Frequency Stability:

What?

Why?

How?

In Which We Cover:

- Some basic terminology
- A bit of radio history
- Examples of some modern transceivers
- Frequency stability requirements for some digital modes
- FST4W modes and uses
- Testing the QRP-Labs QDX digital transceiver
- Modifying the QDX for improved stability
- Test gear for measuring this stuff


HAM Radio Operators
Do It With Frequency!

Measuring Frequency

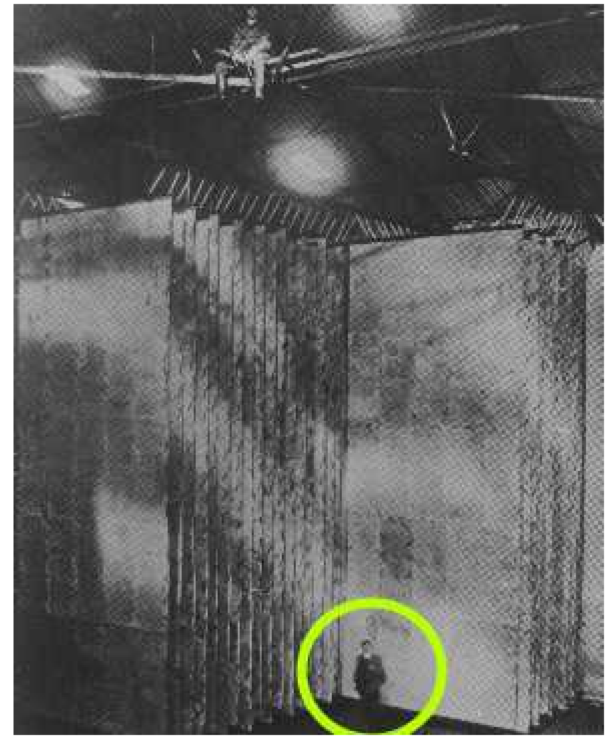
- Accuracy
  - Initial tolerance, retrace, gravity
- Drift / Wander
  - Temperature, Voltage, aging
- Phase Noise / Jitter / Spurious
  - Supply noise, digital synthesis (sampling), mixing products
  - Thermal (See: Schottky, Johnson, Nyquist, Boltzmann)

History of Frequency Stability

- Spark Gap: MHz
  - Heinreich Hertz, 1887 (demonstrated)
  - Guglielmo Marconi, 1896 (practical system)
- AM: KHz
  - Reginald Fessenden, 1900
- FM: KHz
  - Edwin Armstrong, 1933
- SSB: 100 Hz
- Digital Modes: 10 / 1 / 0.1 / 0.01 Hz

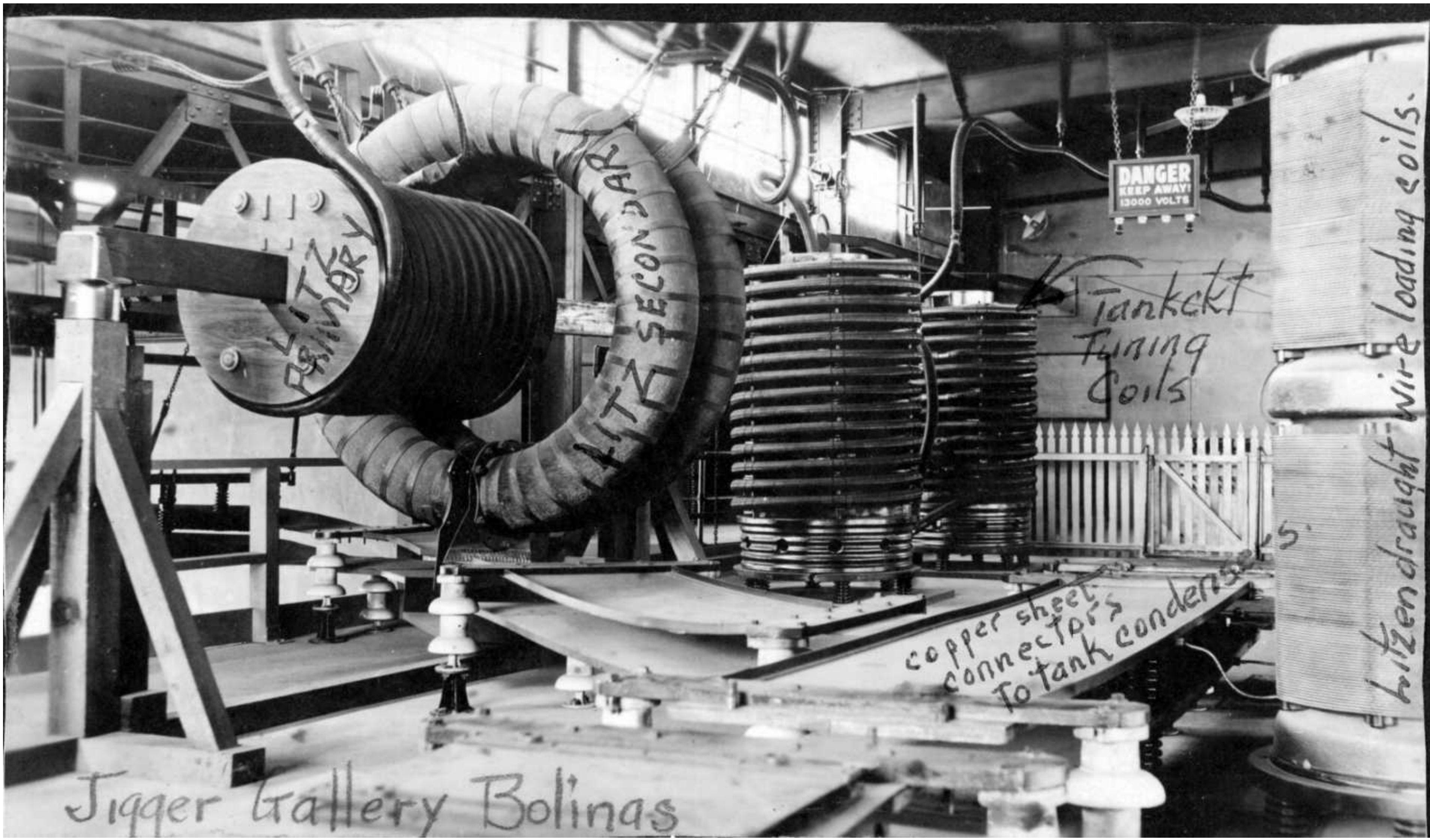
Spark Gap Transmitter

- Interrupter (~750 sparks/sec)
- Broadband emission
- Frequency stability???

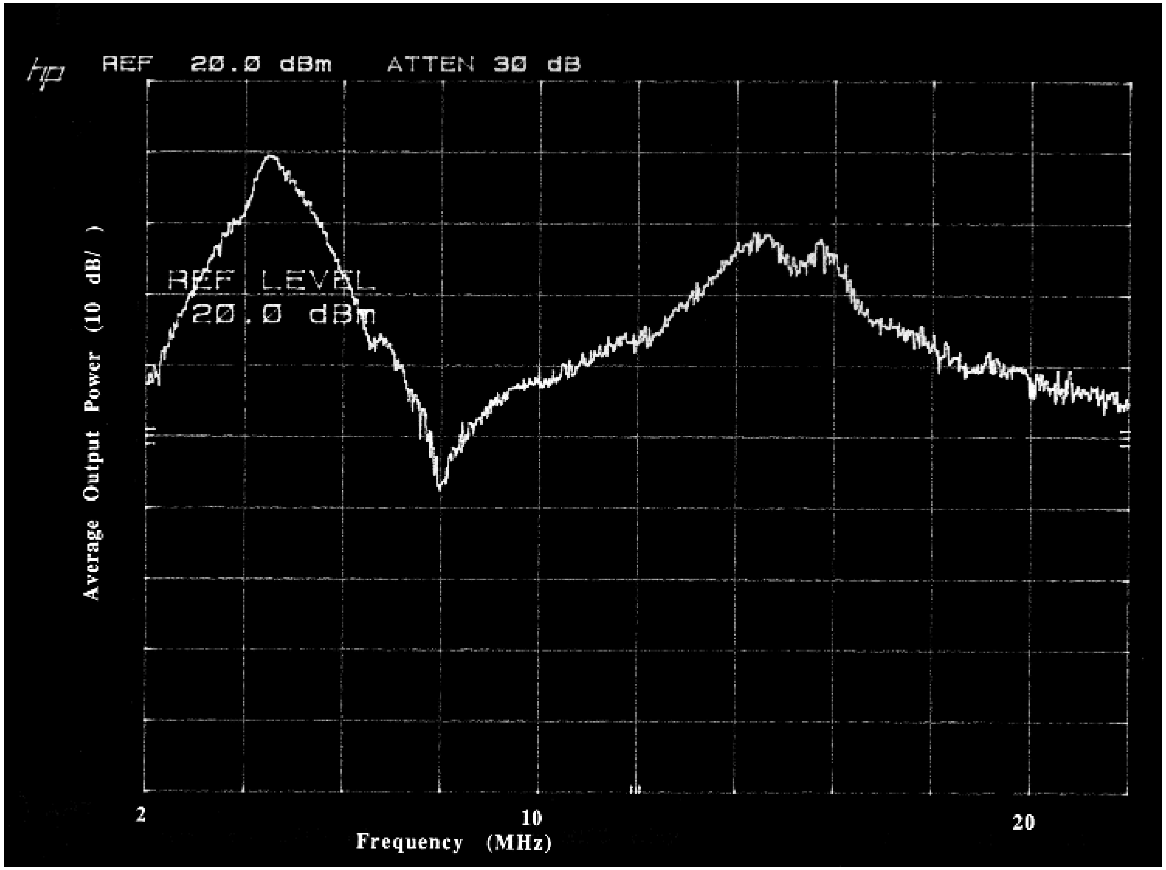


Marconi's Clifton, Ireland Condenser
(That's a man standing down there)

Marconi Spark Gap
Bolinas and Marshall, CA



"5 MHz" Spark-Gap Transmitter

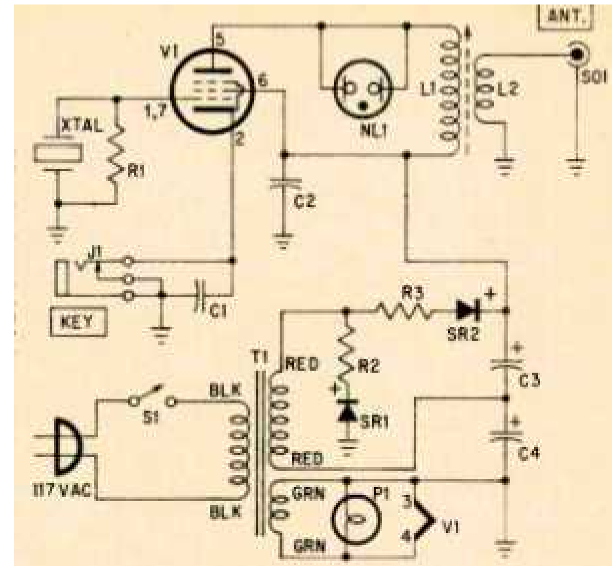


Spectrum Analyzer Plot

Baby's First Receiver: WW II-surplus ARC-5

- I was 12 years old, best friend's dad showed us how to convert for 40-m ham band
- Removed the Dynamotor, used rectified110VAC for the B+ supply (no transformer, be careful how you oriented the wall-plug!
- Pulled plates from VFO tuning capacitor
- Rewired series-connected tube filaments
- Pretty stable for an LC VFO, still drifted

My First Transmitter
(something like this)



- I had one crystal, for 40 meter novice band
- Don't touch the hot key contact!!! – direct high voltage cathode connection
- Chirp, hum, drift galore
- I made contacts with it. Good enough.

Modern Ham Gear

Example: IC-7300

- Frequency stability: Better than ±0.5ppm (–10˚C to +60˚C)
- Good spec for most modes. On 20 meters this is +/- 7Hz
- Internal temperature not the same as room temperature: radio heats up during transmission.
- Some modes require better stability than this

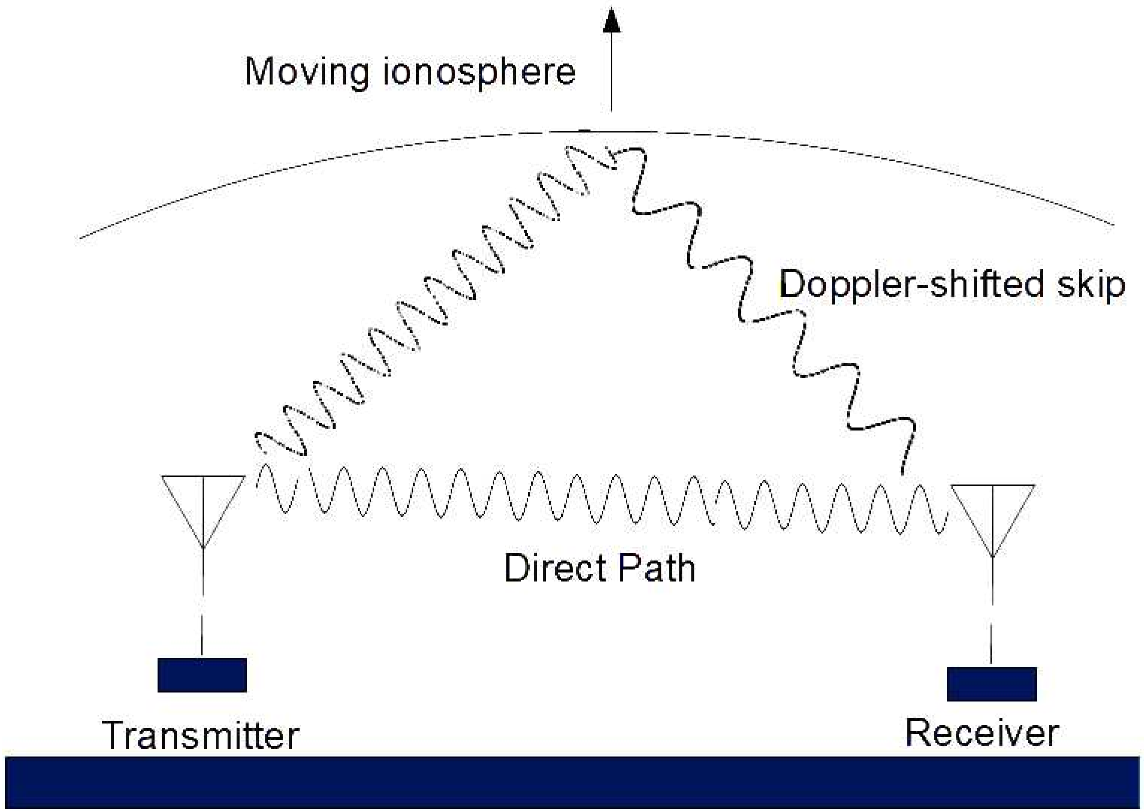
Modern Ham Gear
Example: QRP Labs QDX

- 80/60/40/30/20 or 20/17/15/12/11/10 meter operation, 3-5W output
- USB interface
- FSK digital modes only (wsjtx, JS8Call, etc.)
- $69 partial kit, $45 assembled, + $20 for case
- Frequency stability (measured, temp chamber): ±0.07ppm (+10˚C to +50˚C)
- Good spec for most modes. On 20 meters this is +/- 3.125 Hz

•FST4W ???

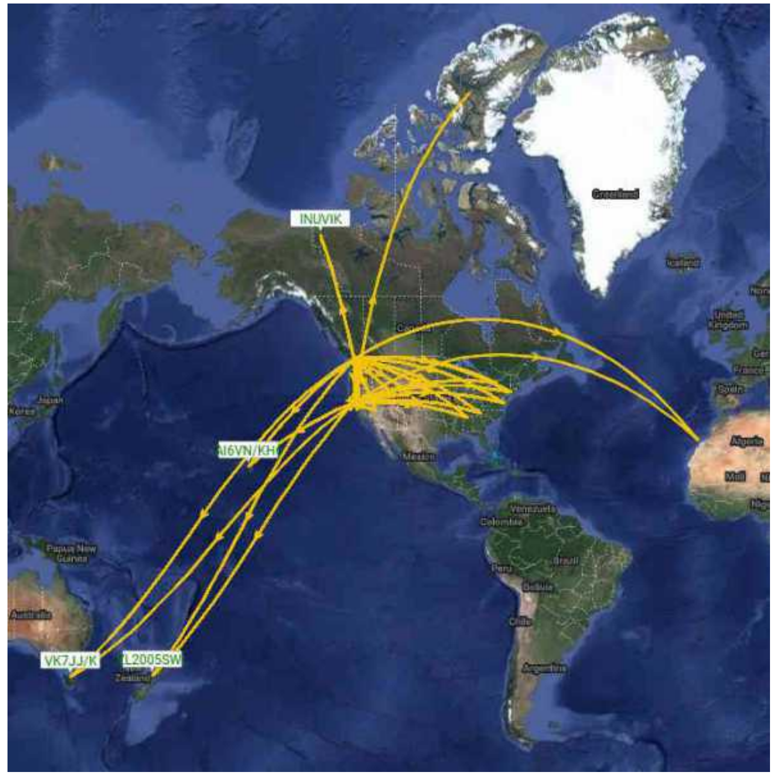
- FST4 and FST4W are digital protocols designed particularly for the LF and MF bands, but also proving useful on HF and above
- Their fundamental sensitivities are better than other WSJT-X modes with the same sequence lengths, approaching the theoretical limits for their rates of information throughput
- FST4 is a two-way QSO mode (like FT8)
- FST4W is a “beacon” mode (like WSPR), being used to monitor propagation and measure ionospheric Doppler shifts (“spectral spreading”)
- FST4W sequence lengths are 120, 300, 900, and 1200 seconds
- FST4W-120 and -300 are generally used on HF “skip” paths
- There is a wide network of wsprdaemon receivers, monitoring FST4W and WSPR beacons

Spectral Spreading



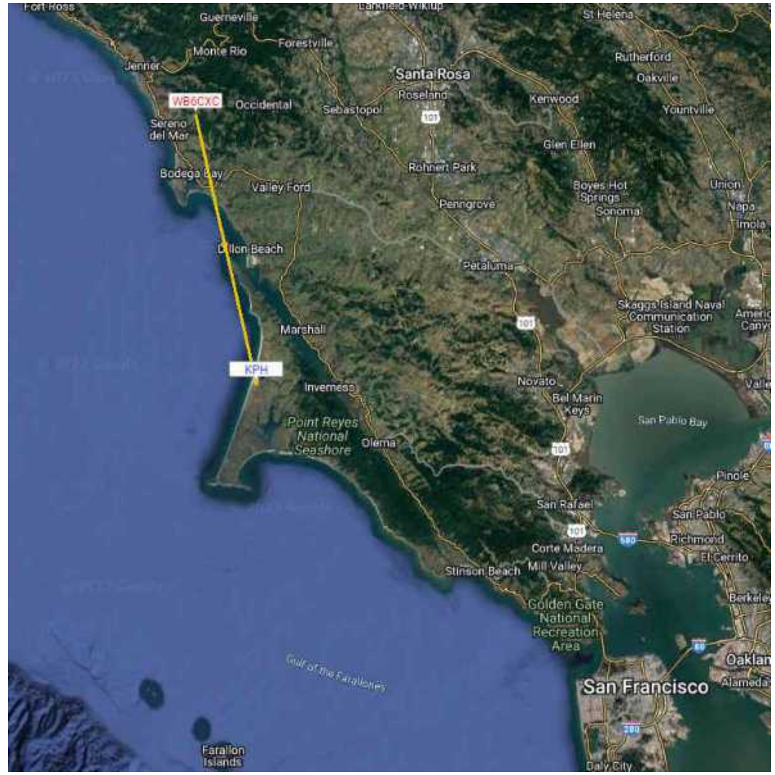
- The “spread” is due to the combination of two (or more) propagation paths, where Doppler Shift causes a frequency shift.
- This can include multi-hop skip
- Accurate frequency measurements can also characterize Doppler shifts

FST4W-1200



- WB6CXC 20 meters, 3W FST4W-1200 transmitters in Friday Harbor WA and Occidental CA
- A few receivers in Europe are not shown
- Many more WSPR receivers than FST4W

FST4W-1200



But one receiving site is almost LOS from my Occidental location:
KPH, the old RCA marine radio station at Point Reyes

KPH - Then

KPH - Now


NPS PHOTO


AM Band
Blocking Filter
Kiwi73
Kiwi77
Kiwi75
Kiwi78
GPS Distribution

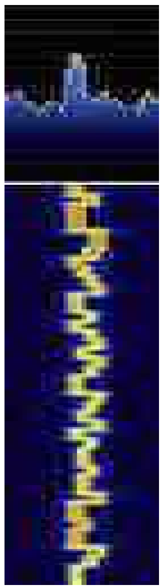
VY0ERC

- Eureka, Ellesmere Island, Nunavut, Canada
- The Club is located in the environs of the Eureka Weather Station which is itself located at 79 degrees 59 minutes N, 85 degrees 56 minutes W on Ellesmere Island
- My friends Glenn (N6GN) and Rob (AI6VN) traveled to VY0ERC to install an antenna and set up a KiwiSDR receiver for wsprdaemon monitoring.

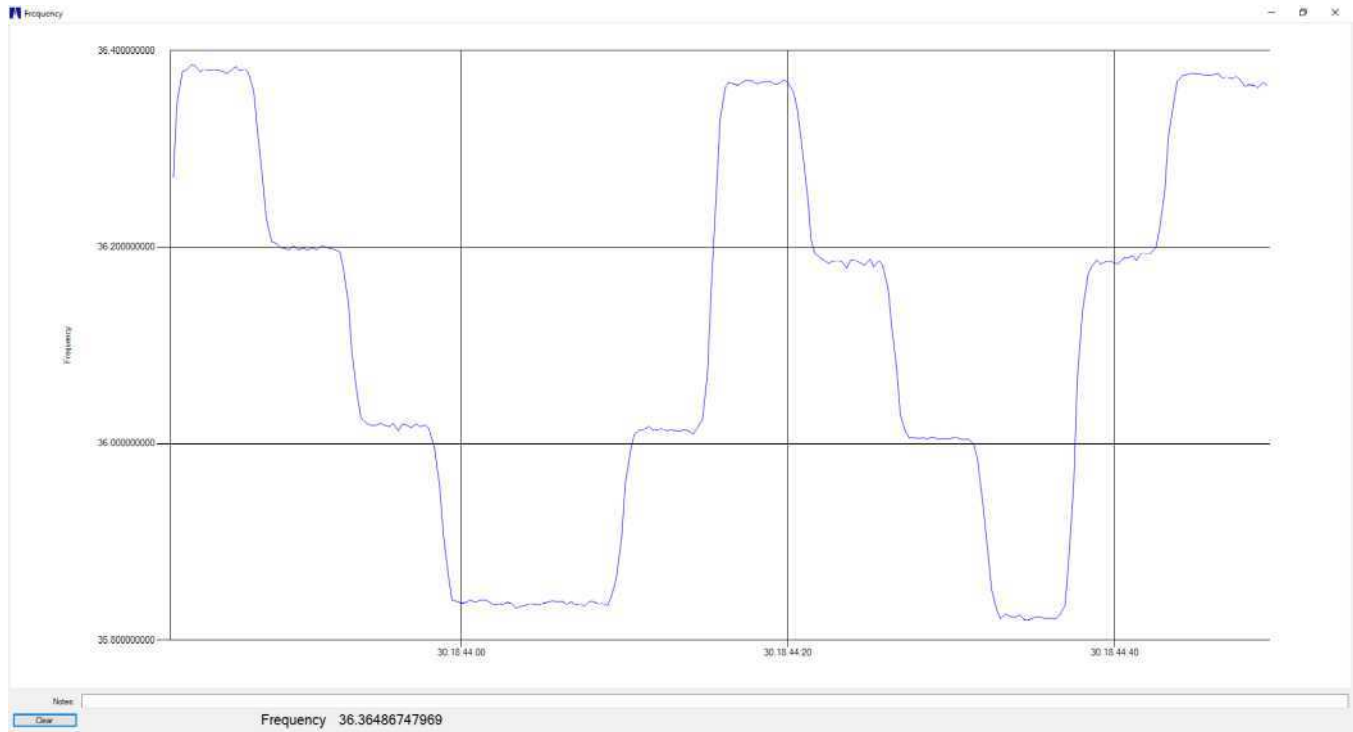
Getting to Stability

And how good is “good enough”?

Plotting Frequency

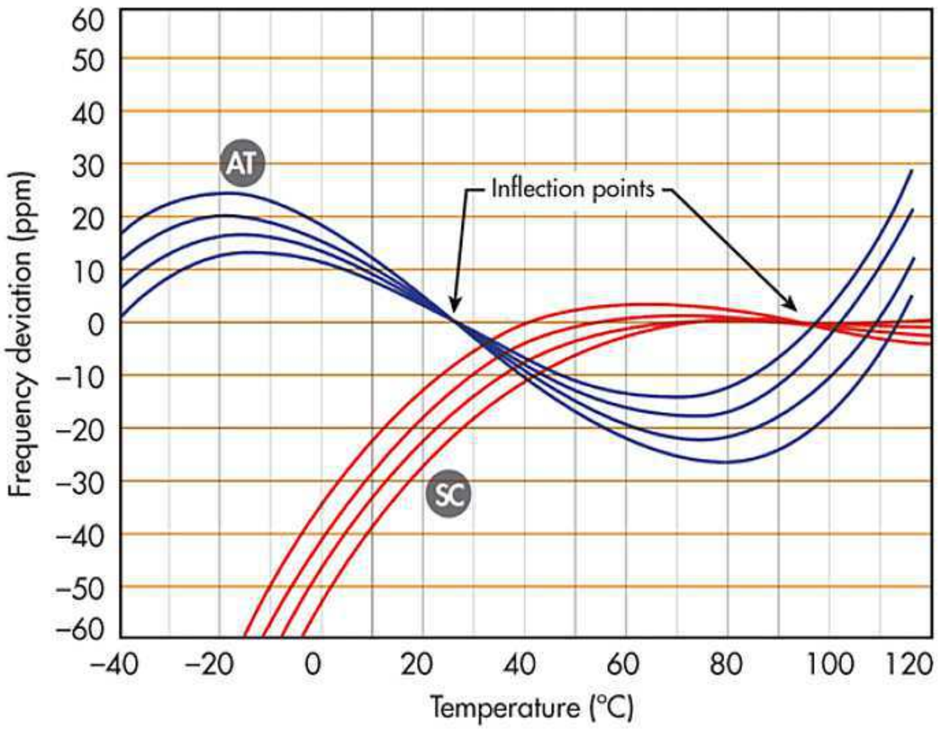


Spectrum
+
Waterfall



Frequency vs Time

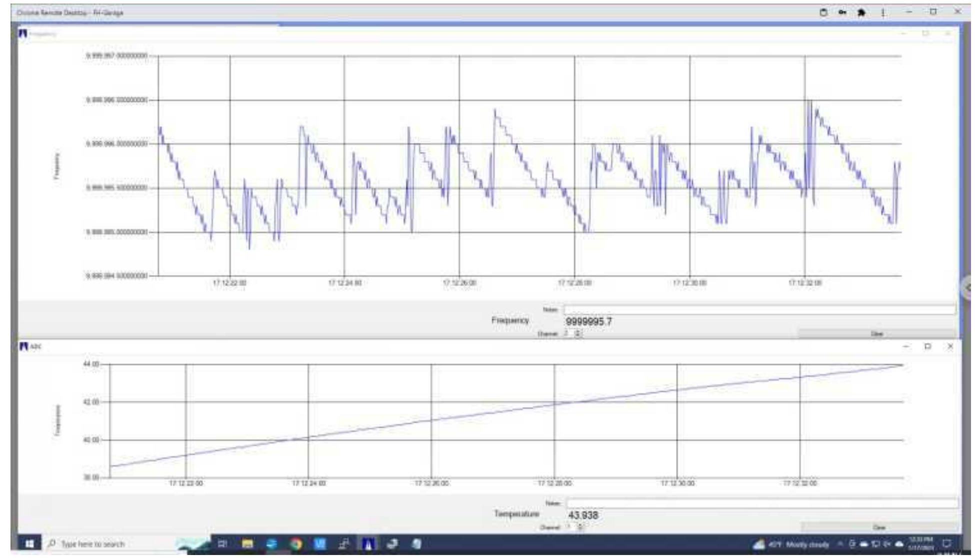
Quartz Crystals



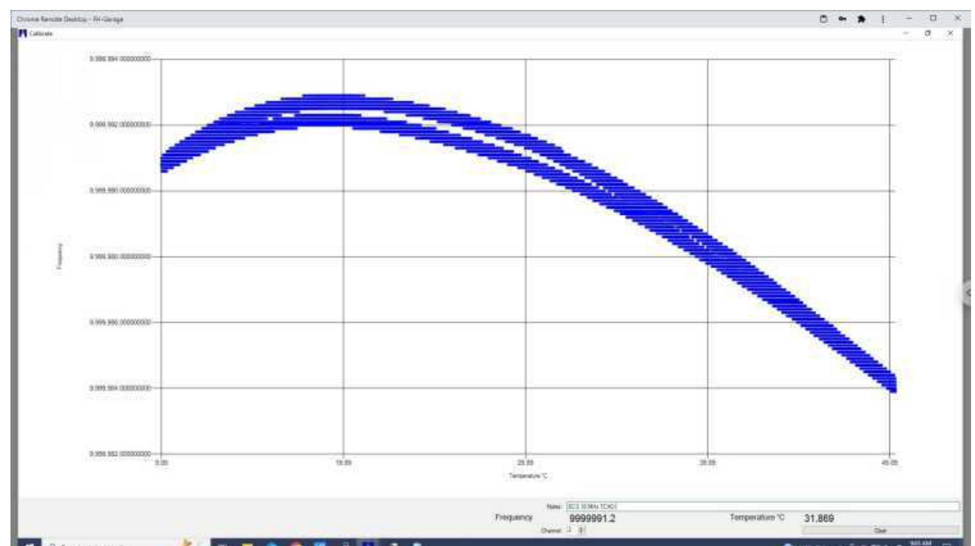
- Virtually all modern ham radios use quartz crystals to provide a stable reference for Phase Locked Loop frequency generation.
- The raw crystal is cut into thin wafers, with different angle of cut providing different frequency-vs-temperature characteristics
- The AT-cut is typical, the SC-cut is often used in OCXOs (Oven Controlled Xtal Oscillator)
- TCXOs (Temperature Compensated Xtal Oscillator) use temperature-dependent tuning to actively tune the oscillation frequency.

TXCO

- This frequency vs time plot is the output of an inexpensive “Fox” TCXO, as the temperature is slowly increased.
- The abrupt frequency shifts due to the digital compensation method make this TCXO unsuitable for narrowband radio applications.



- This frequency vs temperature plot is the output of an inexpensive “ECS” TCXO, as the temperature is slowly increased and decreased.
- Note the smooth frequency variation

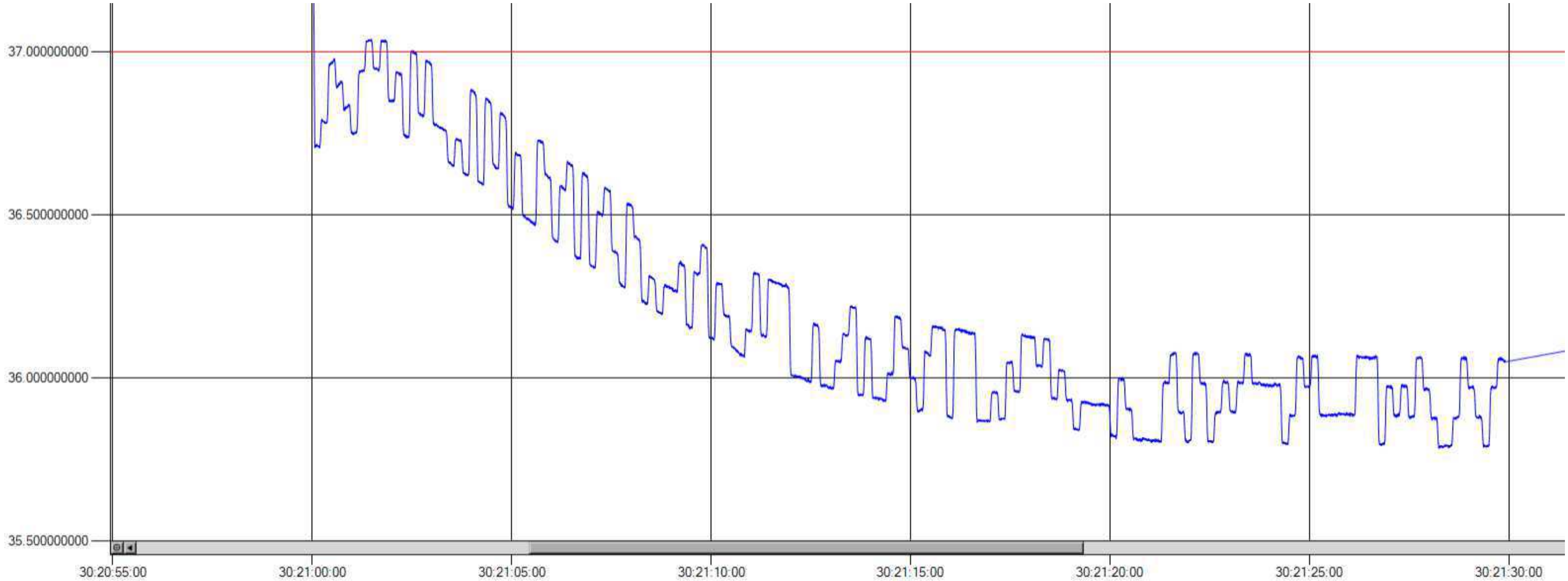


Both of these oscillators meet the same stability specification

QDX Frequency Stability

- This shows the FSK modulation and frequency drift of several WSPR transmissions on 20 meters, using an un-modified QDX. The WSPR steps are 1.4648 Hz, and the symbol length is 1/1.4648, or 0.682 seconds. The full transmission takes almost 110.6 seconds
- The drift during a single transmission is about 0.5 Hz
- This amount of drift is not great, but it is **acceptable for WSPR and most other FSK modes**

QDX Frequency Stability



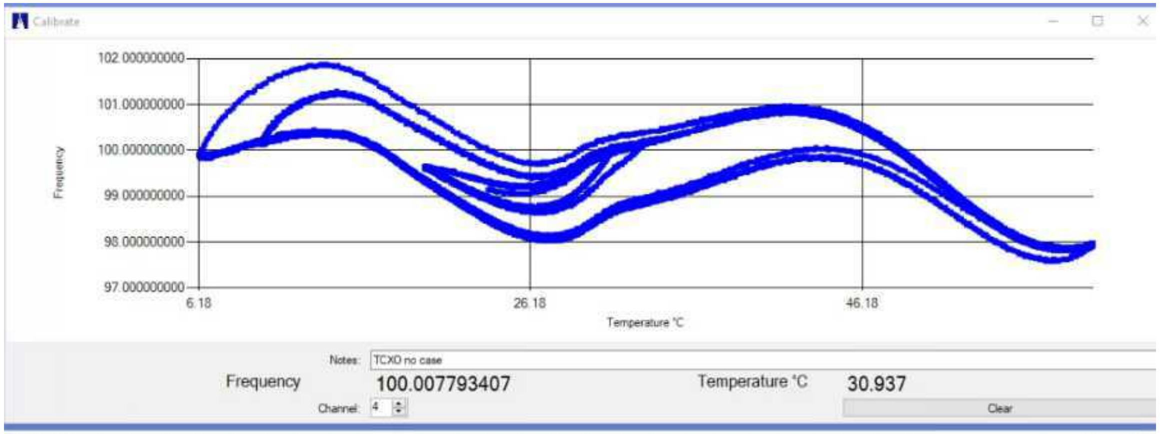
- This shows the FSK modulation and frequency drift of a FSTW4-1800 transmission on 30 meters, using an un-modified QDX. The FSK-4 steps are 0.089 Hz, and the symbol length is 1/0.089, or 11.2 seconds. The full transmission takes almost 1800 seconds, or one-half hour.
- The drift during the transmission is about 1.25 Hz (+/- 0.05 PPM).
- Note that this amount of drift is **completely unacceptable**. The drift has to be less than 0.089 Hz for the transmission to even be decodable.

QDX Oscillator

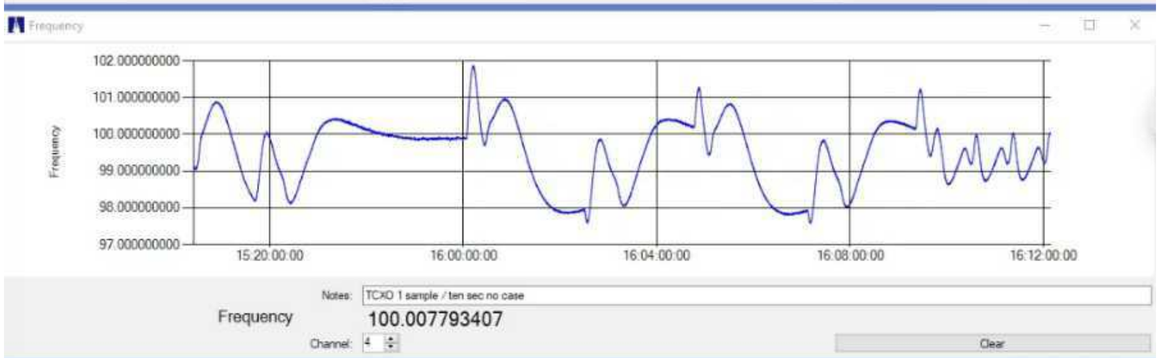
- The QDX uses a high-quality TCXO, but even TCXOs will drift over time, temperature, and voltage.
- The principal drift factor in the QDX is internal heating from the output 5W power amplifier transistors.

QDX TCXO Measurements

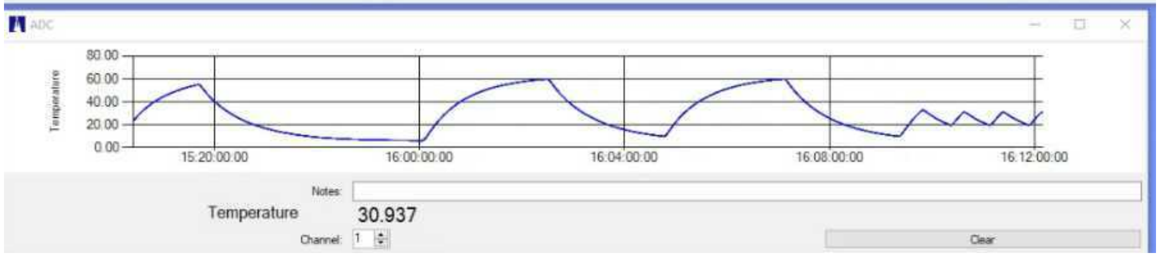
Frequency vs Temperature



Frequency vs Time



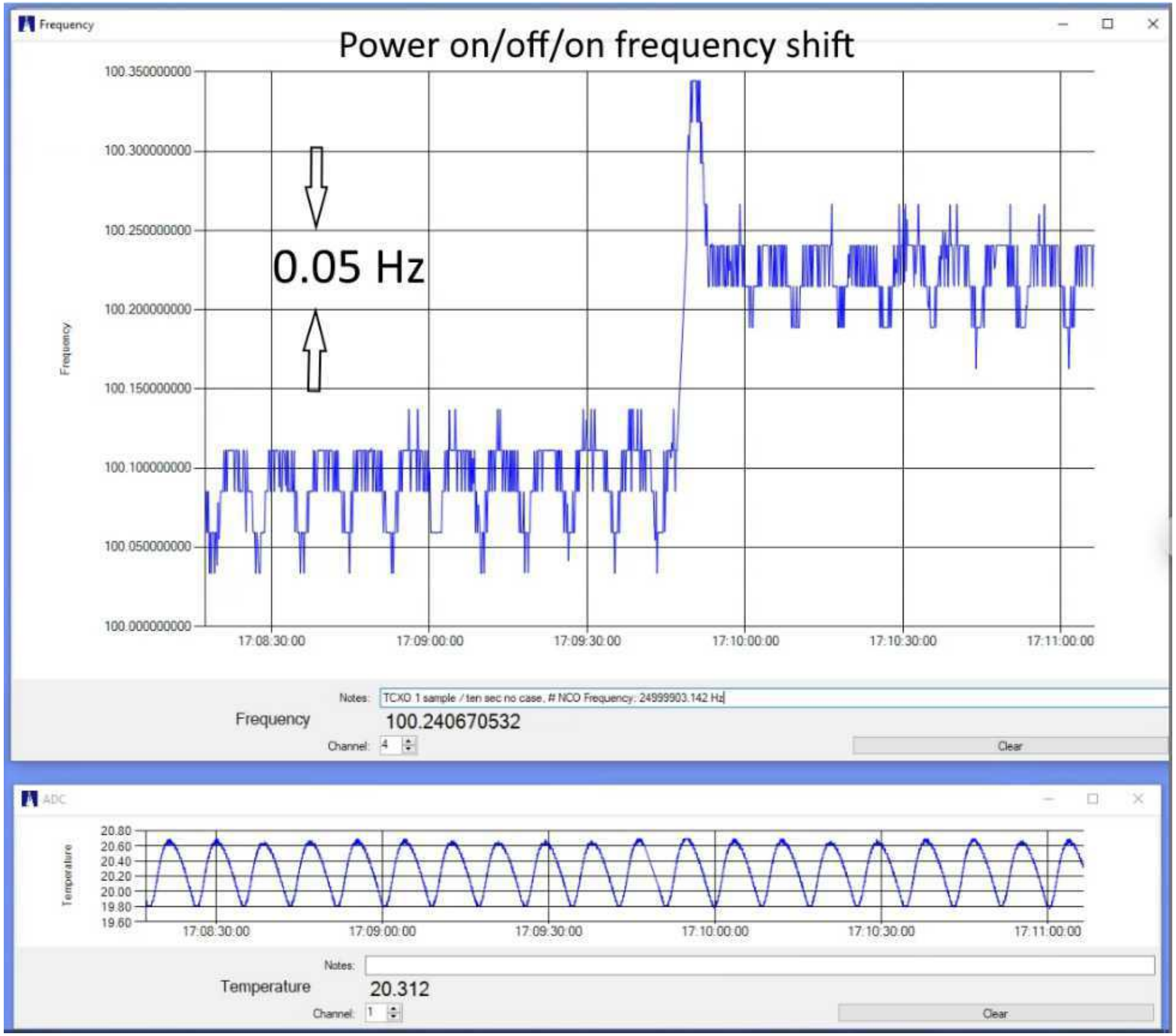
Temperature vs Time



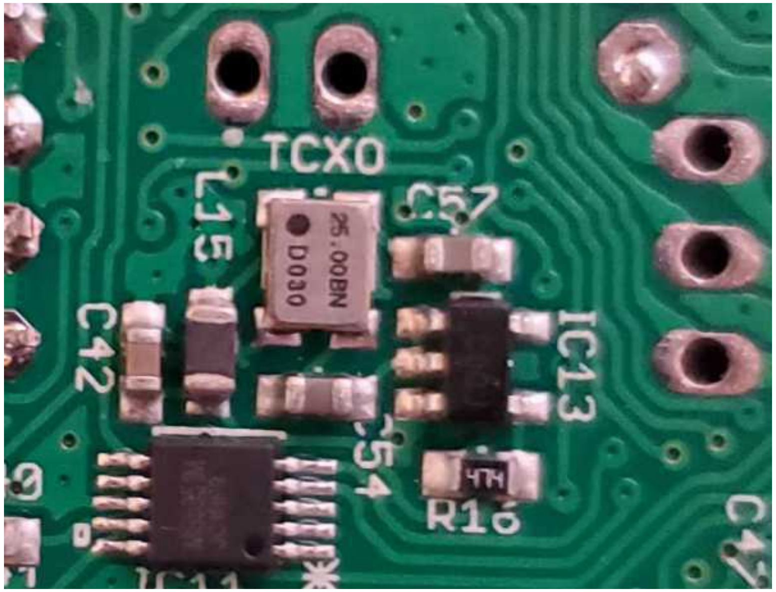
Temperature compensation, but also “retrace”, or thermal hysteresis

QDX TCXO Measurements

- **Retrace** also happens during power-cycling
- During this test the temperature was continuously cycled by 1 degree C, resulting in roughly 0.05 Hz variation.
- Halfway through the test the power was turned off and on
- The frequency shifted by about 0.225 Hz, and stabilized
- This isn't drift, but is still interesting, and critical in some applications
- Even an OCXO has retrace.



Reducing the QDX Frequency Drift



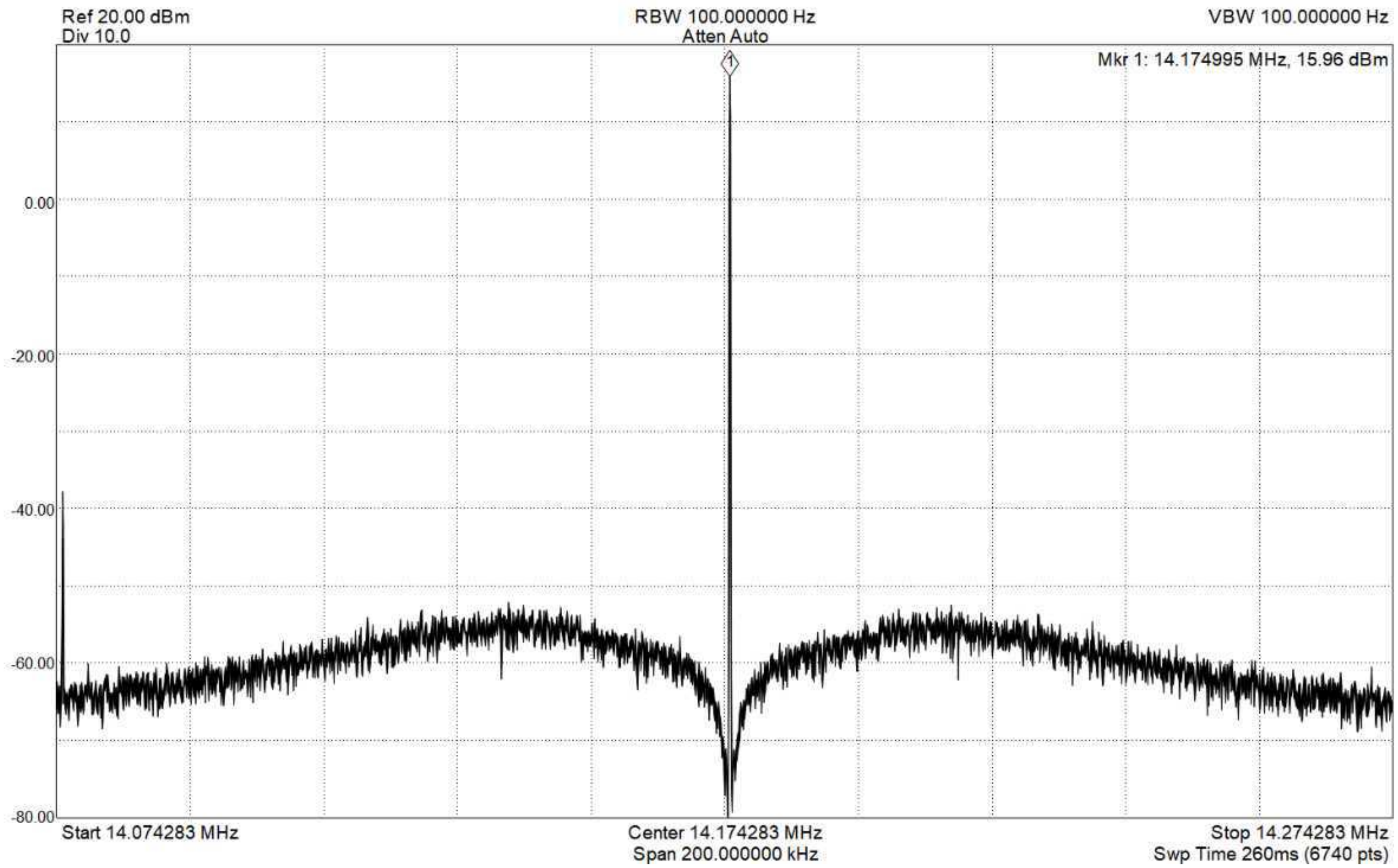
- That little silver square thing is a 25 MHz TCXO -- actually quite a good one
- I discussed options with Hans (the QRP Labs owner and designer)
- Possibility: Sampling a PPS (one Pulse Per Second) from a GPS, measuring the TCXO frequency and compensating in software
- The drift was too fast for this, would need to slow down the rate of change
- Tried adding thermal mass to the TCXO (attaching a brass tab with thermal tape), but this wasn't good enough; the heat was coming via the P.C. Board.

Reducing the QDX Frequency Drift

So I designed a replacement for the TCXO: A Clock Multiplier board

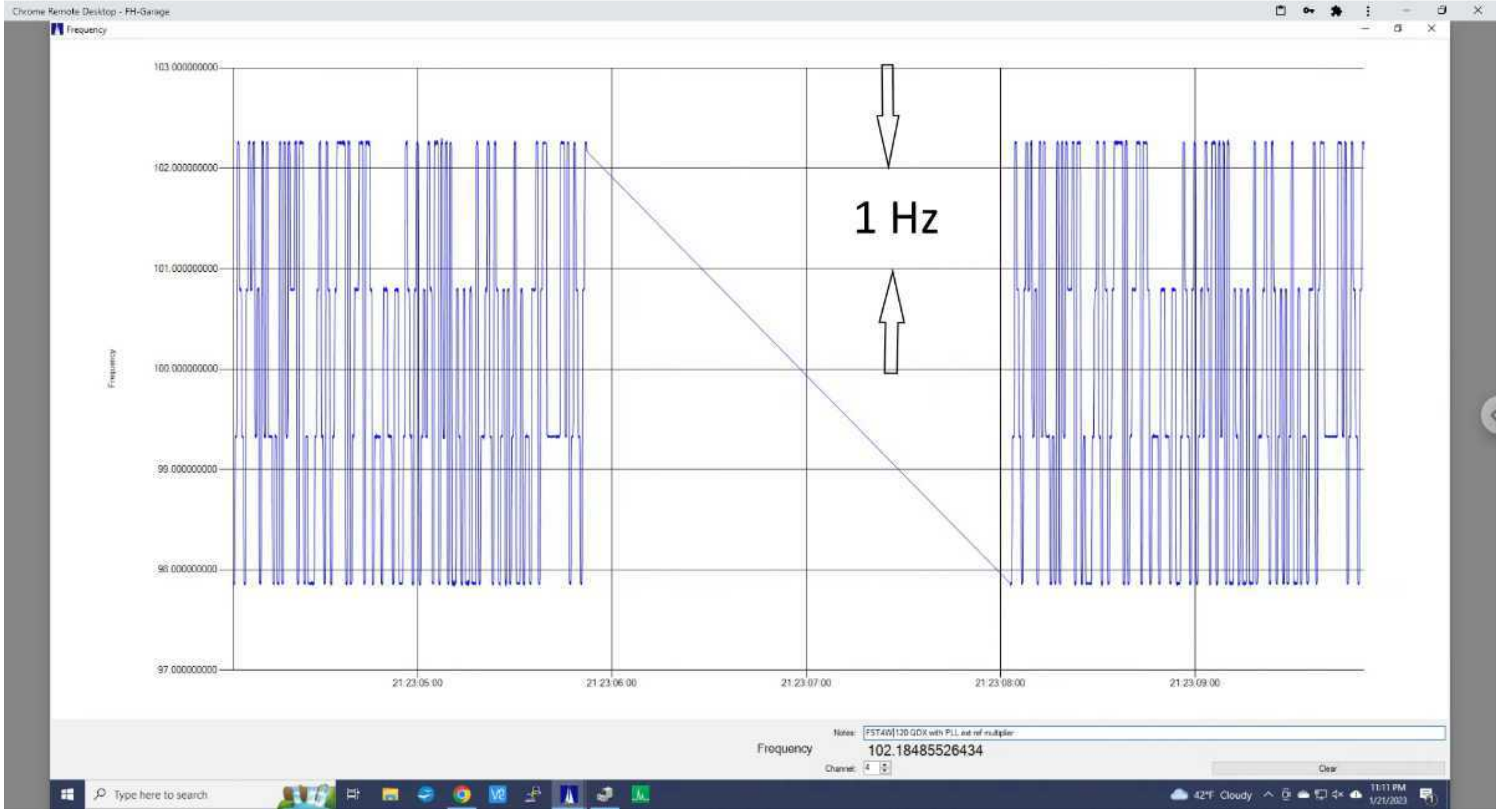
- Takes a stable external 10 MHz or 5 MHz reference clock
- Input protection from transients
- A PLL multiplies the reference clock up to 25 MHz
- Takes 3.3V power from the QDX
- Adds some noise and spurs, but definitely clean enough
- Zero drift (as good as the reference)

QDX With PLL



- Fairly clean spectrum

Zero Drift With External Clock



Measurements
Occidental to KPH

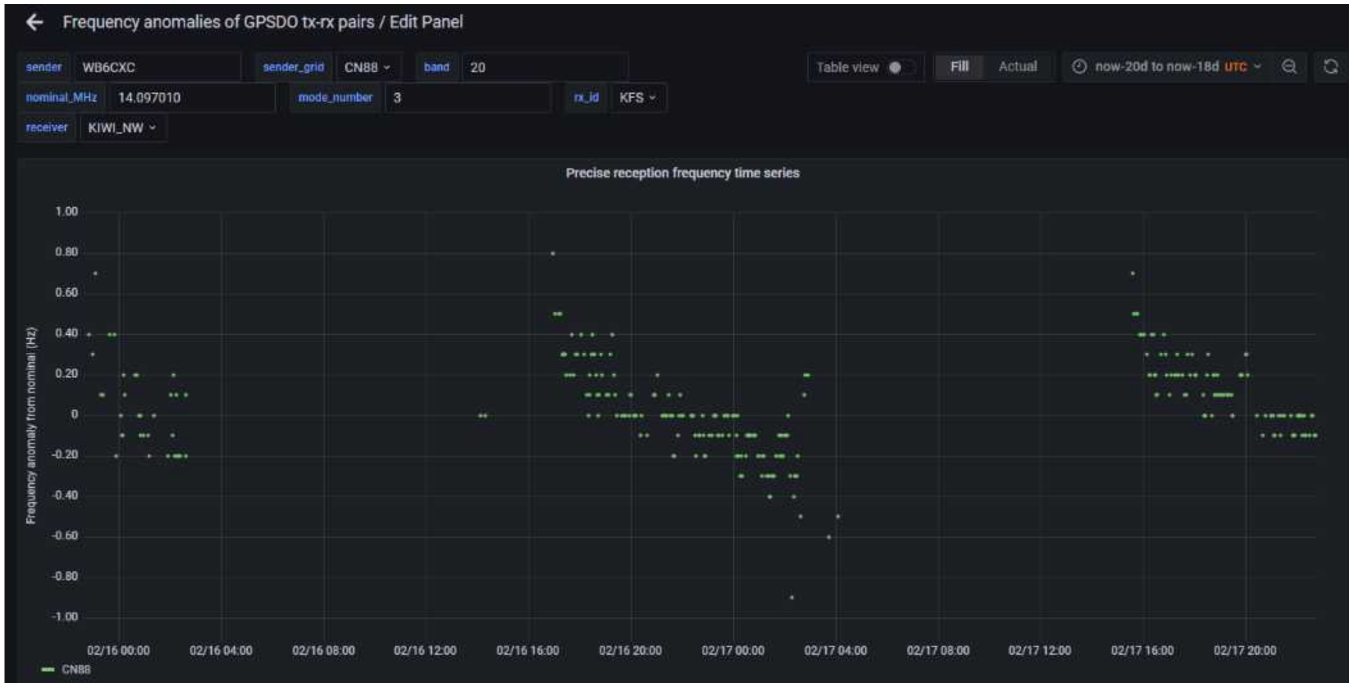
SNR

SPREAD

FREQUENCY

Measurements
Friday Harbor to KFS

Frequency

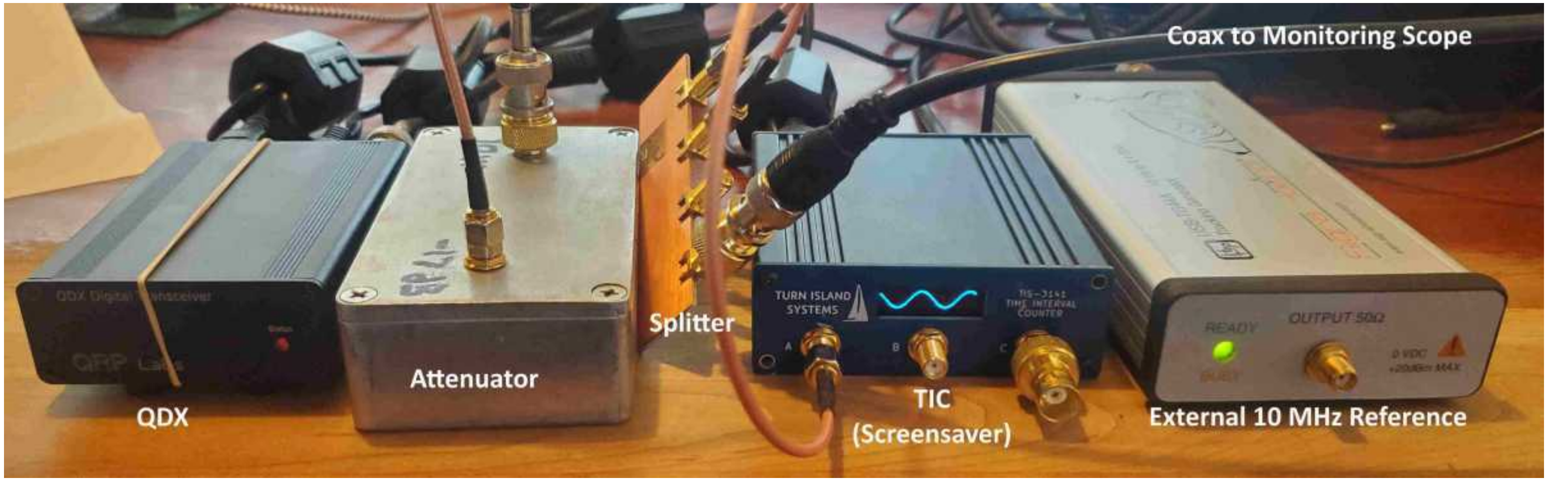


Frequency shift during skip propagation
48 hours

Measurement and Analysis

- Frequency domain
  - Spectrum analyzer
- Time domain
  - Oscilloscope, frequency counter

Frequency Measurement Tools



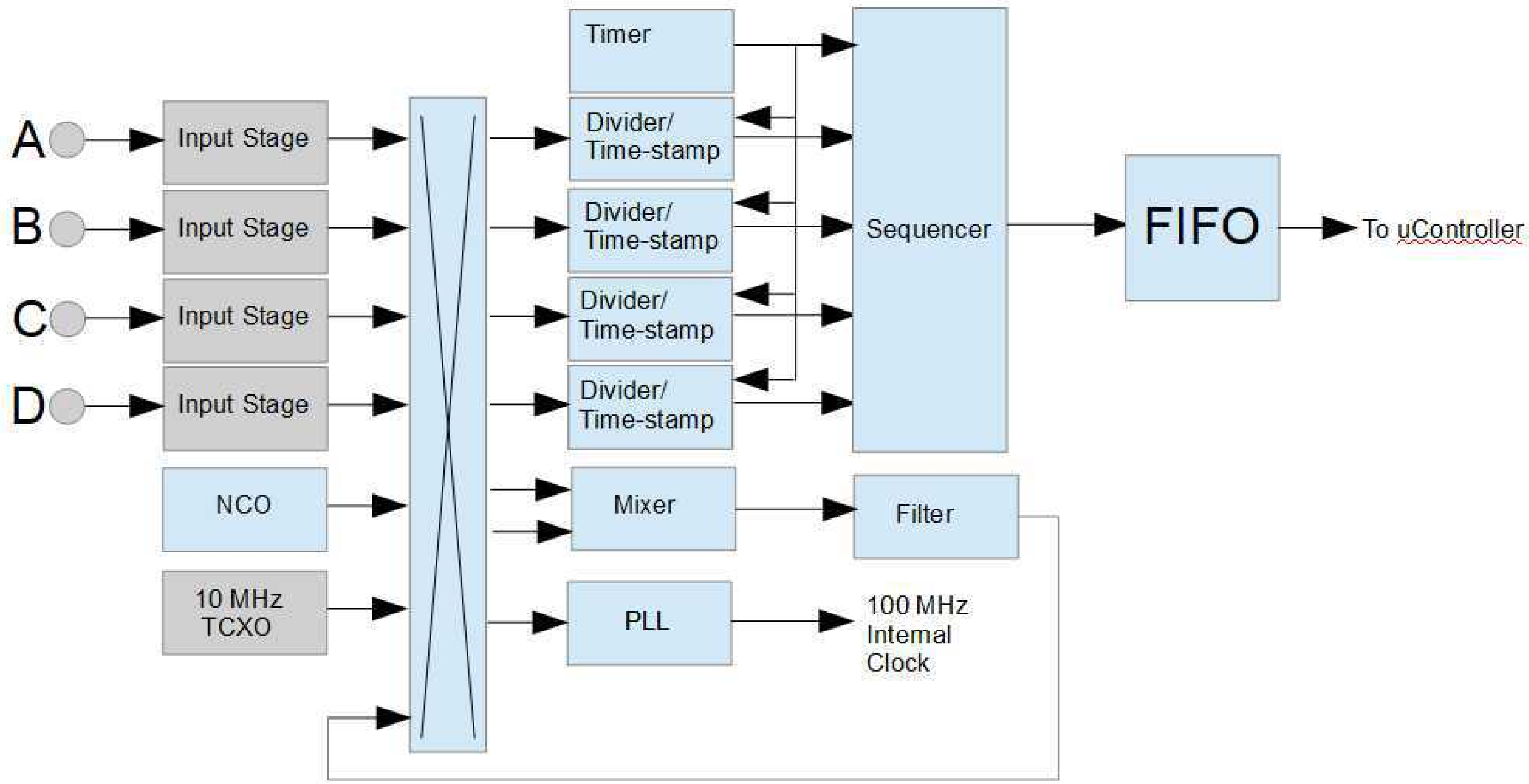
TIC (Time Interval Counter)

- My own design, capable of fast and accurate frequency measurements
- Accepts external 10 MHz reference clock
- 0.001 Hz or better resolution with 14 MHz input, 50 samples per second
- PC GUI for charting and control

External 10 MHz reference,

- either TCXO (shown) or Bodnar GPSDO (GPS Disciplined Oscillator)

Time Interval Counter



Blue boxes are implemented in the FPGA

References

- History:
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- Measurements
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References

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  - SDR Receivers: https://www.radiomarine.org/kph-sdrs
  - Web SDR: http://198.40.45.23:8073/
  -

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Some silly naive comment...

Measuring Frequency

- Accuracy
  - Initial tolerance, retrace, gravity
- Drift / Wander
  - Temperature, Voltage, aging
- Phase Noise / Jitter / Spurious
  - Supply noise, digital synthesis (sampling), mixing products
  - Thermal (See: Schottky, Johnson, Nyquist, Boltzmann)

Oscillator types

- RC, LC
- Mechanical: Tuning fork, ceramic, Quartz crystal, Si MEMS
- Atomic: Rubidium, Cesium laser-cooled atomic fountain with cryrogenic cooling
  (3×10^{-16}, = 1 second in 9.5 billion years)
- Latest Atomic: Cold Atom Ytterbium Optical Lattice
  (2×10^{-18}, = 1 second in 634 billion years)

Xtal oscillators can be temperature-compensated (TCXO) and/or put in an ovenized stable temperature (OCXO).

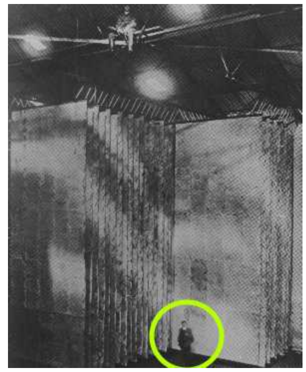
Average frequency is not the same as instantaneous frequency. For example, rubidium standards have significant phase-noise and usually include a tunable OCXO or VCXO in an output clean-up PLL.

History of Frequency Stability

- Spark Gap: MHz
  - Heinreich Hertz, 1887 (demonstrated)
  - Guglielmo Marconi, 1896 (practical system)
- AM: KHz
  - Reginald Fessenden, 1900
- FM: KHz
  - Edwin Armstrong, 1933
- SSB: 100 Hz
- Digital Modes: 10 / 1 / 0.1 / 0.01 Hz

Various modes have different stability requirements. These requirements have tended to become more stringent as time and technology marches on.

Spark Gap Transmitter

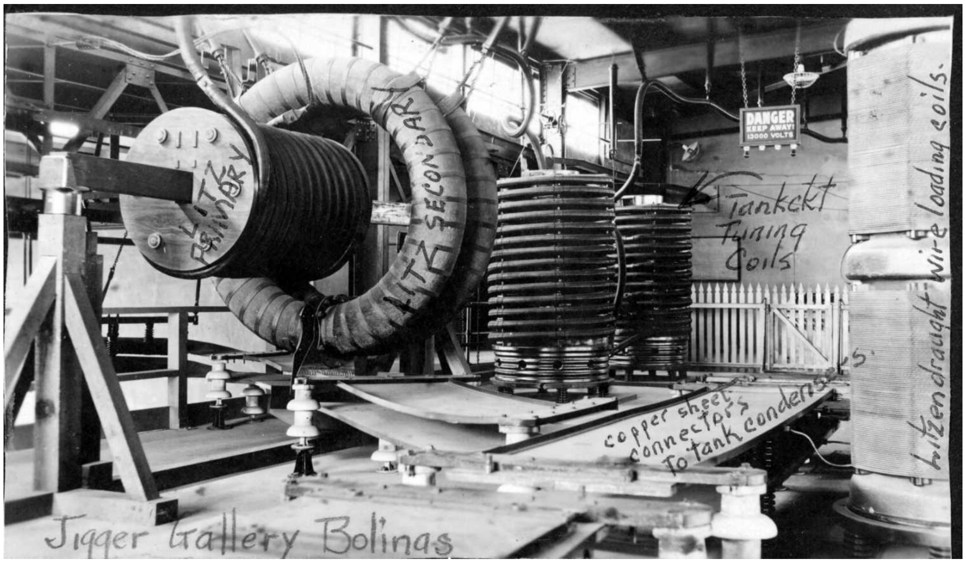


- Interrupter (~750 sparks/sec)
- Broadband emission
- Frequency stability???

Marconi's Clifton, Ireland Condenser
(That's a man standing down there)

Heinrich Hertz built the first one in 1887, Marconi developed a practical system in 1896. Frequency determined by an L/C tank circuit.

Marconi Spark Gap
Bolinas and Marshall, CA



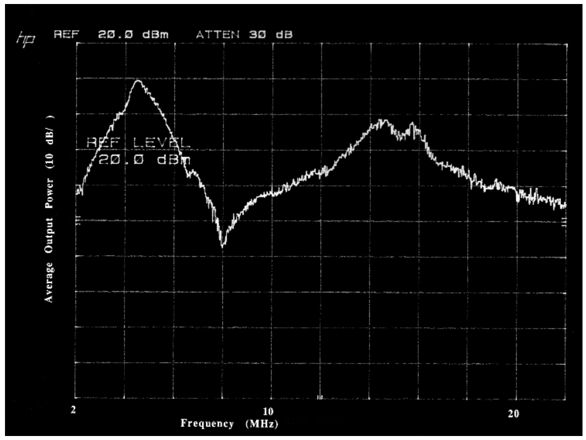
WB6CXC - Frequency Stability 7

In California, American Marconi Co. established a rotary spark-gap transmitter site in Bolinas (“KET”), and a receiving site at Marshall, on Tomales Bay. The frequency was 22.9 KHz, power 230 kW.

Note the “Litz Primary and Secondary” windings, “Tank Circuit Tuning Coils”, “Litz Loading Coils”, and “copper sheets to tank condensers”. See picket fence for scale!

RCA absorbed American Marconi, and by 1930 had transitioned to HF, with 24 HF “circuits” from 6.8 MHz to 18 MHz. The Marshall site didn't have adequate acreage for the large rhombic antennas used, so the site was eventually moved a few miles to Point Reyes, using the call sign KPH. More on KPH later...

“5 MHz” Spark-Gap Transmitter



Spectrum Analyzer Plot

Talk about key-clicks!

The transmitter was essentially a buzzer that energized an LC tank circuit at an audio rate. This example shows a 5 MHz transmitter, but the early commercial ones operated in the KHz region.

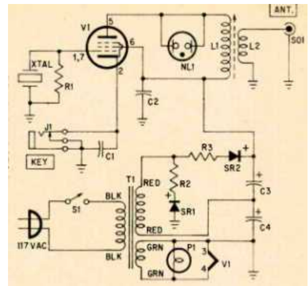
Definitely not a narrow-band mode, and frequency stability was not a big factor.

The AN.ARC-5 Command Radio Set was introduced in 1943 and included a series of receivers and transmitters. These were used on U.S. Navy aircraft during WW II. In 1947 and later they were widely available on the surplus market, and many were converted by hams for amateur operation.

For CW and SSB reception the ARC-5 used a BFO (Beat Frequency Oscillator) and no narrow filters, You could tune on either side of zero-beat.

Converting an ARC-5 receiver for the 40-meter ham band was my introduction to ham radio and electronics.

My First Transmitter
(something like this)



- I had one crystal, for 40 meter novice band
- Don't touch the hot key contact!!! – direct high voltage cathode connection
- Chirp, hum, drift galore
- I made contacts with it. Good enough.

Work the world with one crystal, one tube, and a key!

I got my novice license – WN6CXC – and my Radiotelephone First Class commercial license at the age of nineteen. This was my first transmitter.

While it had a bit of chirp (transient drift) it was considerably more stable than my two-dial Hallicrafters tube receiver. Both of these were practically antiques when I got them, but they were all I could afford.

In the search for frequency stability, I used a 100 KHz crystal oscillator to “calibrate” the receiver, and later built a simple frequency counter using 7400-series logic and LEDs that would display the receiver local oscillator frequency.

Modern Ham Gear

Example: IC-7300

- Frequency stability: Better than ±0.5ppm (–10˚C to +60˚C)
- Good spec for most modes. On 20 meters this is +/- 7Hz
- Internal temperature not the same as room temperature: radio heats up during transmission.
- Some modes require better stability than this

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Example: QRP Labs QDX

- 80/60/40/30/20 or 20/17/15/12/11/10 meter operation, 3-5W output
- USB interface
- FSK digital modes only (wsjtx, JS8Call, etc.)
- $69 partial kit, $45 assembled, + $20 for case
- Frequency stability (measured, temp chamber): ±0.07ppm (+10˚C to +50˚C)
- Good spec for most modes. On 20 meters this is +/- 3.125 Hz

I really like this little transceiver. While it can be used as a general-purpose USB receiver, it's designed for low-speed FSK modes. It uses USB for both audio and control (as does the ICOM-7300), which is a very practical solution when putting together a compact system.

I've built three of these rigs, and it takes 1-2 hours.

The stability is more than adequate for most uses, but not good enough for some of the modes being used for atmospheric research. So some friends and I have come up with modifications...

•FST4W ???

- FST4 and FST4W are digital protocols designed particularly for the LF and MF bands, but also proving useful on HF and above
- Their fundamental sensitivities are better than other WSJT-X modes with the same sequence lengths, approaching the theoretical limits for their rates of information throughput
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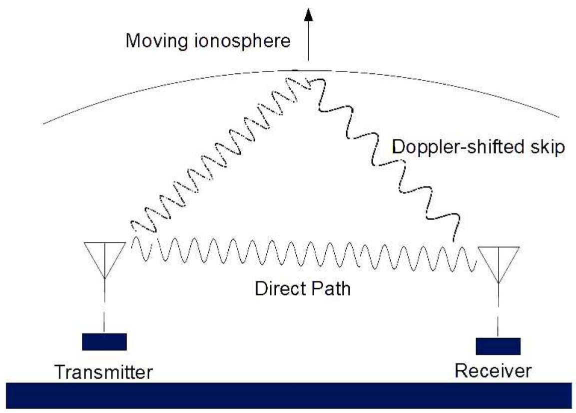
- FST4W is a “beacon” mode (like WSPR), being used to monitor propagation and measure ionospheric Doppler shifts (“spectral spreading”)
- FST4W sequence lengths are 120, 300, 900, and 1200 seconds
- FST4W-120 and -300 are generally used on HF “skip” paths
- There is a wide network of wsprdaemon receivers, monitoring FST4W and WSPR beacons

FST4W-120 uses GFSK (Gaussian Frequency Shift Keying). GFSK filters the FSK transitions which reduces the spurious emissions caused by unfiltered FSK (as used by WSPR). FT8 also uses GFSK, but with less aggressive filtering.

What is wsprdaemon? It is a program written by Rob Robinett (AI6VN) that takes the output from a SDR such as the Kiwi (and soon the QDX), and simultaneously decodes many of the wsjtx modes and speeds (WSPR, FST4W). It collects many decoded parameters such as frequency, SNR, and spectral spread, and makes these available in a database for further analysis.

Spectral Spreading

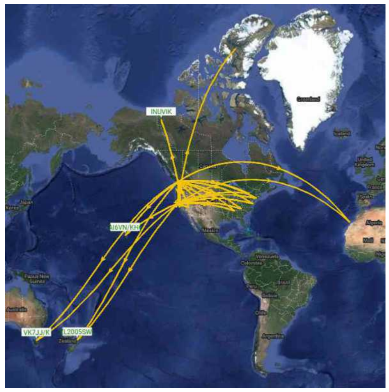


- The “spread” is due to the combination of two (or more) propagation paths, where Doppler Shift causes a frequency shift.
- This can include multi-hop skip
- Accurate frequency measurements can also characterize Doppler shifts

Spectral Spreading is a measure of multipath Doppler shift, and is calculated in wsprdaemon and wsjtx by examining the adjacent decoder FFT bins. It can tell us interesting / useful information about the ionosphere.

Spreading can limit the type and speed of radio transmission, by smearing out the frequencies and creating ISI (Inter-Symbol Interference), reducing the SNR. If it gets bad enough, no amount of increased power will improve things.

FST4W-1200



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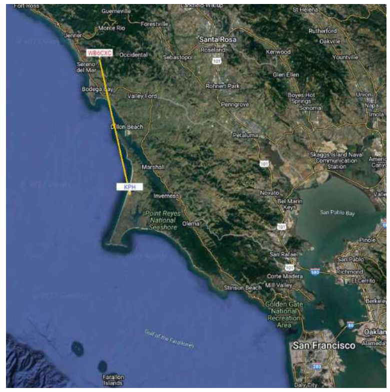
- Many more WSPR receivers than FST4W

FST4W-1200



But one receiving site is almost LOS from my Occidental location:
KPH, the old RCA marine radio station at Point Reyes

KPH - Then

The receive site at Point Reyes was selected by none other than Dr. Harold Beverage (of "Beverage antenna" fame.) He was looking for a a location at the edge of the ocean with plenty of flat land for antennas and a very low electrical noise level for point to point HF reception. The site that became knows as RS on the order wire fit the bill. The station began service in 1930. Coast station KPH moved to the site in 1946.

KPH - Now

KPH shut down commercial operations in 1997, and the property is now owned by the Point Reyes National Seashore. The amateur-run Maritime Radio Historical Society has restored and maintains the facility (and others), and operates many different ham activities, including a bank of seven GPS-disciplined SDR receivers used for FST4W among other things.

VY0ERC

- Eureka, Ellesmere Island, Nunavut, Canada
- The Club is located in the environs of the Eureka Weather Station which is itself located at 79 degrees 59 minutes N, 85 degrees 56 minutes W on Ellesmere Island
- My friends Glenn (N6GN) and Rob (AI6VN) traveled to VY0ERC to install an antenna and set up a KiwiSDR receiver for wsprdaemon monitoring.

I couldn't resist adding this one!

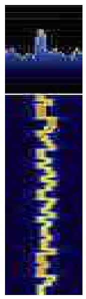
Getting to Stability

And how good is “good enough”?

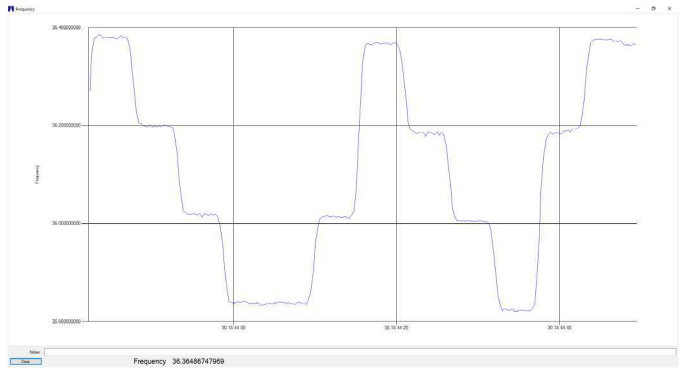
“Good enough” depends on what you are trying to do. Between spark-gap and atomic standards there is an incredible range. Practical ham communications seem to fall into the 100 Hz - .01 Hz range. Test and measurement usually requires stability significantly better than what you are trying to measure.

When we improve frequency stability in one area of a system, we often discover deficiencies in another. With the QDX / Kiwi / FTS4W system it wasn't until we established a near-LOS path with a stabilized transmitter that we discovered that improvements in the receivers were necessary. The LOS path provided a real-world calibration link. My having two stations with the same call, or optionally with call suffixes, showed where software changes were needed.

Plotting Frequency



Spectrum
+
Waterfall

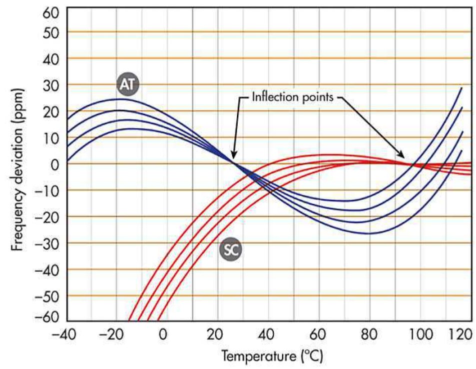


Frequency vs Time

I will be showing plots of changing frequency, displayed vs time, of vs temperature. This is not an oscilloscope trace, which shows voltage vs time.

The spectrum "waterfall" display is also frequency vs time, just turned sideways. The waterfall also usually shows amplitude in a color "heat map" format.

Quartz Crystals



- Virtually all modern ham radios use quartz crystals to provide a stable reference for Phase Locked Loop frequency generation.
- The raw crystal is cut into thin wafers, with different angle of cut providing different frequency-vs-temperature characteristics
- The AT-cut is typical, the SC-cut is often used in OCXOs (Oven Controlled Xtal Oscillator)
- TCXOs (Temperature Compensated Xtal Oscillator) use temperature-dependent tuning to actively tune the oscillation frequency.

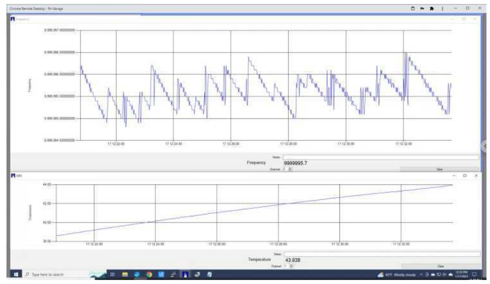
This shows the textbook version of the behavior of various crystal cuts. The cut angle can be varied on three axes, which changes the temperature characteristics, as well as the ability to operate in overtone mode. The oscillators discussed here use fundamental-mode crystals.

Quartz crystals are not the only material used for oscillators (or filters). Micromachined silicon has become popular and other piezoelectric materials have also been used.

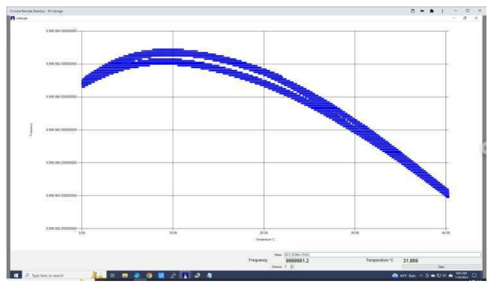
None of these are perfect.

TXCO

- This frequency vs time plot is the output of an inexpensive “Fox” TCXO, as the temperature is slowly increased.
- The abrupt frequency shifts due to the digital compensation method make this TCXO unsuitable for narrowband radio applications.



- This frequency vs temperature plot is the output of an inexpensive “ECS” TCXO, as the temperature is slowly increased and decreased.
- Note the smooth frequency variation



Both of these oscillators meet the same stability specification

That FOX oscillator had me quite confused for a while. I was using it in my counter design and those abrupt frequency steps had me thinking I had a logic or timing bug in my design. These steps won't matter in many applications, but in communications and test gear they can be fatal.

I ended up building a temperature-controlled test chamber to help figure this out.

The TCXO from ECS (and other vendors) shows a more classic and smooth variation over temperature, much like the TCXOs I used to design for miniature VHF transmitters and receivers, used in speech and hearing therapy.

QDX Frequency Stability

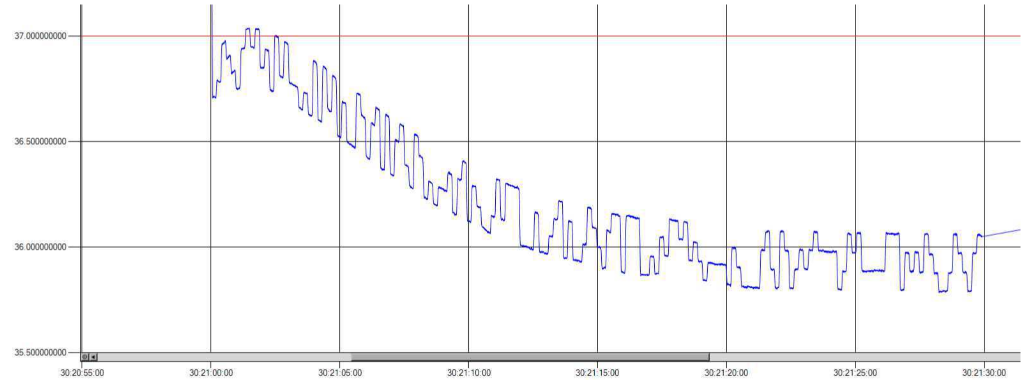
- This shows the FSK modulation and frequency drift of several WSPR transmissions on 20 meters, using an un-modified QDX. The WSPR steps are 1.4648 Hz, and the symbol length is 1/1.4648, or 0.682 seconds. The full transmission takes almost 110.6 seconds
- The drift during a single transmission is about 0.5 Hz
- This amount of drift is not great, but it is **acceptable for WSPR and most other FSK modes**

So how does the QDX look when it comes to frequency stability?

It's pretty good, certainly good enough for “normal” applications. The unit gets warm during long transmissions, and this causes the internal TCXO to drift a little.

This does cause a problem for some modes though.

QDX Frequency Stability



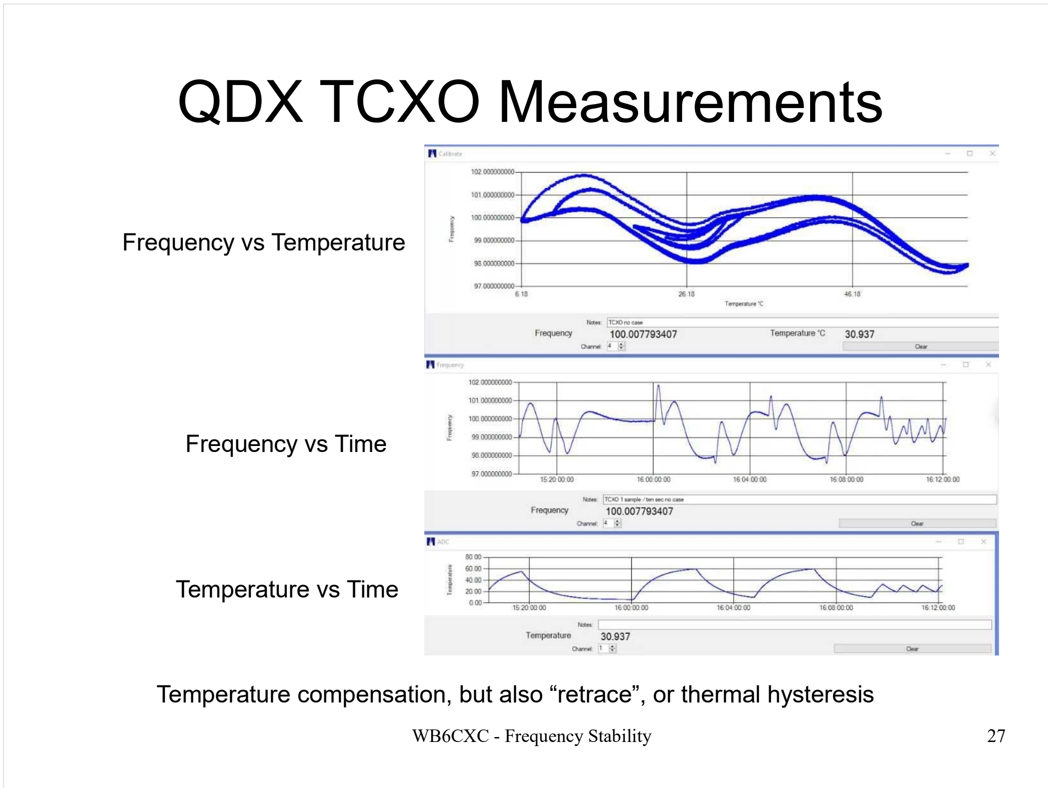
- This shows the FSK modulation and frequency drift of a FSTW4-1800 transmission on 30 meters, using an un-modified QDX. The FSK-4 steps are 0.089 Hz, and the symbol length is 1/0.089, or 11.2 seconds. The full transmission takes almost 1800 seconds, or one-half hour.
- The drift during the transmission is about 1.25 Hz (+/- 0.05 PPM).
- Note that this amount of drift is **completely unacceptable**. The drift has to be less than 0.089 Hz for the transmission to even be decodable.

Here we see the QDX frequency drift during a half-hour FST4W-1800 transmission. Note the initial quick positive shift, then a slow negative drift that more or less stabilizes after twenty minutes or so.

FST4W-1800 probably isn't suited for HF operation, having the narrowest FSK shift of the FST4W modes, but it is a useful frequency stability goal.

QDX Oscillator

- The QDX uses a high-quality TCXO, but even TCXOs will drift over time, temperature, and voltage.
- The principal drift factor in the QDX is internal heating from the output 5W power amplifier transistors.



Measuring the QDX TCXO in the temperature chamber shows a typical smooth compensation curve. In this test I first varied the temperature over a wide, and then over a smaller range.

This measurement also shows “retrace”, which is more of an absolute accuracy problem than a drift one. If there were no retrace we could use digital compensation to achieve much better accuracy. But there is, and we can't.

QDX TCXO Measurements

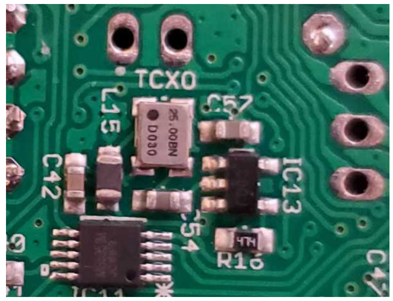
- **Retrace** also happens during power-cycling
- During this test the temperature was continuously cycled by 1 degree C, resulting in roughly 0.05 Hz variation.
- Halfway through the test the power was turned off and on
- The frequency shifted by about 0.225 Hz, and stabilized
- This isn't drift, but is still interesting, and critical in some applications
- Even an OCXO has retrace.

Here, retrace shows up when the oscillator is power-cycled. OCXOs do this, as do Silicon MEMs oscillators.

I was unaware of retrace when I started studying crystal oscillators, at first thinking I was seeing a thermal hysteresis caused by unequal heating and cooling rates of the chamber and the DUT (Device Under Test). But no matter how much I slowed down the temperature change, or forced a uniform temperature gradient, the behavior persisted.

Google to the rescue: Retrace has been known for a long time. We don't know exactly why it occurs, and we can't do much about it – except move to atomic clocks.

Reducing the QDX Frequency Drift



- That little silver square thing is a 25 MHz TCXO -- actually quite a good one
- I discussed options with Hans (the QRP Labs owner and designer)
- Possibility: Sampling a PPS (one Pulse Per Second) from a GPS, measuring the TCXO frequency and compensating in software
- The drift was too fast for this, would need to slow down the rate of change
- Tried adding thermal mass to the TCXO (attaching a brass tab with thermal tape), but this wasn't good enough; the heat was coming via the P.C. Board.

But retrace wasn't the problem here, it was frequency drift. If we could slow down the drift enough, we could use change the QDX frequency settings as the board temperature changed, or use the PPS (Pulse Per Second) signal from an external GPS and the on-board microcontroller to monitor the oscillator frequency and make corrections.

But try as I might, there was just too much heat and the temperature rise was too fast.

Reducing the QDX Frequency Drift

So I designed a replacement for the TCXO: A Clock Multiplier board

- Takes a stable external 10 MHz or 5 MHz reference clock
- Input protection from transients
- A PLL multiplies the reference clock up to 25 MHz
- Takes 3.3V power from the QDX
- Adds some noise and spurs, but definitely clean enough
- Zero drift (as good as the reference)

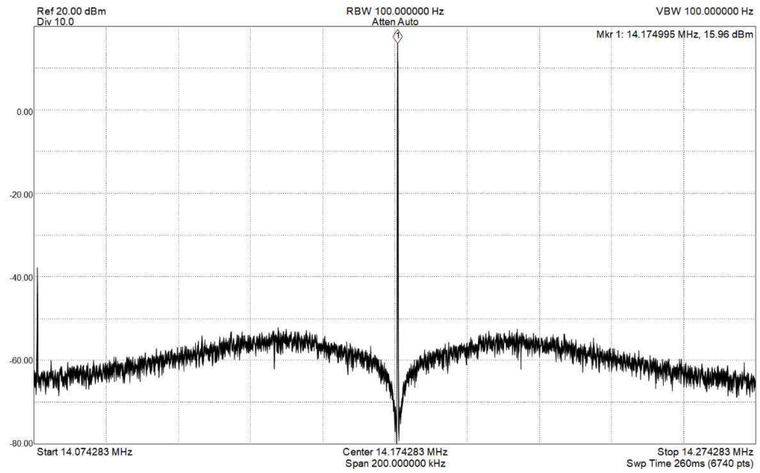
WB6CXC - Frequency Stability 30

This board generates the 25 MHz that the QDX needs, and the original QDX TCXO delivered. The modification to the QDX is trivial.

It was brute-force solution, but this little board cost about $10 in PCB and parts cost to build. We've been using the Leo Bodnar GPSDO (GPS Disciplined Oscillator) to provide the external reference. The GPSDO costs more than the QDX, but the overall performance exceeds that of many higher-cost systems.

The Bodnar GPSDO can also generate a 25 MHz clock directly, and I have a simpler board design that will use that to drive the QDX. I use 10 MHz because much of my test equipment takes a 10 MHz reference.

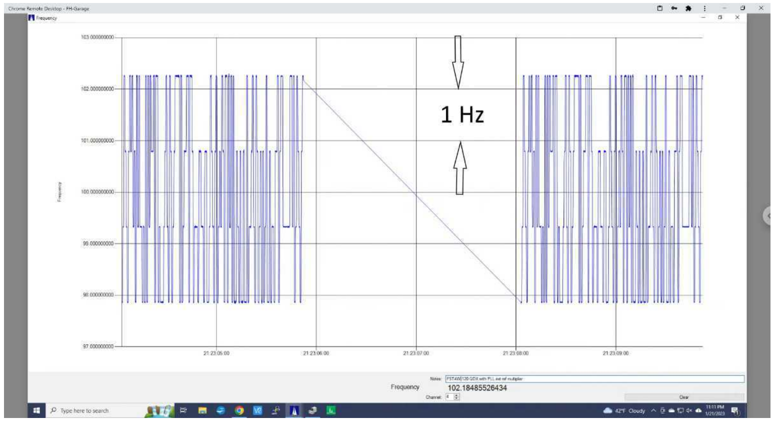
QDX With PLL



- Fairly clean spectrum

Thie spectrum analyzer plot shows the QDX output after the reference clock modification. Harmonics and power are unaffected, but there is a slight increase in the low-amplitude phase-noise close to the signal frequency (shown here). This is typical of an integrated circuit Phase Locked Loop, and has no significant effect on QDX performance.

Zero Drift With External Clock



This shows the drift of the QDX with the external clock modification. The frequency is as stable as the GPS reference.

Measurements
Occidental to KPH

SNR

SPREAD

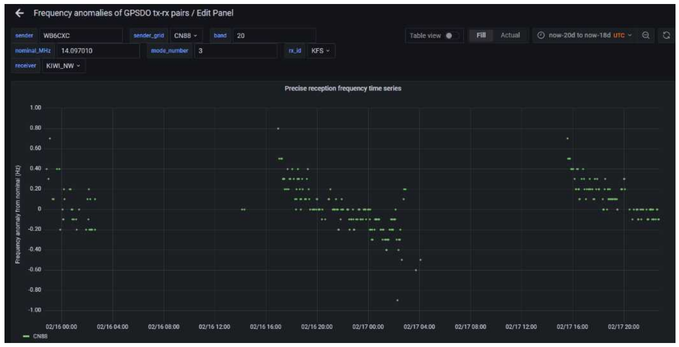
FREQUENCY

Here we see the SNR, spread, and frequency of the stabilized QDX, on the near-LOS path from my Occidental location to the KPH receiver in Point Reyes.

This serves as a reference for the measurement system, and has been quite valuable in calibrating and improving the wsprdaemon network

Measurements
Friday Harbor to KFS

Frequency



Frequency shift during skip propagation
48 hours

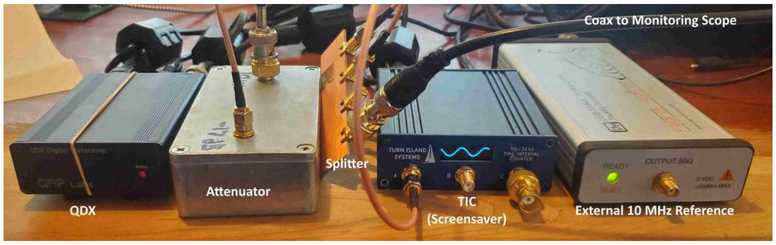
This shows the Friday Harbor transmitter, as received at KFS (another historic radio site near Half Moon Bay, CA, also running SDRs and wsprdaemon.)

Here we can see how the propagation comes and goes during the two-days shown here, and how the changing ionosphere causes first positive, then negative Doppler shift.

Measurement and Analysis

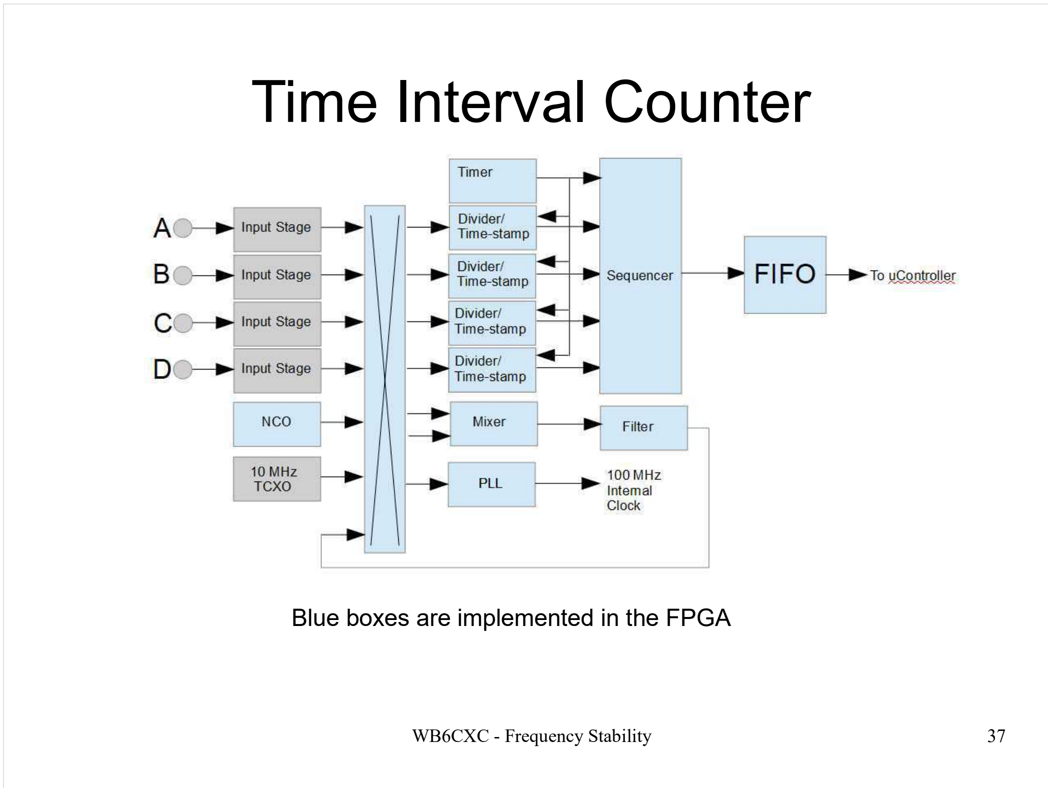
- Frequency domain
  - Spectrum analyzer
- Time domain
  - Oscilloscope, frequency counter

Frequency Measurement Tools



TIC (Time Interval Counter)
- My own design, capable of fast and accurate frequency measurements
- Accepts external 10 MHz reference clock
- 0.001 Hz or better resolution with 14 MHz input, 50 samples per second
- PC GUI for charting and control

External 10 MHz reference,
- either TCXO (shown) or Bodnar GPSDO (GPS Disciplined Oscillator)



As you can probably tell, I'm quite pleased with my Time Interval Counter design. During my QDX tests in order to obtain better, faster, frequency resolution I built an external VFO / mixer / filter, which shifted (not divided) the QDX transmit frequency down into the audio range without loss of accuracy or resolution. This worked very well.

I soon realized that I could implement this feature digitally, within the FPGA. It works well and lets me measure HF frequencies with GPS accuracy and microHz resolution at up to a 50 Hz rate. This proved invaluable when measuring modulation and frequency-transient issues.

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