Distributed coherent SDR systems: GNU Radio rides the White Rabbit

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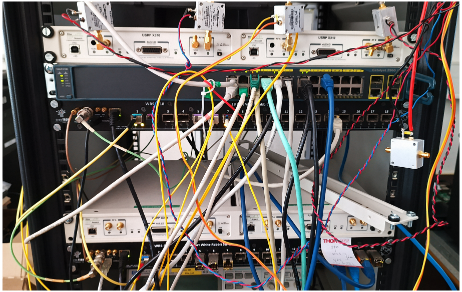
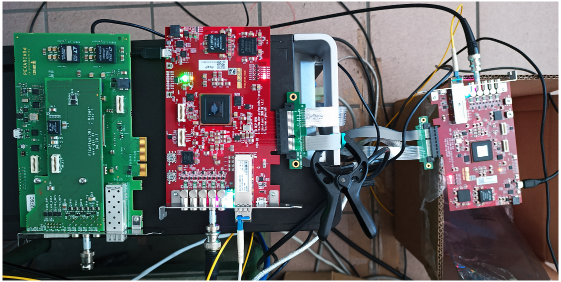


White Rabbit Switch (WRS) + 2$\times$ X310 SDR

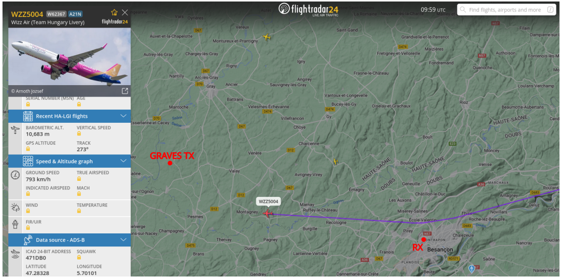
August 29, 2024



GSI White Rabbit PCIe custom boards (courtesy D. Beck, A. Hahn, F. Ameil)

Introduction

- RADAR: RAdiofrequency Detection And Ranging $\Rightarrow$ range resolution given by bandwidth B: $\Delta R = \frac{c}{2B}$
- Noise rises as bandwidth: $N = k_B \cdot T \cdot B = -174 + 10\log_{10}(B)$ dBm
- Narrowband RADAR can still identify distance through (interferometrice) phase analysis...
- ... at the expense of $\lambda/2$ uncertainty on the absolute distance
- Distributed RADAR system: spatial diversity for direction of arrival measurement [1]
- Demonstration: GRAVES space surveillance emitter located 38 km from lab in Besançon (France)



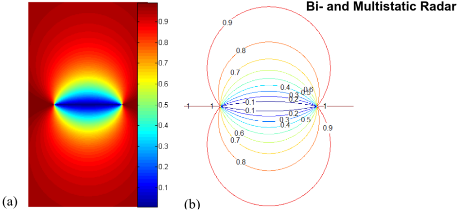
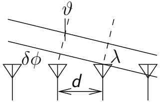


Figure 11: (a) Continuous mapping of reduction factor as a function of target position. (b) Doppler reduction factor cos(β/2)cos(δ=0) contour curves as a function of position in the bistatic plane.

[1] T. Johnsen & K.E. Olsen, *Bi- and Multistatic Radar*, Advanced Radar Signal and Data Processing (2006) at
`https://www.sto.nato.int/publications/STO%20Educational%20Notes/RTO-EN-SET-086bis/EN-SET-086bis-04.pdf`

(Inverse) Fourier transform for azimuth compression of antenna array

Receiver site (RX): replace single antenna with antenna array for direction of arrival measurement



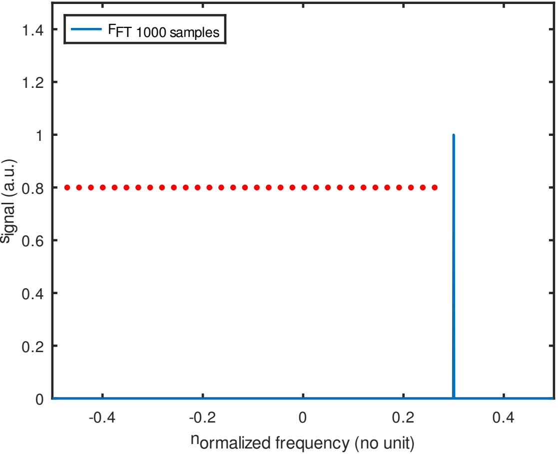
- Uniform Linear antenna Array (ULA): constant distance d between adjacent antennas
- phase at nth antenna at position nd: $n\vec{k}\vec{d} = n\frac{2\pi}{\lambda}d\cos\vartheta$
- we wish to find angle of arrival ϑ, argument of $\underbrace{(nd)}_{antenna} \cdot \underbrace{\left(\cos\vartheta\frac{2\pi}{\lambda}\right)}_{direction}$
- inverse Fourier transform of $\exp(j2\pi k \times nx)$ leads to a Dirac at k so

$$FT(s)_k = \sum_x s(x)\exp(kx) \text{ with } k = \frac{2\pi}{\lambda}\cos\vartheta$$

$\Rightarrow$ collect N samples from P antennas (matrix) and FFT2D to convert
(time, antenna position) to (frequency$_{Doppler}$, azimuth)
assuming fixed conditions during $\int$ time (1 Hz resolution for 1 m/s resolution = 1 s integration time)

Fourier transform

Samples in the time domain → antennas at different locations.



Uniform frequency distribution of frequencies from $-f_s/2$ to $+f_s/2 - f_s/N$ for N samples in the time domain

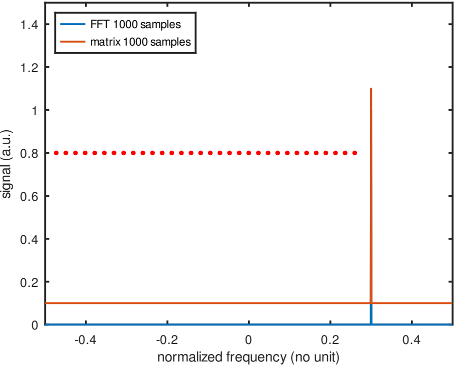
$$\text{abs}(\text{FFT}(s))_\nu = |\sum_t s(t)\exp(-j2\pi\nu t)|$$

with $s(t) = \exp(j2\pi ft)$

```
fs=1;   % sampling frequency
f=.3;   % normalized signal frequency
t=[0:999]/fs;
s=exp(j*2*pi*t*f);
freq=linspace(-fs/2,fs/2-fs/length(s),length(s));
res=abs(fftshift(fft(s)));
plot(freq,res/max(res))
```

High spectral resolution requires many samples during long acquisition = many evenly spaced antennas for DoA.

Matrix expression $N_t \leftrightarrow N_\nu$



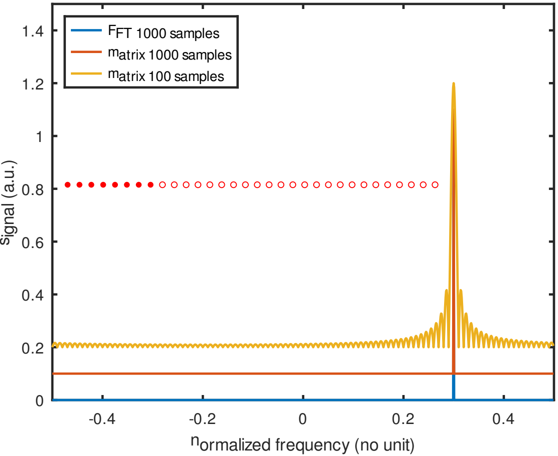
$$\underbrace{\begin{pmatrix} \exp(j2\pi\nu_1 t_1) & \exp(j2\pi\nu_2 t_1) & \exp(j2\pi\nu_3 t_1) & \dots & \exp(j2\pi\nu_N t_1) \\ \exp(j2\pi\nu_1 t_2) & \exp(j2\pi\nu_2 t_2) & \exp(j2\pi\nu_3 t_2) & \dots & \exp(j2\pi\nu_N t_2) \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \exp(j2\pi\nu_1 t_N) & \exp(j2\pi\nu_2 t_N) & \exp(j2\pi\nu_3 t_N) & \dots & \exp(j2\pi\nu_N t_N) \end{pmatrix}}_{M}$$

$$FT(s)_\nu = s \cdot M = \sum_t s(t) \exp(j2\pi\nu t)$$

bijective relation between time and frequency (square matrix)

```
matrix=exp(-j*2*pi*t'*freq);
res=abs(s*matrix);
plot(freq,res/max(res)+0.1)
```

Matrix expression $P_t \leftrightarrow N_\nu$

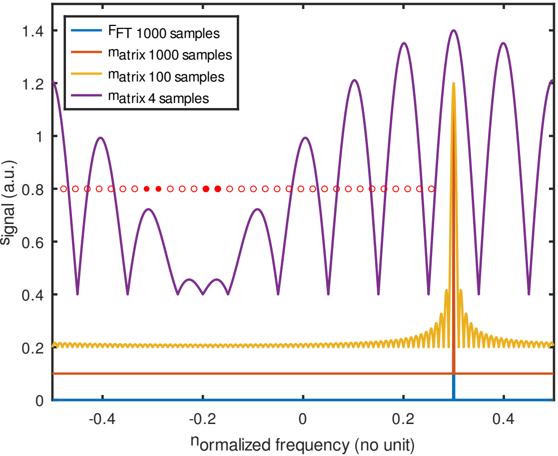


$$\begin{pmatrix} \exp(j2\pi\nu_1 t_1) & \exp(j2\pi\nu_3 t_1) & \dots & \exp(j2\pi\nu_N t_1) \\ \exp(j2\pi\nu_1 t_2) & \exp(j2\pi\nu_3 t_2) & \dots & \exp(j2\pi\nu_N t_2) \\ \vdots & \vdots & \ddots & \vdots \\ \exp(j2\pi\nu_1 t_P) & \exp(j2\pi\nu_3 t_P) & \dots & \exp(j2\pi\nu_N t_P) \end{pmatrix}$$

$P < N$: short time window $\rightarrow$ broader sinc() function

```
ttrunc=t(1:100);
strunc=s(1:100);
matrix=exp(-j*2*pi*ttrunc'*freq);
res=abs(strunc*matrix);
plot(freq,res/max(res)+0.2)
```

Matrix expression $P_t \leftrightarrow N_\nu$

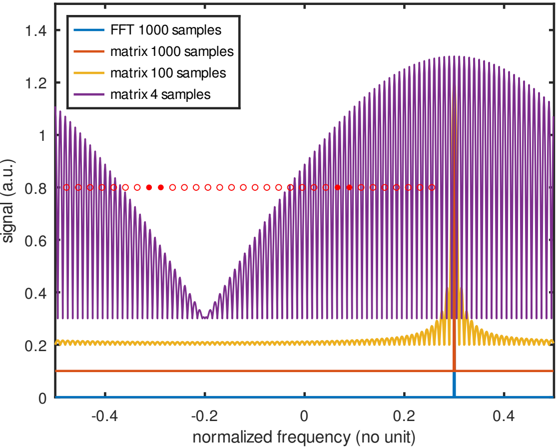


$$\begin{pmatrix} \exp(j2\pi\nu_1 t_1) & \exp(j2\pi\nu_3 t_1) & \dots & \exp(j2\pi\nu_N t_1) \\ \exp(j2\pi\nu_1 t_2) & \exp(j2\pi\nu_3 t_2) & \dots & \exp(j2\pi\nu_N t_2) \\ \exp(j2\pi\nu_1 t_{P-1}) & \exp(j2\pi\nu_3 t_{P-1}) & \dots & \exp(j2\pi\nu_N t_{P-1}) \\ \exp(j2\pi\nu_1 t_P) & \exp(j2\pi\nu_3 t_P) & \dots & \exp(j2\pi\nu_N t_P) \end{pmatrix}$$

4 antenna positions (times) made of two $\lambda/2$ separated pairs closely spaced

```
ttrunc=t([1:2 11:12]);
strunc=s([1:2 11:12]);
matrix=exp(-j*2*pi*ttrunc'*freq);
res=abs(strunc*matrix);
plot(freq,res/max(res)+0.3)
```

Matrix expression $P_t \leftrightarrow N_\nu$

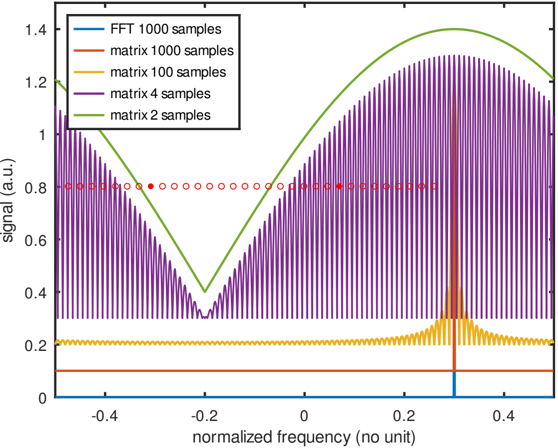


$$\begin{pmatrix} \exp(j2\pi\nu_1 t_1) & \exp(j2\pi\nu_3 t_1) & \dots & \exp(j2\pi\nu_N t_1) \\ \exp(j2\pi\nu_1 t_2) & \exp(j2\pi\nu_3 t_2) & \dots & \exp(j2\pi\nu_N t_2) \\ \exp(j2\pi\nu_1 t_{P-1}) & \exp(j2\pi\nu_3 t_{P-1}) & \dots & \exp(j2\pi\nu_N t_{P-1}) \\ \exp(j2\pi\nu_1 t_P) & \exp(j2\pi\nu_3 t_P) & \dots & \exp(j2\pi\nu_N t_P) \end{pmatrix}$$

4 antenna positions (times) made of two $\lambda/2$ separated pairs widely spaced

```
ttrunc=t([1:2 101:102]);
strunc=s([1:2 101:102]);
matrix=exp(-j*2*pi*ttrunc'*freq);
res=abs(strunc*matrix);
plot(freq,res/max(res)+0.3)
```

Matrix expression $P_t \leftrightarrow N_\nu$

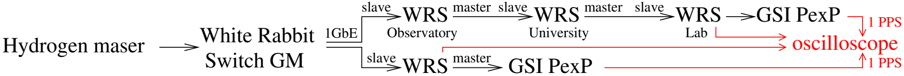


$$\begin{pmatrix} \exp(j2\pi\nu_1 t_2) & \exp(j2\pi\nu_3 t_2) & \dots & \exp(j2\pi\nu_N t_2) \\ \exp(j2\pi\nu_1 t_P) & \exp(j2\pi\nu_3 t_P) & \dots & \exp(j2\pi\nu_N t_P) \end{pmatrix}$$

2 antenna positions (times) widely separated = broad envelope

```
ttrunc=t([1:2]);
strunc=s([1:2]);
matrix=exp(-j*2*pi*ttrunc'*freq);
res=abs(strunc*matrix);
plot(freq,res/max(res)+0.4)
```

White Rabbit time and frequency distribution network




```
WR PTP Core Sync Monitor wrpc-v4.2-22-gaef35918
Esc = exit

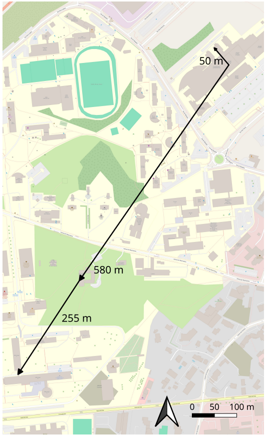
TAI Time:                 Sat, Jul 20, 2024, 07:18:01

Link status:
wru1: Link up   (RX: 1973320, TX: 1094084) IPv4: BOOTP running
Mode: WR Slave   Locked Calibrated

PTP status: slave

Synchronization status:
Servo state:              TRACK_PHASE
Phase tracking:           ON
Aux clock 0 status:       enabled

Timing parameters:
Round-trip time (mu):           820100 ps
Master-slave delay:             392455 ps
Master PHY delays:        TX:   237542 ps, RX:    278370 ps
Slave PHY delays:         TX:        0 ps, RX:      5600 ps
Total link asymmetry:            35190 ps
Cable rtt delay:                298588 ps
Clock offset:                        0 ps
Phase setpoint:                   7308 ps
Skew:                               -3 ps
Update counter:                 327620
```




```
WR PTP Core Sync Monitor wrpc-v4.2-22-gaef35918
Esc = exit

TAI Time:                 Sat, Jul 20, 2024, 07:17:54

Link status:
wru1: Link up   (RX: 15486795, TX: 8270745) IPv4: BOOTP running
Mode: WR Slave   Locked Calibrated

PTP status: slave

Synchronization status:
Servo state:              TRACK_PHASE
Phase tracking:           ON
Aux clock 0 status:       enabled

Timing parameters:
Round-trip time (mu):         10647690 ps
Master-slave delay:            5308217 ps
Master PHY delays:        TX:   237333 ps, RX:    277145 ps
Slave PHY delays:         TX:        0 ps, RX:      7200 ps
Total link asymmetry:            31256 ps
Cable rtt delay:              10126012 ps
Clock offset:                       -1 ps
Phase setpoint:                   3118 ps
Skew:                               -1 ps
Update counter:                2570755
```

800 ns @ 200 m/μs = 80 m$\times$2 ; 10650 ns @ 200 m/μs = 1065 m$\times$2 ;

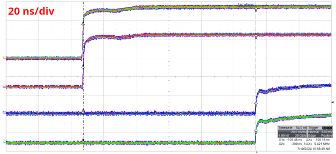
Multistatic passive RADAR implementation

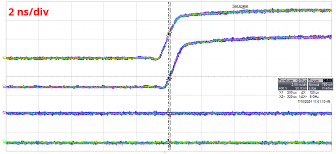
- Two X310 fitted with BasicRX receivers ...
- ... sampling at 200 MS/s so baseband signal from -100 to +100 MHz
- $\Rightarrow$ alias GRAVES from 143.05 MHz to $200 - 143.05 = 56.95$ MHz to avoid LO synchronization
- LO set to 56.95 MHz and decimate until we reach targeted sampling rate
- Doppler shift induced my moving target:

$$\delta f_{Hz} = 2 f_0 \frac{v}{c} \simeq v_{m/s}$$

since $f = 143.05$ MHz $\Rightarrow 2f/c \simeq 1$

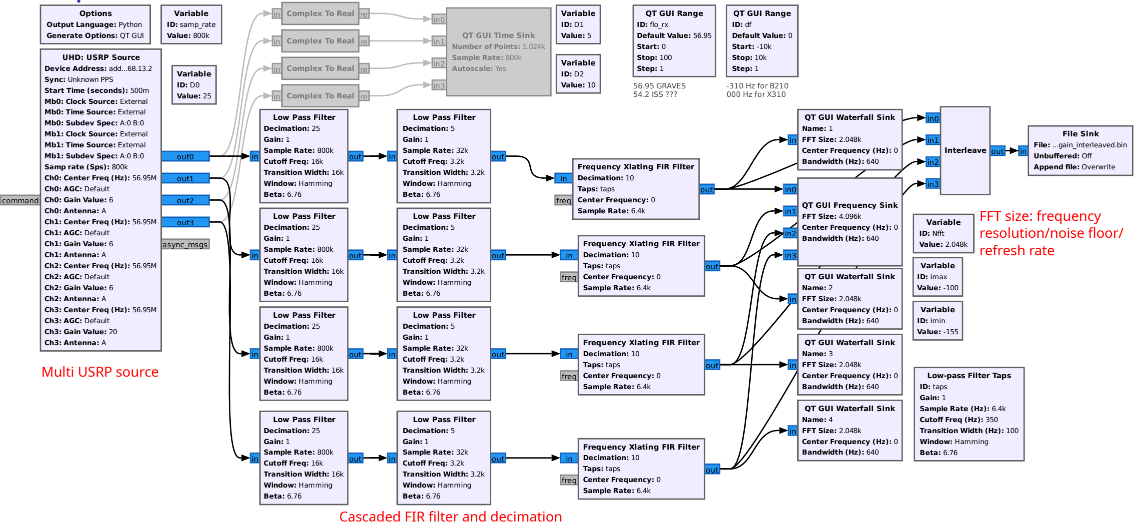
- plane flying at ≤ 1000 km/h induces a Doppler shift $\leq 1000/3.6 = 280$ Hz
- Decimate (cascade of FIR) until the sampling rate reaches ≤ 560 S/s





White Rabbit synchronization: 143.05 MHz period (360°) is 7 ns $\Rightarrow$ 60 ps is 3°
$\Rightarrow$ long baseline antenna array requires compensating for electromagnetic communication delay (200 m/μs)

Acquisition and decimation



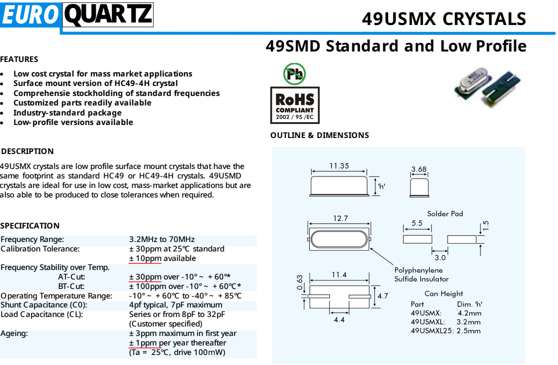
GRAVES beam sweep rate: $1/0.8$ s$=1.25$ Hz $\Rightarrow$ sampling rate $\propto 512\times 1.25=640$ S/s $\Rightarrow$ `factor(640)=`$2^7\times 5$

X310 sampling rate $\propto 200/N$, $N\in\mathbb{N}\Rightarrow$ `factor(200E6)=`$2^9\times 5^8\Rightarrow 200\cdot 10^6/(2\cdot 5^3)=0.8$ MS/s $=640\times 1250$

Decimate by 25, 5 and 10 with transition widths leading to $\simeq 64$ taps: $3\times 64=192$ multiplications/sample

Distant X310 synchronization: use of White Rabbit

- Need for a high quality local oscillator : 10 m/s @ 143.05 MHz is 9.5 Hz Doppler shift or 0.07 ppm.
- Typical low cost quartz resonator ↓: accuracy ±10 ppm, temperature stability ±30 ppm, aging 1 ppm/year (143 Hz !)
- ADC synchronized on hydrogen maser clocking WR grand master and disseminating 1 PPS and 10 MHz to slaves
- Classical setup: dedicated White Rabbit Switch (WRS) running opensource CERN gateware and firmware
- Here: **GSI supplied** dedicated PCIe boards with 10 MHz and 1 PPS output on GPIOs


EUROQUARTZ

49USMX CRYSTALS

49SMD Standard and Low Profile

FEATURES

- Low cost crystal for mass market applications
- Surface mount version of HC49-4H crystal
- Comprehensive stockholding of standard frequencies
- Customized parts readily available
- Industry-standard package
- Low-profile versions available

RoHS COMPLIANT 2002 / 95 /EC

OUTLINE & DIMENSIONS

11.35 'h' 3.68 12.7 Solder Pad 5.5 1.5 3.0 Polyphenylene Sulfide Insulator 0.63 11.4 4.7 4.4

Can Height

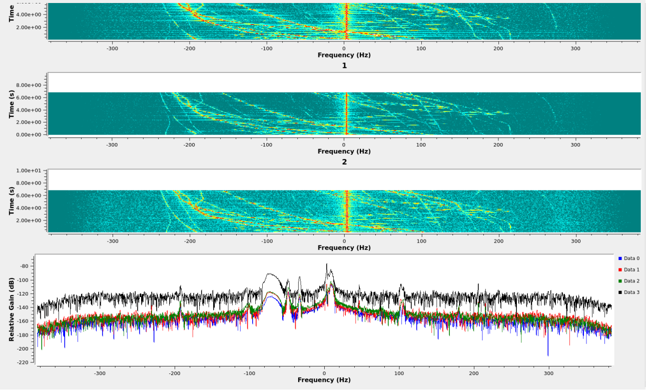
Part	Dim. 'h'
49USMX:	4.2mm
49USMXL:	3.2mm
49USMXL25:	2.5mm

DESCRIPTION

49USMX crystals are low profile surface mount crystals that have the same footprint as standard HC49 or HC49-4H crystals. 49USMD crystals are ideal for use in low cost, mass-market applications but are also able to be produced to close tolerances when required.

SPECIFICATION

Frequency Range:	3.2MHz to 70MHz
Calibration Tolerance:	± 30ppm at 25°C standard ± 10ppm available
Frequency Stability over Temp.	
AT-Cut:	± 30ppm over -10° ~ +60°*
BT-Cut:	± 100ppm over -10° ~ +60°C*
Operating Temperature Range:	-10° ~ +60°C to -40° ~ +85°C
Shunt Capacitance (C0):	4pf typical, 7pF maximum
Load Capacitance (CL):	Series or from 8pF to 32pF (Customer specified)
Ageing:	± 3ppm maximum in first year ± 1ppm per year thereafter (Ta = 25°C, drive 100mW)



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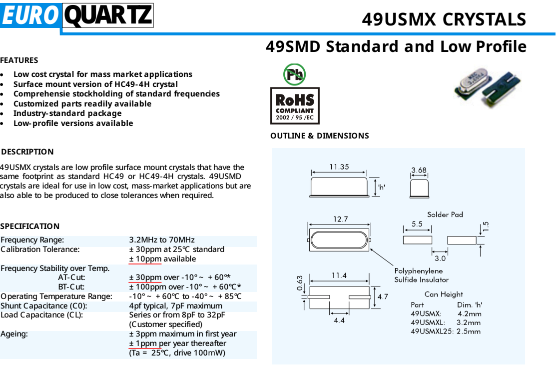
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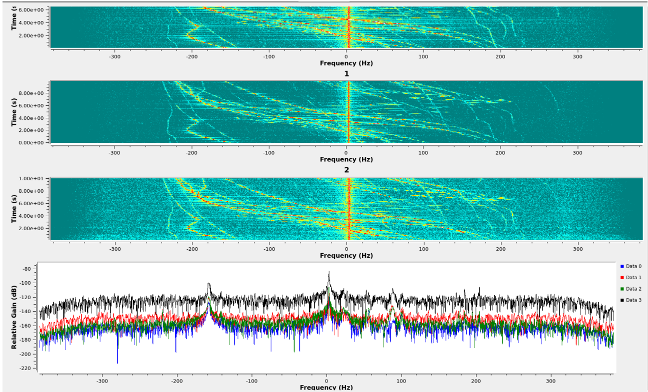
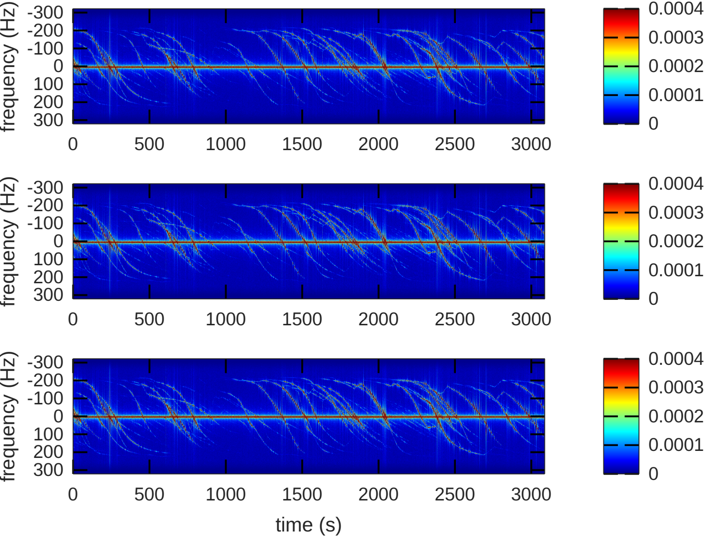


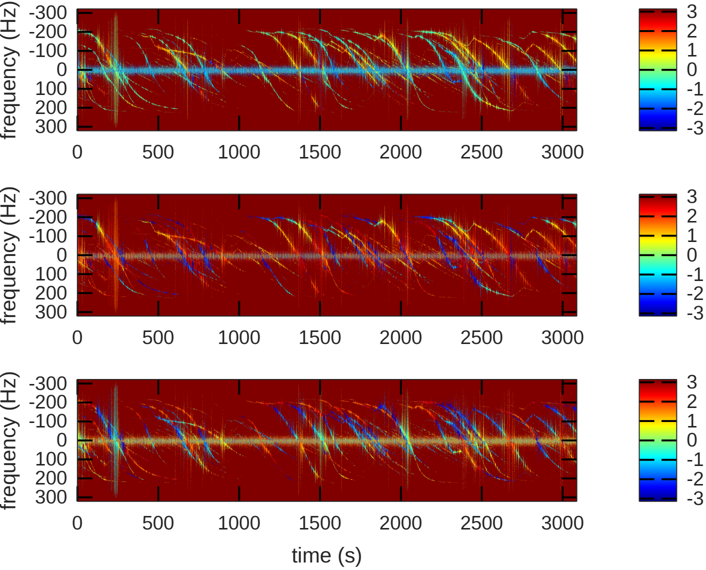
Results: magnitude



GNU Octave processing: short-term FFT

```
fs=640;
x=read_complex_binary('file.bin');
x1=x(1:4:end);
x4=x(4:4:end);
x3=x(3:4:end);
x2=x(2:4:end);
freq=linspace(-fs/2,fs/2-fs/length(x2),length(x2));
N=256;
P=32;
res1=zeros(N,floor(length(x1)/N));  % pre-allocate memory
res2=zeros(N,floor(length(x1)/N));
res3=zeros(N,floor(length(x1)/N));
res4=zeros(N,floor(length(x1)/N));
w=hamming(2*P);
window=[w(1:P) ; ones(N-2*P,1) ; w(P+1:end)]
m=1
for k=1:N:length(x2)-N
   res2(:,m)=fftshift(fft(x2(k:k+N-1))).*window;
   res3(:,m)=fftshift(fft(x3(k:k+N-1))).*window;
   res4(:,m)=fftshift(fft(x4(k:k+N-1))).*window;
   res1(:,m)=fftshift(fft(x1(k:k+N-1))).*window;
         m=m+1;
end
imagesc([0:length(res2)-1]*N/fs,freq,abs(res1),[0 0.0004]);
```

Results: phase difference between antennas



Direction of arrival

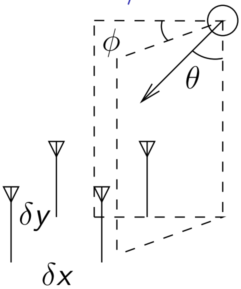
```
thres=0.0001;
k=find(abs(res2)<seuil); res2(k)=NaN;
k=find(abs(res3)<seuil); res3(k)=NaN;
res1(k)=NaN; res4(k)=NaN;
resph=angle(res2.*conj(res1));  % res2/res1 -> phi2-phi1
imagesc([0:length(res2)-1]*N/fs,freq,resph,[-pi pi])
```

$\Rightarrow$ phase evolution from $-\pi$ to $+\pi$

Usage case 1: 2D array for azimuth/elevation

Position seen from the array:

$$\begin{pmatrix} k\cos\theta\cos\phi \\ k\cos\theta\sin\phi \\ k\sin\theta \end{pmatrix} \cdot \begin{pmatrix} \delta x \\ \delta y \\ \delta z = 0 \end{pmatrix}$$

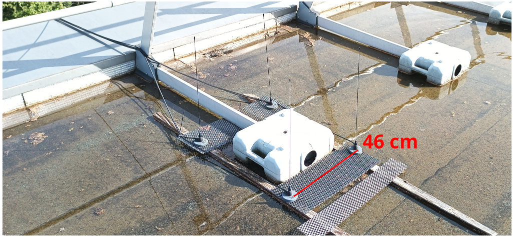


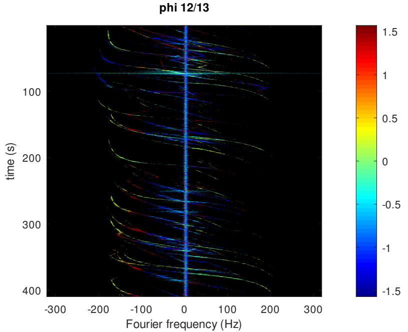
$\Rightarrow$ observed phase differences are

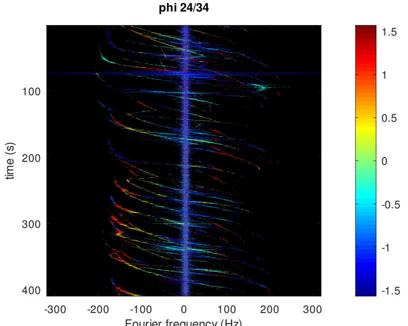
$$\begin{cases} \varphi_{12} = \frac{2\pi}{\lambda}\delta x \cdot \cos\theta\cos\phi \\ \varphi_{13} = \frac{2\pi}{\lambda}\delta y \cdot \cos\theta\sin\phi \end{cases}$$

Since $\delta x = \delta y = \frac{\lambda}{2}$:

$$\begin{cases} \tan\phi & = & \varphi_{12}/\varphi_{13} \\ \pi^2\cos^2\theta & = & \varphi_{12}^2 + \varphi_{13}^2 \end{cases}$$







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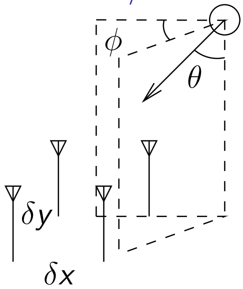
Position seen from the array:

$$\begin{pmatrix} k\cos\theta\cos\phi \\ k\cos\theta\sin\phi \\ k\sin\theta \end{pmatrix} \cdot \begin{pmatrix} \delta x \\ \delta y \\ \delta z = 0 \end{pmatrix}$$

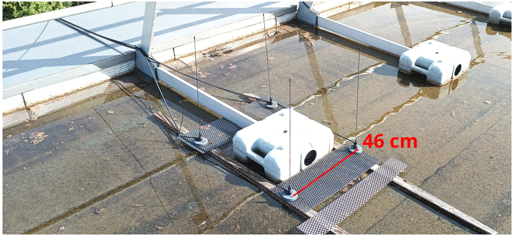


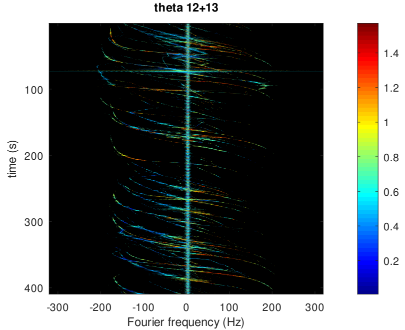
$\Rightarrow$ observed phase differences are

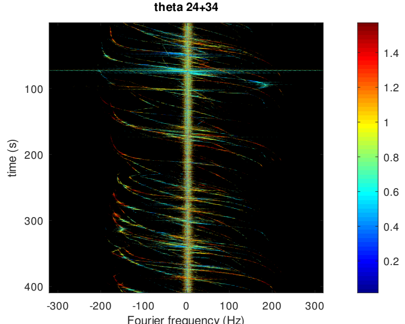
$$\begin{cases} \varphi_{12} = \frac{2\pi}{\lambda}\delta x \cdot \cos\theta\cos\phi \\ \varphi_{13} = \frac{2\pi}{\lambda}\delta y \cdot \cos\theta\sin\phi \end{cases}$$

Since $\delta x = \delta y = \frac{\lambda}{2}$:

$$\begin{cases} \tan\phi = \varphi_{12}/\varphi_{13} \\ \pi^2\cos^2\theta = \varphi_{12}^2 + \varphi_{13}^2 \end{cases}$$

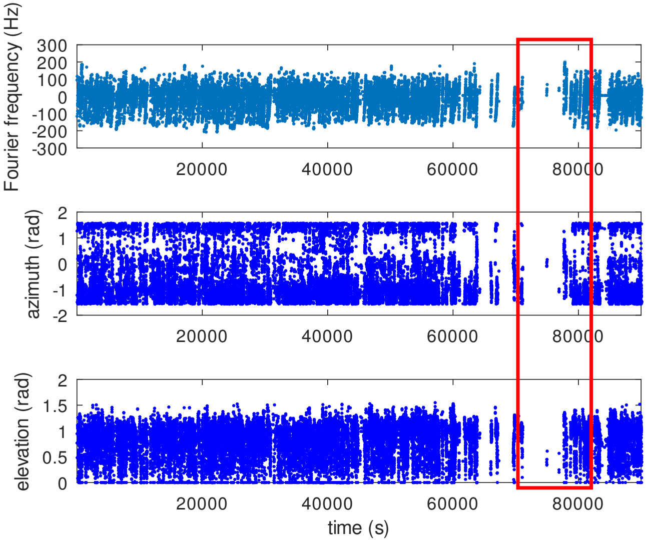






Usage case 1: 2D array for azimuth/elevation

- Excess information: most pixels are noise after FFT to identify Doppler shift induced by plane motion
- Threshold to select relevant information on each antenna (strongest echo)
- Extract azimuth elevation for these Doppler shifts (FFT index) only



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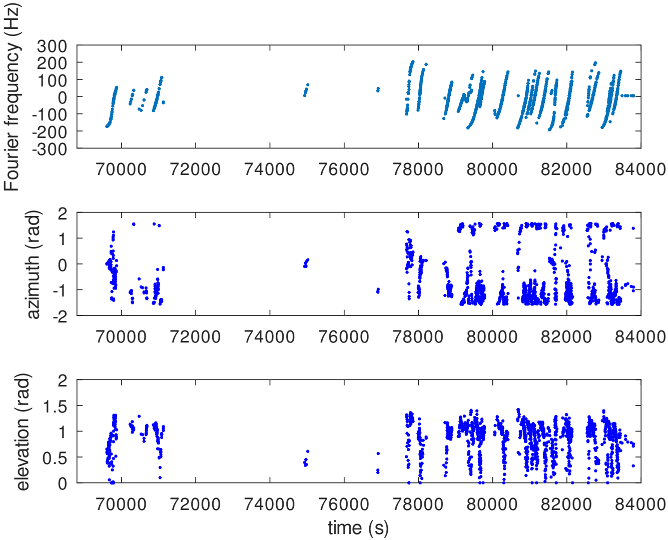
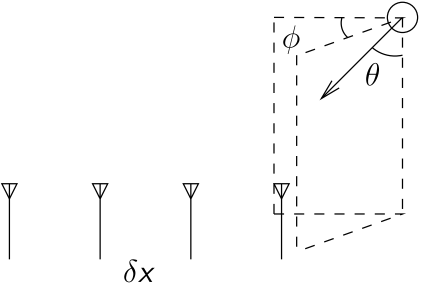


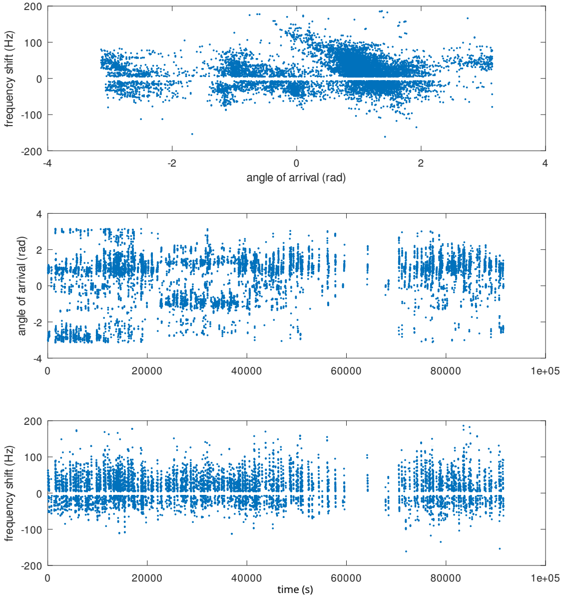
Usage case 2: uniform 1D linear array

Higher resolution direction of arrival



Phase at nth antenna: $\varphi_n = n \cdot k \cdot \delta x \sin\theta \cos\phi$

ULA: benefit from the $N \log(N)$ complexity FFT rather than N^2 matrix multiplication



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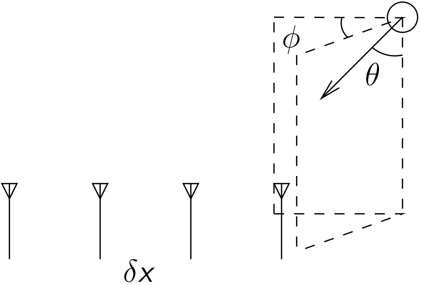

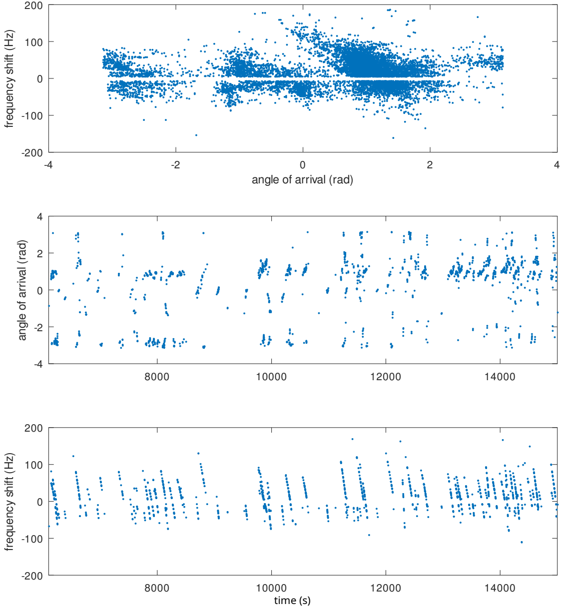

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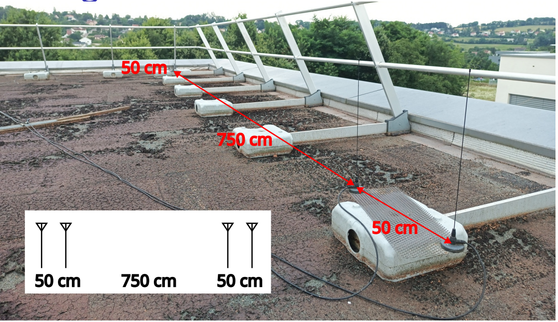

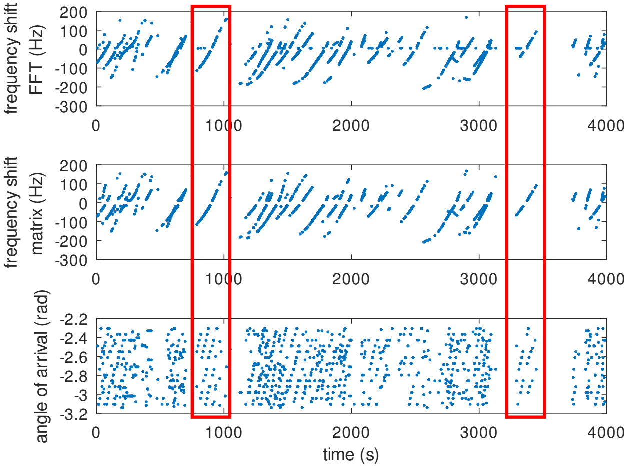

2D non-uniform FFT: two orthogonal FFTs expressed as $M_1 \cdot s \cdot M_2^t$ where M_1 is along time (frequency) and M_2 along space (wavevector)

$t \rightarrow f \stackrel{\text{def}}{=} 1/t$:

```
freq=linspace(-fs/2,fs/2-fs/N,N); t=[0:N-1]/fs;
matrix=exp(-j*2*pi*t'*freq);
```

$x \rightarrow k \stackrel{\text{def}}{=} 1/x$

```
x=[0 0.5 8 8.5]; fc=143.05; lambda=300/fc; dx=lambda/10;
k=linspace(-1/dx,1/dx,P);
matriy=exp(-j*2*pi*x'*k);
```

map: concatenation of time-measurements at each antenna ($4 \times N$)

```
result=abs(fftshift((matrix*map)*matriy,1));
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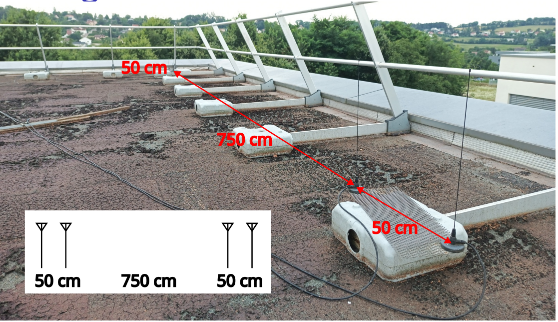

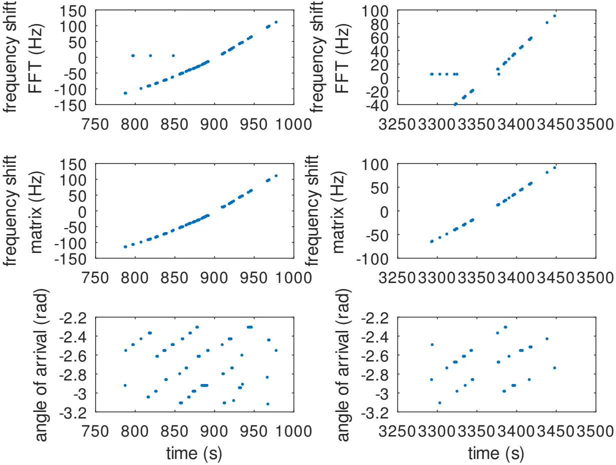

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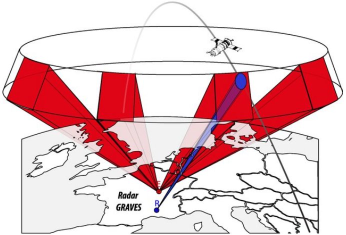
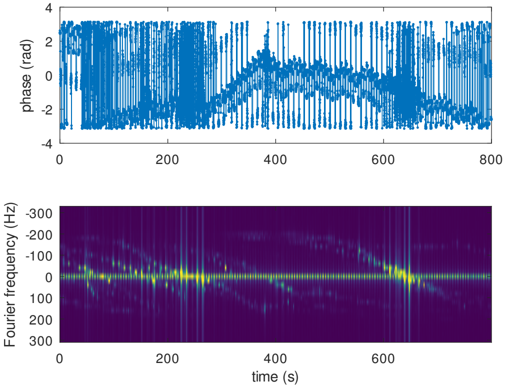
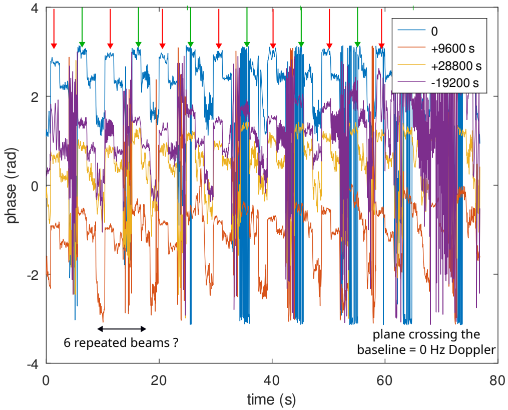
Frequency stability of GRAVES?



- Recording the aliased $200 - 143.05 = 56.95$ MHz … but still a remaining 19.18 Hz despite clocking the X310 with a hydrogen maser compared to the primary reference in Paris Observatory ($\Delta f/f < 10^{-13}$) see [2]
- Electronically steered beam to sweep the sky with the CW
- … need to extract each individual beam and observe phase evolution.





[2] Github issue `https://github.com/EttusResearch/uhd/issues/763`

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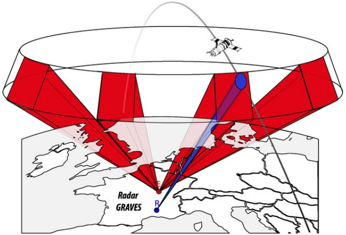

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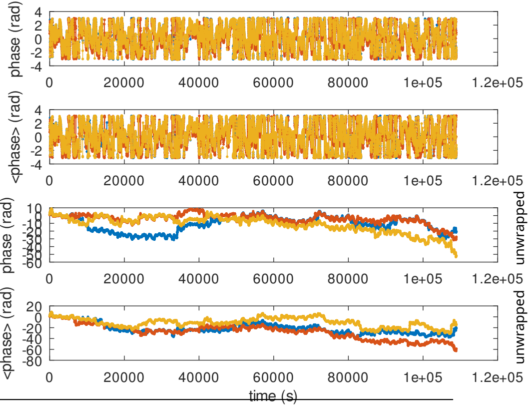

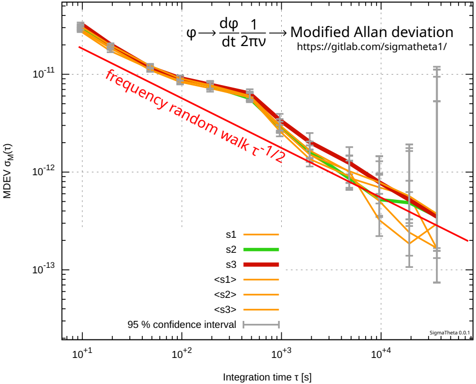

[2] A. Jouade & A. Barka, *Massively Parallel Implementation of FETI-2LM Methods for the Simulation of the Sparse Receiving Array Evolution of the GRAVES Radar System for Space Surveillance and Tracking*, IEEE Access (2019)

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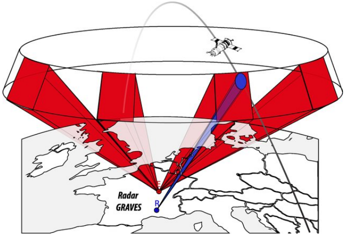

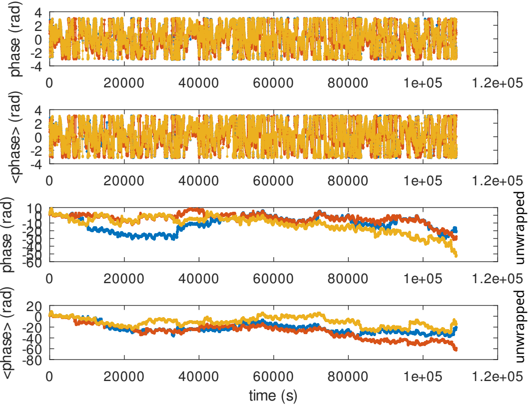

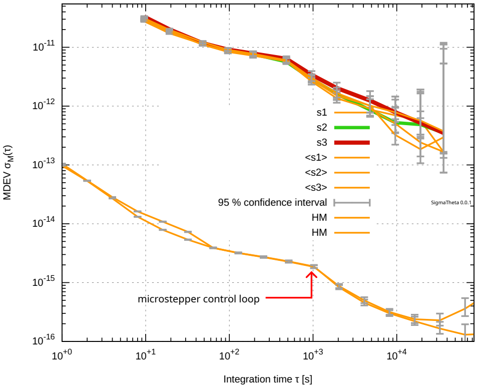

Conclusion

1. Distributed SDR system synchronized with White Rabbit [2] (PTP High Accuracy profile)
2. General framework for passive, distributed RADAR system with direction of arrival analysis ...
3. ... 1D (high resolution azimuth) or 2D (azimuth/elevation), whatever the antenna distribution
4. Demonstrated with moving (plane) targets.
5. Estimate of the frequency stability of each beam ... notice that phase varying from beam to beam does not prevent DoA (relative measurement between antennas, irrelevant of the broadcast signal) ...
6. ... with a stability ($\tau^{-1/2}$) probably limited by the link (10^{-10} @ 1 s)

Additional information

- White Rabbit only generates 1 PPS and 10 MHz: fine with X310, but what about other frequencies?
- Network clock distribution chip: AD9548 ... or generating all RF signals from the WR FPGA [3]

> Long term vision: integrate White Rabbit PTP Core (`wrpc`) as SDR feature with no need for external VCXO, only requiring GbE SFP input for synchronization [4]

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[2] D. Beck, *FAIR from the Control System Perspective*, 13th WR Workshop (2024)

[3] `https://www.white-rabbit.tech/rf-over-wr-cern/`

[4] F. Pfautsch & U. Langenbach, *Light Rabbit: Implementing a White Rabbit node on COTS AMD development boards without relying on external VCXOs*, 13th WR Workshop (2024)