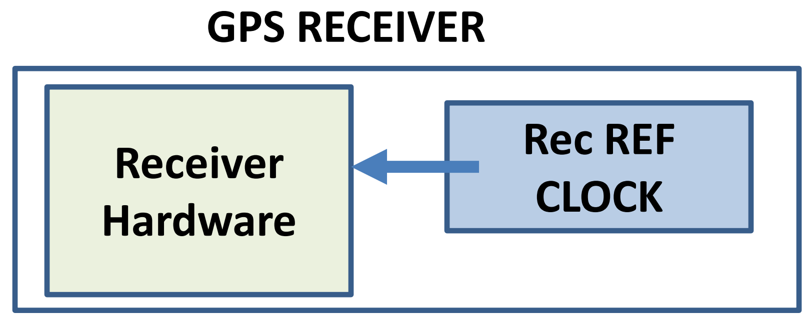
Driving GPS receivers with External Clocks

Dan Doberstein
Saalex, V3.0
Sept 2020

GPS Receivers Typically have dedicated internal Clocks and cannot except an external clock



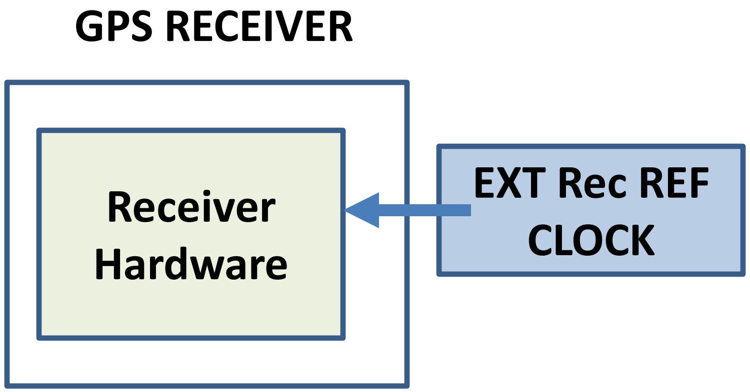
- The internal Ref clock provides the receiver a time reference and frequency reference
- The time reference allows the receiver to measure time of arrival of GPS transmissions, which results in pseudo range observations to each SV
- The frequency reference allows the receiver to produce accurate SV Doppler observations fro each SV

Notes on Rec internal or Local reference Clock

- The receiver wishes its internal/local ref clock was an EXACT copy of GPS Master Clock (GPSMC) in Colorado! (in Rate and Phase)
- Buts its not and its imperfect local clock has Rate and Phase errors wrt GPSMC
- The receiver *measures* rate/phase *errors* of its local ref clock w.r.t GPSMC (from PVT solution)
- Resolving local clock *phase errors* corrects range to SV errors due to local clock phase error w.r.t GPSMC phase (Clock Bias data in UBLOX Mssg)
- Resolving local clock *rate errors* corrects rec based doppler measurements to SV (Clock Drift in UBLOX message)

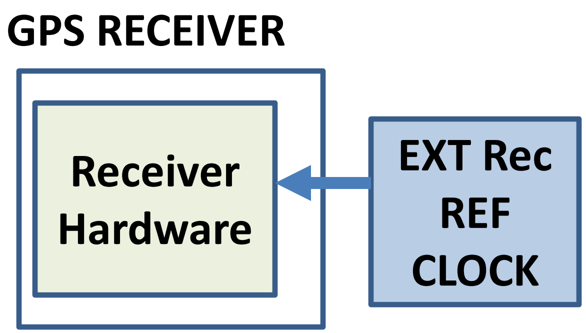
Feeding a GPS Receivers an external clock

- The external Rec REF clock now provides the receiver a time reference and frequency reference
- As with internal clock the receiver uses the external clock as time mark and frequency reference
- Feeding the receiver an external Ref clock allows many different experiments to be executed



Comments on some possible Experiments when feeding GPS receiver an EXT Clock

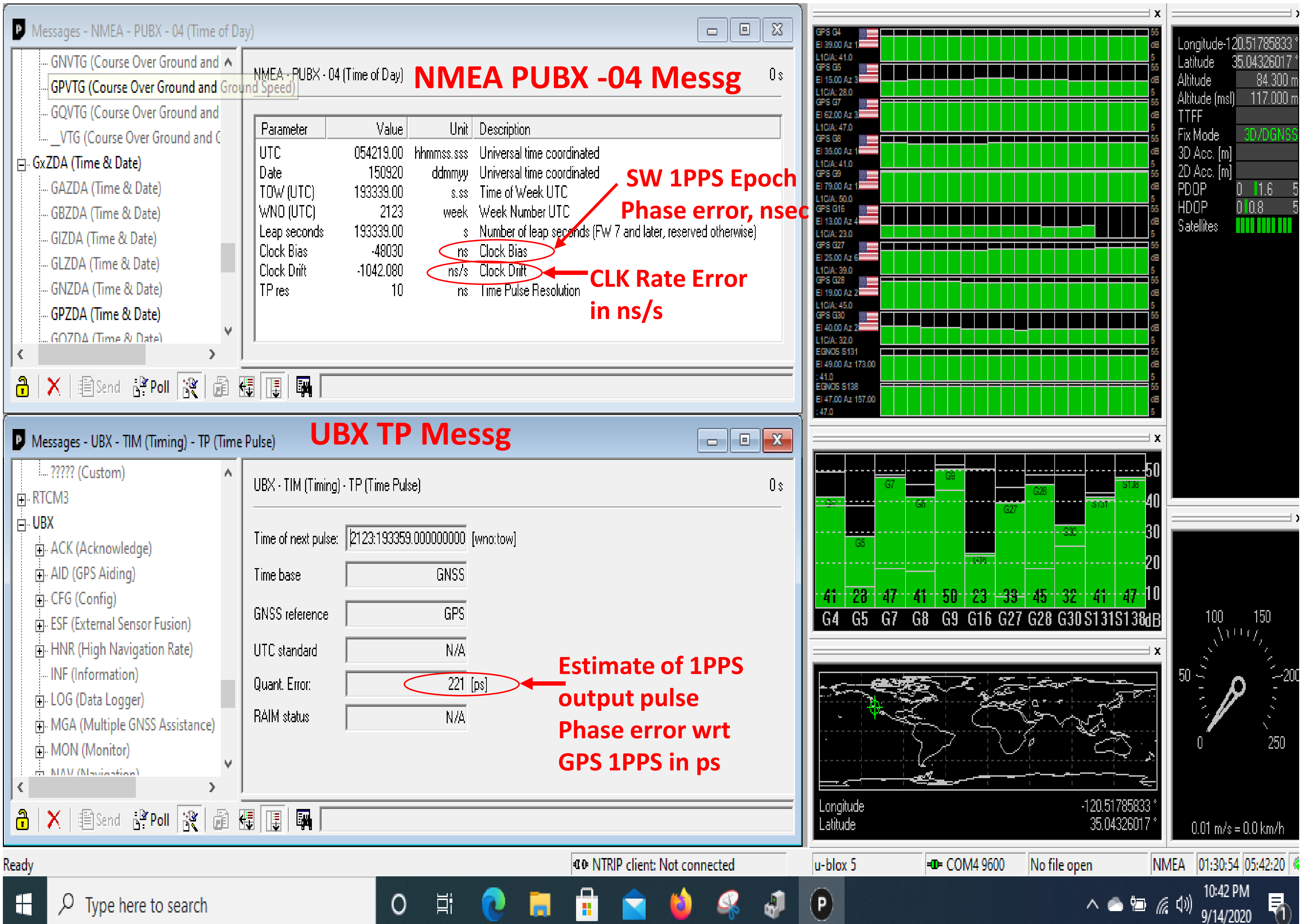
- Like the position case where we know where we are (truth) and we take reported position measurements to form position error, (truth – reported) , we can do the same with an external clock
- If we feed the receiver a clock that has a very tiny rate error we would expect the receiver would report a tiny rate error
- Or we could introduce a known rate error on the external clock and observe what the receiver thinks it is
- Or we could feed a clock with unknown rate error and have the receiver report what it thinks the rate error of the ext clock is
- Or we could observe receiver tracking performance with low fidelity clock and with high fidelity clock
- If we can feed a GPS receiver an external clock many unusual and interesting experiments, measurements and observations can be done



Ublox Receivers Report Clock Phase and Clock Rate errors

- UBLOX reports Rate and Phase errors of its clock weather its an internal clock or an external clock.
- If you know where to look in the many messages the UBLOX receivers these observations/data are present
- The phase error is typically referenced to GPS 1PPS time epoch.
- The UBLOX has two 1PPS time epochs, one is free to wander wrt to GPS 1PPS epoch , the other is corrected to align with GPS 1 PPS epoch
- The corrected 1PPS epoch is sent out as the receivers physical 1PPS signal
- The uncorrected one is typically used to measure TOA against(in SW) , thus any error here appears in the pseudo ranges, as expected (this is the time offset from PVT)
- The UBX Time Pulse Message shows both 1PPS epoch errors with respect to GPS 1PPS
- The Rate error appears in several places, but the PBX -04 message has the high fidelity observation/data.
- Rate error data is typically two to three orders of magnitude more accurate than phase data. This is due to rate measurements can be extracted from delta carrier phase observations. Since a delta is used the carrier phase ambiguity issue is moot.
- The next slide shows a UBLOX Ucenter screen with LEA5T receiver tracking GPS live sky.
- The message windows are UBX TP and NMEA PUBX-04.

Ucenter Output and UBLOX LEA5T Receiver

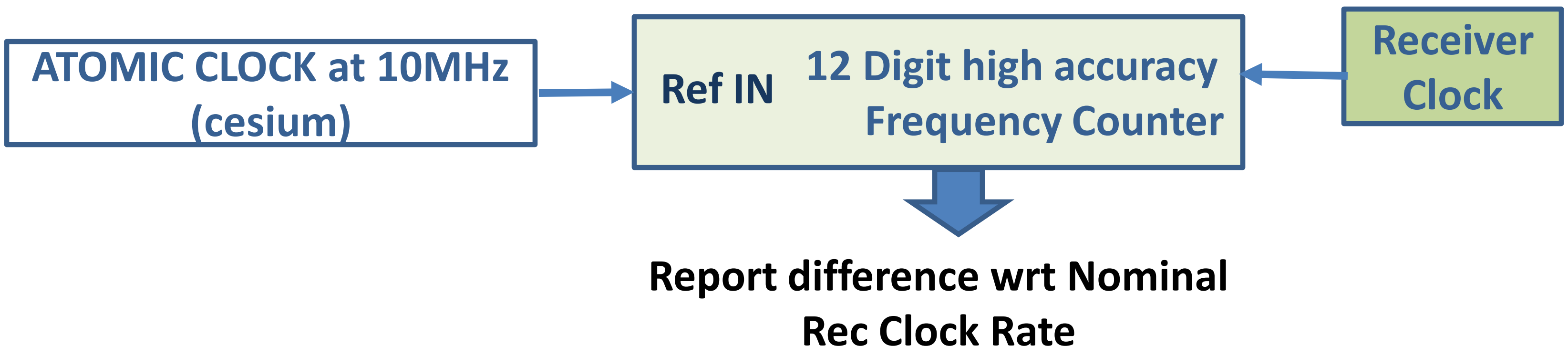


Converting reported receiver clock drift (a rate error) into a frequency error (in Hertz)

- UBLOX reports receiver clock rate error as “clock drift” (see PUBX-04 messg) or the change in phase observed over a known time interval.
- The units reported are nsec/sec.
- This is actually a “unitless” quantity as top and bottom are in seconds.
- Thus clock drift has to be converted to a Hertz error on receiver clock.
- We can do that if we know the NOMINAL rate the receivers clock runs at, in hertz
- The nominal rate is the rate at which the receivers clock would be if it were perfect, with no error.
- If we multiply the nominal receiver clock rate , in Hertz, by clock drift we get the error on the receiver clock.
- UBLOX LEA5T clock runs at nominal rate of 26MHz.
- From UCENTER above the reported clock drift , at moment of screen snap shot (IT MOVES , A LOT, as it’s a cheap clock) , is -1042.08 nsec/sec;
- The rate error in Hertz is then : [26*10^6][-1042.08 *10^-9]= -270.9408Hz
- Or the actual receiver clock frequency is 25,999,729.0592 Hertz
- Note how many digits are shown. Reported clock rate error is accurate to around 1 part in 10^12 (in theory anyway, UBLOX is close to that, sittin still , moving?)

Measurement Model of how a GPS receiver measures rate error so accurately

- Some GPS receivers can measure their clock rate error very accurately
- Here is a model, using test equipment, of what you would have to do , to duplicate the accuracy of the rate error measurement inside a GPS receiver in a lab environment.
- It’s a lot of equipment! And its expensive. GPS receivers do it for peanuts.



What about reported Clock Offset or the time error on receiver provided 1PPS? Can that be reduced by an external clock?

- The short answer is no.
- Phase errors , or clock offset as observed at 1PPS output are difficult to improve upon by addition of an external clock
- Why? Much of the ABSOLUTE error on a receivers 1PPS output , wrt GPS time, is due to uncompensated delays in the antenna cabling , antenna phase center, etc. Even when these are compensated for (there is often an entry for them in rec SW) the degree to which they can be measured and kept stable is a limiting factor.
- What is the best we can hope for , in terms of 1PPS error wrt GPS 1PPS? Typically around 10nsec. (This a single measurement, not averaged. that is about 10feet of range, 1nsec/ft)
- Receivers may claim better accuracy than this , but that number ASSUMES you have zeroed out other phase/delay errors, as outlined above.
- Receiver data will often quote a RMS error of there 1PPS output. That number is assumed to be zero average value, when in fact there is always a bias, or phase offset. The average value typically represents the center of their “hunting” method.
- This method is often digital , ie it adds or subtracts a fixed amount of time to the 1PPS output to keep it “close as possible” to 1PPS GPS time. In other words the 1PPS output pulse position , in time, is quantized. In the LEA5T its 10nsec(?)
- In UBLOX TP message its reported as “quantization error” which reflects the receivers estimate of how far off its 1PPS is from true 1PPS GPS time.

So what does a external clock buy us in terms of impact on 1PPS phase error?

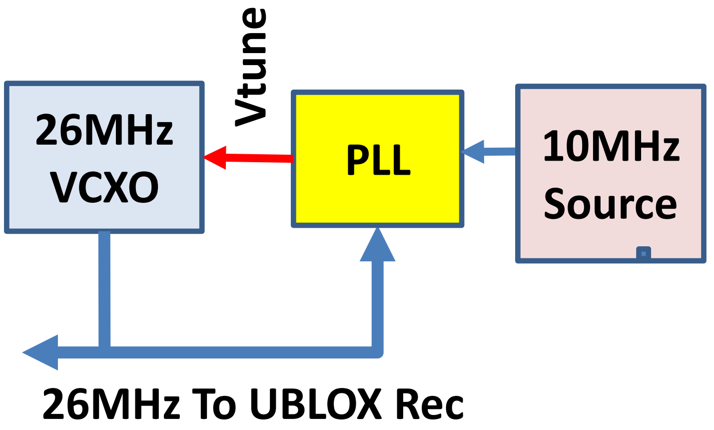
- The short answer is STABILITY on the 1PPS output, or from PVT standpoint better clock offset estimates.
- If you observe to the 1PPS of a UBLOX rec that is using its own internal clock you will see quite a lot of movement against a stable 1PPS from say a quality reference clock, such a as cesium beam type clock.
- This movement is due to rate error on the UBLOX internal clock. Its not exactly 26Mhz , in the LEA5T receiver. And its rate error is changing!
- If you had the rec 1PPS on channel A of a scope and a 1PPS from a cesium on CH B you would see the UBLOX 1PPS move around the 1PPS from the cesium such that its average value is near zero (assuming Cesium set EXACTLY to GPS time AND rec also knows all of its bias/delays, which cant be done, there is always a bias on both!)
- If a high fidelity clock is injected into the UBLOX, like a cesium, the observed movement nearly stops. Instead you would see occasional 10 nsec correction jumps (the quantization step size) perhaps every few hours or so. Instead of many times in a minute.
- Receiver clock offset is solved for in PVT. Any error in receiver clock offset will express its self as a range error too each SV. Thus a MORE STABLE clock makes the receivers job easier in producing better range estimates to each SV it tracks.
- The bottom line is clock phase errors in GPS ALWAYS have a bias on them. Some times we can get rid of them, sometimes we cannot. Generally ANY two clocks ALWAYS have errors in phase no matter what we do to get rid of it! Phase is problematic!

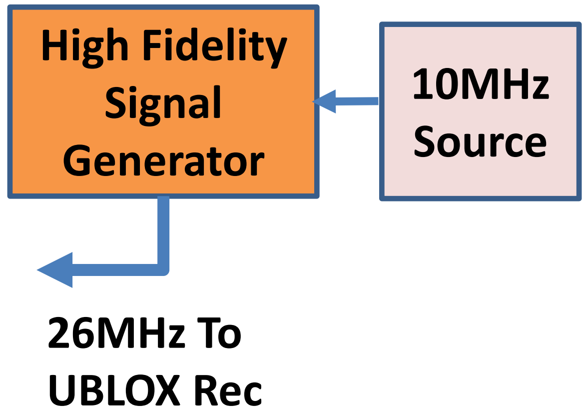
Why is reported Clock Rate error so much more accurate than Reported Clock Phase Error?

- Clock Rate error (drift, from UBLOX) is typically accurate to pico seconds per second
- Rec Clock offset (ie error on its 1PPS wrt GPS 1PPS) is typically accurate to maybe 5 to 10 nsec.
- Errors and Bias in estimating clock phase error are many and cannot easily be eliminated or estimated
- Largest of these is the Iono and Tropo in a single frequency receiver.
- These errors of unknown delay end up as phase errors/bias in the PVT estimate of rec clock offset.
- Rate error is different as it at its root it is the difference of two phase measurements closely spaced in time.
- Assuming that most of unknown time delays in the two phase estimates are identical , they subtract out. Thus the rate error estimates are much better than phase error estimates.

A 26Mhz External Clock Synthesizer or SG for the UBLOX LEA5T Clock

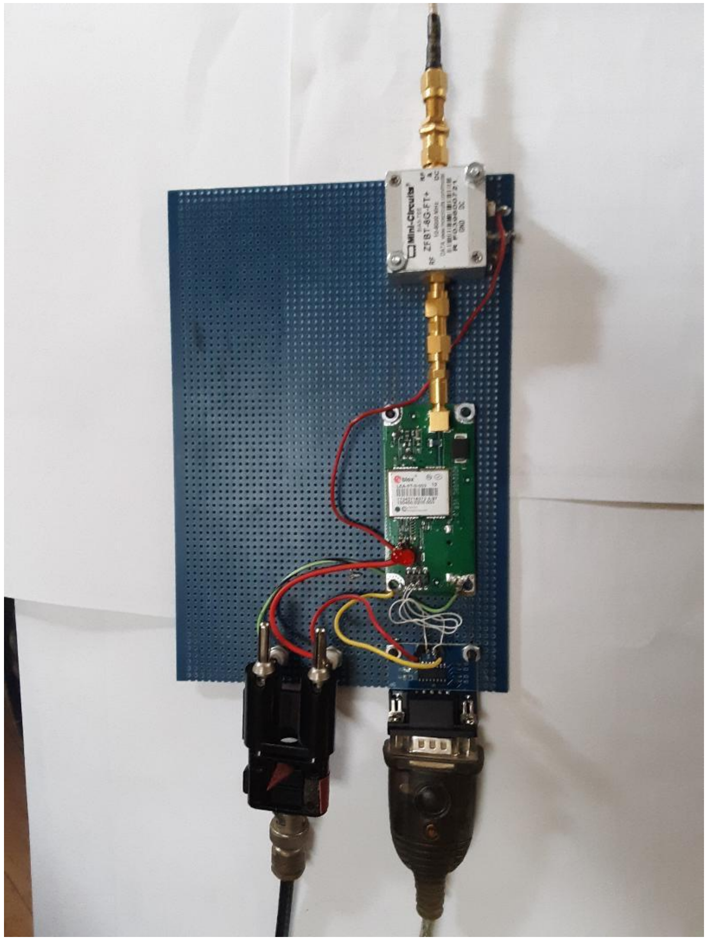
- The UBLOX LEA5T , and others, uses a tiny TCXO osc clock as its time/freq reference.
- Nominal freq is 26MHz.
- We wish to replace it with an external 26MHz clock that can be phase locked to ANY 10MHZ reference.
- We need a synthesizer !
- By phase locking the 26MHz VCXO to ANY external 10MHz reference we can experiment with different types 10MHz sources and observe the effects on the UBLX rec, such as reported rate error.
- The external 10MHz could be a fixed high quality reference , such as cesium, rubidium or OCXO.
- Alternatively a lab grade Signal Generator could be used to supply 26MHz to LEA5t.
- If SG is tied to high quality 10Mhz ref (10Mhz from a GPSO) then we could introduce a known rate error (wrt to GPS rate) , or ramp the rate error , etc. and observe its effects on the LEA5T by examining the reported rate error (clock drift).



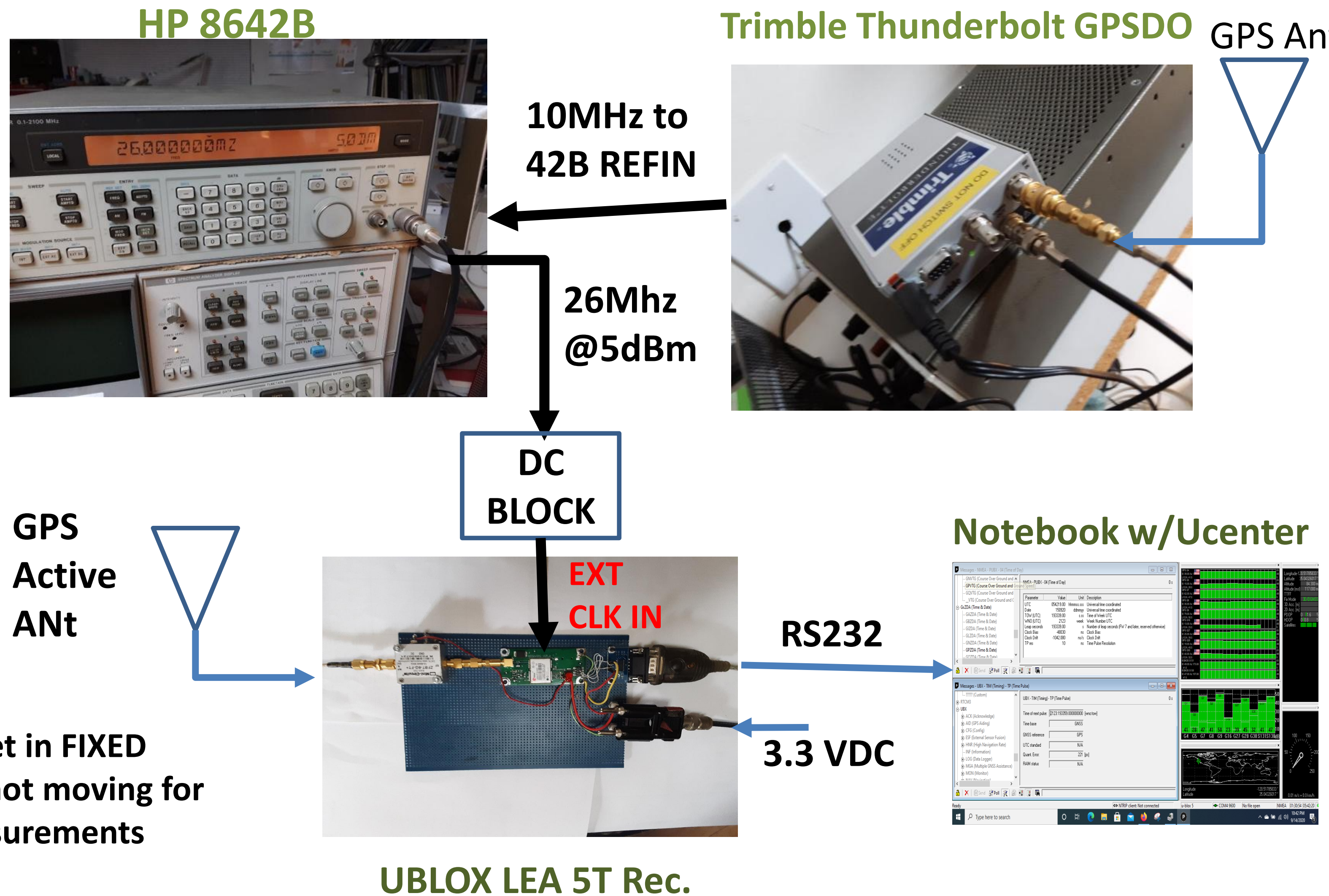


Current LEA5T Hardware

- The LEA5t mounted on a card , from ebay $15, it’s the little pc card, u can see the UBLX rec mounted on it
- It uses a MAX3232 minibrd to convert TTL to RS232 levels
- The silver box at top is a bias tee to feed DC to antenna
- Last is the 3,3vdc connection
- Next step is to pop the lid off the LEA5T, remove the 26MHZ TCXO , attached COAX feed to inject external clock.



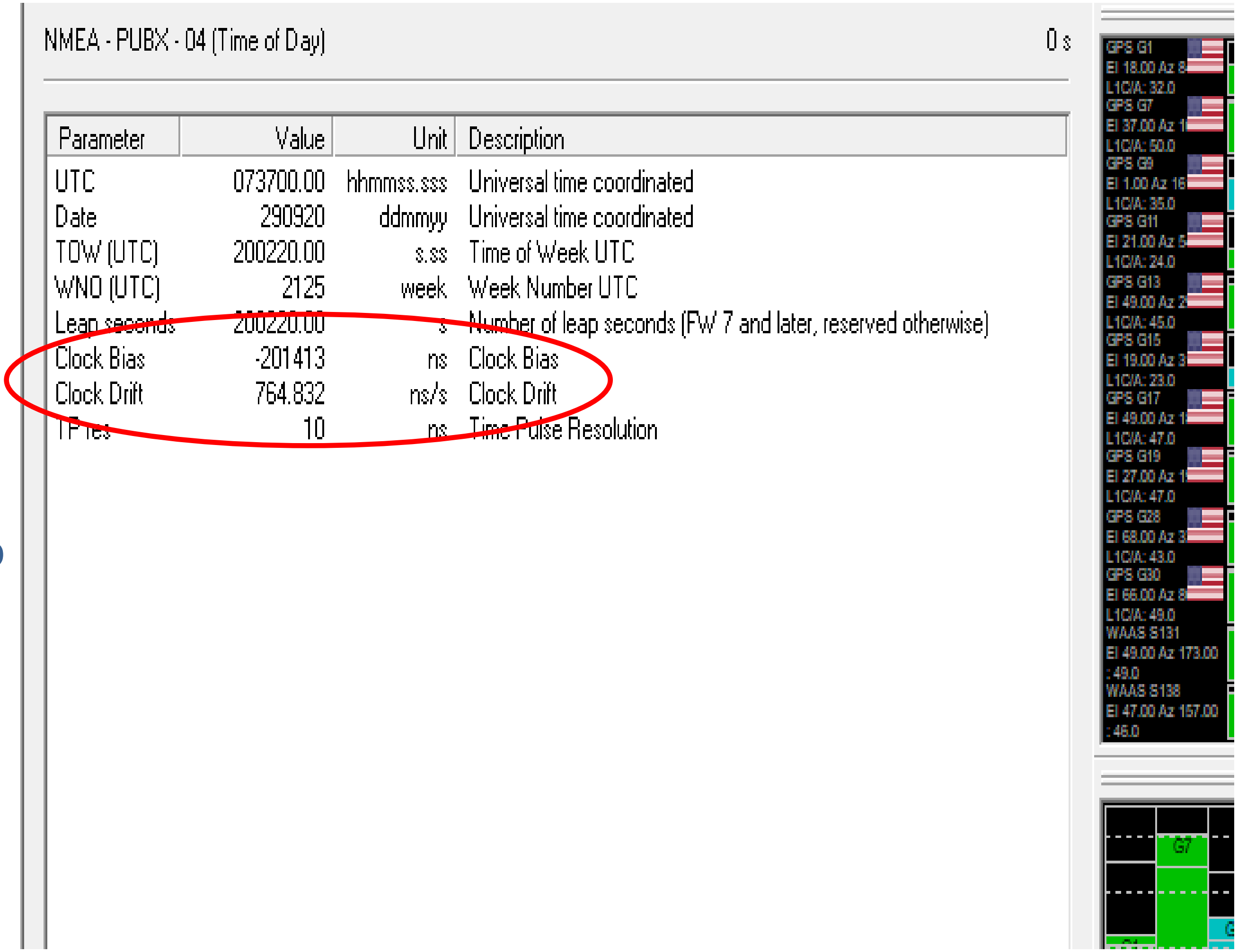
Using HP 8642B Signal Generator to Supply 26Mhz clock to LEA 5T receiver, Test setup



- Rec is set in FIXED mode, not moving for all measurements

Ucenter PUBX-04 Messg with 8642B disconnected from 10Mhz from GPSDO, freerun on its own OCXO reference

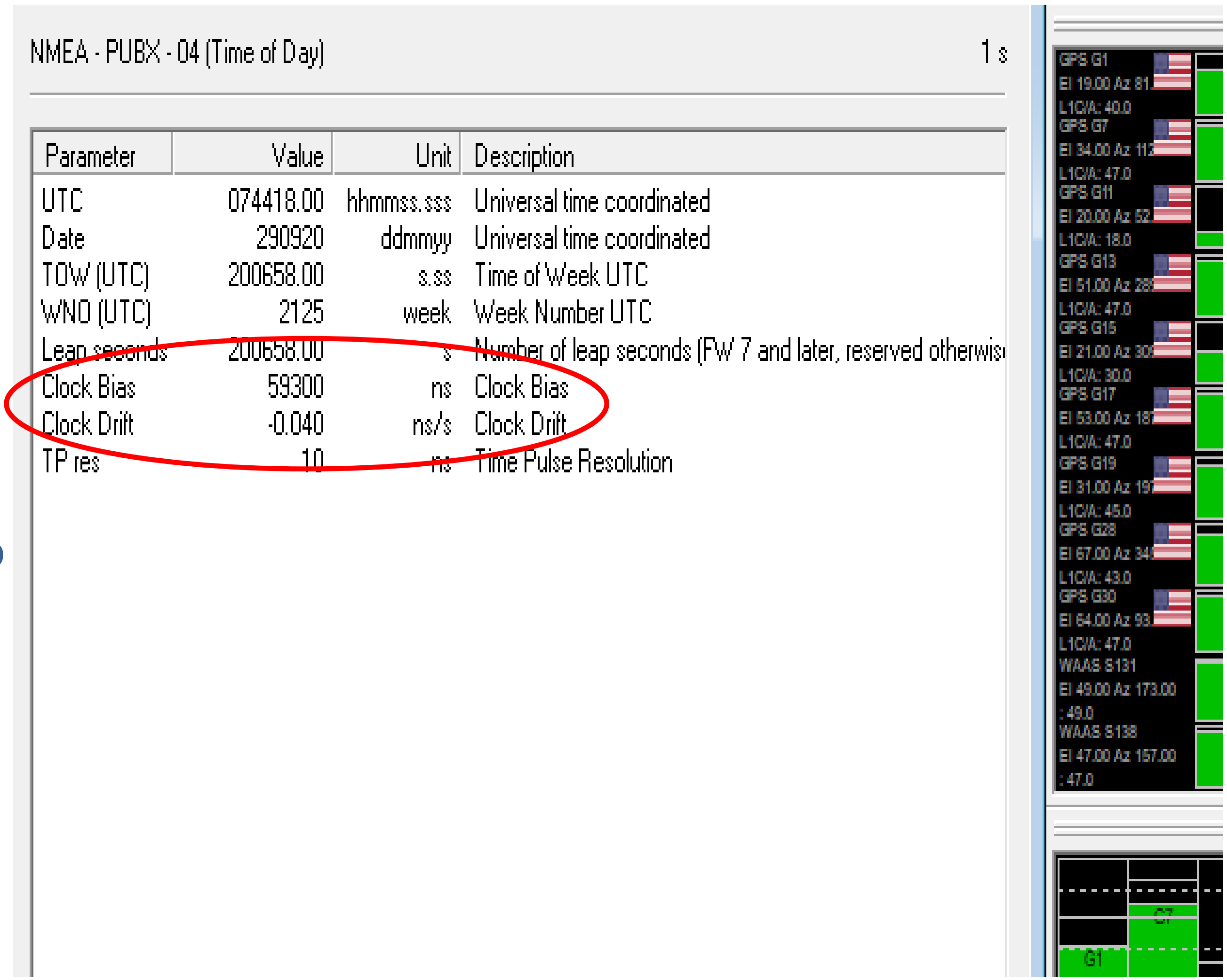
- Reported clock drift is 764 nsec/s
- This was observed to be steady rate error, typ of high quality OCXO
- Note clock bias is non zero.
- Clock bias observed to increase at appox 764ns per second, as expected



Parameter	Value	Unit	Description
UTC	073700.00	hhmmss.sss	Universal time coordinated
Date	290920	ddmmyy	Universal time coordinated
TOW (UTC)	200220.00	s.ss	Time of Week UTC
WNO (UTC)	2125	week	Week Number UTC
Leap seconds	200220.00	s	Number of leap seconds (FW 7 and later, reserved otherwise)
Clock Bias	-201413	ns	Clock Bias
Clock Drift	764.832	ns/s	Clock Drift
TP res	10	ns	Time Pulse Resolution

Ucenter PUBX-04 Messg with 8642B @26MHz , 42B LOCKED to 10Mhz from GPSDO, now 42B is rate locked to GPSMC rate

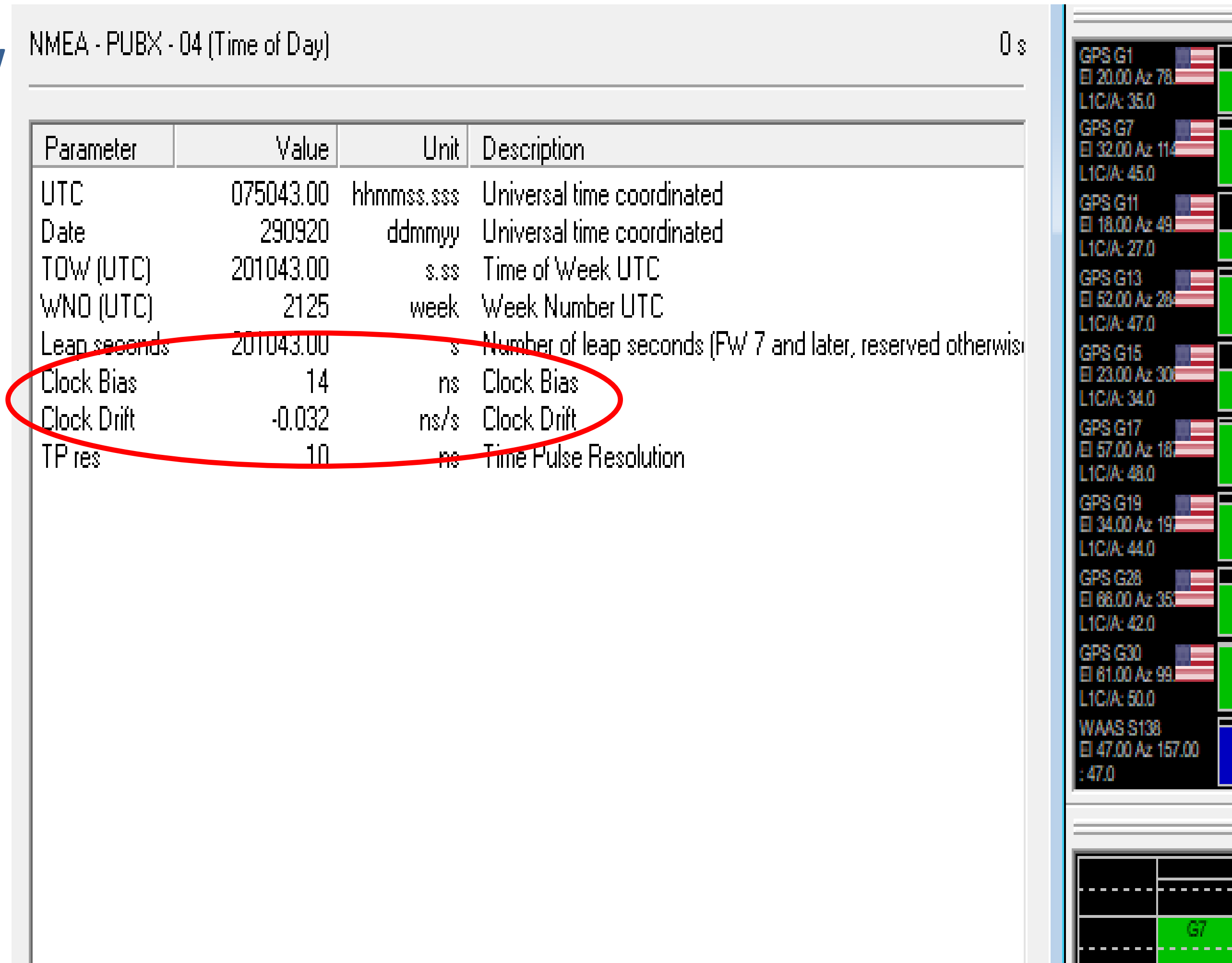
- Reported clock drift is -0.040ns/s
- This was observed to be a low steady rate error typ below 0.1ns/s
- Note clock bias is non zero.
- Clock bias observed to increase nearly steady, as expected



Parameter	Value	Unit	Description
UTC	074418.00	hhmmss.sss	Universal time coordinated
Date	290920	ddmmyy	Universal time coordinated
TOW (UTC)	200658.00	s.ss	Time of Week UTC
WNO (UTC)	2125	week	Week Number UTC
Leap seconds	200658.00	s	Number of leap seconds (FW 7 and later, reserved otherwis
Clock Bias	59300	ns	Clock Bias
Clock Drift	-0.040	ns/s	Clock Drift
TP res	10	ns	Time Pulse Resolution

Ucenter PUBX-04 Messg with 8642B @ 26Mhz LOCKED to GPSDO, Issued HOT Start from Ucenter to LEA5-T

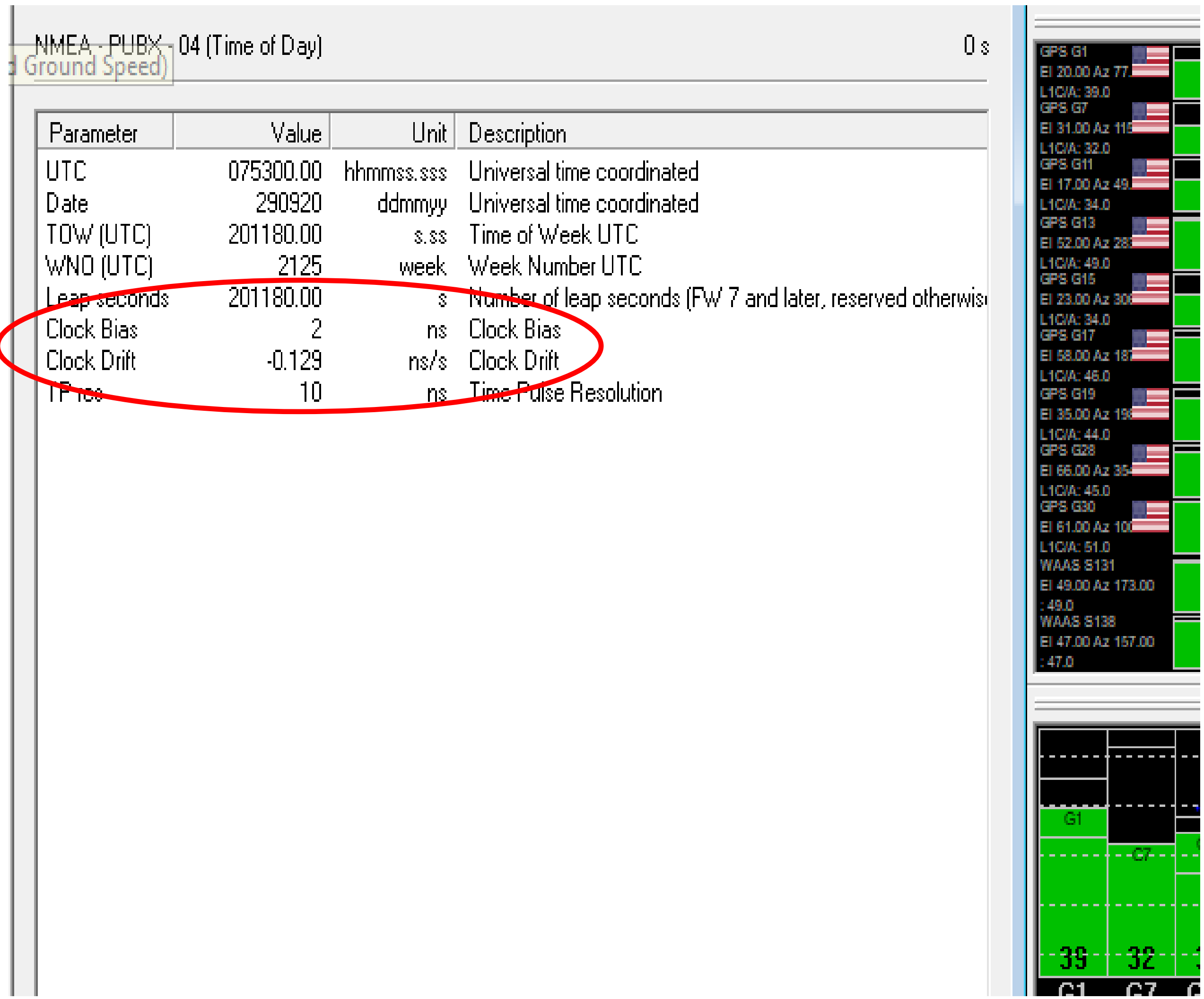
- Reported clock drift is -0.032ns/s, still very low and steady
- Now Clock Bias is very small, 14nsec
- Clock bias observed to hardly move, as expected
- When Clock bias is ZERO nsec this means the measured Pseudo ranges to each SV have NO clock error induced distance error, in other words ignoring other errors the pseudo ranges are now the ACTUAL ranges to SV.



Parameter	Value	Unit	Description
UTC	075043.00	hhmmss.sss	Universal time coordinated
Date	290920	ddmmyy	Universal time coordinated
TOW (UTC)	201043.00	s.ss	Time of Week UTC
WNO (UTC)	2125	week	Week Number UTC
Leap seconds	201043.00	s	Number of leap seconds (FW 7 and later, reserved otherwis
Clock Bias	14	ns	Clock Bias
Clock Drift	-0.032	ns/s	Clock Drift
TP res	10	ns	Time Pulse Resolution

Ucenter PUBX-04 Messg with 8642B 26MHZ LOCKED to GPSDO , Issued HOT Start from Ucenter to LEA5-T, plus 5 minutes from the hot start

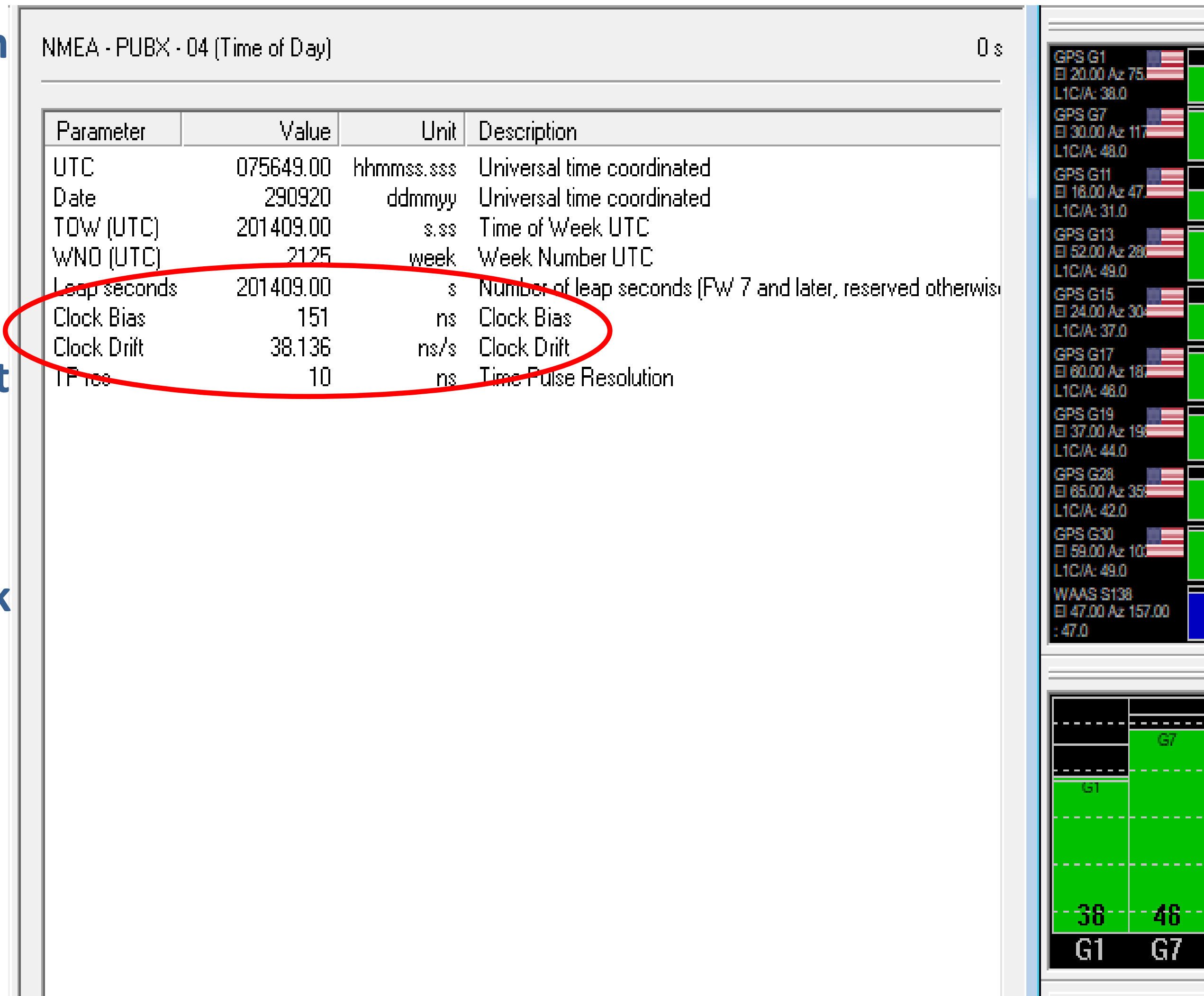
- Waited 5 min after hot start, here is new data
- Reported clock drift is now -0.129ns/s, still very low and steady
- Now Clock Bias is very small, 2nsec
- Clock bias observed to hardly move, as expected
- Clock bias moves around, SLOWLY , small errors, avg value seems to be about zero.



Parameter	Value	Unit	Description
UTC	075300.00	hhmmss.sss	Universal time coordinated
Date	290920	ddmmyy	Universal time coordinated
TOW (UTC)	201180.00	s.ss	Time of Week UTC
WNO (UTC)	2125	week	Week Number UTC
Leap seconds	201180.00	s	Number of leap seconds (FW 7 and later, reserved otherwis
Clock Bias	2	ns	Clock Bias
Clock Drift	-0.129	ns/s	Clock Drift
TP res	10	ns	Time Pulse Resolution

Ucenter PUBX-04 Messg with 8642B @ 26.000001 Mhz LOCKED to GPSDO , Issued HOT Start , Capture right after a hot start

- Introduced 1 Hz error on 26Mhz clock from 42B, 42B still locked to GPSDO
- Reported clock drift is now 38.136 ns/s
- Capture is right after hot start , Clock Bias is very small, 151 nsec,
- Clock bias observed to change at reported clock drift rate
- 26MHz * 38.136 ns/s = 0.991536 Hz, which confirms entered offset at 42B of 1Hz.

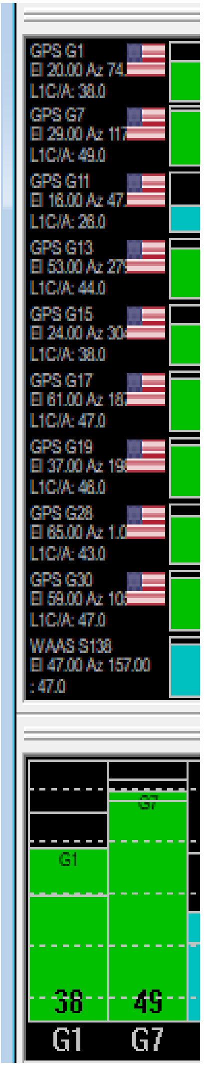


Ucenter PUBX-04 Messg with 8642B @ 26.000001 Mhz LOCKED to GPSDO , Capture few minutes after the hot start

- Waited a bit after the hot start, still have 1hz offset on 26MHz
- Reported clock drift is now 38.410 ns/s
- Capture is 122 sec after hot start , Clock Bias is now , 4652 nsec, its moving due to 1Hz error on 26Mhz from 42B
- 26MHz * 38.410 ns/s = 0.99866 Hz

NMEA - PUBX - 04 (Time of Day) 1 s

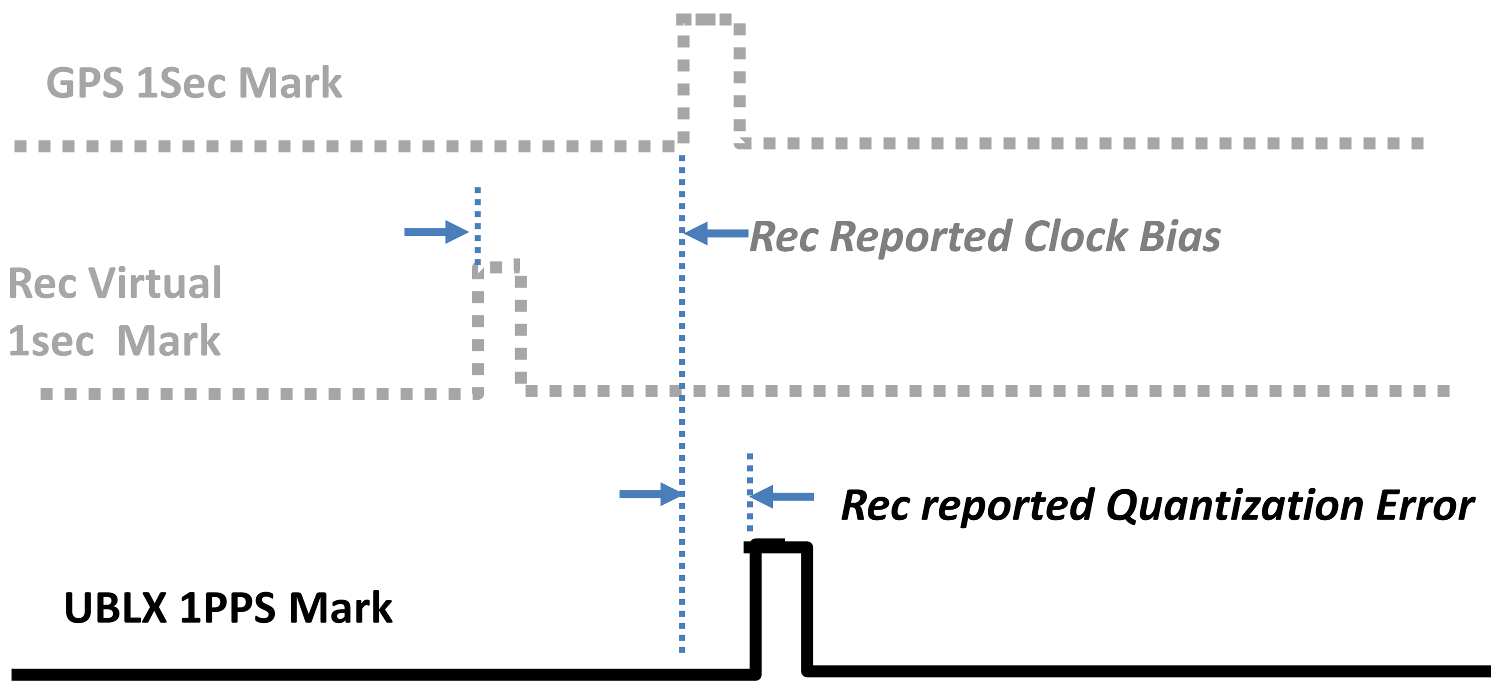
Parameter	Value	Unit	Description
UTC	075846.00	hhmmss.sss	Universal time coordinated
Date	290920	ddmmyy	Universal time coordinated
TOW (UTC)	201526.00	s.ss	Time of Week UTC
WNO (UTC)	2125	week	Week Number UTC
Leap seconds	201526.00	s	Number of leap seconds (FW 7 and later, reserved otherwis
Clock Bias	4652	ns	Clock Bias
Clock Drift	38.410	ns/s	Clock Drift
TP res	10	ns	Time Pulse Resolution



Three 1PPS signals, only one we can easily see or monitor

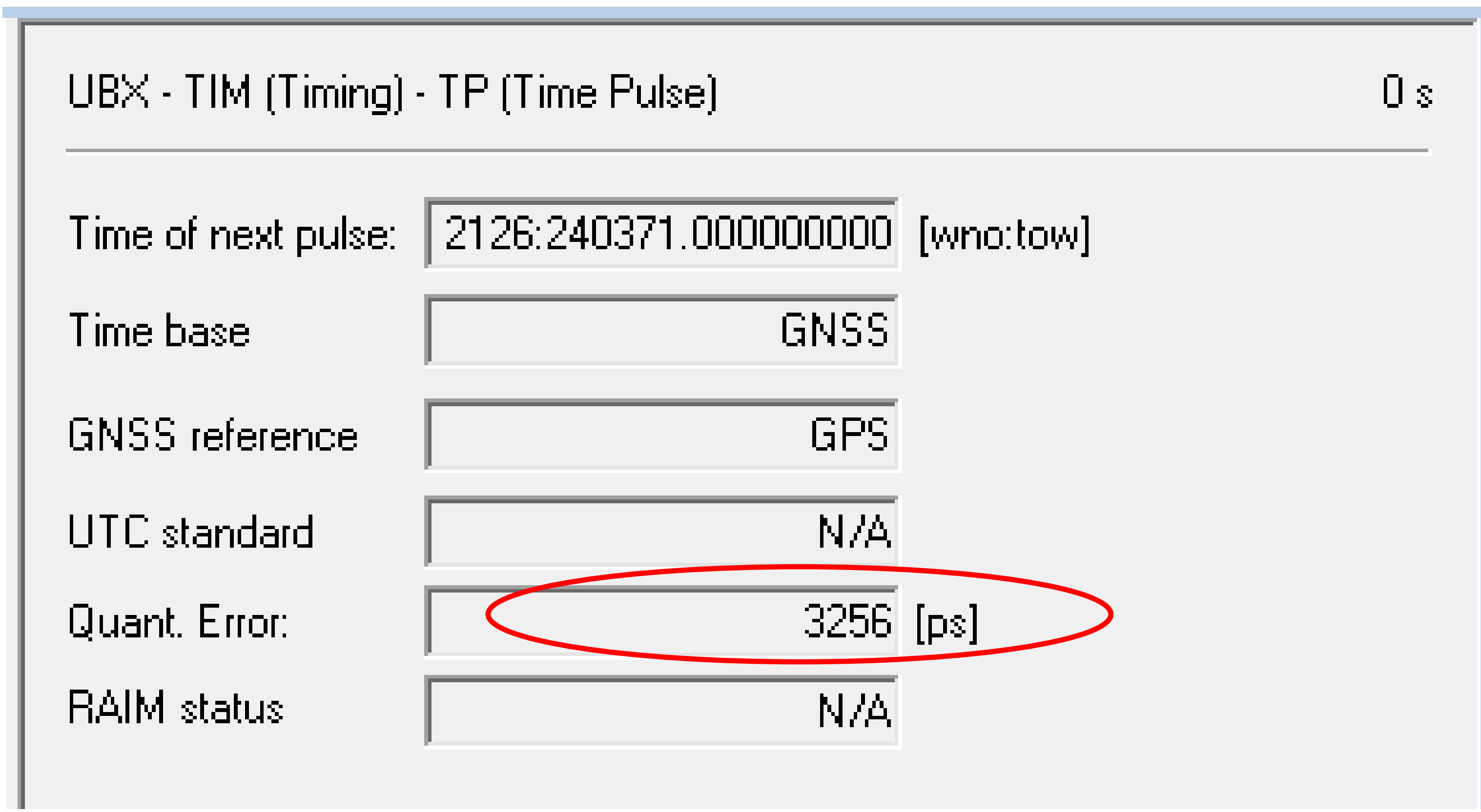
- UBLOX reported clock error data, *Clock Bias* , and *1PPS quantization error*, is with respect to *GPS 1PPS epoch*
- The GPS 1 second epoch can not viewed (except in Colorado springs!), its solved for in UBLOX PVT as a *Clock Bias* with respect to it.
- The SW of the UBLOX receiver has a virtual 1 sec epoch moment , PVT solution returns *Clock Bias* of that virtual mark to GPS 1 sec epoch
- The UBLOX virtual 1sec epoch timing mark has no physical output
- As *Clock Bias* is with respect to virtual timing signals, GPS 1sec epoch and receiver SW timing mark, Clock Bias is allowed to "free run" with large offsets possible with respect to the GPS 1 sec timing mark.
- The UBLOX 1PPS output is the physical logic signal we can monitor with test equipment.
- It is continuously corrected to be as close as possible to the GPS 1PPS time mark as receivers PVT solution and correction resolution allow
- The 1PPS UBLX output signal is corrected by adding or subtracting 10nsec time slices.
- Thus the 1PPS output signal has its own errors wrt GPS time. This error is reported in the UBLX time pulse message as *Quantization error*.

Timing Diagram showing GPS 1sec timing mark, UBLX virtual timing mark and UBLX 1 PPS physical timing mark



Note: If we could see the real time movement of the 1PPS output mark , with reference to GPS 1sec mark, we would see the 1PPS "hunt" back and forth around the GPS 1sec mark with 10nsec step size. This results from the rec trying to keep its 1PPS output lined up with GPS 1PPS by adding/subtracting 10nsec time slices as needed

UBLOX Time Pulse Message showing the current estimated quantization error of the 1PPS output to its solved for GPS 1PPS timing mark



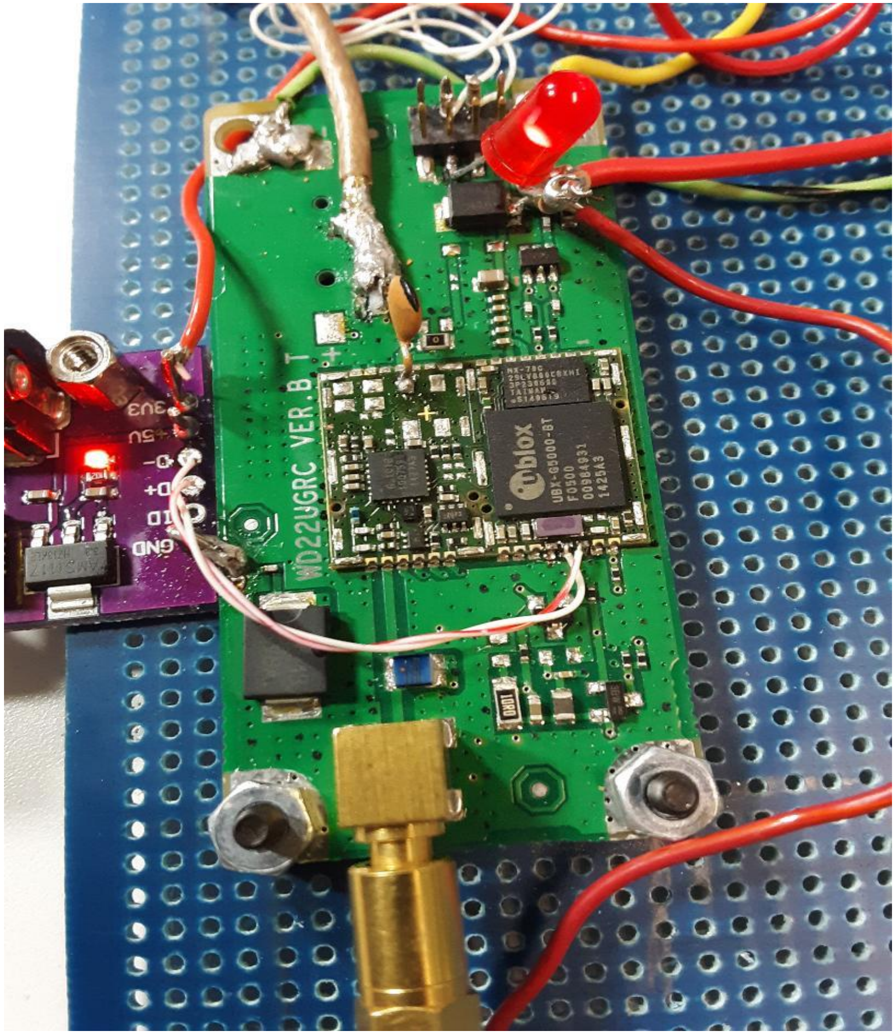
UBLOX-4 PUBX Message showing 1PPS output quantization step size of 10nsec

NMEA - PUBX - 04 (Time of Day) 1 s

Parameter	Value	Unit	Description
UTC	183406.00	hhmmss.sss	Universal time coordinated
Date	061020	ddmmyy	Universal time coordinated
TOW (UTC)	239646.00	s.ss	Time of Week UTC
WNO (UTC)	2126	week	Week Number UTC
Leap seconds	239646.00	s	Number of leap seconds (F
Clock Bias	2	ns	Clock Bias
Clock Drift	-0.028	ns/s	Clock Drift
TP res	10	ns	Time Pulse Resolution

Most recent pic of the UBLOX5T

- Added a USB/5v/3.3 volt supply mini brd, 5T now powered from USB
- I tried to get the USB port working , no luck so far
- The 26MHz coax clock feed comes in at the top of the pic, the little brown thing, a black stripe, is a 4700pf ceramic disc cap, blocks DC.
- The DC block allows the DC present at the logic pin input be undisturbed.
- The four surface mount pads are still ther wher the clock device was , a micro SMD TCXO 26Mhz clock.
- The big LED is attached between 3.3 and 1PPS, it blinks when 1PPS is active, which happens when tracking and getting PVT.



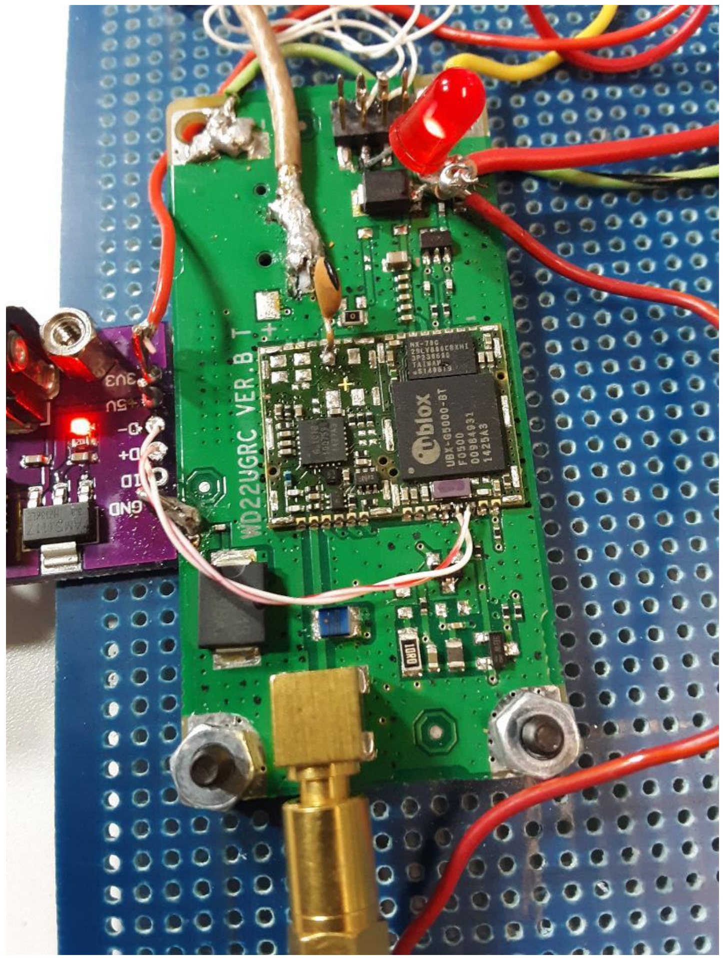
Some Questions

- What are the largest contributors to errors in receiver reported Clock Bias estimates?
- If the Clock Drift is small , and has a bias such that reported values are either always positive or negative what would be the effect on observed 1PPS behavior against GPS 1PPS if seen on an o'scope? *
- Many GPSDO's use the 1PPS output to "lock" a local crystal based clock. If the 1PPS signal from UBLOX has quantization jitter of +/- 10nsec on it what is the effect on the fidelity of that locking process?
- The jitter on the output 1PPS can be reduced by averaging. If the RMS jitter is 10nsec estimate how many pulses must be averaged to reduce the RMS jitter to ~100 pico second (10^-10)
- Can a crystal oscillator be locked to GPS phase and rate without using the 1PPS output signal? If so how?
- Which is higher phase fidelity , UBLOX reported clock bias or the output 1PPS signal?
- Which is reported with more precision , Clock Bias or Clock Drift? Why?
- Describe a system to drive rate and phase error of UBLOX clock to a minimum wrt GPS time/rate.

* In the lab we can use a high fidelity 1PPS from a locked and stable Ruby clock (use 1PPS from a GPSDO rec) as an approximation to GPS 1PPS signal.

Future

- I am working on a self contained 26Mhz source, that can be locked to a 10Mhz ref. This would eliminate the need for the big SG.
- Such a small synth will allow a portable system to measure rate error on 10Mhz references.


WD22UGRC VER.B
GND
blox
UBX-G5000-BT