Analyzing Ionospheric Effects on WWV Timing Signals

Shad Nygren

Datron World Communications

February 7th 2008

Performance You Require • Value You Expect℠

My Background

- Senior Software Engineer at Datron
- Amateur Radio Extra Class – KD7WMX
- MS and BS in Computer Science
- Recently accepted to work on my Ph.D. and I am interested in scientific research
- High Speed Data
- OFDM / 802.11g / 802.11n / WiMAX
- New to HF – I've been with Datron for 2 years
- Originally thought 10.7MHz IF is in the middle of HF band so HF is IF but learned HF is **NOT** IF

Project Description

- Started out as project to measure height of ionosphere
- I learned about the Watterson Model
- I learned there was a great deal of interest in the industry to develop improved ionosphere models, especially wideband models for data
- This project evolved to collect data to support future development of new models

Watterson Model

- Developed in 1970 and has become the standard for HF channel modeling.
- Proposed a stationary model for the HF channel
- Performed limited set of on-air measurements to experimentally validate the model
- Experiment showed that the model was valid for short times ($\approx$ 10 minutes) and for band-limited channels (approximately 10 kHz).

HF Channel Model

- According to Watterson Paper:
- HF ionospheric channels are nonstationary in both frequency and time
- If consideration is restricted to band-limited channels (say, 10 kHz) and sufficiently short times (say, 10 minutes), most channels are nearly stationary and can be adequately represented by a stationary model.

Questions

- How does the ionosphere affect signals that are not within the scope of the Watterson Model?
- What could be done to develop improved models?
- What sources could I use to explore the Ionosphere?

WWV Signal

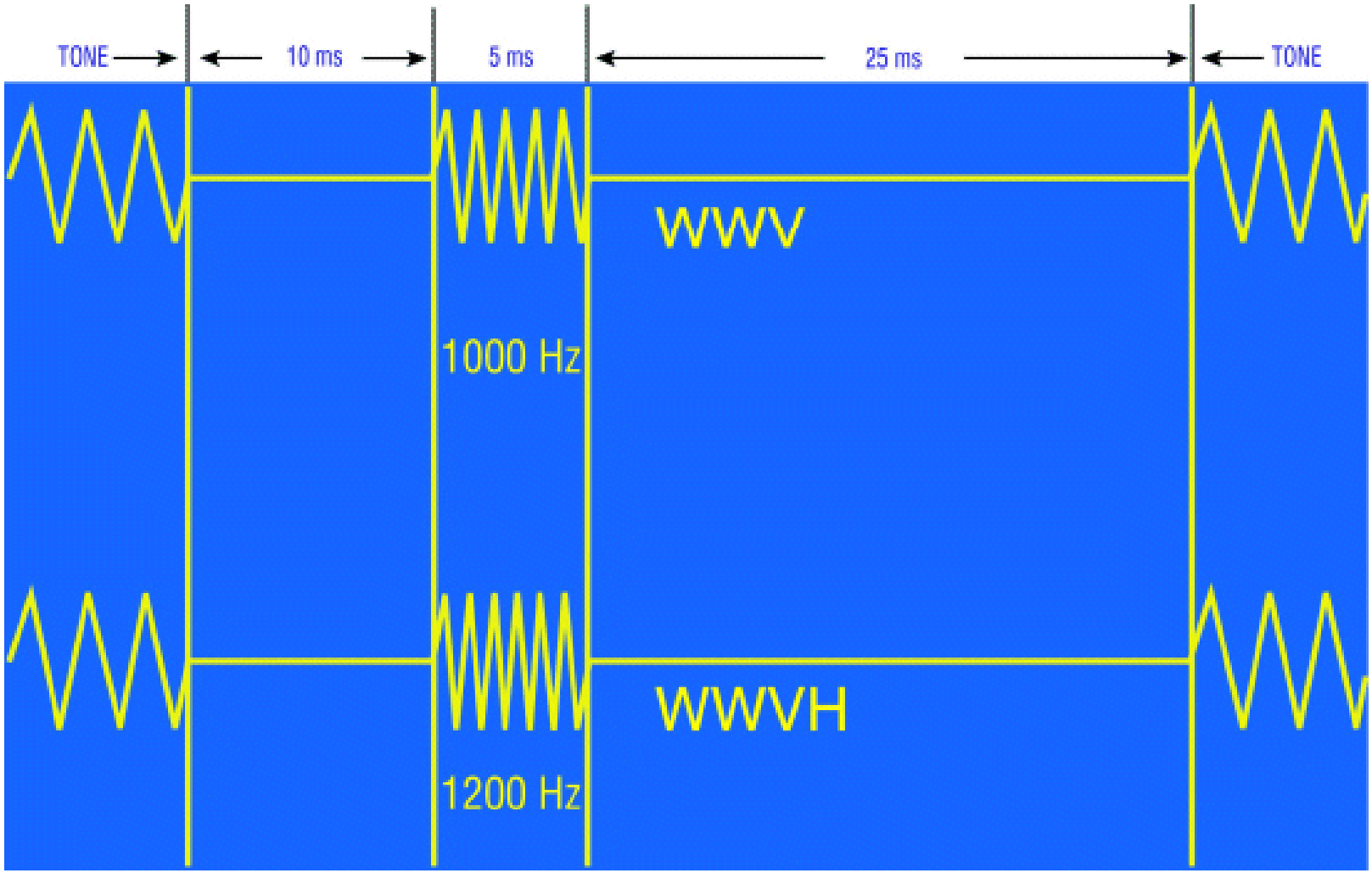
- WWV operates in the high frequency (HF) portion of the radio spectrum.
- The station radiates 10KW on 5, 10, and 15 MHz; and 2500 W on 2.5 and 20 MHz.
- Each frequency is broadcast from a separate transmitter.
- Each frequency carries the same information

WWV

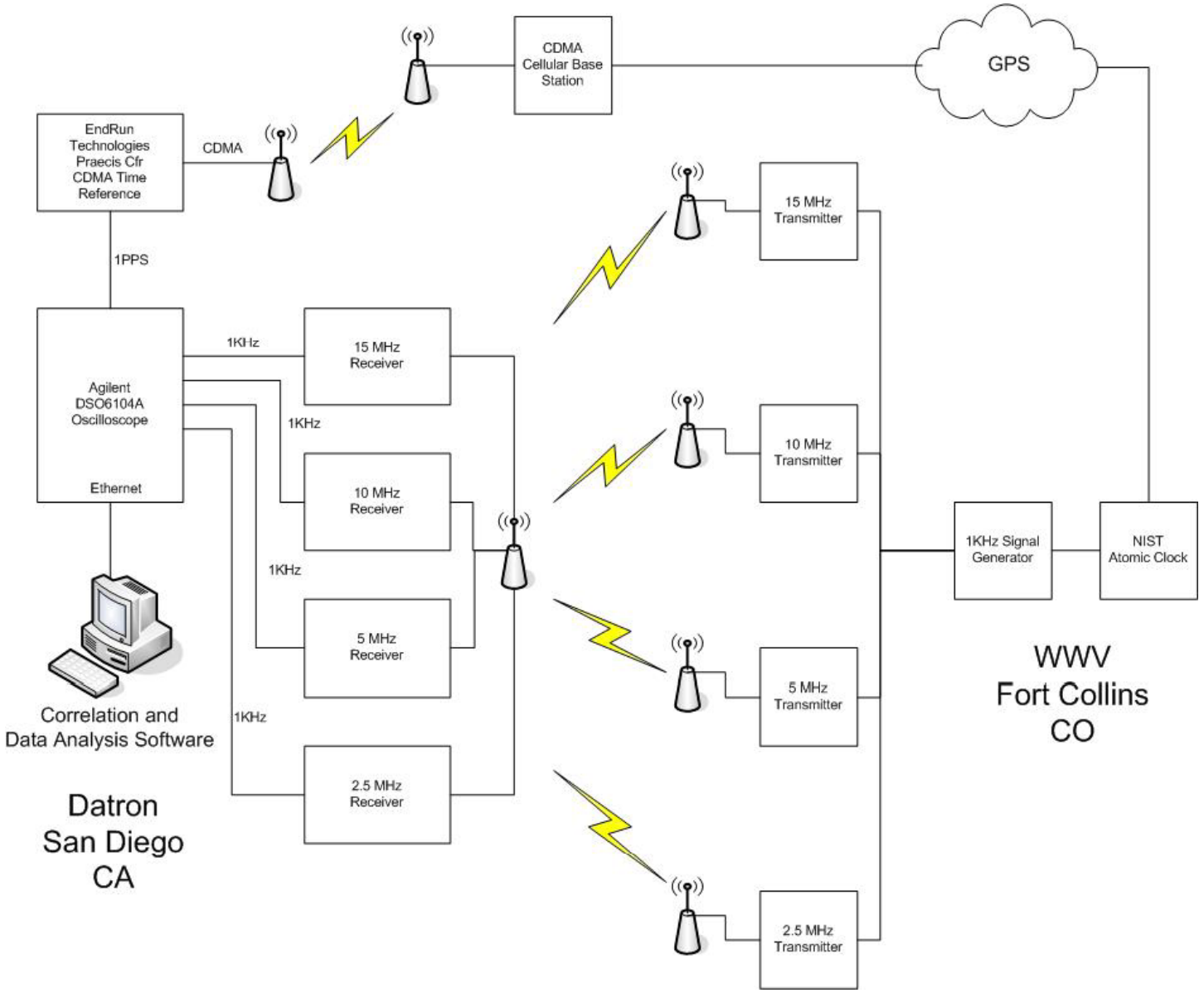
WWV Antenna Coordinates

Frequency (MHz)	Latitude	Longitude
2.5	40° 40’ 55.2" N	105° 02’ 31.3" W
5	40° 40’ 42.1" N	105° 02’ 24.9" W
10	40° 40’ 47.8" N	105° 02’ 25.1" W
15	40° 40’ 45.0" N	105° 02’ 24.5" W
20	40° 40’ 53.1" N	105° 02’ 28.5" W

WWV Signal Format



Experiment Block Diagram



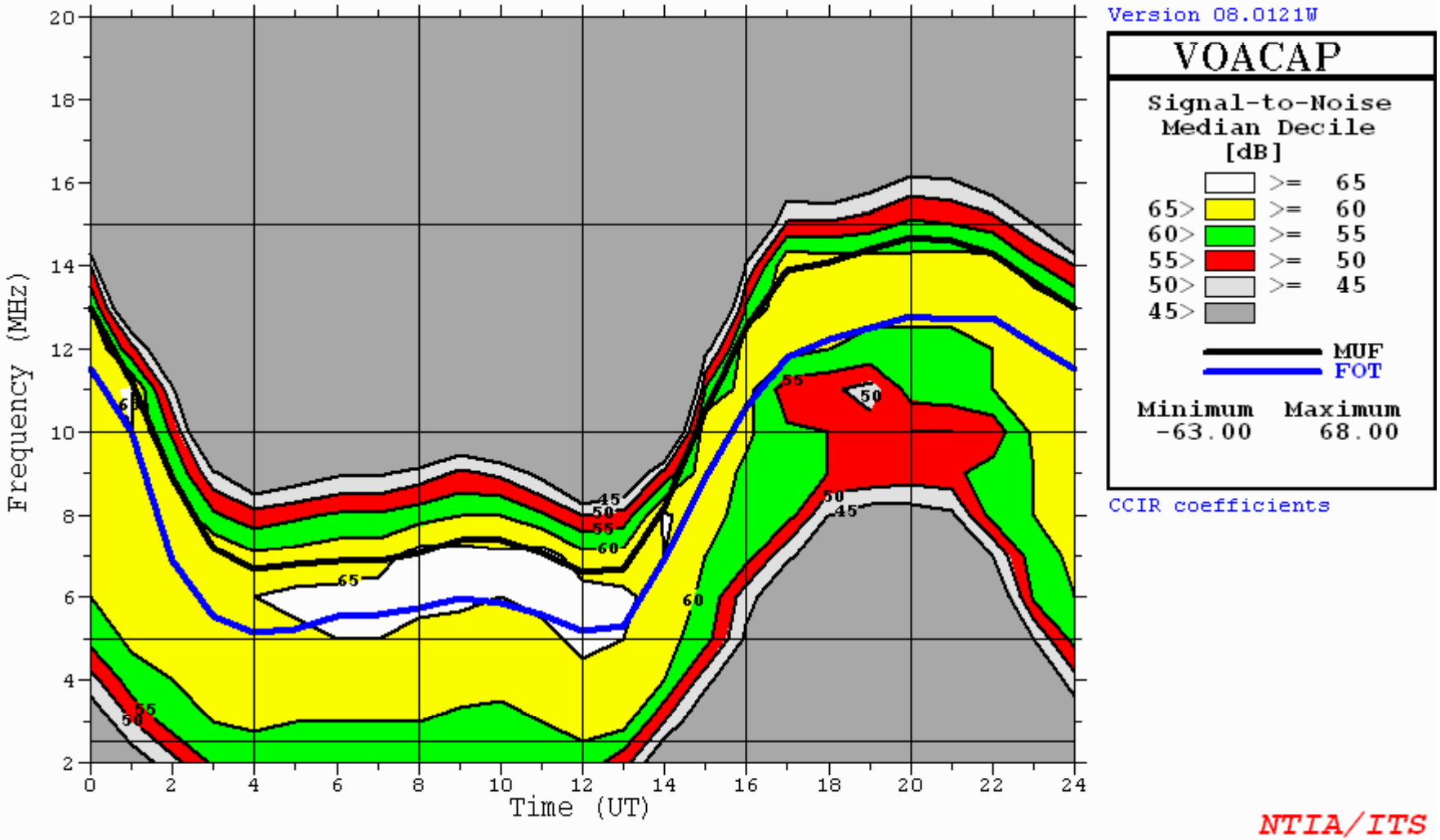
Data Collection & Analysis

- Collect data from receivers using Agilent DSO6104A oscilloscope
- Trigger on 1PPS synched to UTC via CDMA
- Sampling at 50Ksps (20us per sample)
- Correlate with ideal 5ms 1KHz burst transmitted by WWV using custom DSP software I wrote
- Find delay of the received signal relative to UTC
- Analyze variations in delay and phase of received signal

VOACAP SNR

- Use VOACAP to determine the predicted Signal to Noise Ratio
- Calculate for path between Fort Collins CO and San Diego CA
- Calculate for various WWV frequencies
- Calculate using approximate antennas
- Calculate for times throughout the day during February 2008
- Calculate using current Smoothed Sun Spot Number

```
Feb    2008          SSN =   3.                  Minimum Angle= 0.100 degrees
WWV                 Datron                  AZIMUTHS          N. MI.      KM
40.68 N  105.04 W - 33.15 N  117.22 W    236.09   48.74     737.8   1366.3
XMTR  2-30 HFMUFES#35[samples\SAMPLE.35     ] Az=  0.0 OFFaz=236.1  10.000kW
RCVR  2-30 IONCAP #23[samples\SAMPLE.23     ] Az= 48.7 OFFaz=  0.0
3 MHz NOISE = -145.0 dBW     REQ. REL = 90%     REQ. SNR = 73.0 dB
MULTIPATH POWER TOLERANCE =  3.0 dB   MULTIPATH DELAY TOLERANCE =  0.100 ms
```

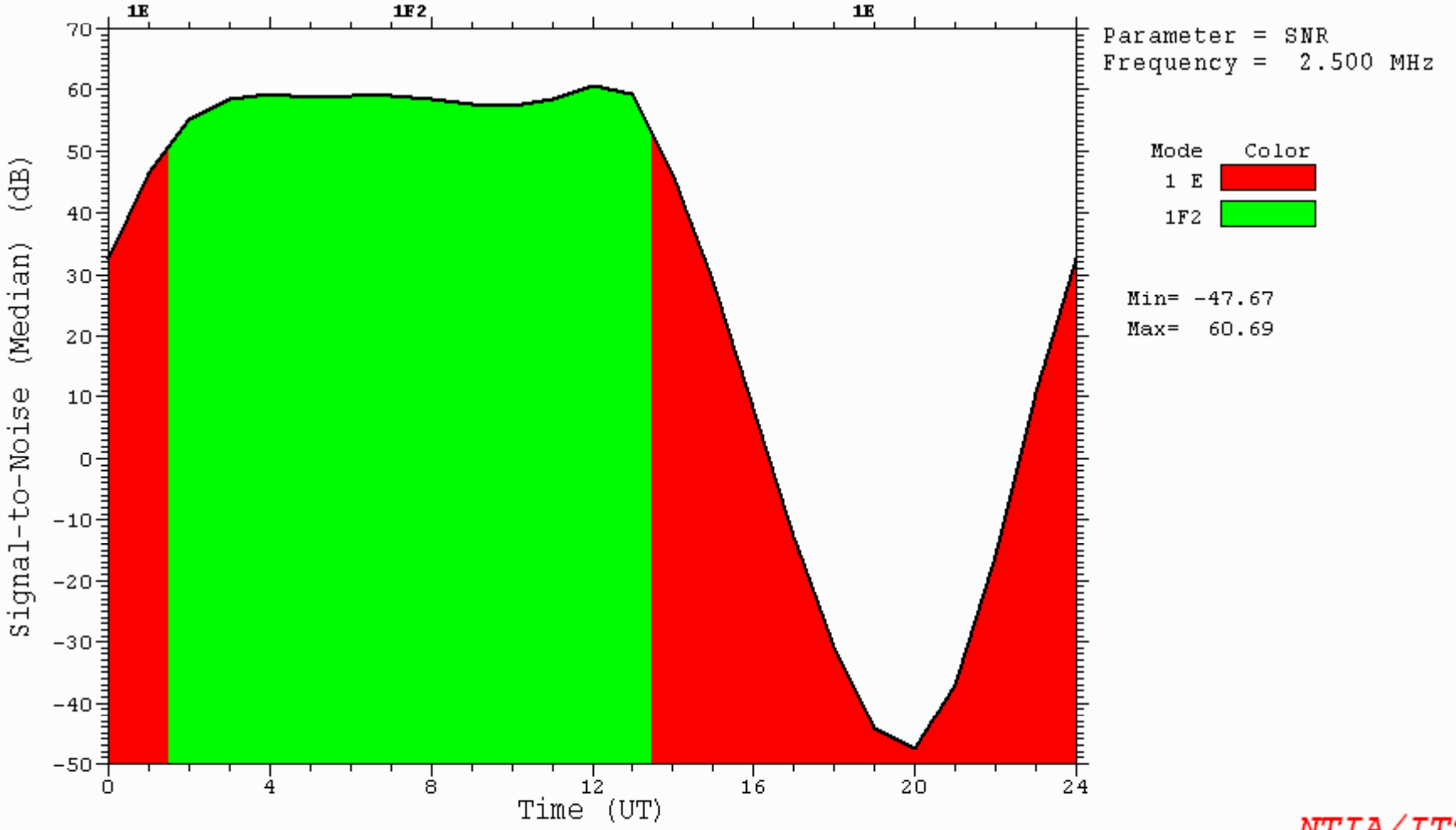


CCIR Coefficients ~METHOD 20 VOACAP 08.0121W PAGE 1

Feb 2008 SSN = 3. Minimum Angle= 0.100 degrees

WWV	Datron	AZIMUTHS		N. MI.	KM
40.68 N 105.04 W	33.15 N 117.22 W	236.09	48.74	737.8	1366.3

XMTR 2-30 HFMUFES#35[samples\SAMPLE.35] Az= 0.0 OFFaz=236.1 10.000kW
RCVR 2-30 IONCAP #23[samples\SAMPLE.23] Az= 48.7 OFFaz= 0.0
3 MHz NOISE = -145.0 dBW REQ. REL = 90% REQ. SNR = 73.0 dB
MULTIPATH POWER TOLERANCE = 3.0 dB MULTIPATH DELAY TOLERANCE = 0.100 ms



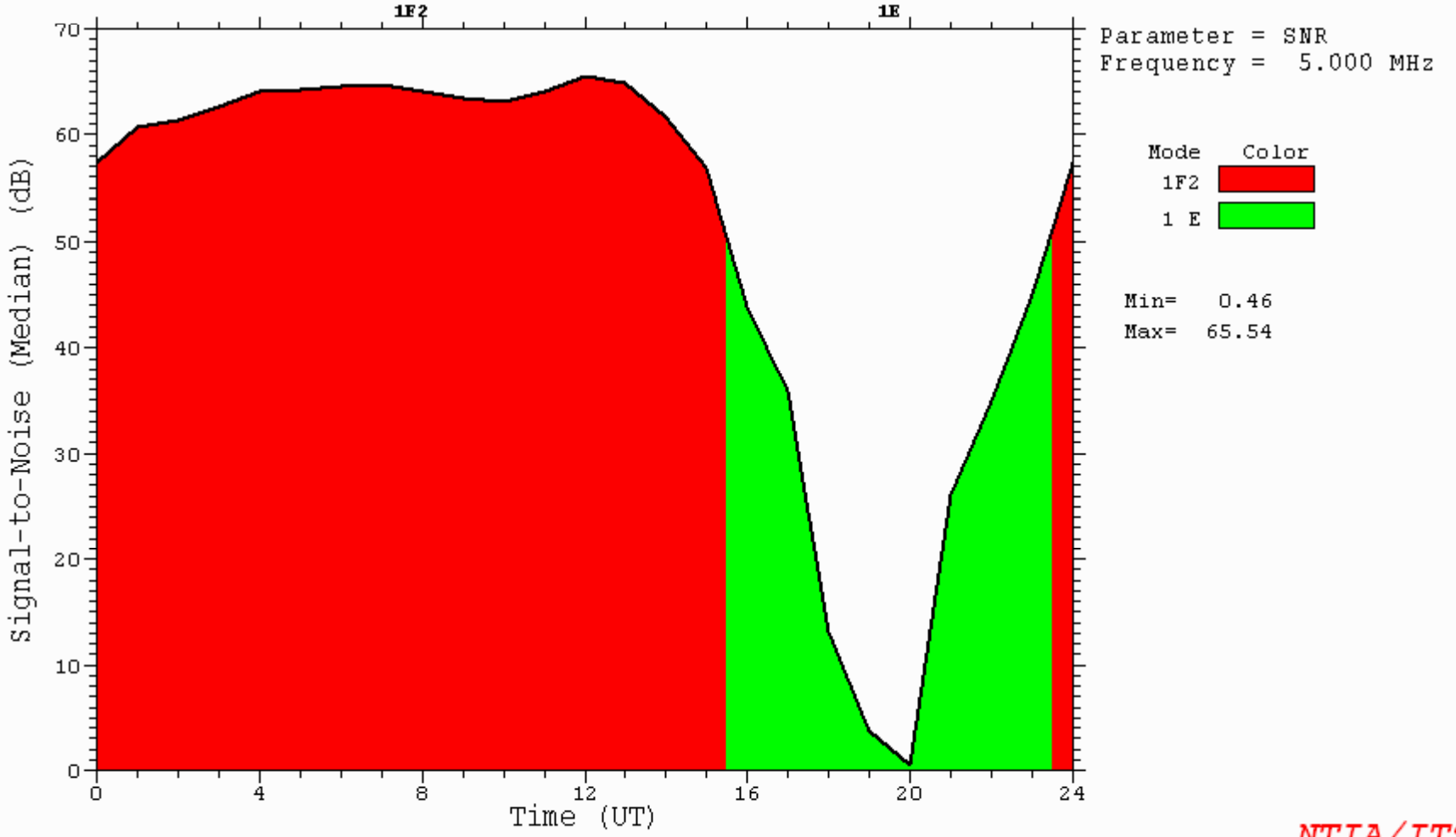
NTIA/ITS

CCIR Coefficients ~METHOD 20 VOACAP 08.0121W PAGE 1

Feb 2008 SSN = 3. Minimum Angle= 0.100 degrees

WWV	Datron	AZIMUTHS		N. MI.	KM
40.68 N 105.04 W -	33.15 N 117.22 W	236.09	48.74	737.8	1366.3

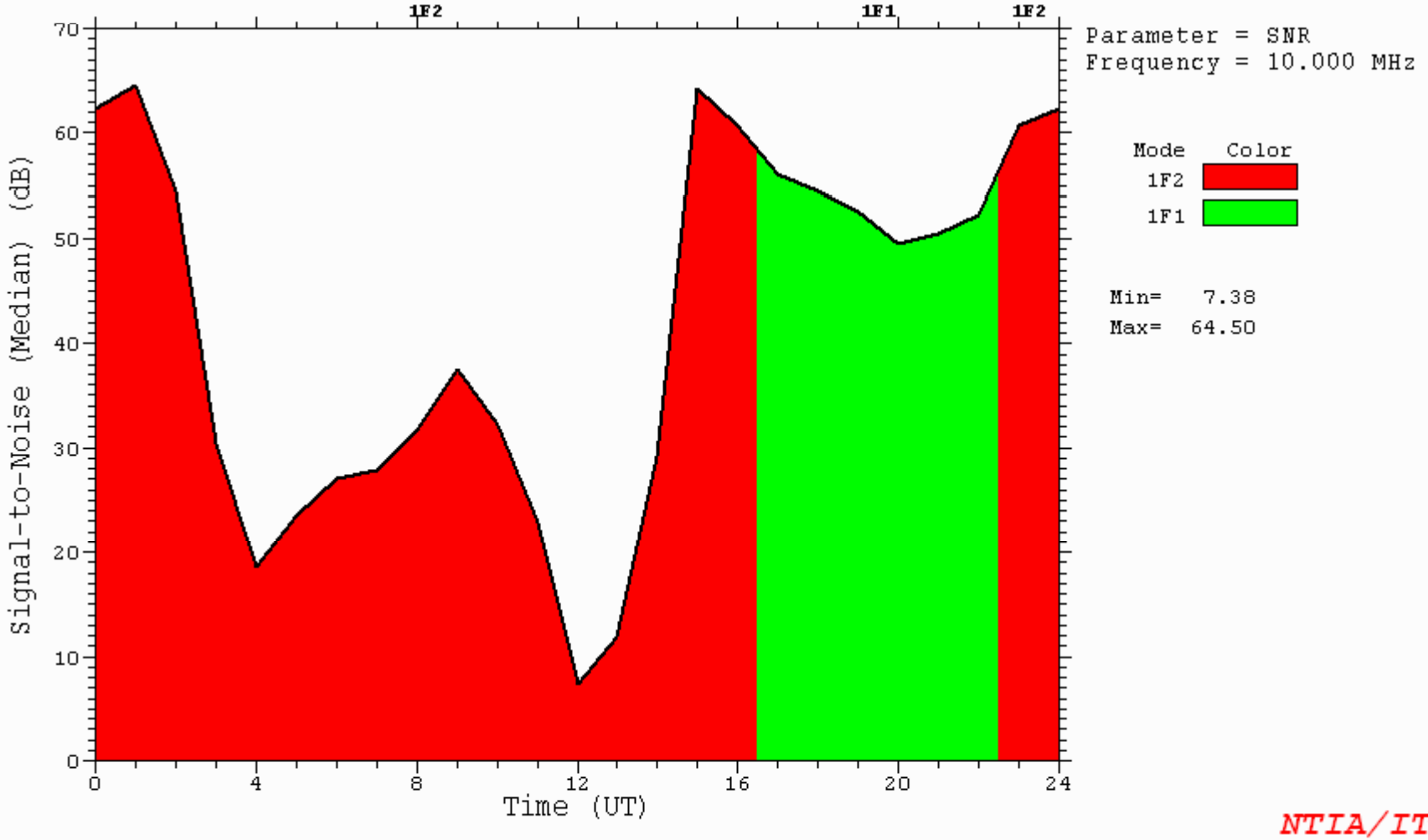
XMTR 2-30 HFMUFES#35[samples\SAMPLE.35] Az= 0.0 OFFaz=236.1 10.000kW
RCVR 2-30 IONCAP #23[samples\SAMPLE.23] Az= 48.7 OFFaz= 0.0
3 MHz NOISE = -145.0 dBW REQ. REL = 90% REQ. SNR = 73.0 dB
MULTIPATH POWER TOLERANCE = 3.0 dB MULTIPATH DELAY TOLERANCE = 0.100 ms



NTIA/ITS

```
     CCIR Coefficients          ~METHOD 20   VOACAP 08.0121W  PAGE   1

Feb    2008           SSN =   3.                 Minimum Angle= 0.100 degrees
WWV                   Datron                 AZIMUTHS          N. MI.      KM
40.68 N  105.04 W - 33.15 N  117.22 W    236.09   48.74     737.8   1366.3
XMTR  2-30 HFMUFES#35[samples\SAMPLE.35     ] Az=  0.0 OFFaz=236.1  10.000kW
RCVR  2-30 IONCAP #23[samples\SAMPLE.23     ] Az= 48.7 OFFaz=  0.0
3 MHz NOISE = -145.0 dBW     REQ. REL = 90%    REQ. SNR = 73.0 dB
MULTIPATH POWER TOLERANCE =  3.0 dB   MULTIPATH DELAY TOLERANCE =  0.100 ms
```



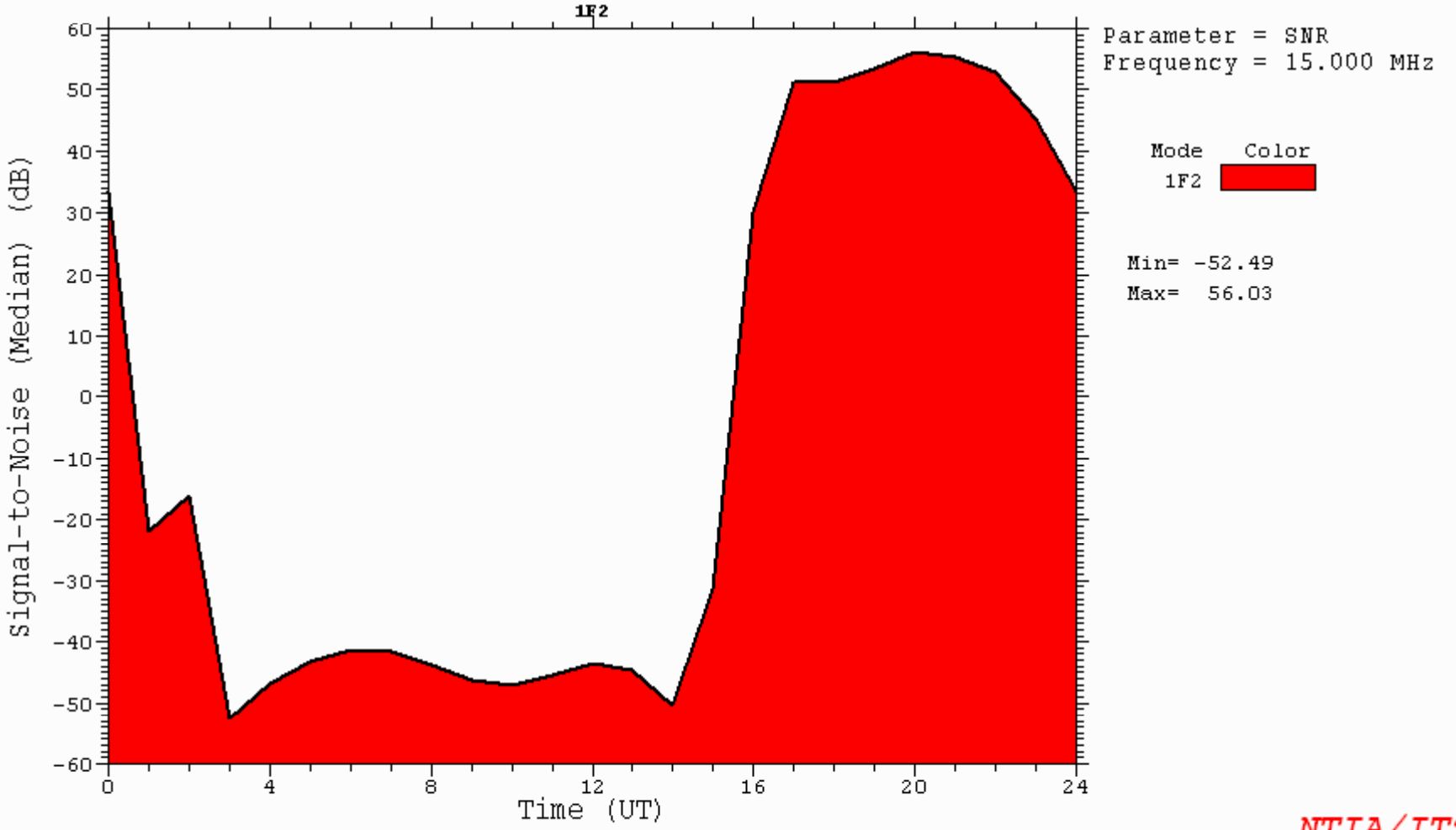
NTIA/ITS

CCIR Coefficients ~METHOD 20 VOACAP 08.0121W PAGE 1

Feb 2008 SSN = 3. Minimum Angle= 0.100 degrees

WWV	Datron	AZIMUTHS		N. MI.	KM
40.68 N 105.04 W -	33.15 N 117.22 W	236.09	48.74	737.8	1366.3

XMTR 2-30 HFMUFES#35[samples\SAMPLE.35] Az= 0.0 OFFaz=236.1 10.000kW
RCVR 2-30 IONCAP #23[samples\SAMPLE.23] Az= 48.7 OFFaz= 0.0
3 MHz NOISE = -145.0 dBW REQ. REL = 90% REQ. SNR = 73.0 dB
MULTIPATH POWER TOLERANCE = 3.0 dB MULTIPATH DELAY TOLERANCE = 0.100 ms



NTIA/ITS

VOACAP Virtual Height

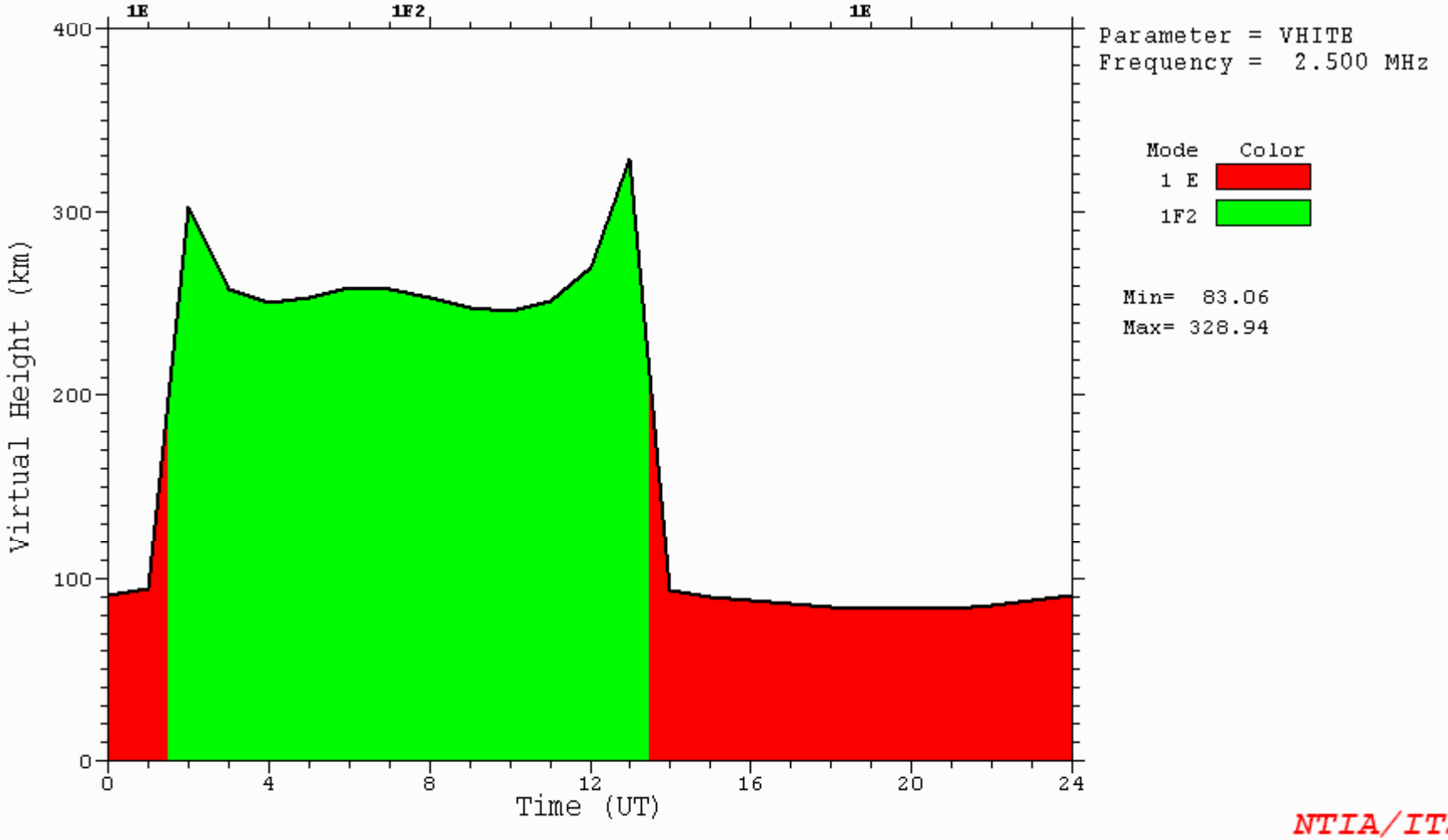
- Use VOACAP to determine the predicted Virtual Height (This was original goal of project)
- Calculate for path between Fort Collins CO and San Diego CA
- Calculate for various WWV frequencies
- Calculate using approximate antennas
- Calculate for times throughout the day during February 2008
- Calculate using current Smoothed Sun Spot Number

CCIR Coefficients ~METHOD 20 VOACAP 08.0121W PAGE 1

Feb 2008 SSN = 3. Minimum Angle= 0.100 degrees

WWV	Datron	AZIMUTHS		N. MI.	KM
40.68 N 105.04 W -	33.15 N 117.22 W	236.09	48.74	737.8	1366.3

XMTR 2-30 HFMUFES#35[samples\SAMPLE.35] Az= 0.0 OFFaz=236.1 10.000kW
RCVR 2-30 IONCAP #23[samples\SAMPLE.23] Az= 48.7 OFFaz= 0.0
3 MHz NOISE = -145.0 dBW REQ. REL = 90% REQ. SNR = 73.0 dB
MULTIPATH POWER TOLERANCE = 3.0 dB MULTIPATH DELAY TOLERANCE = 0.100 ms



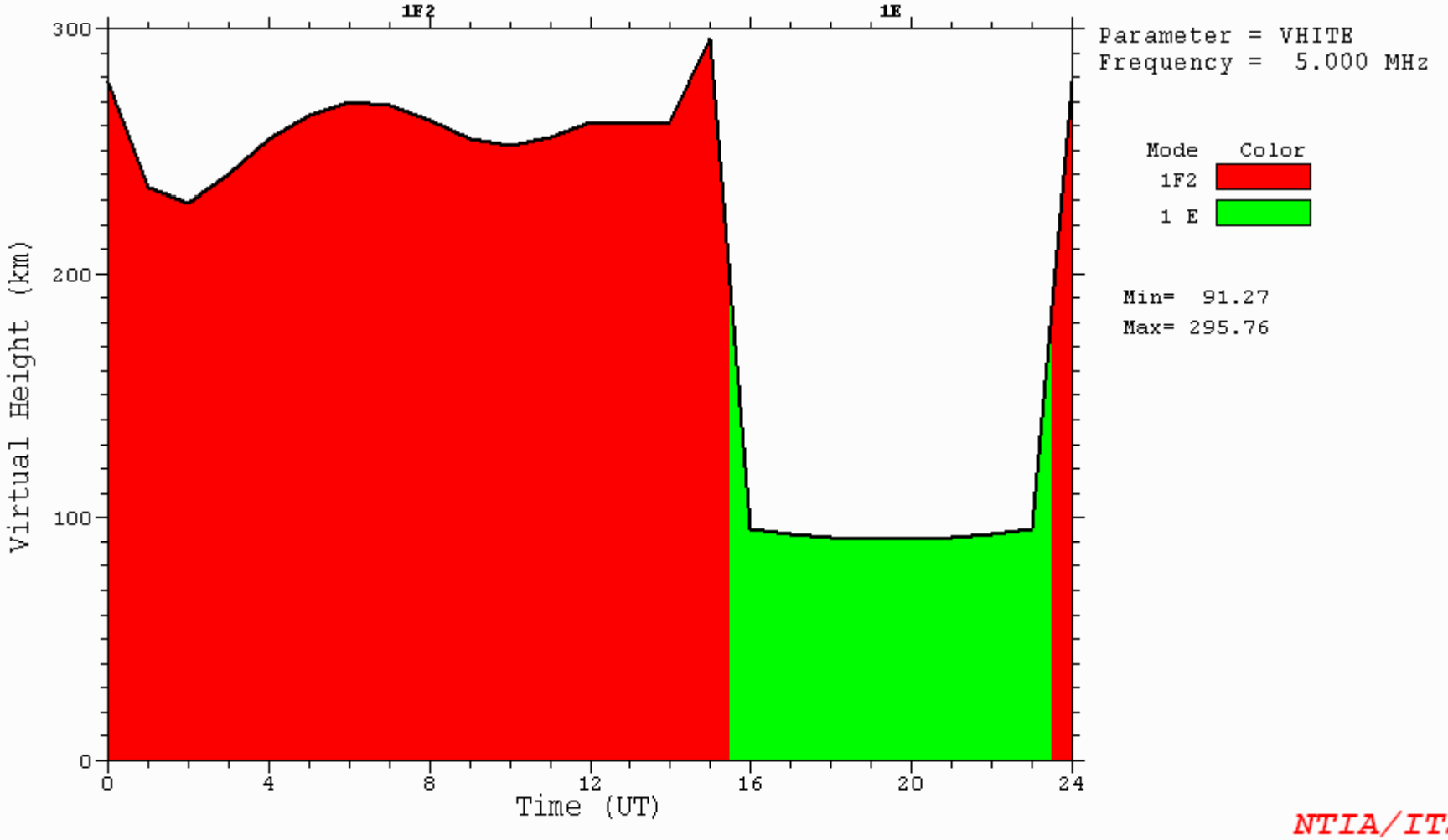
NTIA/ITS

CCIR Coefficients ~METHOD 20 VOACAP 08.0121W PAGE 1

Feb 2008 SSN = 3. Minimum Angle= 0.100 degrees

WWV	Datron	AZIMUTHS		N. MI.	KM
40.68 N 105.04 W -	33.15 N 117.22 W	236.09	48.74	737.8	1366.3

XMTR 2-30 HFMUFES#35[samples\SAMPLE.35] Az= 0.0 OFFaz=236.1 10.000kW
RCVR 2-30 IONCAP #23[samples\SAMPLE.23] Az= 48.7 OFFaz= 0.0
3 MHz NOISE = -145.0 dBW REQ. REL = 90% REQ. SNR = 73.0 dB
MULTIPATH POWER TOLERANCE = 3.0 dB MULTIPATH DELAY TOLERANCE = 0.100 ms



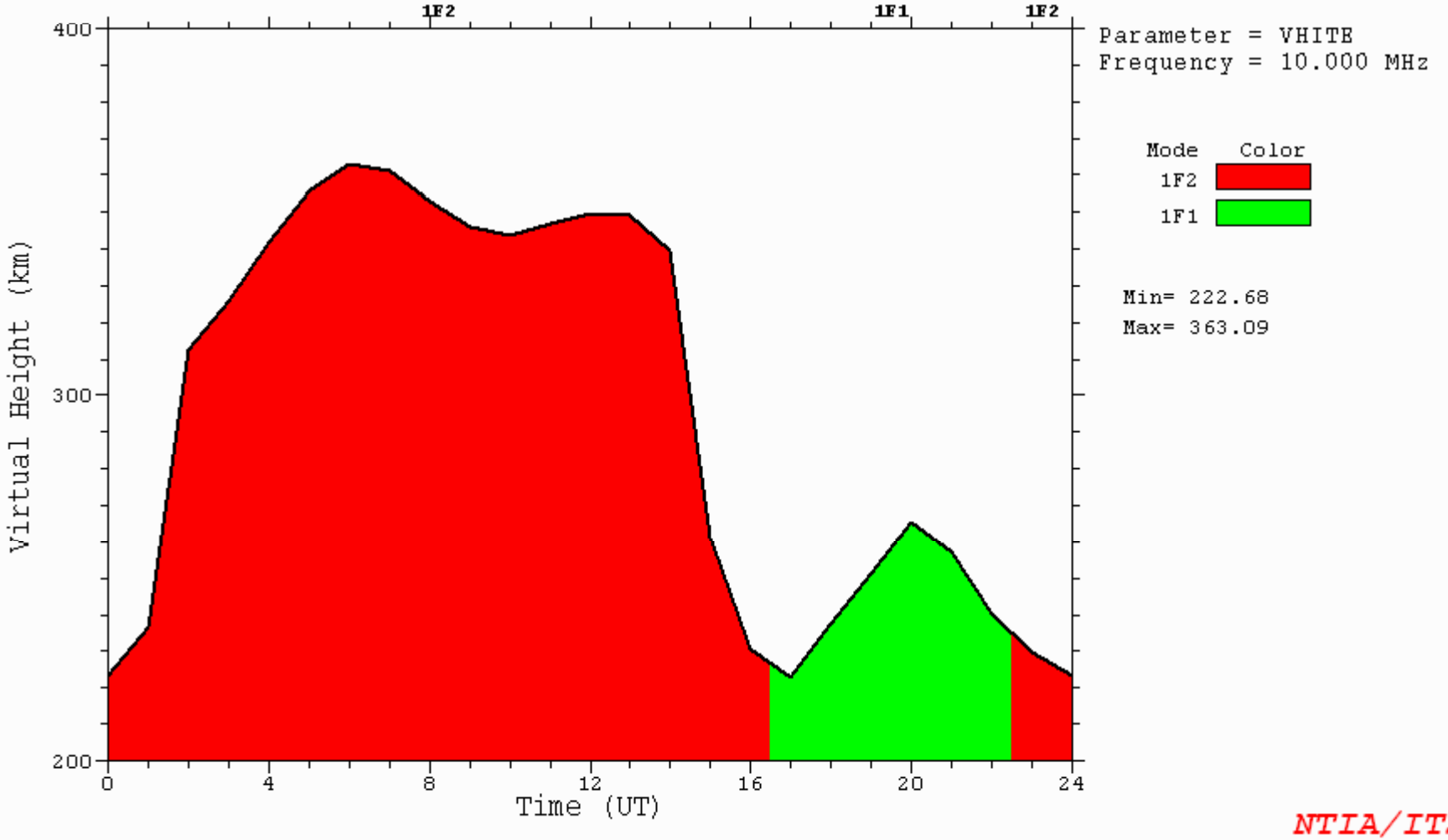
NTIA/ITS

CCIR Coefficients ~METHOD 20 VOACAP 08.0121W PAGE 1

Feb 2008 SSN = 3. Minimum Angle= 0.100 degrees

WWV	Datron	AZIMUTHS		N. MI.	KM
40.68 N 105.04 W -	33.15 N 117.22 W	236.09	48.74	737.8	1366.3

XMTR 2-30 HFMUFES#35[samples\SAMPLE.35] Az= 0.0 OFFaz=236.1 10.000kW
RCVR 2-30 IONCAP #23[samples\SAMPLE.23] Az= 48.7 OFFaz= 0.0
3 MHz NOISE = -145.0 dBW REQ. REL = 90% REQ. SNR = 73.0 dB
MULTIPATH POWER TOLERANCE = 3.0 dB MULTIPATH DELAY TOLERANCE = 0.100 ms



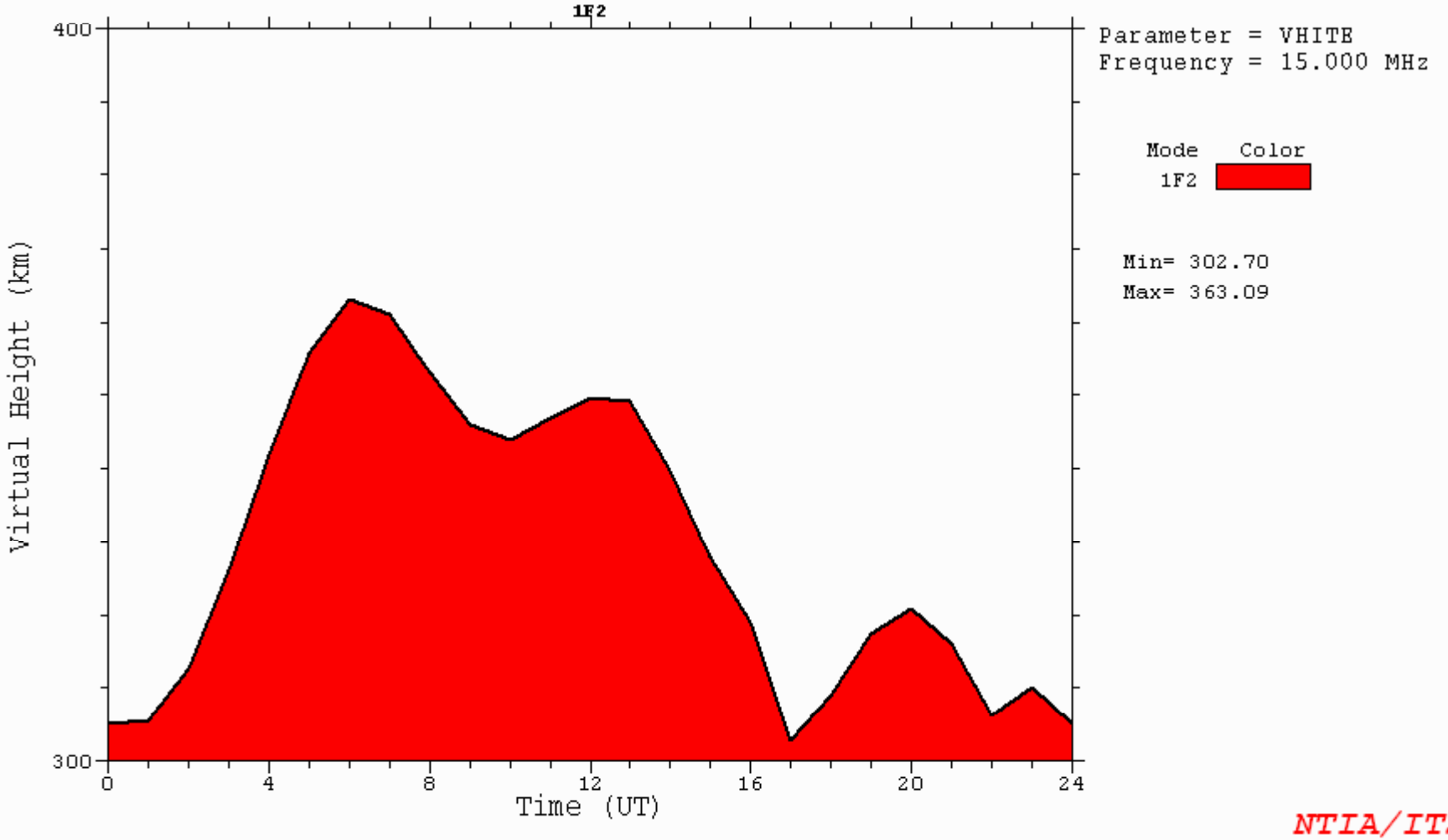
NTIA/ITS

CCIR Coefficients ~METHOD 20 VOACAP 08.0121W PAGE 1

Feb 2008 SSN = 3. Minimum Angle= 0.100 degrees

WWV	Datron	AZIMUTHS		N. MI.	KM
40.68 N 105.04 W -	33.15 N 117.22 W	236.09	48.74	737.8	1366.3

XMTR 2-30 HFMUFES#35[samples\SAMPLE.35] Az= 0.0 OFFaz=236.1 10.000kW
RCVR 2-30 IONCAP #23[samples\SAMPLE.23] Az= 48.7 OFFaz= 0.0
3 MHz NOISE = -145.0 dBW REQ. REL = 90% REQ. SNR = 73.0 dB
MULTIPATH POWER TOLERANCE = 3.0 dB MULTIPATH DELAY TOLERANCE = 0.100 ms



NTIA/ITS

VOACAP Delay

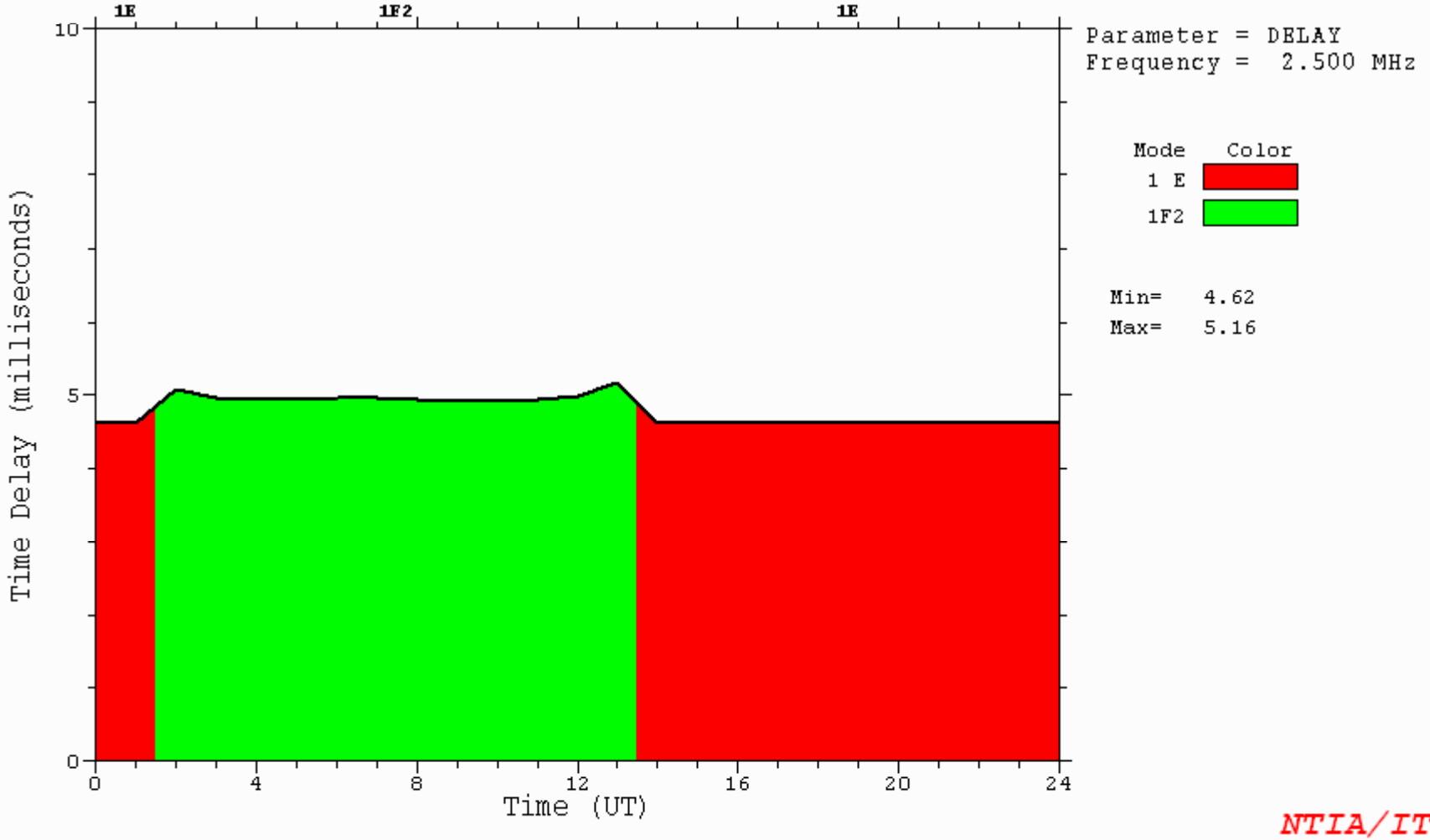
- Use VOACAP to determine the predicted Delay which can be used to determine virtual height
- Calculate for path between Fort Collins CO and San Diego CA
- Calculate for various WWV frequencies
- Calculate using approximate antennas
- Calculate for times throughout the day during February 2008
- Calculate using current Smoothed Sun Spot Number

CCIR Coefficients ~METHOD 20 VOACAP 08.0121W PAGE 1

Feb 2008 SSN = 3. Minimum Angle= 0.100 degrees

WWV	Datron	AZIMUTHS		N. MI.	KM
40.68 N 105.04 W -	33.15 N 117.22 W	236.09	48.74	737.8	1366.3

XMTR 2-30 HFMUFES#35[samples\SAMPLE.35] Az= 0.0 OFFaz=236.1 10.000kW
RCVR 2-30 IONCAP #23[samples\SAMPLE.23] Az= 48.7 OFFaz= 0.0
3 MHz NOISE = -145.0 dBW REQ. REL = 90% REQ. SNR = 73.0 dB
MULTIPATH POWER TOLERANCE = 3.0 dB MULTIPATH DELAY TOLERANCE = 0.100 ms



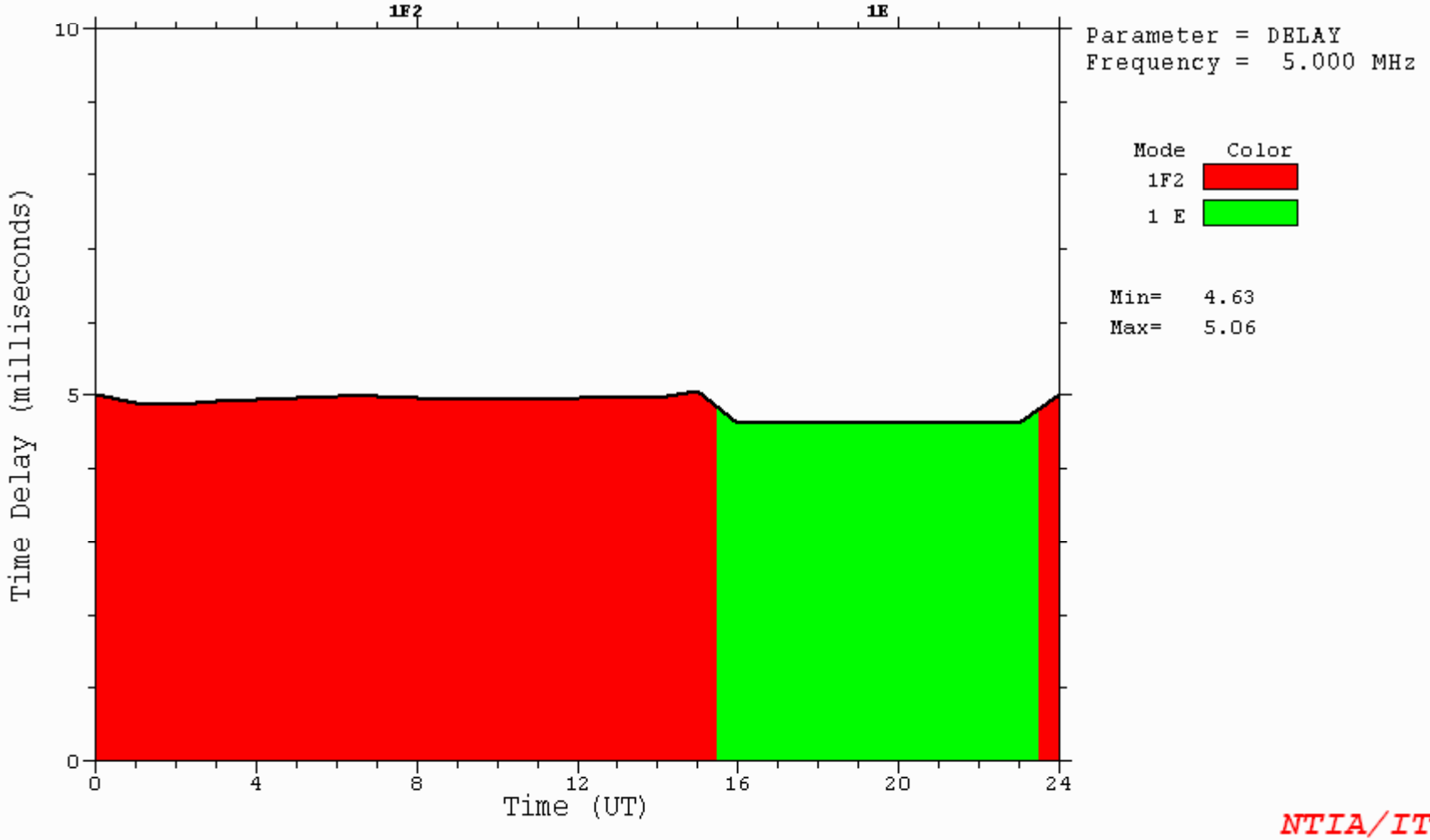
NTIA/ITS

CCIR Coefficients ~METHOD 20 VOACAP 08.0121W PAGE 1

Feb 2008 SSN = 3. Minimum Angle= 0.100 degrees

WWV	Datron	AZIMUTHS		N. MI.	KM
40.68 N 105.04 W -	33.15 N 117.22 W	236.09	48.74	737.8	1366.3

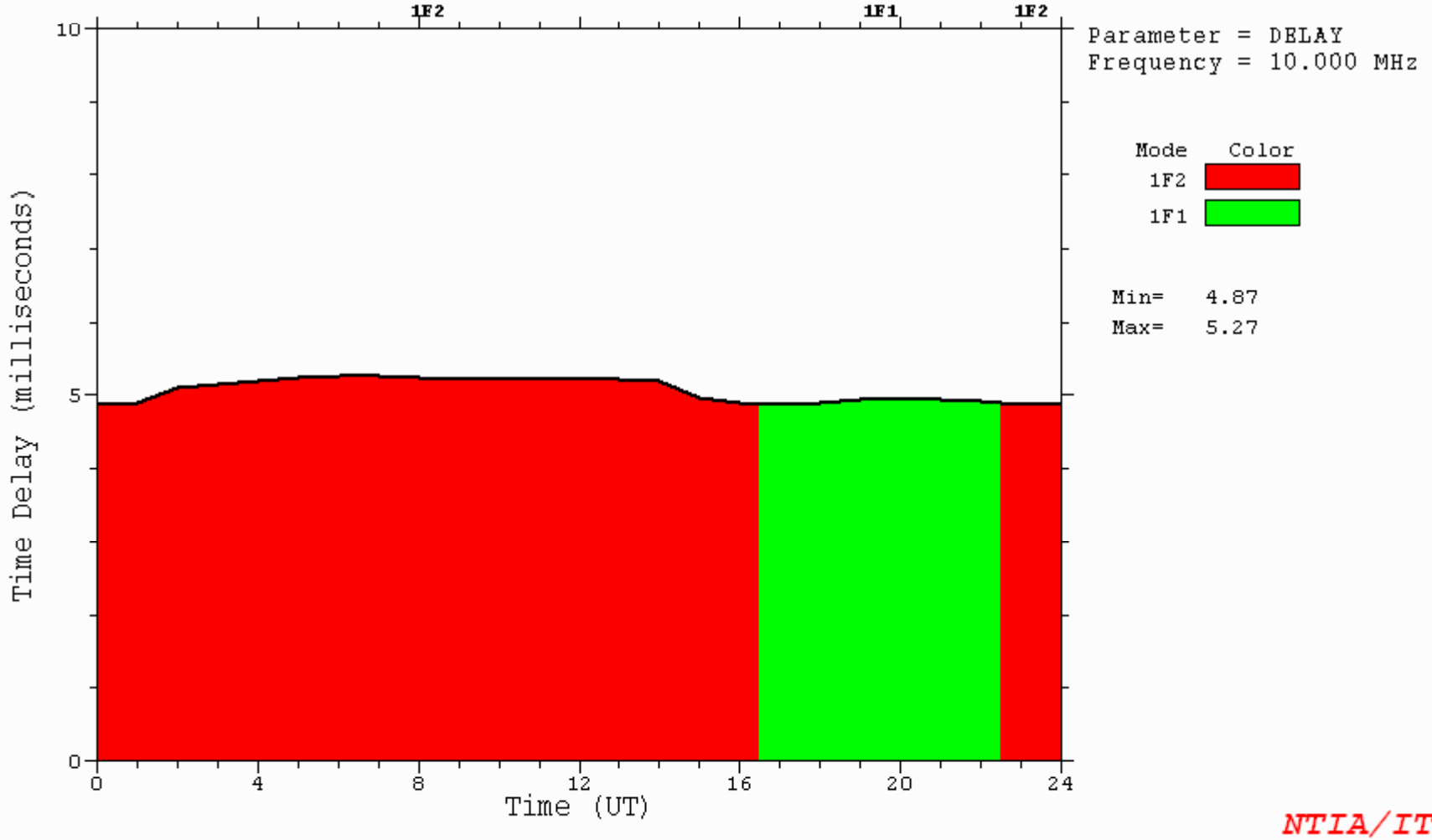
XMTR 2-30 HFMUFES#35[samples\SAMPLE.35] Az= 0.0 OFFaz=236.1 10.000kW
RCVR 2-30 IONCAP #23[samples\SAMPLE.23] Az= 48.7 OFFaz= 0.0
3 MHz NOISE = -145.0 dBW REQ. REL = 90% REQ. SNR = 73.0 dB
MULTIPATH POWER TOLERANCE = 3.0 dB MULTIPATH DELAY TOLERANCE = 0.100 ms



NTIA/ITS

```
     CCIR Coefficients          ~METHOD 20   VOACAP 08.0121W  PAGE   1

Feb    2008           SSN =   3.                Minimum Angle= 0.100 degrees
WWV                   Datron                 AZIMUTHS          N. MI.      KM
40.68 N  105.04 W - 33.15 N  117.22 W    236.09   48.74     737.8   1366.3
XMTR  2-30 HFMUFES#35[samples\SAMPLE.35    ] Az=  0.0 OFFaz=236.1  10.000kW
RCVR  2-30 IONCAP #23[samples\SAMPLE.23    ] Az= 48.7 OFFaz=  0.0
3 MHz NOISE = -145.0 dBW     REQ. REL = 90%    REQ. SNR = 73.0 dB
MULTIPATH POWER TOLERANCE =  3.0 dB   MULTIPATH DELAY TOLERANCE =  0.100 ms
```



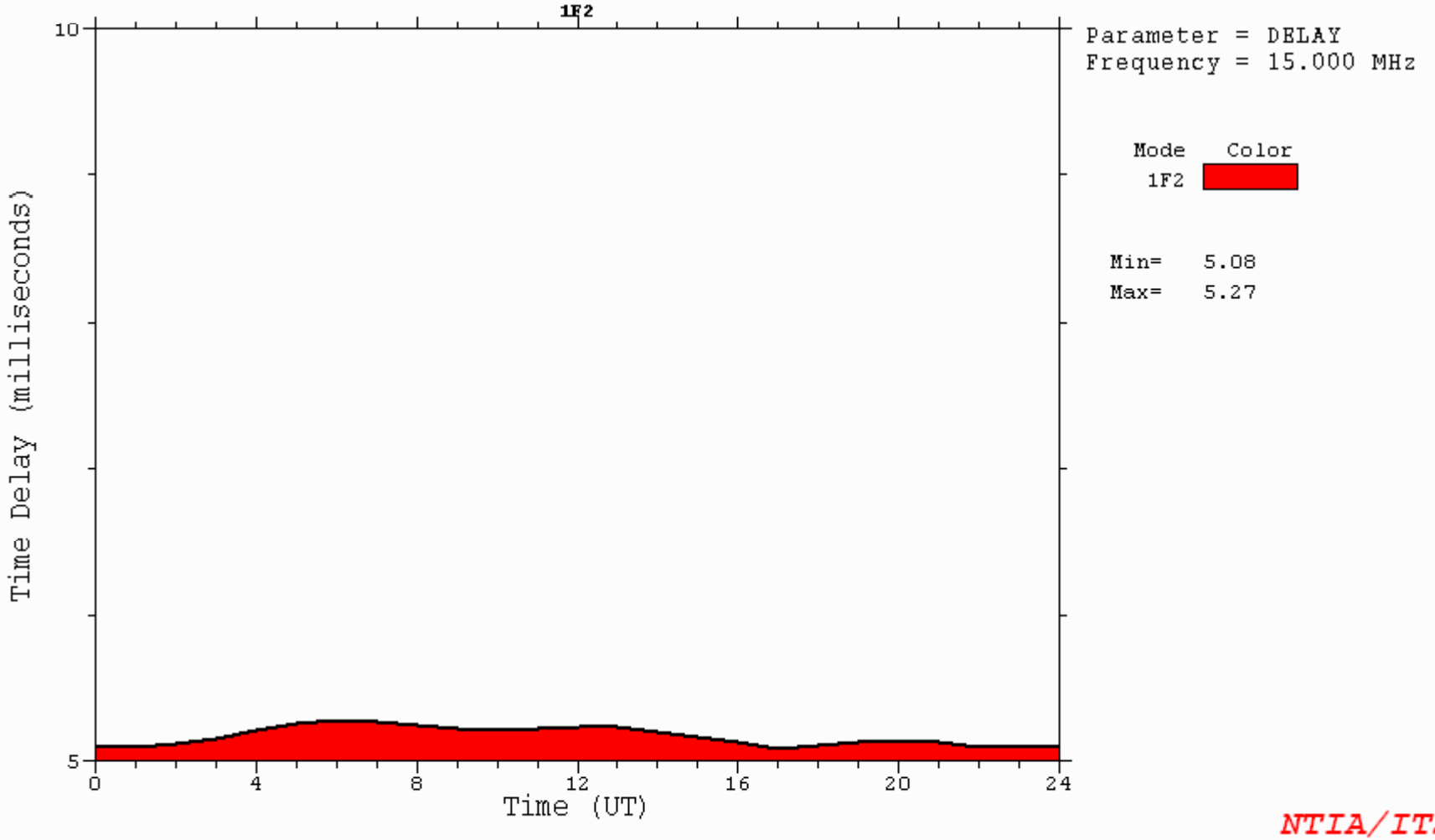
NTIA/ITS

CCIR Coefficients ~METHOD 20 VOACAP 08.0121W PAGE 1

Feb 2008 SSN = 3. Minimum Angle= 0.100 degrees

WWV	Datron	AZIMUTHS		N. MI.	KM
40.68 N 105.04 W -	33.15 N 117.22 W	236.09	48.74	737.8	1366.3

XMTR 2-30 HFMUFES#35[samples\SAMPLE.35] Az= 0.0 OFFaz=236.1 10.000kW
RCVR 2-30 IONCAP #23[samples\SAMPLE.23] Az= 48.7 OFFaz= 0.0
3 MHz NOISE = -145.0 dBW REQ. REL = 90% REQ. SNR = 73.0 dB
MULTIPATH POWER TOLERANCE = 3.0 dB MULTIPATH DELAY TOLERANCE = 0.100 ms



NTIA/ITS

Data Collection Opportunities

- Between 4UTC and 12UTC (Night)
  - 10MHz
  - 5MHz
  - 2.5MHz
- Between 19UTC and 21UTC (Day)
  - 15MHz
  - 10MHz
  - 5MHz

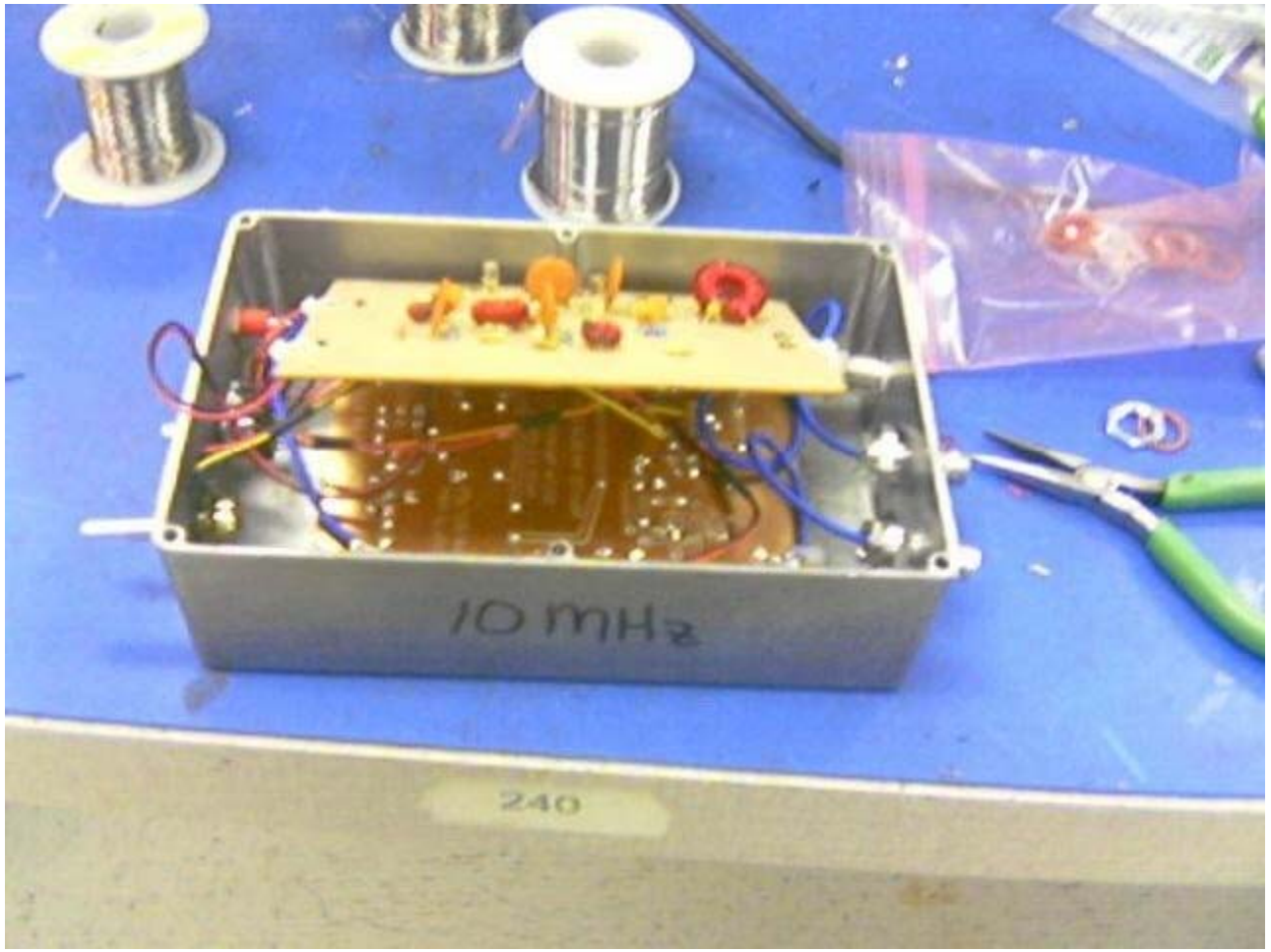
Local Timing Reference

- Praecis Cfr from EndRun Technologies
  - Provides 1PPS within 10us of UTC
  - Provides accurate 10MHz reference
  - Synchronized to CDMA network
  - CDMA network is synchronized to GPS

Custom Receiver Boxes

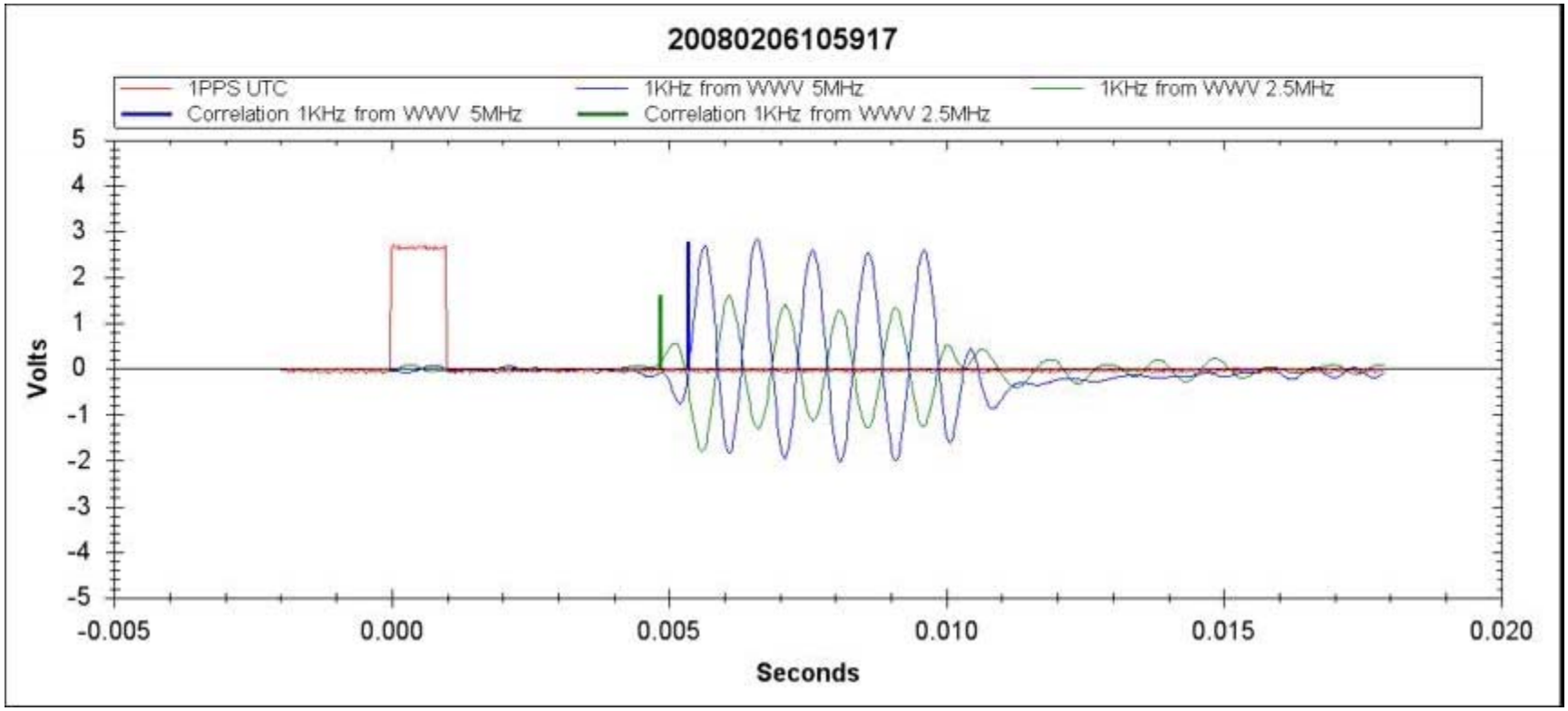
- Direct Conversion Receiver
- No LO – Constant Predictable Phase Response
- Fixed Gain – No AGC
- Based on 10MHz WWV Receiver Experiment at the Amateur and Short Wave Radio Electronics Experimenter's Web Site http://www.qrp.pops.net/wwv_receiver.asp

Custom Receiver Box Internals

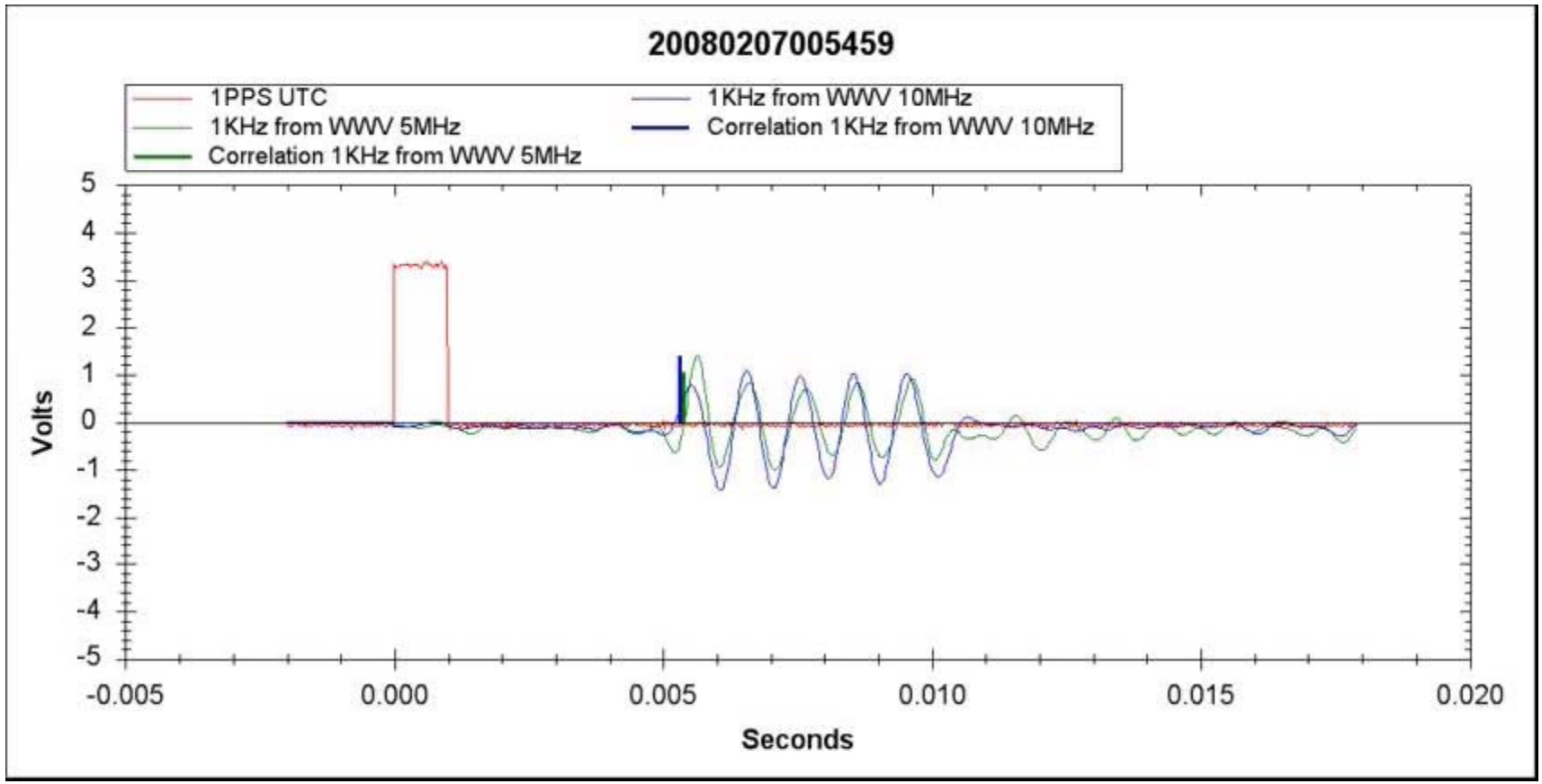


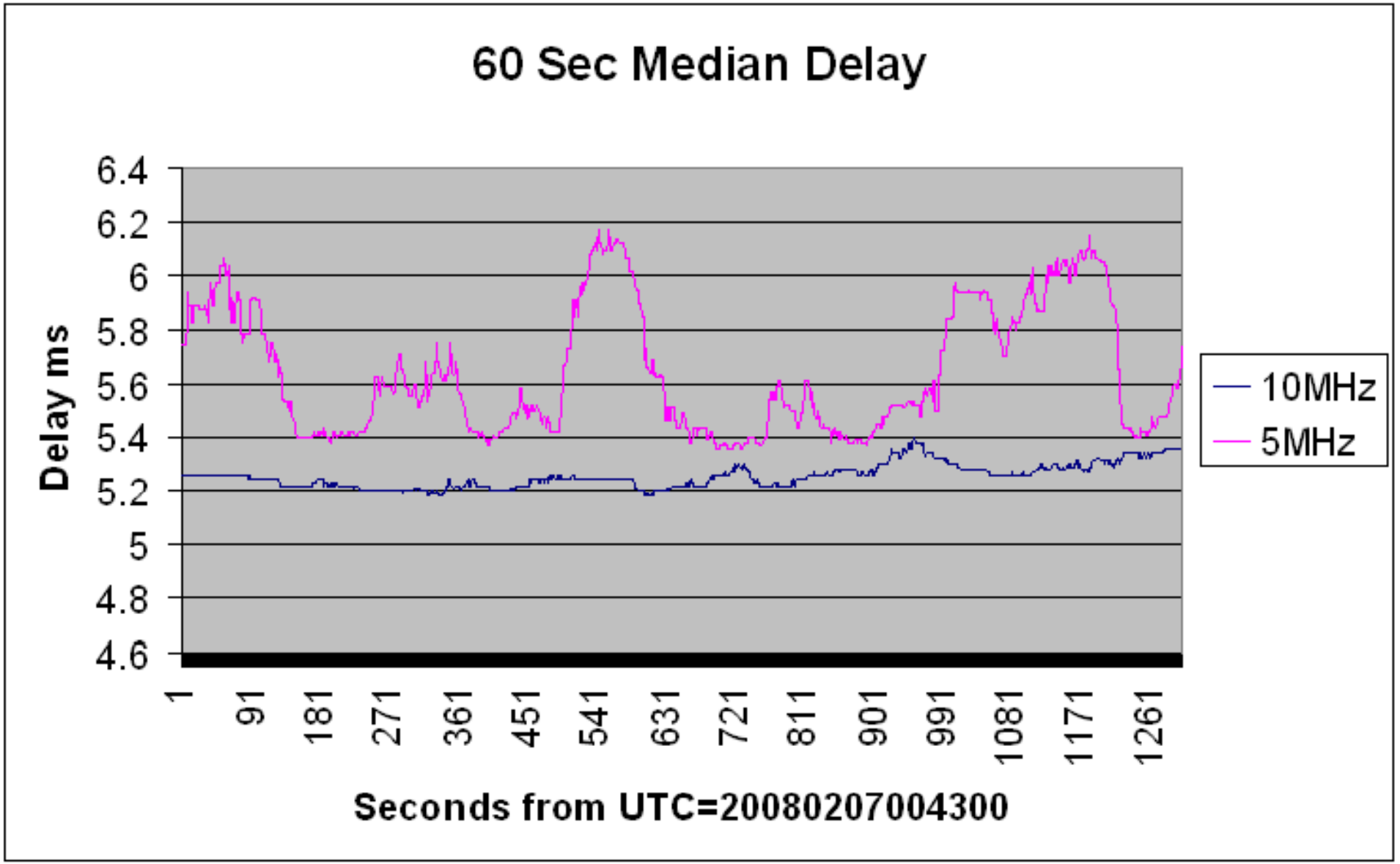
Receiver Boxes Front and Back

2.5MHz & 5MHz & 1PPS



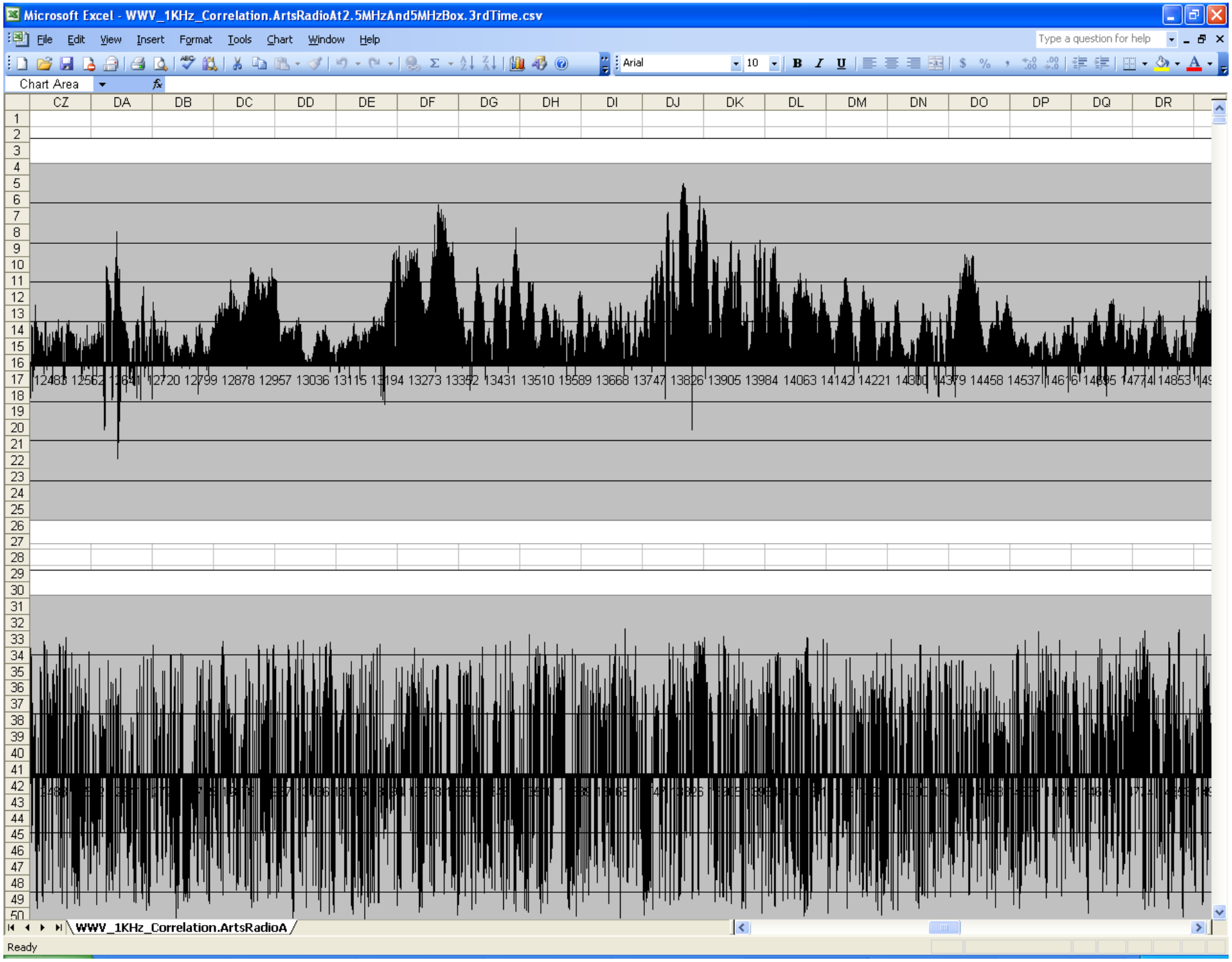
5MHz & 10MHz & 1PPS




60 Sec Median Delay
Delay ms
6.4
6.2
6
5.8
5.6
5.4
5.2
5
4.8
4.6
1
91
181
271
361
451
541
631
721
811
901
991
1081
1171
1261
Seconds from UTC=20080207004300
10MHz
5MHz

Initial Problems with Data Collection

- Inversion of Correlation
- Started with SSB radio to demodulate AM signal from WWV
- The SSB demodulation introduced phase changes because of phase drift in the LO
- Tried Shortwave AM Receiver which was better but still had problems (bottom graph next slide)
- Eventually had to use custom direct conversion receiver (top graph next slide)


Microsoft Excel - WWV_1KHz_Correlation.ArtsRadioAt2.5MHzAnd5MHzBox.3rdTime.csv
File Edit View Insert Format Tools Chart Window Help
Type a question for help
Arial 10
Chart Area
CZ DA DB DC DD DE DF DG DH DI DJ DK DL DM DN DO DP DQ DR
12483 12562 12641 12720 12799 12878 12957 13036 13115 13194 13273 13352 13431 13510 13589 13668 13747 13826 13905 13984 14063 14142 14221 14300 14379 14458 14537 14616 14695 14774 14853
WWV_1KHz_Correlation.ArtsRadioA
Ready

Impact on 110B modem signals

- 110B uses 1800Hz carrier which is similar to the 1KHz used by WWV
- Inversion of correlation would cause severe corruption of the PSK / QAM constellation
- 110B interleaves a continuous sequence of training symbols between every data symbol
- High speed modems do not do this. I've never see this before and I didn't understand why it was done until I did this experiment and realized how much the ionosphere varies and impacts signals

Future Objectives

- Improve Receivers to Collect Better Data
- Continue Collection of Data Throughout the Solar Cycle
- Try to correlate my observations with other Solar and Geophysical measurements.
- Support work to develop improved models of the Ionosphere, both statistical and predictive
- Possibly develop a kit or instructions to get other Ham's involved to collect data from multiple physical locations

Questions?