Frequency Measurement with μHz Accuracy

and some
Science and Engineering Resources Discovered during the Journey

Rev C - W2TX

The ARRL FMT

- The test is run twice each year, April and November
- The test signal is usually transmitted on three frequencies, sequentially. Ex.-20M, 40M, 80M
- On each frequency:
  - Call up: 3-5 min.
  - Key down: 2 min.
- K5CM runs other practice sessions throughout the year

How good do you have to be?

March 2016 FMT

Call	Section	Grid	Average PPX
K7HIL	AZ	DM42ph	1.11E-08
AB4RS	VA	FM18hw	1.15E-08
N3IZN	SDG	DM13ji	1.28E-08
VE3OAT	ON	FN25eg	2.36E-08
N6RDR	ORG	DM13cx	2.43E-08
W6OQI	LAX		2.45E-08
W3JW	VA	FM17tn	2.48E-08
N2GL	ORG	cn85kp	3.76E-08
WA2DVU	SNJ	FM29NC	4.15E-08
VE3GSO	ON	EN92JX	4.22E-08
W4JLE	SC	EM96	4.58E-08
K3KO	NFL	EM90	4.64E-08
VE2IQ	ON	FN15nt	4.69E-08
W2TX	SFL	EL97qw	5.86E-08

- 1x10exp-08 over sky-wave is possible if you have stable ionospheric conditions
- Doppler shifts of up to 0.5 Hz are common, however

How good do you have to be?

- K5CM measures his transmissions to 0.001 Hz.
- To be in the competitive range in 2016, you need to be able to measure all three frequencies to within about 0.01 Hz.
- 0.1 Hz accuracy on all three frequencies might get you in the top 20
- It is not easy! Frequently there are reports submitted that are KHz off.

My First FMT

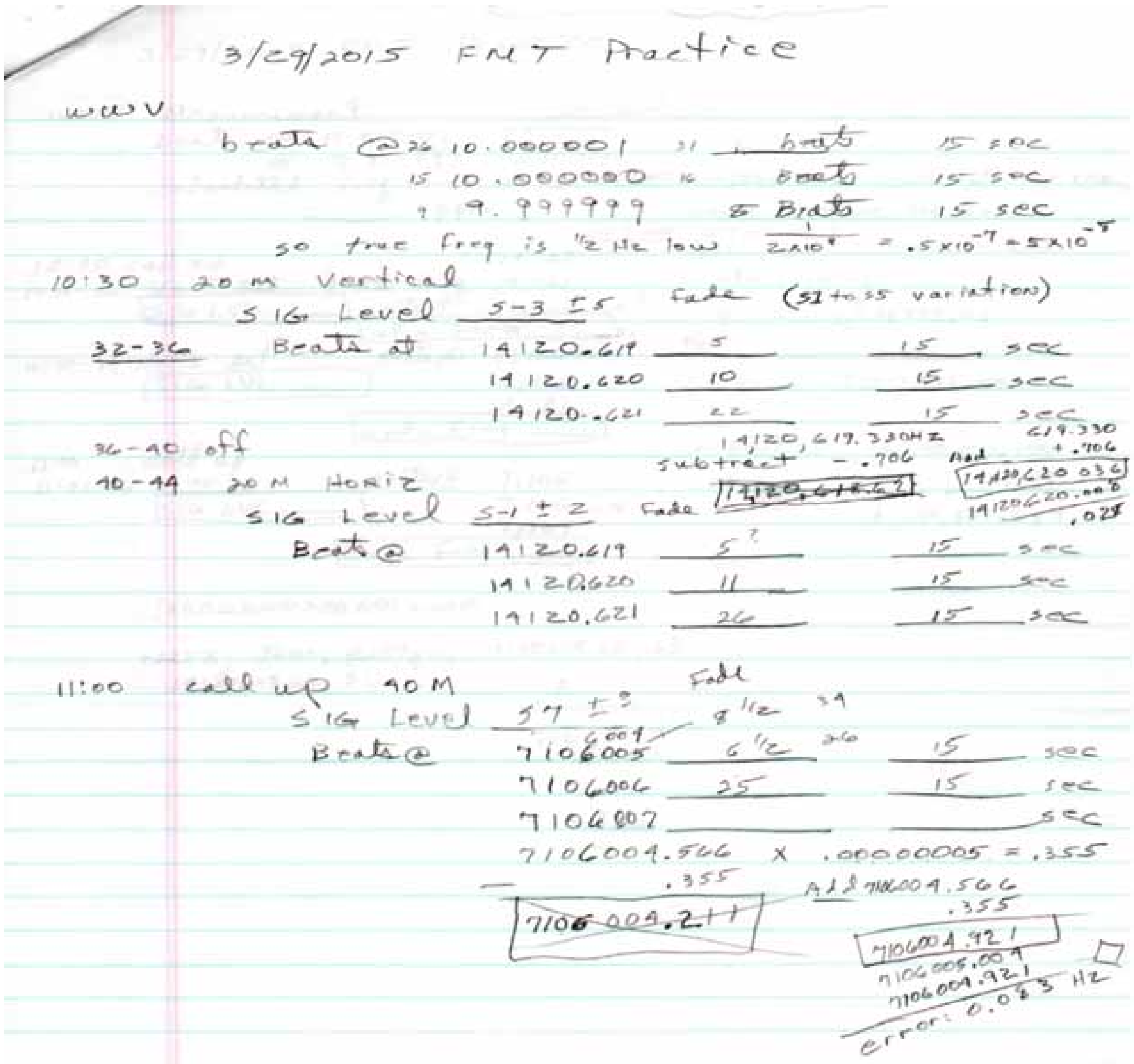
- My station assets
  - FTdx-5000
    - Fully synthesized
    - Can be tuned in 1 Hz steps
    - All internal injection oscillators are phase-locked to the radio's master oscillator
    - The SPOT function generates a tone of known frequency so that by matching a received signal's audio tone (by tuning the radio), the radio displays the received signal's frequency
  - Need some type of timebase for frequency resolution finer than 1 Hz

Equipment used in my first FMT

My First FMT-Method

- Find the FMT signal. The approximate frequency is announced in advance
- Tune the radio in 1 Hz steps while activating the SPOT signal, tune for lowest beat note (less than 1 Hz)
- Set the radio just below the FMT signal. Count the beat notes in a defined time period. Set the radio just above the FMT signal and repeat.
- Extrapolate to estimate the exact frequency

First FMT-Method



3/29/2015 FMT Practice

WWV

beats @ 26 10.000001 31 beats 15 sec
15 10.000000 16 beats 15 sec
9 9.999999 8 Beats 15 sec
so true freq is ½ Hz low $\frac{1}{2\times10^7} = .5\times10^{-7} = 5\times10^{-8}$

10:30 20 m Vertical
SIG Level 5-3 ±5 Fade (S1 to S5 variation)
32-36 Beats at 14120.619 5 15 sec
14120.620 10 15 sec
14120.621 22 15 sec
14120,619.330 Hz
36-40 off subtract -.706
40-44 20 M Horiz ~~14120,618.62~~
SIG Level 5-1 ± 2 Fade
Beat @ 14120.619 5? 15 sec
14120.620 11 15 sec
14120.621 26 15 sec

619.330
+.706
Add 14120,620 036
14120620.008
.028

11:00 call up 40 M
Fade
SIG Level 57 ±3 8½ 39
Beats @ 7106005 (6004) 6½ 26 15 sec
7106006 25 15 sec
7106007 sec
7106004.566 X .00000005 = .355
− .355
~~7106 004.211~~
Add 7106004.566
.355
7106004.921
7106005.004
7106004.921
error: 0.083 Hz

First FMT-Capabilities

- Radio’s reference frequency-WWV
  - 2.5, 5, 10, 15, or 20 MHz.
  - Accuracy of the received WWV depends….
    - Time of day and solar activity can affect how stable the ionospheric reflection is
    - Vertical movement of the ionosphere translates into Doppler shift of the signal
    - Doppler shifts of up to 0.5 Hz are common
- Clock – it was a Timex! I estimate that I can define a 10 second interval +/- 0.25 sec. Might contribute 0.1 Hz error

First FMT - Results

- Out-of-town for the official FMT, but participated in a practice test on 29 March, 2014
- 20M: my error was 0.032 Hz., or 2.3 x 10exp-9
- 40M: my error was 0.084 Hz., or 1.18 x 10exp-8
- Experience would later tell me that I must have had very good propagation conditions, along with a huge measure of beginner's luck
- Lesson learned:
  - Easy to make a mistake in the rush of making a measurement-a simpler process is better
  - Think through what you want to do and make a form that allows you to just fill in the blanks

The Learning Phase

- FTdx-5000 issues
  - I bought the service manual CD for my radio
  - Its OCXO can only be set in approximately 0.1 Hz increments. This contributes a constant ppm error.
  - The DSP circuitry is clocked by a separate, free-running, crystal oscillator at 18.432 MHz divided down to 72 KHz-another source of error
  - Product detection occurs within the DSP at the 30 KHz IF.
  - Subsequent testing suggests the DSP error is -0.12 Hz.
- Clock issues
  - need a simpler way to make fractional-Hz measurements
- Reference frequency issues
  - WWV has Doppler shift
  - Internal oven has warm-up drift

How to Improve?

- Did not want to modify the FTdx-5000 for this “science project”.
  - Need to remove or compensate for the DSP frequency error
  - Decided to resurrect my RF-590
- Discovered the existence of Spectrum Lab SW
- Reference frequency:
  - Something more accurate than WWV reception
  - Need a plan/method to keep it calibrated
  - Improved settability

Spectrum Lab (SL) SW

- Free SW discussed in April 2015 QST article on the FMT
- Uses a computer’s sound card (another oscillator!) to digitize the radio’s audio output
- Sound card oscillator can be calibrated using an audio tone of known frequency-use WWV
- SL uses FFT’s to analyze the audio signal
- Can be configured to provide very fine frequency resolution

Fun with SL

- Decided to "practice" using SL by measuring AM station carrier frequencies.
  - Found two stations that had suspiciously constant carrier frequencies! I later discovered they are GPS-locked
  - Found one station that was initially outside the FCC limit!
- Made my first measurements of Doppler shift of WWV and CHU transmissions

Nearby AM Stations

				8/28/2015	
Freq(KHz)	Call	City	Pwr (KW) Day/Night	Error (Hz)	Comments
540	WFLF	Orlando	50/46	-0.82	
580	WDBO	Orlando	5/5	-0.92	
670	WWFE	Miami	50/1	+9.39	
840	WPGS	Mims	1/-	-1.31	
920	WDMC	Melbourne	5/1	-7.85	
1030	WONQ	Oviedo	45/1.7	-0.5	
1060	WIXC	Titusville	50/5	+2.44	
1160	WIWA	St. Cloud	2.5/0.5	-3.5	
1240	WMMB	Melbourne	1/?	-0.12	GPS locked?
1350	WMMV	Cocoa Beach	1/1	-0.12	GPS locked?
1370	WZTA	Vero Beach	1/0.074	+2.47	
1490	WTTB	Vero Beach	1/?	-7.58	
1510	WWBC	Cocoa Beach	50/25	+2.48	
1560	WLZR	Melbourne	5/-	-1.20	
1590	WPSL	Port St. Lucie	5/0.063	-9.13	
1700	Haiti?			+14.56	

Notes:

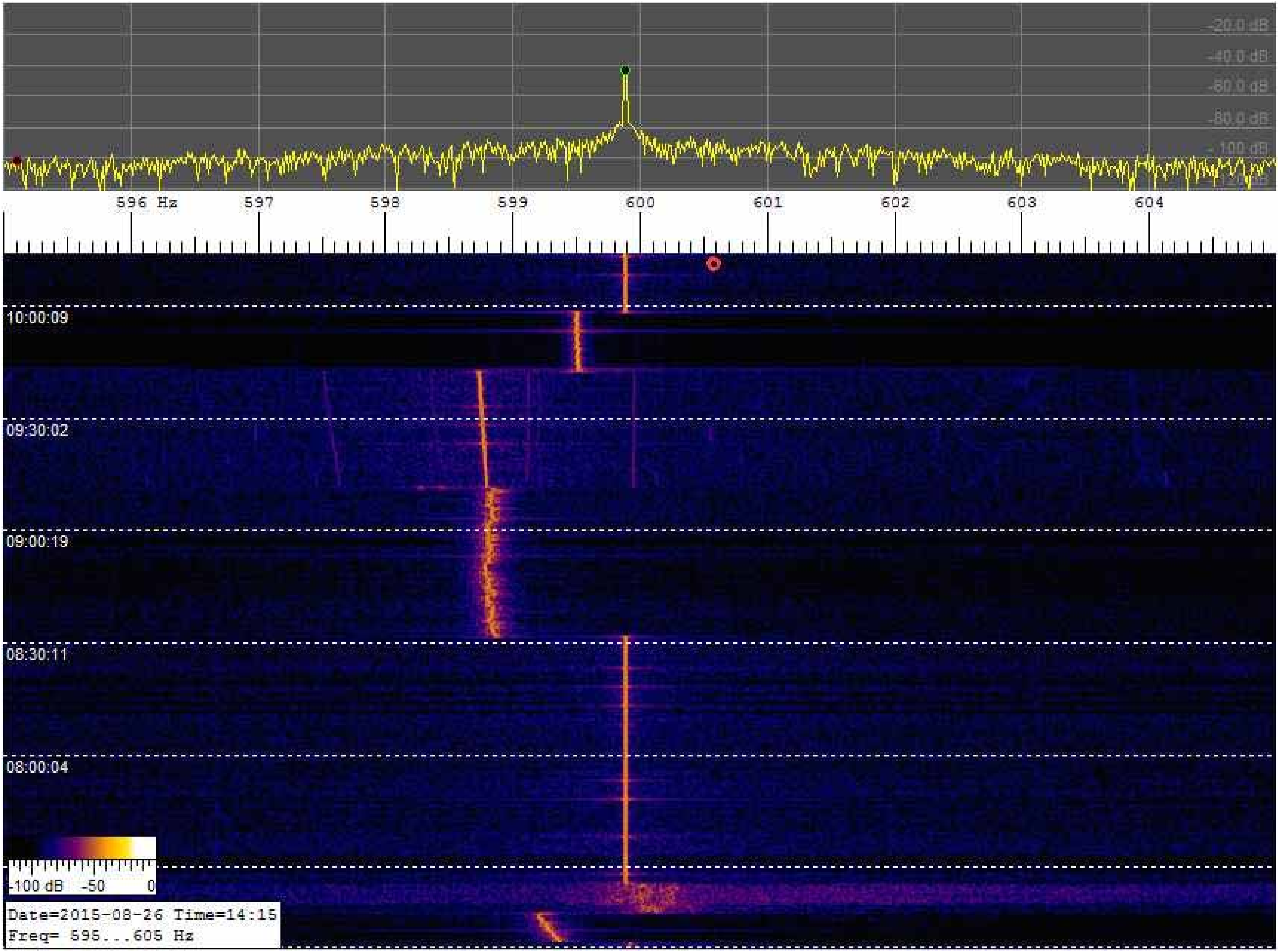
1. FCC requirement for AM Broadcast is to be within +/-20 Hz

The following are notes for the 08/28/2015 data:

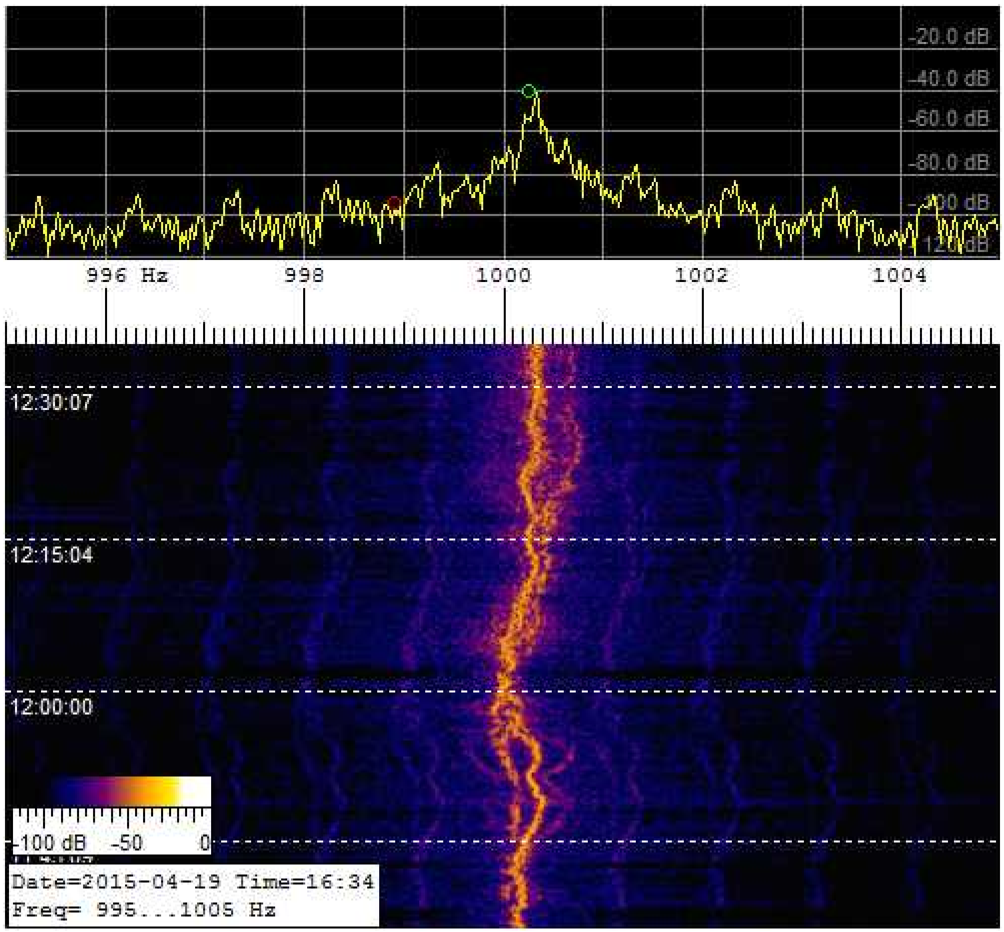
2. Radio used was FTdx-5000, 1 Hz tuning resolution. CW mode was used, with a -500 Hz BFO frequency.

3. The audio output of the FTdx-5000 is fed into a PC timecard that has been calibrated to within 0.01 Hz by measuring WWV's 500 Hz tone for successive 45 second periods. SpectrumLab software is used to analyze the audio. Typically Fc=500 and sp=+/- 10 Hz. Sampling rate = 8000 and FFT bin size = 524,288.

4. Total measuring equipment error is believed to be about +/- 0.03 Hz. ?



-20.0 dB
-40.0 dB
-60.0 dB
-80.0 dB
-100 dB
596 Hz
597
598
599
600
601
602
603
604
10:00:09
09:30:02
09:00:19
08:30:11
08:00:04
-100 dB -50 0
Date=2015-08-26 Time=14:15
Freq= 595...605 Hz


-20.0 dB
-40.0 dB
-60.0 dB
-80.0 dB
996 Hz
998
1000
1002
1004
12:30:07
12:15:04
12:00:00
-100 dB
-50
0
Date=2015-04-19 Time=16:34
Freq= 995...1005 Hz

Problems SL Cannot Fix

- Cannot correct for the radio's oscillator errors
- Long-term calibration depends on a constant sound card crystal oscillator frequency. However, that oscillator's frequency is affected by
  - Temperature changes
  - Mechanical vibration (PC's fan, disc drives)
  - Crystal aging/drift
- The result is a fair amount of drift and "jitter" on the measured frequency

Harris RF-590 Receiver

- All analog-no DSP , avoids the DSP clock issue
- All oscillators used for frequency conversion are phase-locked to a master oscillator operating at 40 MHz. The master oscillator is locked to an internal OCXO at 1, 5 or 10 MHz.
- The master oscillator can, instead, be phase-locked to an <u>external</u> frequency reference at 1, 5, or 10 MHz.

Frequency Standards

Type	Cal. Accuracy	Aging/day	Aging/60 days	Cost-new	Cost-used	Comments
1 MHz OCXO	1x10exp-7	1x10exp-8	6x10exp-7	~$200	$20-$50	"stiction"; periodic cal
10 MHz OCXO	1x10exp-8	1x10exp-8	2x10exp-7	~$200	$20-$50	"stiction"; periodic cal
Rubidium	~10exp-11	5x10exp-13	3x10exp-11		$200-$1200	Needs periodic cal; portable
GPSDO	no cal required				~$100-$300	Derived from NBS; continually corrected; requires an antenna

RF-590

November 2015 FMT

- Used RF-590 with GPSDO
- Used Spectrum Lab SW with the sampling rate (SR) calibrated against WWV’s 500 Hz AM signal
- Prepared a data entry sheet beforehand
- Procedure used:
  – Tuned to FMT signal
  – Recorded the Receiver’s frequency
  – Recorded the peak frequency reading from SL
  – Let Excel perform the calculations

Nov 2015 FMT Results

W2TX

	160m	80m	40m
	1,841,988.57	3,598,131.22	7,064,322.29
	0.00	**0.00**	**-0.08**

Remaining issues

- Accuracy, at this point in time, mainly depended on accuracy of the sound card's sampling rate calibration
- Calibration process was tedious and repetitive due to wandering of the cheap oscillator in the sound card.
- SL has a continuous sampling rate correction option
- Decided to invent GPSDO-BOB

GPSDO-BOB

- Driven by GPSDO 10 MHz output
- Provides multiple outputs
  - 10 MHz sine and square-wave
  - 5 MHz square wave
  - 1 MHz sine and square-wave
  - 100 KHz square-wave (old-timey calibrator)
  - 500 Hz sinewave for continuous sound card calibration routine
    - Found that this routine doesn't work very well, don't understand why

GPSDO-BOB Assembly

- Used PCBExpress schematic capture and PCB layout tools
- Made bulk resistor, capacitor, and connector purchases from China (E-Bay)
- Semiconductors from Mouser and Digi-Key

Further Improvement

- Equipment is good enough to do very well in FMT
- RF-590 (5 PLL's) and the sound card sampling rate calibration were thought to be the largest remaining sources of error.
- Total error thought to be in range of tenths of millihertz.
- What might be possible? Could I get to uHz accuracy? I went off the deep end…..

Sound Card PLL

- Sound card oscillator is a 24.576 MHz cheap (<$5) crystal oscillator. When divided by 512 it provides a 48 KHz sampling clock, etc.
- The Sound Card PLL locks a quality 24.576 MHz crystal oscillator to the 10 MHz GPSDO
- Used to replace the crystal on the sound card
- Sound card sampling rate calibration is now "plug-and-play" and extremely accurate.

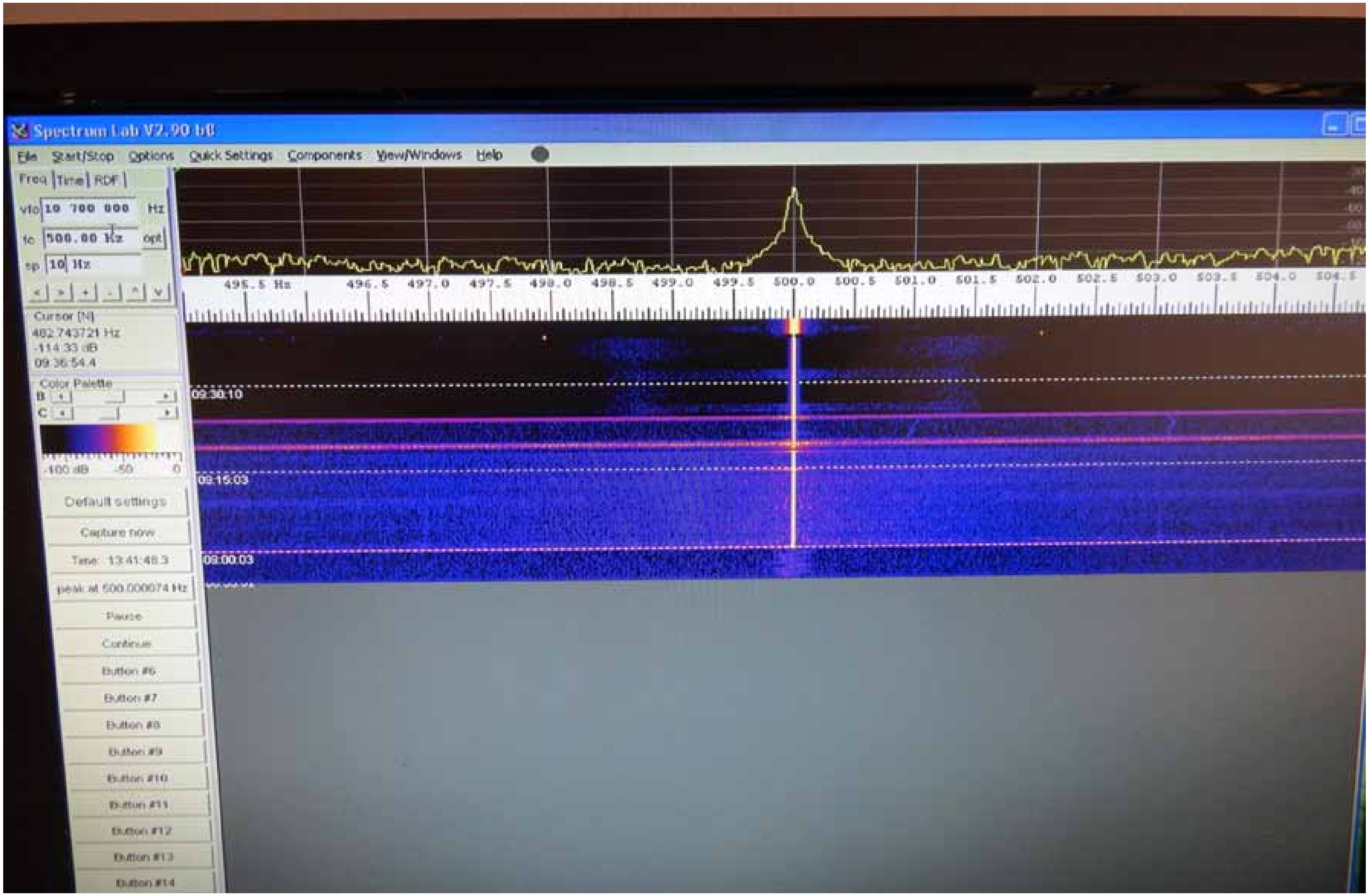
Sound card PLL

- Used a parallel entry PLL chip-1980’s thru-hole technology, but simple
- 10 MHz input, 24.576 MHz output
- Sound card clock is now exactly on frequency-no calibration required

Results

- Very preliminary data suggests I can measure a (1.24 MHz) frequency to within 5x10exp-13, or an error of .62 uHz
- This was done by measuring the WMMB carrier for 90 minutes, and plotting the Allan Deviation
- Longer term data analysis needed to better characterize my measurement setup

SL Measurement of WMMB Carrier



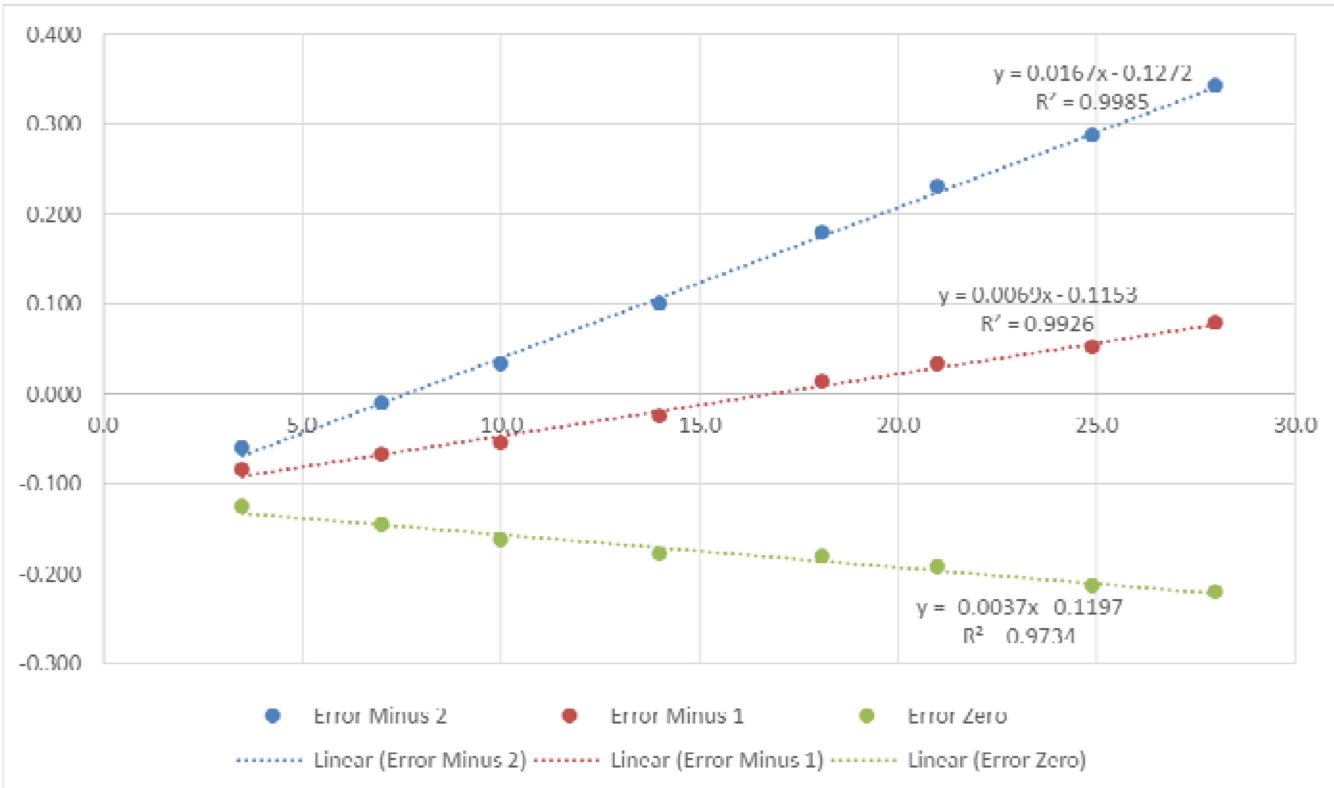
Where to from here?

- How good is it?
  - It is much better than needed for the FMT!
  - Characterize
    - Long-term measurements of WMMB carrier
    - Learn about Allan Deviation (statistical tool)
    - Use statistical tools to characterize frequency stability vs time
- Study simultaneous reception of WWV and the FMT signals-can I correct for sky-wave Doppler shift?

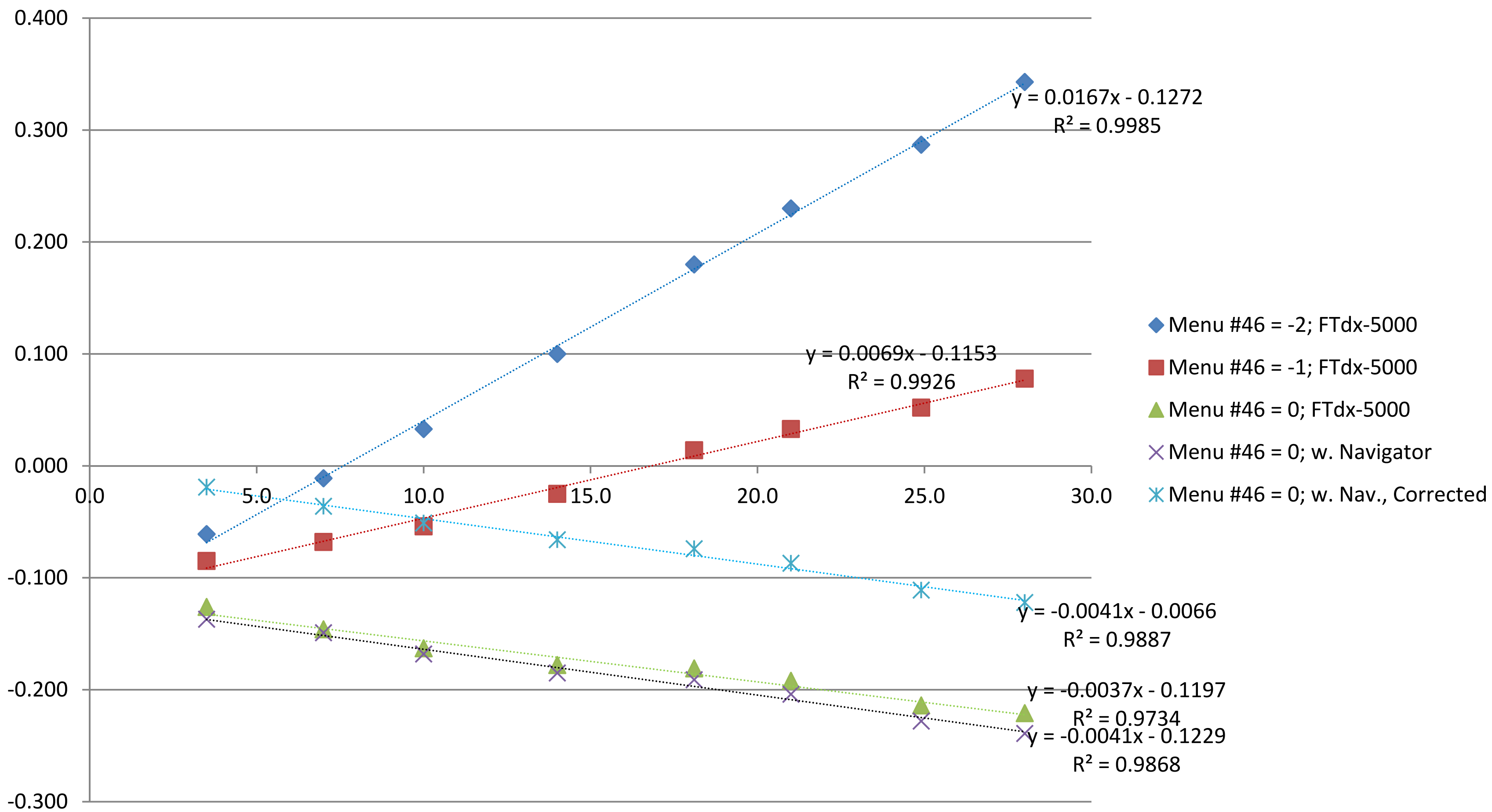
Appendixes

- Re-examine FTdx-5000 performance
- Information web sites
- Other FMT stations' equipment
- PLL Loop filter design notes-ask me, if you are interested

Variability of FTdx-5000 Freq Error



SL calibrated, removes FTdx-5000 DSP offset



Information Web Sites

- Spectrum Lab SW: http://www.qsl.net/dl4yhf/spectra1.html
- Time-Nuts: http://www.leapsecond.com/time-nuts.htm
- FMT-nuts reflector: https://groups.yahoo.com/neo/groups/FMT-nuts/info
- K5CM's FMT site: http://www.k5cm.com/
- FCC Station database: https://www.fcc.gov/media/radio/am-query
- ExpressPCB schematic and layout tools: https://www.expresspcb.com/
- LaPlace Transform plots: http://sim.okawa-denshi.jp/en/detatukeisan.htm
- Good, cheap, pcb's: https://www.seeedstudio.com/fusion_pcb.html
- Allan Variance: https://en.wikipedia.org/wiki/Allan_variance
- Lady Heather GPSDO Control/Monitor: http://www.ke5fx.com/heather/readme.htm

Other FMT Stations' Equipment

Call	Total Error (ppm)	Receiver	Mode used	Reference	Synthesizer	Software	Antenna	Comments
K5CM	0.00000	FT-1000D	AM	HP-Z3801	HP-3336C or PTS-250	Spectrum Lab	160M Vert; 80/40 dipoles	Source of FMT signals
W2TX	0.01132	RF-590	CW	Trimble Thunderbolt		Spectrum Lab	Tuned 64 ft. vertical	
AB4RS	0.01933	HP-3586B		Trimble Thunderbolt	HP-3336C	Spectrum Lab		
WA1ABI	0.02357	WJ-8718		Rb Standard		Spectrum Lab		
WA2DVU	0.03482	HP-3586			HP-3336			
N6SKM	0.03500	FT-857D		GPSDO		FLDigi		
AA6LK	0.04084	FT-847	AM	HP-Z3805A	Marconi-2019	Prologix USB-GPIB	5BTV	
W6OQI	0.04781	HP-3586		HP-Z3801B	HP-3336B			
N3IZN	0.05105	TS-440		Trimble Thunderbolt				
N6RDR	0.05319					K1JT Freq. Meas. Tools		
VE2IQ	0.06909	TS-850	CW				Active E-Probe	
K3KO	0.07016	TS-480		WWV		Spectrum Lab	Indoor 40M dipole	
W3JW	0.08274	IC-7800		GPSDO		Spectrum Lab		
WB4HIR	0.11564	TS-590				K1JT Freq. Meas. Tools		
K6APW/7	0.11745	Ten-Tec		WWV		Uses audio beat note by ear		
W4JLE	0.12657	IC-7100		GPSDO		FLDigi		
KD5MMM	0.12666	FT-847		CHU		Spectrum Lab		
AE5P	0.12965	Flex 6700		GPS		FLDigi		
WB5UAA	0.20529	IC-756 Pro-II		WWV				
AG2M	0.22372	FT-950				Spectrum Lab		
W5TV	0.26631	Flex 6500				FLDigi		
W5AJ	0.27116	K3				Spectrum Lab		
W8TM	0.34696	K3/KSYN3A	CW	WWV				
N8OQ	0.37819	K3		GPSDO by G3RUH		Spectrum Lab	Horizontal loop	
N5DM	0.40006	FT-3000				Digipan 2.0	160/80/40 dipoles	
WB2CMF	0.40149	TS-2000				FLDigi	R-8 vert./dipoles	
VE3GSO	0.51556	FT-950	USB	WWV and CHU		Spectrum Lab		

W2TX FMT Station