On-Air Multipath TDOA Experiments for Ionospheric Layer Height Measurements Using Amateur Radio Stations

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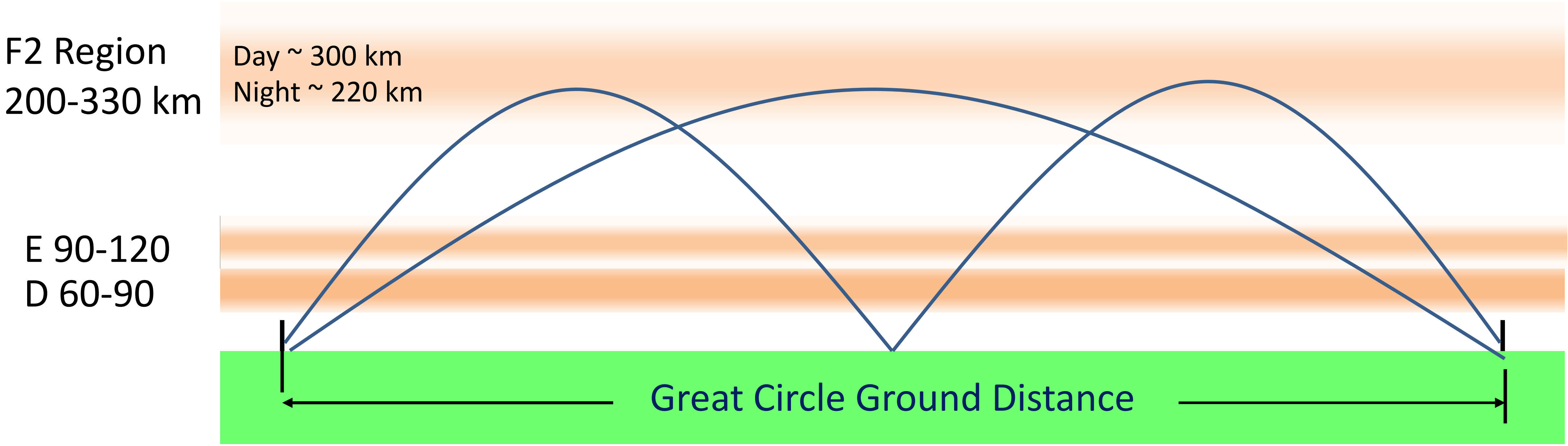
Synopsis

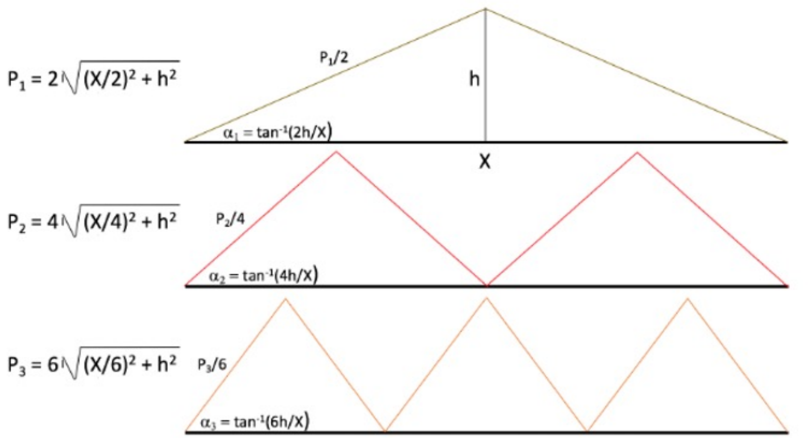
- A HamSCI science objective for the 2023 and 2024 eclipses is to measure how HF propagation changes with eclipse passage. Two parameters of interest are the change in effective F2 ionization layer height caused by the momentary blockage of solar radiation and the symmetry in recovery as solar radiation returns after eclipse. The focus of this effort was to devise a simple way to measure layer height that could be accomplished using amateur radio stations.
- Layer height could be deduced from absolute Time of Flight measurements, but this would require precision absolute time references for both the transmitting and receiving stations such as the 1-pps output available from a GPS Disciplined Oscillator. It would also require extensive characterization of the relatively lengthy propagation delays through the DSP transmit and receive audio processors used in modern amateur radios.
- Over propagation paths that support transmission of multiple hops, short pulse and audio chirp waveforms can be used to measure the Time Difference of Arrival (TDOA) between multipath modes, particularly the 1- and 2- hop modes. TDOA can be processed to infer layer height and it eliminates the need both for absolute time references and for TX/RX time delay characterization. With the TDOA approach, audio signals can simply be fed to the microphone input and recovered from the speaker output of amateur radio equipment using .wav programs on a computer or the built-in audio memories available on many modern transceivers.
- This paper gives details and results of initial on-air experiments to evaluate the TDOA approach to layer height measurement.
- The experiments were conducted between two amateur radio stations in Texas near both the expected Path of Totality and the Austin Ionosonde used for ground truth data. The inferred layer heights gave good agreement to hmF2 ionosonde data.

Simplified 1 and 2 Hop Multipath from The F2 Region

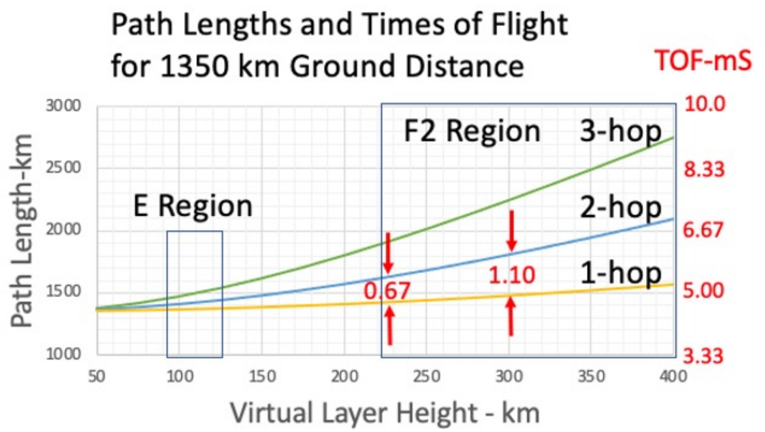


- Multiple hops involving reflection from the earth (and other layers) are possible if ionization levels are sufficient to propagate the required elevation angles. Over a given path, maximum frequency for a 1-hop mode is bounded by the Maximum Usable Frequency (MUF) but the higher-angle 2-hop mode requires a lower frequency that is between the MUF and the critical frequency foF2. The TDOA approach is applicable only over paths where both modes are present.
- Because the 2-hop mode has a longer path length, the Time of Flight (TOF) is longer. A measurement of the Time Difference of Arrival (TDOA) between the 1 and 2 hop modes can be analyzed to approximate layer height. This is a measurement that can be accomplished using unmodified amateur radio equipment by transmitting audio waveforms that are sensitive to the simultaneous presence of multiple time delayed signals. The method should prove useful in following the height changes that occur during a solar eclipse as well as the daily dawn/dusk height changes.

Time Difference of Arrival (TDOA) Between the 1-hop and 2-hop Modes Can be Analyzed to Infer Layer Height



Virtual Height model showing relationship between path length and layer height.
Time of Flight = Path Length / c

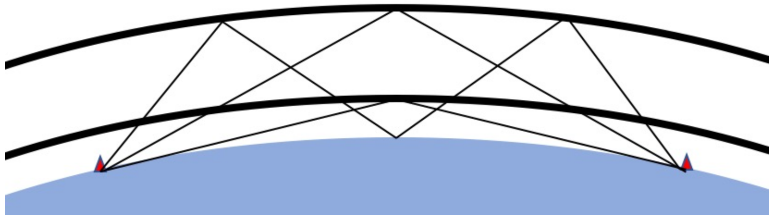


Example: At 1350 km ground distance the Time Difference of Arrival between 1 and 2 hop modes is 0.67 ms at 225 km layer height and 1.10 ms at 300 km.

A Virtual Height model of the ionosphere yields simple formulas relating path length to virtual layer height (left) for a given ground distance. Once path Length is converted to TOF, the TDOA between the 1- and 2- hop modes can be used to infer F2 layer height (right).

Spreadsheet for Calculating TDOA Parameters for a Specified Ground Distance

Ground Distance is entered in cell C3 and the spreadsheet calculates path lengths, takeoff angles, TOF, and TDOA for 1 and 2 hop modes vs. Layer Height. Starting height and height increment can be modified in cells A3 and A4.

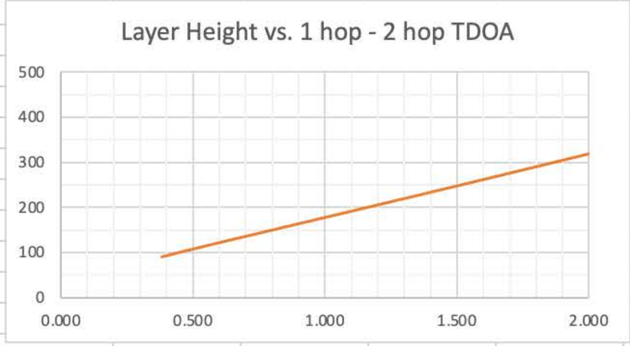


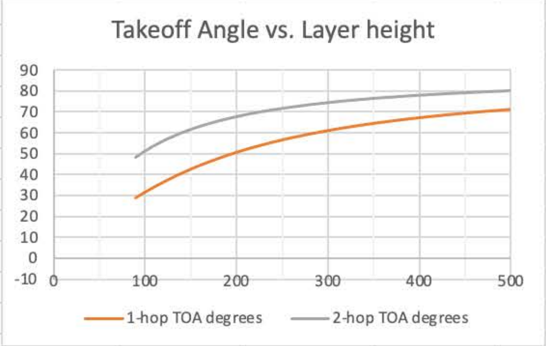
Spherical Earth Virtual Height Model

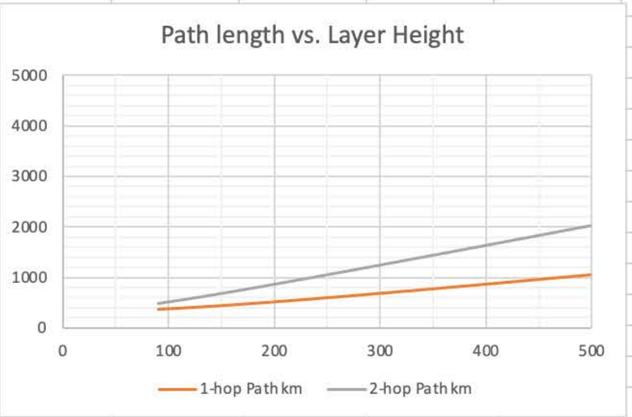
C3   fx   =2*SQRT(2*6378*(6378+A3)*(1-COS(B3/(2*6378)))+A3^2)

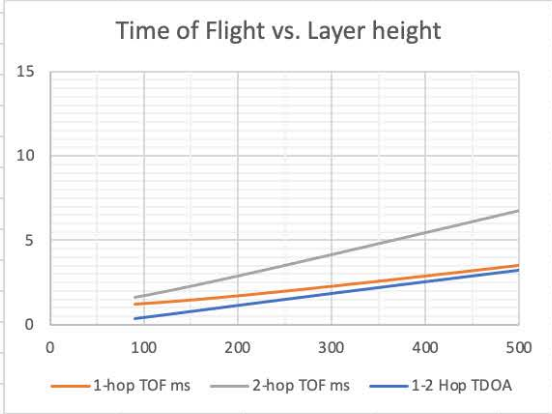
Enter

	A	B	C	D	E	F	G	H	I
1	Layer Height	Ground Dist.	1-hop Path	2-hop Path	1-hop TOA	2-hop TOA	1-hop TOF	2-hop TOF	1 hop-2 hop
2	km	km	km	km	degrees	degrees	ms	ms	TDOA
3	90	317	366	481	28.7	48.1	1.22	1.60	0.382
4	100	317	377	512	31.3	51.0	1.26	1.71	0.450
5	110	317	388	544	33.8	53.6	1.29	1.81	0.519
6	120	317	400	577	36.2	56.0	1.33	1.92	0.590
7	130	317	412	611	38.4	58.0	1.37	2.04	0.661
8	140	317	426	645	40.4	59.9	1.42	2.15	0.732
9	150	317	439	680	42.4	61.5	1.46	2.27	0.804
10	160	317	453	716	44.2	63.0	1.51	2.39	0.876
11	170	317	468	752	45.9	64.4	1.56	2.51	0.948
12	180	317	483	788	47.5	65.6	1.61	2.63	1.020
13	190	317	498	825	49.0	66.7	1.66	2.75	1.091
14	200	317	513	862	50.5	67.7	1.71	2.87	1.163
15	210	317	529	900	51.8	68.7	1.76	3.00	1.234
16	220	317	545	937	53.1	69.5	1.82	3.12	1.306
17	230	317	562	975	54.2	70.3	1.87	3.25	1.377
18	240	317	579	1013	55.4	71.1	1.93	3.38	1.448
19	250	317	595	1051	56.4	71.7	1.98	3.50	1.519
20	260	317	612	1089	57.4	72.4	2.04	3.63	1.589
21	270	317	630	1127	58.3	73.0	2.10	3.76	1.660
22	280	317	647	1166	59.2	73.5	2.16	3.89	1.730
23	290	317	664	1204	60.1	74.0	2.21	4.01	1.800
24	300	317	682	1243	60.9	74.5	2.27	4.14	1.870
25	310	317	700	1282	61.6	75.0	2.33	4.27	1.940
26	320	317	718	1321	62.4	75.4	2.39	4.40	2.010
27	330	317	736	1359	63.1	75.8	2.45	4.53	2.079
28	340	317	754	1398	63.7	76.2	2.51	4.66	2.149

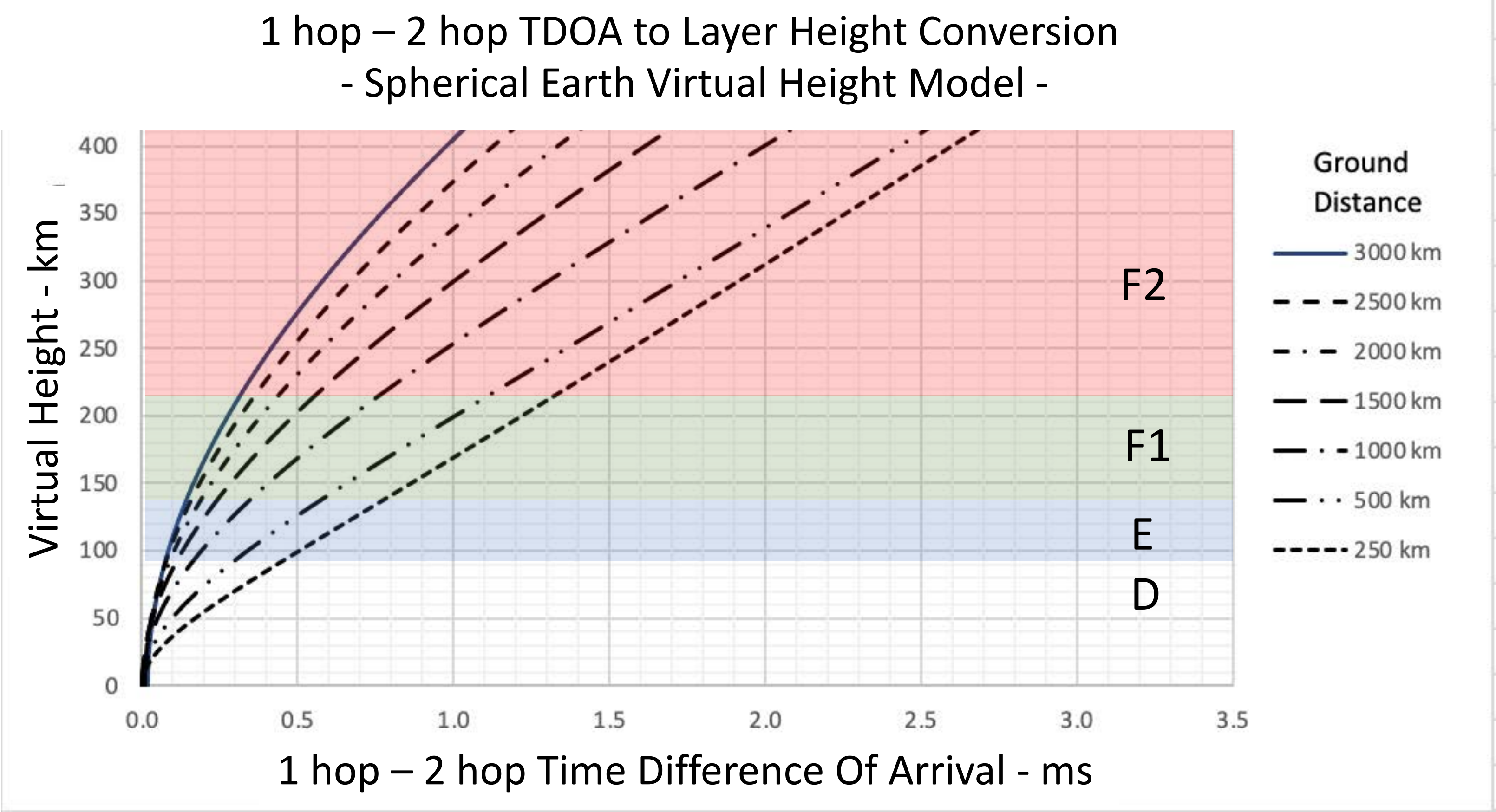








Calculated Relationship Between 1 hop-2 hop Time Difference of Arrival and Virtual Layer Height for Ground Distances Between 250 km and 3000 km



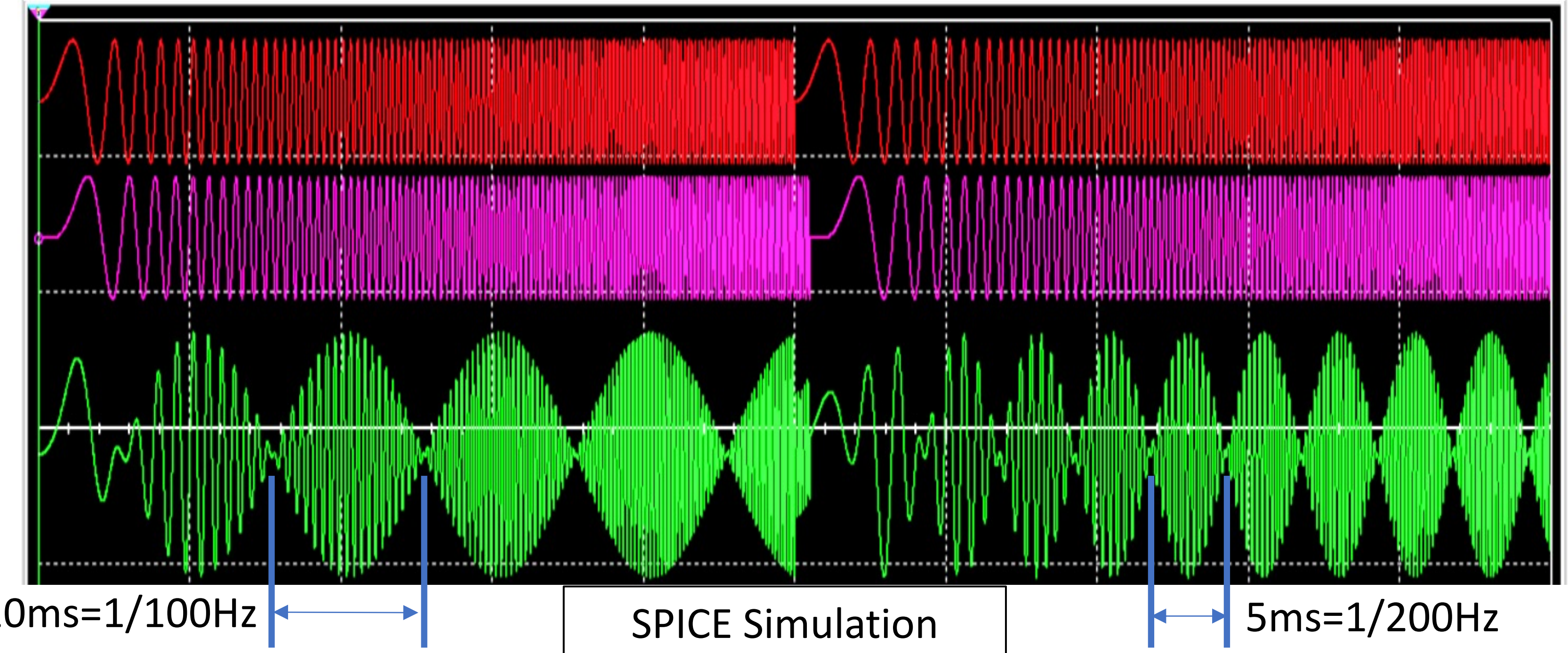
The Time Difference of Arrival between Two Simultaneous Propagation Modes Measured by Transmission of an Audio Frequency Chirp

A. 100 Hz/ms Chirp @ 0 delay (Fast Chirp)

B. Chirp delayed 1 and 2 ms

C. SUM (A+B). Beats occur at period 1/Δf. Summation occurs naturally in receiver during multipath reception.

1 ms Time Delay. Δf = 100 Hz   2 ms Time Delay. Δf = 200 Hz



SPICE Simulation
Time base : 10 ms/div

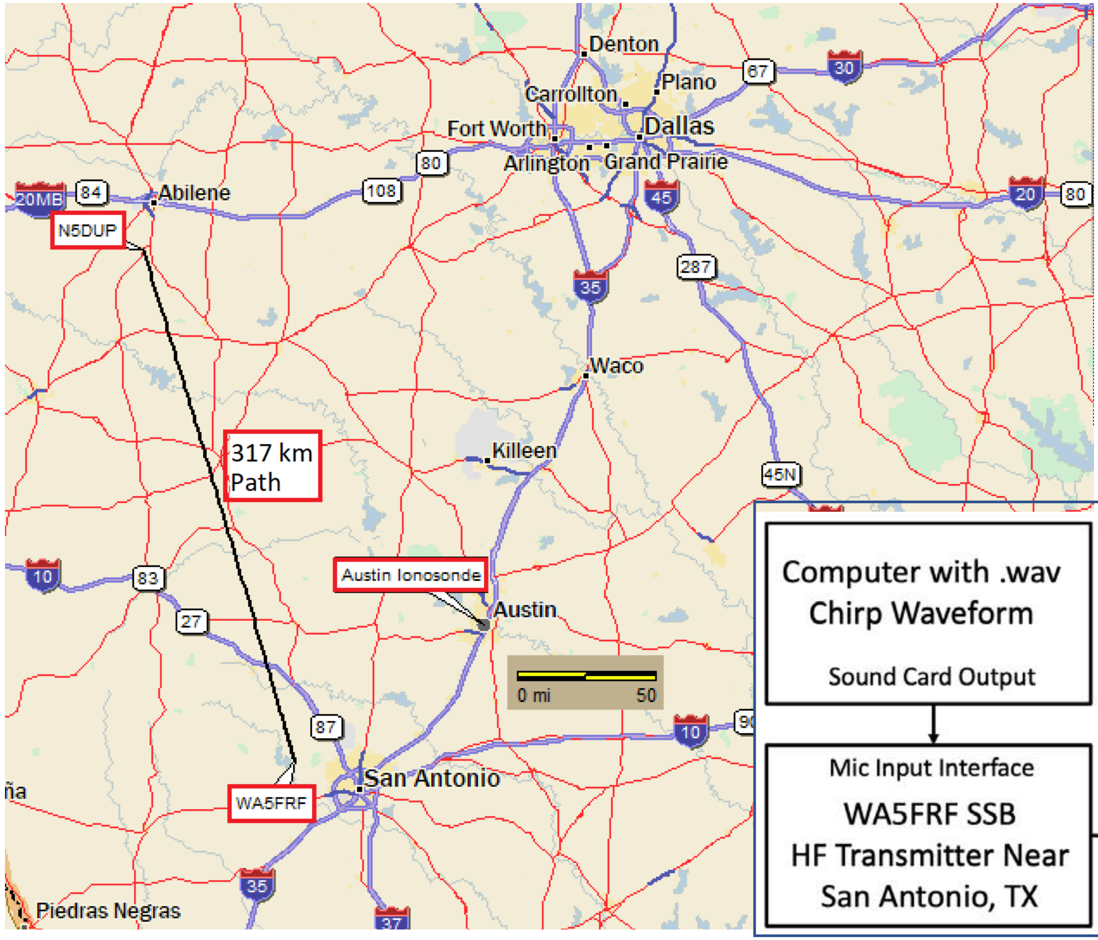
Summation of a linear chirp with a delayed copy of itself produces a difference frequency at Δf = Sweep Rate * Δt. Beat pattern has a period p = 1/Δf. The Time Difference of Arrival (TDOA) can be calculated by:

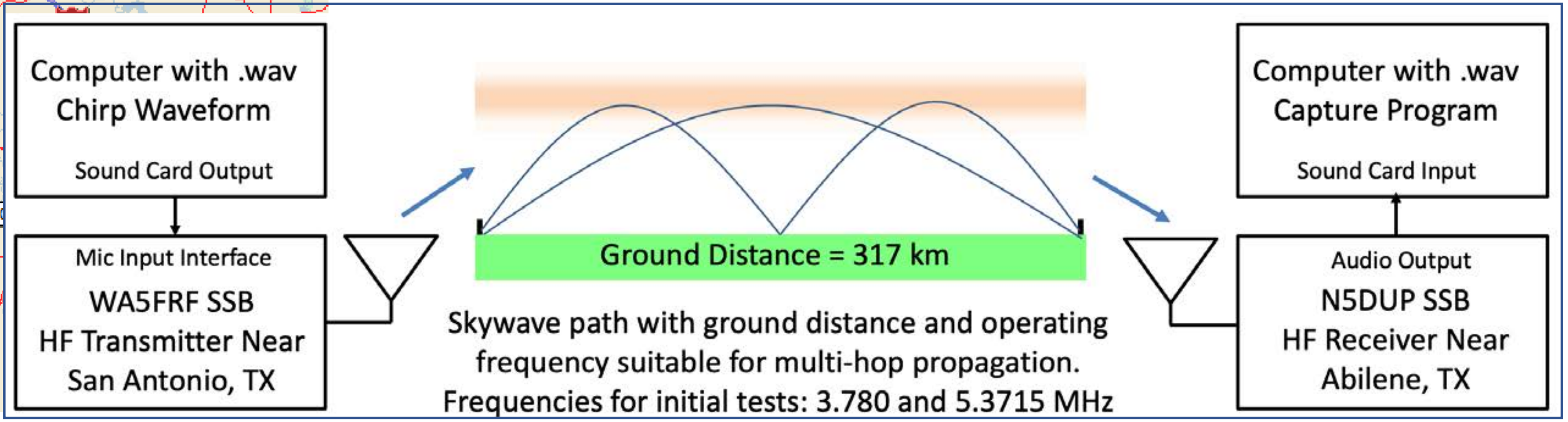
TDOA = 1/ p*Sweep Rate

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

TDOA = 1/(10 ms * 100 Hz/ms) = 1 s/1000 = 1 ms

Geometry and Setup for Initial TDOA On-Air Experiments Using Amateur Radio Stations WA5FRF and N5DUP



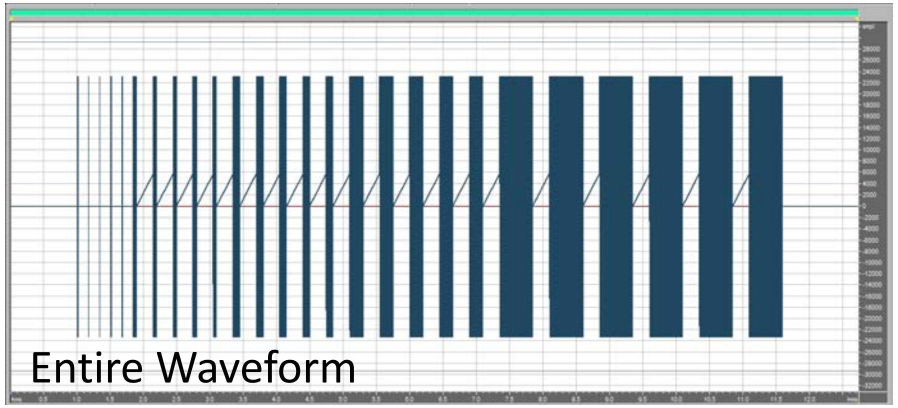


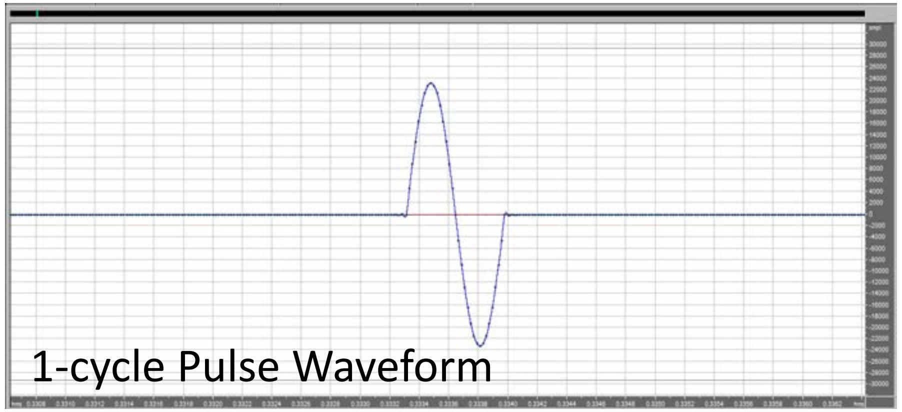
Geometry is convenient for proximity to expected eclipse Path and to the Austin Ionosonde for ground truth data.

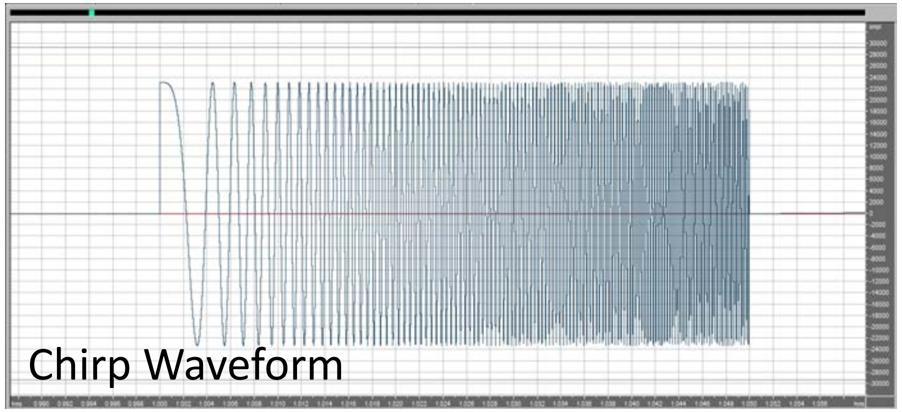
60 m and 75 m frequency bands chosen for likelihood of both 1 hop and 2 hop propagation.

Test Waveforms Used in Initial On-Air Experiments

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





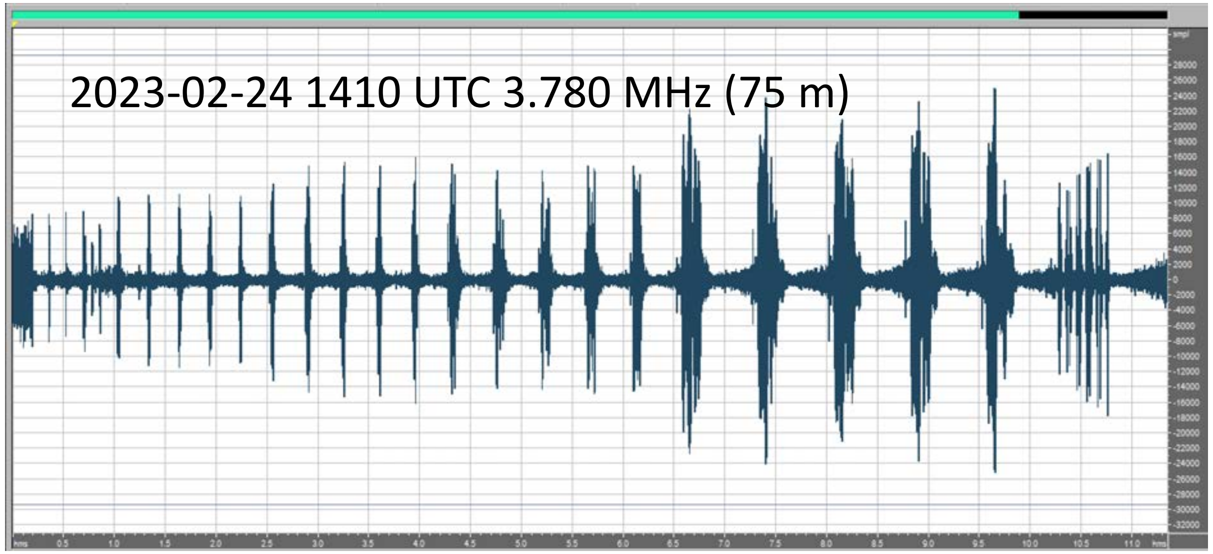


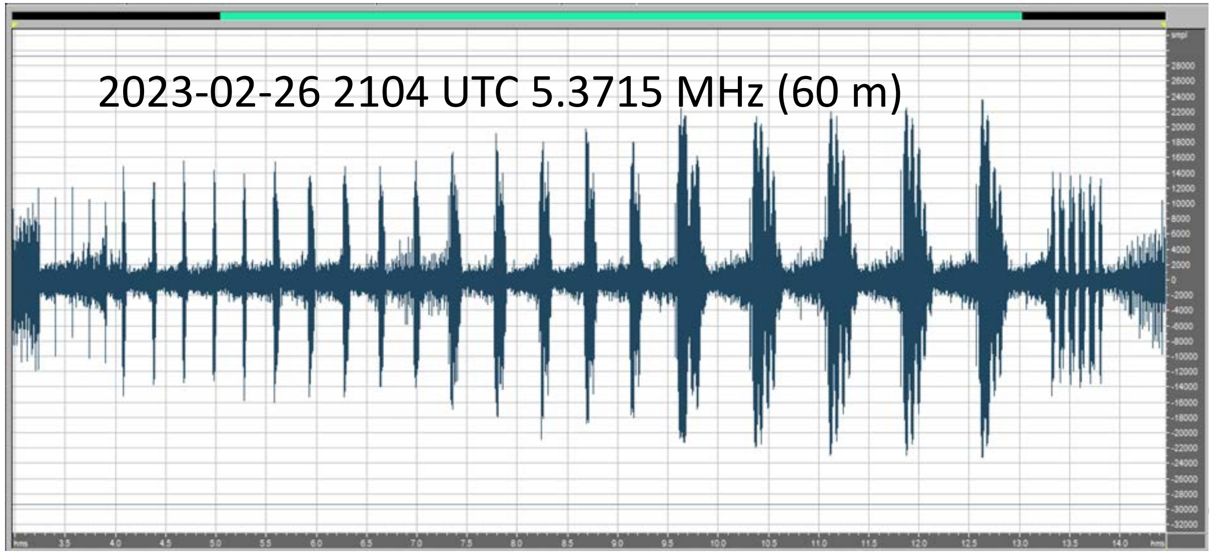
Test waveform generated in Matlab by Kristina Collins KD8OXT

Test Waveforms Transmitted by WA5FRF Near San Antonio and Received by N5DUP Near Abilene

Transmitter: Icom IC-7610
Input: USB audio from computer
Mode: LSB on 75 m, USB on 60 m
Audio Passband: 200-2900 Hz
Power: 100 watts
Antenna: 160 m multiband dipole

Receiver:
Icom IC-7610 on 75 meters, LSB
Icom IC-7300 on 60 meters, USB
Antenna: End-fed multiband dipole
Audio Recorder: Internal audio REC function

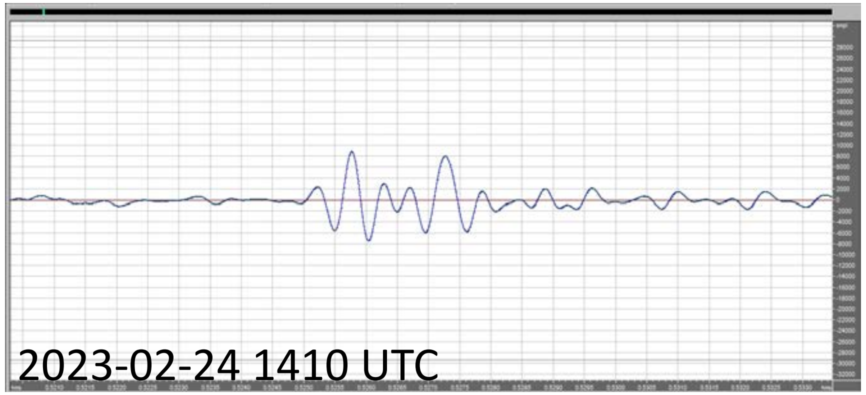




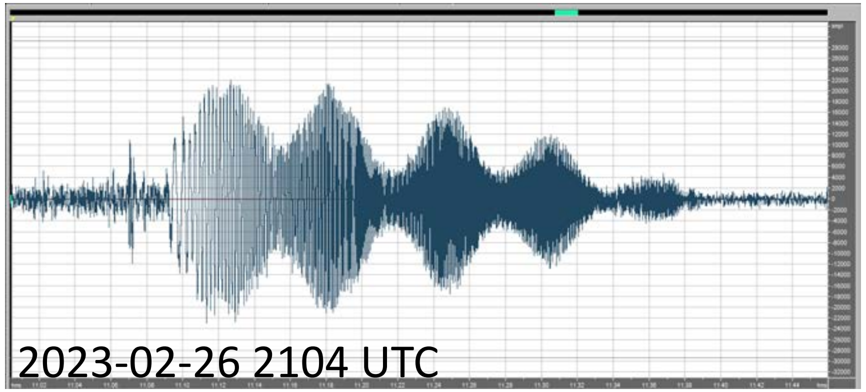
Expanded View of Example Received Waveforms

Waveform interpretation can be complicated by several mechanisms:
- 1 and 2 hop returns from more than one ionization layer
- Modes using multiple hops between layers
- Modes that duct within layers (Pedersen)
- 1-cycle pulses can be distorted by receiver characteristics, making it difficult to recognize correlatable features.
- Chirp waveforms can also be distorted by receiver audio properties such as impulse response, frequency shaping, and AGC characteristics. For example, it was found the fastest chirp rate (100 Hz/ms) gave inconsistent results between the two receivers used in the study.

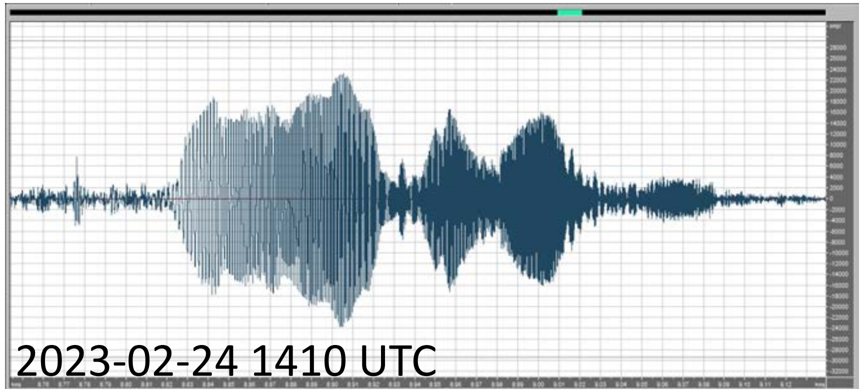
1-cycle pulses with 1.6 ms Time Difference of Arrival. The short pulses have the advantage that TDOA can be read directly from the .wav file time scale.



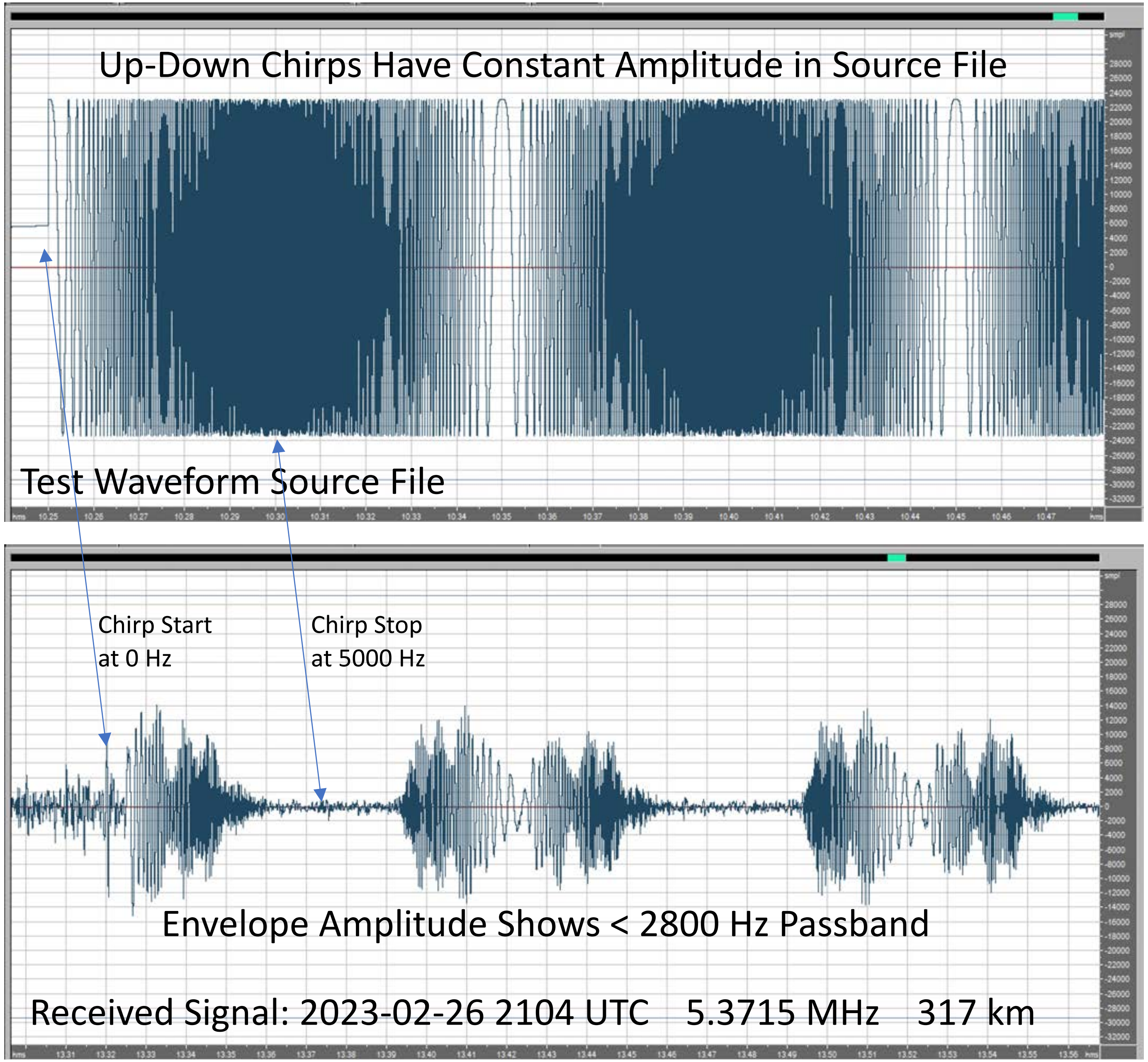
Pristine multipath waveform showing beat pattern from two chirps delayed in time. Analysis suggests these are 1-hop - 2-hop modes from the F2 layer.



Complex chirp waveform with both low frequency and high frequency beat patterns. This suggests 1 and 2 hop returns from both the F2 and E layers.



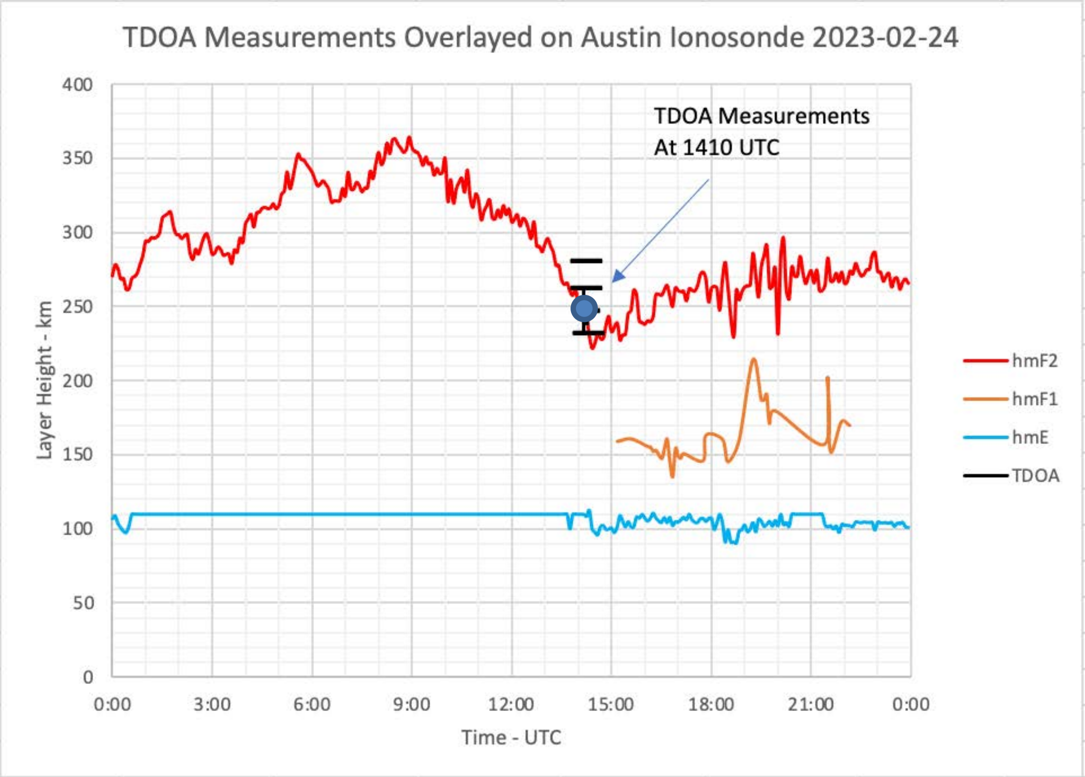
0-5000 Hz Up-Down Chirps Illustrate Envelope Shape Distortion from Bandwidth Limiting in IC-7610 Transmitter And IC-7300 Receiver



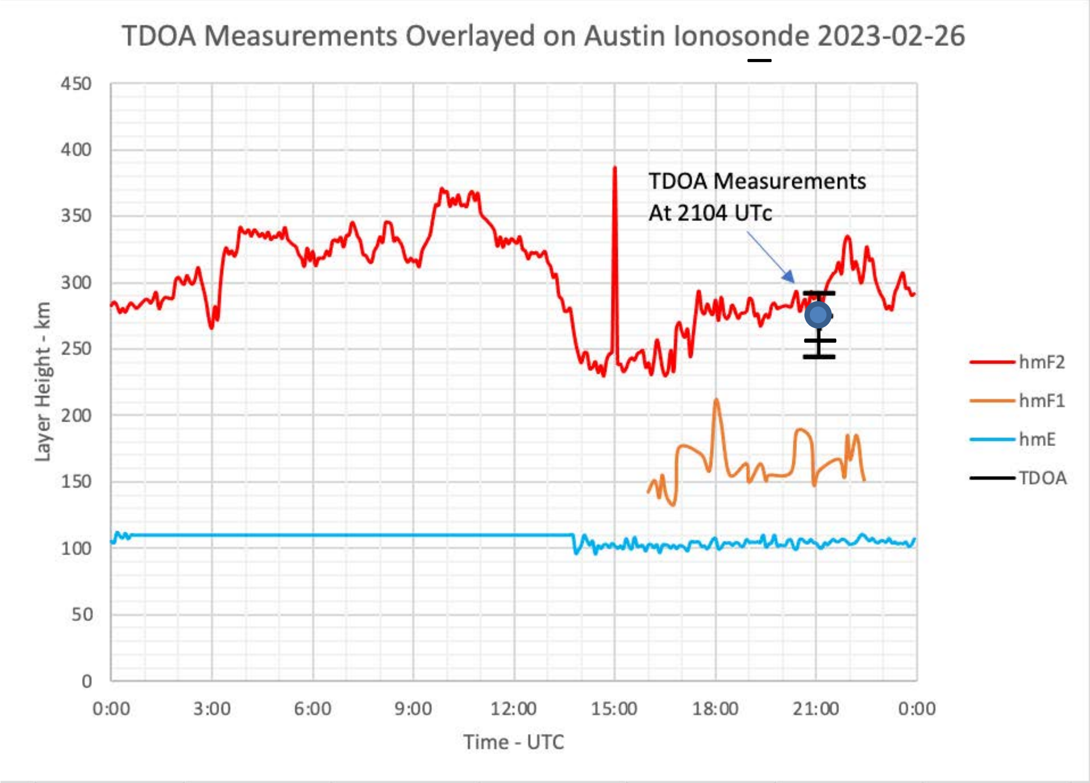
All Repetitions of All Waveforms (Except the 100 Hz/ms Chirps) Were Analyzed and Used to Calculate Indicated Layer Height

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	TDOA First Experiments														
2		Band	Date	Time UTC		Band	Date	Time UTC							
3		75 meters	2/24/23	1410		60 meters	2/26/23	2104			All waveform summary (except 100 Hz/ms chirp)				
4															
5	Waveform	TDOA - ms	Ht. @ 317km	Notes		TDOA - ms	Ht. @ 317kn	Notes		75 meters	2/24/23		60 meters	2/26/23	
6															
7	1cy Pulse 1	1.39	232							14:10:00	232		21:04:00	282	
8	1cy Pulse 2	1.46	242			1.74	282			14:10:00	242		21:04:00	284	
9	1cy Pulse 3	1.51	250			1.76	284			14:10:00	250		21:04:00	284	
10	1cy Pulse 4	1.55	254			1.76	284			14:10:00	254		21:04:00	284	
11	1cy Pulse 5	1.56	256			1.76	284			14:10:00	256		21:04:00	274	
12	Average	1.49	247			1.76	284			14:10:00	234		21:04:00	252	
13	Max	1.56	256			1.76	284			14:10:00	236		21:04:00	258	
14	Min	1.39	232			1.74	282			14:10:00	238		21:04:00	244	
15										14:10:00	244		21:04:00	272	
16	50Hz/ms Chirp					1.69	274	Nulls avble		14:10:00	262		21:04:00	274	
17	50Hz/ms Chirp	1.44	234			1.53	252	1-2, 2-3, 3-4		14:10:00	282		21:04:00	276	
18	50Hz/ms Chirp	1.42	236			1.57	258	Using 2-3		14:10:00	244		21:04:00	264	
19	50Hz/ms Chirp	1.43	238			1.48	244			14:10:00	244		21:04:00	292	
20	50Hz/ms Chirp	1.48	244			1.67	272			14:10:00	256		21:04:00	287	
21	Average	1.44	238			1.59	260			14:10:00	253		21:04:00	263	
22	Max	1.48	244			1.69	274			14:10:00	260		21:04:00	272	
23	Min	1.42	234			1.48	244			14:10:00	240		21:04:00	272	
24										14:10:00	240		21:04:00	263	
25	25Hz/ms Chirp	1.60	262			1.69	274							263	
26	25Hz/ms Chirp	1.74	282			1.70	276			Average	248		Average	272	
27	25Hz/ms Chirp	1.48	244			1.61	264			MAX	282		MAX	292	
28	25Hz/ms Chirp	1.48	244			1.81	292			MIN	232		MIN	244	
29	25Hz/ms Chirp					1.78	287								
30	Average	1.58	258			1.72	279								
31	Max	1.74	282			1.81	292								
32	Min	1.48	244			1.61	264			Waveform	TDOA - ms	Ht. @ 317kn	Notes	TDOA - ms	Ht. @ 317km
33															
34	10 Hz/ms Chirp	1.56	256			1.61	263	Nulls avble		100Hz/ms Chirp	1.05	184	100 Hz/mz	1.64	267
35	10 Hz/ms Chirp	1.54	253			1.67	272	1-2, 2-3, 3-4		100Hz/ms Chirp	1.06	186	Chirp rate	1.52	250
36	10 Hz/ms Chirp	1.59	260			1.67	272	Using 2-3		100Hz/ms Chirp	1.08	188	too fast for	1.52	250
37	10 Hz/ms Chirp	1.45	240			1.61	263			100Hz/ms Chirp	0.96	172	this receiver	1.52	250
38	10 Hz/ms Chirp	1.45	240			1.61	263			100Hz/ms Chirp			- Not	1.59	260
39	Average	1.52	250			1.63	267			Average	1.04	183	Recommended	1.56	255
40	Max	1.59	260			1.67	272			Max	1.08	188		1.64	267
41	Min	1.45	240			1.61	263			Min	0.96	172		1.52	250
42															

Reduced Data from TDOA Experiment Overlaid on Austin Ionosonde hmF2 Data



Most of the data clustered within the narrow error bars with the exception of one flier.



Most of the data clustered together well with the exception of two fliers. The E layer was well established at this time of day and there is evidence of possible 1 hop – 2 hop E layer beats in the data.

Conclusions and Recommendations

- The results of the experiment are encouraging in that the layer heights measured by TDOA gave results consistent with the Austin ionosonde. Radio propagation is of course complex and variable, but the method appears to work under favorable conditions.
- The 1-cycle pulses are valuable because they give a direct indication of TDOA for time-displaced propagation modes and can be used to back up chirp data. However, they are subject to receiver dependent phase shifts and waveshape distortion. The center frequency of 1.5 kHz is the highest frequency that will fit in the audio passband of a typical SSB radio, but the period is still too long for short TDOA's (such as from the E layer).
- The 100 Hz/ms chirp is too fast for the DSP audio processing used in some receivers and will be deleted.
- The bandwidths used in the transmitter and receiver should be set at the widest limits to recover as much of the waveforms as possible. A bandwidth of 5 kHz would be ideal (except on 60 meters where bandwidth is limited to 2800 Hz by regulation). The bandwidth settings in this study was from 200-2900 Hz and gave reasonable results.
- Using the nulls to measure beat note period gave more consistent results than using the peaks.
- The manual data reduction used to reduce the data in this study is very labor intensive and prone to subjective interpretation. An automated means to extract the beat frequencies from the chirp data is needed.