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

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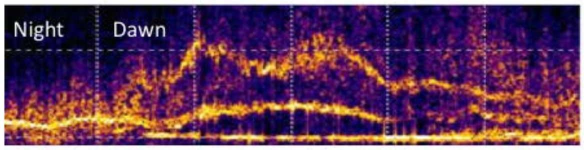
Synopsis

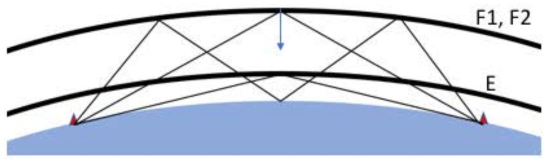


2.5 MHz WWV Morning Spectrogram CO – TX path

- Complex and varied Doppler records have been observed on HF 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 and which can suddenly manifest and disappear in response to varying solar radiation.
- This paper presents data from experiments and analytical techniques designed to understand these effects. The data supports the premise that some of the observed mode splitting can come from different path length velocities associated with single and multiple hop modes as a consequence of changing ionization layer height.
- Supporting data sets include:
  - Comparison of Time-of-Flight (TOF) measurements to ray trace simulations and data predicted by a geometric model for single and multiple hop modes.
  - Comparison of Doppler shifts calculated from ionosonde data to measured Doppler shifts.
  - Comparison of layer height changes calculated from measured Doppler shifts to ionosonde data.
  - Correlation of abruptly manifesting modes 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 Different Path Velocities Between Modes with Different Number of Hops During Times of Changing Layer Height

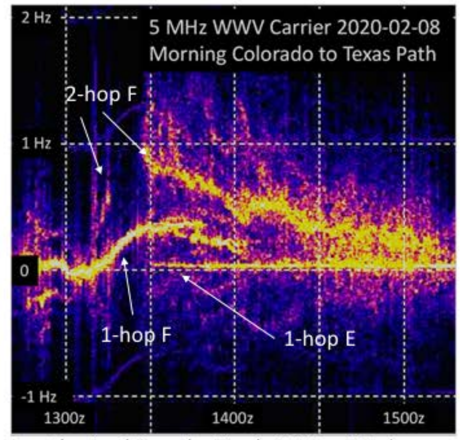
Path Length Increases with Number of Hops. A Descending Layer Height in the Morning Causes the Longer Modes to Shorten Faster, Imparting More Doppler Shift and Giving Rise to Mode Splitting.



This discussion will focus on three of the simplest cases:

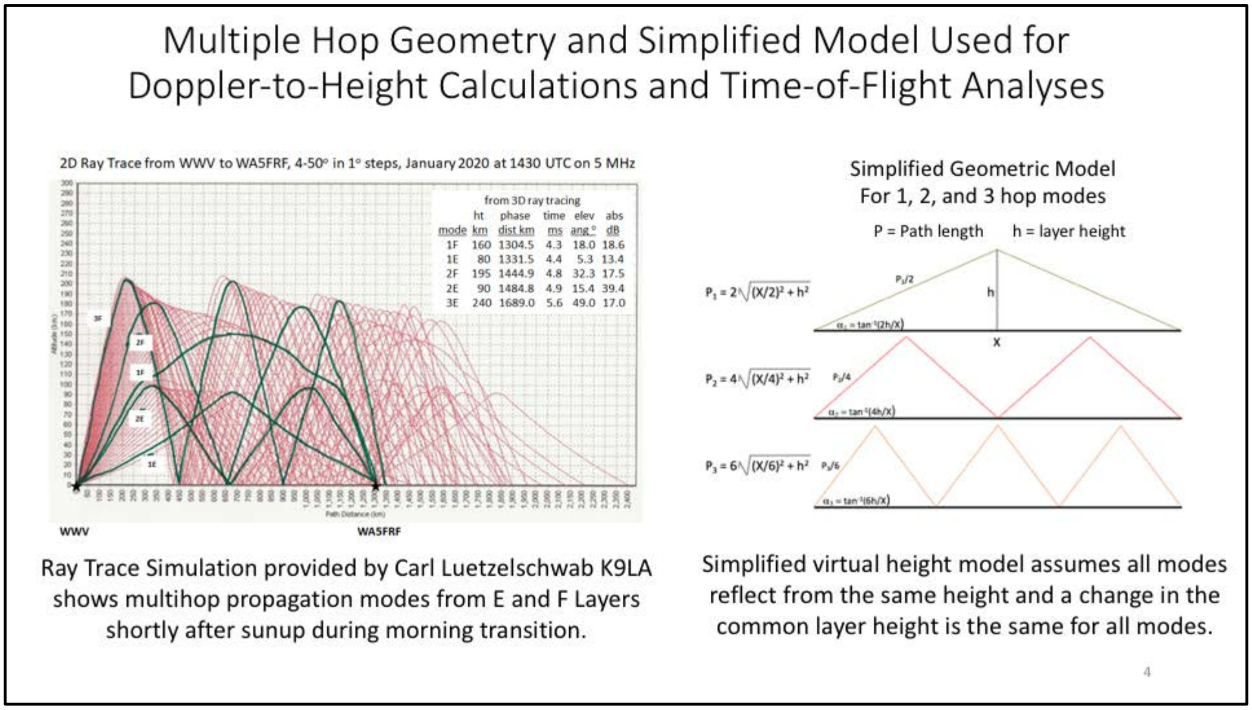
1. 1-hop mode from the F layer
2. 2-hop mode from the F layer
3. 1-hop mode from the E layer

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

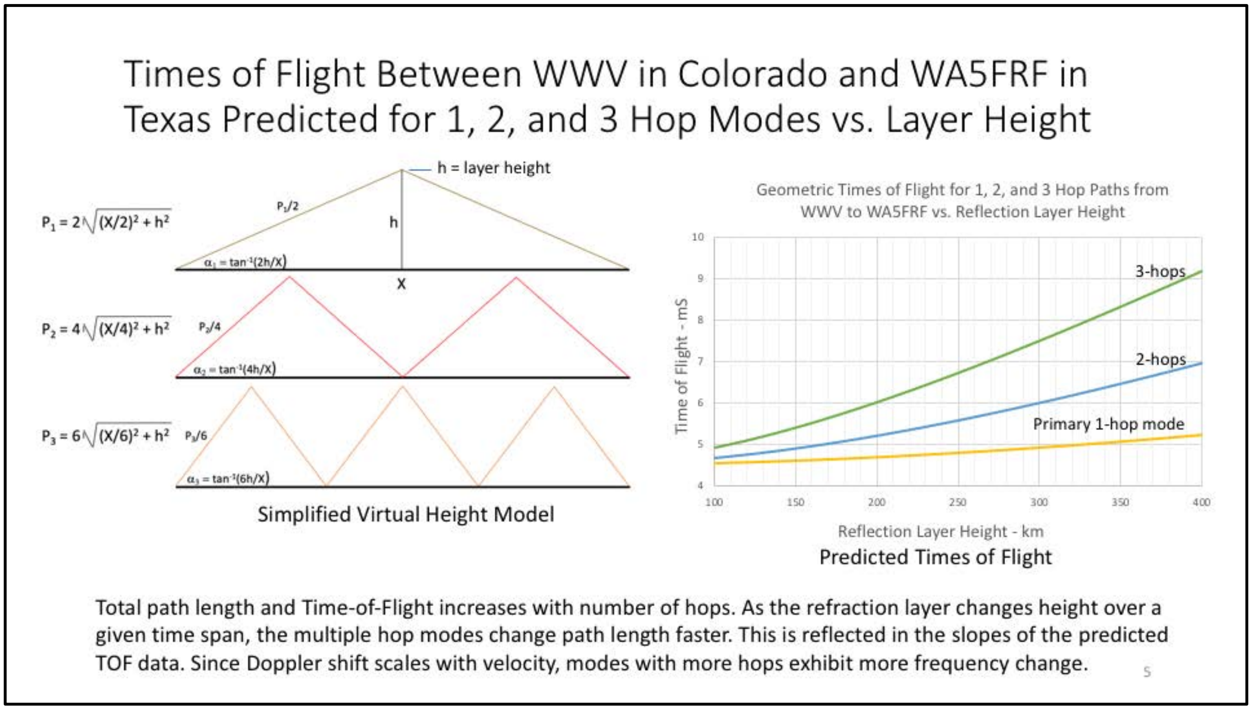


Hypothesized Doppler Track Origins. Mode splitting is the separation of of a single Doppler track into multiple tracks of different frequencies.

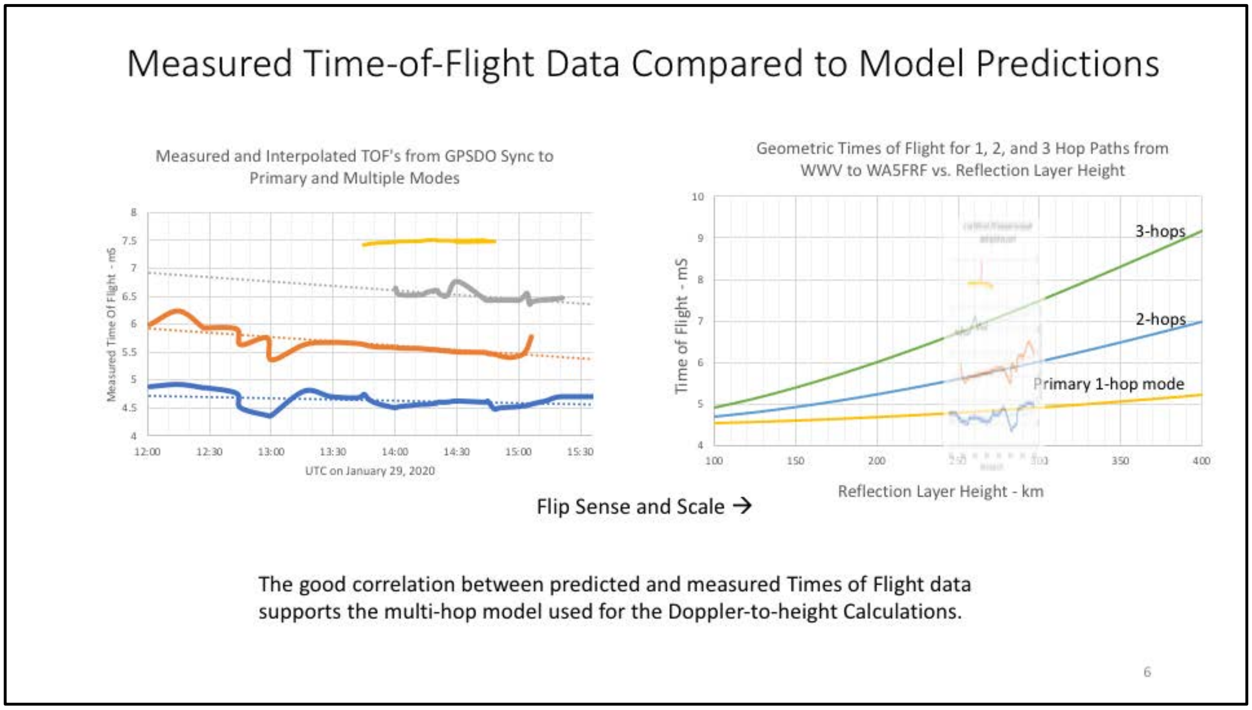
The pictorial on the left depicts 1 and 2 hop modes from the F layer and a 1 hop mode for the E layer. On the right is a spectrogram of Doppler shifts observed during a morning transition showing mode splitting. For a fixed ground distance between TX and RX the propagation path is a function of ionization layer 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 during a morning transition, the multiple hop modes undergo more total change in path length. Since the changes for all modes happen in the same amount of time, the rate of path change, or path velocity increases according to number of hops. Doppler shift scales with path velocity so the Doppler tracks diverge according to velocity to create mode splitting. In the pre-dawn hours before 1300z in this spectrogram, propagation is via a 1-hop mode from a relatively stable F layer. As the sun comes up the F layer starts descending causing a positive Doppler shift. At 1330z sufficient ionization exists to support the higher angle of propagation required for a 2-hop mode, causing it to manifest abruptly with correspondingly more Doppler shift. A single hop mode with little Doppler shift also manifests about this time as the E layer is established. Evidence will be presented that shows why returns from the daytime E layer can exhibit very little Doppler shift. Finally, path velocity slows as layer height settles into daytime heights and the 1 and 2 hop F layer Doppler shifts decay to zero to join the E layer track after approximately 1550z.



The ray trace simulation on the left shows multiple simultaneous propagation modes are possible during a morning transition. The simplified virtual height model on the right focuses only on 1, 2, and 3 hop modes from a common F layer in an attempt to correlate observed Doppler data with the simplest mechanisms. It is changes in path length that drive Doppler, and the model provides a means to relate path length to layer height. Layer height can be independently predicted by ray trace modeling and spot checked by ionosonde data.

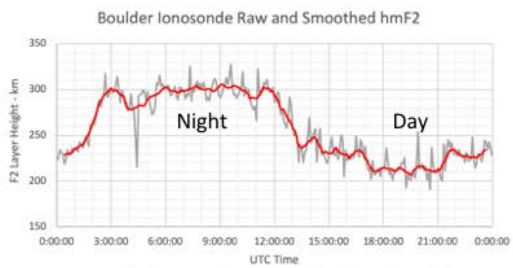


This slide shows the virtual height model with path length formulas on the left. On the right are predicted times of flight for 1, 2, and 3 hop modes from Ft. Collins, CO to near San Antonio, TX. (1350 km ground distance). The total path length and therefore TOF increases with number of hops as a function of layer height. As the common reflection layer changes height over a given time span, the multiple hop modes have more absolute change in path length in the same amount of time and so change path length faster. This is reflected in the slopes of the predicted TOF data.

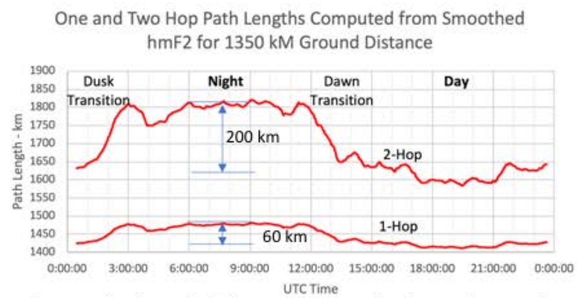


Times of flight from WWV to WA5FRF were measured during a morning transition on January 29, 2020. The measured Time of Flight data is plotted on the left as a function of UTC time. A scatter plot of measured TOF naturally formed in layers according to number of hops as shown on the left. The times of flight decrease with time because ionization lowers during a morning transition. The measured data can be compared to the model predictions on the right 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 when the onset of the morning transition at 1200z was matched up with a layer height near 300 km. Spot checks of individual TOF measurements gave good agreement with PHaRLAP and Prop Lab Pro ray trace predictions for this date.

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



Ionosonde hmF2 data gives the height of the F2 layer versus time over a 24 hour period.



Converting layer height to path length shows the much greater path length change for 2-hop over 1-hop modes.

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 velocity and more Doppler shift.

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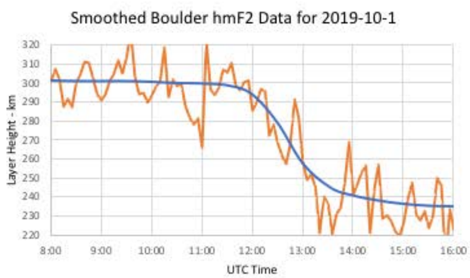
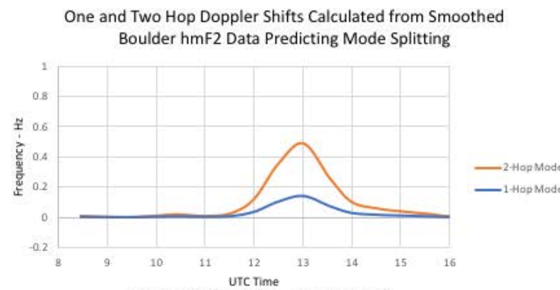
On the left is raw and smoothed hmF2 ionosonde data. Ionosonde hmF2 data plots the height of the F2 layer as a function of time of day. On the right are the path lengths for 1 and 2 hop modes calculated using the relationships developed in the geometric virtual height model. Note the large difference in path lengths and in particular the much larger change in path length over time for the 2-hop compared to the 1-hop mode. 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 has a faster path velocity and incurs more Doppler shift. This is believed to be the root cause of mode splitting.

Doppler Shifts Calculated from Ionosonde Data Using One and Two Hop Formulas Predict Mode Splitting





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.

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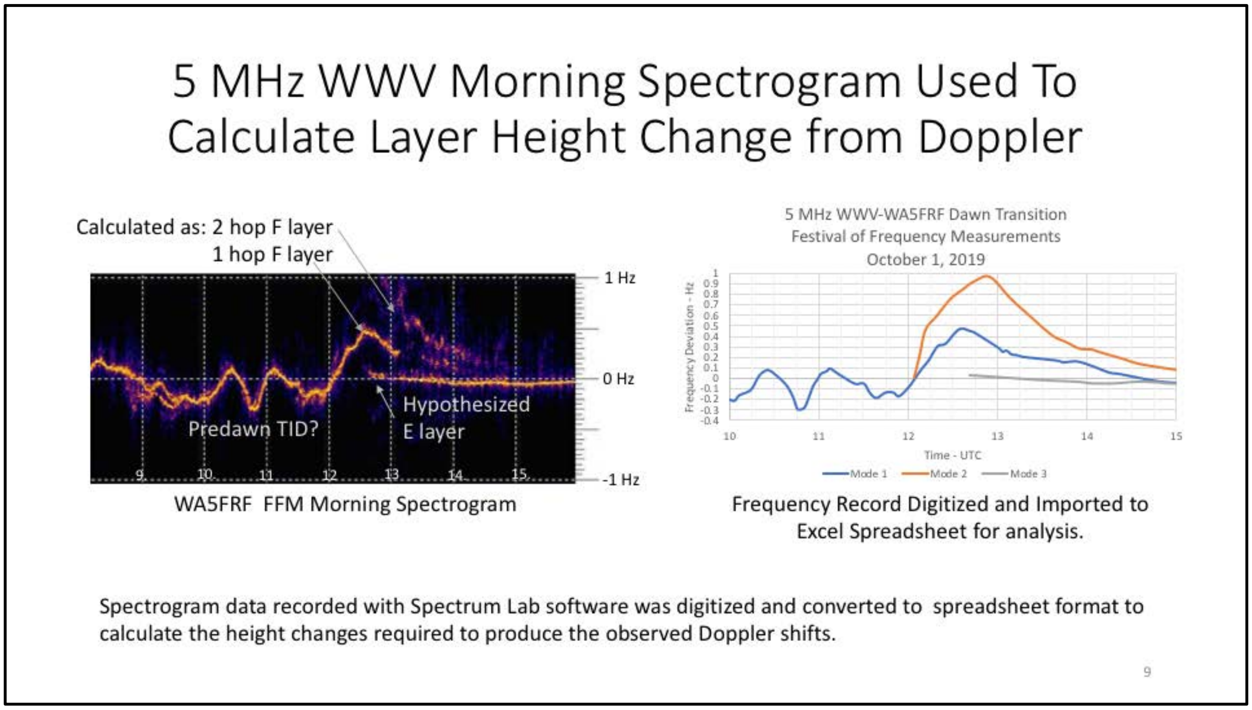
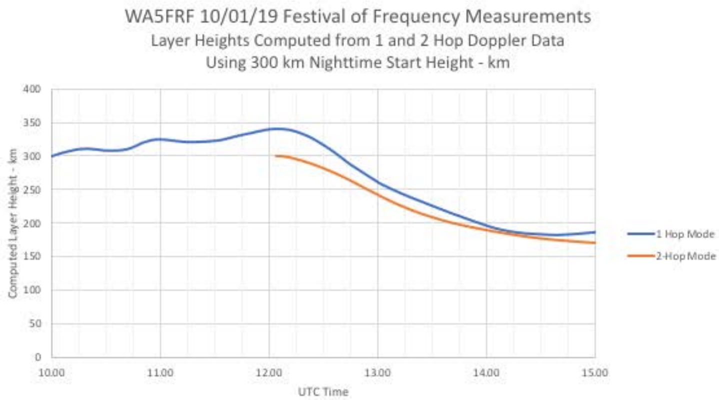
Doppler shift calculations from ionosonde hmF2 data for 1 and 2 hop modes predict mode splitting if you take the different path lengths into account. On the left is raw and interpolated hmF2 data from the Boulder ionosonde. The calculated Doppler tracks showing mode splitting are shown on the right. 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 $\Delta f = -f_0 * v/c$. Frequency dependencies of the index of refraction are not taken into account in this discussion. 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.



Spectrogram data recorded with Spectrum Lab software were digitized and converted to spreadsheet format to calculate the height changes corresponding to the observed Doppler shifts. Raw spectrogram data is on the left and the digitized version used for spreadsheet calculations is on the right. The assumed 1- and 2- hop modes shown in blue and orange are used with their respective path length formulas rearranged to solve for layer height. This data is then compared to hmF2 ionosonde data to test the multiple hop theory.

Layer Height Calculated from Doppler Data Using One and Two Hop Formulas

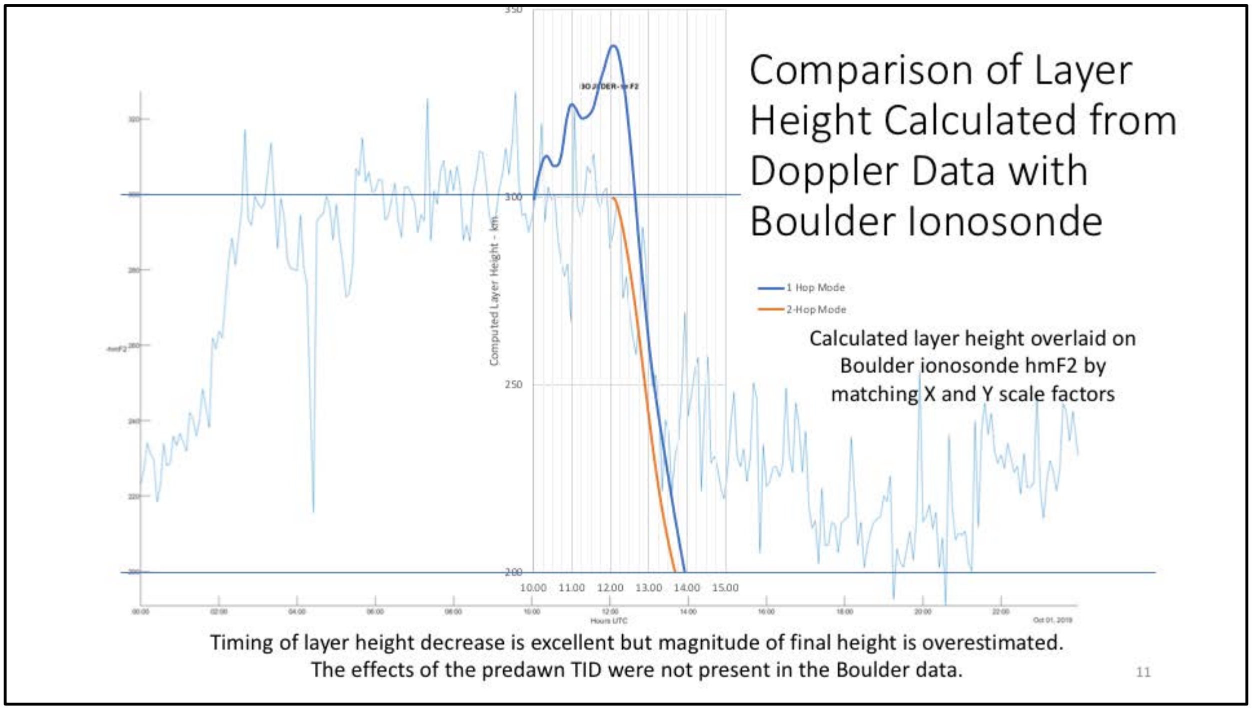


Height profiles were calculated using the 1 and 2 hop relationships from the geometric model and the corresponding Doppler tracks.

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 4) Use a starting height at a given time from ionosonde or ray trace simulation to establish absolute height profile. 10

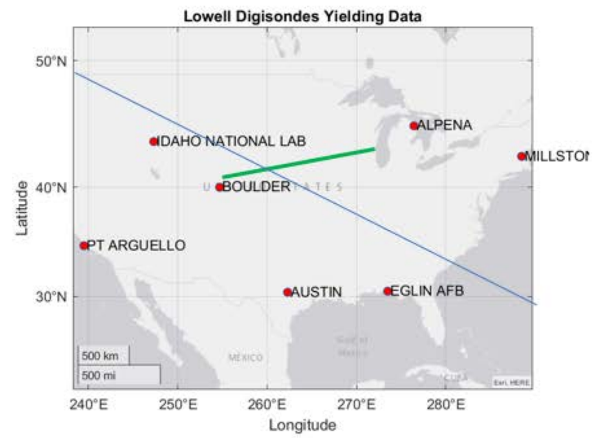
These are the layer height profiles calculated from Doppler data. The profiles were calculated using the 1 and 2 hop relationships between path length and layer height with the corresponding measured Doppler tracks. Of significance is that the separate layer height calculations for the very disparate 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.



This is Boulder hmF2 data for the day the Doppler data was acquired. The height profile plots calculated from observed Doppler were scaled in time and amplitude to match those in the ionosonde plot for direct overlay overlay comparison. (*) Both the 1 and 2 hop derived layer height profiles match up with the ionosonde data very well with time but only approximately in amplitude. This data can therefore be considered qualitative in that the analysis overestimated the amplitude of the height change. Possible causes include frequency uncertainty in the receiver (no GPS Disciplined Oscillator was available), oversimplifications in the geometric model, and neglecting frequency dependencies in the ionosphere. The effects of a predawn Traveling Ionospheric Disturbance are evident in the Doppler-derived data but not in the ionosonde data. Another possible factor is the very different geographic locations between Boulder and the apogee of the propagation path.

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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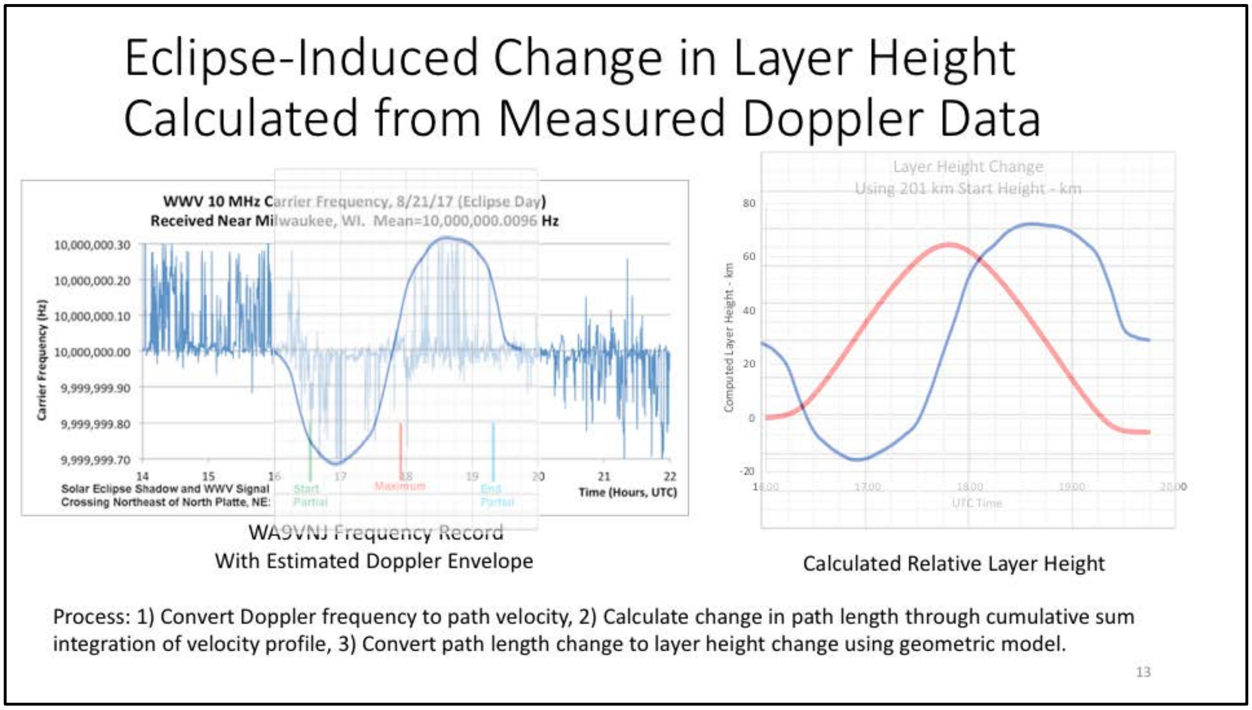
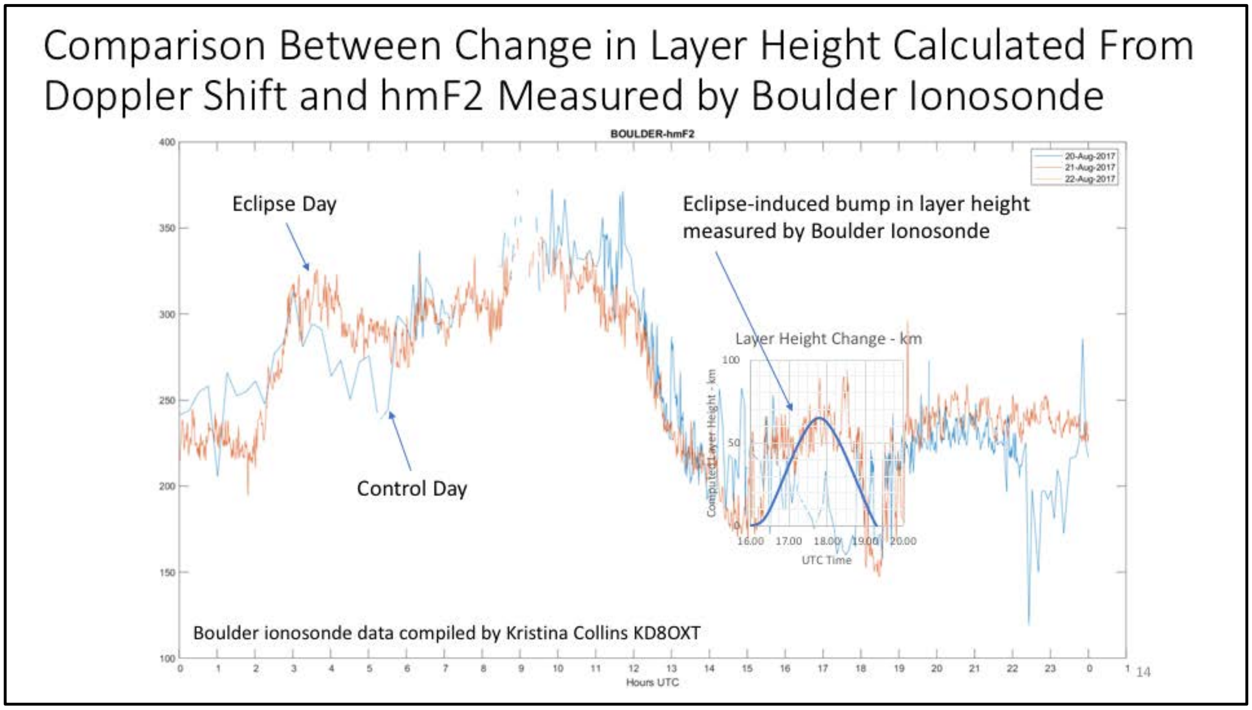
An eclipse produces a rapid change in solar radiation that momentarily modifies layer height which in turn produces Doppler shifts. It provides a change in illumination similar to night and day except for the compressed time and distance scales. This provides a good platform to compare height change 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 in Milwaukee, and the Boulder ionosonde.



The effects of the 2017 eclipse were used to deduce the associated layer height changes for comparison to ionosonde data. On the left is raw data provided by Steve Reyer WA9VNJ. The first step in the analysis was to estimate the actual Doppler shift envelope from this sparsely populated data set.(*) Relative height change then was calculated through this 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 the geometric model. This produced the Gaussian-shaped bell curve on the right (*).

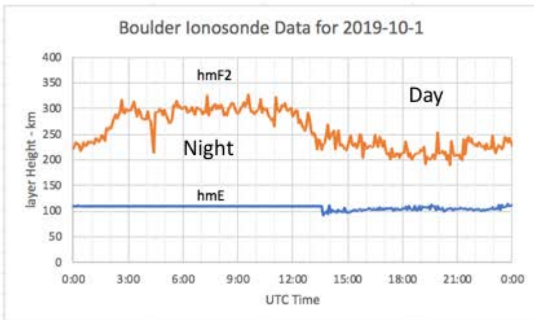
The passage of an eclipse shadow produces a dimming in sunlight followed by return to full brightness. This results in the bell-shaped trajectory in the ionization height profile. Doppler shift scales with path velocity which is the time rate of change, or derivative of path length (dP/dt). The resulting 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.

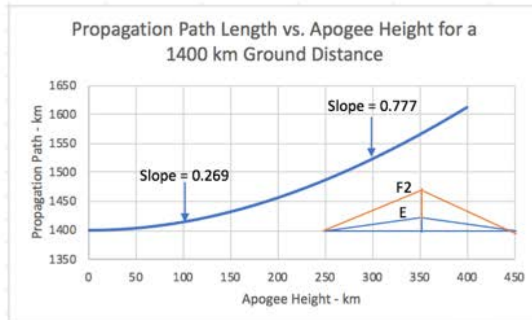


Shown are Boulder ionosonde hmF2 records for a control day (blue trace) and the day of the eclipse (brown trace). Note the momentary rise in layer height near 1700z present on the eclipse day but not on the control day. This is the effect of the eclipse. The layer height profile calculated from Doppler was scaled to match the ionosonde plot in both axes for direct overlay (*). The height and time scale factors are set the same for both graphs but absolute time of day had to be offset for best fit to account for the time difference between the Boulder ionosonde and the path apogee. Boulder is approximately 725 km west of apogee, or almost a full time zone. The layer height profile calculated from Doppler showed good correlation with ionosonde data in both amplitude and duration.

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

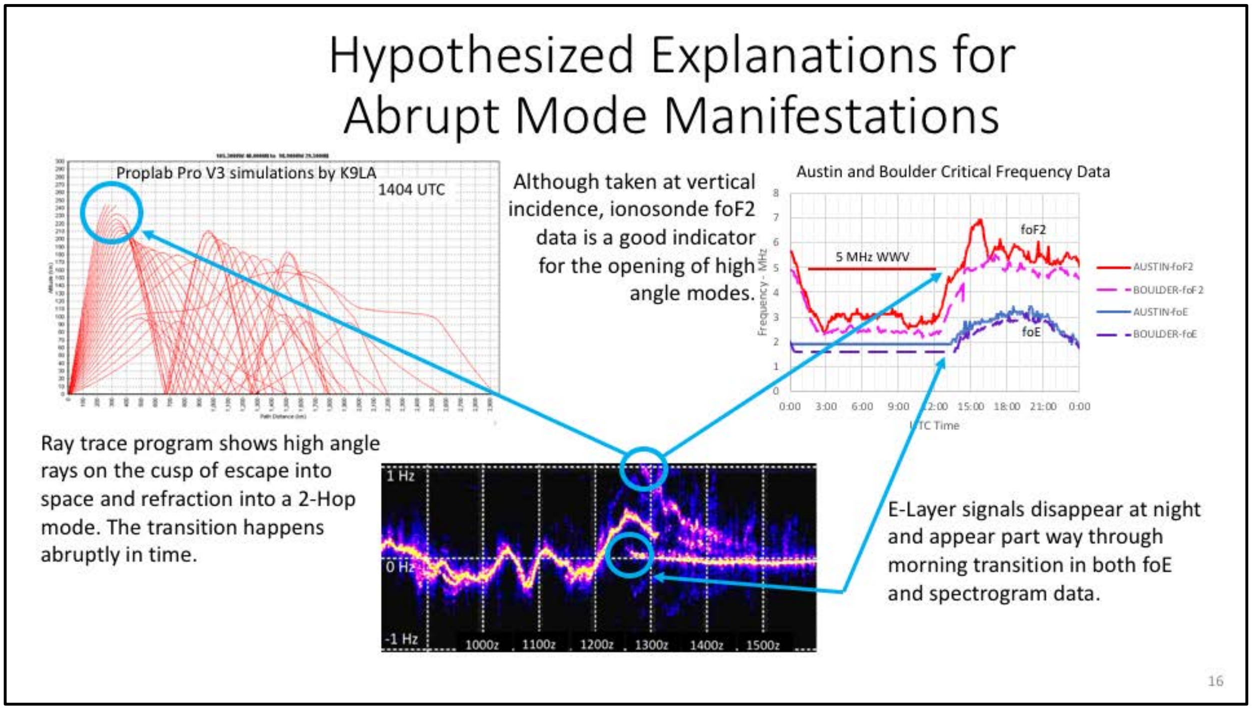
1. The E Layer shows smaller height changes with changing solar radiation.
2. The E layer is often not present over this path during the rapidly changing dawn and dusk transitions.

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.

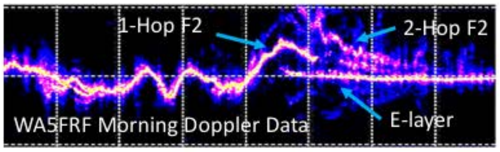
One way to identify returns from the E layer in this data set is by their characteristically low Doppler shift. Two reasons for low Doppler shift from the E Layer are shown. On the left are hmF2 and hmE ionosonde data plotted on the same graph. The E layer shows smaller height changes compared to the F layer. Whereas the F2 layer wanders over a height range of about 50 km from about 1330z to the end of the UTC day the E layer changes are only about 10 km. Besides the comparatively stable height profile compared to the F layer, geometric effects shown on the right further reduce the path length changes from the already small height variations. Changes in path length start out small for low layer heights and progressively increase as height increases. The curve on the right plots the propagation path length versus apogee height. The slope of this curve gives the rate of change in path length with layer height. Note that slope at an E layer height of about 100 km is only about 1/3 of that at an F layer height of 300 km. Both effects combine to yield comparatively small Doppler shifts for returns from the E layer.

Another identifier for E layer returns can be obtained by correlating the abrupt manifestation of a low Doppler shift mode in a spectrogram with the appearance of the E layer in ionosonde data. Note the E layer is not present during the evening and morning transitions. The appearance of the E layer in ionosonde data can be correlated with sudden manifestation of low-Doppler shift data in spectrograms to identify an E layer mode.



Shown here are correlations between a ray trace program in the upper left, a morning spectrogram in the lower center and ionosonde data showing foF2 and foE data in the upper right. Two abrupt mode manifestations are highlighted. The sudden appearance of the 2-hop mode from the F layer is theorized to happen because the mode must wait for the increase in ionization occurring during a morning transition to reach a level sufficient 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. The foF2 ionosonde data can be used as an indicator of when conditions favorable for high angle propagation are likely to occur. Ionosonde foF2 and foE data give the highest frequency at which a ray at vertical incidence will be returned to earth. The sudden appearance of the 1-hop E layer mode in the spectrogram can be correlated with the similarly abrupt appearance of the E layer in the hmE and foE ionosonde data. The times do not match up exactly. A possible reason is the difference in signal amplitudes between from the different propagation modes. The angle of propagation is vertical for the ionosonde but is at grazing incidence for the low angle skywave path creating the spectrogram data. As ionization increases through the morning transition the low angle mode comes in before the vertical ionosonde mode.

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 hop modes that showed Times-of-Flight consistent with a geometric virtual height model and with ray trace predictions.

2. Calculating 1- and 2-hop morning Doppler from hmF2 Ionosonde data predicted mode splitting similar to measured data.

3. Calculating layer height profile from measured Doppler data gave results generally consistent with hmF2 ionosonde data. The different formulas for 1- and 2-hop modes gave nearly the same layer height profile when used with the corresponding Doppler track data.

4. Calculation of the F2 layer height disturbance from measured Doppler shifts during the 2017 eclipse gave results consistent with 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.

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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.