Time Difference of Arrival Analysis for Layer Height Estimation

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1. Introduction

A HamSCI science objective for the 2023 and 2024 eclipses is to use amateur radio stations to measure how HF radio propagation changes with eclipse passage. Two parameters of interest are the change in effective F2 ionization layer height caused by the momentary blockage of solar radiation and the symmetry in recovery as solar radiation returns. Two methods developed by HamSCI volunteers using transmissions from standard time and frequency station WWV were Time of Flight (TOF) measurements facilitated by the WWV per-second timing ticks[1] and mathematical analyses of Doppler shifts observed on the carrier frequency[2]. These measurements profiled the height change in the F2 layer every morning and evening in response to waxing and waning sunlight and similar effects that occur during an eclipse[3]. The experiments depended on the ultra-high timing and frequency precision unique to WWV. But the HamSCI objective for the 2023-2024 eclipses is to use data obtained from ordinary amateur radio stations. While well-equipped amateur radio stations with skilled operators could indeed perform these measurements, to do so would require precision absolute time and frequency references for both the transmitting and receiving stations. Modern GPS Disciplined Oscillators (GPSDO) can provide the required reference signals but they are expensive, not in widespread use, and can be used with only a few high-end amateur radios. An additional complication for calibrated TOF measurements is correcting for the relatively long time delays through the DSP transmit and receive audio processors used in modern radios. An additional issue with Doppler measurements is the relatively long transmission time needed to acquire the data. What is needed is an alternate measurement technique that is simple, fast, and usable with common amateur radios.

2. Time Difference of Arrival Analysis for Layer Height Estimation

Over propagation paths that support transmission of multiple hops, very short pulses and an audio chirp are waveforms that are both simple to generate and simple to analyze for measuring the Time Difference of Arrival (TDOA) between multipath modes. For this application it is the 1- and 2- hop modes from the F2 layer that are of interest because F2 layer height is most sensitive to sunlight variations, simultaneous propagation of both modes frequently occurs on frequencies below 10 MHz, and TDOA information can be used to infer layer height. The TDOA approach eliminates the need for the absolute time reference that would otherwise be required for a direct Time of Flight (TOF) measurement and requires no special characterization of time delays through the radios. The audio waveforms can be fed to the microphone input and recovered from the speaker output of amateur radio equipment using a .wav program on a computer. Extracting the TDOA measurement from the received waveform can be accomplished by direct measurement using the calibrated time base in the .wav handling program.

For a given TX-RX path, the arrival times for multiple hops from a common ionization layer are geometrically bound by ground distance, layer height, and hop geometry. Because the 2-hop mode is longer than the 1-hop mode it arrives at the receiver at a later time. Figure 1a illustrates this relationship in a generalized sketch of ionospheric refraction from the F2 layer. Figure 1b shows the virtual height model that simplifies the refraction geometry with a point reflection from an equivalent height using a constant wave speed c. Simple formulas can be derived from the virtual height model that facilitate calculation of path lengths and times of flight from ground distance and layer height. Figure 1c shows results of path length and time of flight calculations for a ground distance of 1350 km as a function of layer height. As suggested by the two examples in Figure 1c, a 1 hop – 2 hop TDOA measurement can be used to infer effective layer height without the need for an absolute TOF measurement. For a 1350 km ground distance the 1 hop – 2 hop TDOA is 0.67 ms for a 225 km layer height and 1.10 ms at 300 km. Because the measurement can be accomplished quickly with common amateur radios and .wav file software it is well suited to the HamSCI objective of tracking how effective layer height changes with time over specific paths during passage of the eclipse.

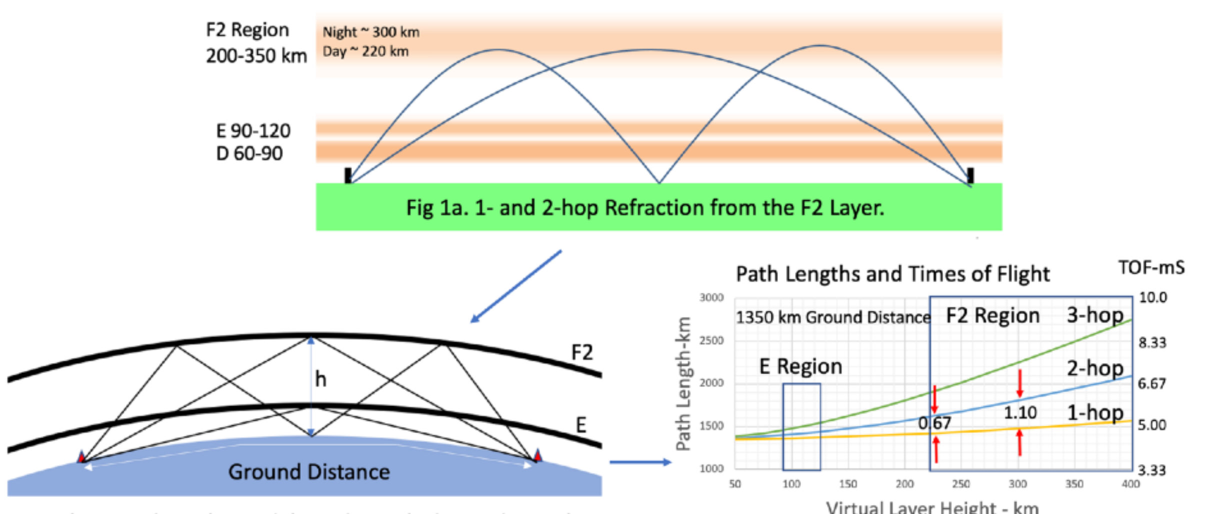

Fig 1b. Virtual Height model Used to Calculate Relationship between Virtual Height h and Path Length.
Time of Flight = Path Length / c

Fig 1c. TDOA Example: At 1350 km ground distance the Time Difference of Arrival between 1 and 2 hop modes is 0.67 ms at 225 km layer height and 1.10 ms at 300 km.

Figure 1 Formulas Derived from a Virtual Height Model of Multipath Ionospheric Propagation Used to Approximate Layer Height from 1-hop/2-hop Time Difference of Arrival (TDOA)

3. Audio Waveforms for Time Difference of Arrival Measurements

The dominant modulation format for voice amateur radio communications is Single Sideband (SSB) with a smaller following devoted to legacy Amplitude Modulation (AM). Both of these modes conveniently can be used to transmit audio waveforms suitable for TDOA measurements. Three suitable waveforms include 1) a very short audio pulse, 2) an audio chirp, and 3) an analog pseudorandom code sequence. Of these, the first two are most the attractive to amateur radio operations because they are easy to generate and can be decoded directly from a .wav file without special software. A constraint on TDOA resolution is the audio bandwidth available in amateur communications transceivers which is usually 3 kHz or less.

In March of 2021 Phil Erikson from Haystack Observatory and Steve Cerwin from HamSCI presented a summary paper to the National Institute of Standards and Technology (NIST)[4] regarding the science experiments using Standard Time and Frequency Station WWV mentioned in the Introduction. Subsequently NIST requested recommendations on audio waveforms they could add to WWV and WWVH transmissions that would enhance their utility for performing ionospheric science experiments. Members of the HamSCI community, Case western Reserve University, and the author created a .wav file that contained audio waveforms intended to characterize WWV's legacy tube-type transmitters and to test the viability of transmitted AM audio waveforms to perform atmospheric physics experiments. These waveforms were centered at 2.5 kHz with 5 kHz of bandwidth to match the audio characteristics of their existing transmitters. WWV began transmitting the waveforms every hour at 8 minutes past the hour for WWV and 48 minutes past the hour for WWVH. Analysis of data[5] sent by WWV at 5 MHz and received by the author in South Texas showed both the short pulses and fast chirp waveforms were indeed useful for measuring the TDOA between the 1 and 2 hop modes. As of this writing, the waveforms are still being transmitted at 8 and 48 minutes past the hour on all WWV/WWVH frequencies.

The TDOA measurement using the short pulses is performed simply by measuring the time difference between the two received pulses directly using the calibrated time scale on the .wav file. A TDOA measurement using a linear audio frequency chirp can also be accomplished by a visual analysis on the .wav file. The simultaneous presence of a chirp waveform with a delayed copy of itself produces a beat note at a frequency that is equal to the product of the sweep rate and the time delay. The beat note visibly manifests itself as amplitude scalloping on the composite chirp envelope which is similar in appearance to an amplitude modulated carrier. Figure 2 illustrates an example. Figure 2a shows a stereo .wav file containing two chirps of Sweep Rate SR = 100 Hz/ms displaced in time by 1 ms and in amplitude by 3 dB to simulate 1

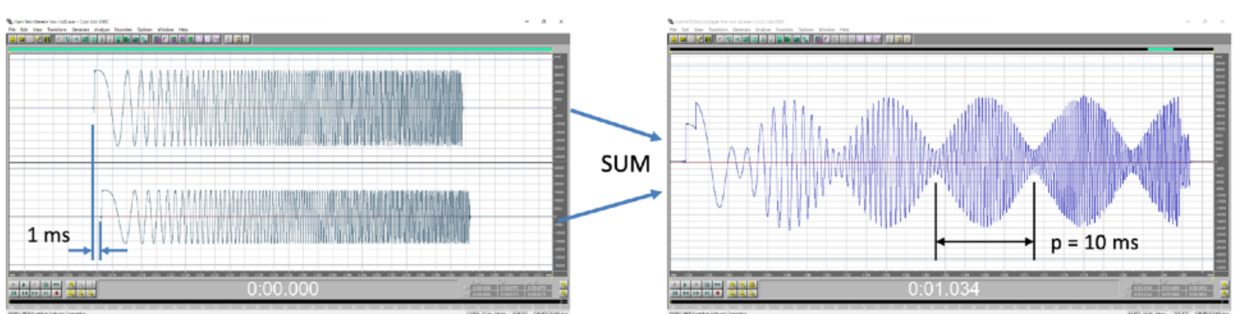

Fig 2a. Two 100 Hz/ms Chirps with 1 ms Time Delay. Delayed Chirp is 3 dB lower in Amplitude.

Fig 2b. Summation produces a Waveform with a Beat Note of Period p = 10 ms.

Summation of a linear chirp with a delayed copy of itself produces a difference frequency at Δf = Sweep Rate * Δt. Beat pattern has a period $p = 1/\Delta f$. The Time Difference of Arrival (TDOA) can be calculated by:

$$\text{TDOA} = 1/(p*\text{Sweep Rate})$$

Example: two 100 Hz/ms chirps 1ms apart produce a difference frequency of 100Hz, which has a period of 10 ms.

$$\text{TDOA} = 1/(10\text{ ms} * 100\text{ Hz/ms}) = 1\text{ s}/1000 = 1\text{ ms}$$

and 2 hop signals. Figure 2b shows an electronic summation exhibiting the 100 Hz beat note. Period p is measured between adjacent nulls and TDOA is calculated from 1/(p*SR).

4. On-Air Field Validation

A field validation of short pulse and chirp TDOA measurements were conducted between amateur radio stations WA5FRF and N5DUP in Texas. Figure 3 gives a map showing the 317 km propagation path and orientation with respect to the Austin ionosonde used for ground truth. Test frequencies of 3.780 MHz and 5.3175 MHz were chosen to maximize probability of simultaneous 1 and 2 hop modes.

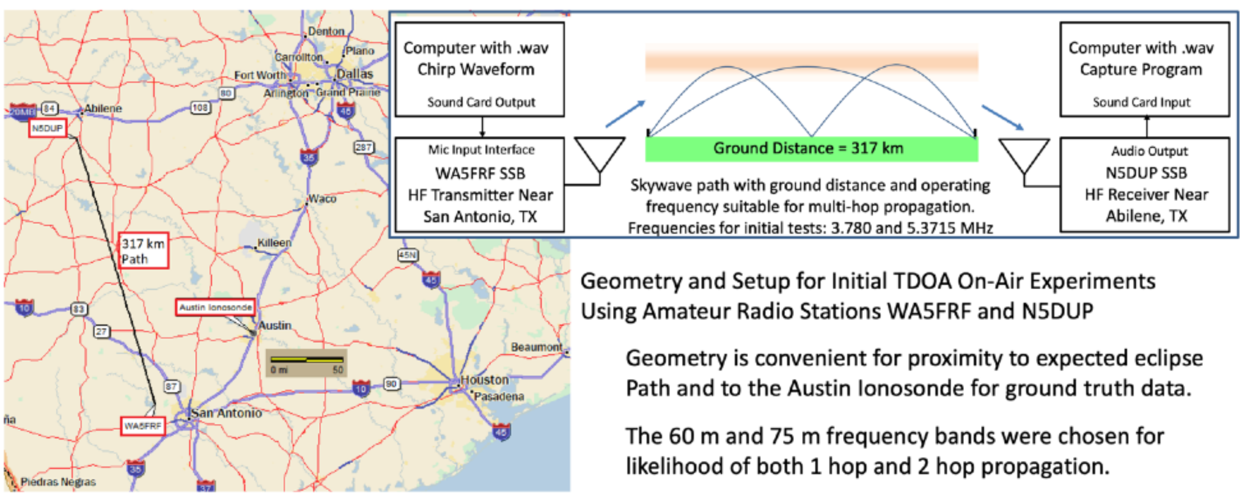

Figure 3 Setup for On-Air TDOA Measurements between Amateur Radio Stations WA5FRF and N5DUP.

A test waveform based on results of the WWV experiments was devised for the tests. The waveform consisted of the following elements:

1. 5 Repetitions: 1-cycle pulse centered at 1.5 kHz.
2. 5 Repetitions: 100 Hz/ms chirp. 0-5 kHz in 50 ms
3. 5 Repetitions: 50 Hz/ms chirp. 0-5 kHz in 100 ms
4. 5 Repetitions: 25 Hz/ms chirp. 0-5 kHz in 200 ms
5. 5 Repetitions: 10 Hz/ms chirp. 0-5 kHz in 500 ms
6. 5 Repetitions of concatenated up-down chirps at 100 Hz/ms

All repetitions of the first 5 waveforms were analyzed for both tests. Examples of the received data, the analytical process, and results are summarized in Figure 4.

Figure 4a shows examples of the received short pulse and chirp waveforms. Both indicate a TDOA of 1.6 ms. The family of curves shown in Figure 4b were calculated from a spreadsheet developed from the virtual height model shown in Figure 1b to convert TDOA to layer height for

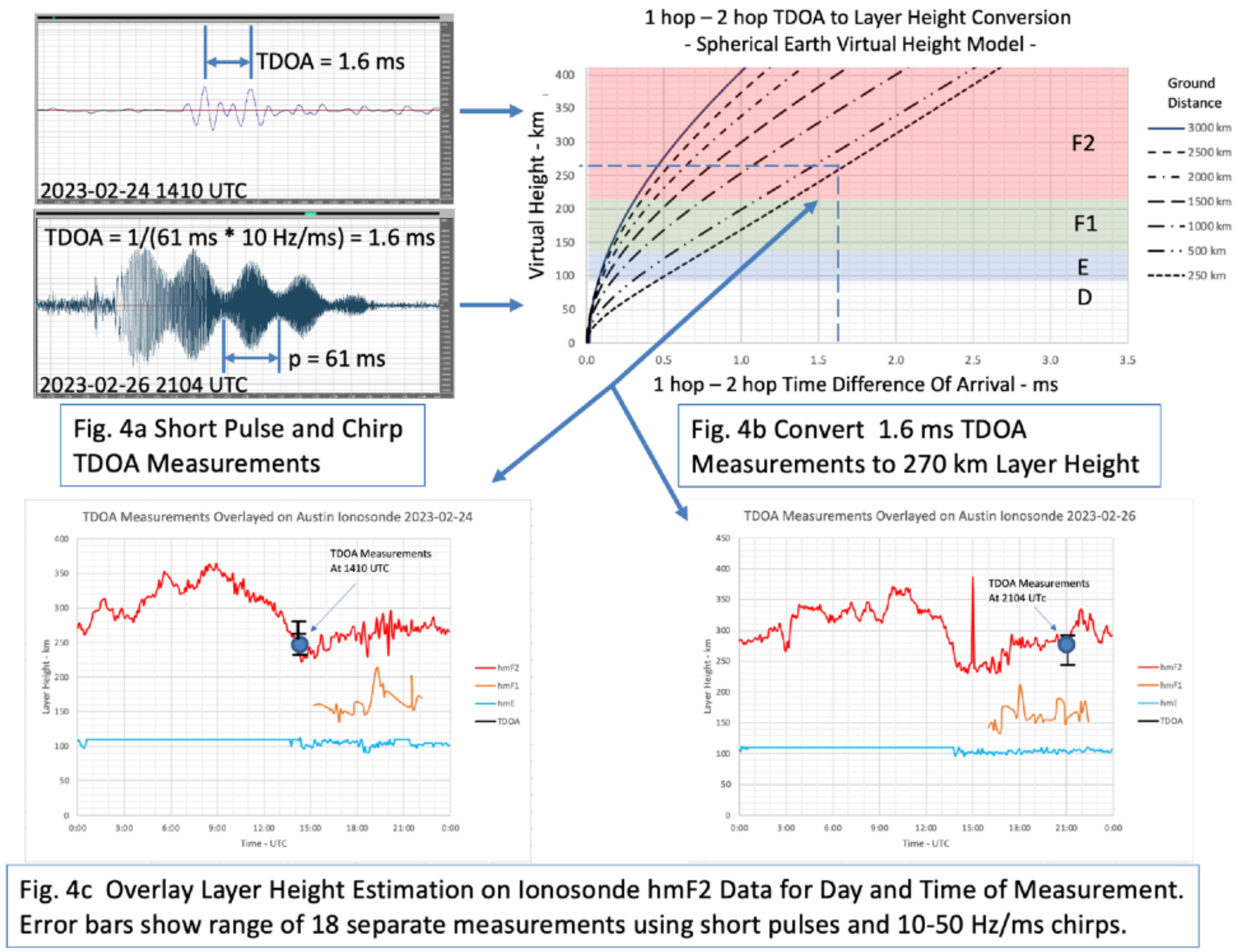

Figure 4 Results of the Texas On-the-Air TDOA Tests are Consistent with Austin Ionosonde hmF2 Data.

ground distances from 250 to 3000 km. This spreadsheet was used to convert the 317 km ground distance and 1.6 ms TDOA to a virtual layer height of 270 km. The average and spread of all data points are overlaid on the Austin ionosonde hmF2 plots for the time and day of the tests in Figure 4c.

5. Conclusions and Recommendations

The field tests on 3.785 MHz and 5.3715 MHz show the TDOA methodology should be able to provide the desired layer height profiling during the upcoming 2023 and 2024 eclipses. Actual test methodology is still under development but will likely recommend setting up pre-established propagation paths between participating stations taken on 6-10 minute intervals from at least 2 hours before to 2 hours after local maximum. One item identified in the field test was that the fastest chirp (100 Hz/ms) was too fast for the DSP audio processing in one of the receivers and gave inconsistent results. Therefore only the slower chirps will be recommended. Also, because of the large volume of data, development of code to perform an automated Fourier transform to extract the beat frequency data from the chirps is highly recommended.

[1] Steve Cerwin. (2020, March 20). WWV Time Tick Arrival Time Study to Investigate Multiple Modes During Daily Dawn and Dusk Transitions. Zenodo. https://doi.org/10.5281/zenodo.7191497

[2] Steve Cerwin, Kristina Collins, Dev Joshi, & Nathaniel Frissell. Experimental and Computational Methods to Analyze Complex Doppler Behavior of Ionospherically Induced Doppler Shifts on HF Signals. https://doi.org/10.5281/zenodo.7847505

[3] WA9VNJ Eclipse

[4] Steve Cerwin, & Dr. Phillip Erickson. (2021, March 25). Selected HamSCI Science Experiments Using Unique Properties of WWV, WWVH, and WWVB. Zenodo. https://doi.org/10.5281/zenodo.4715704

[5] Steve Cerwin WA5FRF. (2022). WA5FRF WWV/H Characterization Signal Notes. Zenodo. https://doi.org/10.5281/zenodo.5908600