)
- Height of reflection calculated from auto-correlation Doppler shows expected features:
  - A. Descent during morning local time
  - B. Ascent at start of eclipse
  - C. Sudden end to propagation as foF2 had fallen such that $MUF_{2460\ km}$ < 25 MHz.
  - D. Rise of ~38 km in reflection height due to eclipse. Very similar to Oct. '23 results.

Collins, K. et al., 2023. Crowdsourced Doppler measurements of time standard stations demonstrating ionospheric variability. *Earth System Science Data Discussions*, 15(3): 1403-1418.
Griffiths, G., 2024. Measuring height of reflection at HF. *RSGB RadCom,* 100(8): 42-44.

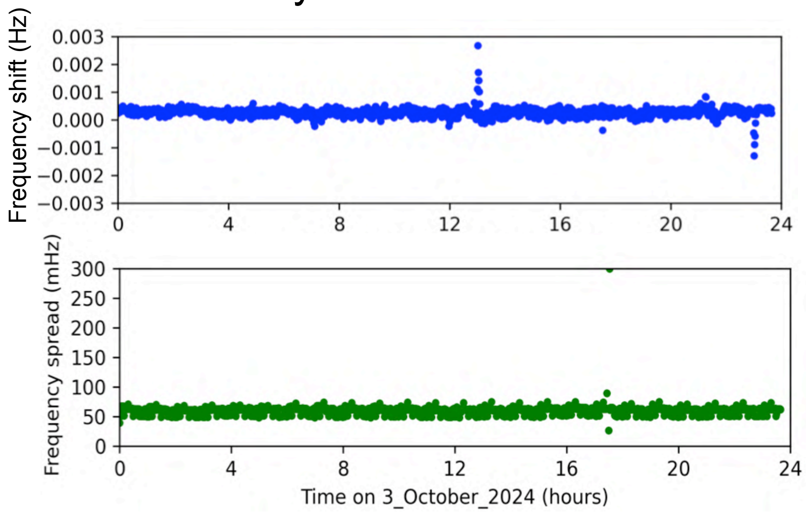
Aside: Autocorrelation Frequency Check WWV 10 MHz ~7 km LOS

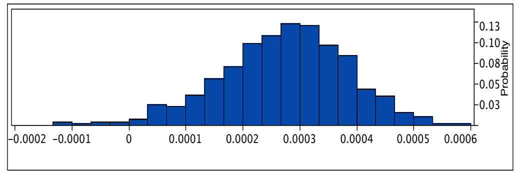
Grape V1.2 DRF W0DAS 1: GPSDO but reliant on soundcard clock accuracy.



- Mean frequency offset *likely* soundcard clock error
- Higher baseline frequency spread, *possibly* soundcard clock jitter/phase noise
- Peak in frequency spread ~16:00 UTC *likely* NVIS propagation multipath. Antenna is a low 15 MHz dipole

Grape RX888 WsprDaemon WW0WWV/0: GPSDO entirely. Antenna is a 10 MHz Vertical.



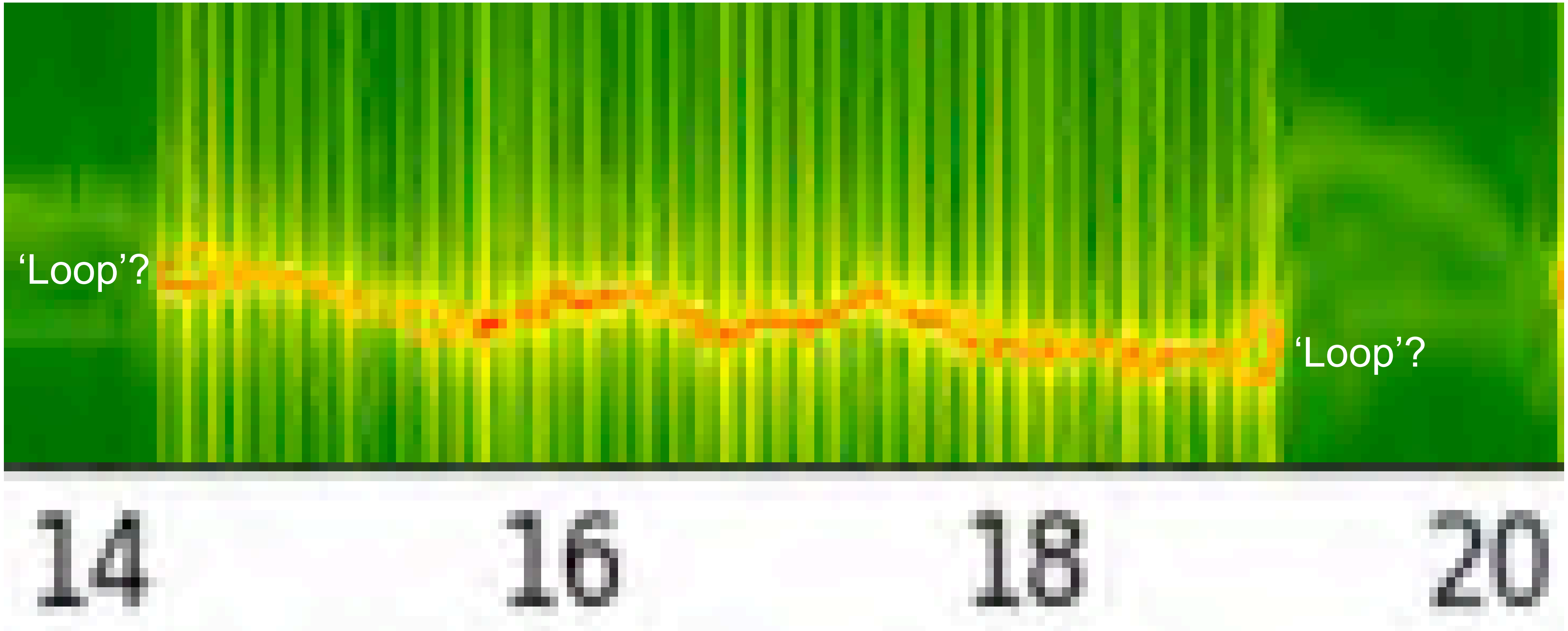


Mean offset = +0.28 mHz Std. deviation = 0.16 mHz

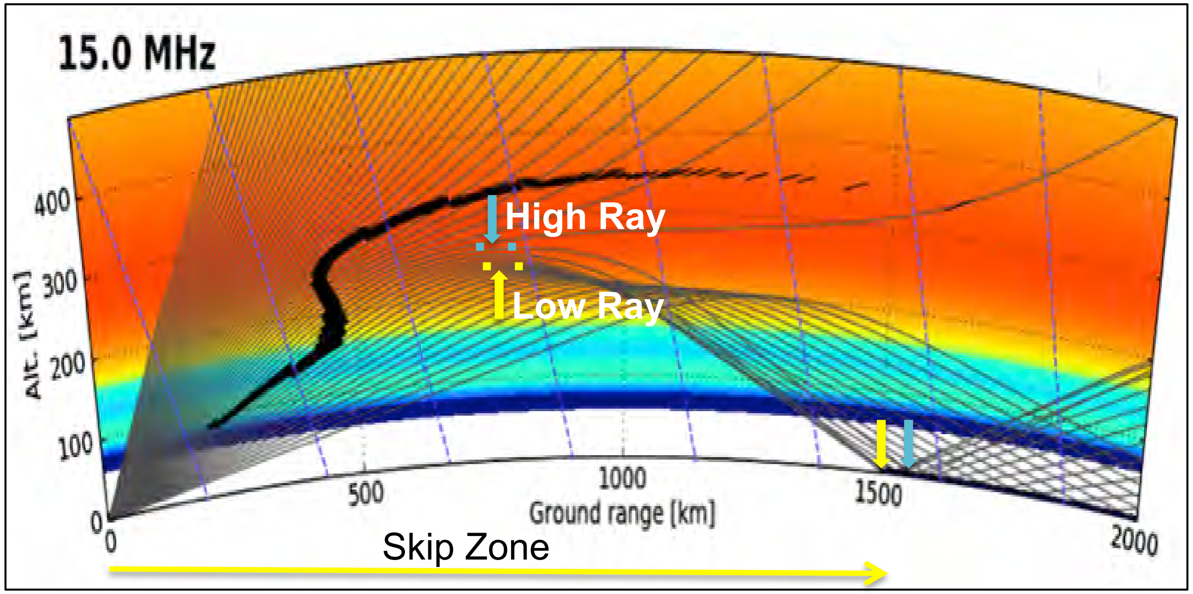
With thanks to Dave Swartz W0DAS, WWV ARC and NIST

Time to Zoom in... Doppler Trace is not Unimodal

WWV 25 MHz to W2NAF on 8 April 2024: ‘Loops’ as the band opens and closes?

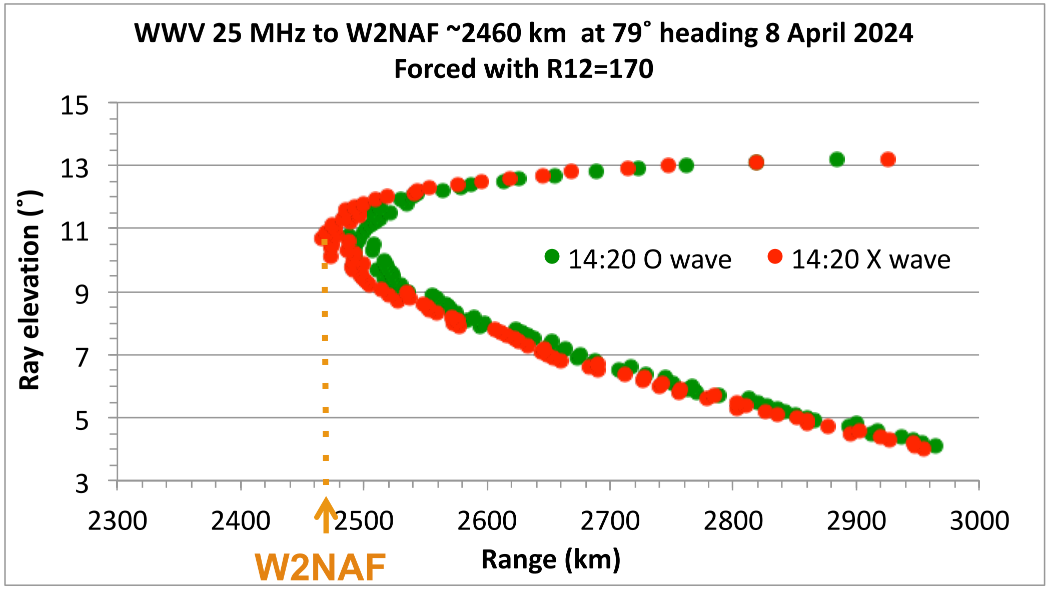


Clues in this HamSCI Ray Trace: High and Low Rays



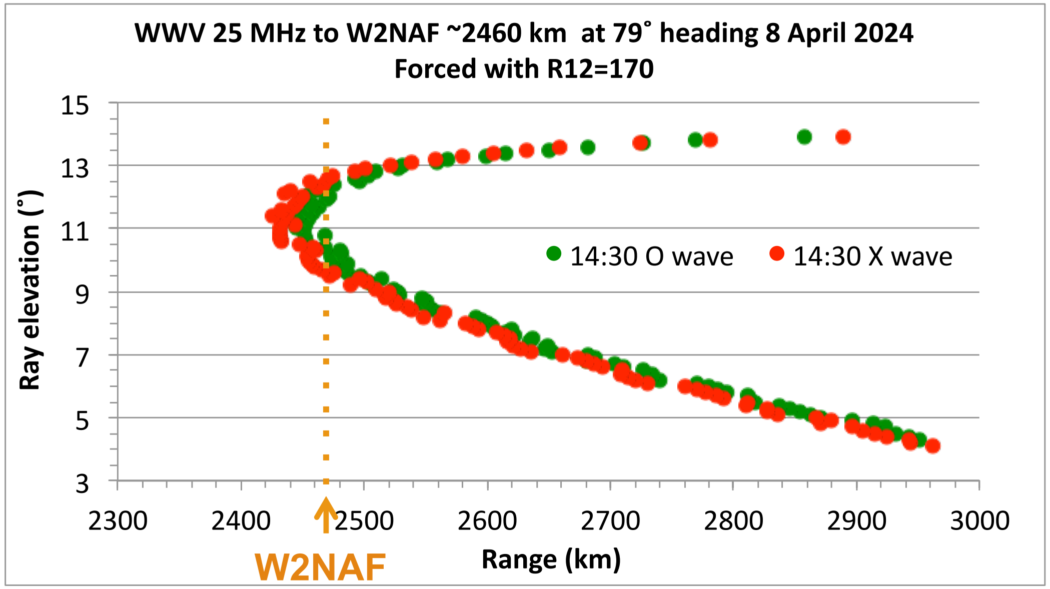
- The transmitted ray that defines the edge of the one-hop Skip Zone is *not* the ray with highest elevation.
- Therefore, it has to be a ray transmitted at lower elevation.
- The implication is that, beyond the *very* edge of the Skip Zone, for a certain distance, there will be two ray arrivals: a High Ray and a Low Ray.
- They will *not* have been reflected at the same height.

Another View of High and Low Rays



- PyLap simulation (forced band opening at 14:20 UTC with R12=170) suggests:
  A. The X wave would be the first to be received
  B. The High and Low Ray zone covers ~500 km in range.
- *If* slope of ray elevation vs. range is a valid proxy, we would see bifurcation and greatest rate of change of Doppler shift immediately after band opens.
- Note how density of ray elevations with range is highest just beyond Skip Zone. Suggests higher signal strength.

Another View of High and Low Rays



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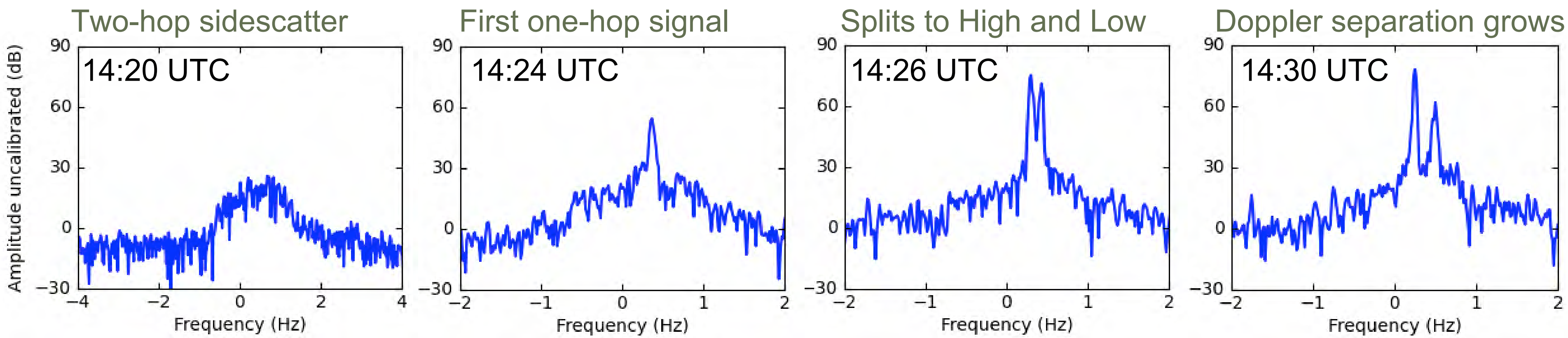
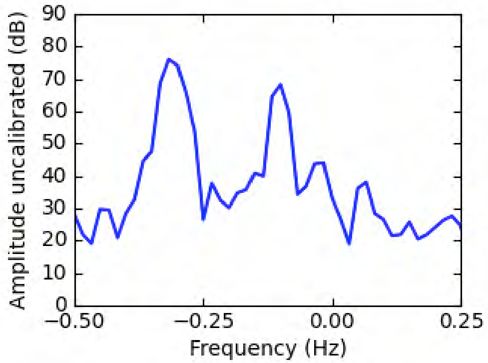
Step 4: Frequency Domain Analysis

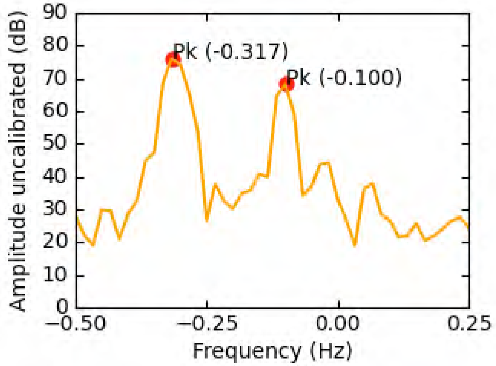
```
# Set up constants and arrays
Hann_factor=1.63        # Energy correction factor # https://community.sw.siemens.com/s/article/window-correction-factors
samp_rate=10            # in Hz
time_window=60          # in seconds
m_samples=samp_rate*time_window
# generate x axis, which is frequency
x=fftshift(fftfreq(m_samples,1/samp_rate))    # fftshift moves zero frequency to centre
# generate Hann window of length m_samples (i.e. 600 samples)
window = signal.windows.hann(m_samples)
yf=fftshift(fft(data[0:m_samples,frequency]*window, norm="forward", overwrite_x=False) * Hann_factor)     # do FFT and ffshift, Hann correct
yf=20*np.log10(np.abs(yf))
```

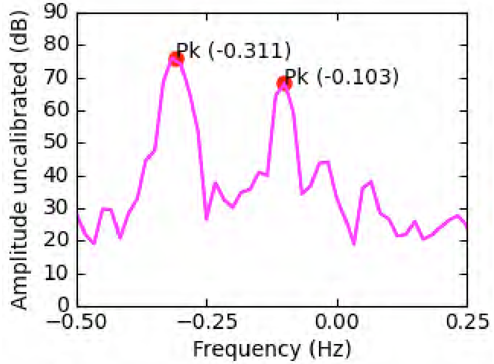


Step 5: Identify & Separate High and Low Ray Doppler Shift

I'm after accurate digital values for the Doppler shift, individually, for the High and Low rays. Includes methods new to me.







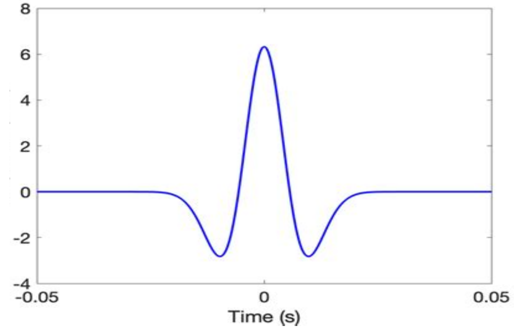
Example zoomed in spectrum showing well-separated High and Low ray Doppler shifts.
At 18:00 UTC.

1. Python function signal.find_peaks_cwt uses Continuous Wavelet Transform to fit wavelets to the spectrum.
2. Outputs list of peak amplitudes. Find two highest (*here assume High and Low rays*), and get frequencies with 1/60 Hz i.e. 0.01667 Hz resolution.

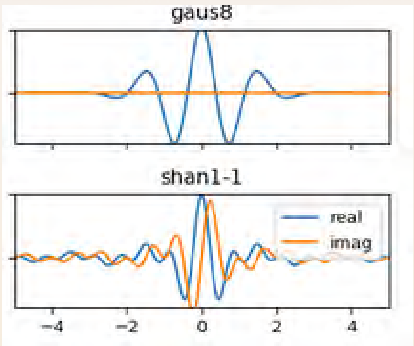
Doppler values after three-point interpolation, at peak and +/- one bin. No wider else might include other peak if close together.

Continuous Wavelet Transforms (CWT) and a Mexican Hat

"The general approach is to smooth *vector* by convolving it with *wavelet (width)* for each width in *widths*. Relative maxima which appear at enough length scales, and with sufficiently high SNR, are accepted."
Source: scipy documentation



Ricker (Mexican Hat, Sombrero) Wavelet.
Default and well suited for peaks

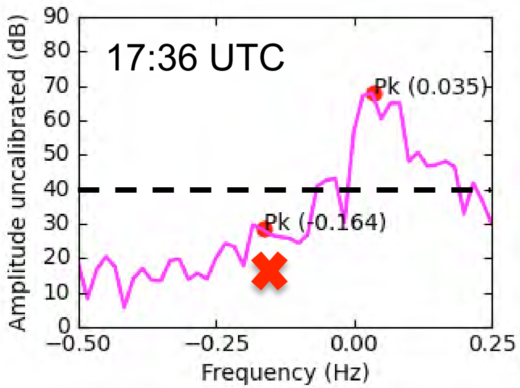


Some other wavelets, from
pywavelets.readthedocs.io/en/latest/ref/cwt.html

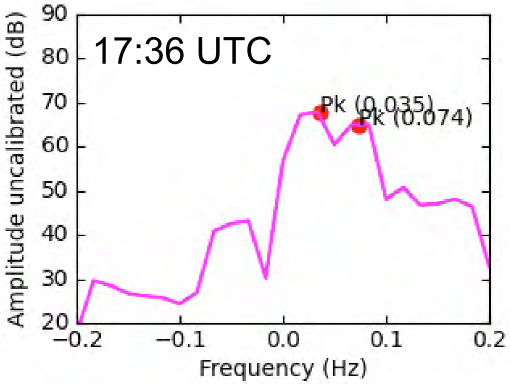
```
peakind = signal.find_peaks_cwt(yf, widths=np.arange (2,4))
max=np.argmax(yf[peakind])          # Amplitude of max peak
index_max_1st=peakind[max]          # Its frequency index
freq_max_1st=x[index_max_1st]       # Its frequency
```

Choice of widths: If minimum is 1, risk of assigning 'random spike' close in to first peak as the second peak
If maximum >4, risk of not accepting narrow peak as a true peak.
Empirical compromise… but we will revisit.

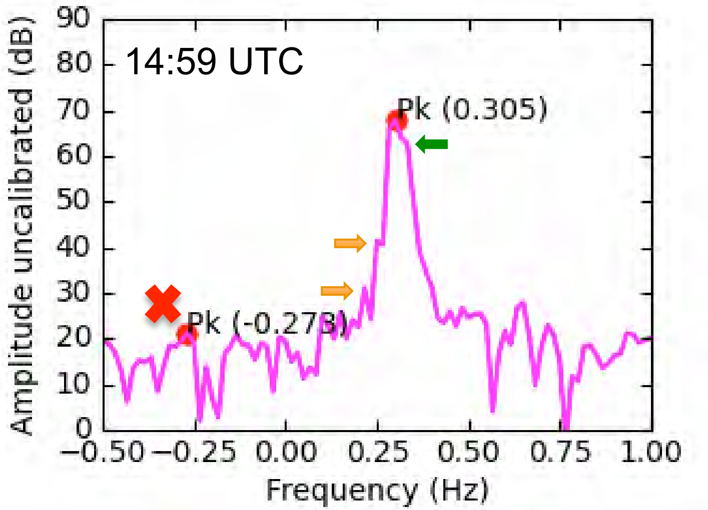
Caution: Unaided CWT not a Robust Solution



CWF second peak wrong. Second peak obvious, distinct peak HF of first peak.

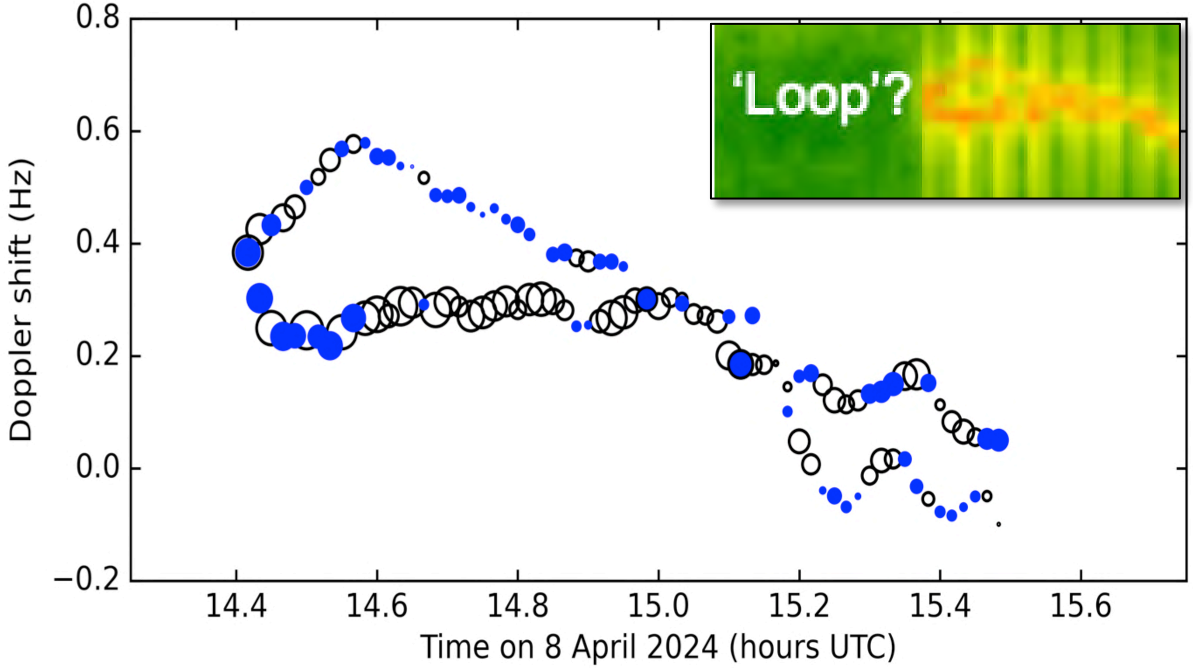


Zoom in… Setting min width = 1 did find second peak, at 0.074 Hz.



CWF second peak wrong. No second peak obvious. Likely just slightly HF of first peak. Before and after spectra showed the two Doppler shifts crossed. Min width = 1, no change.

Step 5a: Time Series of First Peak and Second Peak Doppler



First Peak   Second Peak

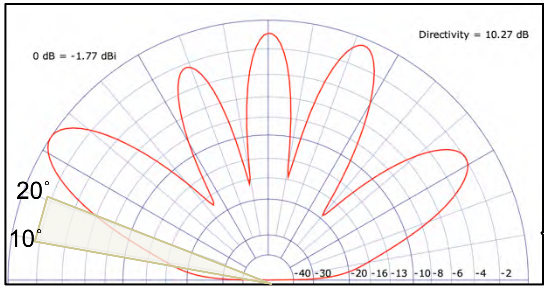
Size proportional to log amplitude.

- In this algorithm, so far, we are plotting First and Second peaks assigned by amplitude.
- High and Low rays mixed up. Their amplitudes vary: one is not always the stronger.
- Cannot separate to High and Low ray on amplitude given overlap.
- No real difference in frequency spread, so not usable as a separation parameter.

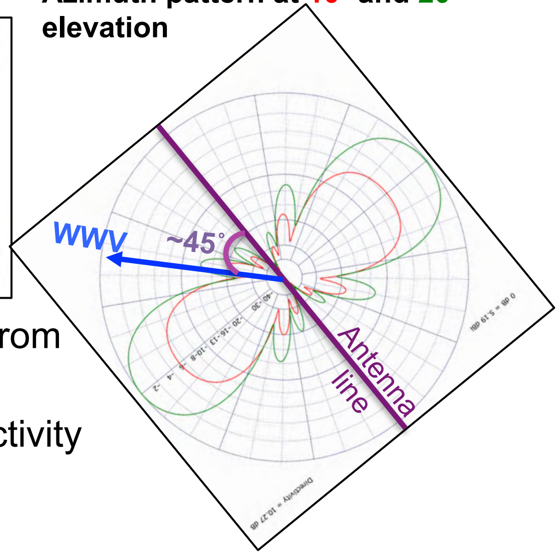
Aside: W2NAF WSPRDaemon/Grape Antenna Information

- W2NAF at 41.335˚N, 75.601˚W
- WWV at 40.680˚N 105.040˚W
- Distance 2459 km at 278˚ from W2NAF
- Buckmaster 80 m Off-Centre Fed Dipole* at ~25 ft elevation
- Broadside 52° (~NE – ~SW)
- For this study with WWV, from model:
  - 10 dB range in elevation response -16 dB at 10˚ to -6 dB at 20˚
  - Sidelobe azimuth response some 13 dB down. *Based on 52˚ broadside*.
  - *If* path deviated from great circle potential to fall into nulls 10˚ either side.
- Should the antenna be characterized as a part of the scientific apparatus?

Elevation pattern at 45˚ azimuth



Azimuth pattern at 10˚ and 20˚ elevation



Antenna beam pattern outputs from CocoaNEC2.0 model on a Mac.

Average to poor ground: conductivity 4 mmho/m and ε_r 13.

Model run by G3ZIL

* www.dxengineering.com/parts/bmt-dx-ocf-hp

Step 5b: Separate and Identify High and Low Rays: Methods

An amateur's Machine Learning approach to ray Doppler separation

Initial Training Set
First ten minutes with Doppler assuredly for one ray

↓

a) Support Vector Regression with Radial Basis Function
b) Facebook Prophet

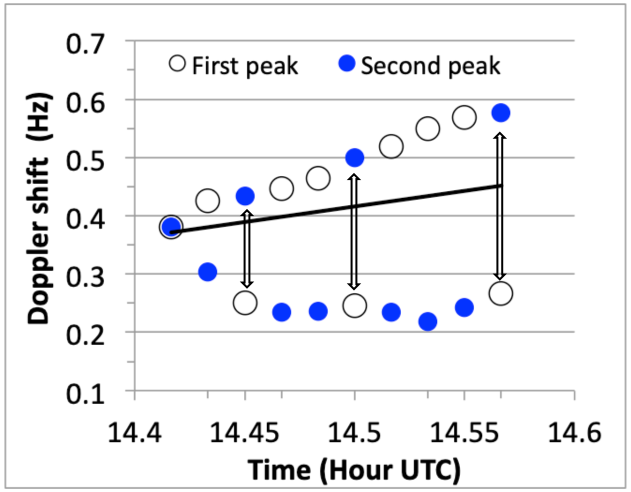
1. Linear regression of ten First Peak Doppler values.
2. Gives a 'Set One' with consistent Doppler.

3. Try two machine learning methods:
4. Predict First Peak Doppler one minute ahead, given assured ten minute learning set.
5. Test whether First or Second Peak Doppler is closest to prediction.
6. Assign closest to Set One, the other to Set Two.
7. *Increment training set by one minute and repeat*

Step 5b: Separate and Identify High and Low Rays: Methods

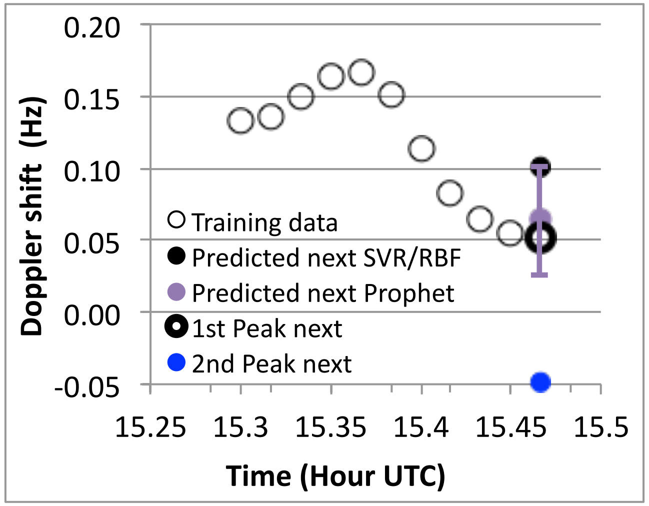
Special case of initial divergence between the two rays makes simple *linear* option effective.

Obvious which initial residuals to swap (black arrows).

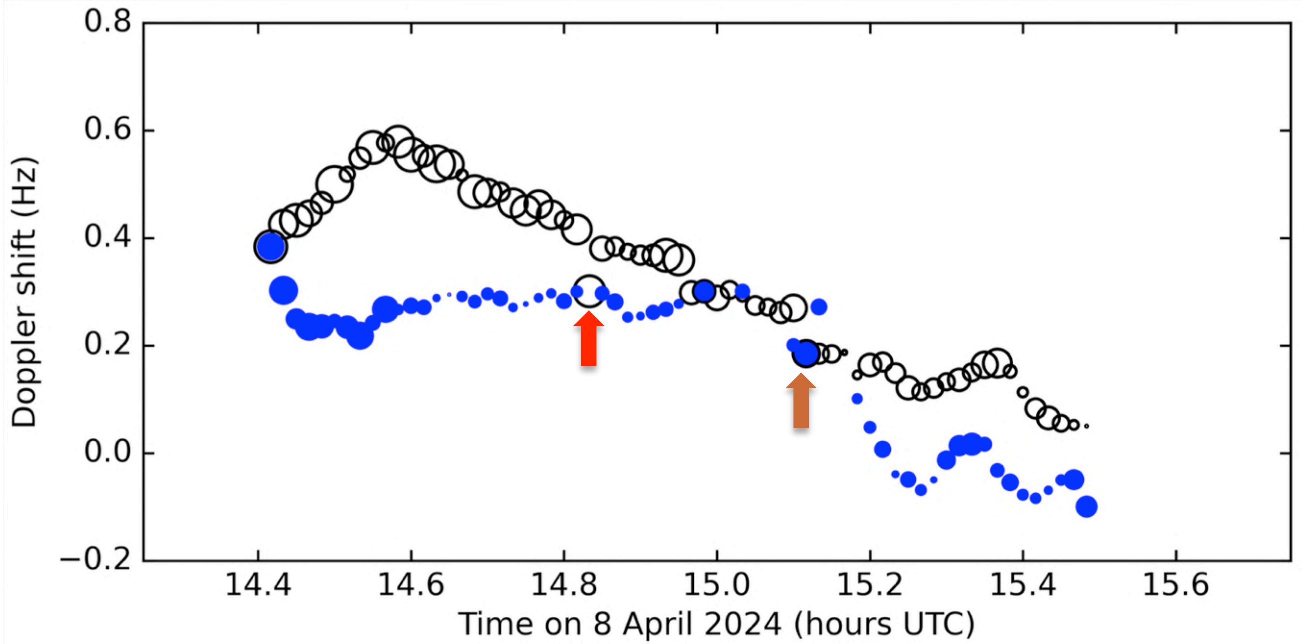


Topic really requires in-depth study.
This is me dipping my toe into what may be a quagmire.
With 10-point learning:

- Support Vector Regression with Radial Basis Function disappointing as predictor.
- Prophet better, although looks to be via a linear fit!



Step 5b: Separate and Identify High and Low Rays: Results

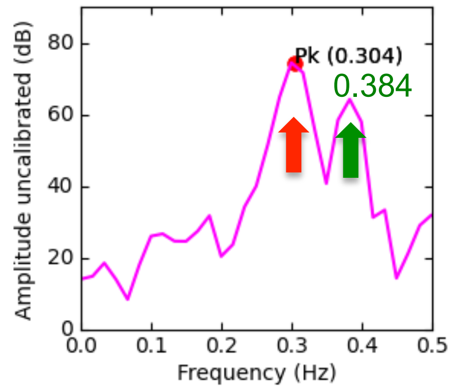


Two probable errors.
3% error rate

Size proportional to log amplitude.

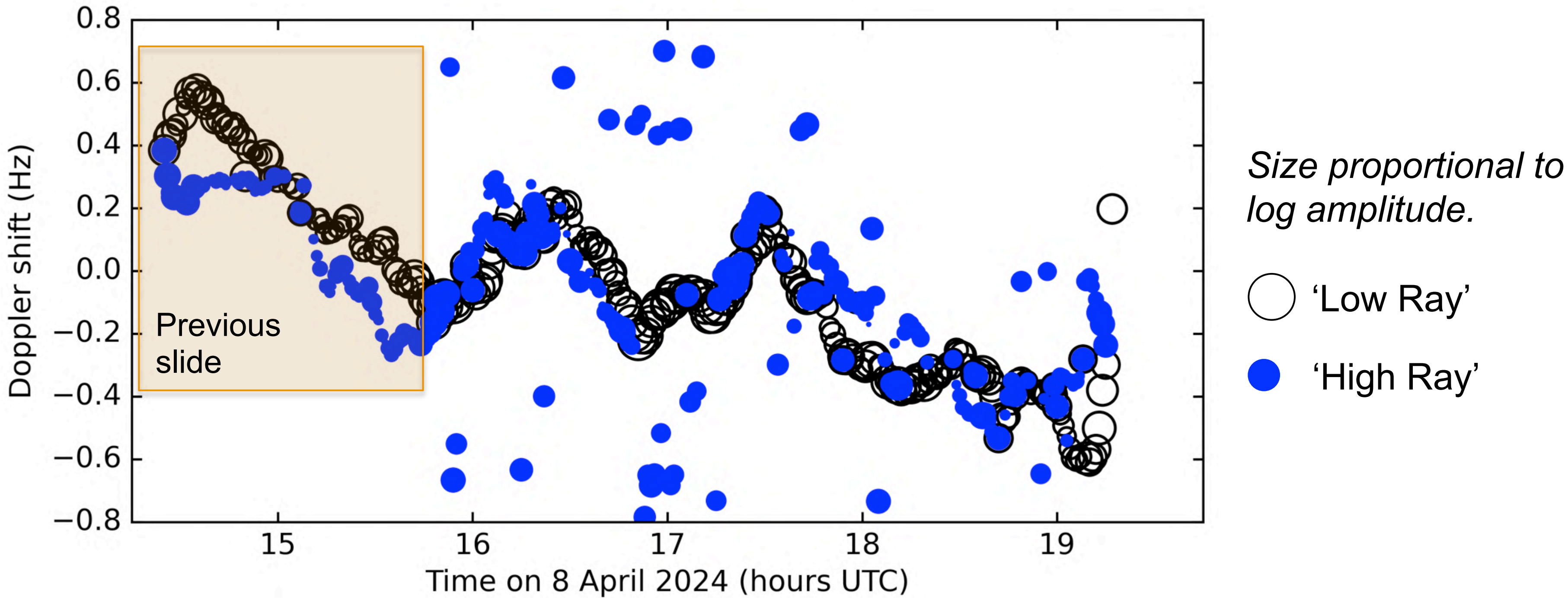
'Low Ray'

'High Ray'



Ray identification: Initial Doppler positive for both rays. It is morning, height of reflection descends. But, for 'High Ray', elevation angle rises, reducing Doppler shift relative to 'Low Ray', reflection height descending, but not as fast.

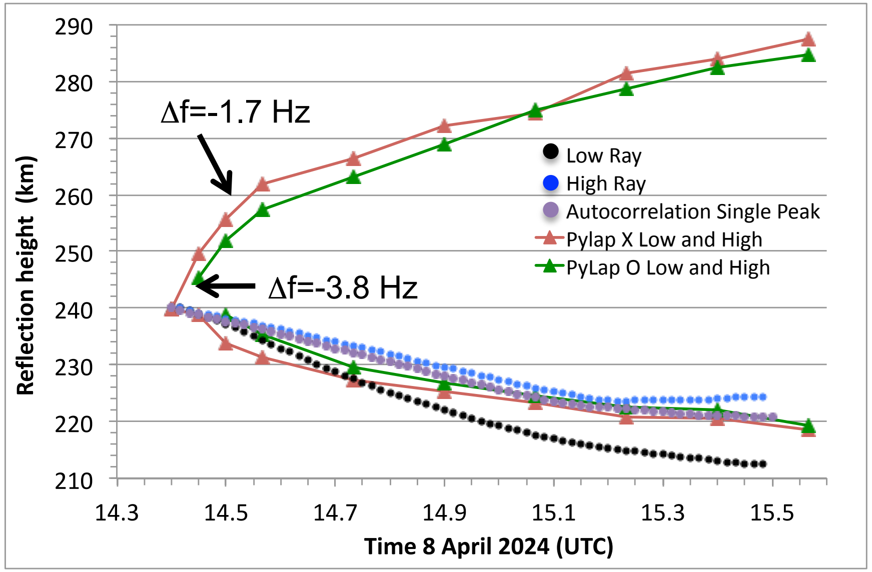
Clearly more work needed…



Multiple High Ray errors, but Low Ray looks reasonable.

Height of reflection of ‘Low’ and ‘High’ rays (*or are they?*)

- Reflection Height from **Autocorrelation Doppler** tracks Low Ray **O** and **X** waves maximum height from PyLap.
- However, reflection heights from bimodal spectra, which I thought as being from the **Low** and **High** rays, bracke PyLap Low ray values.



- Derivation of reflection height clearly a most useful diagnostic.
- Now I am completely flummoxed!
- No sign whatsoever of negative and decreasing Doppler shift in the PSWS spectrogram.

A. Where *is* the High ray seen in PyLap?

B. Why are we not seeing it in the Doppler spectra?

C. Should I trust PyLap here?

D. What propagation paths/modes *did* give rise to the two observed Doppler shifts?

E. What am I missing or misunderstanding?

TID modulation of arrival angles: Multimodal Doppler?

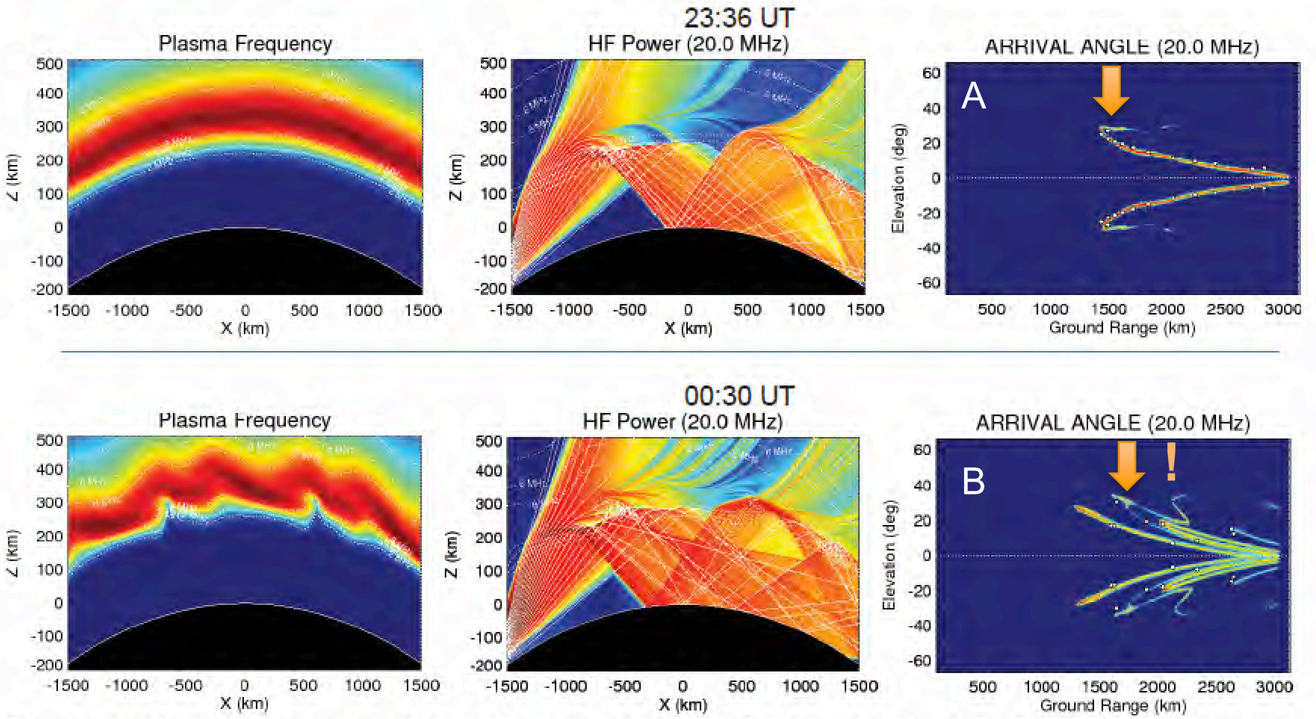


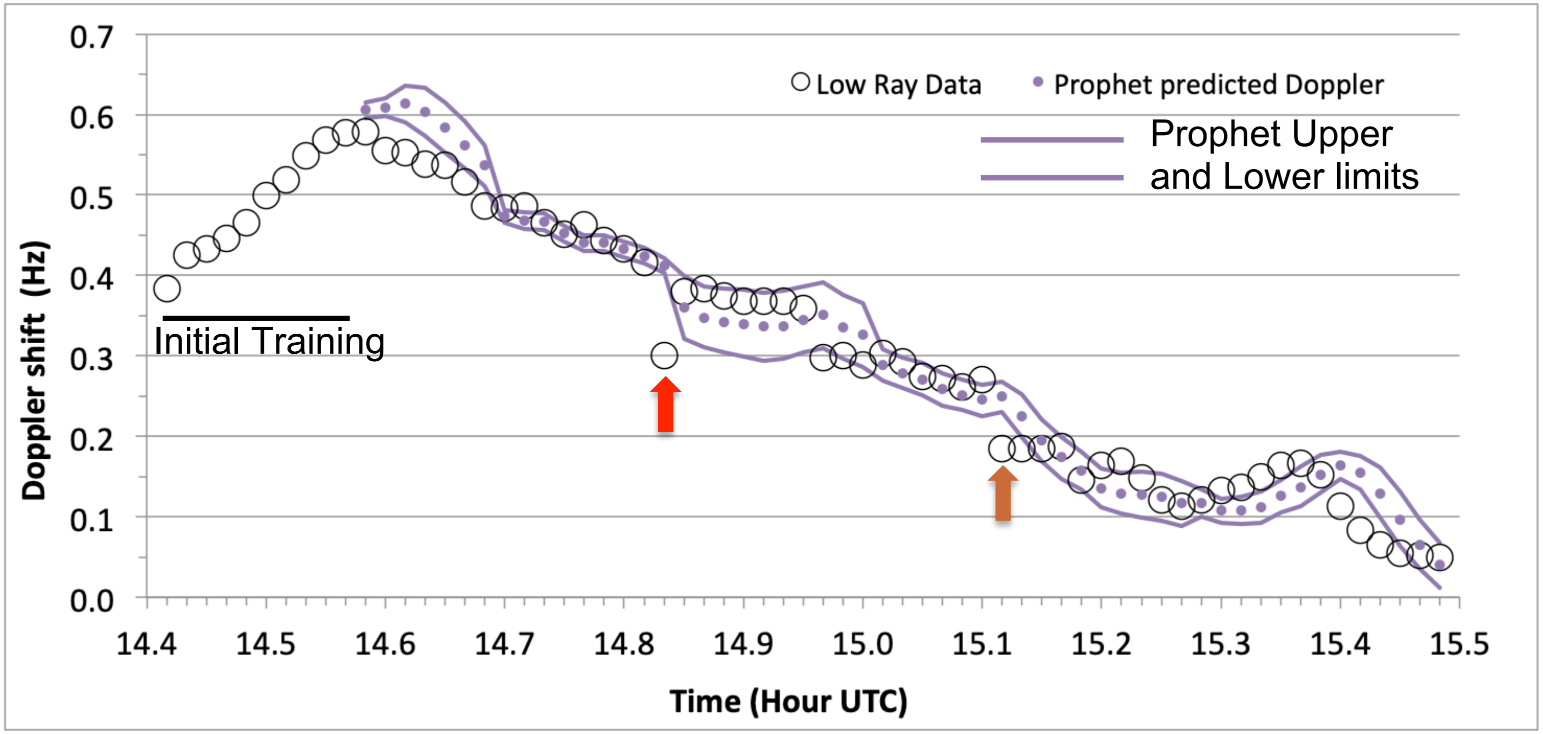
Figure 1. Plasma frequency (left), HF power (dB) (middle) and arrival angle (right) from wave-optics simulation of a 20 MHz wave propagating through a developing ionospheric disturbance

Carrano, C.S. and Rino, C.L., 2023. Wave-Optics Modelling of High Frequency (HF) Propagation through the Structured Ionosphere. *Report to the US Air Force Research Lab* by authors at Boston College. AFRL-RY-WP-TR-2023-0013

Available at https://apps.dtic.mil/sti/trecms/pdf/AD1202815.pdf

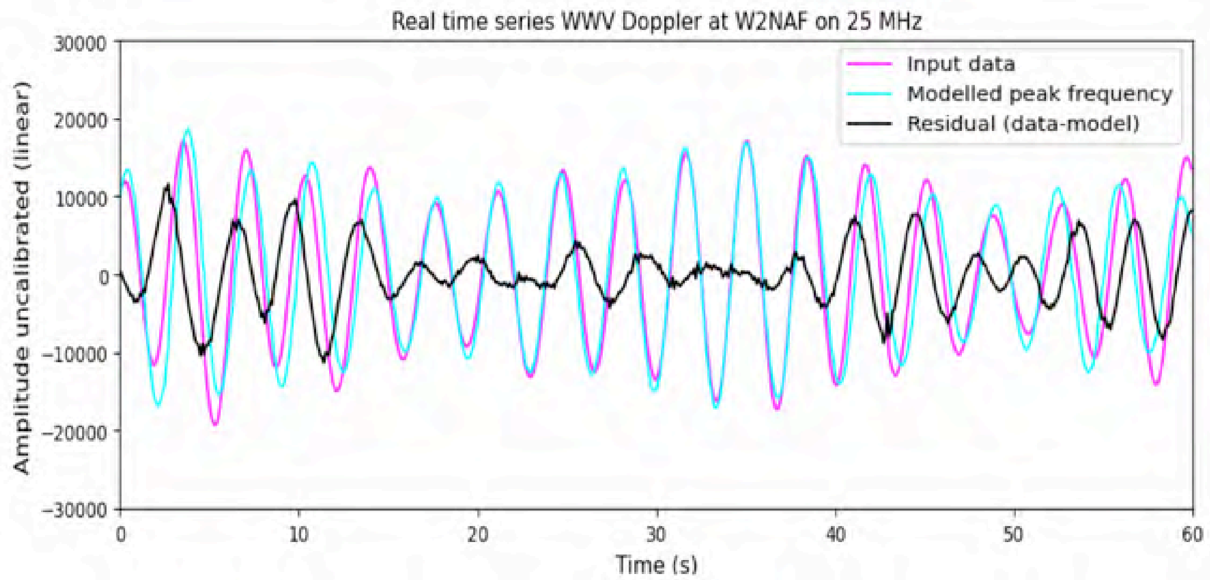
With this study, I've dipped my toes into 'A'. Perhaps it's a springboard to search out examples of 'B'?

Prophet: Do Doppler values lie between Prophet limits?



29 out of 55 Low Ray Doppler values lie within Prophet's upper and lower limits (53%)

The Gorin approach: Coherent removal of dominant peak



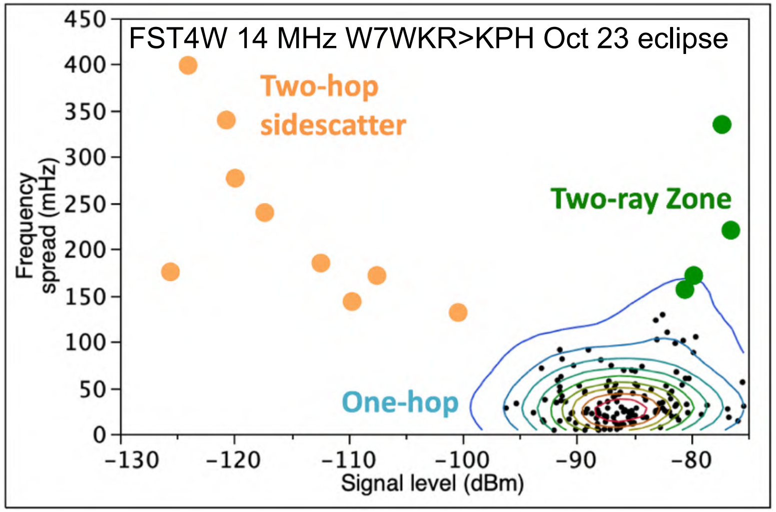
Might be a useful approach, but removal of a coherent modelled signal from a bimodal signal that is not coherent (to milliHertz) over a one-minute interval is problematic.

* Thanks to Joe Gorin and Peter Freeman K6RFT for the introduction

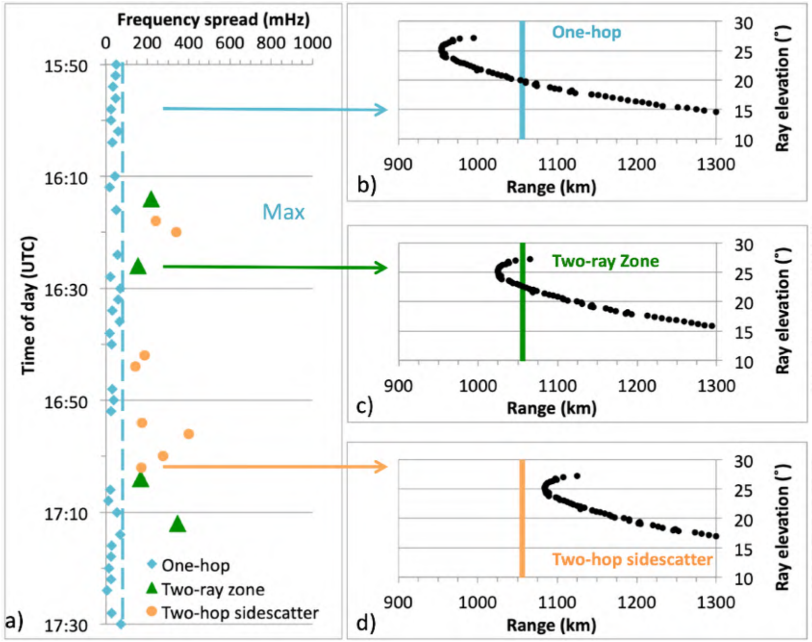
Following a suggestion from Joe Gorin*, retired Master Engineer in Signal Analysis at HP:

- Model a sinusoid at the estimated frequency of the dominant peak.
- Search +/- 15 mHz either side for frequency with maximum cross correlation. Model that one.
- Form autocorrelation over all lags forming one cycle.
- Lag at peak autocorrelation gives us the optimum initial phase.
- Find signal level each whole cycle.
- Modelled sinusoid now has closest frequency, best-fit phase, and best fit amplitude.
- Coherent subtraction.

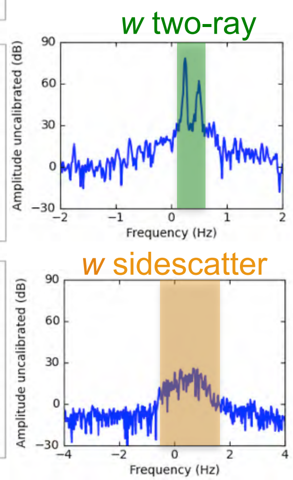
Does Grape Doppler Resolve FST4W Spread Speculation?



At the March 2024 HamSCI workshop I could only speculate whether green spots were from High and Low Ray zone, causing high spread at high signal level.



Griffiths, G., 2024. The October 2023 annular eclipse: some effects on HF propagation. *RSGB RadCom,* 100(7): 40-42.



WWV to W2NAF 25 MHz