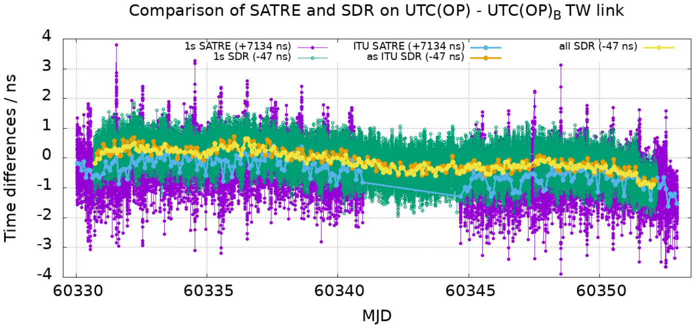
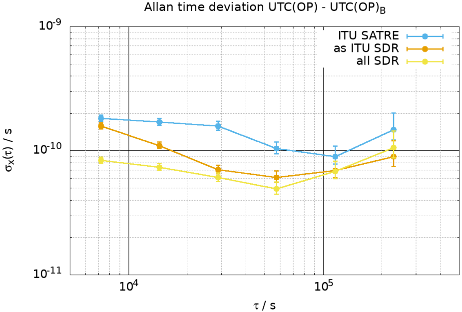
Results of a Software Defined Radio (SDR) Implementation of Two Way Satellite Time and Frequency Transfer (TWSTFT) Emitter and Receiver System

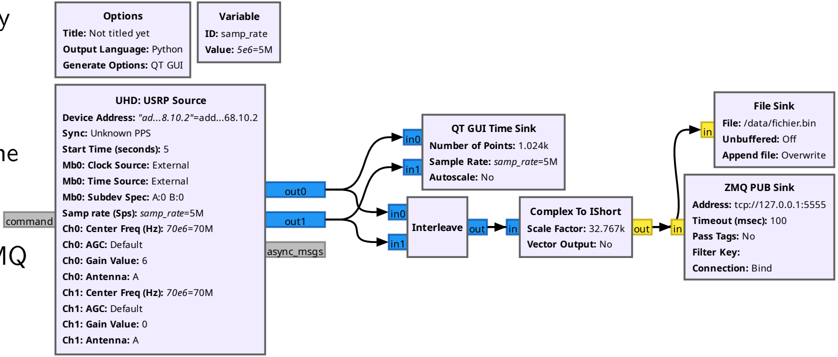
J.-M Friedt[1], B. Chupin[2], M. Lours[2], É. Meyer[1], O. Chiu[2], F. Meyer[1], W. Daniau[1], J. Achkar[2]
[1] LNE-LTFB, FEMTO-ST T/F & Observatoire de Besançon, Besançon, France
[2]LNE-SYRTE, Observatoire de Paris - Université PSL, CNRS, Sorbonne Université, Paris, France
jmfriedt@femto-st.fr, Joseph.Achkar@obspm.fr





Outline

- **Signal processing**: sub-sampling period time delay estimate (correlation peak fitting)
- **Emitted** code properties and generic test setup: need for fine synchronization
- **Hardware drift** of X310 receiver during warmup ⇒ ZMQ communication
- **Reception**: post-processing
- **SAW delay line** simulator



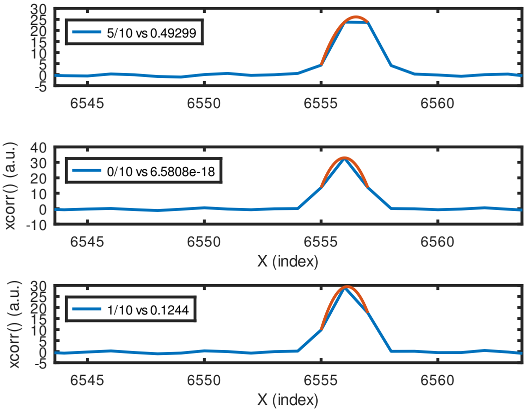
Requirement: sub-sampling period time delay estimate

TWSTFT through a geostationary satellite:

- allocated bandwidth: 5 MHz
- sampling period matching allocated bandwidth: 200 ns
- targeted resolution and stability: 200 ps
- need to gain 1000-fold between resolution and sampling period !

Solution: cross-correlation peak fitting, improving timing resolution over the sampling period with a factor equal to the signal to noise ratio

- sampling at 5 MS/s the 5 MHz channel requires interpolating (Fourier domain 0-padding) to avoid peak fitting artefacts [a]

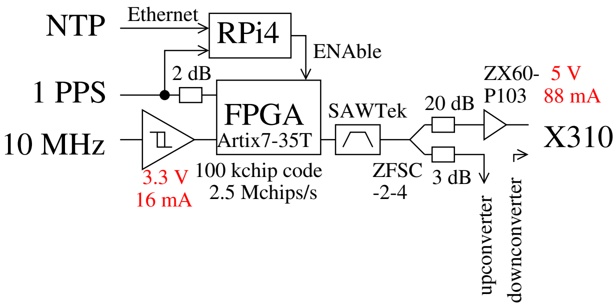



```
M=65536;    N=17;    P=10;
x=rand(65536,1);x=x-mean(x);
x=conv(x,ones(N,1)/N);
x1=x(1:P:end);    x2=x(6:P:end);
s=xcorr(x1,x2);   plot(s);
[~,m]=max(s);     [a,b]=polyfit([-1:1],s([m-1:m+1]),2);
u=linspace(-1,1,1000);y=polyval(a,u);
hold on;plot(m+u,y);xlim([M/P-10 M/P+10])
```

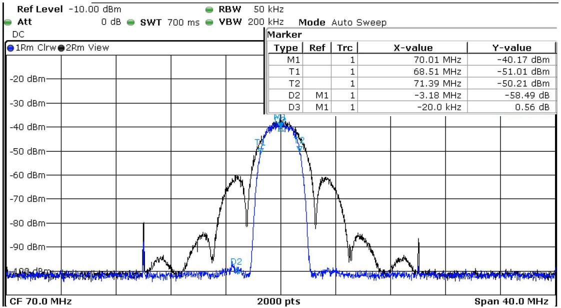
[a] J.-M Friedt & al., *Development of an opensource, openhardware, software-defined radio platform for two-way satellite time and frequency transfer*, Joint EFTF/IFCS, Toyama, Japan (2023)

SDR emitter

- Generic pseudo-random code generator with tunable code length and modulation scheme (BPSK, QPSK with two-state GPIO output at the moment $\Rightarrow$ **phase modulations**)
- Input-output 1-PPS signals (for calibration)
- TWSTFT: digital processing time delay is cancelled assuming the same algorithm is used on both sides
- Need to **finely synchronize emission** time: satellite moving at $\leq$5 ns/s and $\delta\tau \leq 200$ ps $\Rightarrow$ emit within $0.2/5 = 40$ ms $\Rightarrow$ **active** probing of NTP time and trigger emission on next PPS



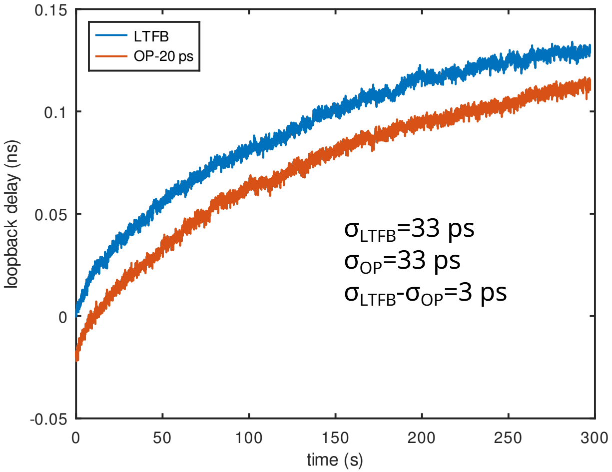
https://github.com/oscimp/amaranth_twstft



Black=SATRE modem ; blue=SAW filtered FPGA output

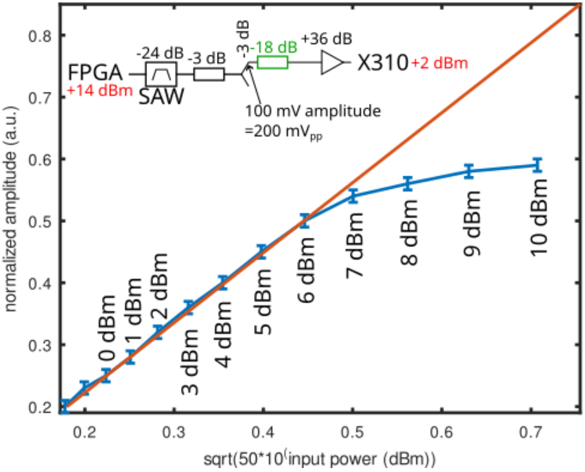
SDR receiver

- **Record** signal during the UTC odd hour: test measurement schedule, beginning and end of hour, for 5 min
- **post-process** recorded signal during the UTC even hour
- aims at **hardware agnostic** solution, but at the moment using Ettus Research X310 with BasicRX daughter boards on both ends
  - problem of fine delay drift at warmup (cancelled when using the same hardware on both ends) $\Rightarrow$ keep acquisition (FPGA + ADC) running, streaming data only recorded during sessions (UDP/ZeroMQ Publish-Subscribe)



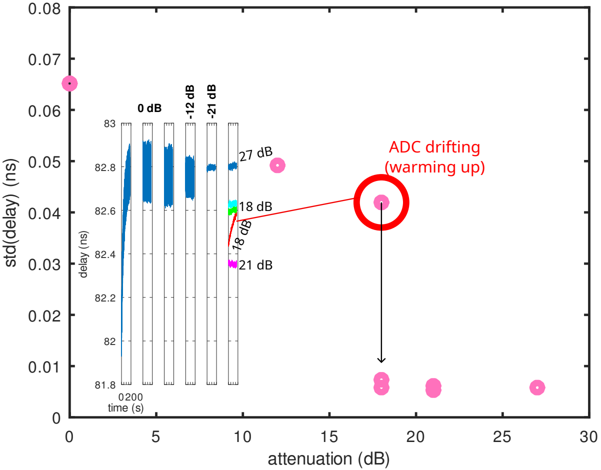
SDR receiver

- **Record** signal during the UTC odd hour: test measurement schedule, beginning and end of hour, for 5 min
- **post-process** recorded signal during the UTC even hour
- aims at **hardware agnostic** solution, but at the moment using Ettus Research X310 with BasicRX daughter boards on both ends
  - problem of fine delay drift at warmup (cancelled when using the same hardware on both ends) ⇒ keep acquisition (FPGA + ADC) running, streaming data only recorded during sessions (UDP/ZeroMQ Publish-Subscribe)
  - tune input power despite recorded samples not clipping



SDR receiver

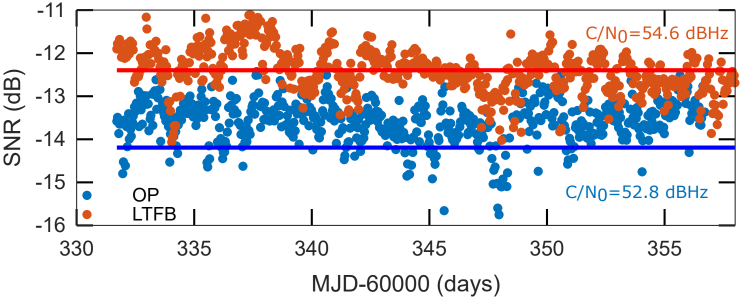
- **Record** signal during the UTC odd hour: test measurement schedule, beginning and end of hour, for 5 min
- **post-process** recorded signal during the UTC even hour
- aims at **hardware agnostic** solution, but at the moment using Ettus Research X310 with BasicRX daughter boards on both ends
  - problem of fine delay drift at warmup (cancelled when using the same hardware on both ends) $\Rightarrow$ keep acquisition (FPGA + ADC) running, streaming data only recorded during sessions (UDP/ZeroMQ Publish-Subscribe)
  - tune input power despite recorded samples not clipping
  - time delay standard deviation as a function of input power



Reception: post-processing

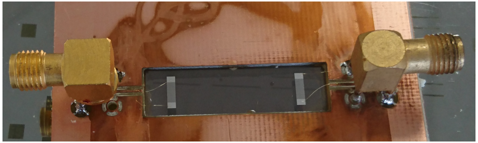
- Record signal at 5 MS/s, 16 bit/sample, 2 channels (loopback and downlink), IQ
  $\Rightarrow 5 \cdot 10^6 \times 2 \times 2 \times 2 = 40$ MB/s= 13.2 GB in 5.5 minutes or 144 GB/hour

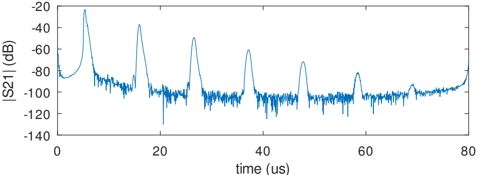
- At the moment: only code **acquisition** with polynomial fit, **no DLL/PLL**
- BPSK modulated payload (NTP second) not decoded
- SNR $\rightarrow$ C/N0 from aligned code power v.s background noise density

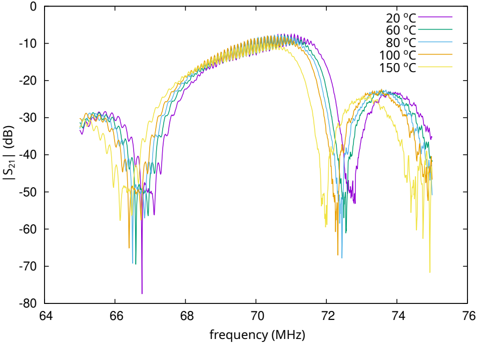


Satellite simulator

- **Doppler** shift readily tested by shifting receiver local oscillator with respect to emitter local oscillator
- Continuous time delay in the ns/s range: **analog Surface Acoustic Wave** (SAW) delay line
- 70 MHz center frequency, 5 MHz bandwidth
- high temperature sensitivity on YXl/128° lithium niobate
- acoustic velocity of 3979 m/s for a time delay of 5.3 μs for a **21.3 mm**-long delay line
- 100 K temperature variation leads to a group delay variation of **37 ns/100 K** considering the 70 ppm/K temperature sensitivity of YXl/128° LNO $\Rightarrow$ only 1/6th of sampling period at 5 MS/s (or 1/2 after interpolating by 3)

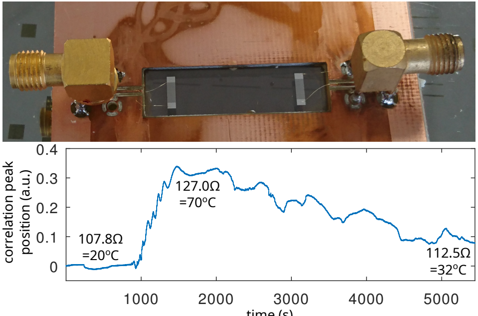


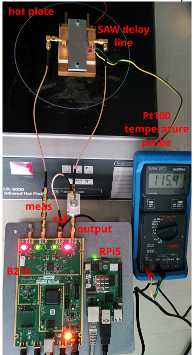




Satellite simulator

- **Doppler** shift readily tested by shifting receiver local oscillator with respect to emitter local oscillator
- Continuous time delay in the ns/s range: **analog Surface Acoustic Wave** (SAW) delay line
- 70 MHz center frequency, 5 MHz bandwidth
- high temperature sensitivity on YXl/128° lithium niobate
- acoustic velocity of 3979 m/s for a time delay of 5.3 μs for a **21.3 mm**-long delay line
- 100 K temperature variation leads to a group delay variation of **37 ns/100 K** considering the 70 ppm/K temperature sensitivity of YXl/128° LNO $\Rightarrow$ only 1/6th of sampling period at 5 MS/s (or 1/2 after interpolating by 3)

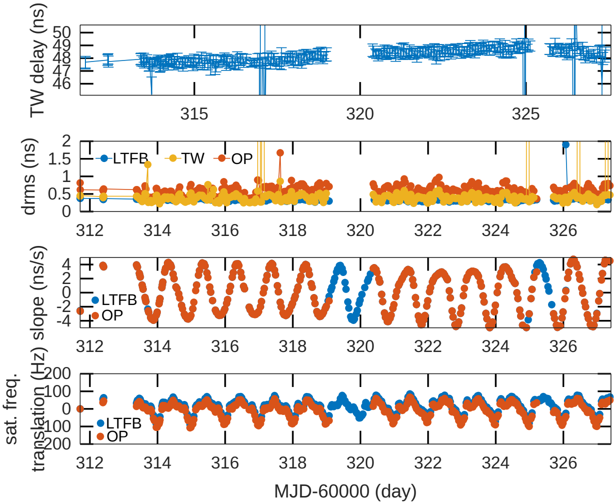




Conclusion

- Assembled a complete testbed (hardware and software) for developing TWSTFT systems
- Demonstrated a functional link for 3 weeks with performance comparable to SATRE modem
- Open for further development (modulation scheme: QPSK, BOC? payload?)

`https://github.com/oscimp/amaranth_twstft`



TODO:

- stabilize the system and demonstrate longer sessions
- complement code acquisition with tracking
- time calibration (PPS propagation delays)
- get rid of the commercial VSAT upconverter and downconverter (full SDR up to microwaves)