ABSTRACT

Experimental and Computational Methods to Analyze Complex Doppler Behavior of Ionospherically Induced Doppler Shifts on HF Signals

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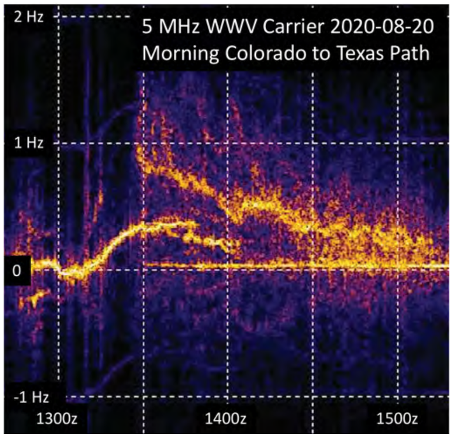
The HamSCI community has been studying apparent frequency shifts in the reception of HF skywave signals from radio station WWV in Ft. Collins, CO. Causes for frequency shifts in the received signal are recognized as complex and varied. Leading candidates are Doppler shifts resulting from dynamic changes in refraction layer height and the behavior of modes at incidence angles at the cusp between escape into space and refraction back to earth. Observations have shown the most radical frequency disturbances occur during the diurnal transitions between night and day, with the morning transitions exhibiting more radical behavior than evening. Other changes in solar radiation such as passage of an eclipse shadow or solar flares produce similar results. In all cases the frequency swings were found to follow the rate of change of propagation path length. Specific behaviors studied include mode splitting, where the Doppler shift diverges into multiple overtone-related tracks, modes that abruptly manifest and disappear during the transition, and asymptotic behavior where Doppler tracks exhibit a rapid frequency change followed by extinction. A morning transition spectrogram showing some of these characteristics is shown in the accompanying figure. This paper describes experiments and analytical procedures devised to better understand these phenomena. They include Time-of-Flight measurements reconciled with a geometric model of the ionosphere to infer propagation modes, use of the geometric model to calculate layer height changes from measured Doppler shifts, and comparison of specific features between spectrogram and ionosonde data sets. Data from two morning transitions and the 2017 total eclipse are given. Plausible explanations for several aspects of observed frequency swings are postulated.



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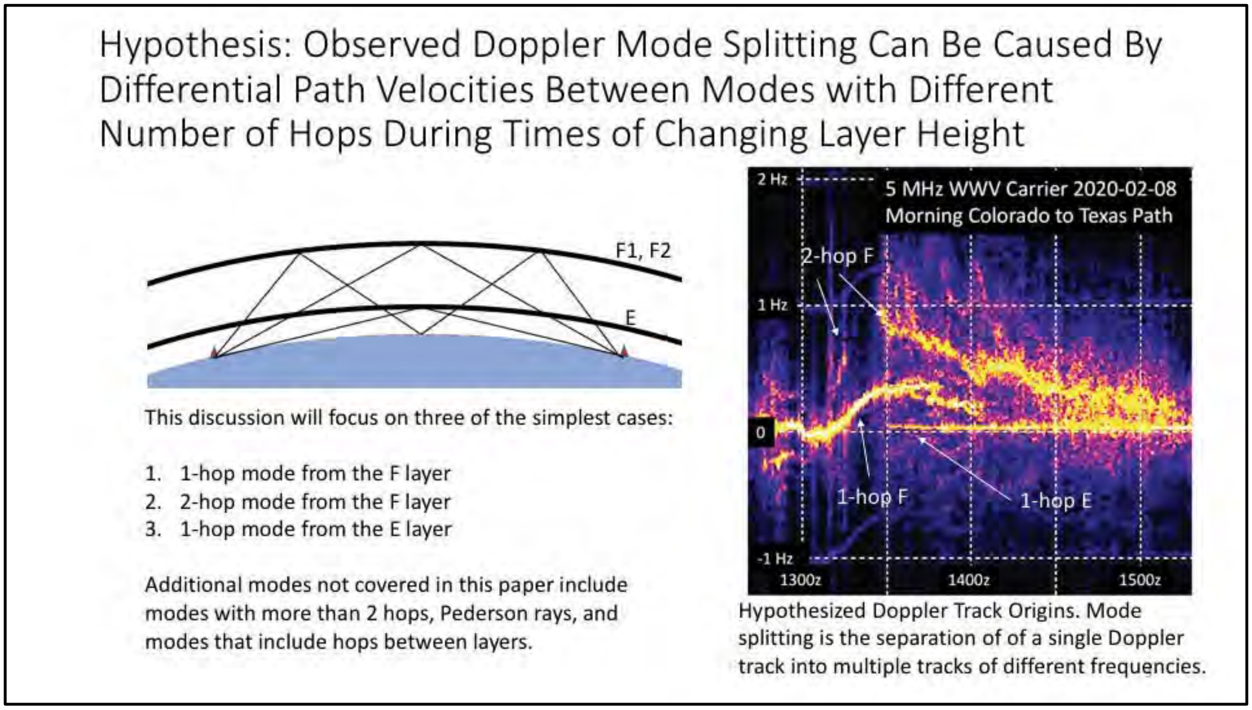
Synopsis

- Complex and varied Doppler records have been observed on transmissions from WWV in Colorado to a receiving station in Texas. Of particular interest is mode splitting during morning transitions between night and day where the Doppler signature often splits into different tracks that bear an overtone relationship and which can suddenly manifest and disappear in response to varying solar radiation.
- This paper presents data and analytical techniques that support the premise that some of the observed mode splitting can be attributed to the different path length changes that correspond to single and multiple hop propagation modes.
- Supporting data sets include:
  - Comparison of Time-of-Flight (TOF) measurements taken during a morning transition to data predicted by a geometric model for single and multiple hop modes and ray trace simulations.
  - Calculation of Doppler shifts predicted for different propagation modes from ionosonde data and comparison with measured Doppler data.
  - Calculation of the change in refraction layer height from measured Doppler data and comparison with ionosonde data.
  - Correlation of modes that manifest abruptly with ionosonde data and with IRI ray trace programs that show rays on the cusp of escape into space and refraction back to earth.



Hypothesis: Observed Doppler Mode Splitting Can Be Caused By Differential Path Velocities Between Modes with Different Number of Hops During Times of Changing Layer Height

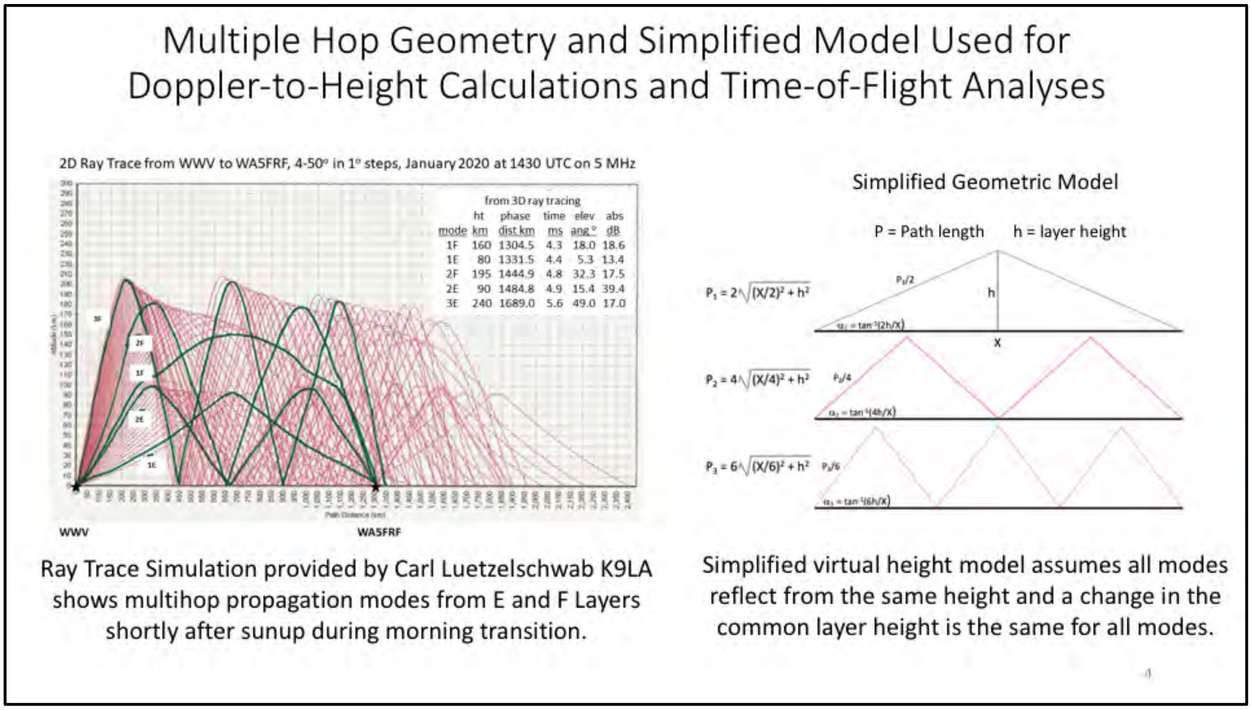
This discussion will focus on three of the simplest cases:

1. 1-hop mode from the F layer
2. 2-hop mode from the F layer
3. 1-hop mode from the E layer

Additional modes not covered in this paper include modes with more than 2 hops, Pederson rays, and modes that include hops between layers.

Hypothesized Doppler Track Origins. Mode splitting is the separation of of a single Doppler track into multiple tracks of different frequencies.

For a fixed ground distance between TX and RX the propagation path is a function of ionization height and number of hops. Multiple hop modes have a longer total path length which increases with number of hops. As a common ionization layer descends, the multiple hop modes undergo more total change in path length. Since the changes happen in the same amount of time, the rate of path change, or path velocity increases according to number of hops. Because Doppler shift scales with path velocity the modes diverge according to velocity to create mode splitting.



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

from 3D ray tracing

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.

Simplified Geometric Model

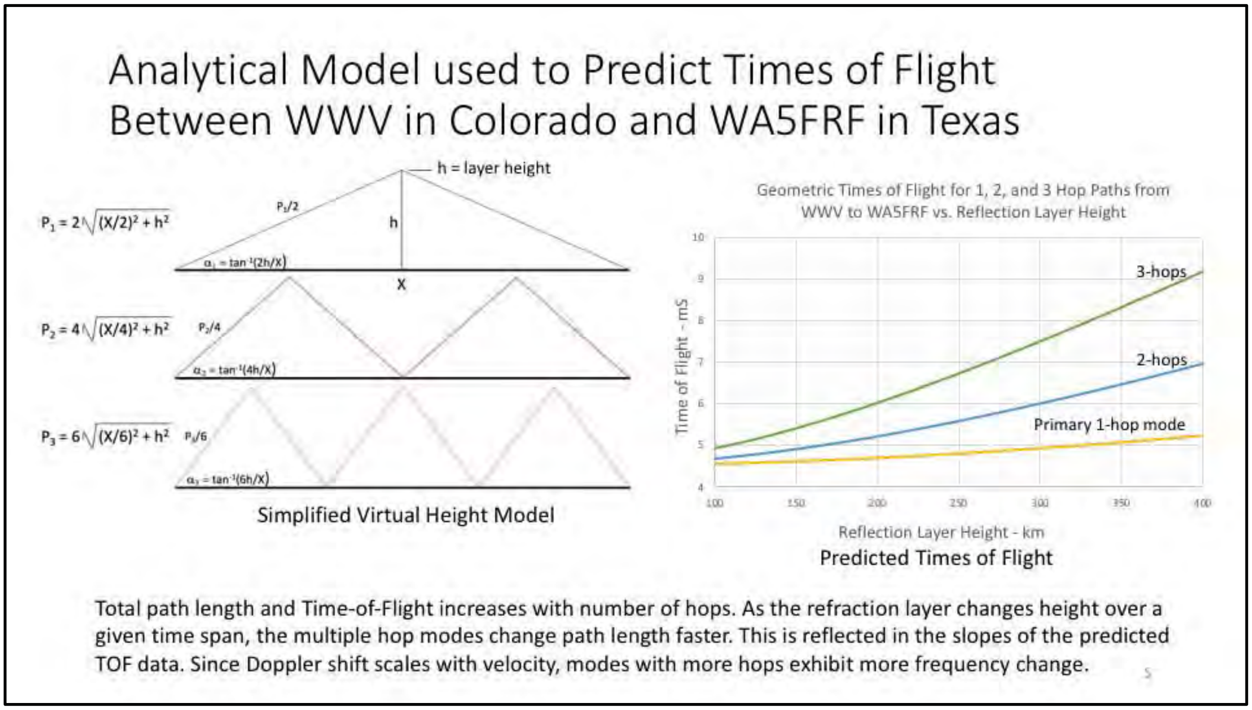
P = Path length h = layer height

$P_1 = 2\sqrt{(X/2)^2 + h^2}$

$P_2 = 4\sqrt{(X/4)^2 + h^2}$

$P_3 = 6\sqrt{(X/6)^2 + h^2}$

Simplified virtual height model assumes all modes reflect from the same height and a change in the common layer height is the same for all modes.



Analytical Model used to Predict Times of Flight Between WWV in Colorado and WA5FRF in Texas

$P_1 = 2\sqrt{(X/2)^2 + h^2}$

$P_2 = 4\sqrt{(X/4)^2 + h^2}$

$P_3 = 6\sqrt{(X/6)^2 + h^2}$

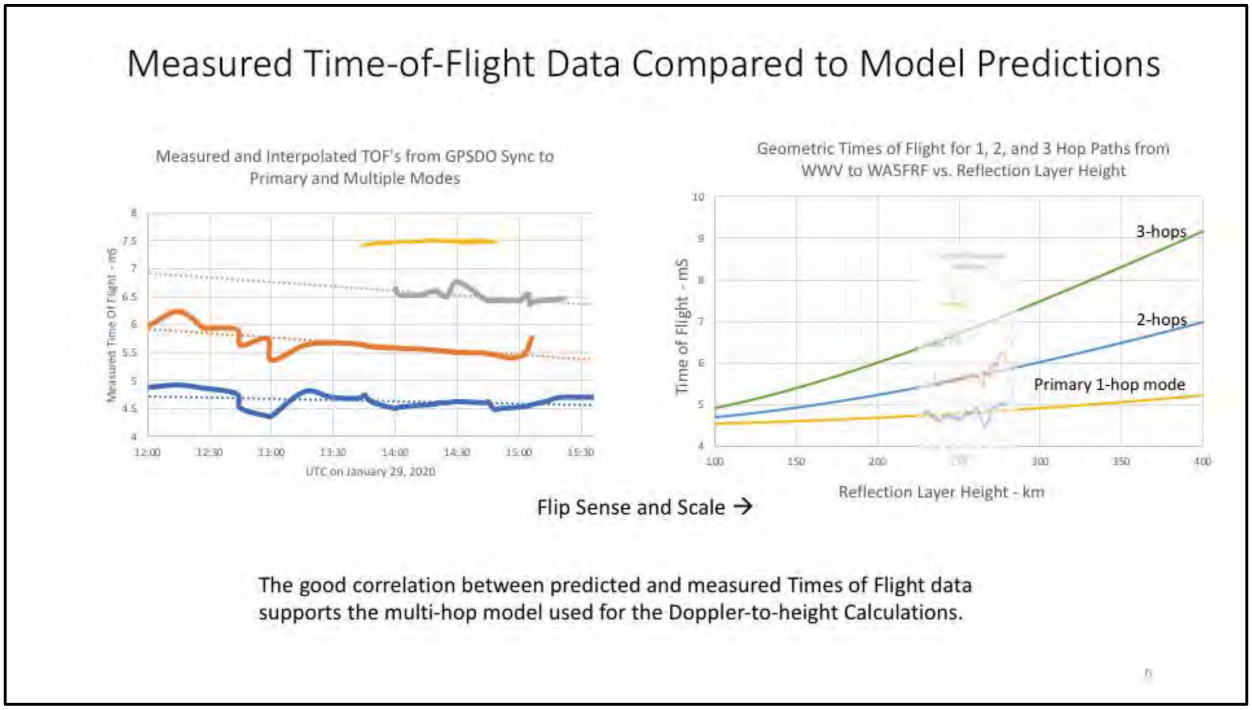
Simplified Virtual Height Model

Geometric Times of Flight for 1, 2, and 3 Hop Paths from WWV to WA5FRF vs. Reflection Layer Height

Predicted Times of Flight

Total path length and Time-of-Flight 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 reflected in the slopes of the predicted TOF data. Since Doppler shift scales with velocity, modes with more hops exhibit more frequency change.

Simplified geometric model used to predict times of flight for 1, 2, and 3 hop modes from Ft. Collins, CO to near San Antonio, TX. (1350 km ground distance). Total path length and TOF increase 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 reflected in the slopes of the predicted TOF data.

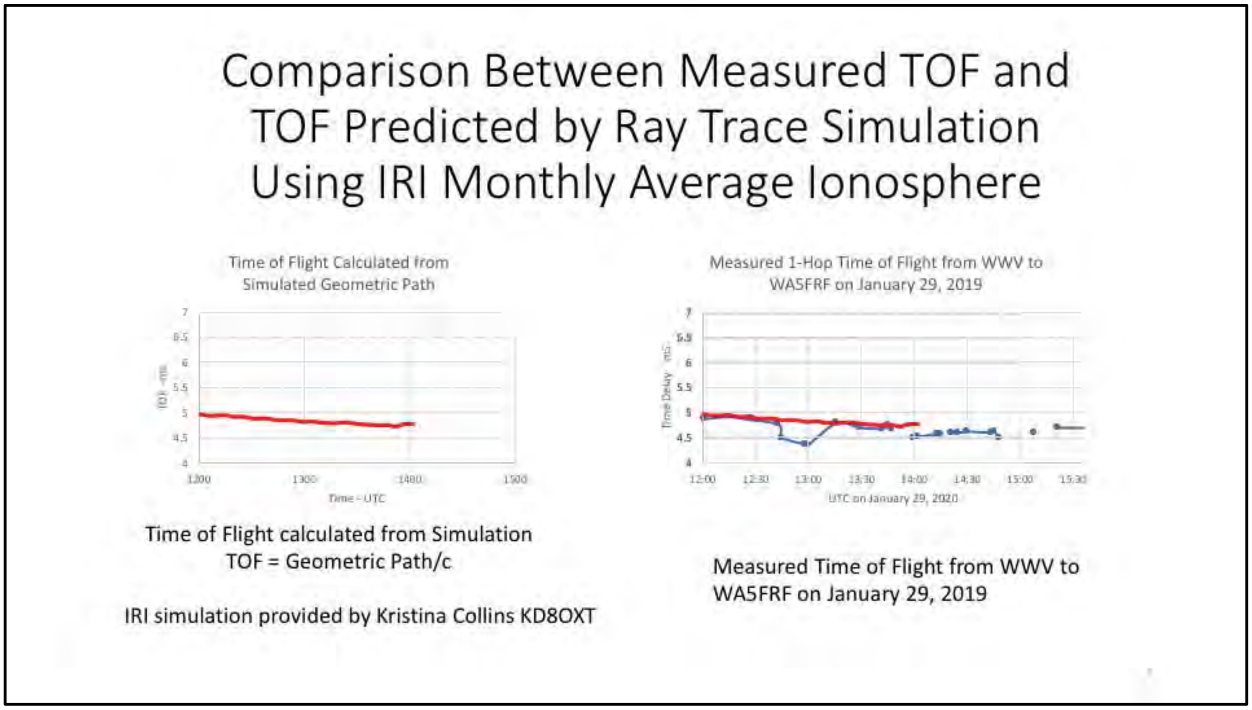


Measured Time-of-Flight Data Compared to Model Predictions

Flip Sense and Scale →

The good correlation between predicted and measured Times of Flight data supports the multi-hop model used for the Doppler-to-height Calculations.

Times of flight from WWV to WA5FRF were measured during a morning transition on January 29, 2020. The measured Time of Flight data is plotted on the left as a function of UTC time. A scatter plot of measured TOF naturally formed in layers according to number of hops. The times of flight decrease with time because ionization lowers with time during a morning transition. The data can be compared to the model predictions by first flipping sense to match the ascending layer height used for the model predictions and then adjusting the chart scale for best fit. Good correlation occurred at a layer height of 250 km. Spot checks of individual TOF measurements gave good agreement with PHaRLAP and Prop Lab Pro ray trace predictions for this date.



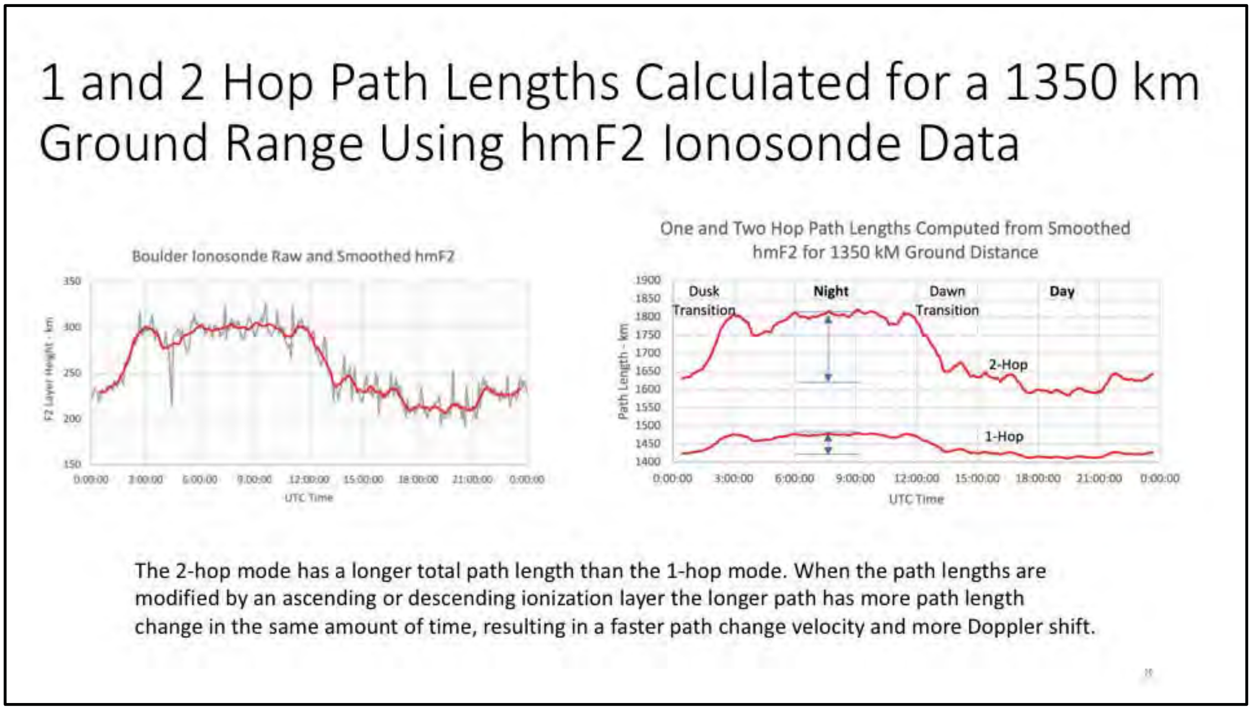
Comparison Between Measured TOF and TOF Predicted by Ray Trace Simulation Using IRI Monthly Average Ionosphere

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

IRI simulation provided by Kristina Collins KD8OXT

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

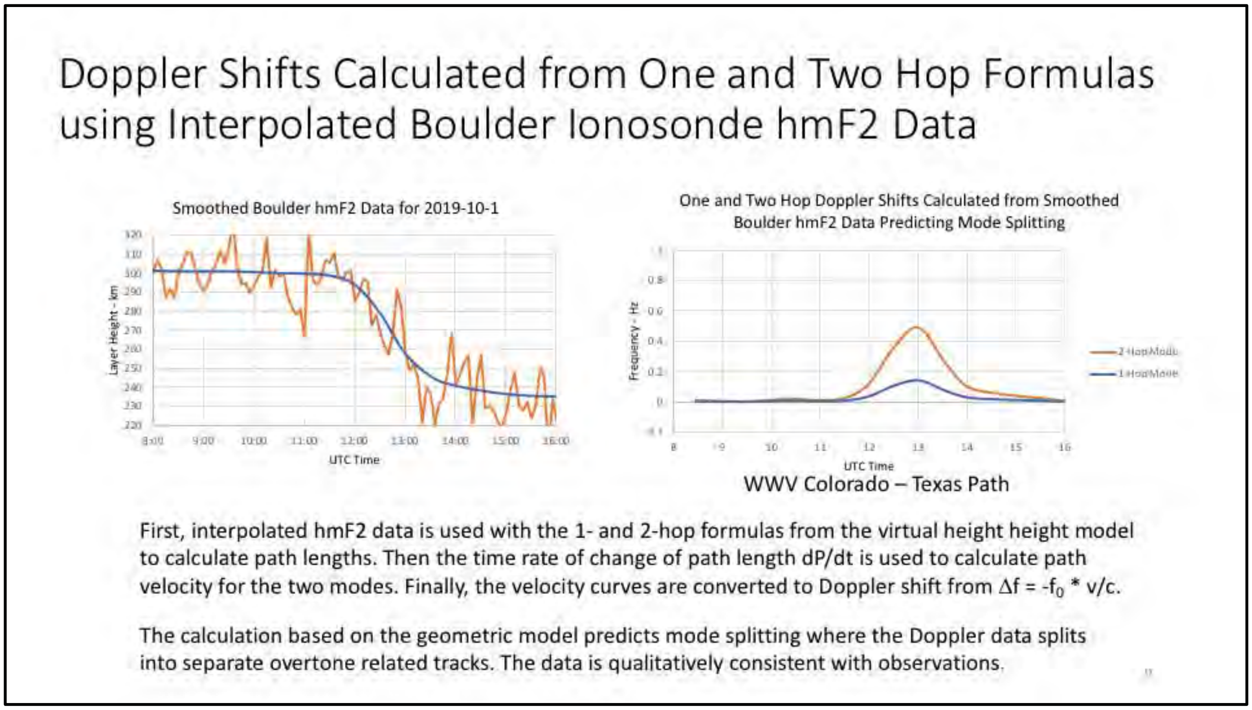
The chart on the left shows Time of Flight data from an IRI ray trace program using the monthly average ionosphere for this date. Overlaying this chart on the WWV time tick data shows good agreement between the 1 hop data and the IRI model. Spot checks of measured data showed good agreement with PHaRLAP models for 1, 2, and 3 hop modes.



1 and 2 Hop Path Lengths Calculated for a 1350 km Ground Range Using hmF2 Ionosonde Data

The 2-hop mode has a longer total path length than the 1-hop mode. When the path lengths are modified by an ascending or descending ionization layer the longer path has more path length change in the same amount of time, resulting in a faster path change velocity and more Doppler shift.

Ionosonde hmF2 data plots the height of the F2 layer as a function of time of day. Converting the layer height profile from hmF2 into path length profiles using the relationships developed in the geometric model graphically shows the large difference in path length change between 1 and 2 hop modes. The rate of change in path length during the transitions between night and day is what gives rise to Doppler shifts. Because the 2-hop mode undergoes a larger path length change in the same amount of time, it incurs more Doppler shift. This is the root cause of mode splitting.



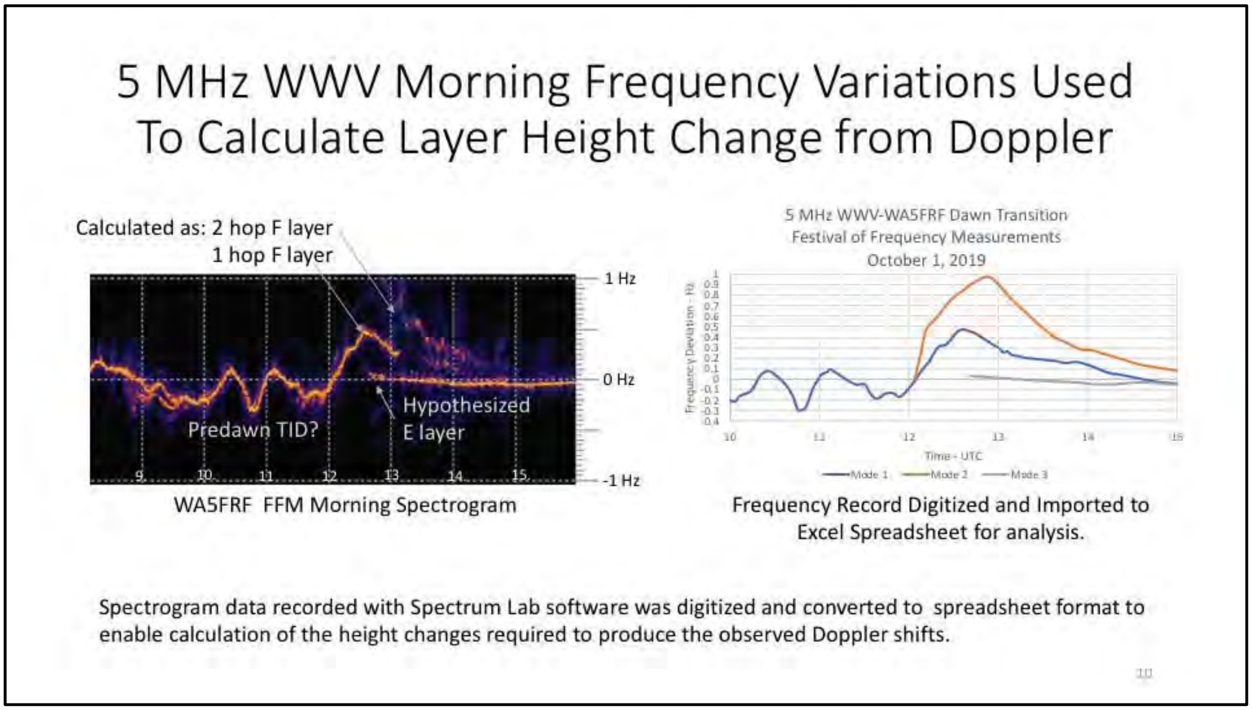
Doppler Shifts Calculated from One and Two Hop Formulas using Interpolated Boulder Ionosonde hmF2 Data

WWV Colorado – Texas Path

First, interpolated hmF2 data is used with the 1- and 2-hop formulas from the virtual height height model to calculate path lengths. Then the time rate of change of path length dP/dt is used to calculate path velocity for the two modes. Finally, the velocity curves are converted to Doppler shift from $\Delta f = -f_0 * v/c$.

The calculation based on the geometric model predicts mode splitting where the Doppler data splits into separate overtone related tracks. The data is qualitatively consistent with observations.

Doppler shift calculations based on ionosonde hmF2 data for 1 and 2 hop modes predict mode splitting.



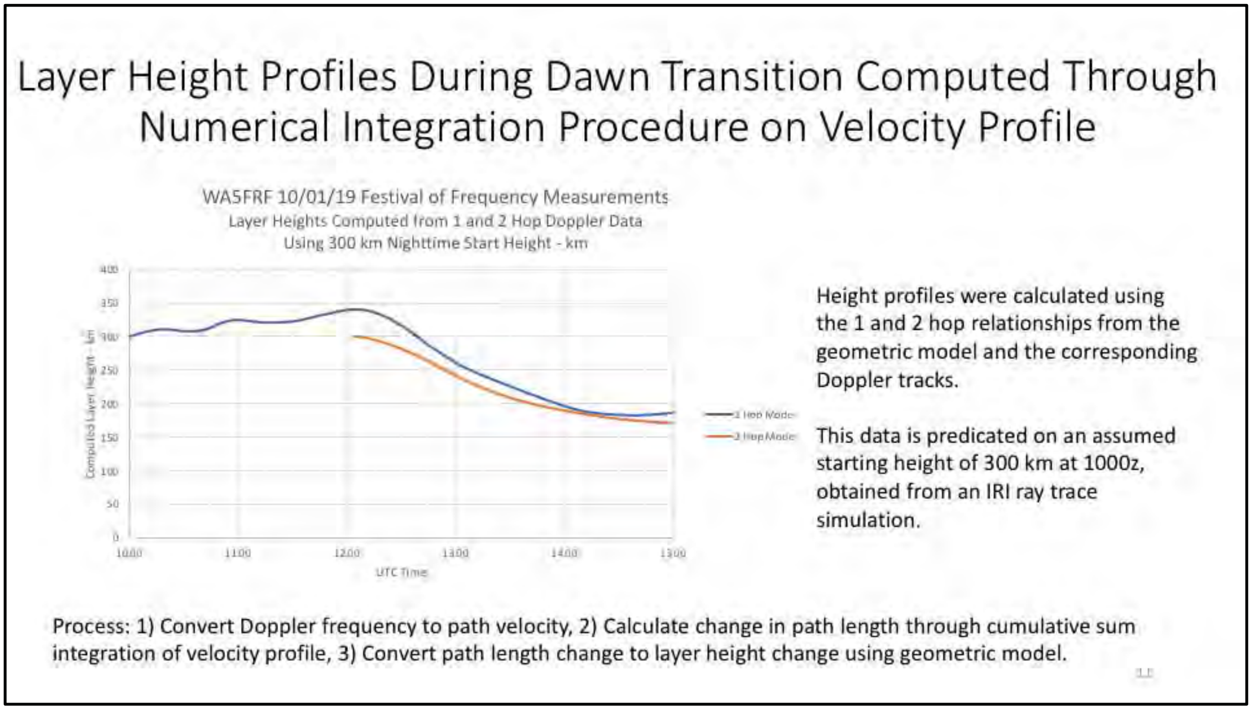
5 MHz WWV Morning Frequency Variations Used To Calculate Layer Height Change from Doppler

WA5FRF FFM Morning Spectrogram

Frequency Record Digitized and Imported to Excel Spreadsheet for analysis.

Spectrogram data recorded with Spectrum Lab software was digitized and converted to spreadsheet format to enable calculation of the height changes required to produce the observed Doppler shifts.

Spectrogram data recorded with Spectrum Lab software was digitized and converted to spreadsheet format to enable calculation of the height changes required to produce the observed Doppler shifts. This data is then compared to hmF2 ionosonde data to test the multiple hop theory.



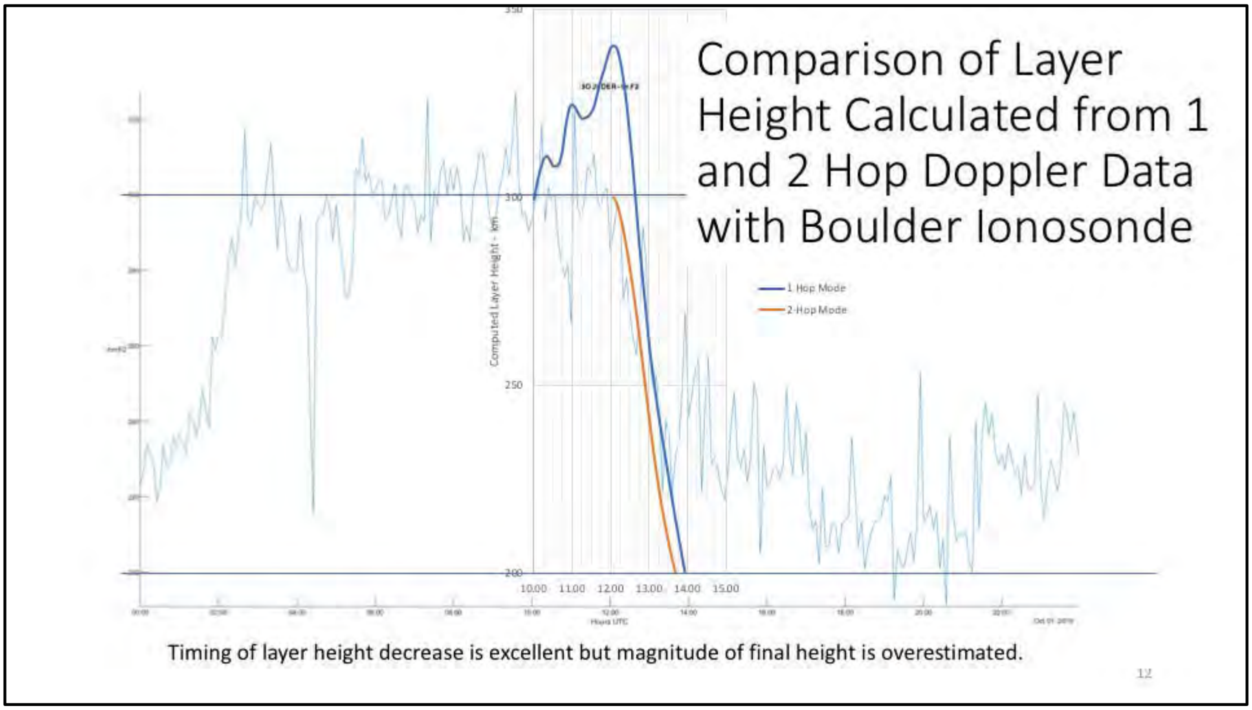
Layer Height Profiles During Dawn Transition Computed Through Numerical Integration Procedure on Velocity Profile

Height profiles were calculated using the 1 and 2 hop relationships from the geometric model and the corresponding Doppler tracks.

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.

These are the layer height profiles calculated from the Doppler data. The profiles were calculated using the 1 and 2 hop relationships between path length and layer height and the corresponding measured Doppler tracks. Of significance is that the separate layer height calculations for the very disparate Doppler tracks gave nearly the same answer for the layer height profile. Because the process of mathematical integration loses the absolute zero reference a starting height must be obtained from another source. In this case, it was from IRI simulation data provided by Kristina Collins KD8OXT.



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 overestimated.

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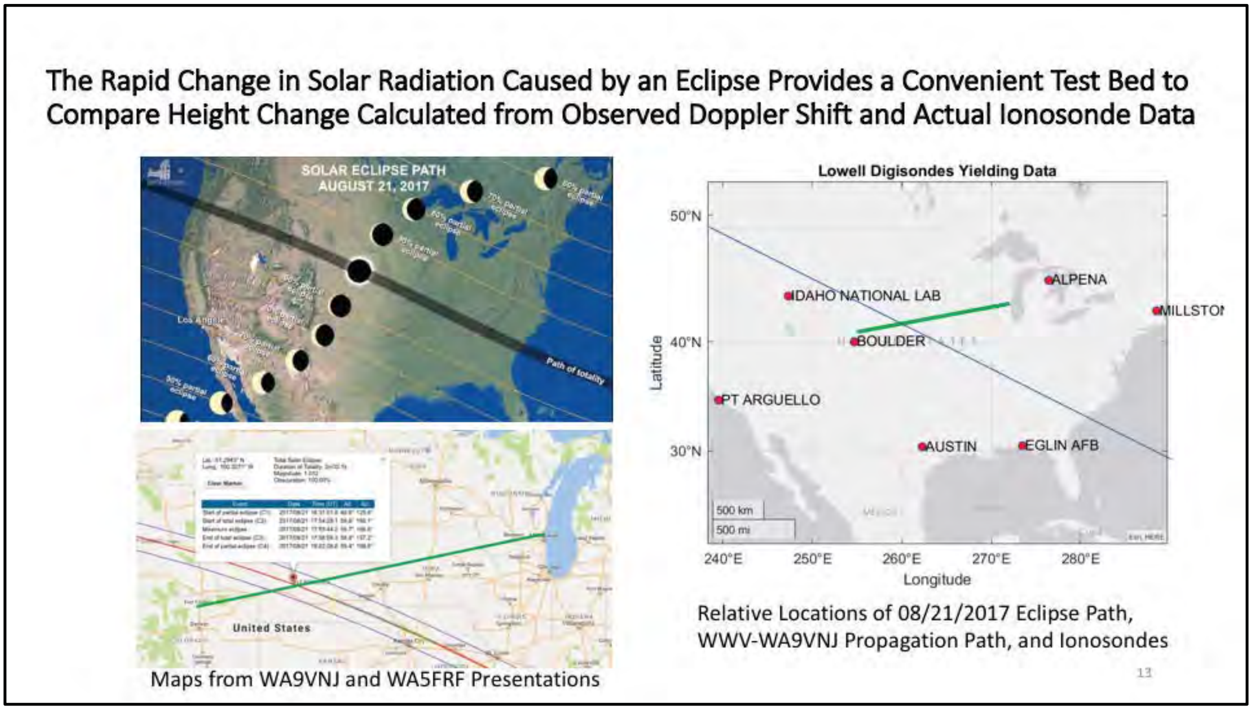
Height profile data scaled in time and amplitude and overlaid on top of Boulder Ionosonde data. Both the 1 and 2 hop derived layer height profiles match up with the ionosonde data. The analysis overestimated the amplitude of the height change. Possible causes include frequency uncertainty in the receiver (no GPSDO was available), oversimplifications in the geometric model, and neglecting frequency dependencies in the ionosphere.



The Rapid Change in Solar Radiation Caused by an Eclipse Provides a Convenient Test Bed to Compare Height Change Calculated from Observed Doppler Shift and Actual Ionosonde Data

Maps from WA9VNJ and WA5FRF Presentations

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

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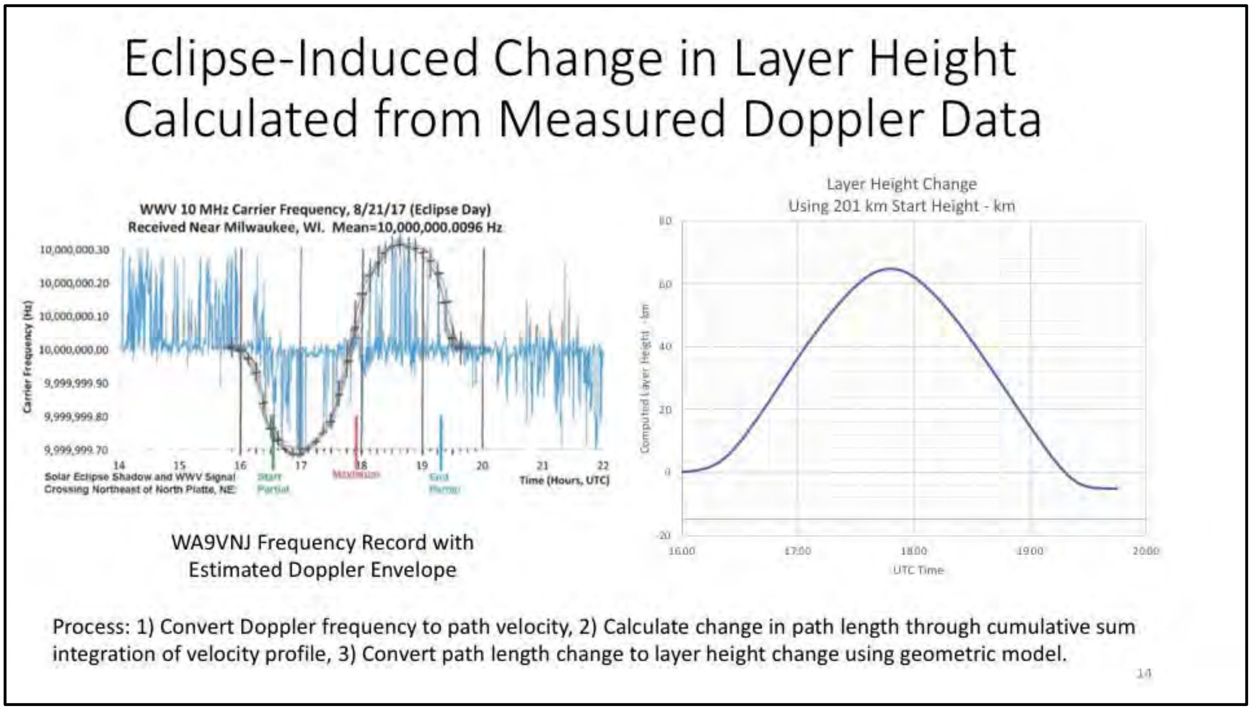
An eclipse produces a rapid change in solar radiation that produces Doppler shifts and momentarily modifies layer height. It provides a good platform to compare height change calculated from observed Doppler shift and actual ionosonde data. These maps show the relative locations of the eclipse path of totality, the WWV 10 MHz transmitter, the receiver at WA9VNJ, and the Boulder ionosonde.



Eclipse-Induced Change in Layer Height Calculated from Measured Doppler Data

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.

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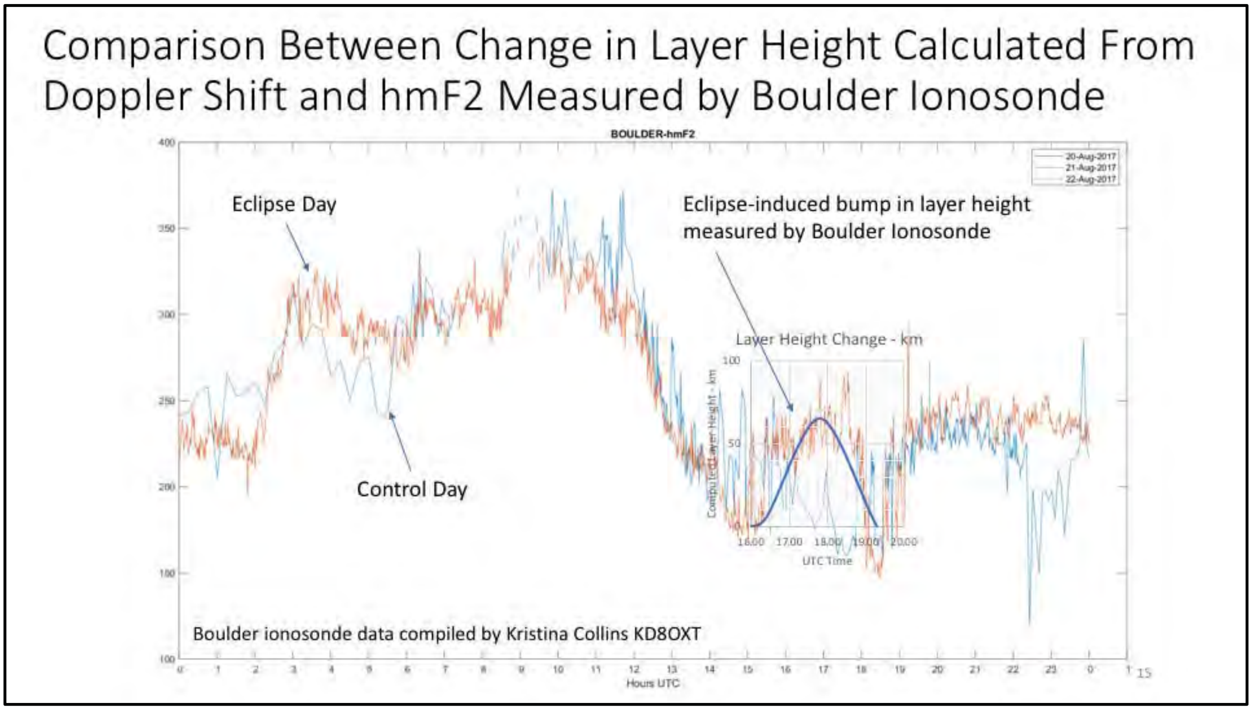
The passage of an eclipse shadow produces a dimming in sunlight followed by return to full brightness. This results in a bell-shaped rise in the layer height profile. Doppler shift scales with path velocity which is the time rate of change, or derivative of path length (dP/dt). The resulting Doppler track is an S-shaped curve which swings negative first in response to the rate of height increase, a zero crossing as height quits ascending and starts descending, followed by a positive swing as the layer comes back down. In essence, the Doppler track follows the speed of path length change caused by the change in layer height. The layer height profile can be deduced by performing an inverse cumulative sum integration procedure on path velocity, computed from measured Doppler data. Here, the S-shaped Doppler curve on the left was converted to path velocity at 10 MHz, which in-turn was integrated to produce the bell-shaped height profile on the right.



Comparison Between Change in Layer Height Calculated From Doppler Shift and hmF2 Measured by Boulder Ionosonde

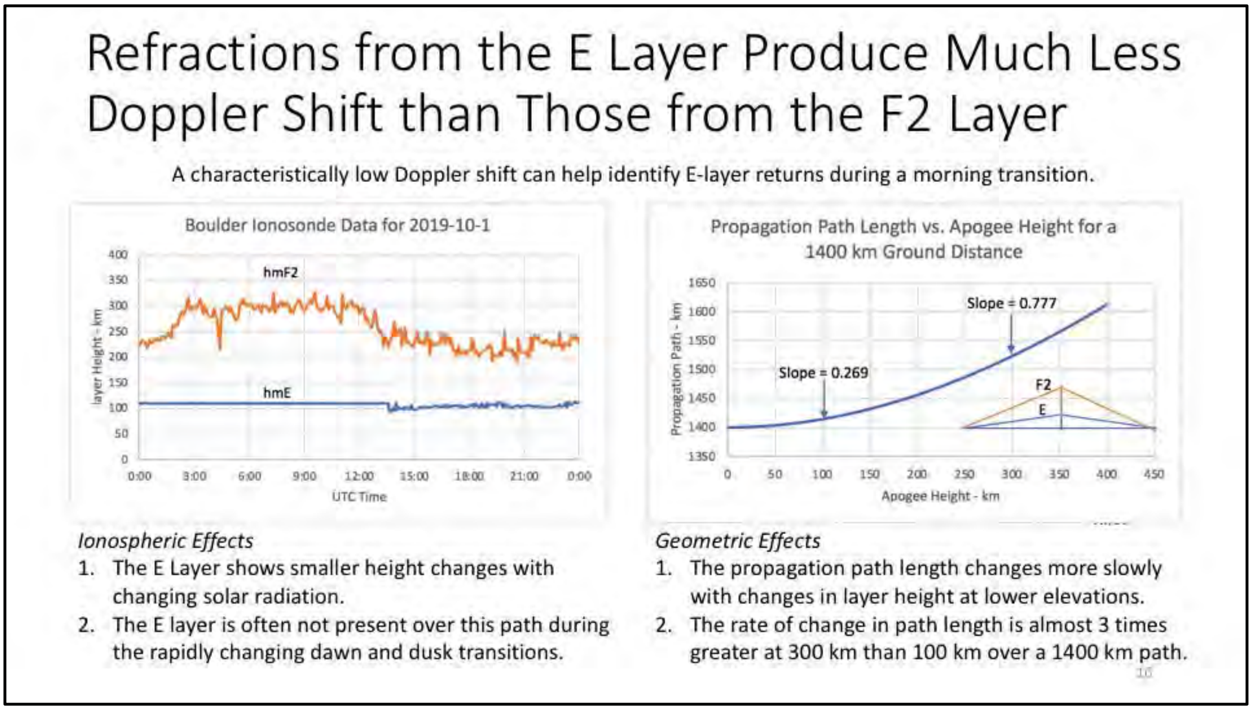
Eclipse Day

Control Day

Eclipse-induced bump in layer height measured by Boulder Ionosonde

Boulder ionosonde data compiled by Kristina Collins KD8OXT

The computed layer height profile overlaid on Boulder ionosonde data. The height and time scale factors are set the same for both graphs but time offset is adjusted for best fit. Profile amplitude and duration show good correlation. Correlation of timing is complicated by the large east-west distance offset between path apogee and the Boulder ionosonde (they are in different time zones).



Refractions from the E Layer Produce Much Less Doppler Shift than Those from the F2 Layer

A characteristically low Doppler shift can help identify E-layer returns during a morning transition.

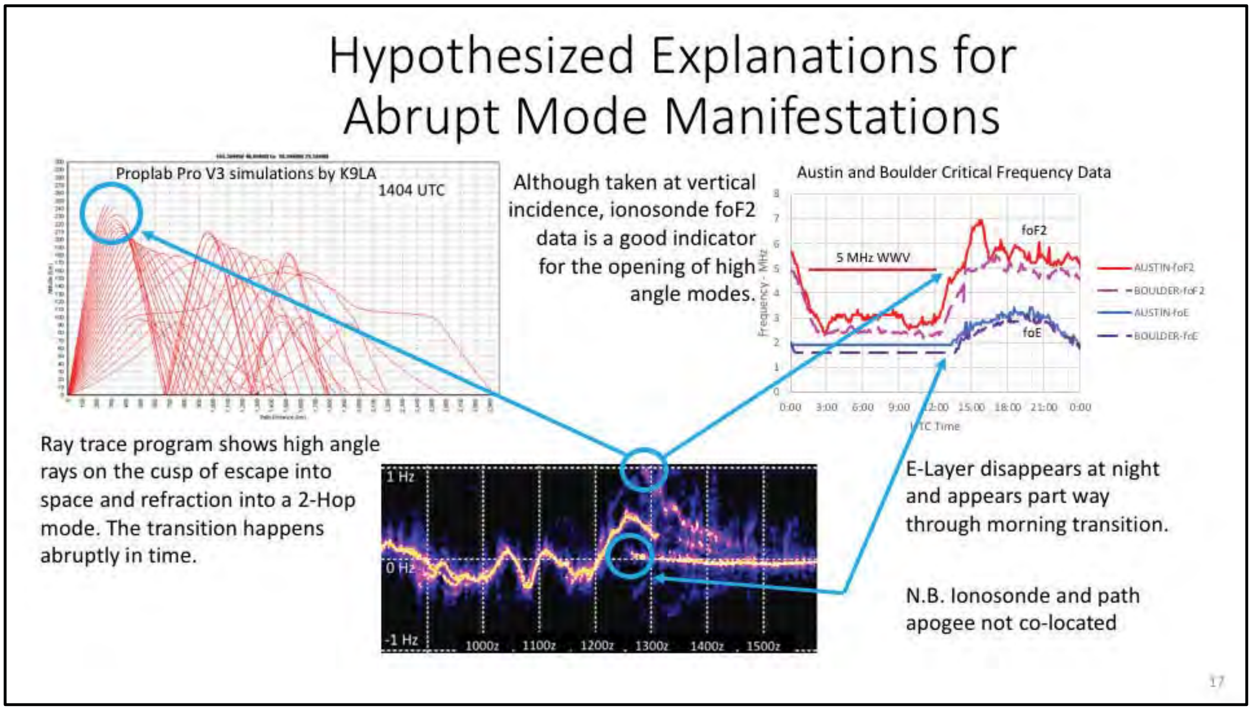
Ionospheric Effects

1. The E Layer shows smaller height changes with changing solar radiation.
2. The E layer is often not present over this path during the rapidly changing dawn and dusk transitions.

Geometric Effects

1. The propagation path length changes more slowly with changes in layer height at lower elevations.
2. The rate of change in path length is almost 3 times greater at 300 km than 100 km over a 1400 km path.

One way to identify returns from the E layer is by their characteristically low Doppler shift. Another is by correlating their abrupt manifestation in a spectrogram with the presence of the E layer in ionosonde data.



Hypothesized Explanations for Abrupt Mode Manifestations

Although taken at vertical incidence, ionosonde foF2 data is a good indicator for the opening of high angle modes.

Ray trace program shows high angle rays on the cusp of escape into space and refraction into a 2-Hop mode. The transition happens abruptly in time.

E-Layer disappears at night and appears part way through morning transition.

N.B. Ionosonde and path apogee not co-located

Two abrupt mode manifestations are shown here. The sudden appearance of the 2-hop mode from the F layer happens because the mode must wait for sufficient ionization to support the required high angle of radiation. Prior to this time high angle rays simply escape into space, as shown in the ray trace data. foF2 ionosonde data (critical frequency for near vertical incidence propagation) can be used as an indicator of conditions favorable for high angle propagation. The sudden appearance of the 1-hop E layer mode can be correlated with appearance of the E layer in hmE and foE ionosonde data.

Summary of Supporting Evidence for Theorized Doppler Track Mode Splitting

E-layer

1. Ionosonde data shows the E-layer undergoes little height change with changing solar radiation. Additionally, because of the lower altitude, height changes in the E-layer result in only ~1/3 the path length change as an equivalent change in the F-layer. Therefore E-layer returns are characterized by small Doppler shifts.
2. Ionosonde data shows the E-layer disappeared at night and reappeared at dawn, consistent with the abrupt manifestation of the mode part way through the dawn transition from night to day.

1- and 2-Hop F2

1. Time of Flight experiments confirmed simultaneous reception of multiple modes that showed Times-of-Flight consistent with a geometric model and ray trace predictions.
2. Calculation of morning Doppler shifts for 1- and 2-hop modes from Boulder hmF2 Ionosonde data predicted mode splitting similar to measured data.
3. Calculation of layer height profile from morning Doppler data gave results generally consistent with Boulder hmF2 data. The different formulas for 1- and 2-hop modes gave nearly the same layer height profile when used with the corresponding Doppler tracks.
4. Calculation of the F2 layer height disturbance during the 2017 eclipse from the 10 MHz bipolar Doppler swings was consistent with Boulder ionosonde hmF2 data.
5. The abrupt manifestation of the 2-Hop F2 mode part way through the morning transition is consistent with delayed opening of the required high angle mode as predicted by foF2 ionosonde data and ray trace programs.

Conclusions and Recommendations

- Doppler shifts over a given propagation path have been shown to follow to the time derivative of changes in path length, in turn a function of ionization layer height. The relationship between single and multiple hop path lengths and apogee height can be approximated from a geometric virtual height model.
- Time of Flight measurements gave results consistent with geometric model and ray trace simulation predictions.
- Doppler shifts showing mode splitting can be predicted by differentiating a smoothed version of ionosonde hmF2 data after converting layer height to path length for the different modes.
- Effective layer height change can be deduced by the inverse integration process on measured Doppler data and reconciliation with path length through use of a geometric model.
- The ionosonde layer-height-to-Doppler calculation correctly predicted mode splitting but under-reported amplitude. Similarly, the measured Doppler-to-layer height calculations correctly mapped 1 and 2 hop modes to the same height profile but over-reported amplitude. However, frequency dependencies in the ionosphere such as treated by Appleton-Hartree were not taken into account in this study. Other sources of error include oversimplifications in the model and geolocation differences. The Boulder ionosonde was not co-located with path apogee but was ~750 km away. Understanding the sources of error through careful experiments with a more refined geometric model could help understanding the physics of ionospheric propagation.
- Several experiments suggest the height changes responsible for Doppler shifts 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.
- A specific experiment to better correlate Doppler-inferred height change with ionosonde measurements is recommended. 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.