Estimation of Ionospheric Layer Height Changes From Doppler Frequency and Time of Flight Measurements on HF Skywave Signals

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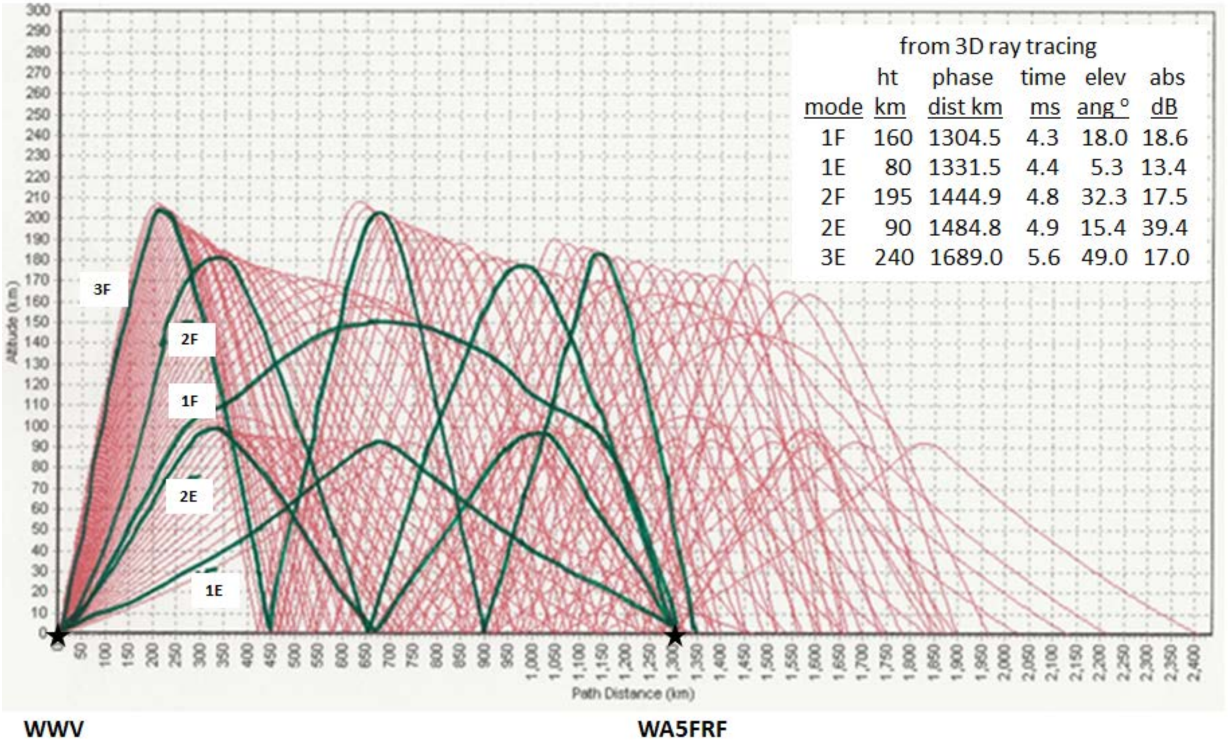
Synopsis

- Multiple ionospheric data sets including Doppler frequency spectrograms, ionosonde data, Time of Flight, and supporting ray trace simulations have been acquired on different days, frequencies, and events.
- Recent analysis techniques have been developed to:
  - Calculate the change in refraction layer height from observed Doppler data.
  - Correlate the data sets in a combined attempt to understand specific elements of Doppler shifts and mode splitting observed over a Colorado-Texas path.
- Data and analyses are presented for:
  - Positive Doppler shifts and mode splitting during the morning transition of the 10/01/2019 Festival of Frequency Measurements
  - Bipolar Doppler frequency swings during the 08/21/2017 Total Eclipse
  - Time-of-Flight measurements taken during the morning transition on 01/29/2020

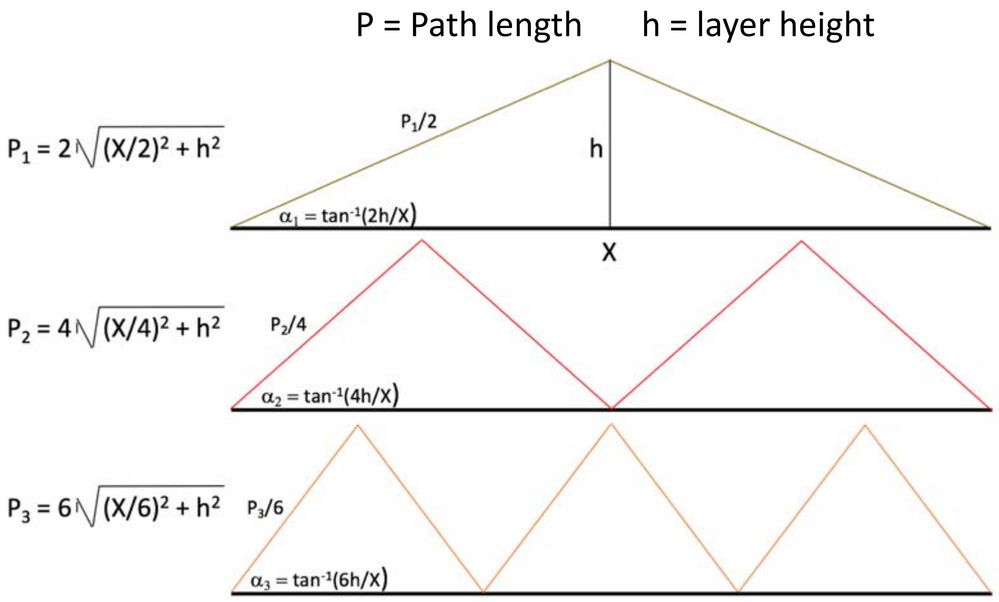
Multiple Hop Geometry and Simplified Model Used for Doppler-to-Height Calculations and Time-of-Flight Analyses

2D Ray Trace from WWV to WA5FRF, 4-50° in 1° steps, January 2020 at 1430 UTC on 5 MHz



mode	ht km	phase dist km	time ms	elev ang °	abs dB
1F	160	1304.5	4.3	18.0	18.6
1E	80	1331.5	4.4	5.3	13.4
2F	195	1444.9	4.8	32.3	17.5
2E	90	1484.8	4.9	15.4	39.4
3E	240	1689.0	5.6	49.0	17.0

Ray Trace Simulation provided by Carl Luetzelschwab K9LA shows multihop propagation modes from E and F Layers shortly after sunup during morning transition.

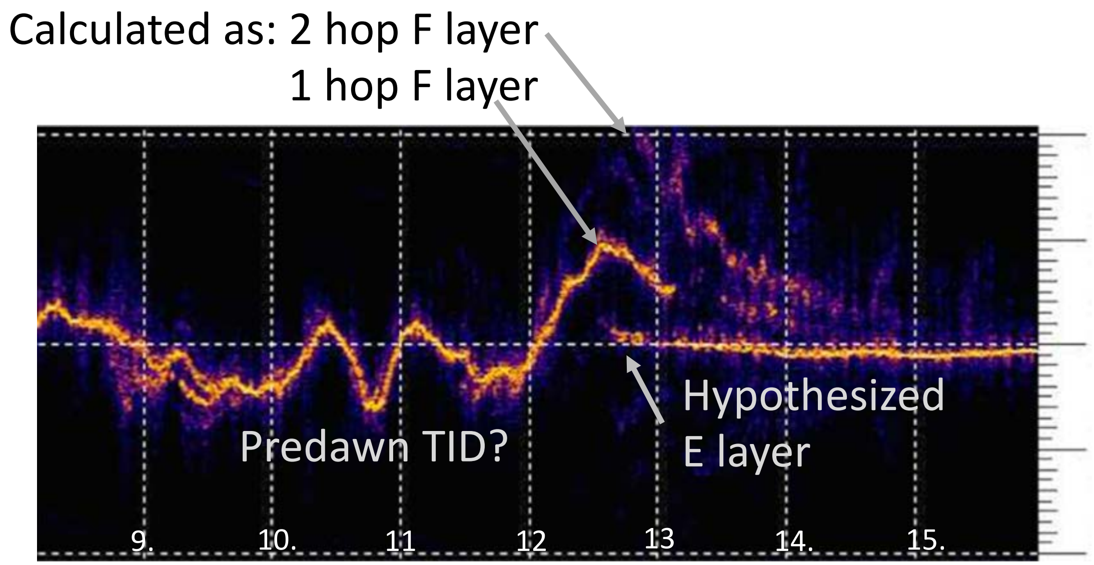


Changes in layer height affect path lengths according to number of hops. Paths with more hops between fixed points are longer and therefore shorten faster with the same height change.

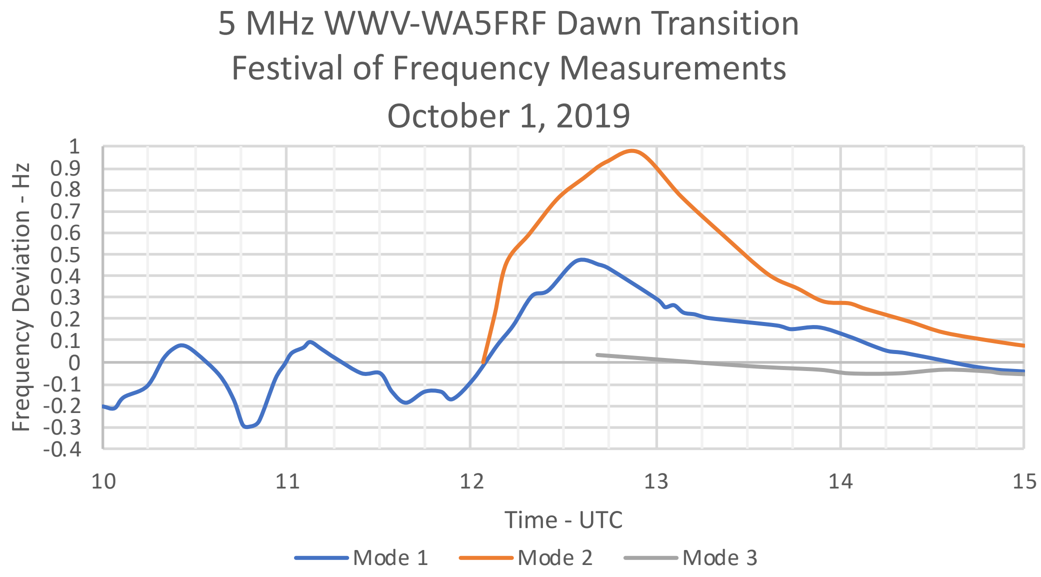
Section 1. Positive Doppler Shifts and Mode Splitting During the Morning Transition of the 10/01/2019 Festival of Frequency Measurements

- Path: WWV in Ft. Collins, CO to WA5FRF near San Antonio, TX.
- Frequency: 5 MHz
- Note: No GPSDO available for this data set

5 MHz WWV Frequency Variations Recorded October 1, 2019



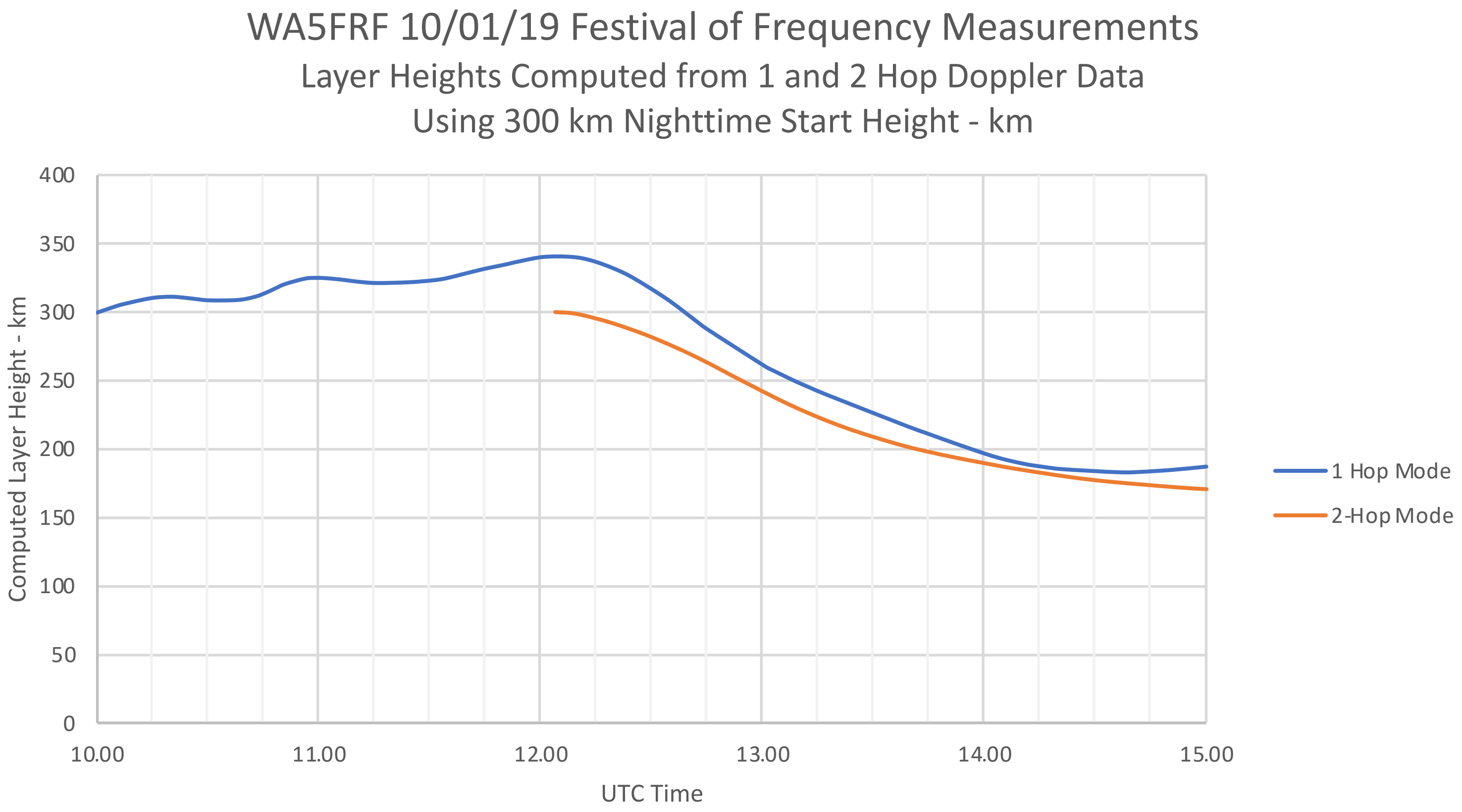
WA5FRF FFM Morning Spectrogram



Frequency Record Digitized and Imported to Excel Spreadsheet for analysis.

No GPDSO was available for this data set. Frequency calibration was obtained from daytime WWV carrier on 5 MHz. The predawn TID identified by Nathaniel Frissell W2NAV complicated layer height calculations.

Layer Height Profiles During Dawn Transition Computed Through Numerical Integration Procedure on Velocity Profile

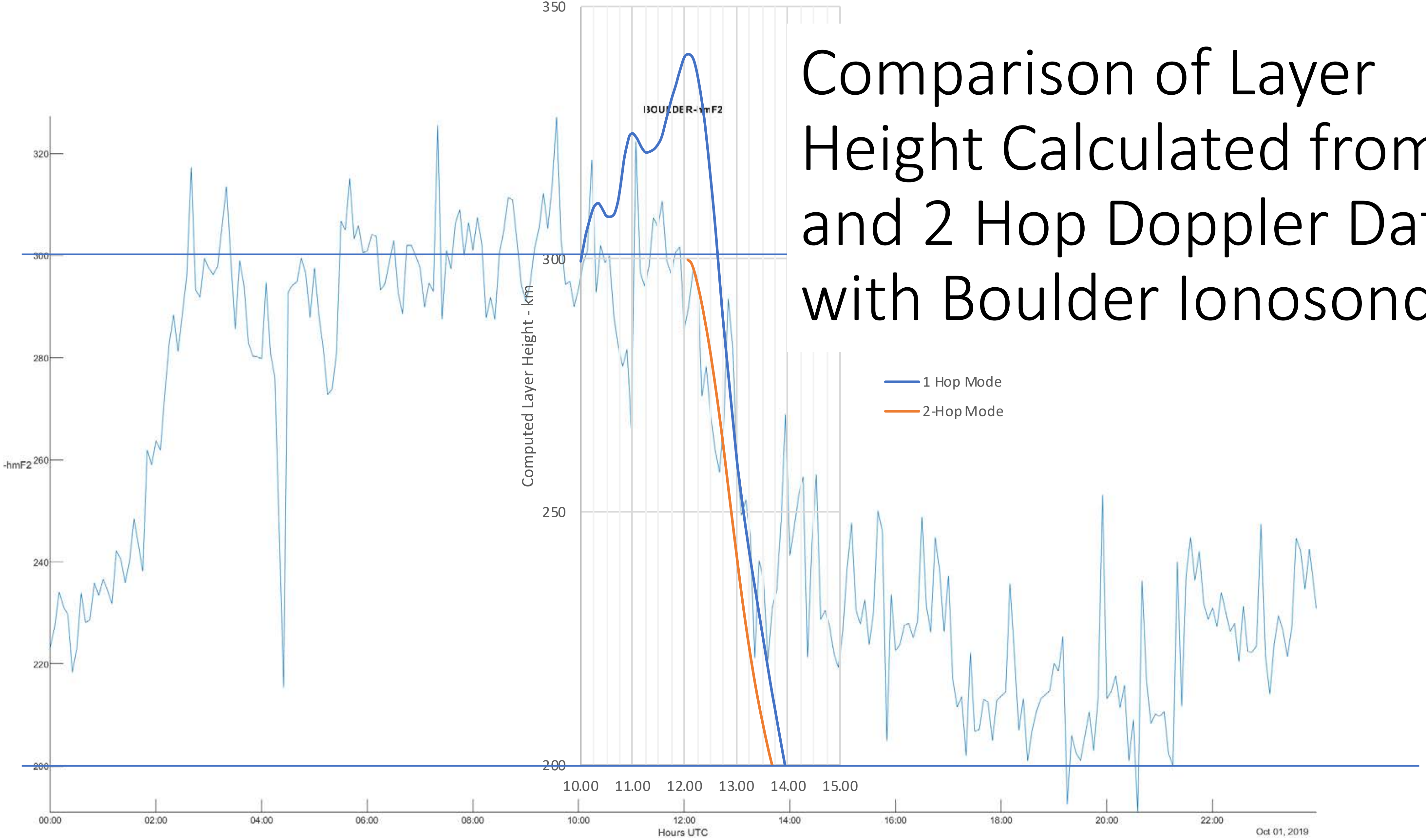


Height profiles were calculated using the 1 and 2 hop relationships in the previous geometric model.

This data is predicated on an assumed starting height of 300 km at 1000z, obtained from an IRI ray trace simulation.

Process: 1) Convert Doppler frequency to path velocity, 2) Calculate change in path length through cumulative sum integration of velocity profile, 3) Convert path length change to layer height change using geometric model.

Comparison of Layer Height Calculated from 1 and 2 Hop Doppler Data with Boulder Ionosonde

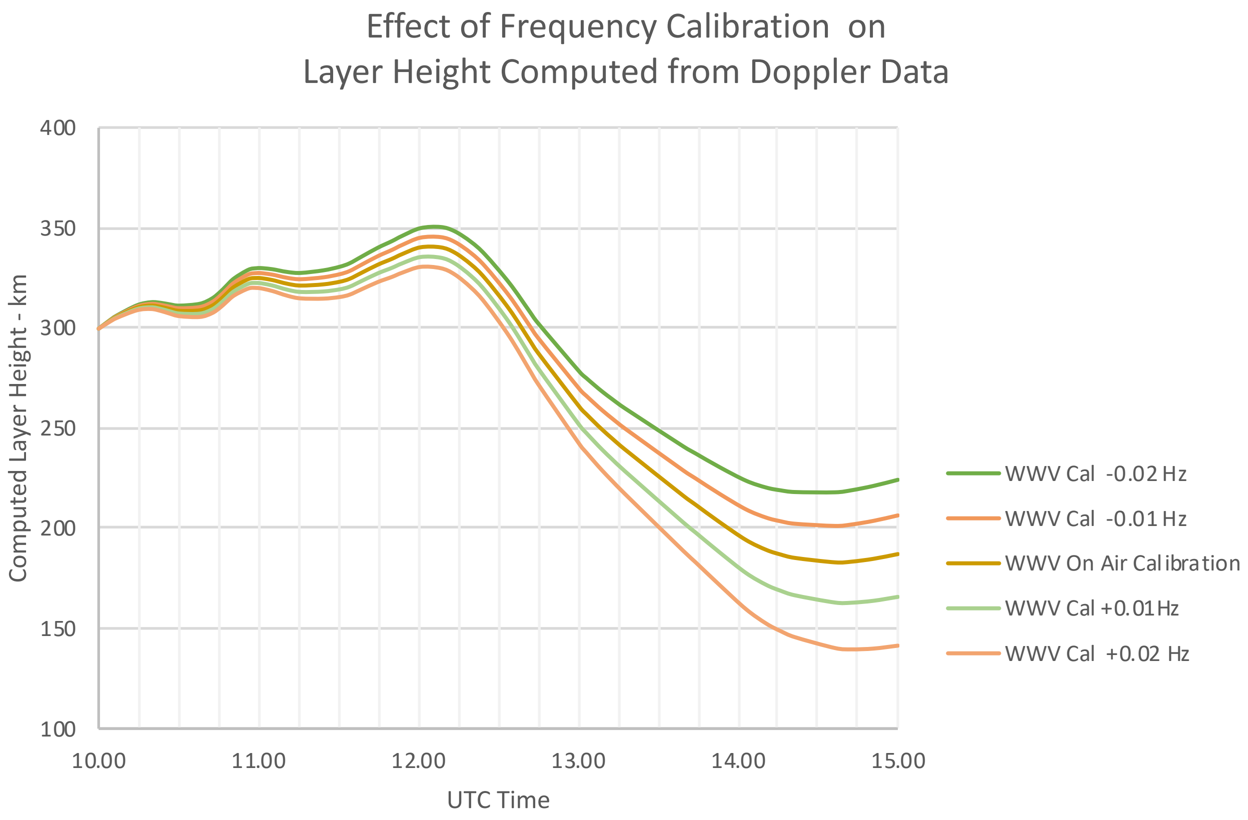


Timing of layer height decrease is excellent but magnitude of final height is off by 35 km. Why?

A Little Frequency Error Goes a Long Way in Layer Height Calculation from Doppler Data

A frequency error represents a constant path velocity offset that adds up to a large layer height error when integrated over the time window of the experiment.

A GPSDO was not available for this data set so the receiver was calibrated using on-air measurement of daytime WWV carrier at 5 MHz. An absolute frequency error of only ~0.015 Hz accounts for the observed error.

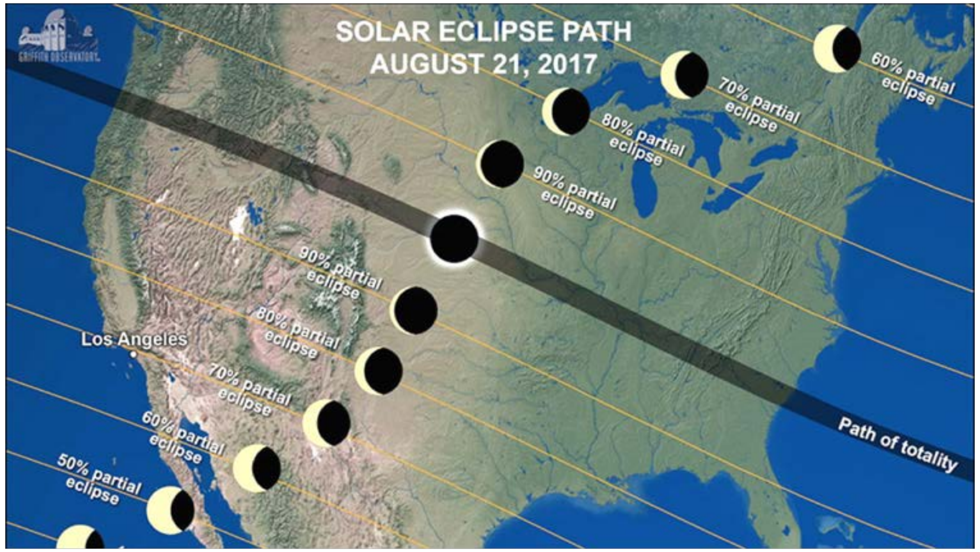


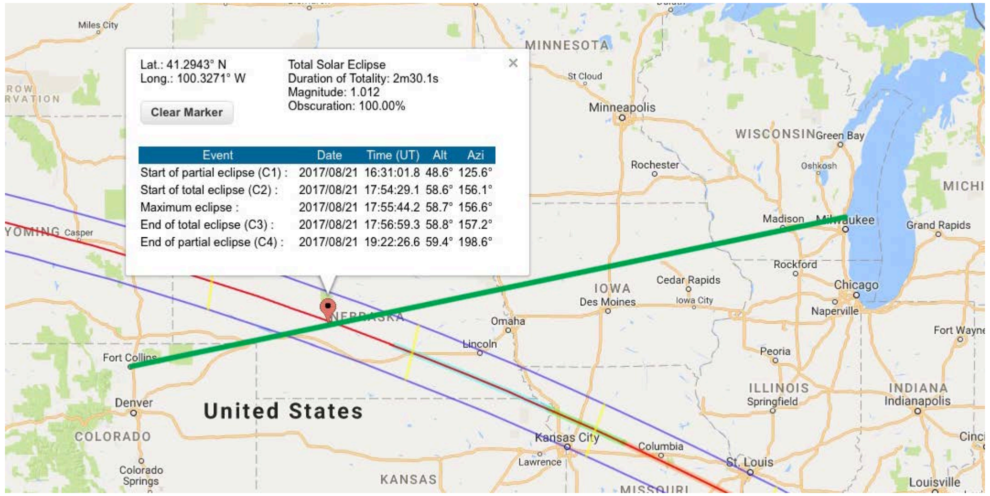
A 0.04 Hz range in frequency uncertainty results in a layer height spread of 80 km over a 5 hour time span for this path.

Section 2. Bipolar Doppler Frequency Swings Observed by WA9VNJ During the 08/21/2017 Total Eclipse

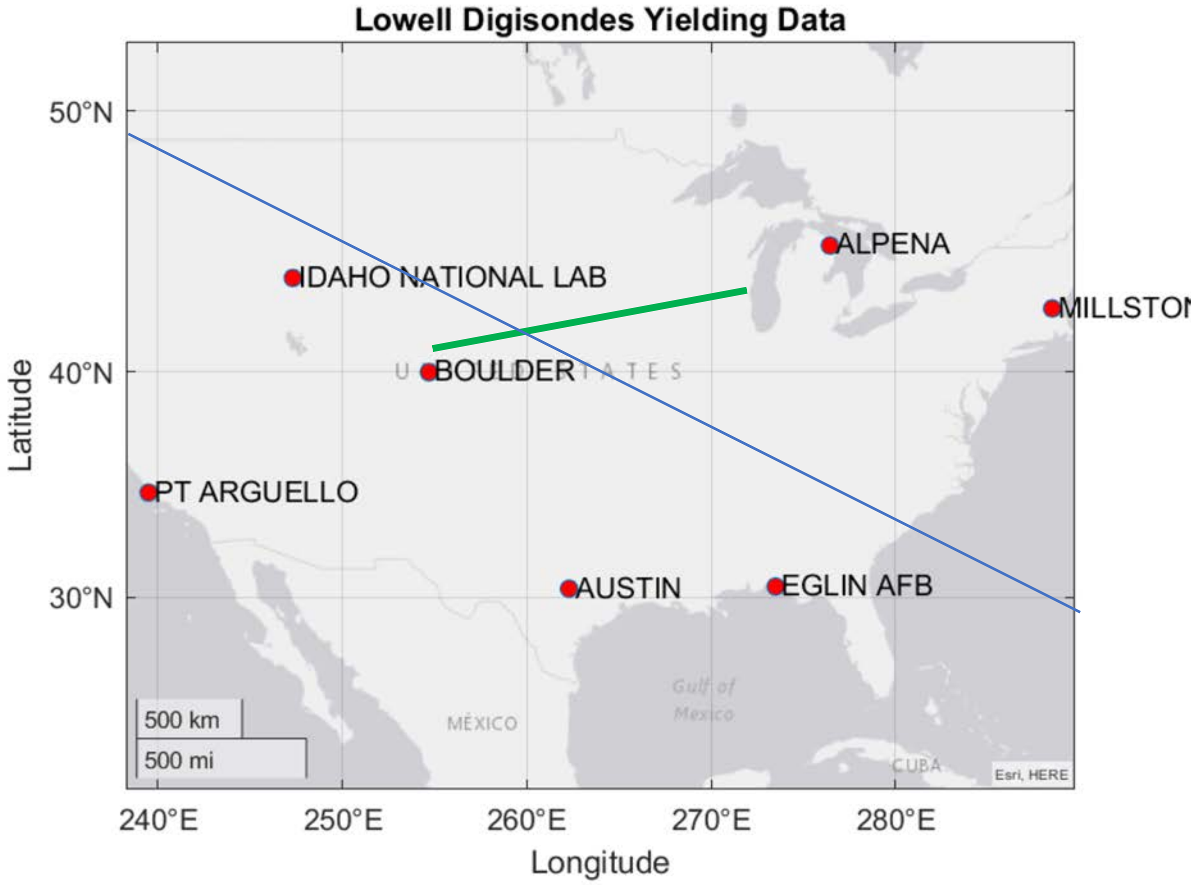
- Path: WWV in Ft. Collins, CO to WA9VNJ near Milwaukee, WI.
- Frequency: 10 MHz

Relative Locations of 08/21/2017 Eclipse Path, WWV-WA9VNJ Propagation Path, and Ionosondes



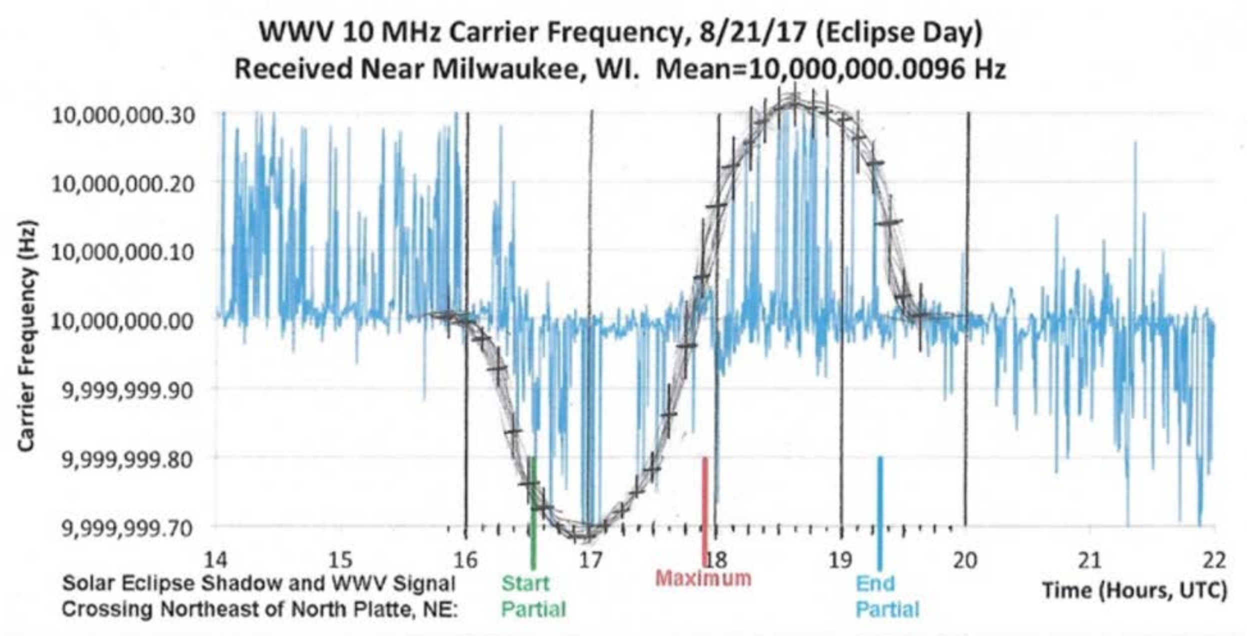


Maps from WA9VNJ and WA5FRF Presentations

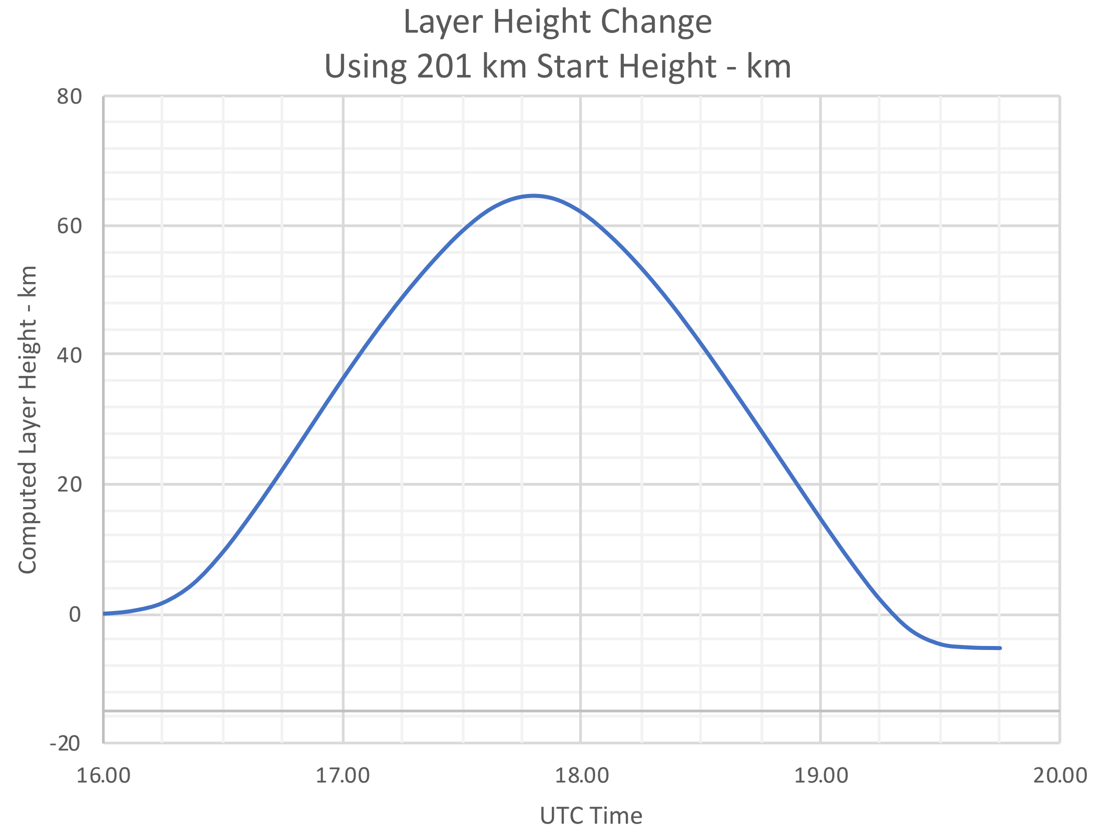


Boulder is closest ionosonde to propagation path

Measured Doppler Data and Calculated Change in Layer Height

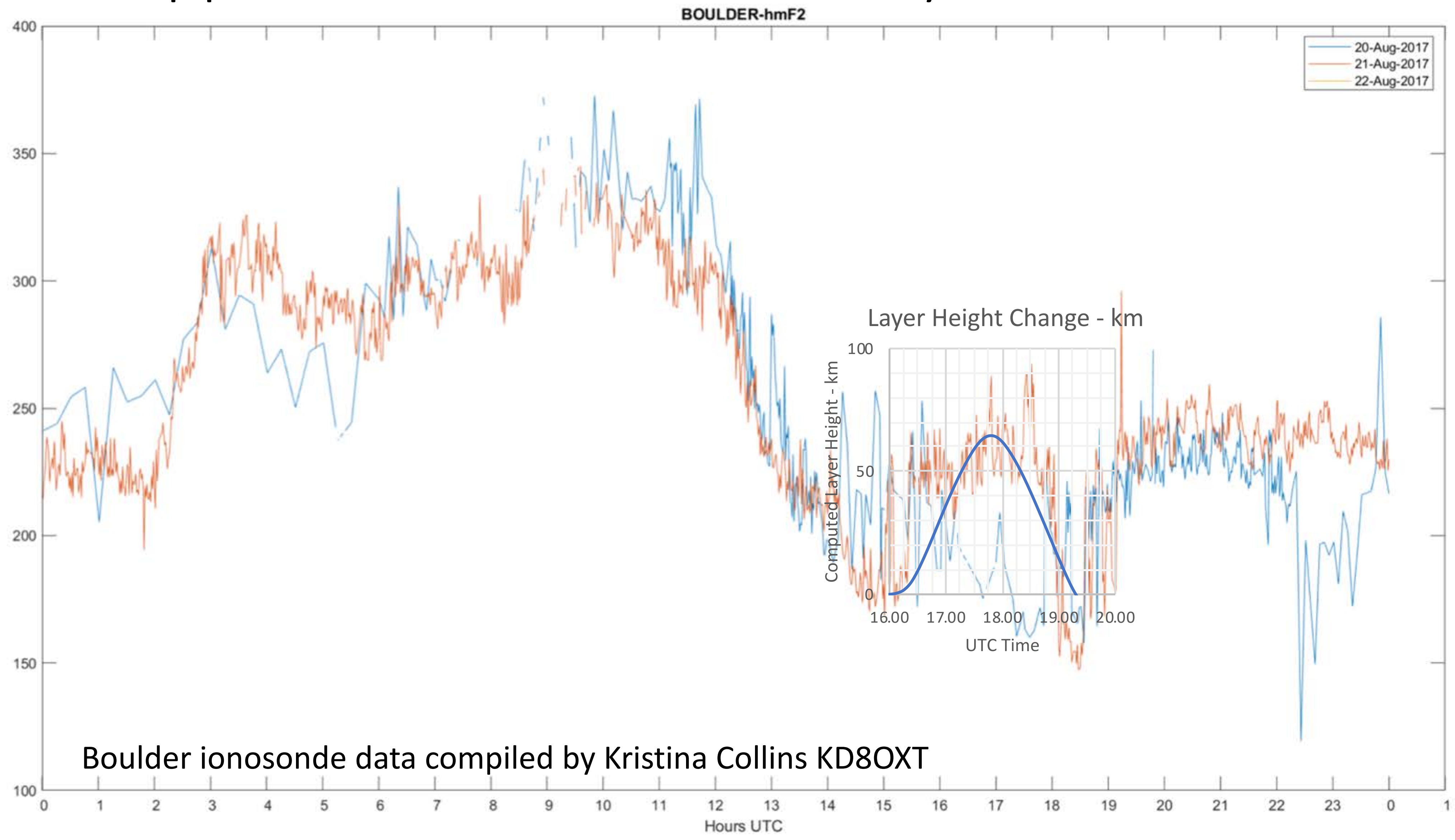


WA9VNJ Frequency Record with Estimated Doppler Envelope



Process: 1) Convert Doppler frequency to path velocity, 2) Calculate change in path length through cumulative sum integration of velocity profile, 3) Convert path length change to layer height change using geometric model.

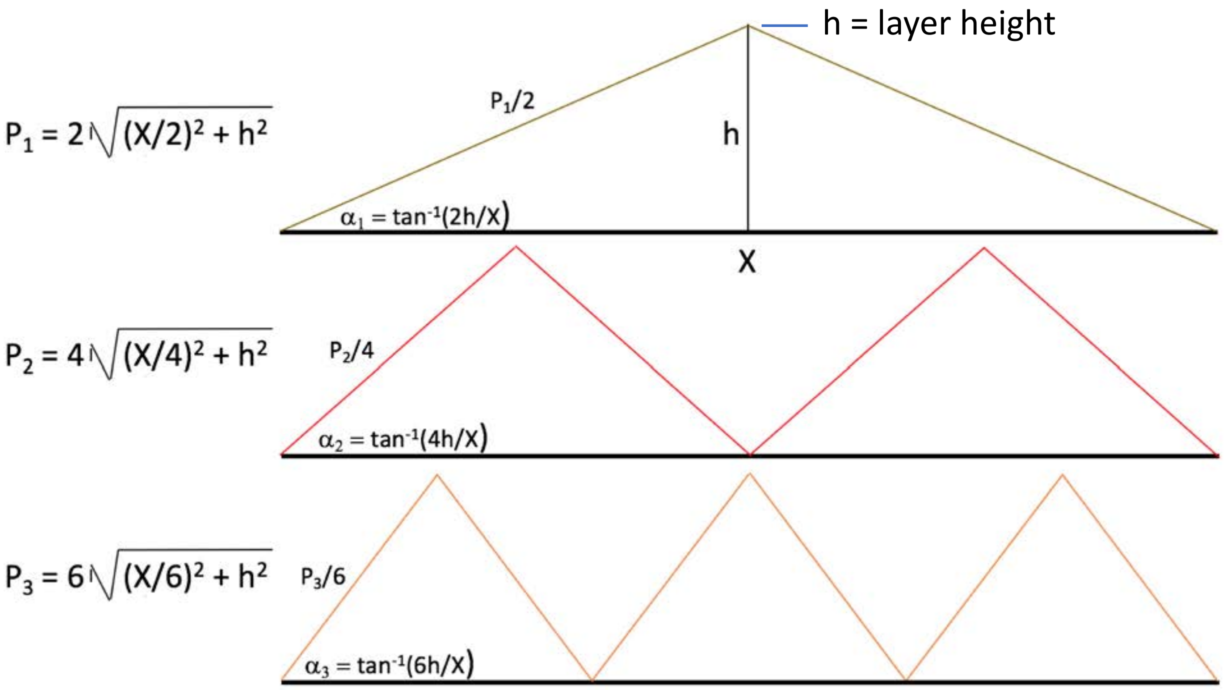
Comparison Between Change in Layer Height Calculated From Doppler Shift and Measured by Boulder Ionosonde

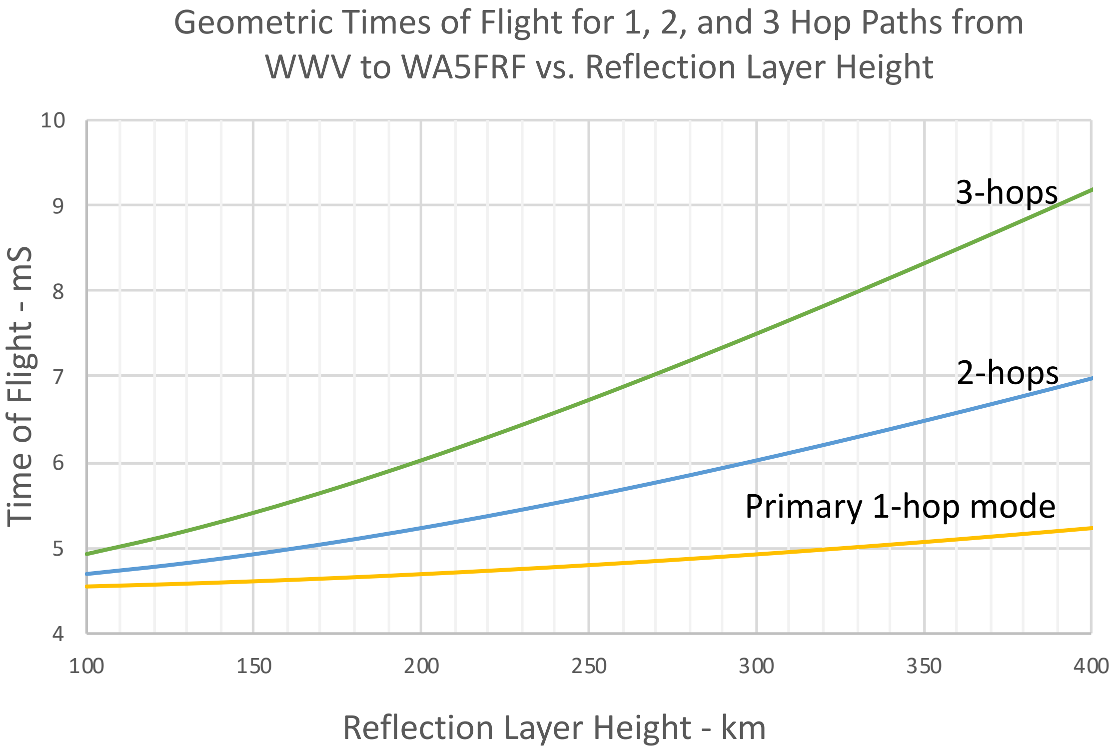


Section 3. Time-of-Flight Measurements Taken During the Morning Transition on 01/29/2020

- Path: WWV in Ft. Collins, CO to WA5FRF near San Antonio, TX.
- Frequency: 5 MHz

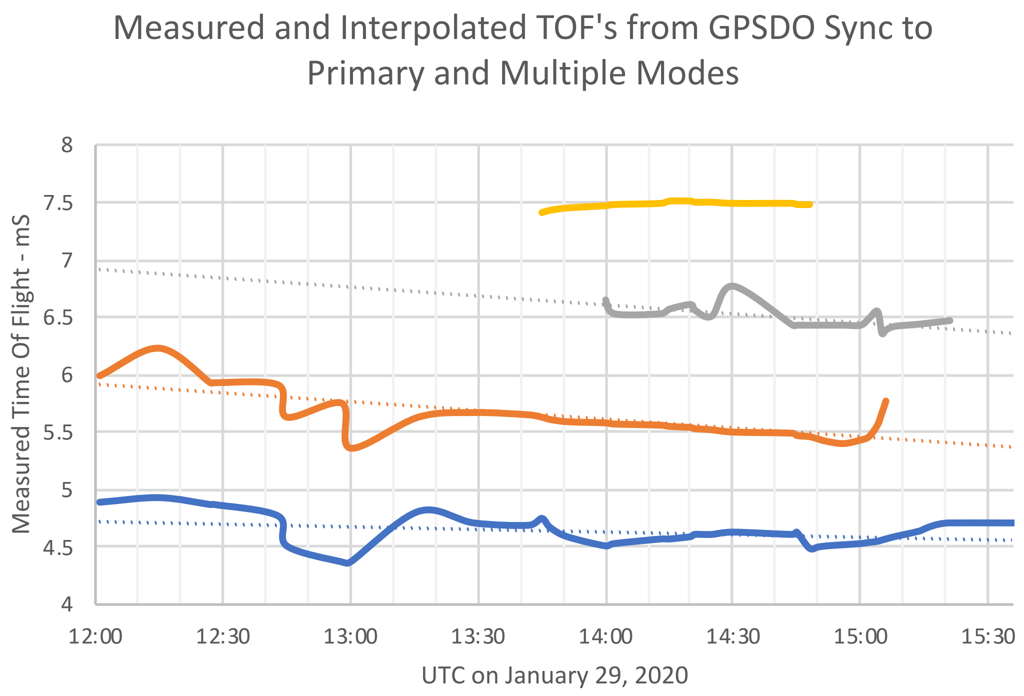
Geometric Model for 1, 2, and 3 Hop Paths Used to Calculate Expected Pulse Timing

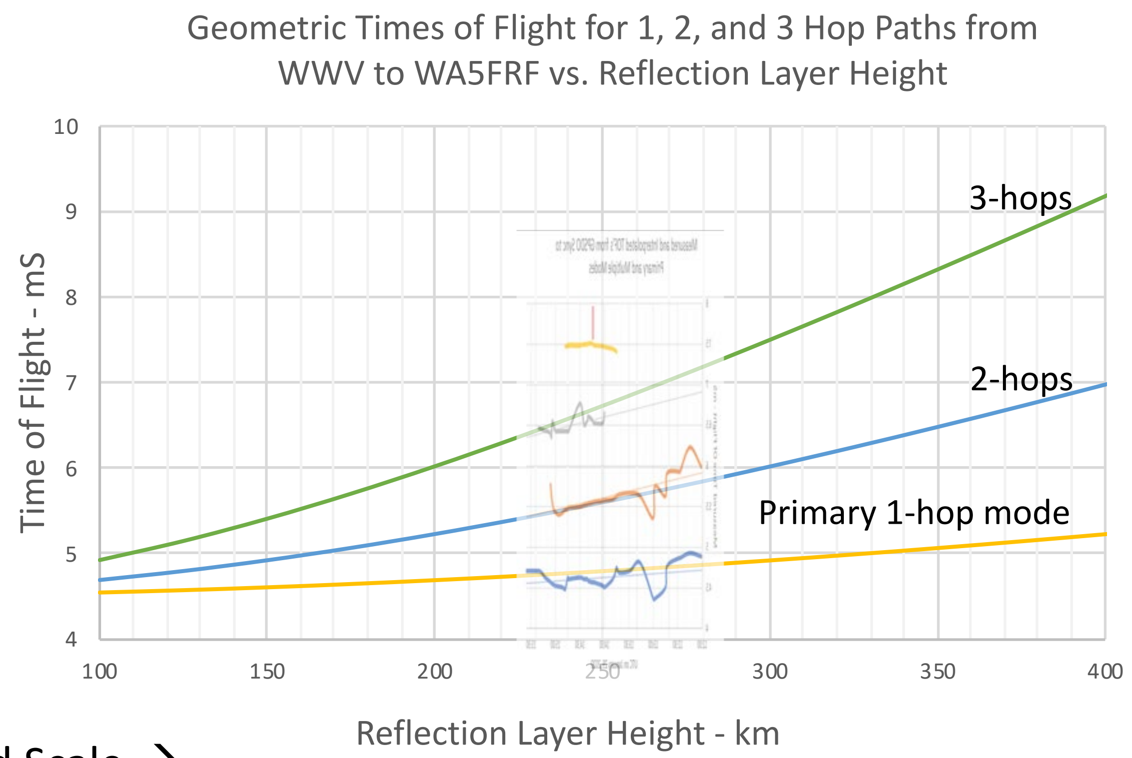




Total path length increases with number of hops. As the refraction layer changes height over a given time span, the multiple hop modes change path length faster. This is also reflected in the slopes of the predicted TOF data. Since Doppler shift scales with velocity, modes with more hops exhibit more frequency change.

Scaling Measured Data for Best Fit on Multi-Hop TOF Model Provides a good Match at a Layer Height of 250 km

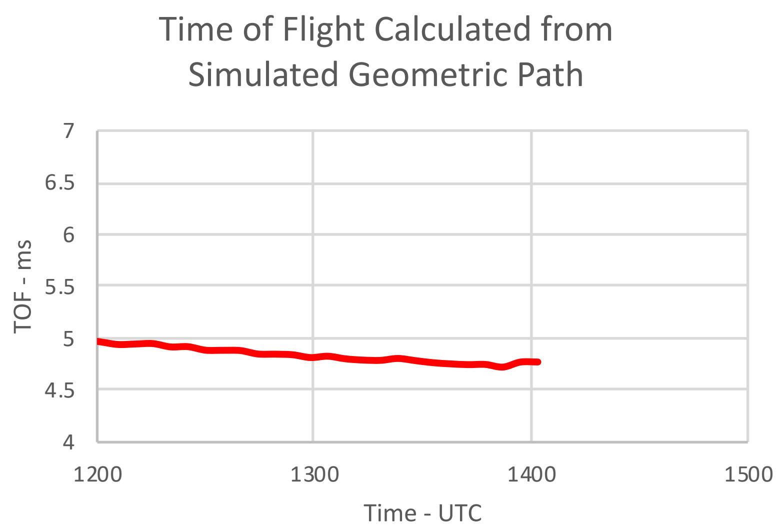




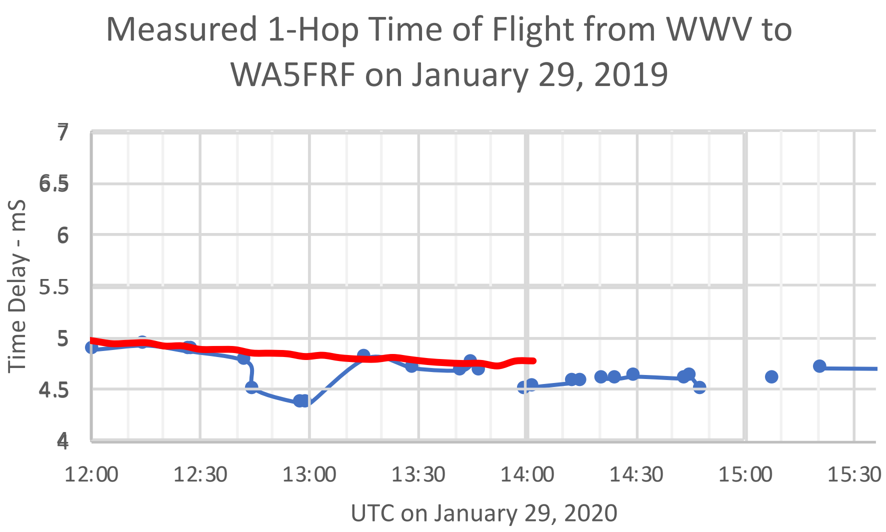
Flip Sense and Scale →

The good correlation between predicted and measured Times of Flight data supports the multi-hop model.

Comparison Between Measured TOF and TOF Predicted by Ray Trace Simulation Using IRI Monthly Average Ionosphere



Time of Flight calculated from Simulation
TOF = Geometric Path/c



Measured Time of Flight from WWV to WA5FRF on January 29, 2019

Conclusions and Recommendations

- Doppler shifts over a given propagation path have been attributed to the time derivative of changes in ionization layer height. The layer height change can be quantitatively deduced by an inverse integration process on measured Doppler data. Layer height profiles have been calculated from measured Doppler data by this method and compared with ionosonde data. The results of these initial tests are encouraging.
- Combining calculated data with ray trace modeling and a geometric model showed results consistent with the premise that some aspects of mode splitting can be attributed to simultaneous multiple hop modes. Time of Flight measurements were also consistent with this premise.
- Several experiments suggest Doppler-producing height changes and other frequency turbulence effects occur at the F layer. In contrast, the E layer shows relative height stability in the face of diurnal transition periods and eclipse passages. Signals believed to be refracted from the E layer show comparative frequency stability.
- More data under differing conditions are needed to better untangle multiple processes. Methods to automate collection of Doppler and Time-of-Flight data are also needed. The methods must be capable of separating data from multiple simultaneous propagation modes.
- A specific experiment to correlate Doppler-inferred height change with ionosonde measurements is proposed. The experiment would use a GPSDO stabilized transmitter and receiver symmetrically disposed on either side of an ionosonde. The idea is to place the apogee of the skywave path directly over the ionosonde. Experimental data would be acquired during morning and evening transitions. A significant enhancement would be to add a timing marker on the transmitted signal to implement Time-of-Flight measurements.