Using Narrowband Chirps Transmitted through Conventional HF Amateur Radios to Measure Changes in Ionospheric Reflection Height

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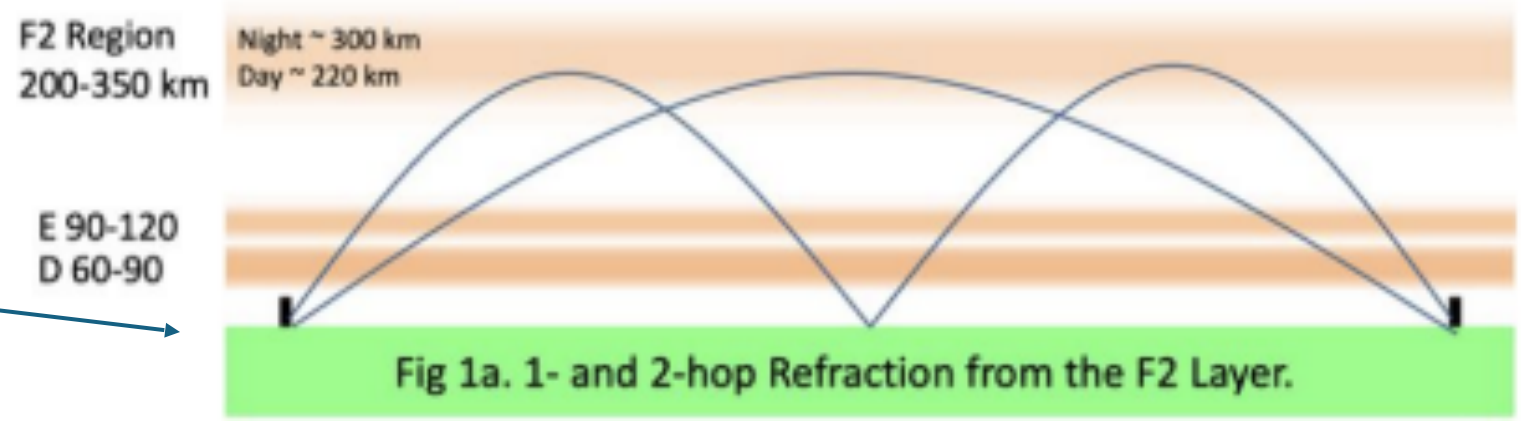
Introduction

- The HamSCI objective for the 2023 and 2024 eclipses is to use amateur radio stations to measure how HF radio propagation changes with the passage of an eclipse over a large geographic area
- During an eclipse, the ionosphere loses solar radiation thereby affecting its layer height
- Two primary parameters are of interest: The TDOA (time difference of arrival in ms between 1-hop and 2-hop propagation modes) and the layer height of the F2 region (in km)
- We use programming techniques learned in the DSP course at the University of Scranton to automate this process

Fig 1. Depiction of the 1-2 hop refractions from the F layer specifically



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Transmitted Waveform

- We can measure TDOA by transmitting audio waveforms that are sensitive to time displacement when summed
- Waveforms are selected: 1-cycle linear pulses, **linear audio chirps**, PN bursts, 1 kHz tone
  The only equipment needed are commercial off-the-shelf (COTS) single sideband (SSB) amateur radio transceivers (IC-7610)
- SSB format allows us to facilitate the transmission of audio waveforms which are short audio pulses (chirps) that we can process in waveforms (.wav files)

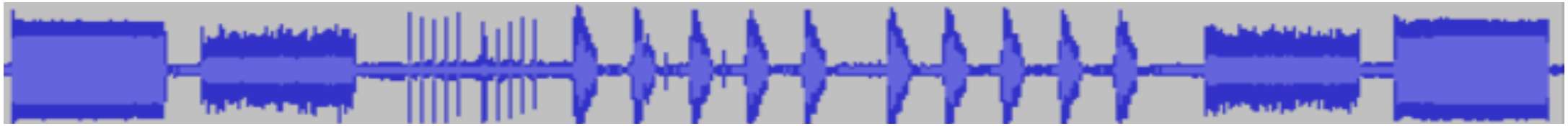

Fig 2a. raw waveform depicting the 10 Hz/ms sweep rate chirps transmitted during the Apr 8 eclipse

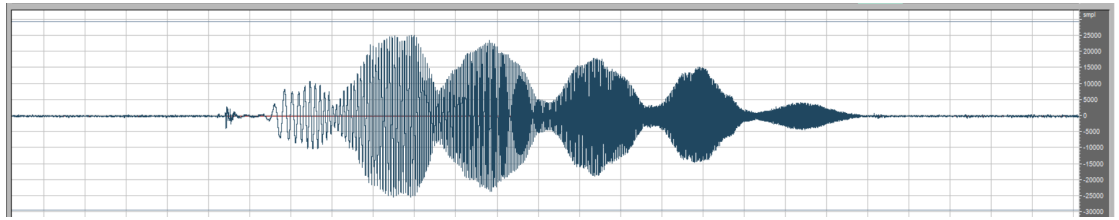

Fig 2b. Example of a singular chirp showing clean modulation between two nulls

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Methodology

- Analysis is desired for two primary data sets: WA5FRF-N5DUP (317 km) and WA5FRF-AB5YO (8.77 km)
- For the October 14, 2023 eclipse, data was acquired from 1130 UTC to 1930 UTC on 15 -minute intervals
- For the April 8, 2024 eclipse, data was acquired from 1400 UTC to 2100 UTC on 10-minute intervals
- We analyzed the same two primary data sets for both the eclipses

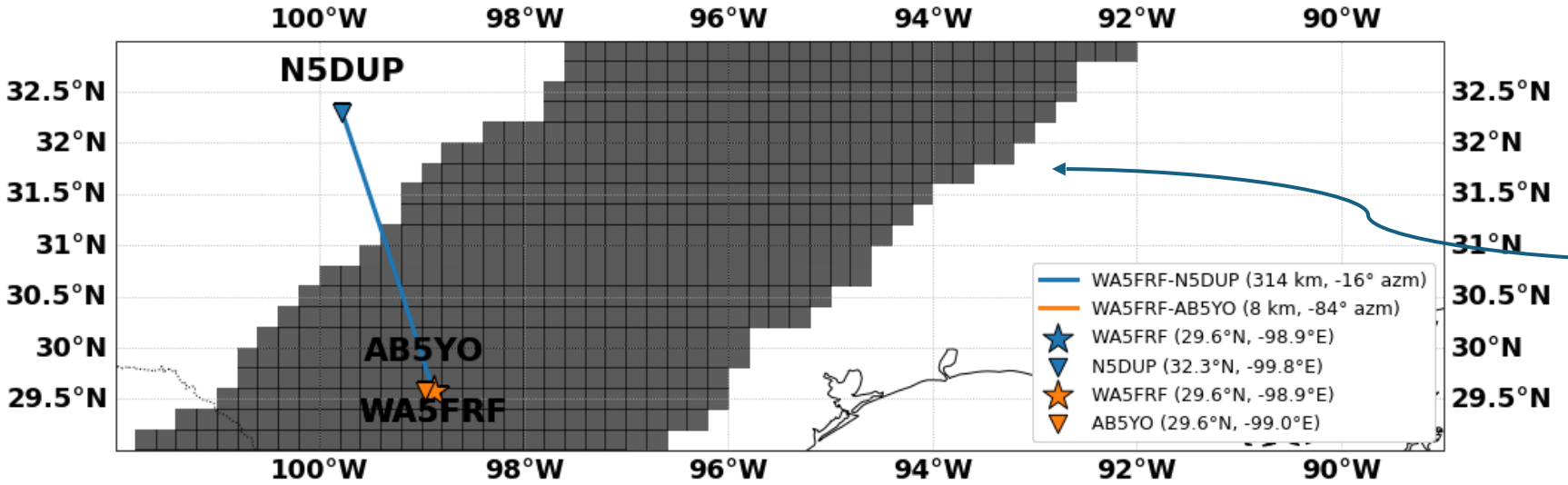

Fig 3. Graph illustrating the 8 April 2024 eclipse path and the distance between the TX station WA5FRF and the two RX stations N5DUP, AB5YO on different ground distances

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Processing of the waveform

- To automate the process, we import the waveforms to our python notebook
- Before analyzing anything, we normalize the incoming waveform
- We then square the data, leaving a unipolar waveform (the signal is always beyond the zero point)
- Envelope detection is used to give a waveform that is only the **top** outline of the original waveform
- The last step to process the waveform for analysis is to zero-average to obtain the bipolar representation of the maximum frequency

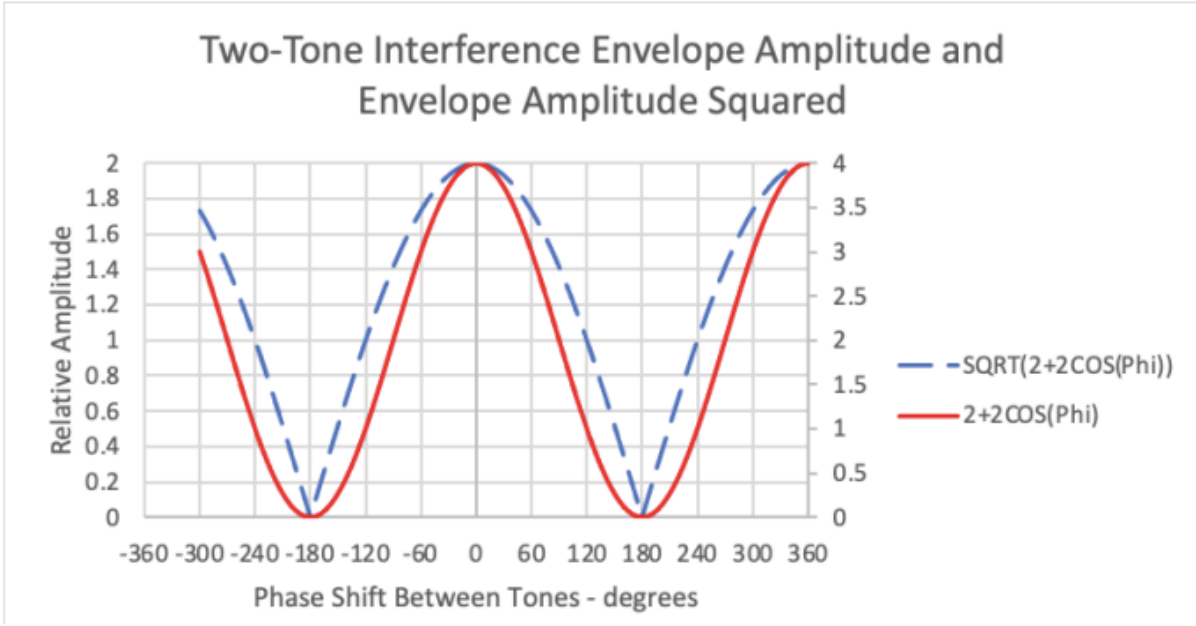

Fig 4. The Envelope Amplitude of Two-Tone Interference can be Converted to a sine Wave by Squaring the Waveform

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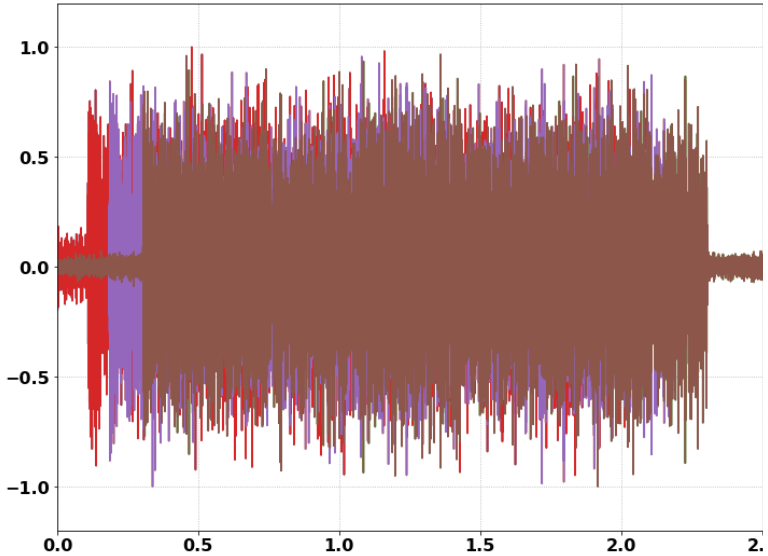
Cross-Correlation Analysis

- To find the TDOA of each chirp, we must first ensure that chirp analysis begins at the exact same time for the process to be automated. This process is done using **cross-correlation.** This measures the similarity between two **different** signals as a function of displacement of one relative to the other.
- The samples we used for the correlation were the sharp 1-cycle pulses for the October eclipse and the PN burst for the April 8 eclipse. We used the PN Burst so that the correlation would be accurate every

Fig 5a. PN burst used to correlate the waveforms



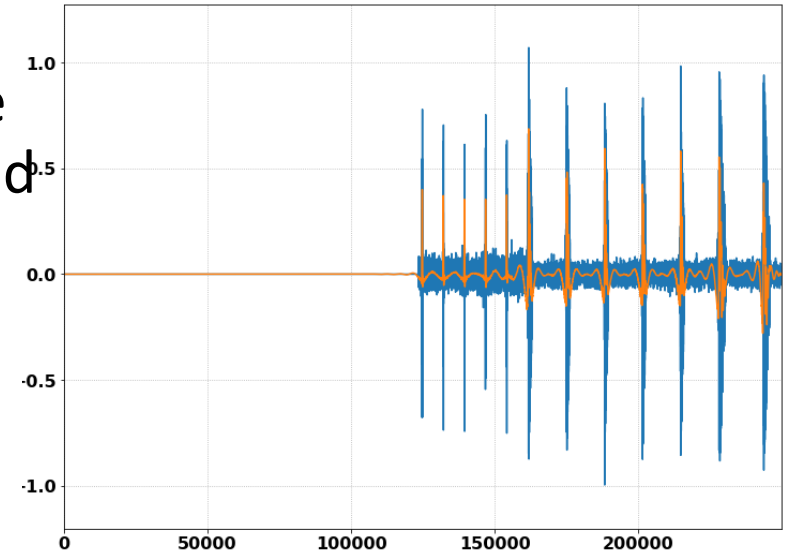


Fig 5b. 1500 Hz sweep rate 1 cycle pulses used to correlate the waveforms

Fast Fourier Transform Conversion

- We now compute the FFT or Fast Fourier Transform for each chirp. This converts the time domain representation of the signal into the frequency domain
- Finding the relevant time and magnitude allows us to look for patterns that are desirable for the frequency domain, such as a chirp with clean modulation that was clearly transmitted and had no noise that could disrupt the maximum frequency
- This maximum frequency is dubbed the "Beat Note Frequency"

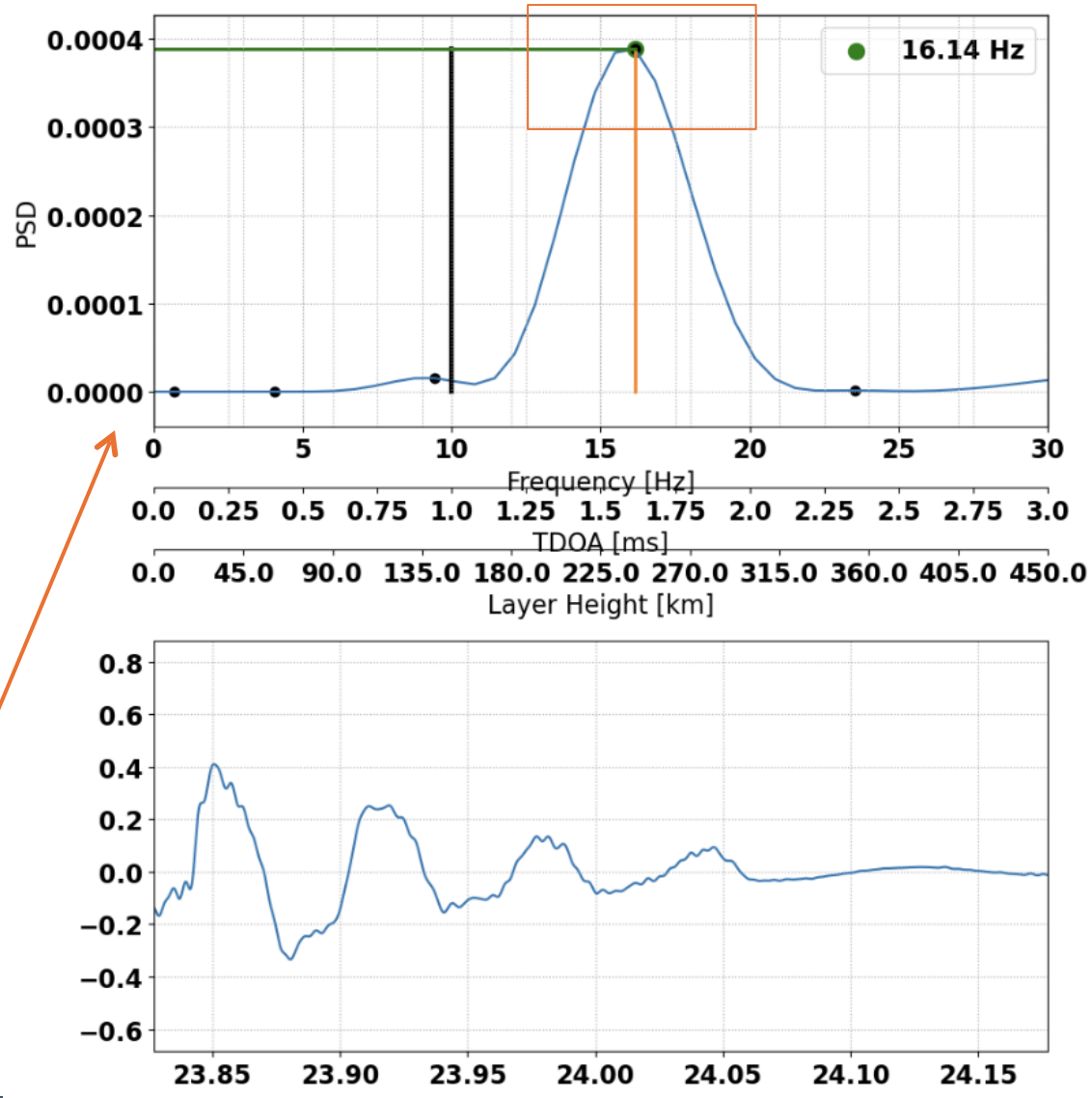


Fig 6. Representation of the beat note frequency, the max frequency at the x-axis of the FFT

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Conversion from Frequency to TDOA

- From the BNF we can compute TDOA.
- Each respective chirp in each data set has a different sweep rate, which is the rate at which frequency changes over time.
- For the October 2023 eclipse, we had four different sweep rates (100, 50, 25, and 10 Hz/ms).
- For the April 2024 eclipse we only kept the 10 Hz/ms, since the lowest sweep rate led to the most reliable results.
- TDOA is equivalent to the maximum frequency seen after taking the FFT and then dividing it by that chirps respective sweep rate.

$$\text{TDOA (ms)} = \text{BNF (Hz)} / \text{SR (Hz/ms)}$$

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Automatically Converting the TDOA to Layer Height

- Using a layer height conversion chart provided by Steve Cerwin WA5FRF, we can use the gathered TDOA values for each set of chirps and return a formula that can compute the Layer Height in kilometers across VARIOUS ground distances
- For our specific purposes, the ground distance for WA5FRF-AB5YO was 8.77 km (a NVIS path) while the ground distance for WA5FRF-N5DUP was 317 km
- This mathematical model for layer height for a NVIS path or a path less than or equal to 250 km is 150 * TDOA (ms) (AB5YO)
- The model for 250- 500 km is 142.2 * TDOA(ms) + 36.1 (N5DUP)

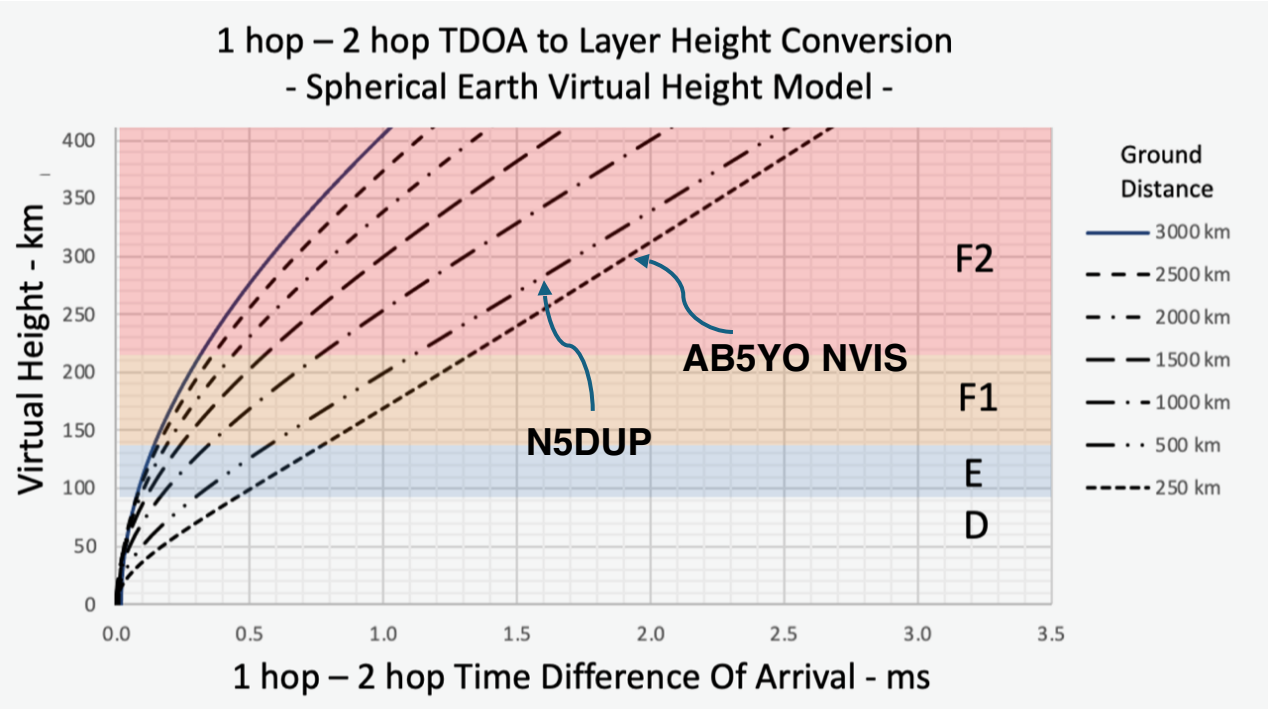
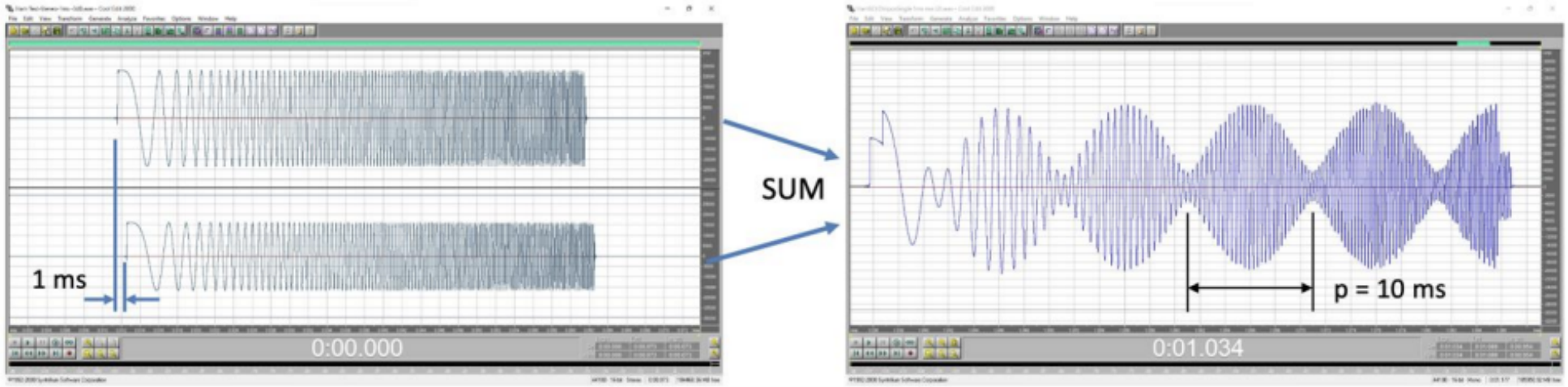


Fig 7. 1-2 hop mode TDOA to layer height conversion provided by WA5FRF

Other analysis techniques Manual WA5FRF

- Steve Cerwin; WA5FRF conducted his own manual analysis that also utilized a similar “beat note” method
- He manually determined the best chirps which showed modulation in each waveform file, measured the difference between two nulls, and then determined the period by simple time displacement
- Because he calculated the period, instead of dividing by the sweep rate as we did in our automated technique, he MULTIPLIED by the sweep rate

Fig 8. Summation that produces a beat note of period 10 ms



Other analysis techniques Auto-correlation K1FR

- Tom McMahan; K1FR used another approach
- Autocorrelation: by correlating the received waveform with a copy of itself, we essentially align this signal with a ‘delayed’ version and measuring exactly how similar these two waveforms are
- By identifying the peaks in the correlation function, we can determine the time differences between when the signal arrives at the receiver (TDOA)

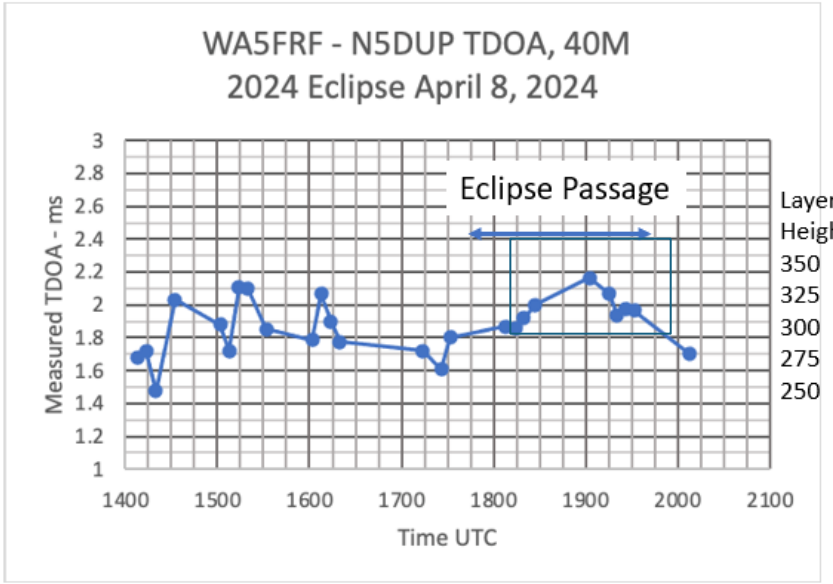
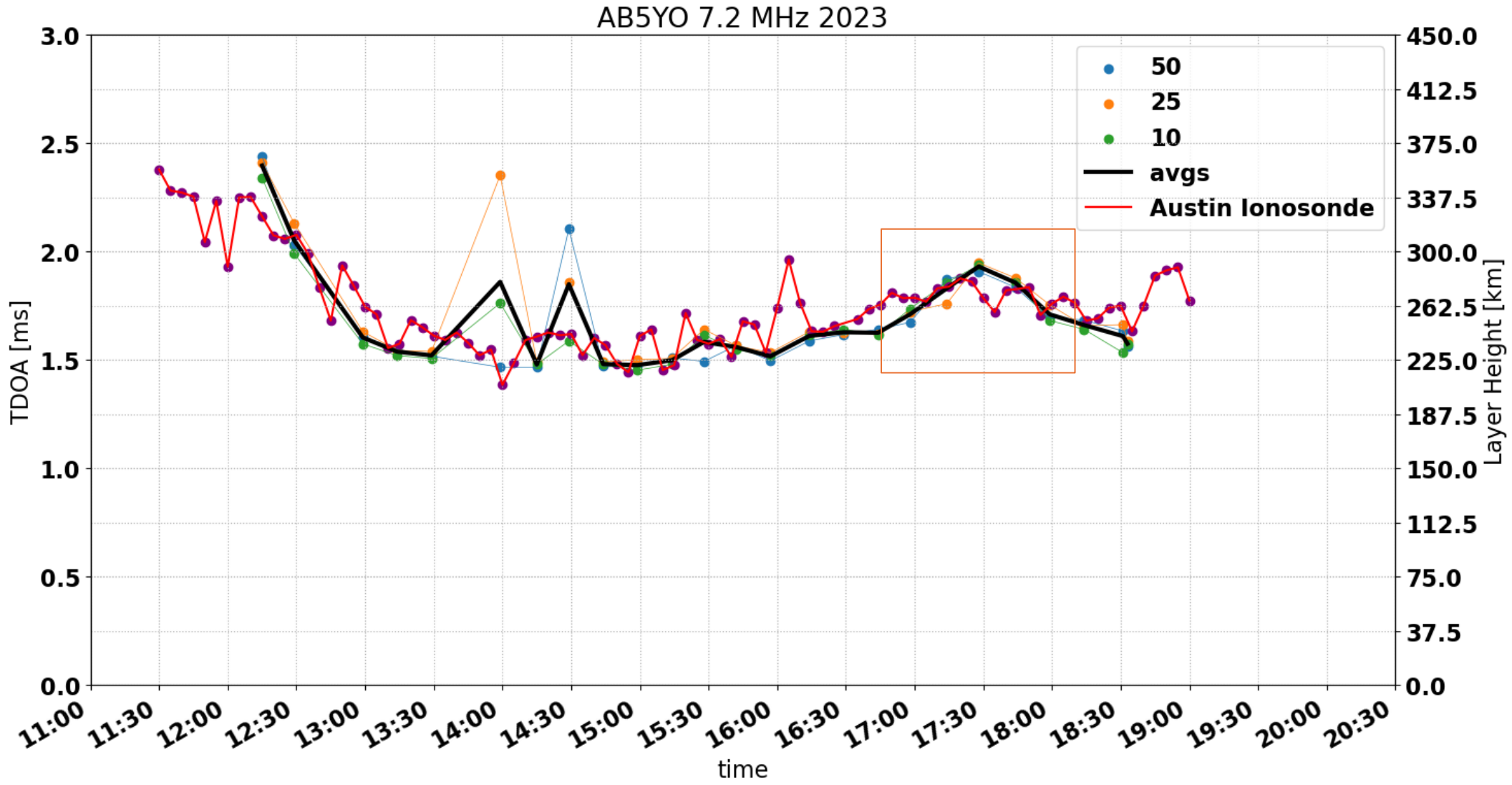


Fig 9. Autocorrelated plot on the WA5FRF-N5DUP 7.2 MHz band

Results 2023 October 2023 9 km path 7.2 MHz



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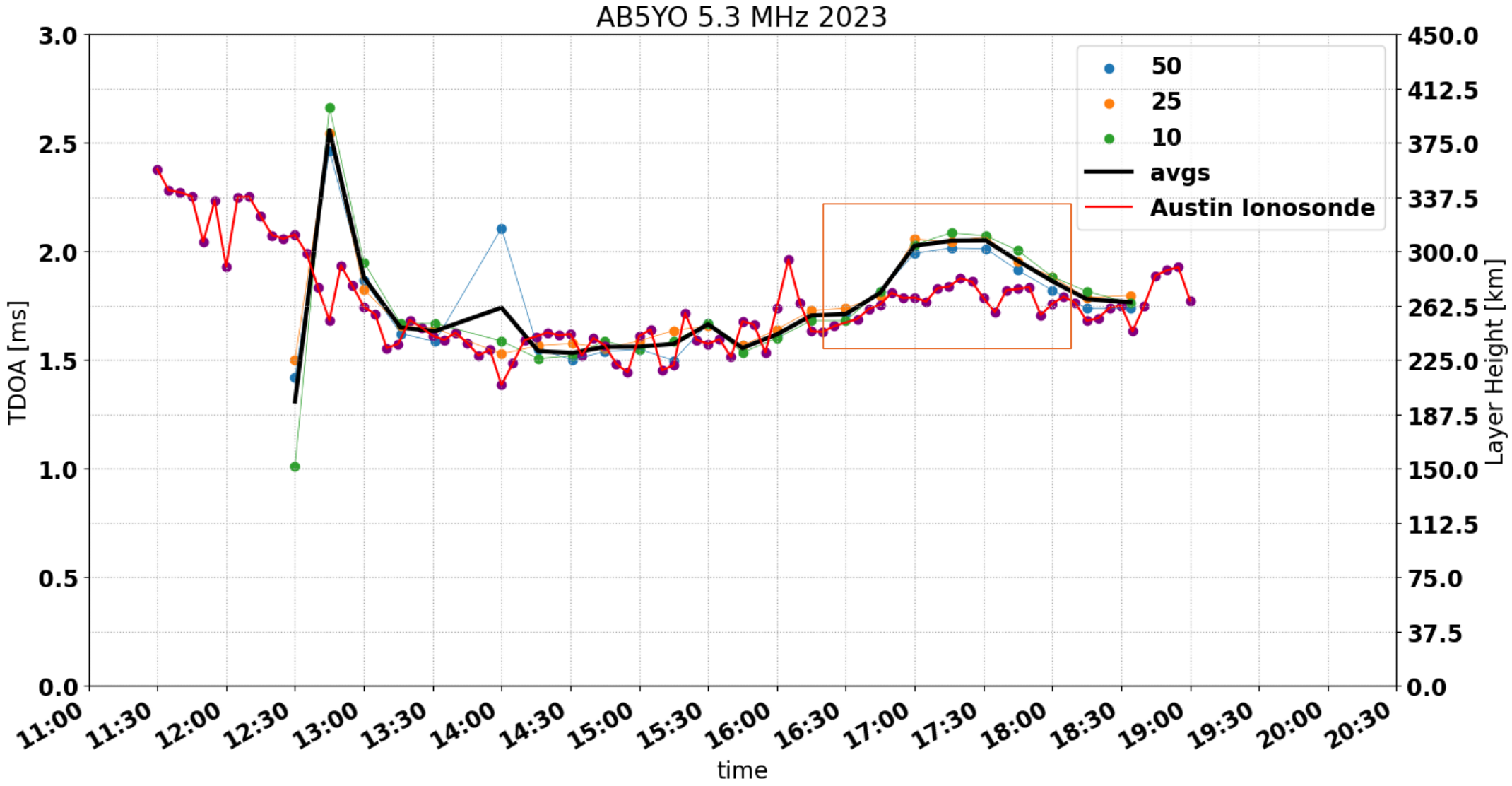
Results October 2023 5.3 MHz 9 km path



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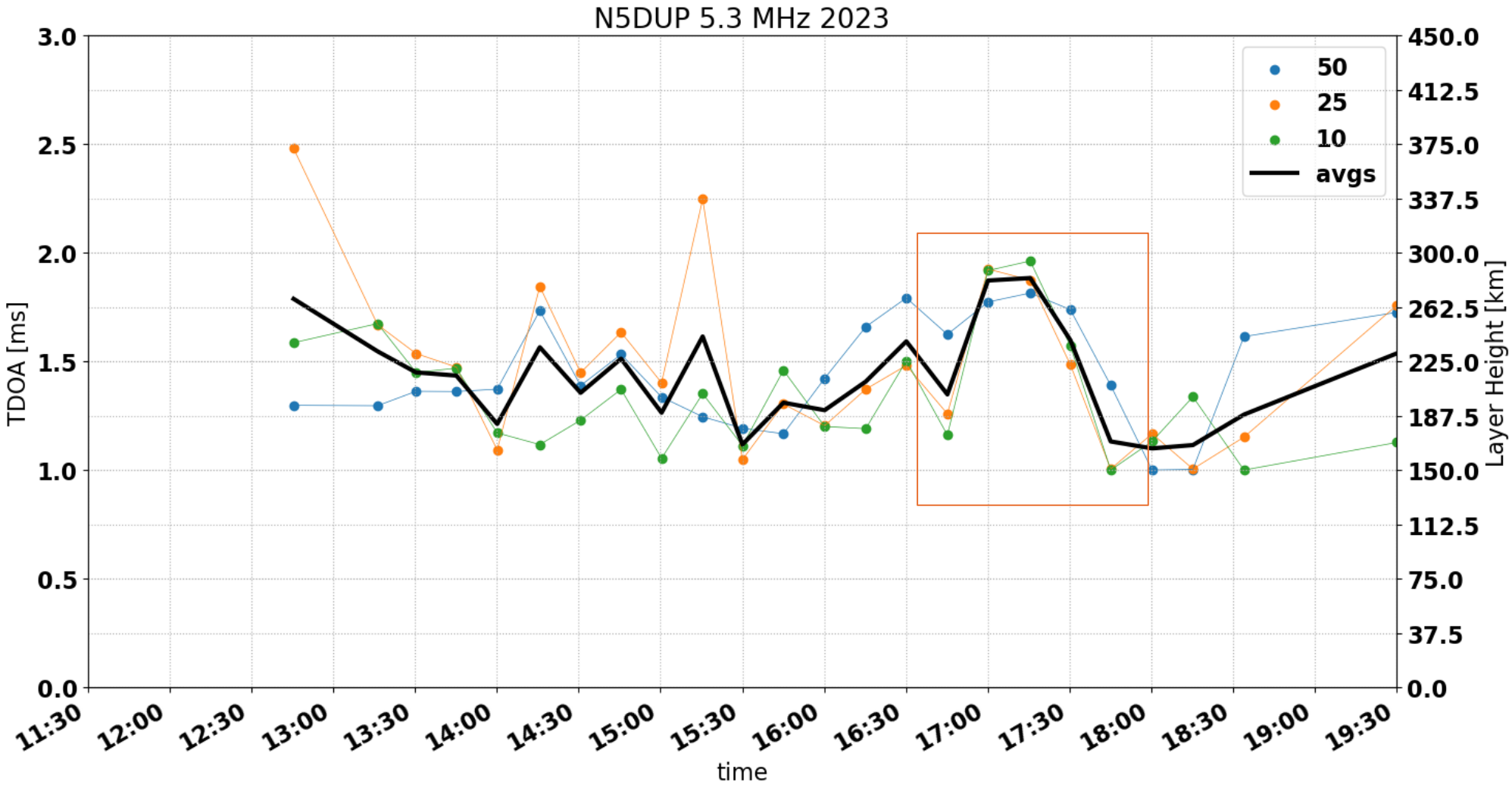
Results October 2023 5.3 MHz 317 km path



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- Preliminary results for the October 2023 Solar eclipse where other analysis techniques were not considered and only compared to the Austin ionosonde showed a clear bump around 1730 UTC for the three different sets of sweep rates that were averaged. These data sets are across the exact same ground distances and the same 5.3 MHz and 7.2 MHz bands
- We initially considered the 100 Hz/ms sweep rates for the averaging, however due to the nature of radio technology, the audio filters may have difficulty with the faster sweep rate. We saw drastic averaging improvements when we considered the 50, 25, and 10 Hz/ms sweep rates

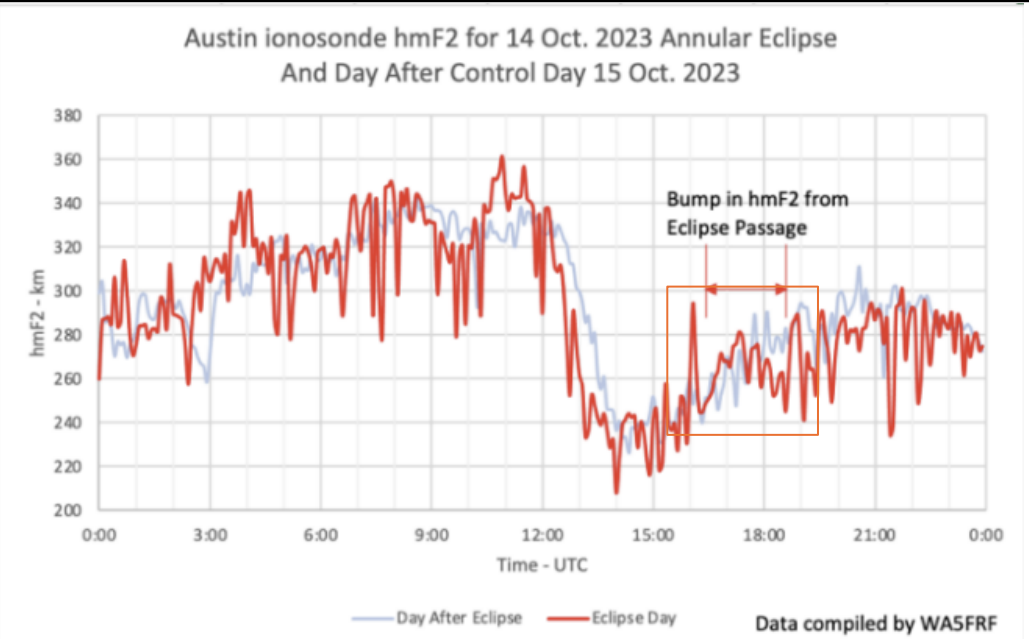
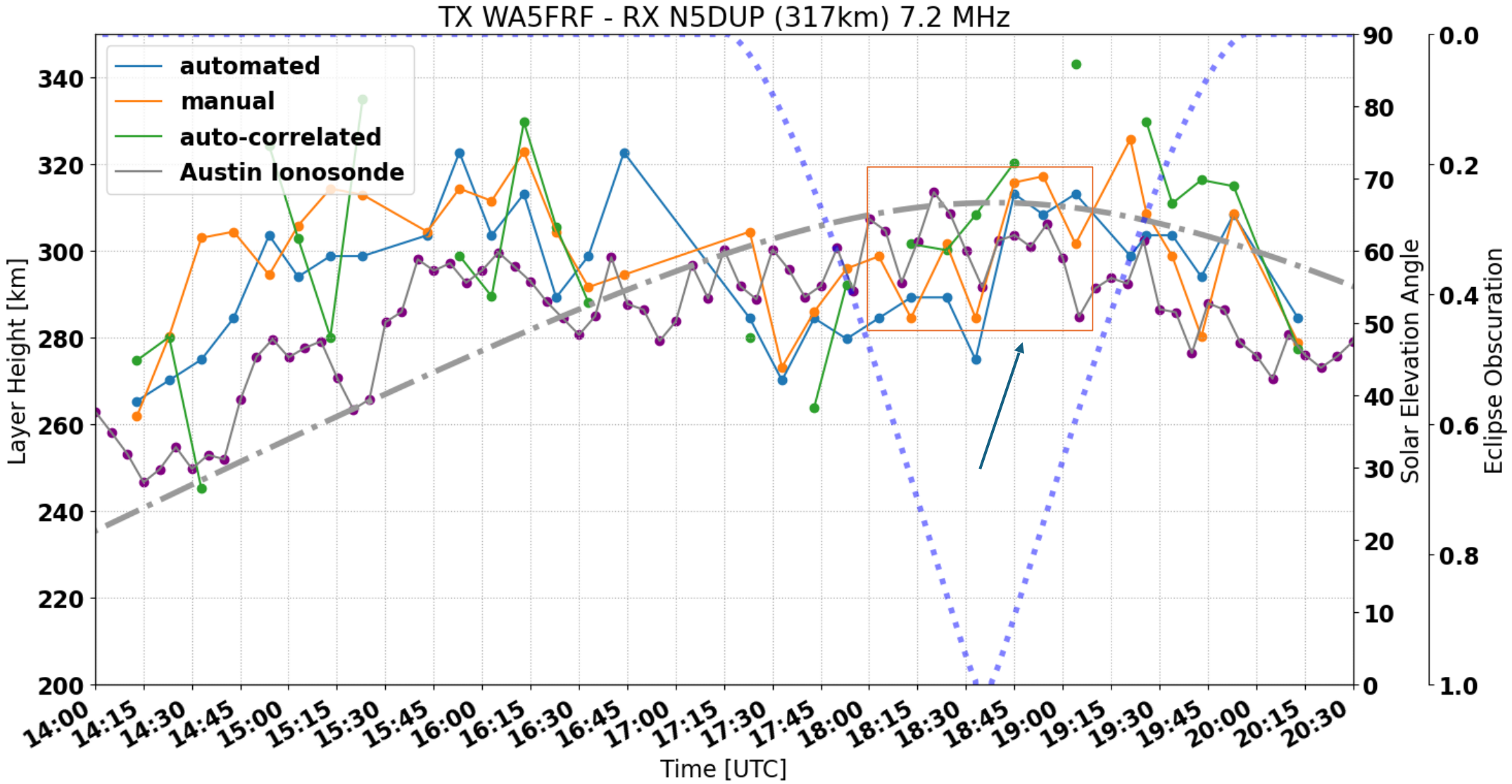


Fig 10. Austin Ionosonde data for the October 14, 2023 eclipse. We see a change in layer height at around 1730-1800 UTC

Results April 2024 Eclipse



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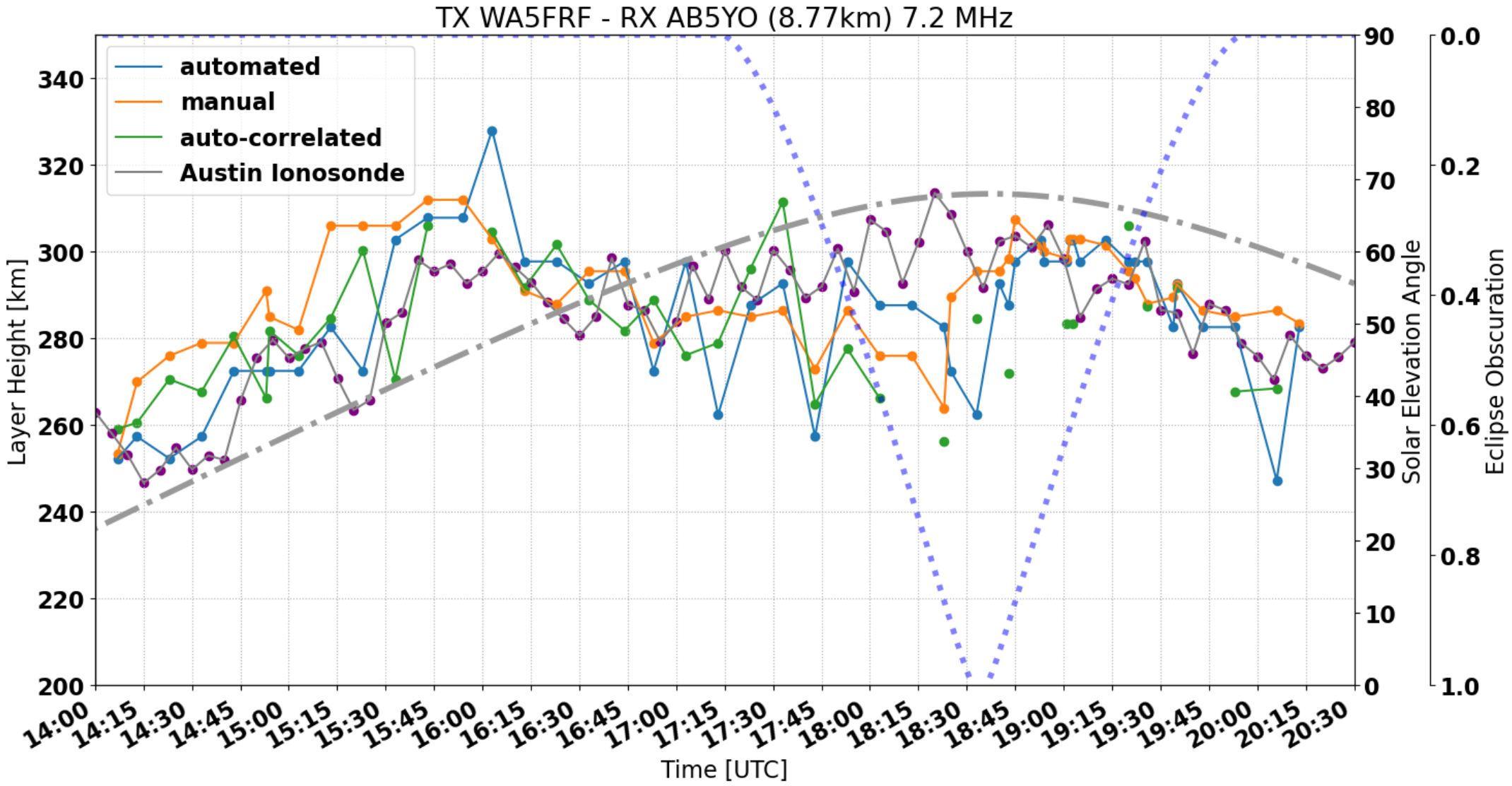
Results April 2024 Eclipse cont.



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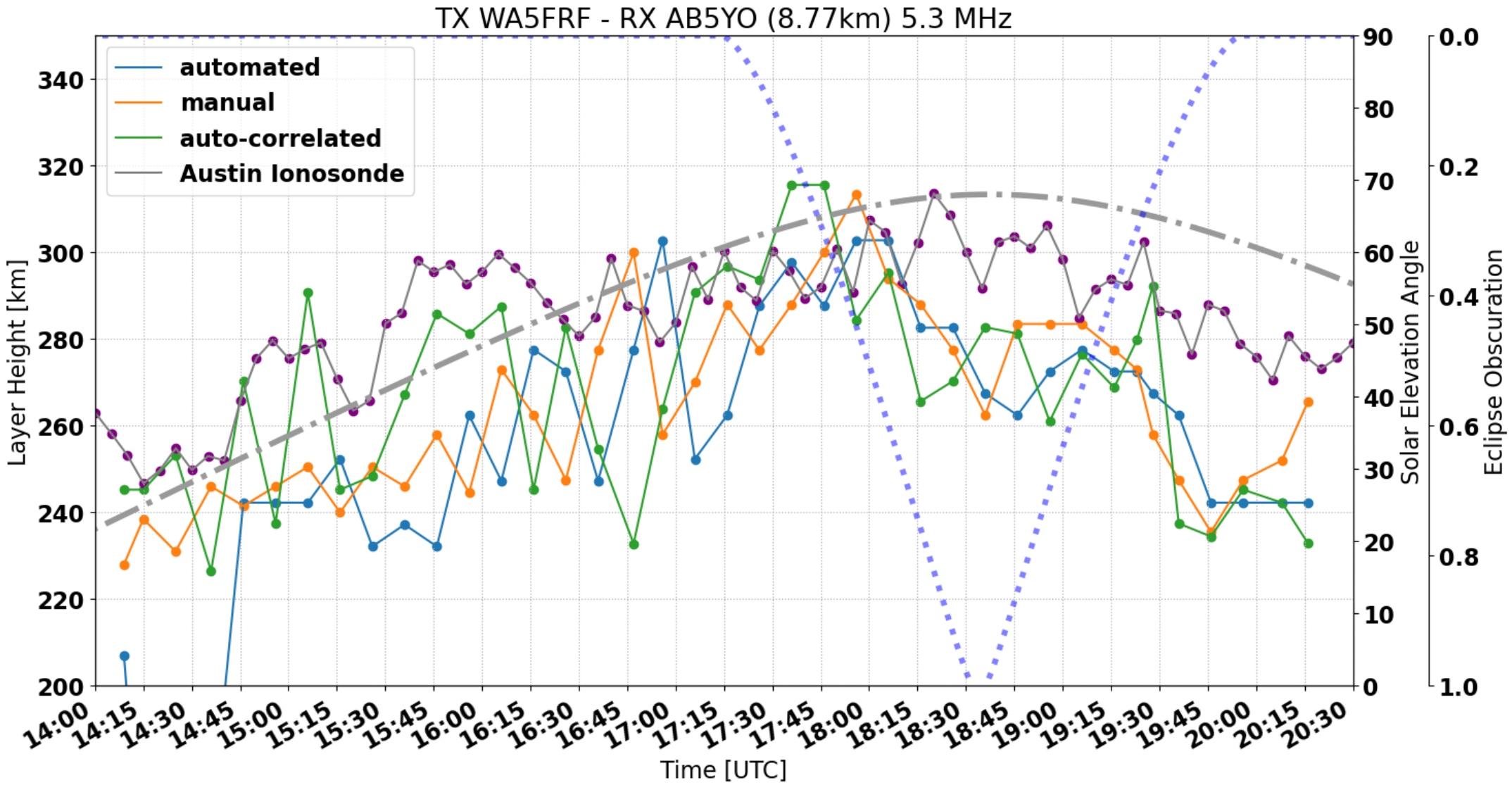
Results April 2024



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Discussion April 2024 Eclipse

- Results for the April 2024 eclipse indicate that while layer height was at a maximum during the greatest obscuration period of eclipse day, there was no rapid increase in layer height.
- The only two data sets which showed any kind of bump are the 7.2 MHz N5DUP data and the 5.3 MHz AB5YO data.
- The Austin Ionosonde also failed to see a significant increase in layer height, using much more complex TOF (Time of Flight) calculation.
- This further ensures the validity of the aforementioned techniques due to little discrepancy, and similarity to the Austin Ionosonde.

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Possible Multipath Modes

- The multipath modes previously observed were the 1 and 2 Hop modes off the F2 layer.
- A ray trace model shows that simultaneous E and F layer propagation is possible
- This results in other TDOA values

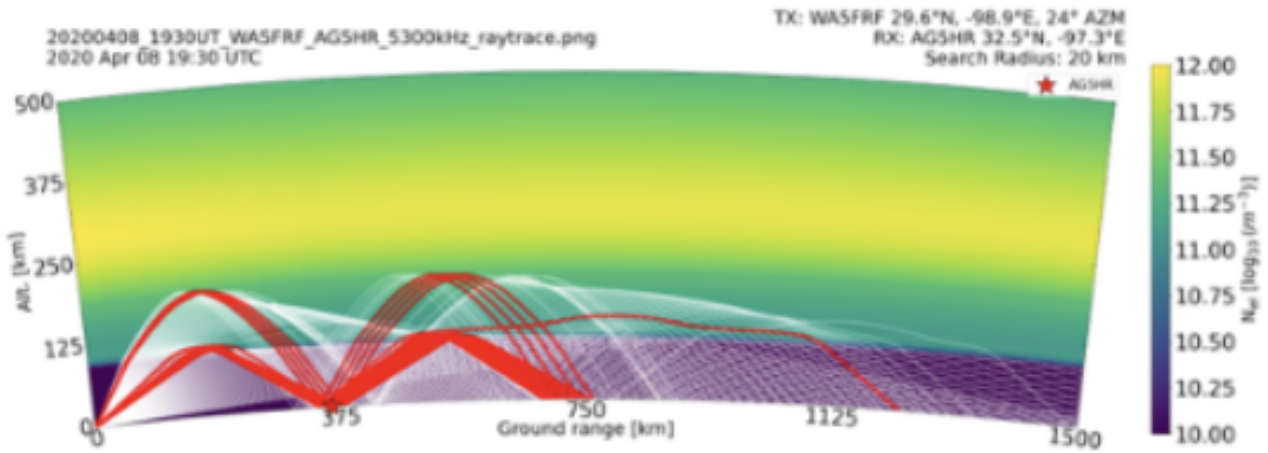
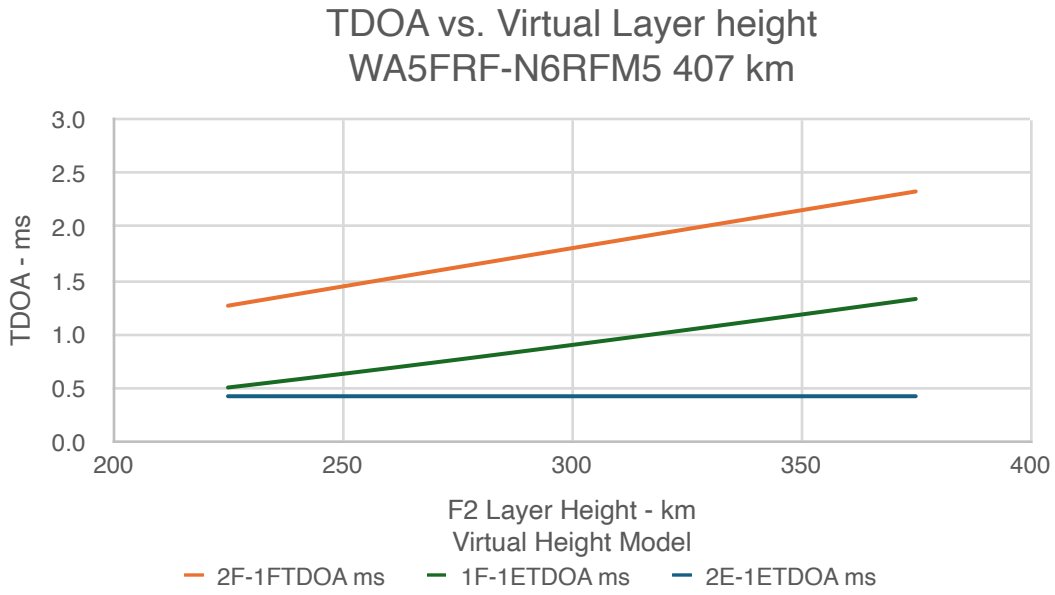
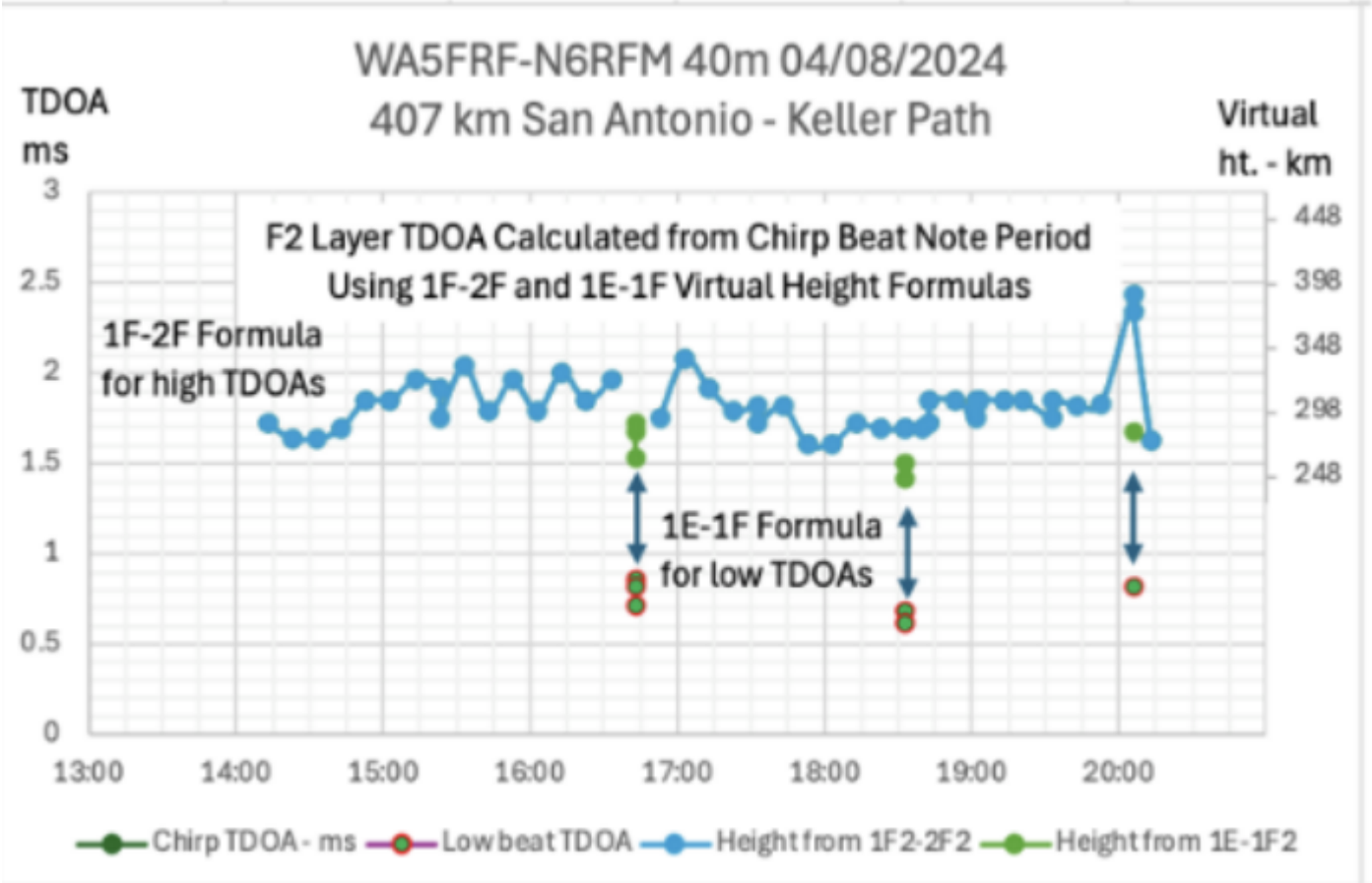


Fig 11. Ray Trace Model Compiled by W2NAF Nathaniel Frissell



Multipath Propagation observed in Rx: N6RFM

- A new ground distance (407 km) was considered for April 2024
- This data set also contained normal F2 1hop-2hop TDOAs and chirps with lower beat notes.
- Some values (when converted to TDOA) were either too low or too high
- When using a new virtual height equation, they merge with the computed 1F-2F data



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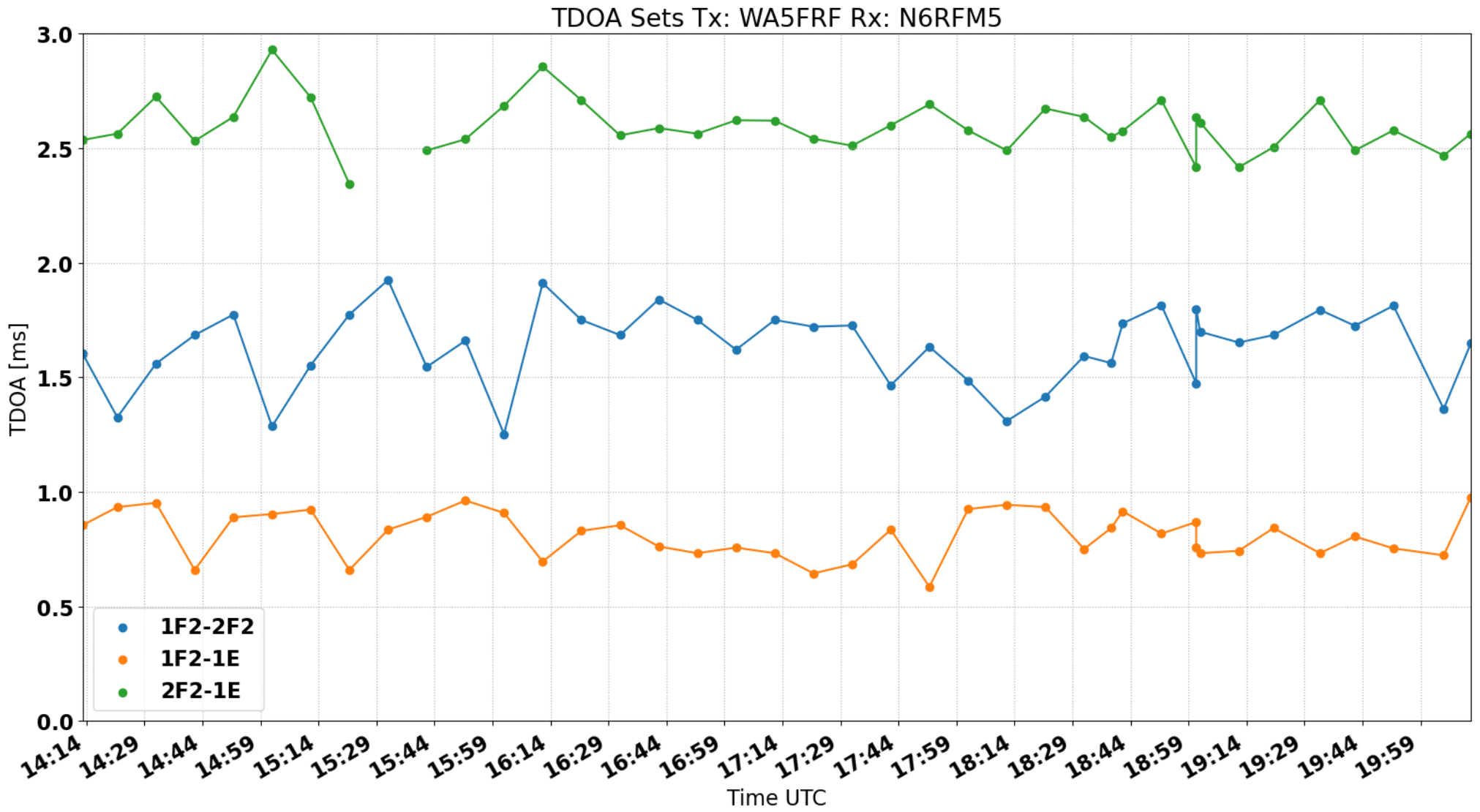
Automated Analysis of Multiple Modes (7.3 MHz Band)



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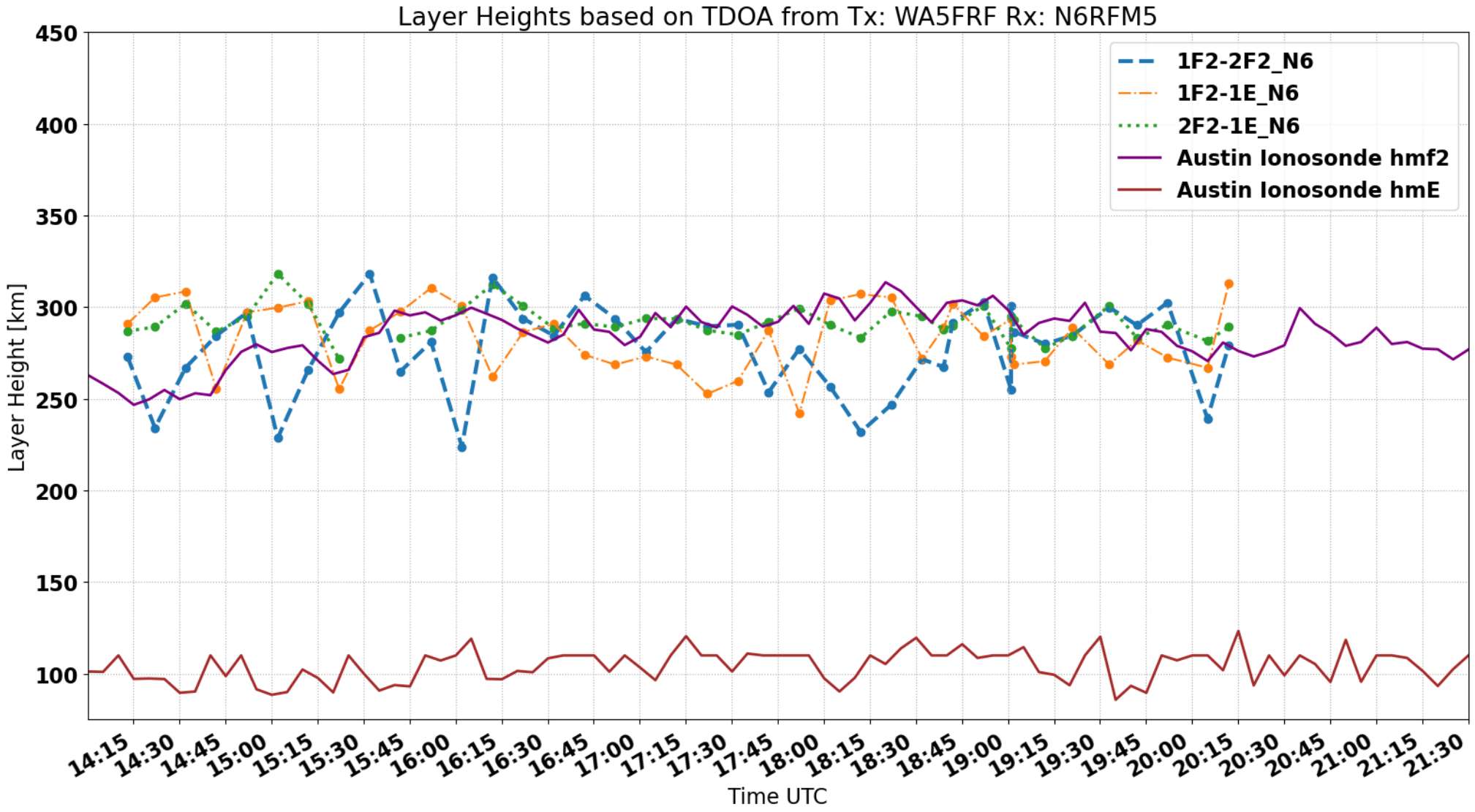
N6RFM Layer Heights for multiple modes



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Summary

- DSP analysis techniques have allowed us to compute results in layer height and TDOA values that correlate to values from the hmF2 readings seen in the Austin Ionosonde
- The October 2023 5.3 MHz – 7.2 MHz bands for AB5YO and N5DUP provided the most desirable results, consistent to what we would expect with an eclipse bump
- The manually decoded data provided by WA5FRF, and the automated data agree in computing TDOA/Layer Height before and after obscuration for the 2024 eclipse
- Future work includes automating this technique, something James Ervin KI5UXW has worked on

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Acknowledgments

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We are grateful for the financial support of the United States National Science Foundation, NASA, and Amateur Radio Digital Communications (ARDC).

HamSCI silhouette photo by Ann Marie Rogalcheck-Frissell KC2KRQ.

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Fig 11. Crew responsible for the recordings for the Tx: WA5FRF – Rx: W3USR (University of Scranton) for the 14 MHz band

Thank you!

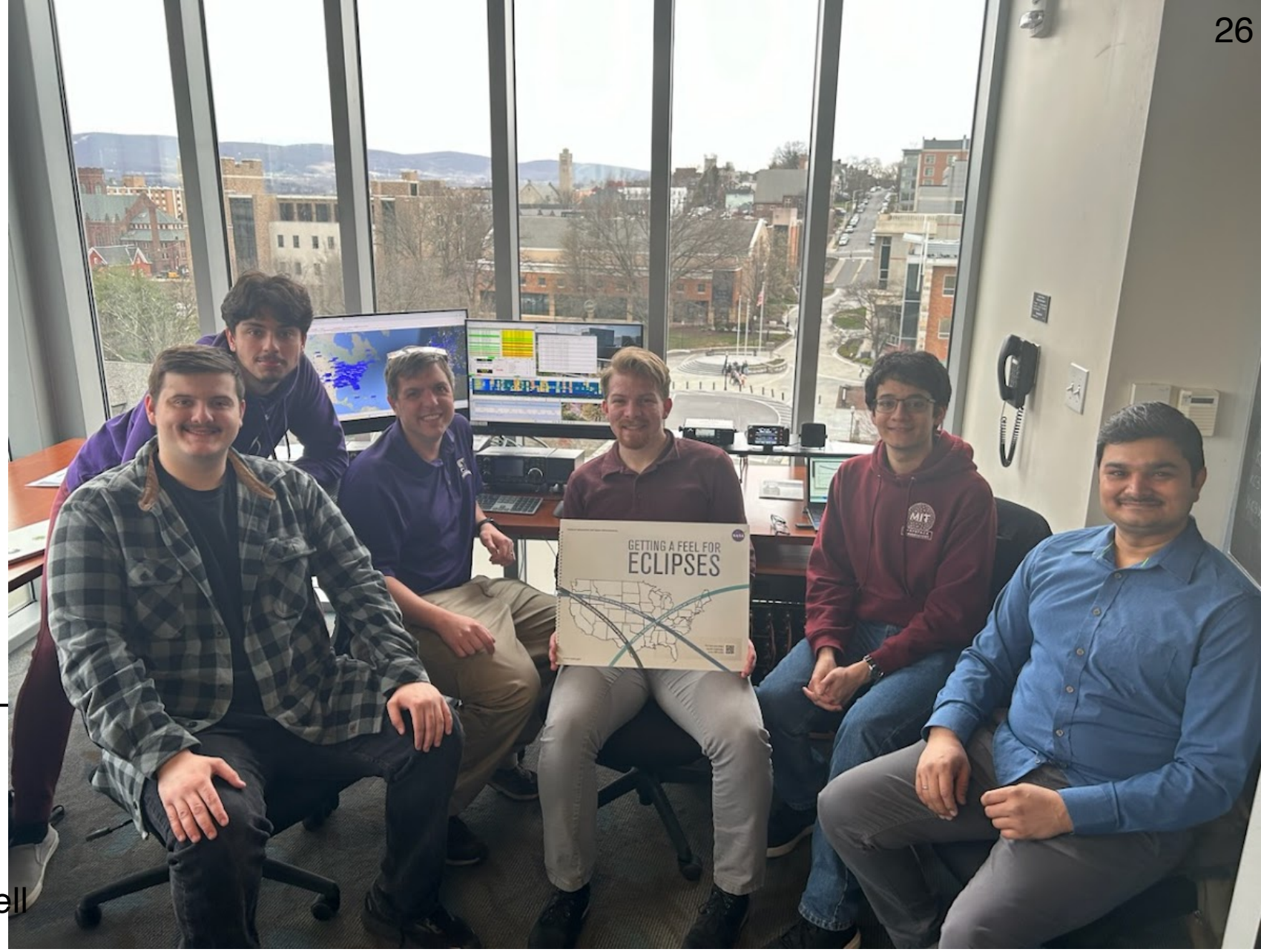

Photo by Ann Marie Rogalcheck-Frissell

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