An Informal Evaluation of a Leo Bodnar GPS Frequency Reference

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• Introduction

This document describes the results of an informal evaluation of a Leo Bodnar Electronics GPS-Locked Precision Frequency Reference [1].

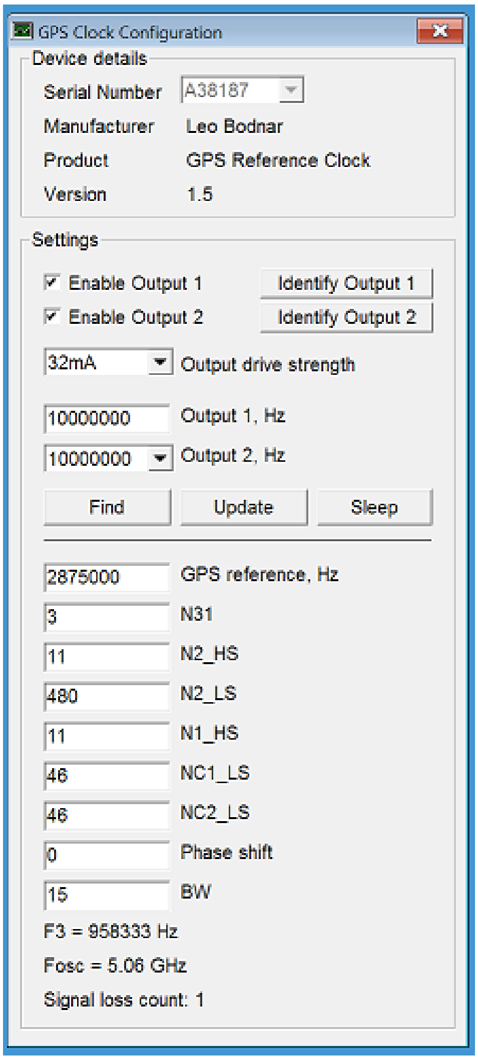
• GPSDO Description

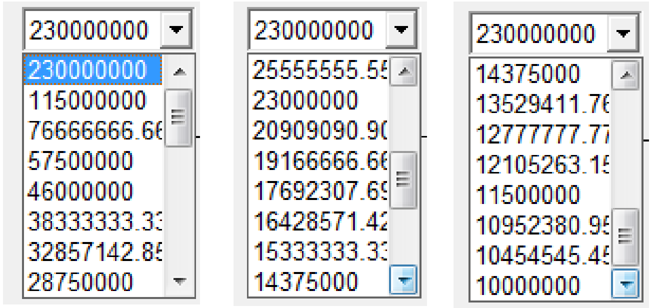
The Leo Bodnar GPS-Locked Precision Frequency Reference, a GPS disciplined oscillator or GPSDO, is the combination of a GPS receiver, a temperature compensated crystal oscillator (TCXO) and a two channel frequency synthesizer. It is strictly a frequency reference (no 1 PPS signal or other time or position information is provided) intended primarily to serve as a frequency reference for radios. The frequency of the TCXO is disciplined by the GPS reference to have high accuracy, and its two 3.3V 50 ohm low-jitter CMOS outputs can be configured for various frequencies between 450 Hz and 800 MHz. It can be powered by either by its USB port or an external 12 VDC supply. The device is packaged in a small 1" high x 2" wide x 3 ½" deep aluminum box [2] as shown in Figure 1. The specifications for the unit are shown in Appendix I. General information about GPS disciplined oscillators will be found in Reference 3.

Fig. 1. GPS Frequency Reference

• GPS-Locked Frequency Reference Setup

The GPS-Locked Frequency Reference is set up using its GPS Clock Configuration Windows® program (see Figure 2) after connecting it to a PC via its USB port and connecting a suitable GPS antenna. Begin by enabling the desired outputs and set their strengths. Then enter the desired primary Output 1 frequency and press the Find button to find its synthesizer settings. The Output 2 frequency can then be selected from the pull-down list; only those secondary frequencies are available. For example, for a 10 MHz Output 1 primary frequency, the available Output 2 secondary frequencies are shown in Figure 3. The Identify Output buttons flash the LED adjacent to their corresponding output. The Update button sets the device to the selected secondary frequency, and saves the frequency information in the device. The Sleep button shuts down the internal processor for minimum noise. The boxes below show the internal synthesizer settings, which are associated with its Silicon Labs Si5328 synthesizer [4]. Indicators at the bottom right show loss of GPS and PLL lock. It is not necessary to open the GPS Clock Configuration program to use the device.





Available Output 2 secondary frequencies for 10 MHz Output 1 primary frequency

Other combinations of frequencies are also possible by directly setting the synthesizer parameters, e.g., to get 10MHz and 125MHz [5]:

```
GPS Reference 100000
N31 1
N2_HS 11
N2_LS 5000
N1_HS 11
NC1_LS 50
NC2_LS 4
Phase shift 0
BW 7
```

Get +11 dBm at 125 MHz with clean spectrum.
Largest spur = -45 dBc @10 MHz
Region around carrier very clean
Largest spurs -70 dBc at ±300 kHz.
No very close in spurs or pronounced noise pedestal

Figure 2. GPSDO Configuration Screen

Figure 3. Secondary Frequency Selection List

• GPS-Locked Frequency Reference Synthesizer Architecture

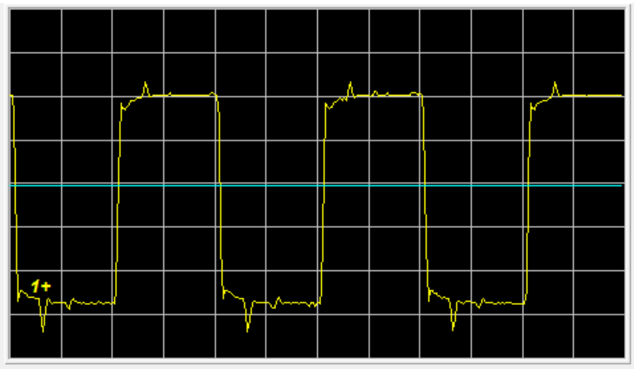
The GPS-Locked Frequency Reference Si5328 synthesizer has three major cascaded blocks, an input frequency divider (N3), a phase locked oscillator multiplier (N2) and a pair of output frequency dividers (NC1 & NC2). The phase locked oscillator multiplier (called a DSPLL because its loop filter uses digital signal processing) has a pair of cascaded dividers (N2_HS and N2_LS) whose product sets the multiplications factor. The output divider chain starts with N1_HS followed by NC1_LS for output 1 and NC2_LS for output 2. Because the outputs share the same N1_HS divider, once the first output frequency is selected, the second output is limited to frequencies that are a submultiple of the common N1_HS divider output. As an example, consider the 10 MHz and 125 MHz settings shown above. 100 kHz from the GPS reference is multiplied by N31=1 and the product of N2_HS=11 and N2_LS=5000 to become a PLL VCO output frequency of 5.5 GHz. That is divided by N1_HS=11 to 500 MHz and then by either NC1_LS=50 to 10 MHz for output 1 or NC2_LS=4 to 125 MHz for output 2.

• **GPS-Locked Frequency Reference Operation**

GPS-Locked Frequency Reference operation requires only that its antenna be connected and that it be powered via its USB cable or 12 VDC connector. Its configuration is set up by a downloadable Windows® PC program via its USB port; subsequent operation does not require the PC connection. No other monitoring software is provided. The unit quickly acquires GPS and synthesizer PLL lock, and the 3.3V CMOS squarewave outputs become syntonized to the GPS reference [6].

• **GPS-Locked Frequency Reference Outputs**

The outputs from the GPS-Locked Frequency Reference supply 3.3V CMOS nominal squarewaves into a 50 Ω as shown in Figure 2. They can be low pass filtered to provide a sinusoidal waveform as shown in Figure 3 (the filter used was a Mini-Circuits Model BLP-15+ having a 15 MHz cutoff [7]). The GPSDO output was set to its maximum 32 mA strength.



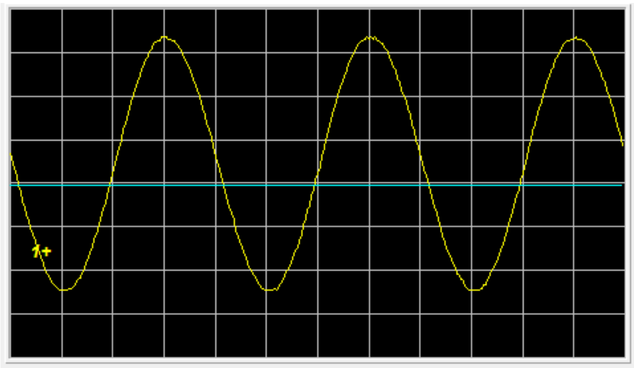


Figure 2. GPSDO Squarewave Output
2.96 V p-p, 1.12 VDC, +15.8 dBm

Figure 3. GPSDO Filtered Sinewave Output
2.96 V p-p, 1.08 VDC, +14.6 dBm

Both: 10 MHz, 500 mV/div vertical, 25 ns/div horizontal

When the two outputs are at the same frequency, their relative phase can be adjusted in certain discrete steps with the Phase Shift pull-down list setting. At 10 MHz, these are steps of 7.83 degrees.

• **GPS-Locked Frequency Reference GPS-Disciplined Stability**

An overnight run was performed to measure the GPS disciplined oscillator versus a local rubidium frequency standard. The observed short-term stability is that of the TCXO while the long term accuracy is determined by the GPS reference, a very inexpensive way to obtain an absolute standard of time and frequency.

The 1-second fractional frequency record is shown in Figure 3, and the resulting frequency stability is shown in Figure 4.

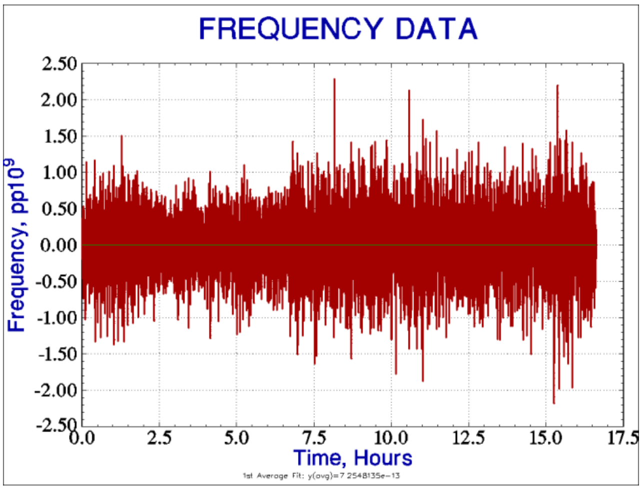


Figure 3. GPSDO Overnight Frequency Record

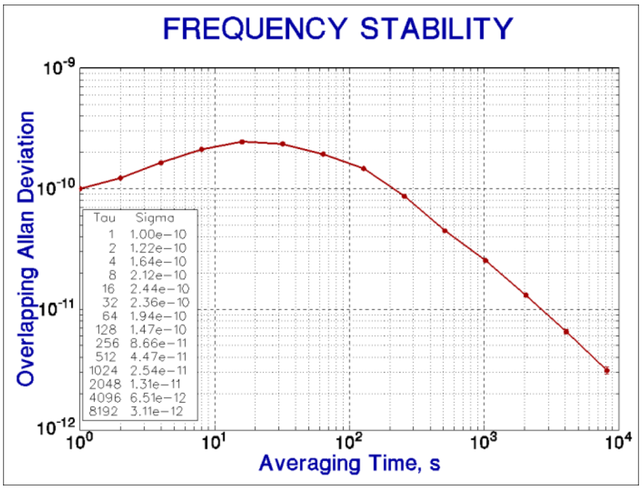


Figure 4. GPSDO Overnight Stability Plot

The GPSDO frequency record is quite clean, nearly free of disturbances and cyclic variations. The short-term stability has a random walk FM characteristic (α=-2) that is probably mainly due to TCXO thermal sensitivity. The longer-term stability shows white/flicker PM noise from the GPS reference that averages down with tau. The loop time constant appears to be around 15 seconds, which seems appropriate, although a slightly longer value might be better. The white FM noise of the Rb reference is well below the GPSDO noise at all averaging times and does not affect the measurement. The average frequency offset of about $+7.3 \times 10^{-13}$ is consistent with other measurements of the Rb reference.

• GPSDO Holdover and Recovery Phase Record

The antenna was disconnected from the GPSDO at the end of the overnight run to observe its holdover characteristics. The front panel LEDs immediately started flashing and the phase of the GPSDO 10 MHz output began to slew at about -0.6 ns/s indicating a frequency error of about -6×10^{-10} (see Figure 6). That behavior is quite reasonable for a TCXO-based GPSDO. The phase slope slows briefly and then accelerates, accumulating microseconds of phase error in a few minutes. When the GPS antenna is reconnected, the phase quickly recovers. In this case, it is the associated frequency error (rate of change of phase) that matters.

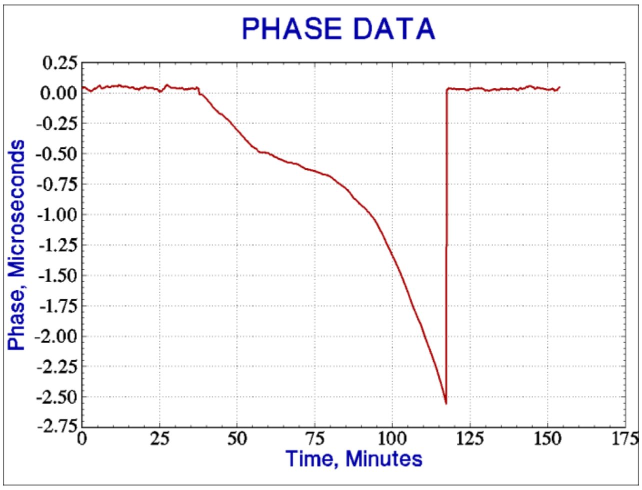


Figure 6. Holdover & Recovery Phase Record

Holdover mode frequency error is the biggest disadvantage of a TCXO GPSDO compared with a unit having an ovenized crystal oscillator, Rb frequency standard, chip scale atomic clock, or another more stable local oscillator.

• GPSDO Phase Noise

In the frequency domain, the TCXO phase noise was measured using a TimePod cross spectrum analyzer [8] as shown in Figure 7.

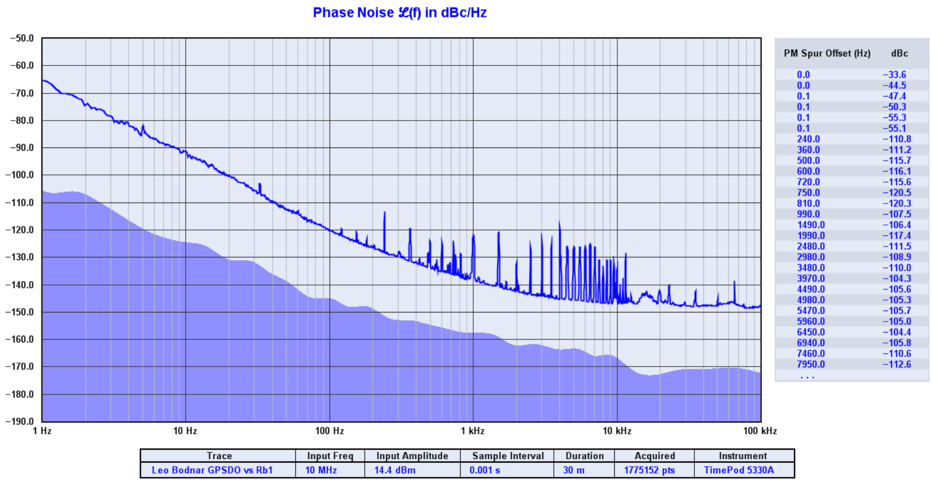


Figure 7. GPSDO Phase Noise

At sideband frequencies of 100 Hz and above, the measured phase noise is essentially the same as specified (see Appendix I). Below 100 Hz, the phase noise generally follows a -30 dB/decade flicker FM characteristic, and at 1 Hz is about -65 dBc/Hz, a little better that that, a value that corresponds very closely to the $1x10^{-10}$ ADEV measured in the time domain. The discrete spurious do not seem to be powerline related and are of unknown origin. The GPSDO was operated from a linear DC supply, its USB cable was disconnected, and its internal processor was off. It is likely that they come from the measuring system or Rb reference.

• GPS-Locked Frequency Reference Applications

The obvious application for this GPSDO is to serve as an absolute frequency reference for an instrument, radio, etc. As long as it is locked to GPS, it provides high accuracy at low cost. The dual adjustable output frequencies add versatility for applications such as direct digital synthesizer (DDS) clocking and receiver local oscillators.

A GPSDO can also be used to calibrate (syntonize) a local ovenized crystal oscillator (OCXO) or rubidium frequency standard (RFS). If the frequency standard is compared against the GPSDO over a period of several days, the GPS and TCXO noise can be averaged sufficiently that a good determination can be made for the OCXO or RFS frequency offset, which can then be adjusted below the $pp10^{11}$ level (a practical limit for an RFS, one that needs only occasional recalibration). A syntonized RFS then provides an excellent local frequency reference at all averaging times.

This GPSDO also makes a good companion for the PicoPak DDS clock measurement module [9], especially since it is similarly packaged and low in cost.

• Conclusions

The Leo Bodnar GPS Precision Frequency Reference is a small GPS disciplined oscillator that performs quite well and is suitable for non-demanding applications requiring accurate frequency syntonization at a fraction of the cost of a local atomic frequency standard with a traditional GPS timing receiver. Its main limitations are the lack of position and time information, and the short-term and thermal instability of its TCXO, especially in holdover mode. It would be nice to add the ability to set a PC clock from the GPS receiver, particularly for field situations where no NTP was available. The wide range synthesizer offers great flexibility for output frequency, although its secondary frequency selection is limited. The output spectral purity is excellent.

• References

1. Precision Frequency Reference (GPS Clock), Leo Bodnar Electronics LTD, Northampshire, UK, www.leobodnar.com. Sold in the United States as GPS-Locked Precision Frequency Reference by Force12, www.force12inc.com.
2. The enclosure appears to be a Hammond 1455C801. It is nicely machined, but unmarked.
3. M.A. Lombardi, L.M. Nelson, A.N. Novick and V.S. Zhang, “Time and Frequency Measurements Using the Global Positioning System”, *Cal Lab*, July-September 2001, pp. 26-33.
4. *Si53XX Family Reference Manual*, Silicon Labs, Austin, TX 78701, 2013, http://www.silabs.com/Support%20Documents/TechnicalDocs/Si53xxReferenceManual.pdf
5. Leo Bodnar, private communication 05/22/16.
6. During lock acquisition, the two front panel LEDs flash, and they are on steadily during normal locked operation. Otherwise, there is no monitoring of satellite tracking, and no GPS time or receiver location information.
7. Data Sheet, BLP-15+ Coaxial Low Pass Filter, 50 Ω, DC to 15 MHz, Mini-Circuits, Brooklyn, NY 11235, http://www.minicircuits.com/pdfs/BLP-15+.pdf
8. Data Sheet, TimePod 5330A Programmable Cross Spectrum Analyzer, Miles Design/Symmetricom/Microsemi, May 2013, www.miles.io/TimePod_5330A_user_manual.pdf
9. W.J. Riley, “A DDS Clock Measurement Module”, Hamilton Technical Services, January 2016, http://www.wriley.com/A%20DDS%20Clock%20Measurement%20Module.pdf

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May 23, 2016

Appendix I

Leo Bodnar GPS-Locked Frequency Reference Specifications
(Accessed from www.leobodnar.com 05/21/16)

Low-jitter GPS-locked precision frequency reference 450 Hz to 800 MHz output

This device outputs two synchronised low-jitter reference clocks locked to GPS signal.

Long term stability of output signal is defined by high accuracy of GPS Caesium references and theoretically approaches $1x10^{-12}$.

Short term signal quality is defined by internal TCXO clock source providing high-quality, low phase noise clock signal with sub-picosecond RMS jitter.

Digital PLL allows main output reference frequency to have almost any value between 450Hz and 800MHz.

Two outputs can be individually enabled and set to different frequencies. Second output frequency depends on the first output. If both outputs have the same frequency their relative phase shift can be adjusted. This can be used, for example, to generate two signals with 90° phase shift for use in I/Q mixer.

Both output signals are at 3.3V CMOS levels with 50 Ohms characteristic impedance. Their output drive levels can be adjusted.

Output power level (measured at 10MHz, fundamental power channel):
+13.3dBm, drive setting 32mA
+12.7dBm, drive setting 24mA
+11.4dBm, drive setting 16mA
+7.7dBm, drive setting 8mA

Operation requires continuous presence of GPS signal, however temporary loss will be tolerated seamlessly. Active or passive antennas are supported. An active antenna with 3 metre cable is provided with the device but can be substituted if necessary. GPS acquisition time after power-up is around 30 seconds. If GPS signal is lost, digital PLL will maintains best estimated output frequency based on historical data. On reacquisition of GPS lock, output is seamlessly brought back in sync with GPS reference. Entry and exit of frequency hold is glitch-less.

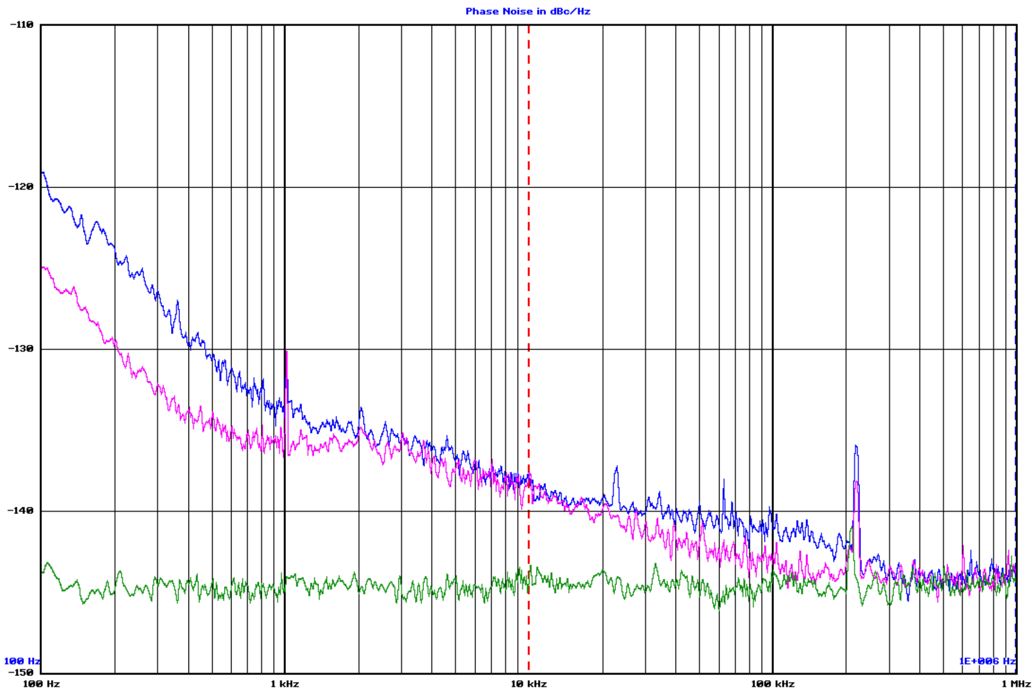
All frequency and output settings are fully user-configurable via USB connection from Windows PC.

GPS clock can be powered from USB input and/or external 5-15VDC power input including standard +13.8V PSUs or car battery. USB connection to Windows PC is required only for one-off configuration. All settings are stored inside the device and maintain values when off.

Examples of use include: 10.000MHz, 1.000MHz or other frequency reference for lab equipment and instrumentation reference for transmitter equipment – HAM rigs, propagation beacons, frequency markers, reference for receiving equipment, RTL SDRs (28.8MHz) and band scanners, calibration source for radio receivers, master clock for audio and video equipment, DACs and studio recording gear.

Measured phase noise of standard (TCXO) version is equal or better than:

-120 dBc/Hz at 100 Hz
-133 dBc/Hz at 1 kHz
-137 dBc/Hz at 10 kHz
-140 dBc/Hz at 100 kHz
-144 dBc/Hz at 1 MHz



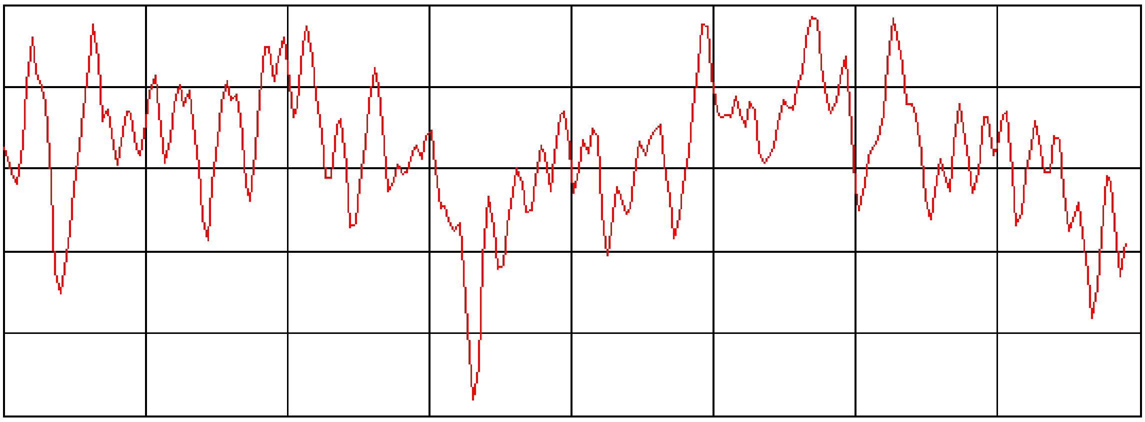
Trace	Carrier Hz	Carrier dBm	dBc/Hz at 10000 Hz	Residual FM Hz	RMS Noise Rads	RMS Jitter	SSB C/N dB	Sweep	Instrument
Standard GPS clock (TCXO)	11 997 628	4.35	-138.3	5.18E+001	1.04E-004	1.4E-012 s	-82.7	438s	E4406A
Custom GPS clock (crystal)	11 997 627	4.35	-137.7	5.13E+001	9.52E-005	1.3E-012 s	-83.4	471s	E4406A
Measurement setup noise floor	11 997 624	4.35	-143.3	4.88E+001	8.46E-005	1.1E-012 s	-84.5	439s	E4406A

WJR Comments re the GPS-Locked Frequency Reference specifications:

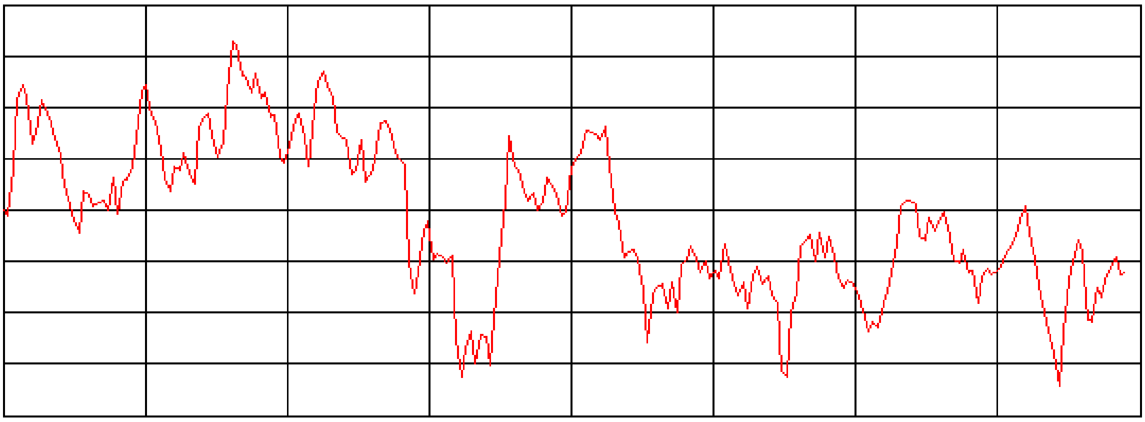
1. The accuracy of the GPS frequency reference is not based on a cesium frequency standard, but rather an ensemble of ground-based clocks (mainly hydrogen masers) that are, in turn, steered for agreement with clocks at the US Naval Observatory. The GPS satellite clocks (mainly rubidium frequency standards) are steered by the GPS system with respect to those ground-based clocks. Cesium enters the picture mainly as the international definition of frequency.
2. See Reference 3 for more information about GPS frequency transfer accuracy.
3. The GPS antenna is an extra-cost item.
4. The phase noise data are at about 12 MHz. They would be about 1.6 dB lower (better) at 10 MHz, and will be correspondingly worst at higher output frequencies.
5. The standard TCXO phase noise plot (blue curve) has a -30 dB/decade (flicker FM noise) characteristic) between 100 Hz and 1 kHz. If extrapolated to 1 Hz from the carrier, this would become -60 dBc/Hz at 10 MHz, corresponding to a time domain stability (Allan deviation) of about 1.6×10^{-10}.

Appendix II

Two TCXO-Based GPS Disciplined Oscillators versus a Rubidium Frequency Standard



GPSTCXO2 (Jackson Labs GPSTCXO)



GPSREFCLK (Leo Bodnar GPS Reference Clock)

Scales: 10 min/div Horizontal, 10 ns/div Vertical, Tau=20 s (similar to disciplining time constants)

The noise levels are similar, and mostly uncorrelated. Their antennas were close together. The noise level of an OCVCXO-based GPSDO is about half as much, and the noise of the Rb reference is much less.