Time of flight measurement with sub-sampling period resolution using Software Defined Radio

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Introduction

- Software Defined Radio collects a continuous stream of data at a sampling rate f_s
- Time interval between samples is $t_s = 1/f_s$
- Time resolution is t_s

$\Rightarrow$ RADAR range resolution

$$\Delta R = \frac{c}{2B}$$

with B the available bandwidth in the RF band or sampling rate at baseband.

Question: are we limited in the time of flight measurement capabilty to t_s?

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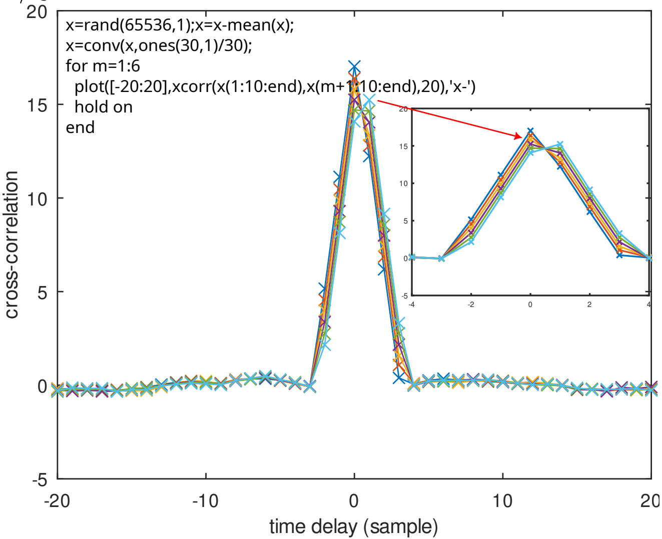
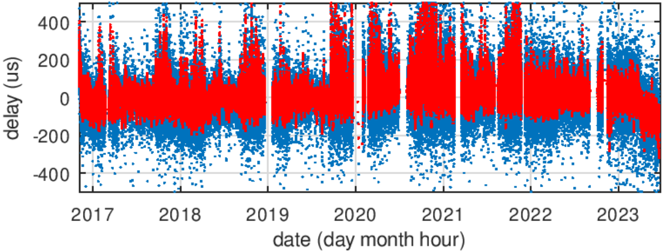


Sub-sampling period time of flight measurement

- Spectrum spreading can be achieved in many ways (short pulse, frequency sweep, **noise**)
- Matched filter = cross-correlation between the received signal and the local copy of the transmitted signal
- Oversampling by polynomial fit of the correlation peak *under the assumption* that a single echo is searched
- Timing **improvement** = **signal to noise ratio** of the recorded data
- Instead of a single transition anywhere between two sampling points, the cross-correlation integrates the delay over a long sequence

Application examples:

- ionospheric propagation time delay
- time transfer (e.g. DCF77 [1])
- DCF77: 645 Hz phase modulation [2] on top of amplitude modulation and yet time resolution $\ll 1000/645 = 1.55$ ms



[1] J.-M. Friedt, C. Eustache, É. Carry, E. Rubiola, *Software-Defined Radio Decoding of DCF77: Time and Frequency Dissemination with a Sound Card*, Radio Science **53**(1), Jan 2017.

[2] `https://www.eecis.udel.edu/~mills/ntp/dcf77.html`

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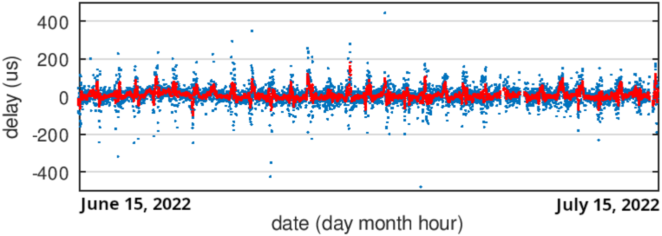

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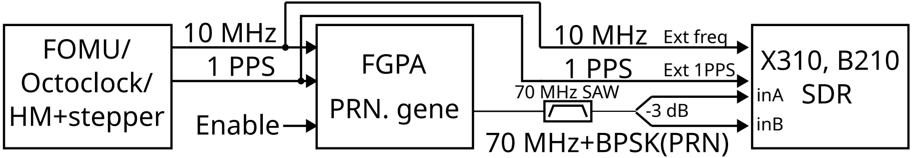
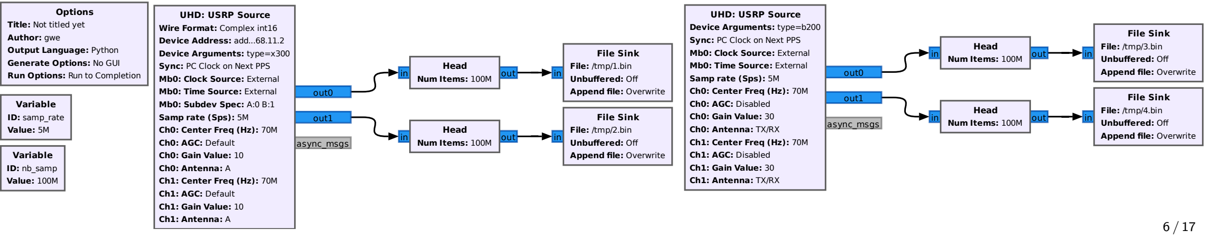
Experimental setup

- 100 kchip long (40 ms at 2.5 Mchips/s) pseudo random sequence generator (PRN) running on an FPGA, triggered by one PPS and clocked by 10 MHz
- 1-PPS generated from 10 MHz to start the PRN
- X310=FPGA processing baseband collected data (100 MS/s) ; B210=AD9361 RF frontend (70-6000 MHz LO, 5 MS/s) & FPGA on USB ; XTRX=Lime Microsystems LMS7002 frontend & FPGA on PCIe





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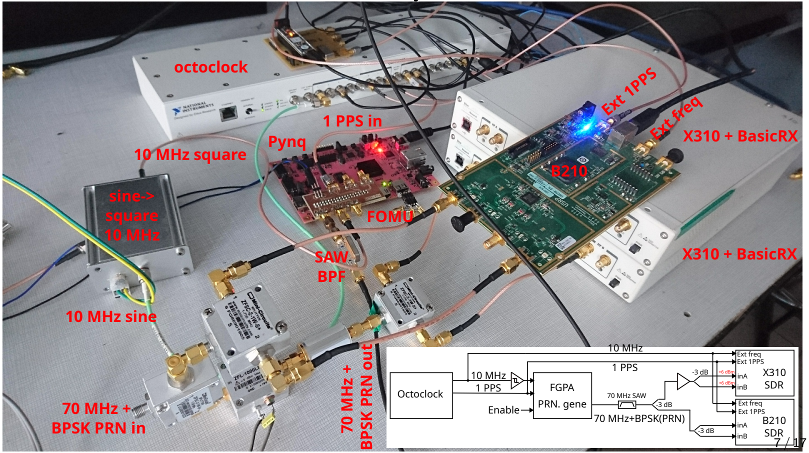
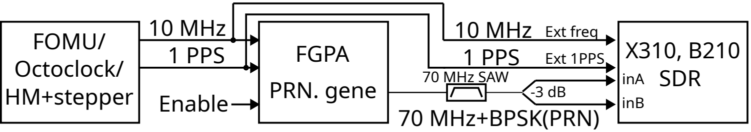
Portable PRN generator and BPSK or QPSK modulator: `https://github.com/oscimp/amaranth_twstft`

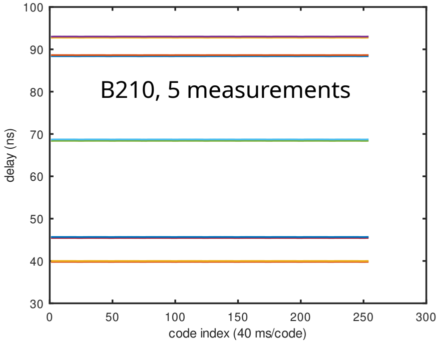


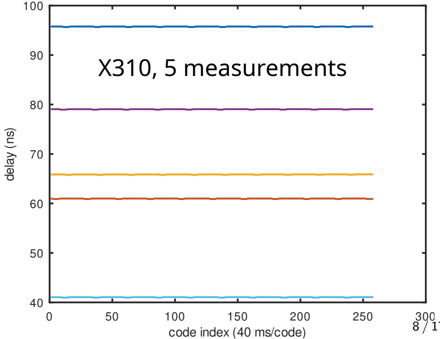
Single channel analysis (X310, B210, external clock FOMU)

- Acquisition triggered by 1-PPS generated by 10 MHz clocking the X310 or B210 (and FPGA)
- Measurement repeated multiple times (up to 1000)
- Sampling at $T_s = 5$ MS/s (200 ns sampling period)

  $\Rightarrow$ targeted $\delta T \ll T_s$
- **Single channel** fluctuation of cross-correlation peak maximum randomly located within sampling period
- B210: $\sigma_\tau(1) = \sigma_\tau(2) = 6$ ps (high tunable frontend gain)
- X310: $\sigma_\tau(1) = \sigma_\tau(2) = 37$ ps at lower SNR

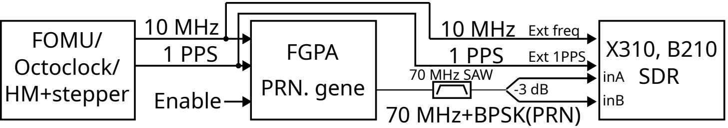


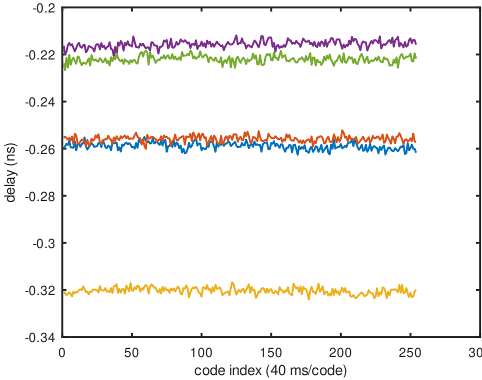




Differential analysis (B210, external clock FOMU)

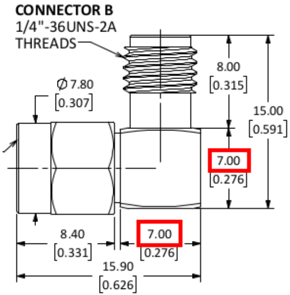
- B210: complex AD936x radiofrequency frontend
- $\langle \tau_1 - \tau_2 \rangle = -0.2545$ ns
- $\sigma_{\tau_1 - \tau_2} = 41.6$ ps
- $max_{\tau_1 - \tau_2} - min_{\tau_1 - \tau_2} = 104.7$ ps

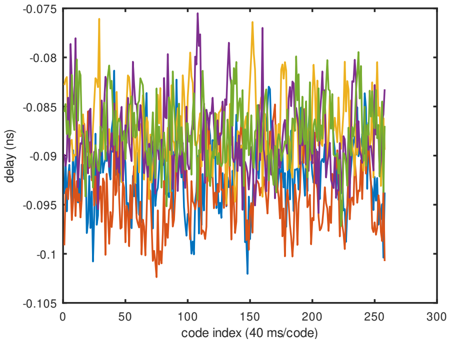


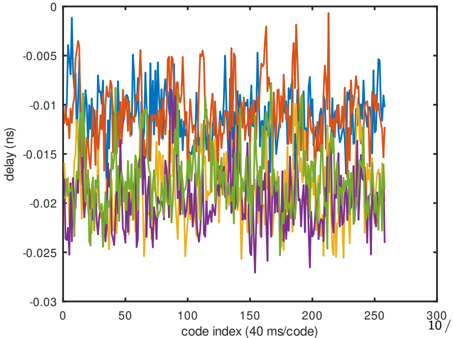


Differential analysis (X310, external clock)

- Same length between splitter and inputs
  - $\langle \tau_1 - \tau_2 \rangle = -0.0156$ ns
  - $\sigma_{\tau_1 - \tau_2} = 4.2$ ps
  - $max_{\tau_1-\tau_2} - min_{\tau_1-\tau_2} = 8.7$ ps
- SMA right angle on one channel
  - $\langle \tau_1 - \tau_2 \rangle = -0.0898$ ns
  - $\sigma_{\tau_1 - \tau_2} = 3.0$ ps
  - $max_{\tau_1-\tau_2} - min_{\tau_1-\tau_2} = 6.7$ ps
- length difference 0.0742×20 cm/ns$= 1.484$ cm at 200 m/μs

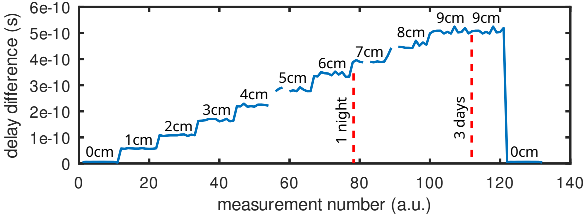


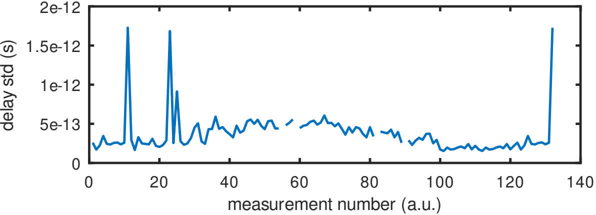


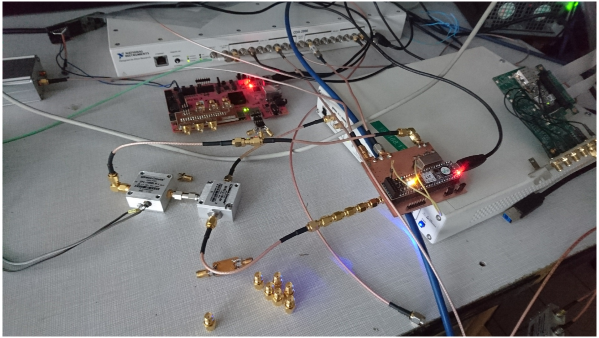


X310 platform delays between channels (external clock)

5 MSamples/s SDR measurement or 200 ns sampling period T_s: $5 \cdot 10^{-13} = T_s/(4 \cdot 10^5)$



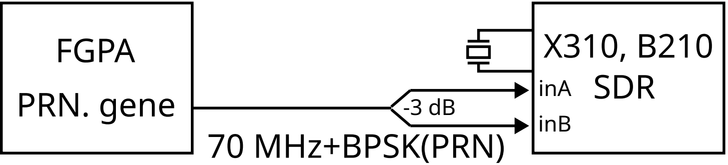


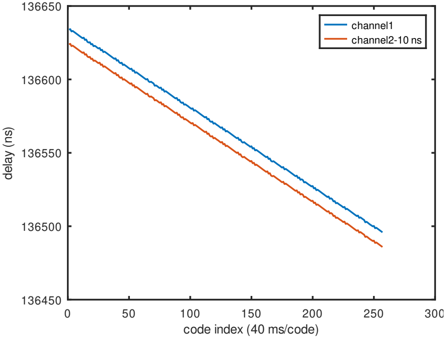


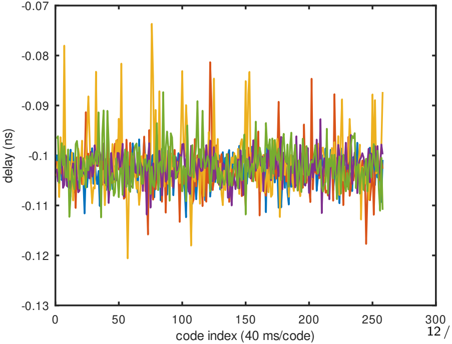
Sub-ps measurement resolution
(1 cm=50 ps @ 20 cm/ns)

Differential analysis (X310, internal clock)

- rejection of common mode oscillator with differential analysis?
- $\langle \tau_1 - \tau_2 \rangle = -0.1024$ ns
- $\sigma_{\tau_1 - \tau_2} = 0.7$ ps
- $max_{\tau_1 - \tau_2} - min_{\tau_1 - \tau_2} = 1.7$ ps

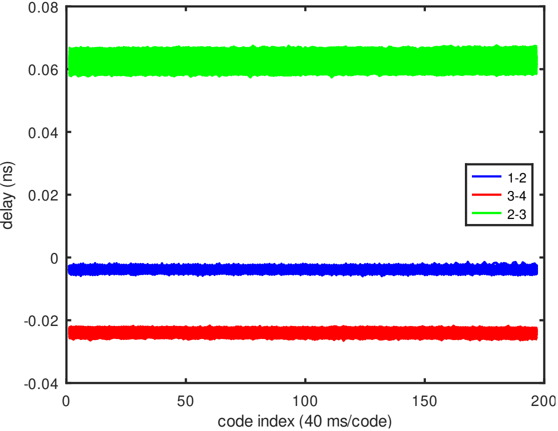




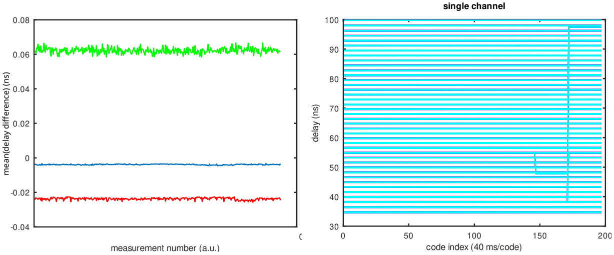


Synchronizing two X310, external clock (Octoclock)

Overlay of all measurements (difference)



Single channel analysis: random position within [30 : 100] ns (@ 5 MS/s)



Differential analysis:

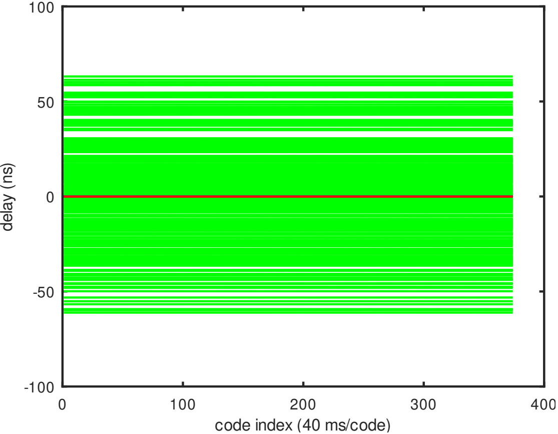
- $\langle\sigma(X310_{1-2})\rangle = 0.54$ ps ; $\langle\sigma(X310_{3-4})\rangle = 0.3$ ps $\langle\sigma(X310_{1-3})\rangle = 0.3$ ps within each measurement
- $\sigma(\langle X310_{1-2}\rangle) = 0.2$ ps ; $\sigma(\langle X310_{3-4}\rangle) = 0.64$ ps $\sigma(\langle X310_{1-3}\rangle) = 1.6$ ps from one measurement to another

Needed for **multiconstellation/multiband** GNSS monitoring

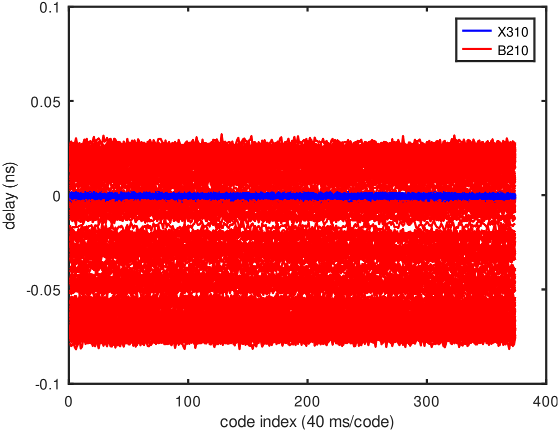
Synchronizing B210 and X310, external clock (Octoclock)

- $\langle\sigma(X310_{1-2})\rangle = 0.6$ ps, $\langle\sigma(B210_{1-2})\rangle = 1.5$ ps, $\langle\sigma(B210_1 - X310_1)\rangle = 2.5$ ps within each trace
- $\sigma(\langle X310_{1-2}) = 0.6$ ps, $\sigma(\langle B210_{1-2}\rangle) = 38$ ps, $\sigma(\langle B210_1 - X310_1\rangle) = 28$ ns within each trace $\Rightarrow$ no synchro between X310 and B210 during successive measurements

Green=B210-X310 ; red=B210-B210 ; (blue=X310-X310)

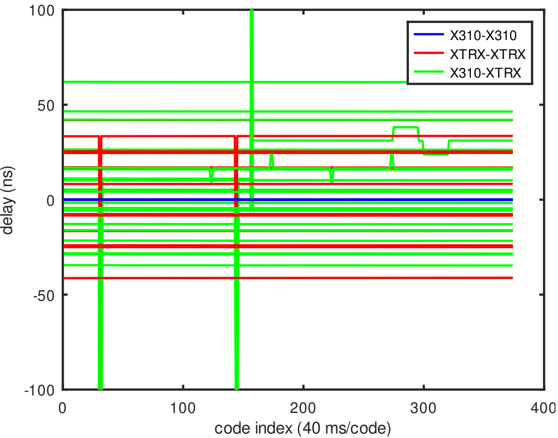


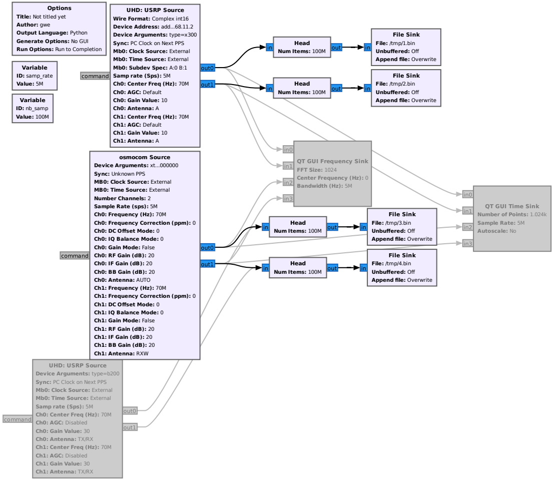
Zoom on B210-B210 ; X310-X310



Synchronizing X310 and XTRX, external clock (Octoclock)

- $\langle\sigma(X310_{1-2})\rangle = 0.5$ ps, $\langle\sigma(XTRX_{1-2})\rangle = 375$ ps, $\langle\sigma(X310_1 - XTRX_1)\rangle = 1.5$ ns within each measurement
- $\sigma(\langle X310_{1-2}\rangle) = 0.2$ ps, $\sigma(\langle XTRX_{1-2}\rangle) = 19.8$ ns, $\sigma(\langle X310_1 - XTRX_1\rangle) = 18.4$ ns from one measurement to the next, i.e. no synchronization between X310 and XTRX





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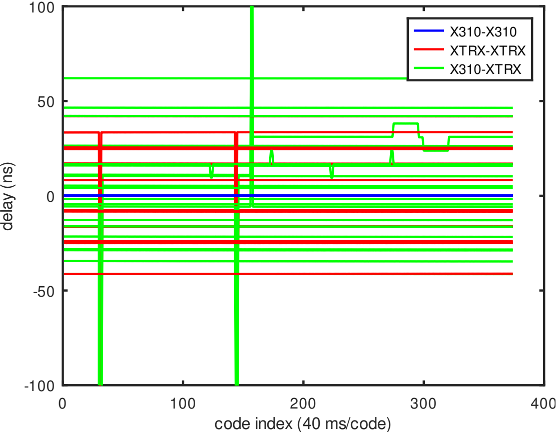
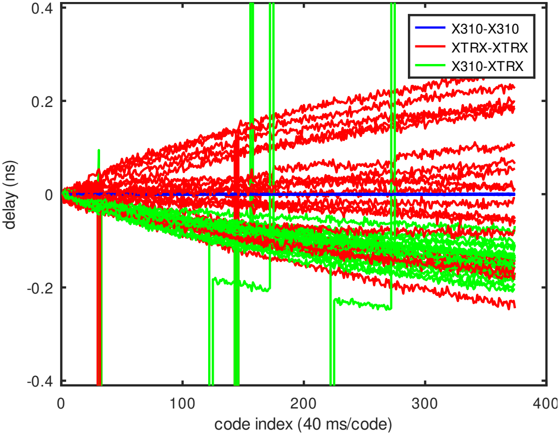
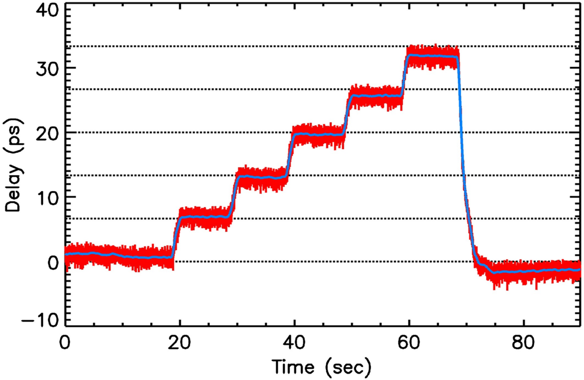
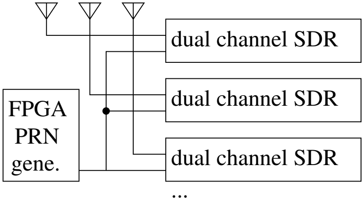




Conclusion

- Distribution of fine timing information by generating a pseudo-random sequence sampled by one channel of each SDR signal, the other channel sampling the signal of interest
- Sub-ps resolution in agreement with S. Kawamura & al "Water vapor estimation using digital terrestrial broadcasting waves" (2017) [a] and S. Yasuda & al "Horizontal Atmospheric Delay Measurement Using Wireless Two-Way Interferometry (Wi-Wi)" (2018) [b] $\longrightarrow$
- LMS7002 to be assessed beyond the XTRX.
- X310 and B210 both usable for sub-100 ps time transfer, XTRX more questionable (drift during integration)
- impact for DoA/correlation analysis of XTRX drift? (200 ps=110° angular phase drift at 1575 MHz during 15 s integration duration)





[a] https://agupubs.onlinelibrary.wiley.com/doi/10.1002/2016RS006191

[b] https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2018RS006770