Radio Propagation Time Of Flight Measurements: HamSCI Work in Progress

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Abstract

Time Of Flight measurements over multiple paths can be a valuable tool when validating and refining radio propagation models. This presentation will discuss current methods in use and several new projects and designs that are being developed for the HamSCI PSWS program. These will include the “Time-Sync Injector” and associated software, which is used with a Software Defined Radio such as the RX-888 to allow accurate Time Of Arrival measurement of received signals. Also described will be the “Time-Stamp Transmitter”, which generates flexible-format time-stamped signals, and a new receiver design, based on the RX-888, but intended to serve as a platform for future time and frequency measurement projects.

Introduction

Paul Elliott:

- Retired electronics engineer
- Vice President TAPR BOD
- Ham Extra – WB6CXC – first licensed around 1974
- Became involved with HamSCI via the wsprdaemon group
- I don't get on the air much, but I like designing stuff
- Have a *very* small company to make / sell these designs:

TURN ISLAND SYSTEMS

Introduction

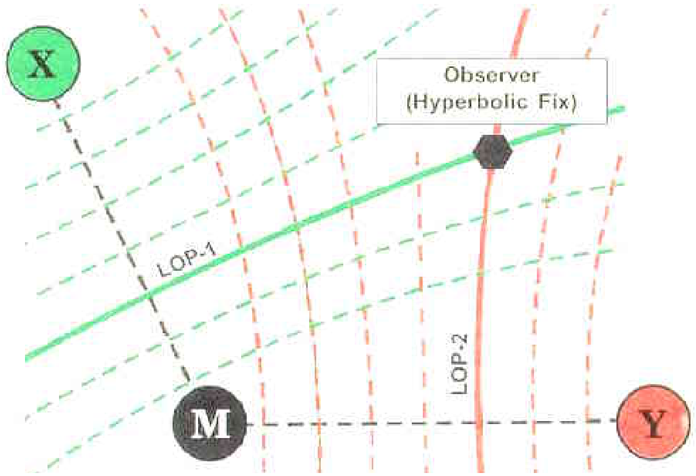
The HamSCI and wsprdaemon communities have made great progress in developing a distributed network of transmitters and receivers capable of using WSPR / FST4W modes to measure the Doppler shift and several other parameters of propagated signals across many different paths and frequencies. We are typically measuring Doppler shift with better than 10 milliHz accuracy.

But one parameter we've only occasionally explored is Time of Flight and related measurements. This is not new technology by any means, but this presentation will describe tests and equipment designed to be “ham-friendly” and easy to set up. We still have much work to do – transmitter design, transmit protocols, decoding software, database design, etc. are definitely ongoing projects.

This presentation will cover a bit of relevant history, some work in progress, and plans for the future.

Terminology

TOT: Time of Transmission
TOF: Time of Flight
TOA: Time of Arrival
TDOA: Time Difference of Arrival
PPS: Pulse Per Second
LOP: Line of Position



LORAN: Uses three known-location transmitters. The unknown-location receiver measures the TDOA to determine two hyperbolic Lines of Position. The intersection of these two LOPs is the receiver's position. Approximately. After GPS became affordable many fishing boats ripped out their war-surplus LORAN units, so about 45 years ago I bought one and used it to figure out the Lat/Lon of my garage. This was the genesis of my interest in Time of Flight

This is not a new thing for the HamSCI community

- Hams have been deploying Time of Arrival-measuring systems for LF/VLF signals – Jonathan Rizzo (KCEEY)*
- And have been using WWV time-tick TOA measurements to differentiate among various propagation modes – Steve Cerwin (WA5FRF)*
- Adding chirp modulation signal to WWV for TOF analysis – Kristina Collins (KD8OCT)*
- Transmit, receive, and recording of PPS BPSK signal during the 2023 / 2024 solar eclipses – Clint Turner (KA7OEI)*

Most of the HF TOF/TOA work to date has used WWV, WWVH as the transmit source. More transmit locations should be useful.

Most received-signal analysis has been in a single location (or just a few). More time-synched receive sites should be useful.

* See links at end of presentation for more details

Next Steps?

Goal: simple, inexpensive, easy to deploy transmit and receive TOF/TOA systems, integrated into the wsprdaemon network and database.

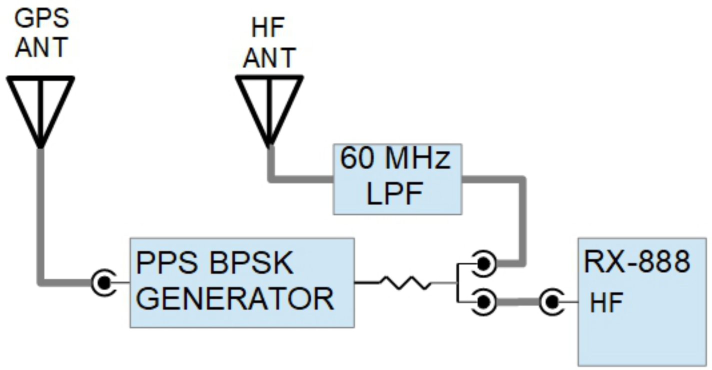
- This is a “tool kit” approach, providing data for general propagation analysis.
- Receiver timesync resolution and accuracy 1 us (or better). TOA accuracy depends on signal characteristics.
- Timesync capability is easily added to existing GPSDO-referenced RX-888 receivers.
- Timestamp transmitter is quite flexible – a good thing since protocols are TBD!
- Add TOA / TOF times to wsprdaemon database

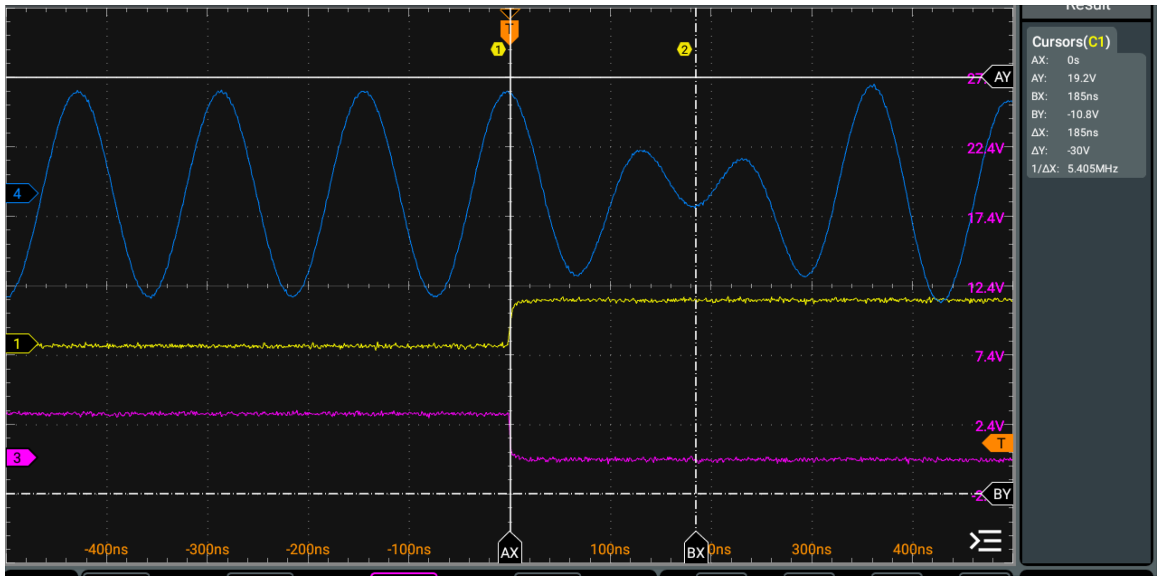
Time Sync Injector

The injector generates a clock signal that is BPSK (Binary Phase Shift Keying) phase alternating on GPS PPS intervals.

This signal is coupled into the RX-888 SDR “HF” input. There is essentially no filtering of the square wave modulation – a wide modulation bandwidth – but this isn't a serious issue in this application.

The signal frequency is 84.225 MHz, which is above the RX888 Nyquist frequency (the RX-888 sample clock is 129.6 MHz). This signal is aliased down to 45.375 MHz where it is demodulated and decoded by ka9q-radio, then used to establish the .wav file timestamps.





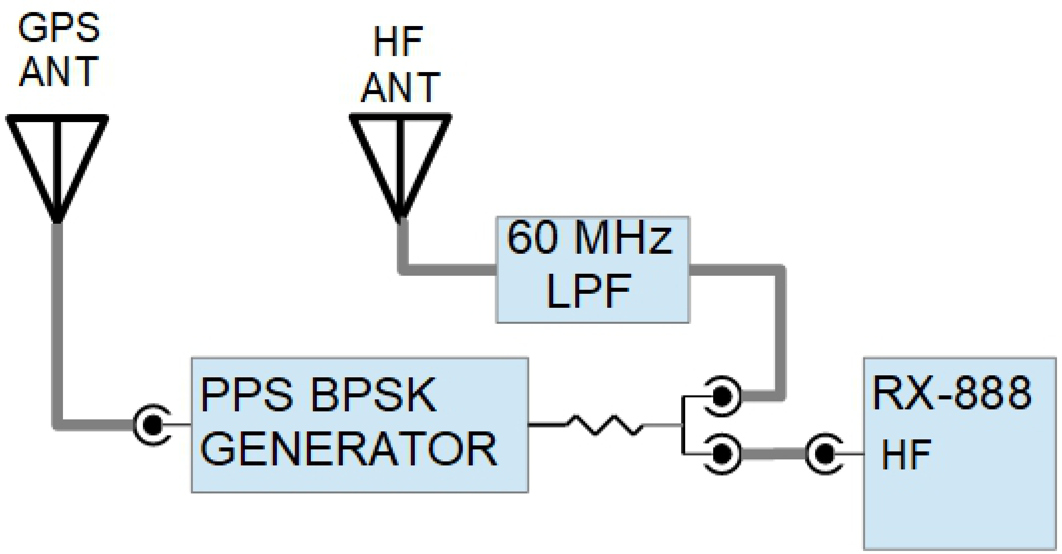
Why 84.225 MHz?

The signal frequency is 84.225 MHz, which is above the RX888 Nyquist frequency (the RX-888 sample clock is 129.6 MHz).

This high frequency was chosen to eliminate potential re-transmission of the BPSK signal.

The typical external low-pass filter (or filter + preamp) will attenuate this signal by 70 dB or more before it reaches the antenna. With the injector level at -33 dBm this means any re-transmitted signal will be less than 1 picowatt.

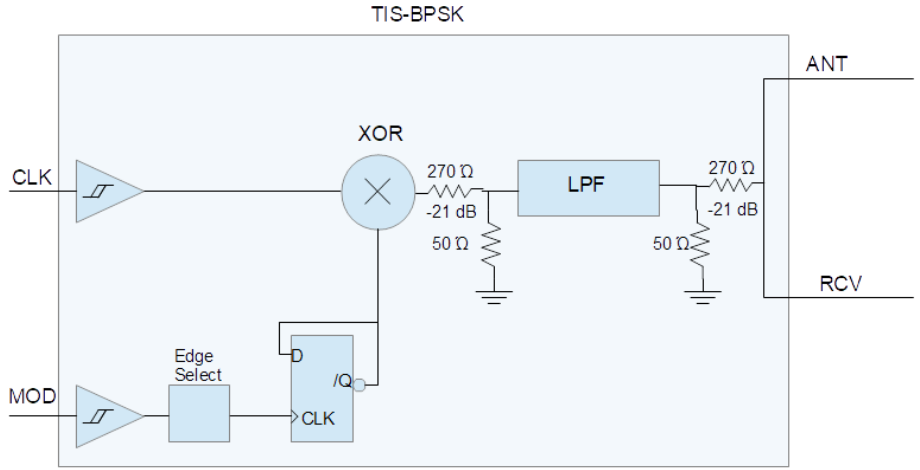
This 84 MHz signal will be further attenuated by the RX-888 internal LPF by about 25 dB.

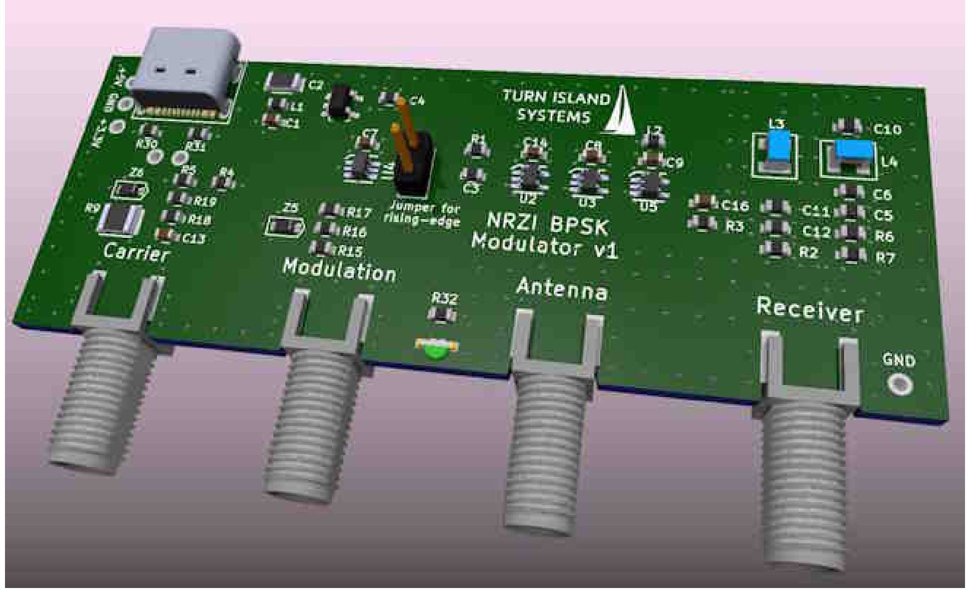


Some RX-888 installations use half-rate sampling, which puts the aliased BPSK signal at 19.425 MHz. The BPSK signal frequency was chosen to ensure that with either sample rate all harmonics out to the 7th do not alias any closer than 475 KHz to any “ham-interesting” band (including WWV, etc.)

Proof of Concept

- First try at a PPS BPSK timesync injector
- Input: PPS and 84.225 MHz clock (from dual-output Bodnar)
- Output: RX-888 SDR
- Using ka9q-radio code, timesync code by Scott Newell
- After testing, installed at WW0WWV (Ft. Collins CO)





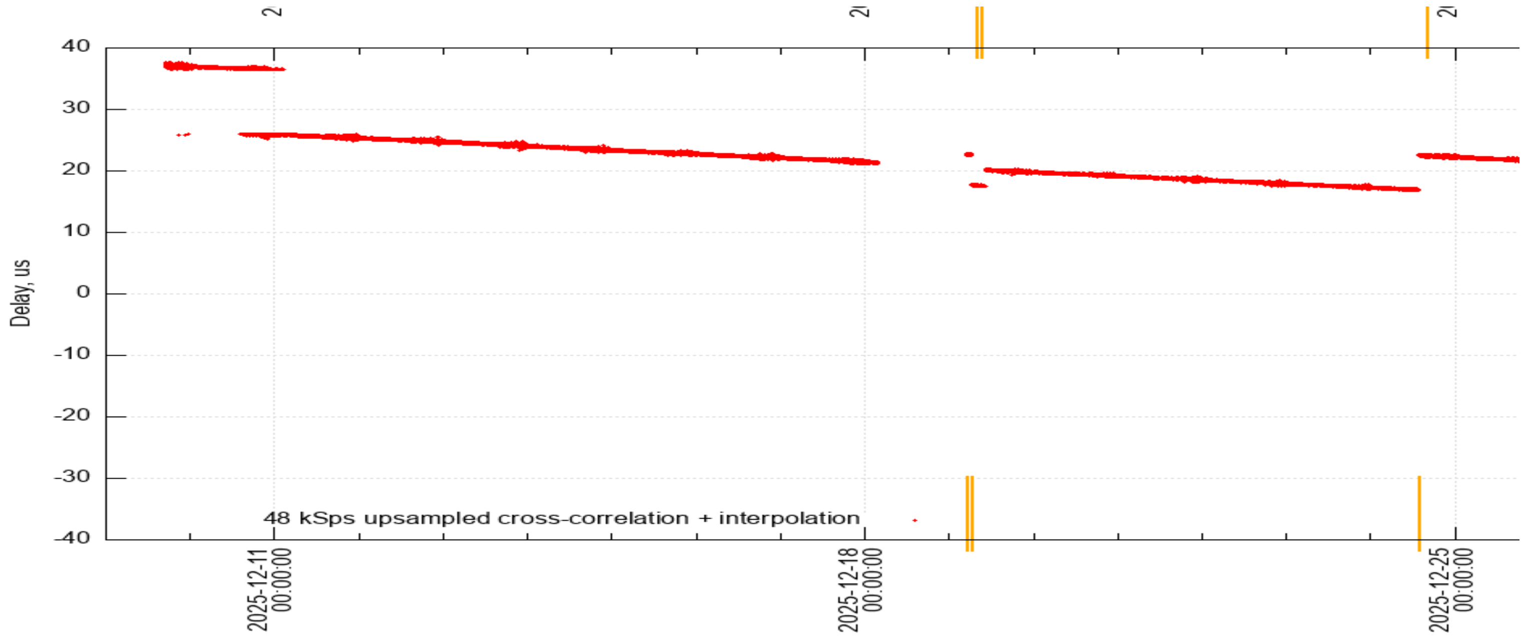
Puzzling Evidence

To verify the performance of the TimeSync modulator / receiver system we used the WWV time-tick transmissions on all frequencies as a local (near-field) timestamp reference signal. It worked great, with better than microsecond resolution – but after a while a problem was revealed:

Why is the measured delay **drifting 5us / week**? A software bug?

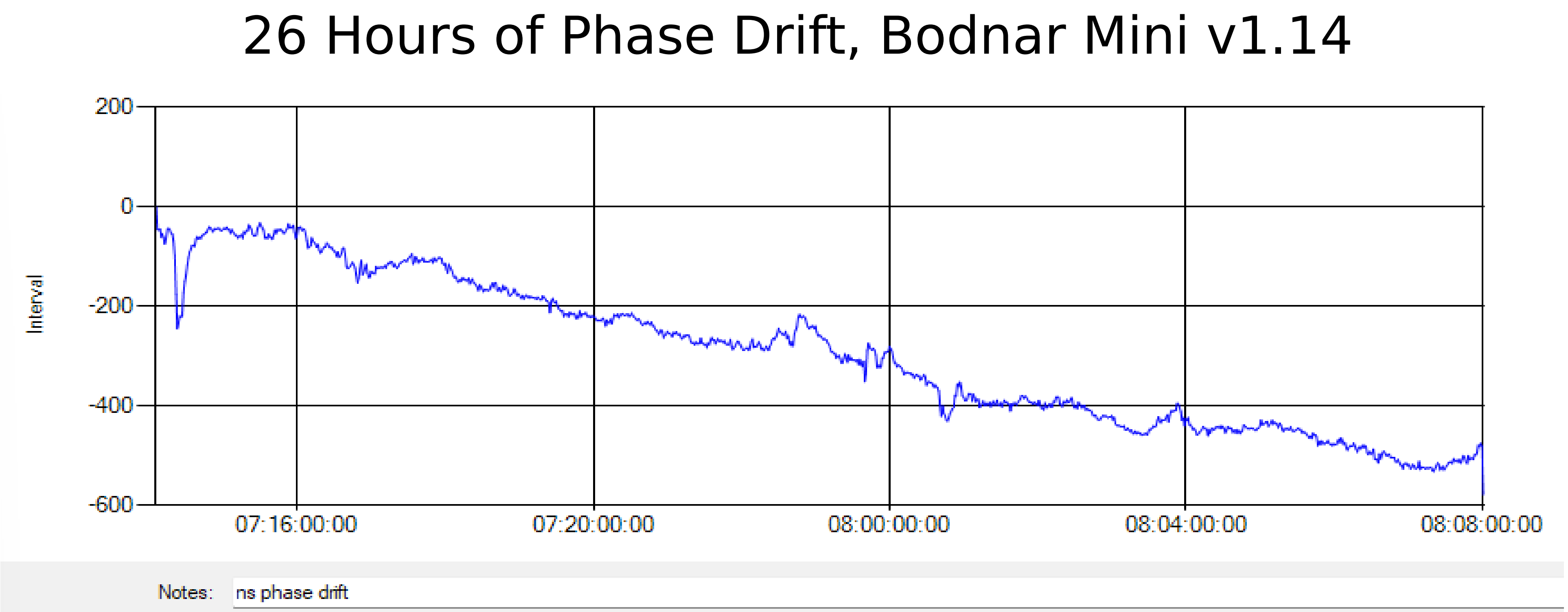
It **can't** be the RX-888 reference clock! – that's a GPSDO set to 27 MHz.

Or can it???



Fun fact: there are significant delays in getting the WWV time-ticks out to the antennas, and each transmit frequency has a different delay: https://www.nist.gov/system/files/documents/calibrations/sp250-67.pdf (page 134)

Measuring the Bodnar Mini



- Using GPS PPS to measure phase drift of Bodnar Mini v1.14
- uController timer clocked by 27 MHz Bodnar, sampled by PPS ISR (two sources of jitter)
- Vertical: ns
- Horizontal: day:hour:minute:second
- About **8 ps/second drift** (more or less, noisy measurement) : about 216 uHz freq error.

Your GPSDO May Not Be Perfect

After much testing we determined that the Bodnar miniGPS as shipped has an output **frequency error of about 200 uHz** when delivering a 27 MHz clock. While this is not significant in typical SDR operation and measurement of Doppler shift, it will result is a slow addition of phase error when measuring TOA – about 17 ns per hour.

Apparently this error is a deliberate trade-off for faster GPS clock acquisition and settling. But there is a firmware update that eliminates this error: v1.20, available from Bodnar.

The newer LBE-1420 does not have this frequency error.

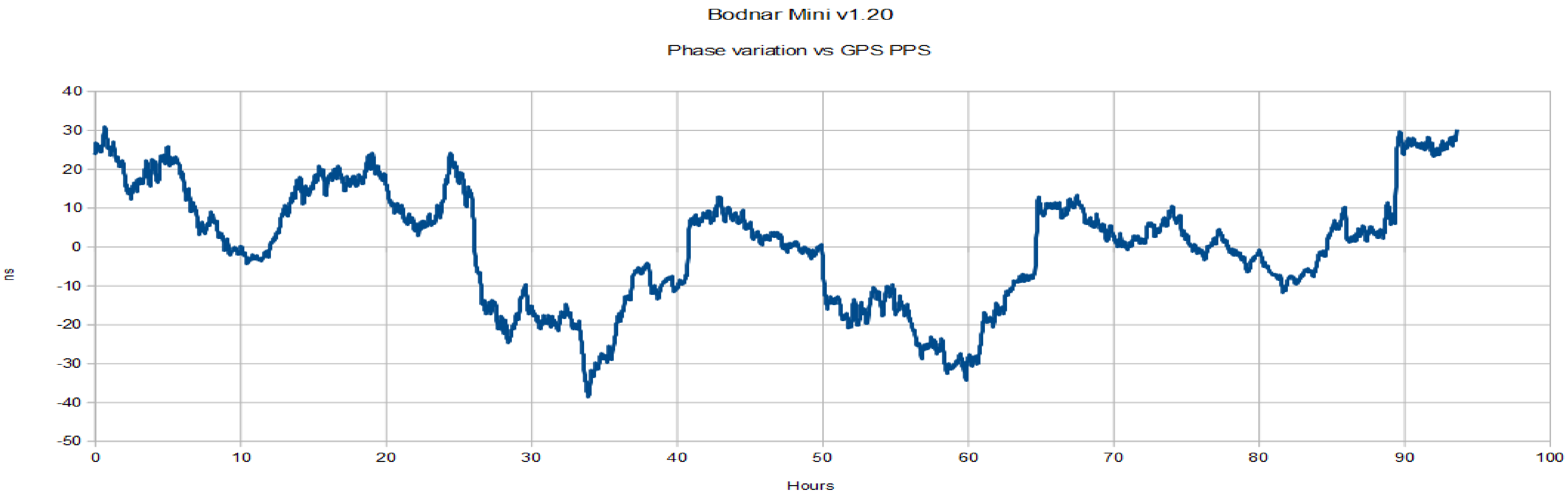
A future revision of the TimeSync software may be able to adaptively re-synchronize to avoid this long-term time error.

Holdover – The Bodnars have significant frequency error during loss of GPS signal. This is a problem during major ionosphere disruption. Do we need a GPSDO with better holdover?

miniGPS

LBE-1420

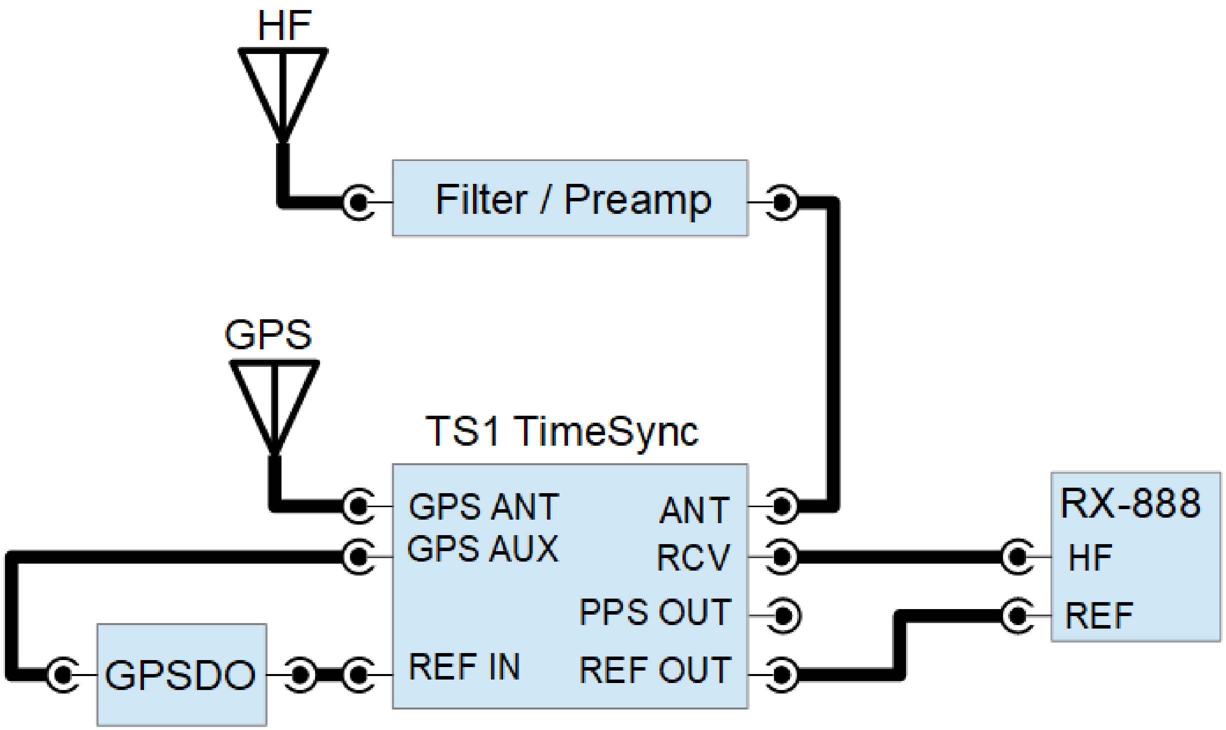
Bodnar Mini GPSDO After Update

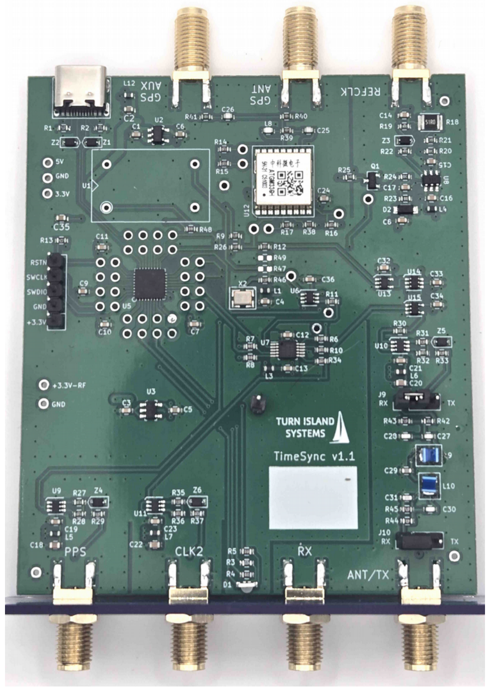


After updating the Bodnar Mini with firmware version 1.20, the long-term frequency accuracy became better than my measurement setup. The chart above shows the smoothed phase variation between the Bodnar clock output (at 27 MHz) and the PPS output of an inexpensive GPS module, measured over a 93 hour interval.

No measurable frequency error.

The TIS-TS1 TimeSync





So I designed the TS1 TimeSync. This has the same PPS-modulated carrier injection, but eliminates the need for a second GPSDO. It also provides for timestamped transmit mode with a 10 mW output (refinements to come).

The TimeSync

- Easy upgrade to existing RX-888 PSWS installations
- Fairly inexpensive (approx $270)
- Can use any typical GPSDO reference clock frequency
- Can generate any output clock frequency (receiver sync input, or transmitter output)
- With ka9q-radio updates lets the RX-888 be used for many types of TOA measurement
- The TimeSync can serve as a timestamped transmitter with better than 500 ns accuracy. (formats in development and TBD)
- USB/serial port available for monitoring and configuration, software updates

The TimeSync At KPH

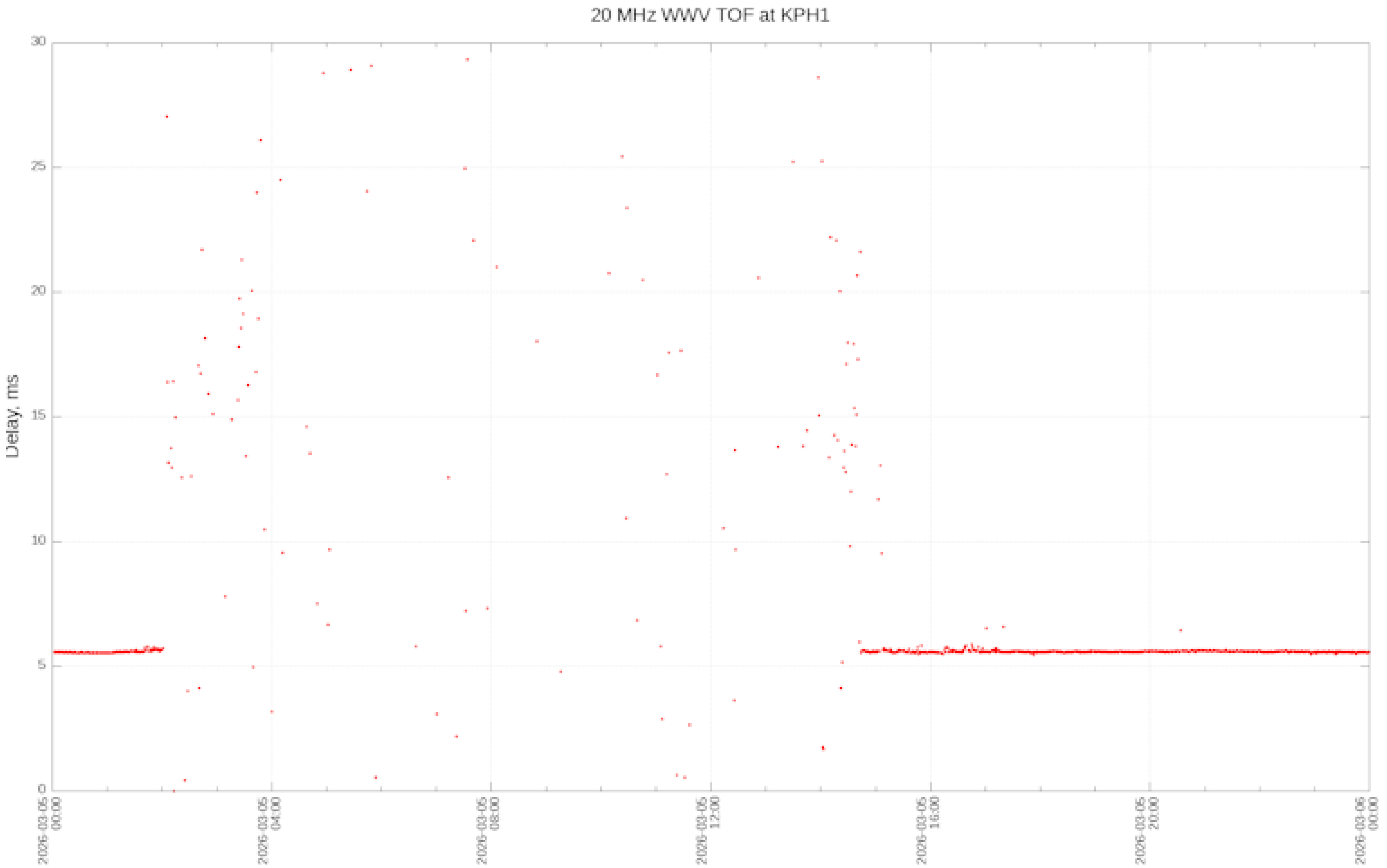
On Feb 16 2026 Rob and I installed a prototype Timesync at the KPH receiver site. The hardest part was squeezing the box into place on a crowded shelf.

But with three SMA jumpers and a USB connection the TimeSync was quickly in service.

Results: WWV to KPH Propagation Time of Flight

We have just begun testing and refining the system, but here is an example of a TOF measurement using the TimeSync and Scott Newell's ka9q-radio additions:

Here we see 24 hours of WWV “top of minute” signal reception at KPH – a 1570 km path, and a measured TOF of about 5.5 ms.



Summary

- Easy to deploy TimeSync design, ready for next build
- Will have BPSK pulse shaping for timestamp transmitter application

- Starting work on wsprdaemon database to include TOA / TOF measurements
- Starting timestamp transmitter protocol development
- ka9q-radio timesync software development continues

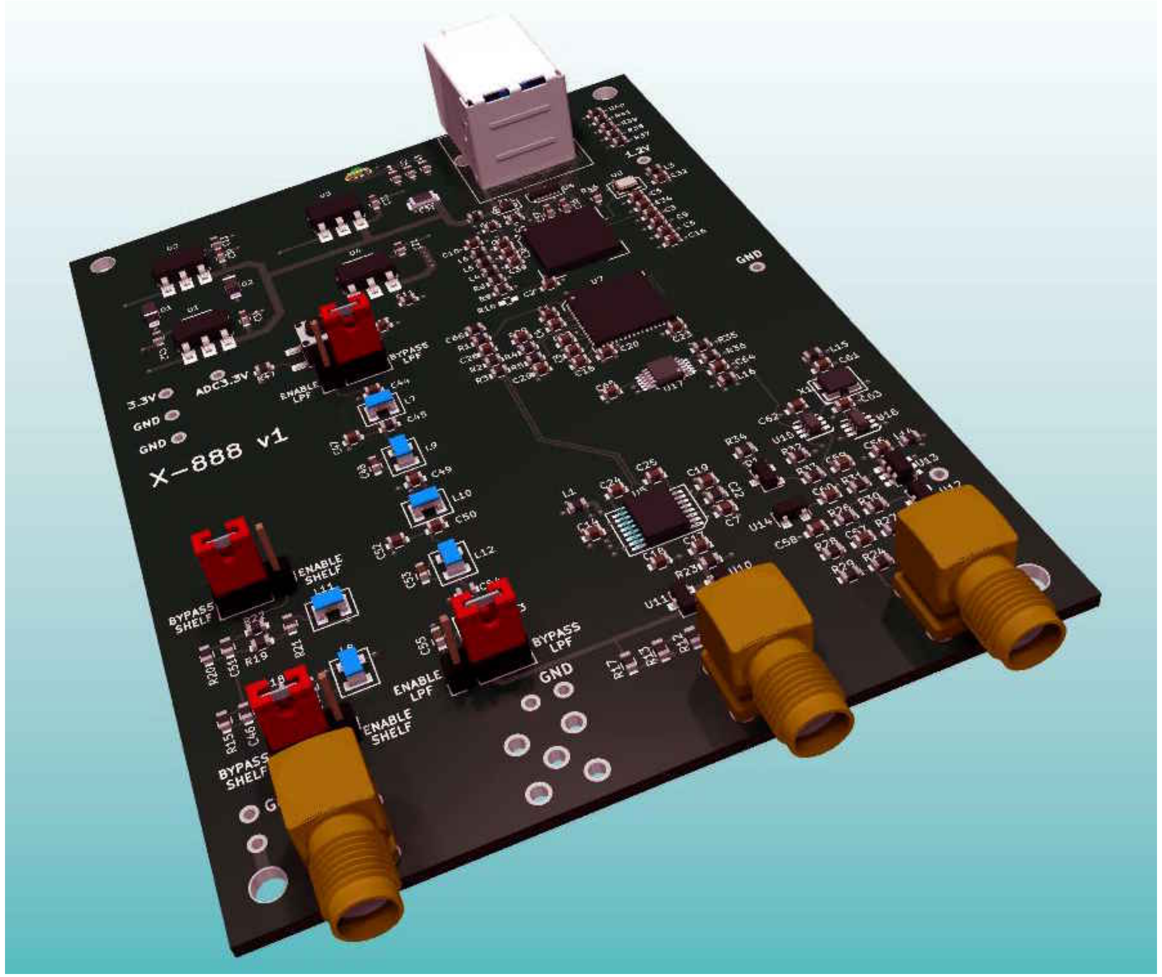
- TOF data from the WWV to KD7EFG path (using Clint Turner's BPSK timesync injector) has been used by Gwyn Griffiths to validate propagation analysis tools

One Last Thing: NEW-888 Project

IN DESIGN

A new SDR receiver based on the RX-888

- HF-only
- Improved external clock interface
- Improved front-end filtering
- Improved low-frequency response
- Improved thermal design
- Larger board dimensions
- Using 0603 surface-mount components for easier modifications
- True open-source, all design files available for future evolution.



Links

- **Jonathan Rizzo - The DASI2 HamSCI Whistler Catcher VLF Reception System**
  https://hamsci.org/publications/dasi2-hamsci-whistler-catcher-vlf-reception-system
- **Clint Turner - Technical description - KA7OEI Eclipse TX and RX equipment -**
  https://www.ka7oei.com/eclipse/eclipse_gear_1b.pdf
- **Clint Turner - Multi-band transmitter and monitoring system for Eclipse monitoring**
  https://ka7oei.blogspot.com/2023/10/multi-band-transmitter-and-monitoring.html
- **Steve Cerwin - WWV Time Tick Arrival Time Study to Investigate Multiple Modes During Daily Dawn and Dusk Transitions**
  https://www.youtube.com/watch?v=LlzJb4HGjiM
- **Steve Cerwin - HamSCI HF multipath propagation mode analysis [...] time difference of arrival**
  https://www.frontiersin.org/journals/astronomy-and-space-sciences/articles/10.3389/fspas.2026.1723511/full
- **Kristina Collins - WWV/H Scientific Modulation**
  https://www.hamsci.org/wwv
- **Gwynn Griffiths - A Python data analysis and synthesis toolbox for PSWS Doppler data: A time-of flight case study**
  https://hamsci.org/hamsci-2026-program
- **NEW-888 (work very much in progress)**
  https://github.com/fourfathom/New-888
- **Turn Island Systems**
  https://turnislandsystems.com/
- **wsprdaemon**
  https://www.wsprdaemon.org/
- **TAPR**
  https://tapr.org/

Acknowledgments

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HamSCI silhouette photo by Ann Marie Rogalcheck-Frissell KC2KRQ.

Thank you!