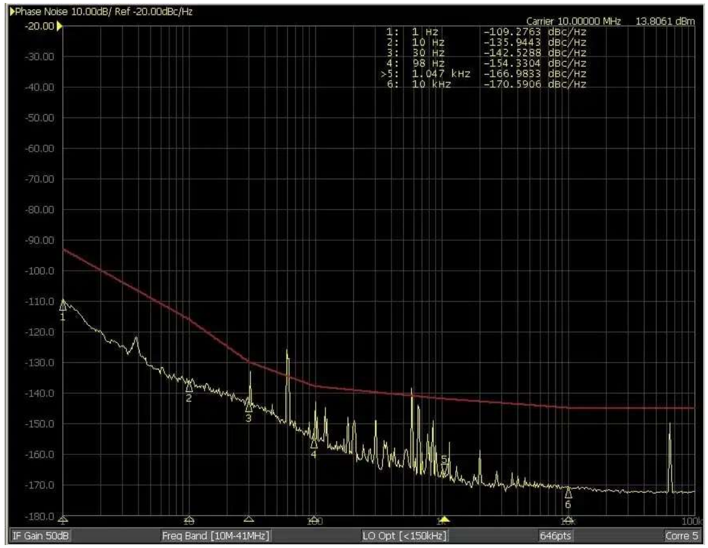
On the need for stable oscillators: from GNSS spoofing to RADAR

J.-M Friedt (with support from E. Rubiola)
Email: jmfriedt@femto-st.fr

FEMTO-ST Time & Frequency department, Besançon, France



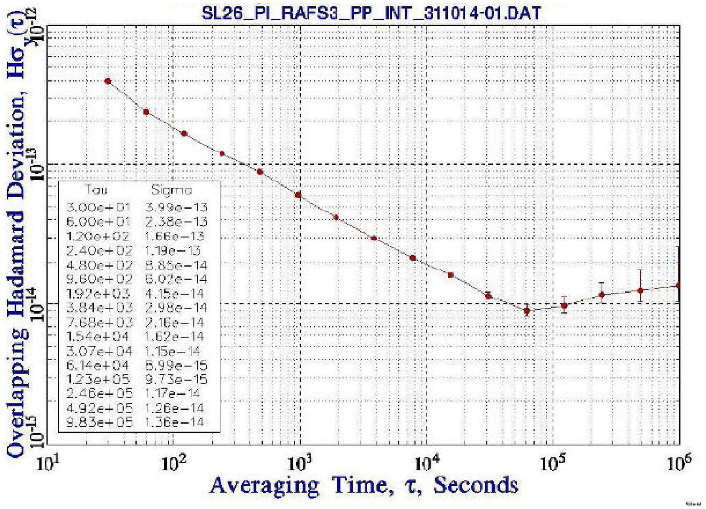


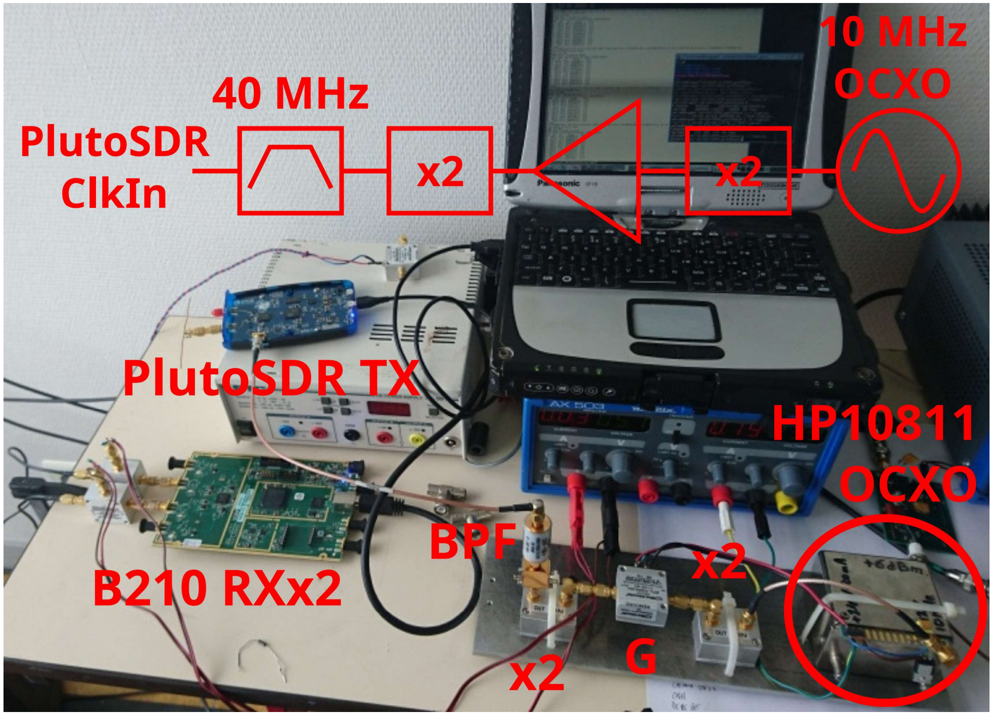
Figure 4: RAFS typical stability

https://safran-navigation-timing.com/the-importance-of-low-phase-noise-in-mobile-applications/
https://safran-navigation-timing.com/product/rafs/

October 9, 2025

High stability oscillator for GNSS spoofing

- DLL/PLL loop constants are tuned for signals generated from atomic clocks (0.3 Hz/s Doppler shift)
- Poor stabilility LO driving the SDR induces phase jumps and unlocks DLL/PLL
- Since clocking PlutoSDR with 10 MHz OCXO multiplied $\times 4$ (40 MHz clock input of AD9361), excellent results[1]

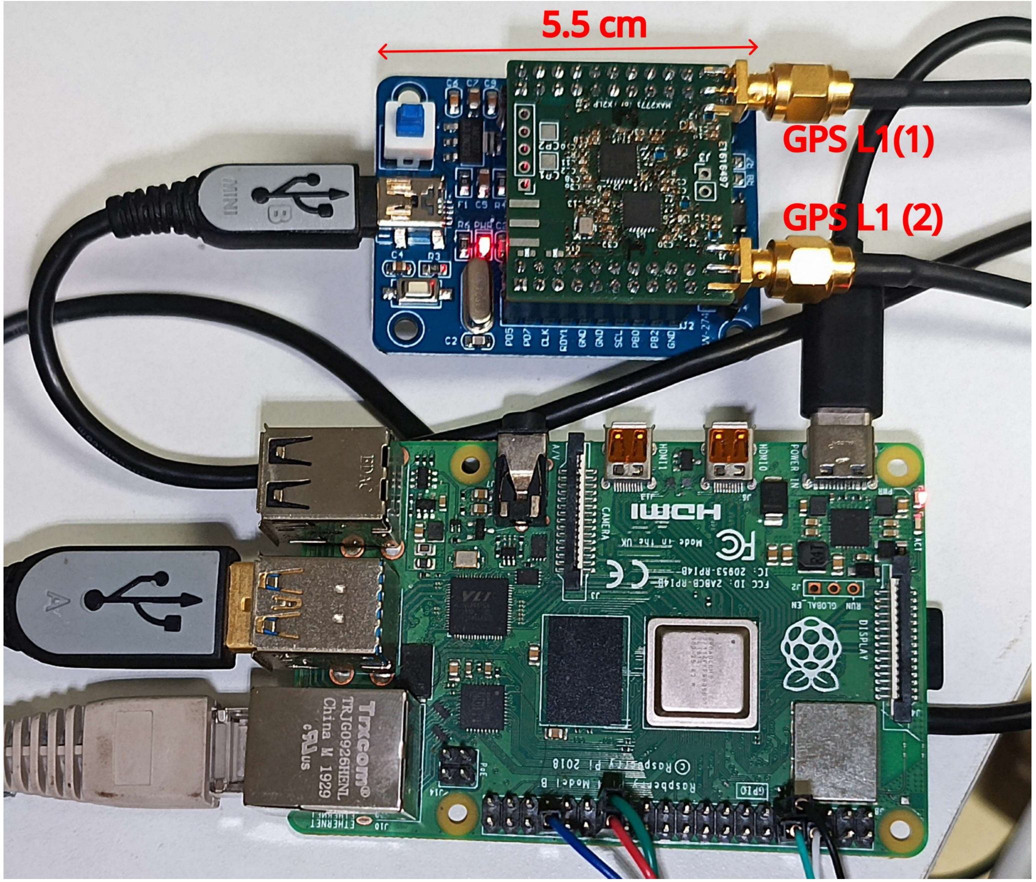


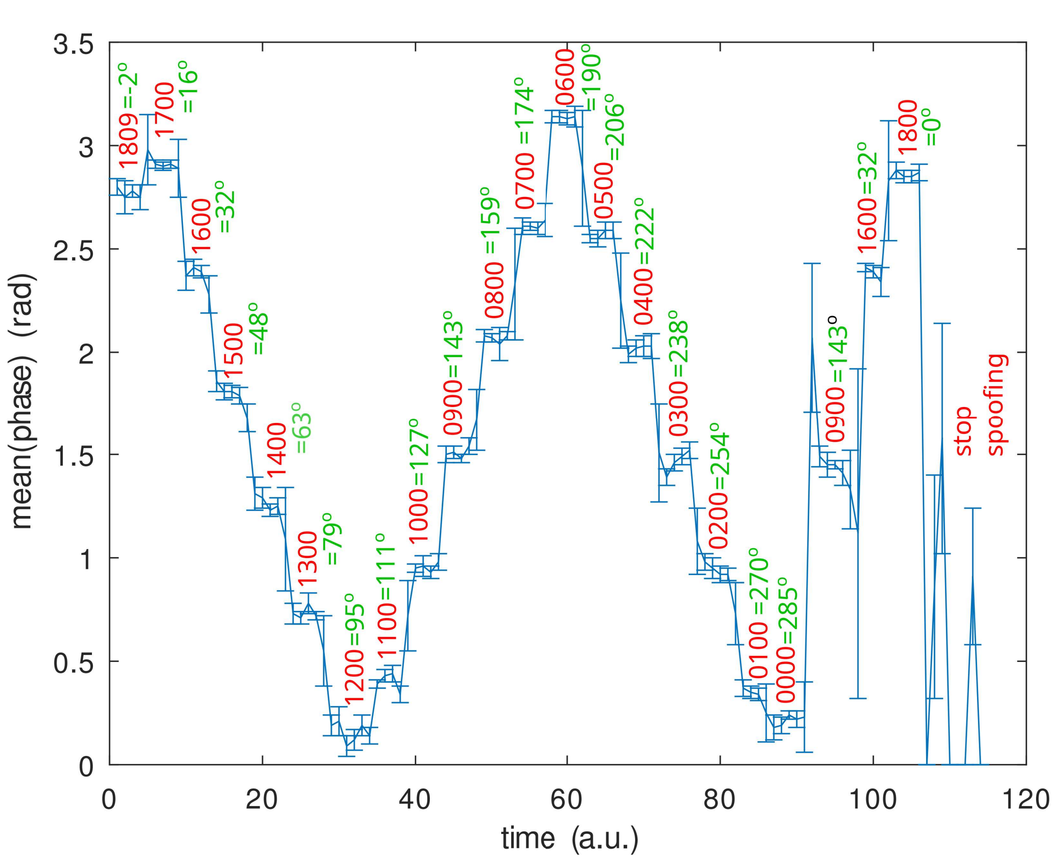
- Basic setup for becoming familiar with CRPA...

[1]W. Feng, J.-M Friedt, G. Goavec-Merou, F. Meyer, *Software Defined Radio Implemented GPS Spoofing and Its Computationally Efficient Detection and Suppression*, IEEE Aerospace and Electronic Systems Magazine **36**)(3), March 2021

Dual MAX2771 for GNSS spoofing detection and direction of arrival

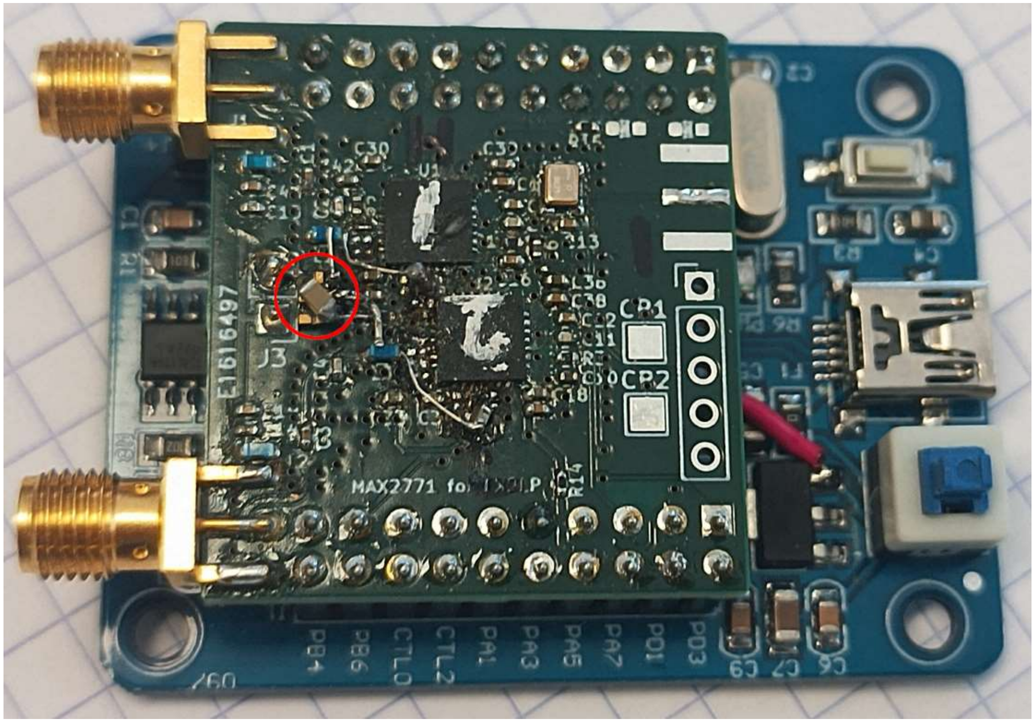
- Low power, low cost GNSS spoofing detection, but too few bits for CRPA
- Codeless decoding for BPSK/BOC spoofing detection and direction of arrival measurement, but...
- ... DoA drift from PLL warming up[2]
- Oscillator drift and recalibration (5th overtone of 312.5 MHz oscillator [3])

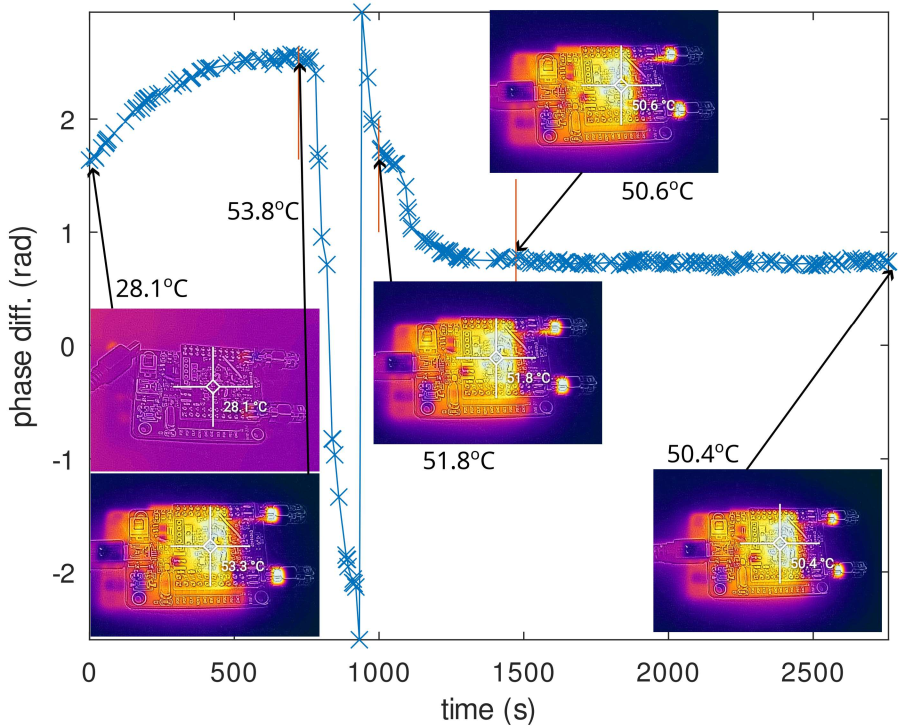




Dual MAX2771 for GNSS spoofing detection and direction of arrival

- Low power, low cost GNSS spoofing detection, but too few bits for CRPA
- Codeless decoding for BPSK/BOC spoofing detection and direction of arrival measurement, but...
- ... DoA drift from PLL warming up[2]
- Oscillator drift and recalibration (5th overtone of 312.5 MHz oscillator [3])



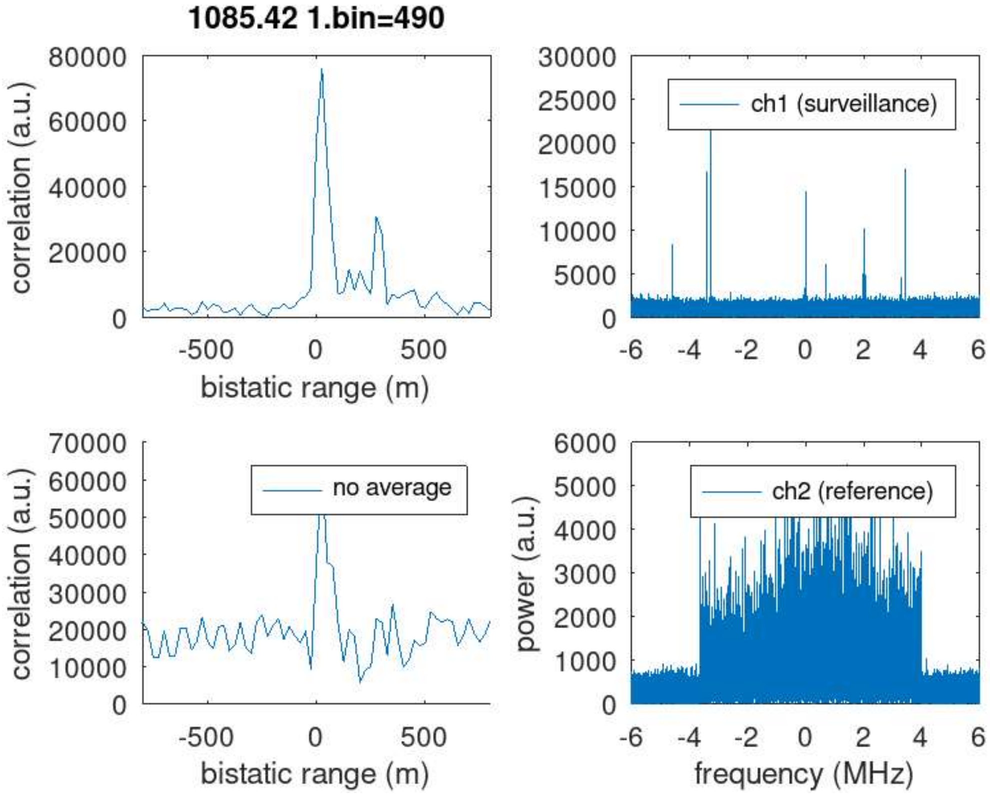


[2] https://github.com/jmfriedt/max2771_fx2lp/tree/main/250610_calibrate_phase

[3] https://www.mouser.fr/c/passive-components/frequency-control-timing-devices/oscillators/?frequency=312.5

Dual MAX2771 for passive radar

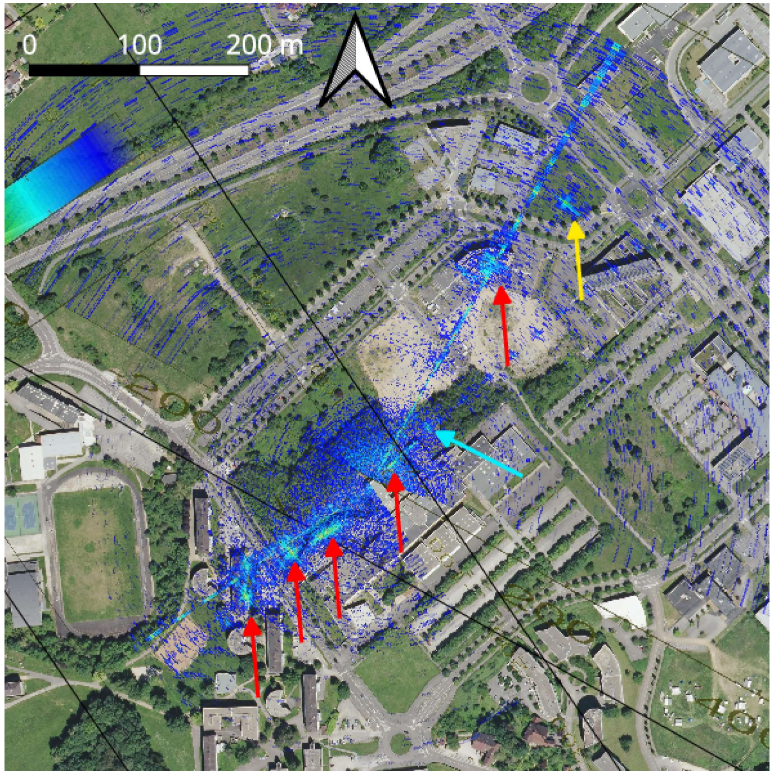
- using DVB-T signals: external frequency transposition (mixer) from UHF to L-band[4]
- Range is a comparison of emitted and received at frequency offset inverse of time of flight
- Improve range resolution with frequency stacking: collecting from successive frequency bands assumes **stable phase** (time domain $\rightarrow$ FFT $\rightarrow$ stack spectra $\rightarrow$ $\times^*$ (xcorr) $\rightarrow$ iFFT)
- SAR processing: iFT along the antenna position (azimuth) requires **stable phase** during acquisition

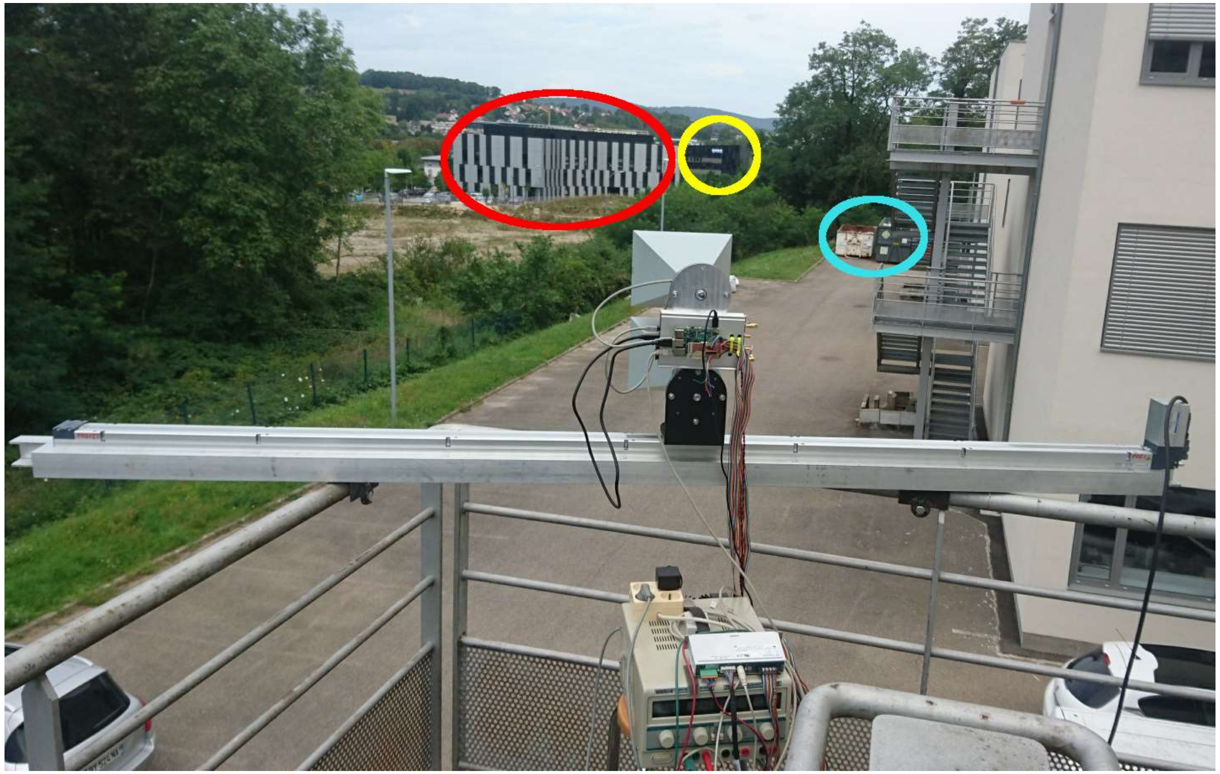


[4]https://github.com/jmfriedt/max2771_fx2lp/blob/main/250608_no_preamp/2_490MHz.png

Synthetic Aperture RADAR – SAR

- using DVB-T signals: external frequency transposition (mixer) from UHF to L-band
- Range is a comparison of emitted and received at frequency offset inverse of time of flight
- Improve range resolution with frequency stacking: collecting from successive frequency bands assumes **stable phase** (time domain → FFT → stack spectra → $\times^*$ (xcorr) → iFFT)
- SAR processing: iFT along the antenna position (azimuth) requires **stable phase** during acquisition [4]



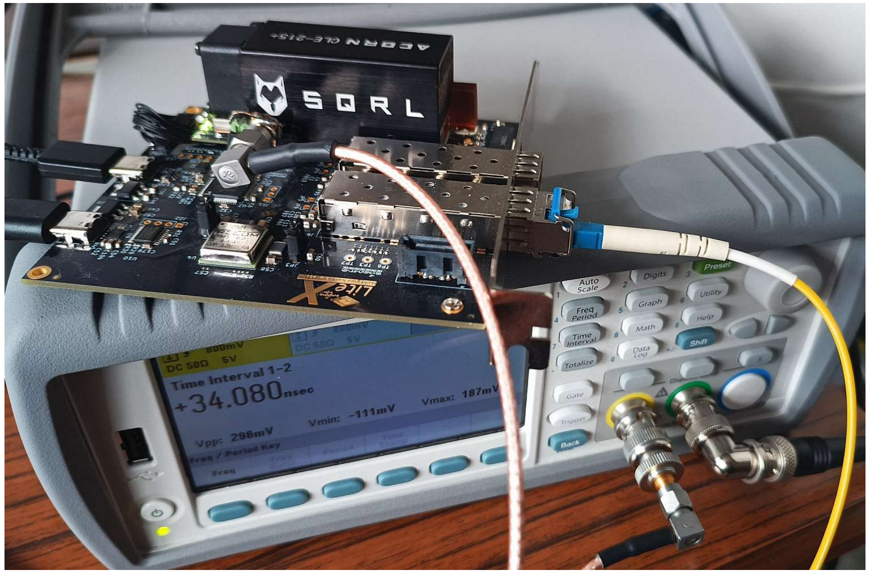


[4] https://github.com/jmfriedt/SDR-GB-SAR

White Rabbit running on general purpose FPGA boards (SDR platforms)

Integrating White Rabbit in **generic SDR hardware**:

- Shared oscillator is fine for nearby receivers, but what about distributed radar?
- White Rabbit phase detection requires two tunable local oscillators $\Rightarrow$ dedicated hardware (Si571)
- What about generic FPGA-based SDR receivers?
- White Rabbit as a generic LiteX library[a]
- White Rabbit for Enjoy Digital M2SDR syntonization[b]
- Only requires FPGA + SFP: see `https://github.com/oscimp/wr_acorn/tree/main/RPi_HAT` for WR-enabled M2SDR on Raspberry Pi5

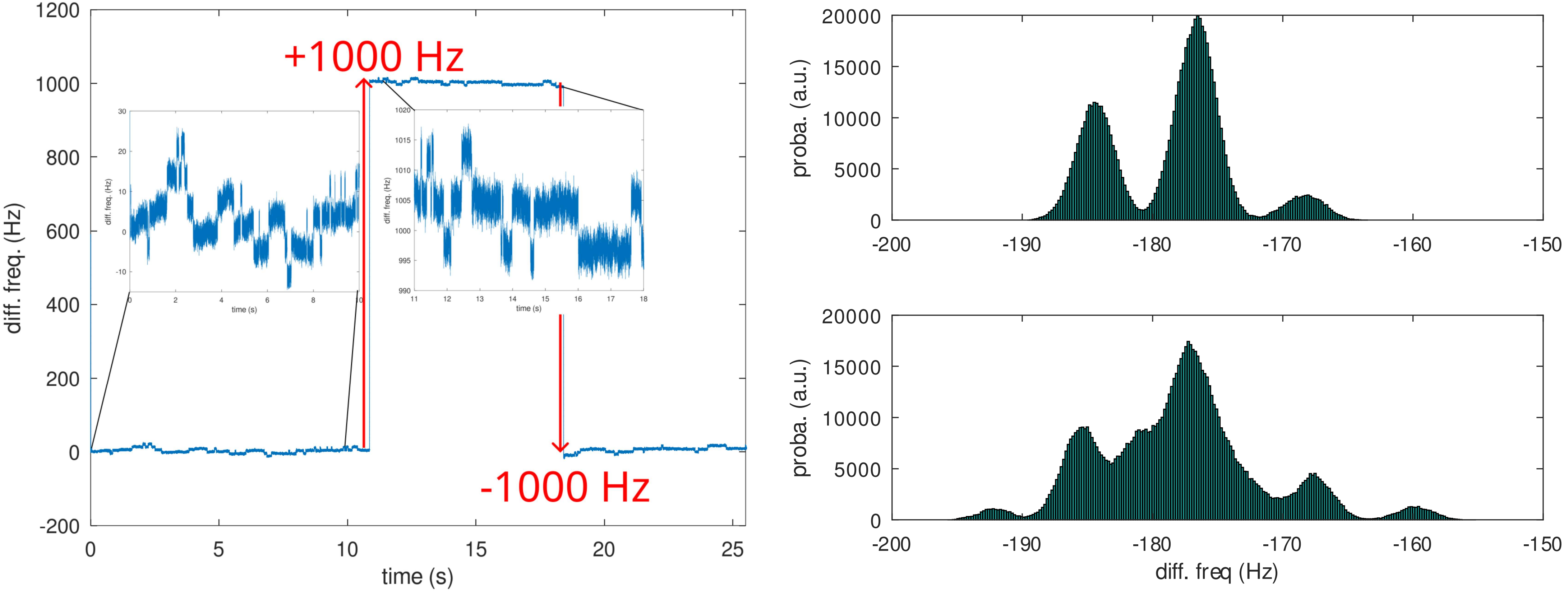


---

[a] `https://github.com/enjoy-digital/litex_wr_nic`
[b] `https://github.com/enjoy-digital/litex_m2sdr`

MEMS oscillator?

- ACORN CLE-125+ is driven by a Abracon ASDMPLV-200.000MHZ MEMS oscillator
- Estimate LO stability by X310 SDR acquisition → FM detector (freq. detector)
- Frequency jumps ⇒ poor WR performance



Good enough for driving bitcoin mining FPGA (Acorn CLE215+), but not for GNSS spoofing/passive radar analysis (time of flight difference ⇒ phase jumps)

Phase noise induced decoherence, phase noise/Allan deviation relationship

- RF over White Rabbit: using the FPGA for White Rabbit synchronization **and RF acquisition/processing**[5]: ADC ENOB determined through jitter[6] σ_τ: $SNR_{degradation} = 20\log_{10}(2\pi f_{in}\sigma_\tau)$
- local oscillator characterization S_φ (dBrad^2/Hz=dBc/Hz+3 dB)

$$S_\varphi(f) \rightarrow S_y = S_\varphi(f) \times \frac{f^2}{\nu^2} \rightarrow \sigma_y(\tau) = \int |H(f)|^2 \cdot S_y(f) \cdot df$$

with[7] $|H(f)|^2 = 2\frac{\sin^4(\pi\tau f)}{(\pi\tau f)^2}$ and $\sigma_\tau = \sqrt{\int S_\varphi(f) \cdot df} = \sqrt{B \cdot S_\varphi}$ for white phase noise: jitter estimate from phase noise analysis for WR standard consistency using $\sqrt{\int |H(f)|^2 \cdot S_\varphi(f) \cdot df}$ with $H(f) = \sin(2\pi \cdot f \cdot \tau_0)$ since $PPS_{n+1} - PPS_n$ leads to a filtering function $H^2(f) = sin(2\pi \cdot f \cdot \tau_0)^2$ and $\tau_0 = 1$ s for 1-PPS

- RADAR/VLBI: extract signal below noise through correlation...
- ... tradeoff between correlation integration duration (improves SNR as N the number of samples) and coherence function from long term local oscillator fluctuations[8]

$$C(T) = \left|\frac{1}{T}\int_0^T \exp(j\varphi(t)) \cdot dt\right| \rightarrow \langle C^2(T)\rangle = \frac{1}{T^2}\int_0^T\int_0^T \langle \exp(j(\varphi(t) - \varphi(t')))\rangle \cdot dt \cdot dt'$$

for estimating decoherence$= 1 - \sqrt{\langle C^2\rangle}$, with analytical expressions for various Allan deviation slopes.

[5] https://www.white-rabbit.tech/rf-over-wr-cern/
[6] T. Neu, *Jitter vs SNR for ADCs*, Texas Instruments TIPL4704 (2017)
[7] https://rubiola.org/pdf-lectures/Scientific%20Instruments%20L06-10,%20Oscillators.pdf slide 49
[8] A.R. Thompson *& al.*, *Interferometry and synthesis in radio astronomy*, Springer Nature (2017), chap. 9.5.2 pp.434–

White Rabbit Device Requirements And Validation Methods, 0.2.5 (Aug. 2025)

Requirement
Precision: in the test setup where the DUT is synchronized to a GM as described in 3.1b, a series of 10 measurements is performed. Before each measurement, the link and synchronisation between the GM and the DUT is re-established. Each measurement provides the standard deviation (sdev) over 2 minutes (i.e., 120 samples) of the time difference (skew, 1.3.3.6) between the PPS output of the GM and the DUT as described in 4.5.1, i.e., $skew_{sdev}[n]$, where n is {1:10}. The results shall be as follows in the **specified operating temperature range** which shall include room temperature: - Precision: p(**temp**) = max ($skew_{sdev}[n]$) < 100ps Where **temp** is constant temperature as follows - Room temperature (1.3.3.7). - If **operating temperature range** is specified for synchronisation in the datasheet beyond room temperature, o Minimum temperature in the specified operating temp range o Maximum temperature in the specified operating temp range Beyond meeting the above basic accuracy criteria, with respect to the value of precision, the performance classes are defined as follows:

WR Precision Class	For all t, p(temp) within range
WR Class 1 (a.k.a. basic)	50 – 99 ps
WR Class 2	25 – 49 ps
WR Class 3	12 – 24 ps
WR Class 4	6 – 11 ps
WR Class 5	< 6 ps

Offset from Carrier [Hz]	1	10	100	1 k	10 k	100 k	Maximum RMS jitter 1Hz-100kHz
WR PN class	Maximum SSB phase noise for the offset from carrier [dBc/Hz]						[ps]
WR Class I (a.k.a. basic)	-70	-70	-95	-120	-130	-130	28.3
WR Class II (a.k.a. low-jitter)	-90	-90	-107	-125	-135	-135	3.6

The above criteria shall be met when measured at constant temperature as follows:

- for room temperature (1.3.3.7), or
- for the minimum- and maximum temperature if an operating temperature range is specified for synchronisation in the datasheet.

GM MDEV: in the test setup where the DUT in GM Mode is synchronized to the time and frequency source as described in 3.1c, Modified Alan Deviation (MDEV) is measured for 1000s between the 10MHz output of the time and frequency source and the DUT as described in 4.5.2, i.e., MDEV measured with equivalent noise bandwidth of 50Hz. The results shall meet the criteria specified for MDEV "WR Class I (a.k.a. basic)" in the table below.
Beyond meeting the basic PN criteria, with respect to the values of MDEV, the performance classes are specified in the Table below (see also Figure 3 for equivalent visual representation).

Tau [s]	0.01	0.1	1	10	100
WR MDEV class	Max MDEV(tau)				
WR Class I (a.k.a. basic)	1E-9	1E-10	1E-11	1E-12	1E-13
WR Class II	3.16E-10	1E-11	1E-12	1E-13	1E-14

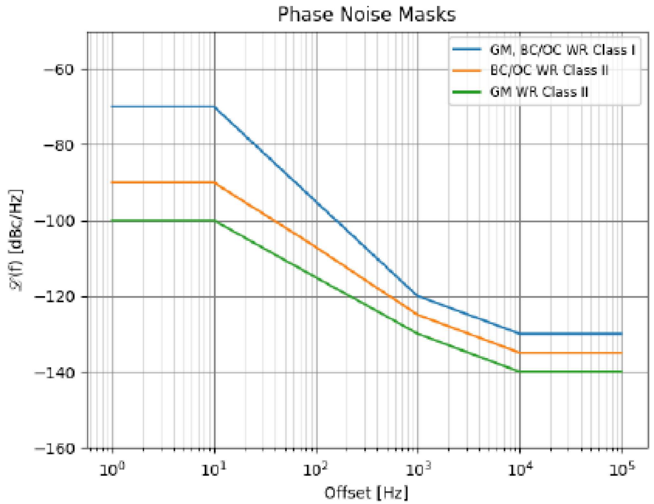


Figure 2 - Phase Noise masks for P.3 and P.4

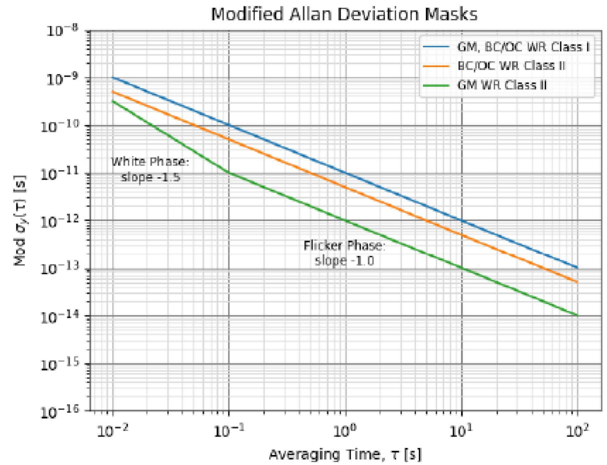
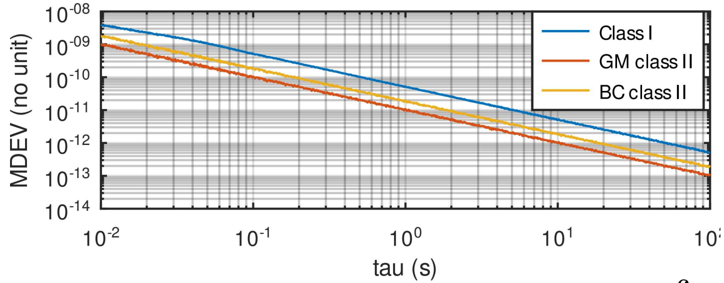


Figure 3 - MDEV mask for P.5 and P.6

Numerical integration: extending noise **to 10 MHz** ($\gg$ 100 kHz)

- no $\sin^2()$ filtering: 36.0 ps (Class I), 13.1 ps (Class II)
- $\pm$0.5 s $\sin^2()$ weight ($\tau = 1$ s): 25.4 ps (Class I), 9.2 ps (Class II)
- Decoherence of $\nu = 500$ MHz signal: -130 dBc/Hz @ 10 kHz:10 MHz
  $\Rightarrow h_2 = 10^{-13+0.3-14} = 10^{-26.7}$ @ 100 ns:100 μs
  $\Rightarrow \langle C^2 \rangle = \exp(-h_2 \cdot f_h \cdot \nu^2) = 0.995$ & $1 - \sqrt{\langle C^2 \rangle} = 2.5 \cdot 10^{-3}$ @ 500 MHz but 0.22 @ 5 GHz (https://github.com/oscimp/wr_acorn/tree/main/phase_to_time)



Phase noise to MDEV numerical $\int$

White Rabbit Device Requirements And Validation Methods, 0.2.5 (Aug. 2025)

Requirement

Precision: in the test setup where the DUT is synchronized to a GM as described in 3.1b, a series of 10 measurements is performed. Before each measurement, the link and synchronisation between the GM and the DUT is re-established. Each measurement provides the standard deviation (sdev) over 2 minutes (i.e., 120 samples) of the time difference (skew, 1.3.3.6) between the PPS output of the GM and the DUT as described in 4.5.1, i.e., $skew_{sdev}[n]$, where n is {1:10}. The results shall be as follows in the **specified operating temperature range** which shall include room temperature:

- Precision: p(**temp**) = max ($skew_{sdev}$[n]) < 100ps

Where **temp** is constant temperature as follows

- Room temperature (1.3.3.7).
- If **operating temperature range** is specified for synchronisation in the datasheet beyond room temperature,
  - o Minimum temperature in the specified operating temp range
  - o Maximum temperature in the specified operating temp range

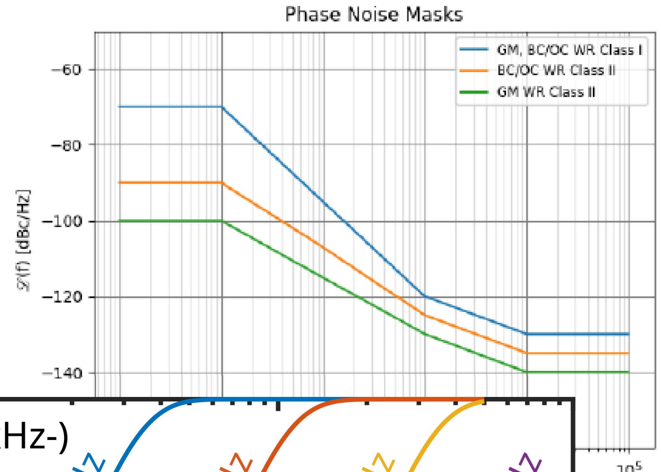
Beyond meeting the above basic accuracy criteria, with respect to the value of precision, the performance classes are defined as follows:

WR Precision Class	For all t, p(temp) within range
WR Class 1 (a.k.a. basic)	50 – 99 ps
WR Class 2	[illegible]
WR Class 3	[illegible]
WR Class 4	[illegible]
WR Class 5	[illegible]

Offset from Carrier [Hz]	1	10	100	1 k	10 k	100 k	Maximum RMS jitter 1Hz-100kHz
WR PN class	Maximum SSB phase noise for the offset from carrier [dBc/Hz]						[ps]
WR Class I (a.k.a. basic)	-70	-70	-95	-120	-130	-130	28.3
WR Class II (a.k.a. low-jitter)	-90	-90	-107	-125	-135	-135	3.6

The above criteria shall be met when measured at constant temperature as follows:

- for room temperature (1.3.3.7), or
- for the minimum- and maximum temperature if an operating temperature range is specified for synchronisation in the datasheet.



GM MDEV: in the test setup where the DUT in GM Mode is synchronized to the time and frequency source as described in 3.1c, Modified Alan Deviation (MDEV) is measured for 1000s between the 10MHz output of the time and frequency source and the DUT as described in 4.5.2, i.e., MDEV measured with equivalent noise bandwidth of 50Hz. The results shall meet the criteria specified for MDEV "WR Class I (a.k.a. basic)" in the table below.

Beyond meeting the basic PN criteria, with respect to the values of MDEV, the performance classes are specified in the Table below (see also Figure 3 for equivalent visual representation).

Tau [s]	0.01	0.1	1	10	100
WR MDEV class	Max MDEV(tau)				
WR Class I (a.k.a. basic)	1E-9	1E-10	1E-11	1E-12	1E-13
WR Class II	3.16E-10	1E-11	1E-12	1E-13	1E-14

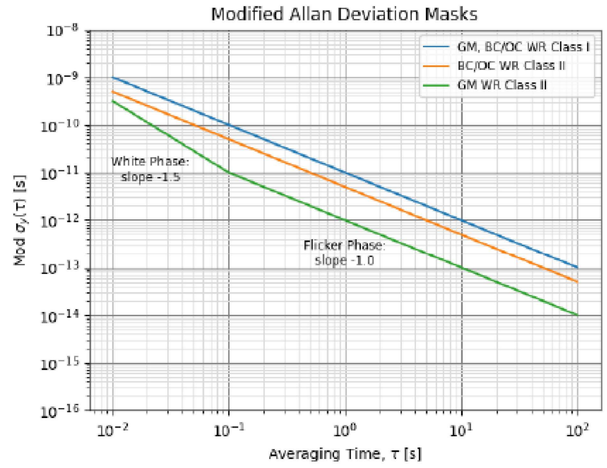
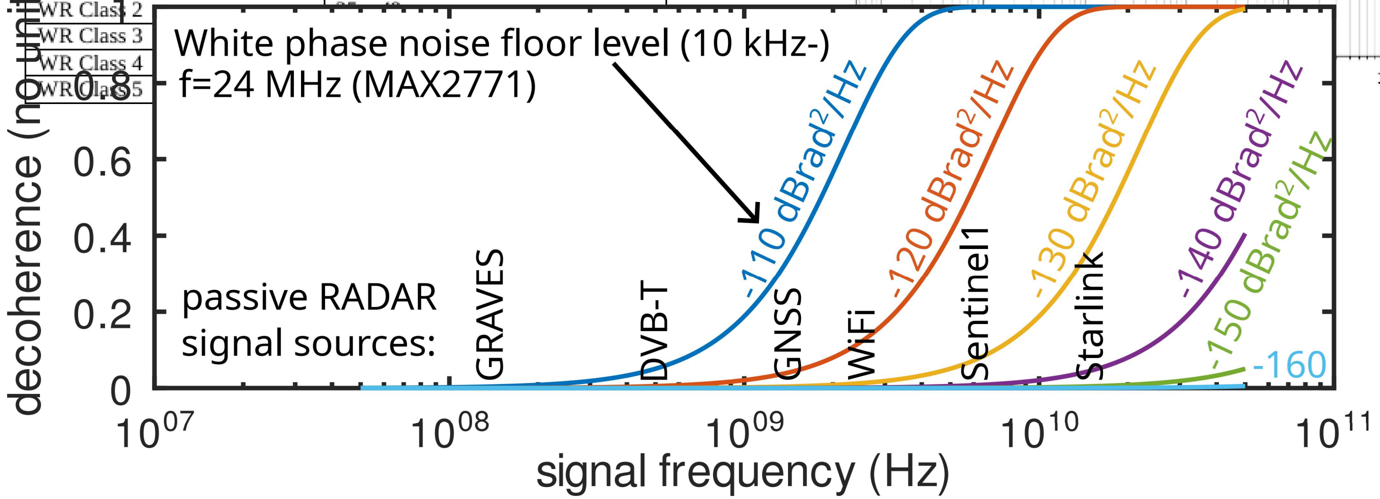
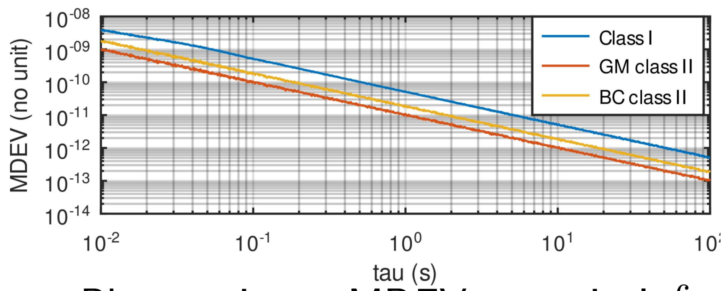


Figure 3 - MDEV mask for P.5 and P.6

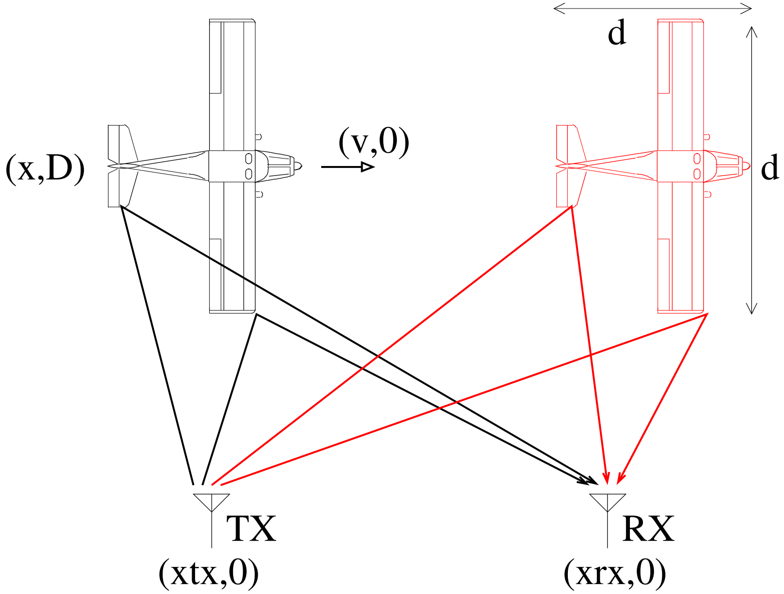




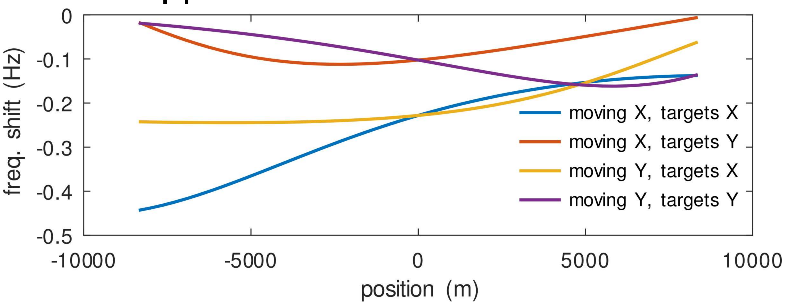
Phase noise to MDEV numerical $\int$

GRAVES ISAR (Inverse SAR) analysis

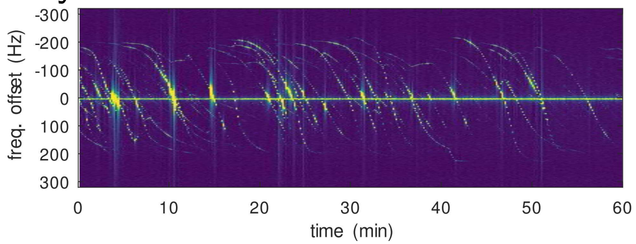
- ISAR: static receiver but moving target to benefit from micro-Doppler features
- 0.1 rad at 143.05 MHz for 6 min: $1 \cdot 10^{-10}$ @ 300 s or $4 \cdot 10^{-13}$ @ 1 s



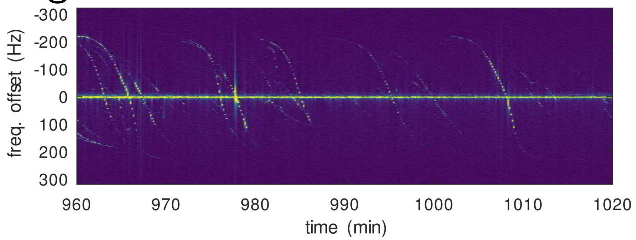
Micro-doppler shift simulation:

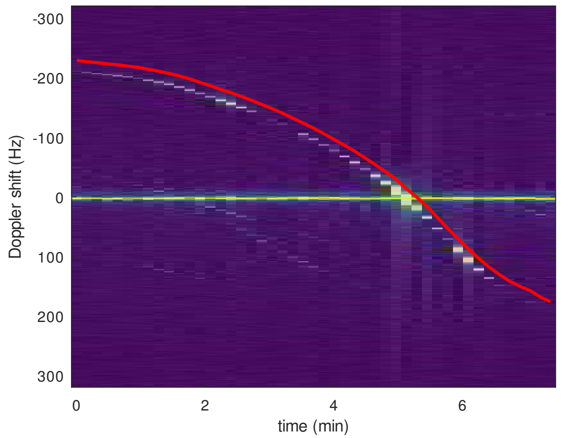


Daytime

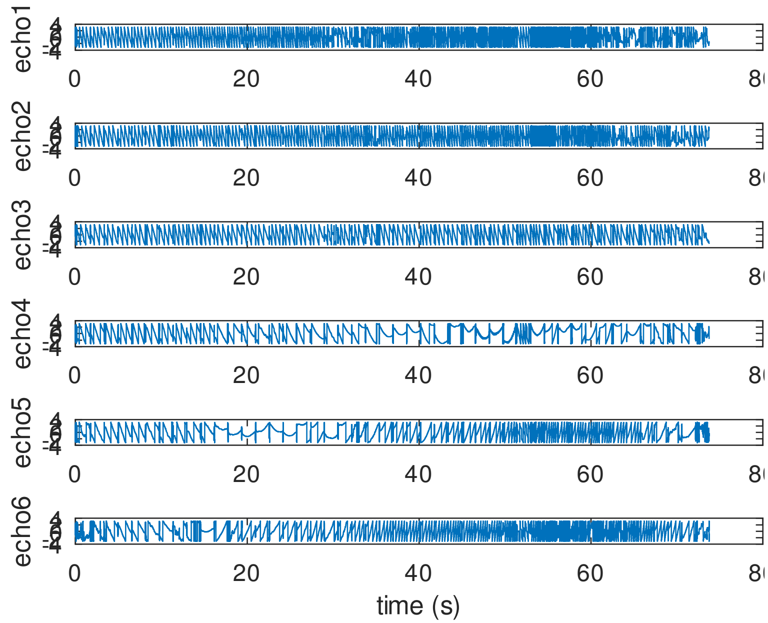


Nighttime





Evolution of the residual phase for the 6 beams broadcast by GRAVES[a]:



[a] F. Colone *& al.*, *VHF Cross-Range Profiling of Aerial Targets Via Passive ISAR: signal processing schemes and experimental results*, IEEE Trans. on Aerospace and Electronic Systems **53**(1) 218–235 (2017)

Conclusion and perspectives

Conclusion

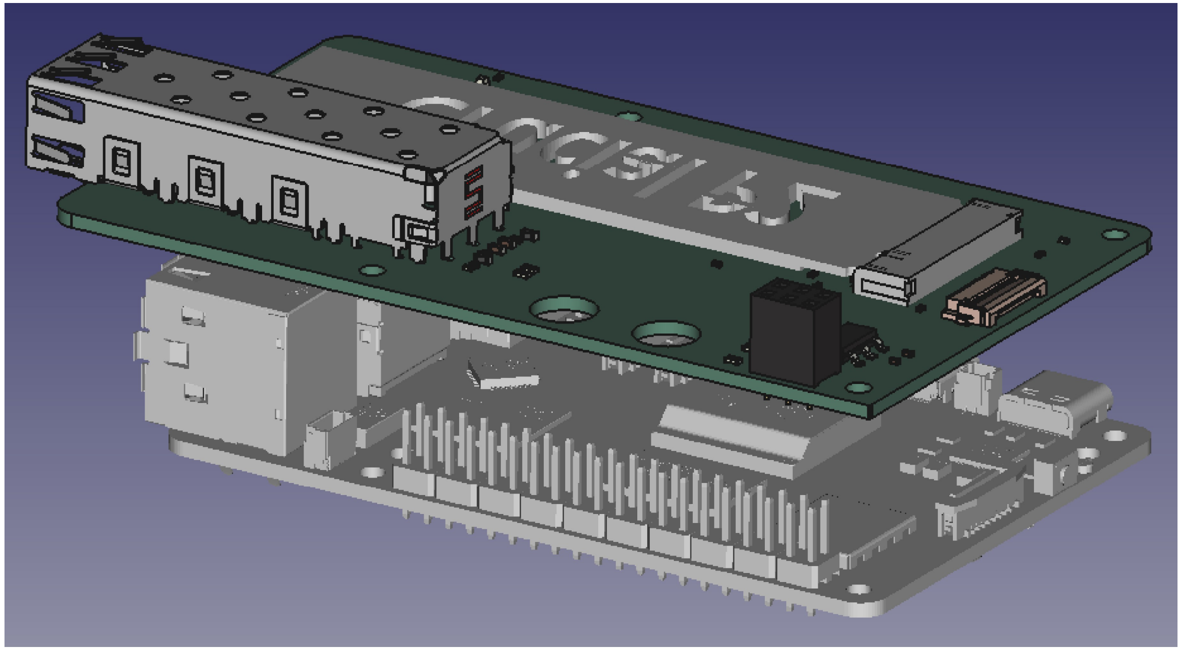
- The need for high stability oscillator is probably often exagerated[9],
- ... but some applications do justify stable phase over durations of milliseconds to minutes.
- Demonstration in the context of GNSS spoofing, spoofing detection, SAR and ISAR

Perspectives

- White Rabbit synchronization of general purpose SDR platforms (beyond syntonization)
- NISAR L-band signal for passive RADAR[10]

Resources

- `https://github.com/jmfriedt/max2771_fx2lp` ←—
- `https://github.com/jmfriedt/wr_acorn`
- `https://github.com/jmfriedt/SDR-GB-SAR`
- `https://github.com/enjoy-digital/litex_m2sdr`



White Rabbit enabled Raspberry Pi5 with M2SDR.

[9] "In some ways the Würzburg seemed over-engineered, or perhaps it had functions that could not yet be guessed at: 'the most remarkable feature of this unit is its very high frequency stability, which is much higher than needed for its present purpose.' "
D. Lewis, *Churchill's Shadow Raiders: The Race to Develop Radar, World War II's Invisible Secret Weapon*, Citadel Press. (2020)

[10] W. Feng, J.-M. Friedt, P. Wan, *SDR-implemented passive bistatic SAR system using Sentinel-1 signal and its experiment results*, MDPI Remote Sensing **14**(1) 221– (2022)