Software Defined Radio for Time and Frequency applications: Example of Passive Monitoring of TWSTFT & Other Timing Signals

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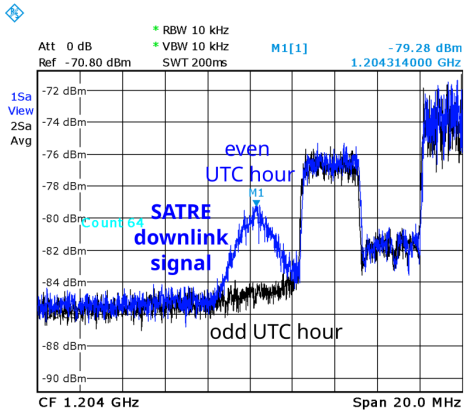
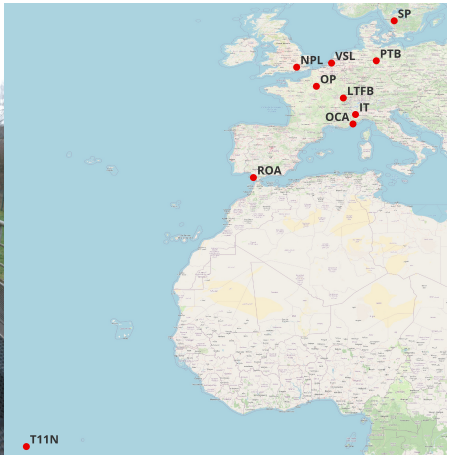
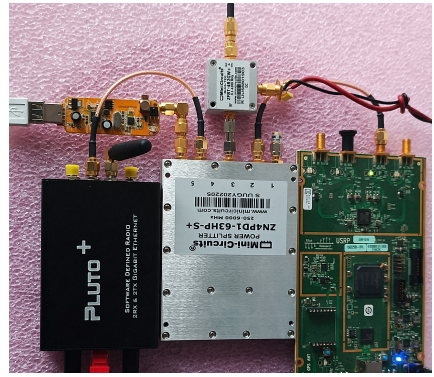


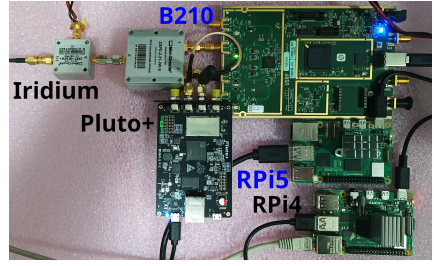


Outline

- Definition of the Software Defined Radio (SDR) paradigm
- Usage example: Two Way Satellite Time & Frequency Transfer (TWSTFT) for one-way time and frequency dissemination
- Usage example: Global Navigation Satellite Systems (`gnss-sdr`) for 1-PPS generation
- Challenges and issues

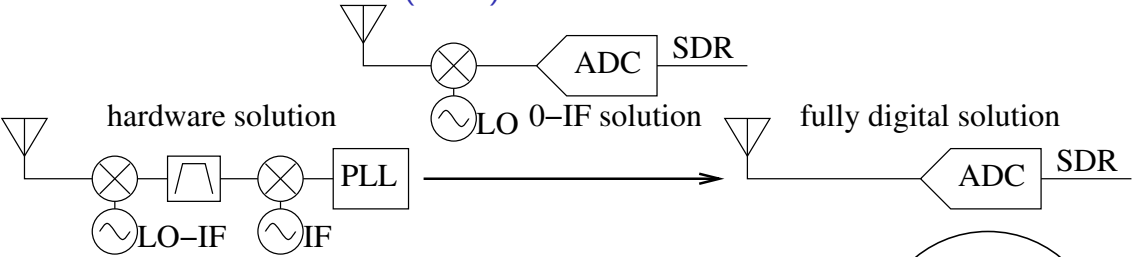
SDR at the convergence of powerful computing platforms, fast sampling and communication interfaces + flexible and accessible software libraries





1. J.-M Friedt, *À l'écoute des messages transmis par satellite en orbite basse : Iridium*, MISC Hors Série 29 (2024)
2. J.-M Friedt, *RADAR passif bistatique au moyen d'une Raspberry Pi4, d'une radio logicielle et du satellite Sentinel-1*, Hackable **41** pp.108–130 (Mar.-Apr. 2022)
3. 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), pp.221- (2022)
4. W. Feng, J.-M Friedt, *SDR Implemented Ground-based Interferometric Radar for Displacement Measurement*, IEEE Trans. on Instrumentation and Measurement **70**, 8502218 (2021)
5. J.-M Friedt, *Décodage par radio logicielle du VOR pour le positionnement sans GPS*, Hackable **36** (Jan.-Feb.-Mar. 2021)
6. 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
7. J.-M Friedt, W. Feng, *Analyse et réalisation d'un RADAR à synthèse d'ouverture (SAR) par radio logicielle*, GNU/Linux Magazine France 240, 242, 244 (2020)
8. J.-M. Friedt, W. Feng, *Anti-leurrage et anti-brouillage de GPS par réseau d'antennes*, MISC 110 (Jul.-Aug. 2020)
9. J.-M Friedt, *Décodage d'images numériques issues de satellites météorologiques en orbite basse : le protocole LRPT de Meteor-M2*, GNU Linux Magazine France (226, 227, 228) (2019)
10. J.-M Friedt, *RADAR passif par intercorrélation de signaux acquis par deux récepteurs de télévision numérique terrestre*, GNU/Linux Magazine France 212 pp.36- (Feb. 2018)

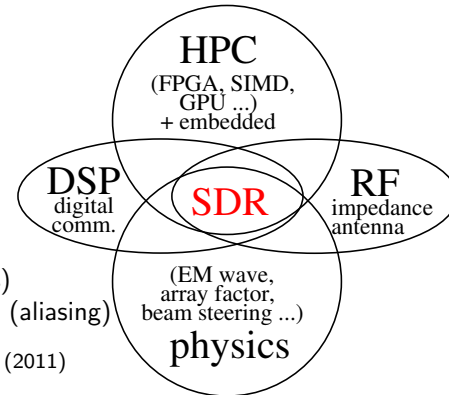
Software Defined Radio (SDR)



- Get rid of unstable and irreproducible analog components
- Sample as close as possible to the radiofrequency signal (digitize)
- All processing performed as software, removing hardware dependence

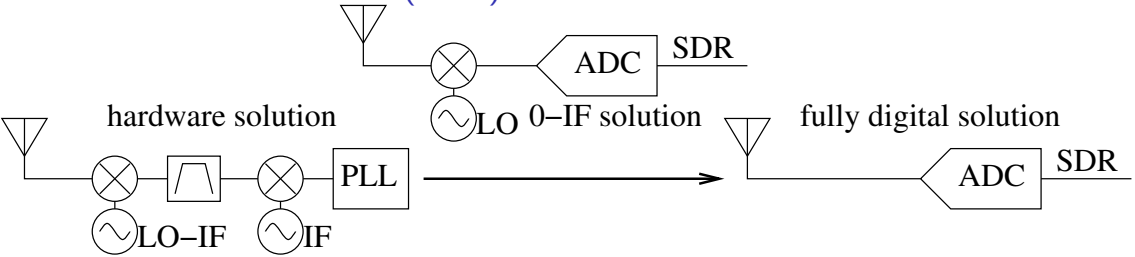
$\Rightarrow$[a]
- stability (algorithms do not age)
- reconfigurability (on the fly parameter changes)
- flexibility (build hardware once and use for many applications)

BUT finite dynamic range (quantization) and discrete time sampling (aliasing)



[a] D.A. Mindell, *Digital Apollo: human and machine in spaceflight*, MIT Press (2011)

Software Defined Radio (SDR)



- Get rid of unstable and irreproducible analog components
- Sample as close as possible to the radiofrequency signal (digitize)
- All processing performed as software, removing hardware dependence

$\Rightarrow$ GNU Radio, the free and open-source SDR library

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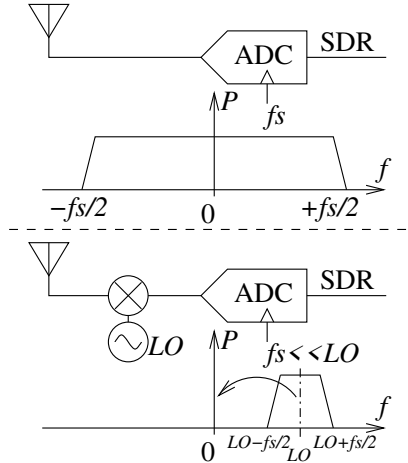
SDR: frequency transposition and IQ components

- Frequency transposition to bring the "narrowband" signal of interest without sampling from DC (removes the risk of strong interference out of band)
- SDR naturally manipulates complex numbers (Fourier transform of a real signal is even $\Rightarrow$ non-even baseband spectra require complex numbers)
- Generate I (Identity) and Q (Quadrature) real and imaginary part with an IQ mixer fed with $\cos(\omega t)$ and $\sin(\omega t)$
- Problem: IQ imbalance when I and Q components are not the same weight (amplitude) and not phase shifted by 90°



Sentinel-1 Level 1 Detailed Algorithm Definition

4.1 Raw Data Analysis

Raw data analysis is required in order to perform corrections of the I and Q channels of the raw signal data. The classical raw data correction (applied for instance in the case of ENVISAT-ASAR and RADARSAT-2) involves (see also Section 9.2):

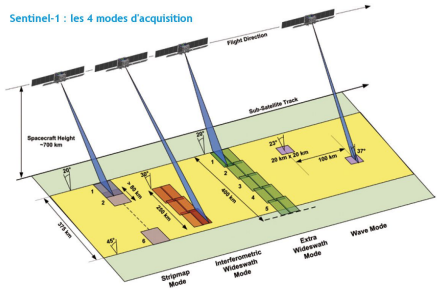
- I/Q bias removal
- I/Q gain imbalance correction
- I/Q non-orthogonality correction

For Sentinel-1 however, the instrument's receive module performs the demodulation in the digital domain, therefore the I/Q gain imbalance and I/Q non-orthogonality corrections are no longer necessary.

The raw data analysis necessary for the raw data correction of ASAR data is defined in [R-6]. Since the IPF also supports the processing of ASAR data, for completeness, the ASAR raw data analysis scheme is reproduced in this section.

Even though for Sentinel-1 the I/Q gain imbalance and the I/Q non-orthogonality corrections are not necessary, they will be made available optionally, using configuration input parameters. Irrespective to the correction flag though, the Raw Data Analysis described in this section will be performed and the results reported for both ASAR and Sentinel-1 data.

Sentinel-1 : les 4 modes d'acquisition



SDR usage example: ESA Sentinel-1

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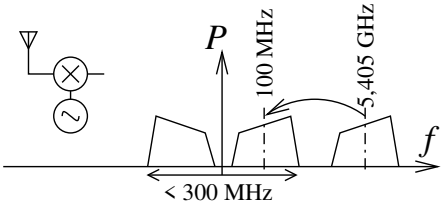
Even though for Sentinel-1 the I/Q gain imbalance and the I/Q non-orthogonality corrections are not necessary, they will be made available optionally, using

- First frequency transposition: 5.405 GHz $\rightarrow$ 100 MHz with a single real mixer fed with a local oscillator at 5.305 MHz
- Real value sampled at 300 MS/s: even spectrum ranging $\pm$150 MHz
- Second "perfect" digital transposition to bring the signal to baseband:

```
t=[0:number_of_samples-1]/fs;
lo=exp(j*2*pi*freq*t);
res=signal.*lo;
```

- digital `lo` is "perfectly" in quadrature and both components with same amplitude



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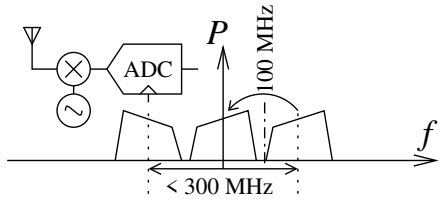


TWSTFT signals for one-way dissemination

- Metrology Institutes broadcast every even UTC hours signals for clock comparison
- Transatlantic + European comparison through a geostationnary satellite, Telstar11N (37.5° W)
- Downlink frequency: see
  `https://webtai.bipm.org/ftp/pub/tai/data/2024/time_transfer/twstft/`

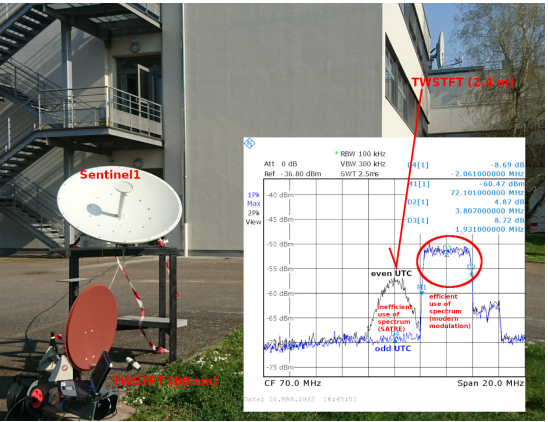
```
* LAB       OP
* REV DATE  2023-08-14
* ES   OP01 LA: N  48 50 09.236      LO: E  02 20 05.873   HT:    78.00 m
* REF-FRAME ITRF88
* LINK   23 SAT: TELSTAR 11N         NLO: E 322 27 00.000  XPNDR: 999999999 ns
*           SAT-NTX: 10953.9500 MHz  SAT-NRX: 14253.9500 MHz  BW:   4.1 MHz
* LINK   21 SAT: TELSTAR 11N         NLO: E 322 27 00.000  XPNDR: 999999999 ns
*           SAT-NTX: 11497.0600 MHz  SAT-NRX: 14047.7400 MHz  BW:   3.9 MHz
```

- 10.95395 GHz is well above most COTS SDR: frequency transposition using TV reception LNB (9.75 GHz)
- One way time transfer requires **compensating for** relay satellite motion (± 30 km $= \pm 100$ μs)

$\Rightarrow$ use the emitter known position (**spatial diversity**) to identify the satellite position in space [1]

[1] J.-M Friedt, *Passive reception of Two-Way Satellite Time and Frequency Transfer (TWSTFT) signals from a geostationary satellite, or GPS upside down*, GNU Radio Conference (2022) at `https://pubs.gnuradio.org/index.php/grcon/article/view/131` and video at `https://www.youtube.com/watch?v=gHNQUVdCBZw`

TWSTFT signals for one-way dissemination

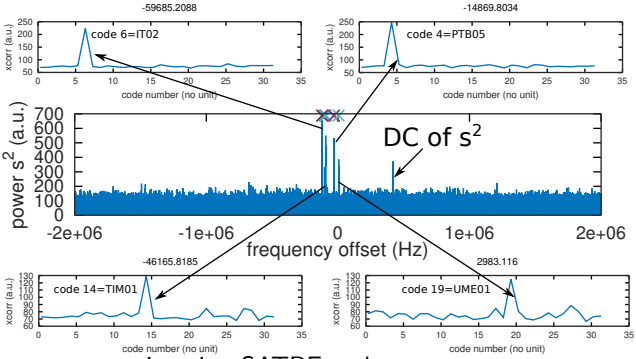


Experimental setup: COTS TV receiving equipment and B210 (AD9361 LO$\in$ [70 : 6000] MHz) SDR receiver

- TV-satellite reception LNB oscillator at 9.75 GHz ...
- ... brings TWSTFT signal at 1.21 GHz within SDR receiver range, recorded at 10 MS/s (complex IQ)

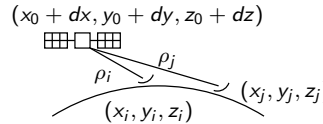
after correcting for coarse 4 MHz LO offset @ 11 GHz (LNB) downlink frequency

- Time & frequency synchronization signals broadcast every even UTC hour from metrology laboratories
- BPSK signal received (carrier offset detected by squaring) allowing for frequency correction ...
- ... and SATRE modem codes correlated with consistent frequency offset



See `https://github.com/oscimp/gr-satre` for reverse engineering SATRE codes

Case of the flying satellite: TWSTFT measurements



- Problem[2]: SATRE modem only allows **two** remote station recording (TX, RX) + ranging

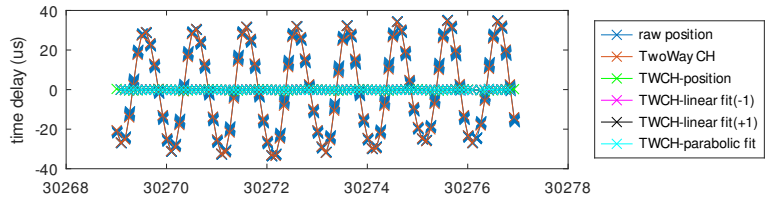
```
MJD-30000    TX RX     TWSTFT          MJD-30000    TX RX     TWSTFT
30269.008750 0  2  0.262574433740    30269.004583 7  7  0.263385893418
30269.008750 2  0  0.262560214541
30269.008750 3  5  0.258320951287
30269.008750 4  6  0.267146103376
30269.008750 5  3  0.258321274787
30269.008750 6  4  0.267146198976
30269.010833 0  6  0.263450368676
30269.010833 1  5  0.264703887898
30269.010833 2  4  0.266271014767
30269.010833 4  2  0.266271049438
30269.010833 5  1  0.264703726492
30269.010833 6  0  0.263436279669    30269.025417 7  3  0.258673786481
                                     30269.031667 7  5  0.263042528946
                                     30269.037917 7  2  0.263074586173
```

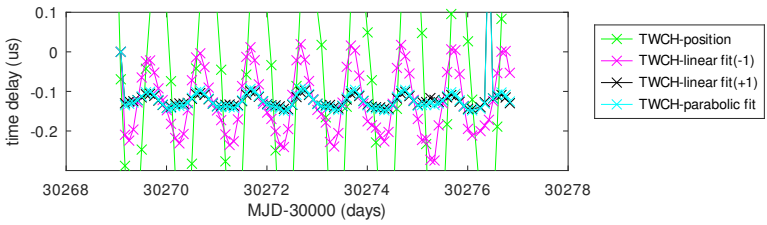
$\Rightarrow$ **using** the satellite position for estimating the delay to a third station requires interpolation

[2] `https://webtai.bipm.org/ftp/pub/tai/data/2024/time_transfer/twstft/`

Case of the flying satellite: TWSTFT measurements

TWSTFT fitted (least square optimal solution) satellite position from OP, NPL, PTB, ROA, SP, VSL



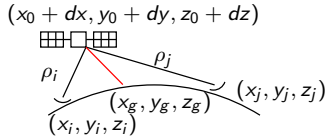


Standard deviation on the residual is

- 0.08 μs when interpolating with the previous sample recorded about 2 h before the current measurement,
- 0.05 μs when interpolating with the next sample recorded a few minutes after the current measurement,
- 0.048 μs when using a parabolic fit

↗ Residue to CH after removal of the satellite position contribution (no orbital model)

Case of the passive observation of TWSTFT signals using SDR



- At any given time, we receive all broadcasting stations (**no** interpolation)
- **Record** and **post-process**: no constraint with computational power
- As opposed to TWSTFT recordings, we observe time of flight **differences**
- $\Rightarrow$ **cancellation** of the satellite to passive ground station and satellite internal delay contributions (calibration?)
- linearized range with unknown (dx, dy, dz) satellite position close to parking position[3] (x_0, y_0, z_0):
- the red part $\nearrow$ including receiver delay and satellite transponder delay cancels

$$\underbrace{c \times (t_i - t_{ref})}_{\text{observation}} \simeq \rho_i + \frac{x_0 - x_i}{\rho_i} dx + \frac{y_0 - y_i}{\rho_i} dy + \frac{z_0 - z_i}{\rho_i} dz - \rho_{ref} - \frac{x_0 - x_{ref}}{\rho_{ref}} dx - \frac{y_0 - y_{ref}}{\rho_{ref}} dy - \frac{z_0 - z_{ref}}{\rho_{ref}} dz$$

If we consider the emitters affected by unknown time delays t_{TXi} then

$$c(t_i - t_{ref}) - \rho_i + \rho_{ref} \simeq \left(\frac{x_0 - x_i}{\rho_i} - \frac{x_0 - x_{ref}}{\rho_{ref}}\right) dx + \left(\frac{y_0 - y_i}{\rho_i} - \frac{y_0 - y_{ref}}{\rho_{ref}}\right) dy + \left(\frac{z_0 - z_i}{\rho_i} - \frac{z_0 - z_{ref}}{\rho_{ref}}\right) dz \underbrace{- c t_{TXi} + c t_{TXref}}_{c t_{i-ref}}$$

[3] https://gssc.esa.int/navipedia/GNSS_Book/ESA_GNSS-Book_TM-23_Vol_I.pdf page 152

Case of the passive observation of TWSTFT signals using SDR

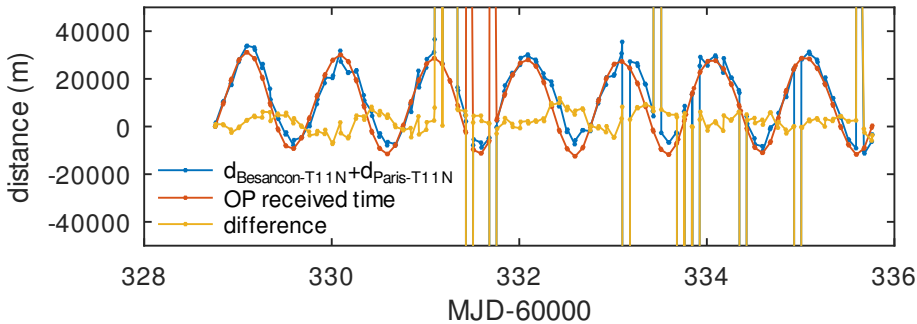
- **Problem**: SATRE modem Pulse Repetition Interval (PRI) is 4 ms ⇒ possible mistake by multiples of 4 ms: $(\rho_{OP} - \rho_i)/c =$

OP-OP=	0
OP-NPL=	-0.192
OP-VSL=	-1.066
OP-SP=	-3.708
OP-PTB=	-2.170
OP-IT=	-0.158
OP-ROA=	4.205

vs observations

OP-OP=	0	correction
OP-NPL=	3.737	-4 ms
OP-VSL=	2.922	-4 ms
OP-SP=	0.303	-4 ms
OP-PTB=	1.825	-4 ms
OP-IT=	3.840	-4 ms
OP-ROA=	0.223	+4 ms

- 4 s long records = 1000 measurements/session
- Only keep measurements when all stations are broadcasting (min 11 & min 20 of even UTC)



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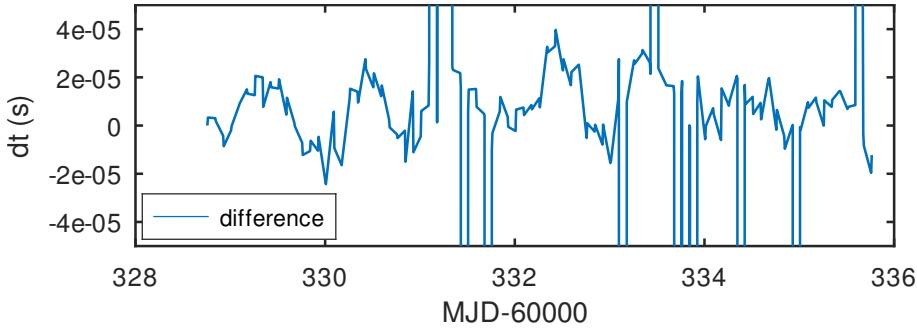
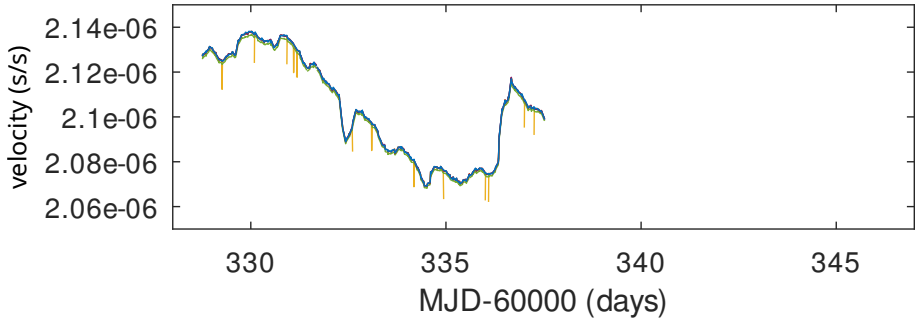


Adding some assumption on satellite kinematics [4]

- So far all position estimates are individual from each other
- Add the assumption that position is velocity integrated and that minimal external acceleration disturbances will affect velocity
- Projected velocity observed as time of flight drift within each session **but** frequency measurement is mixed with **local oscillator frequency offset** (= inaccurate sampling rate)
- target ±5 ns/s=5 ppb **but** quartz oscillator is already 2 ppm off and fluctuating with environment



[4] See C. Rieck, P.Jarlemark & K. Jaldehag, *Utilizing TWSTFT in a passive configuration*, Proc. 48th Annual Precise Time and Time Interval Systems and Applications Meeting (2017)

Velocity measurement through SDR

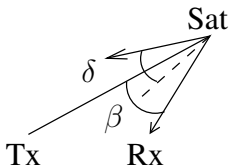
- Velocity through Doppler: need for a stable frequency reference ⇒ replace quartz oscillator with hydrogen maser
- Satellite transponder (14 GHz uplink →11 GHz downlink) is not stable, use **code drift** for velocity estimate (≃ns/s)
- Bistatic velocity induced Doppler shift: from bistatic RADAR Doppler shift [5] measurement:

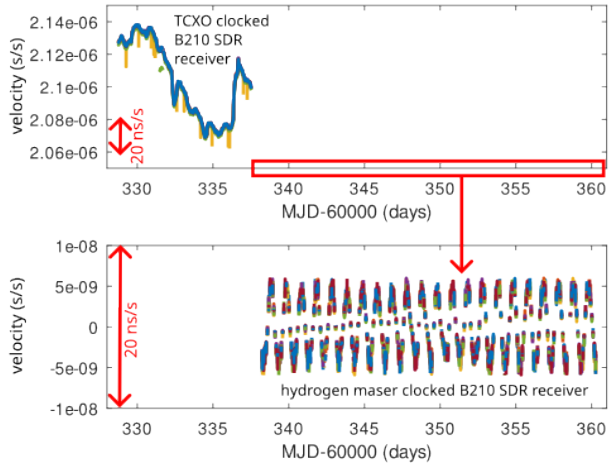
$$\delta f = (f_{up} + f_{down})\frac{v}{c}\cos(\delta)\cos(\beta/2)$$

with $\beta \simeq cst$ and δ varying with satellite position and motion direction

- $\cos(\beta) = \frac{\rho^2_{TX-SAT} + \rho^2_{RX-SAT} - d^2_{TX-RX}}{2 \times \rho_{TX-SAT} \cdot \rho_{RX-SAT}}$

$\beta_{OP-NPL} = 0.49°$
$\beta_{OP-VSL} = 0.29°$
$\beta_{OP-SP} = 0.67°$
$\beta_{OP-PTB} = 0.34°$
$\beta_{OP-IT} = 0.85°$
$\beta_{OP-ROA} = 1.29°$
$\simeq$ monostatic configuration





[5] https://www.sto.nato.int/publications/STO%20Educational%20Notes/RTO-EN-SET-086/EN-SET-086-04.pdf, Eq. (6)

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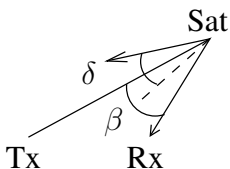
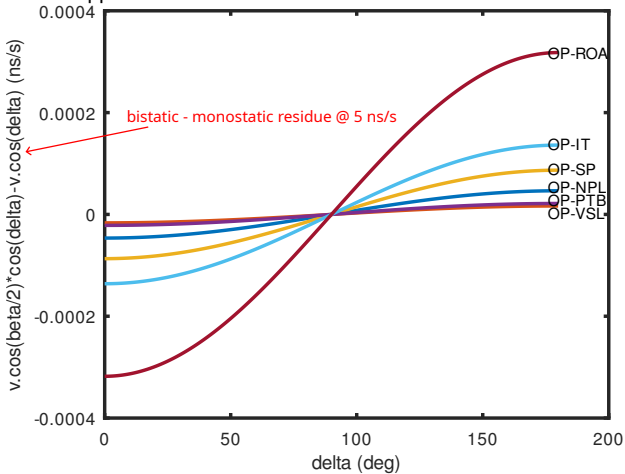
$$\delta v = |\vec{v}| \cos(\delta) \cos(\beta/2)$$

with $\beta \simeq cst$ and δ varying with satellite position and motion direction

- $\cos(\beta) = \frac{\rho^2_{TX-SAT} + \rho^2_{RX-SAT} - d^2_{TX-RX}}{2 \times \rho_{TX-SAT} \cdot \rho_{RX-SAT}}$

$\beta_{OP-NPL} = 0.49°$
$\beta_{OP-VSL} = 0.29°$
$\beta_{OP-SP} = 0.67°$
$\beta_{OP-PTB} = 0.34°$
$\beta_{OP-IT} = 0.85°$
$\beta_{OP-ROA} = 1.29°$
$\simeq$ monostatic configuration





[5] https://www.sto.nato.int/publications/STO%20Educational%20Notes/RTO-EN-SET-086/EN-SET-086-04.pdf, Eq. (6)

On the need to add celestial mechanics?

- Two celestial mechanics toolboxes for modelling space flight
  - GMAT from NASA Goddard Space Flight Center [6]
  - Orekit [7] from CS Group/Airbus Defence and Space/ESA/Thales Alenia Space...
- in both cases, challenging initialization (weight, solar pannel area, initial orbital parameters since Two-Line Elements (TLE) description is hardly suitable for geostationary satellite orbit description)
- solution can only be broadcast for a few hours in the future

  C. Rieck, P. Jarlemark & K. Jaldehag, *Passive Utilization of the TWSTFT Technique*, EFTF (2018):
  "I. Orbit perturbations
  The robust detection and mitigation of satellite orbit maneuvers are most important and can, if erroneous in a real-time scenario, cause substantial timing errors and/or downtime for a passive station. Also, the **lifetime of a published orbit is limited. Continuous active measurements are expected to always reflect the true orbit with sufficient accuracy[7]. A default window length of 1/6 orbit, i.e. 4h**, is chosen to dynamically describe the orbit with rapid updates. If the orbit defining measurements are temporary sparse, it may however be important to include orbit perturbation models to aid the orbit determination. "
- station keeping manœuvers (chemical thrusters)/continuous station keeping (electrical thrusters)
- consider these manœuvers around the parking position as acceleration perturbations?
- try tuning the orbital parameters until they match observations and then propagate... work in progress [8]

[6] `https://opensource.gsfc.nasa.gov/projects/GMAT/index.php`
[7] `https://www.orekit.org/`
[8] `https://github.com/jmfriedt/orekit_orbit_determination`

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L. Hu & al., *Geostationary orbit determination using SATRE*, Advances in Space Research **48** 923-–932 (2011)
"3. Orbit determination methodology
A post-process statistical orbit determination method with Batch-least-square filter has been used. The orbit determination is **conducted for every three successive days**, and the parameters to be estimated include six orbit elements at the origin epoch, solar radiation pressure coefficient every 6 h, a pair of empirical RTN (R: radial, T: transverse, N: Normal) perturbations in transverse direction (include sine term and cosine term) every 6 h, one satellite transponder delay, and station range biases which are estimated by iteration."

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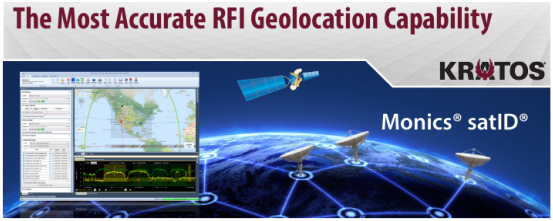
Security implication of SDR

- Replay attacks[9]: record and replay
- Jamming attacks: loss of service [a]
- Spoofing attacks: synthesize signal and broadcast



[a] *Silencing Unwanted Coverage Iran Jams Satellite Signals Carrying Foreign Media*, Der Spiegel (2010)

[9] `https://github.com/oscimp/usrp_recordAndReplay`

SPACENEWS

Commercial

Eutelsat says satellite jammers within Iran are disrupting foreign channels

Jason Rainbow October 7, 2022

This article is more than **12 years old**

Jordan denies illegal jamming of al-Jazeera World Cup TV

Arabic satellite TV channel confirms World Cup broadcasts were jammed from Jordan as government categorically denies involvement

Ian Black, *Middle East editor*

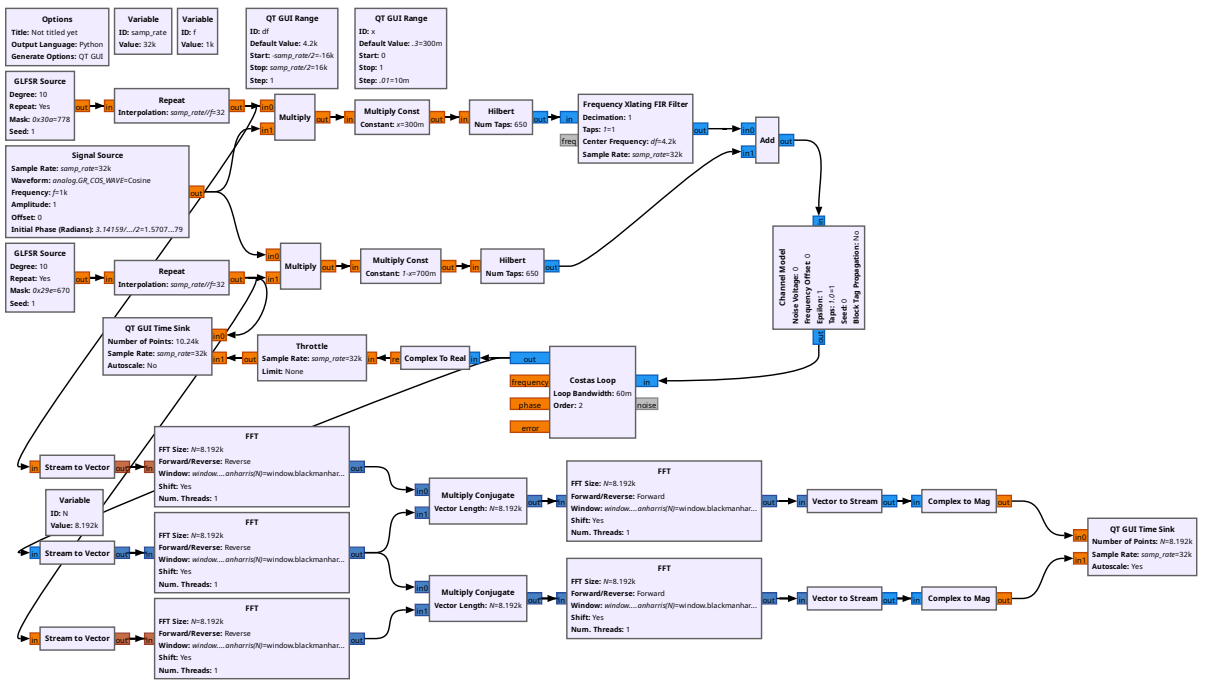
SPACE

Libya Accused of Jamming Satellite Signals

PARIS – Mobile satellite services operator Thuraya Telecommunications says it has "conclusive evidence" that Libya, one of its shareholders, is the source of "unlawful and intentional jamming" of Thuraya signals in Libya and surrounding areas over the past week.

March 2, 2011, 6:47 AM CET / Source: Space.com

By Peter B. de Selding, Space News Staff Writer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Output Language: Python
Generate Options: QT GUI
Variable
ID: samp_rate
Value: 32k
Variable
ID: f
Value: 1k
QT GUI Range
ID: df
Default Value: 4.2k
Start: -samp_rate/2=-16k
Stop: samp_rate/2=16k
Step: 1
QT GUI Range
ID: x
Default Value: .3=300m
Start: 0
Stop: 1
Step: .01=10m
GLFSR Source
Degree: 10
Repeat: Yes
Mask: 0x30a=778
Seed: 1
Repeat
Interpolation: samp_rate//f=32
Multiply
Multiply Const
Constant: x=300m
Hilbert
Num Taps: 650
Frequency Xlating FIR Filter
Decimation: 1
Taps: 1=1
Center Frequency: df=4.2k
Sample Rate: samp_rate=32k
Add
Signal Source
Sample Rate: samp_rate=32k
Waveform: analog.GR_COS_WAVE=Cosine
Frequency: f=1k
Amplitude: 1
Offset: 0
Initial Phase (Radians): 3.14159/.../2=1.5707...79
GLFSR Source
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Mask: 0x29e=670
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Repeat
Interpolation: samp_rate//f=32
Multiply
Multiply Const
Constant: 1-x=700m
Hilbert
Num Taps: 650
Channel Model
Noise Voltage: 0
Frequency Offset: 0
Epsilon: 1
Taps: 1.0=1
Seed: 0
Block Tag Propagation: No
QT GUI Time Sink
Number of Points: 10.24k
Sample Rate: samp_rate=32k
Autoscale: No
Throttle
Sample Rate: samp_rate=32k
Limit: None
Complex To Real
Costas Loop
Loop Bandwidth: 60m
Order: 2
frequency
phase
error
noise
Stream to Vector
Variable
ID: N
Value: 8.192k
FFT
FFT Size: N=8.192k
Forward/Reverse: Reverse
Window: window....anharris(N)=window.blackmanhar...
Shift: Yes
Num. Threads: 1
Multiply Conjugate
Vector Length: N=8.192k
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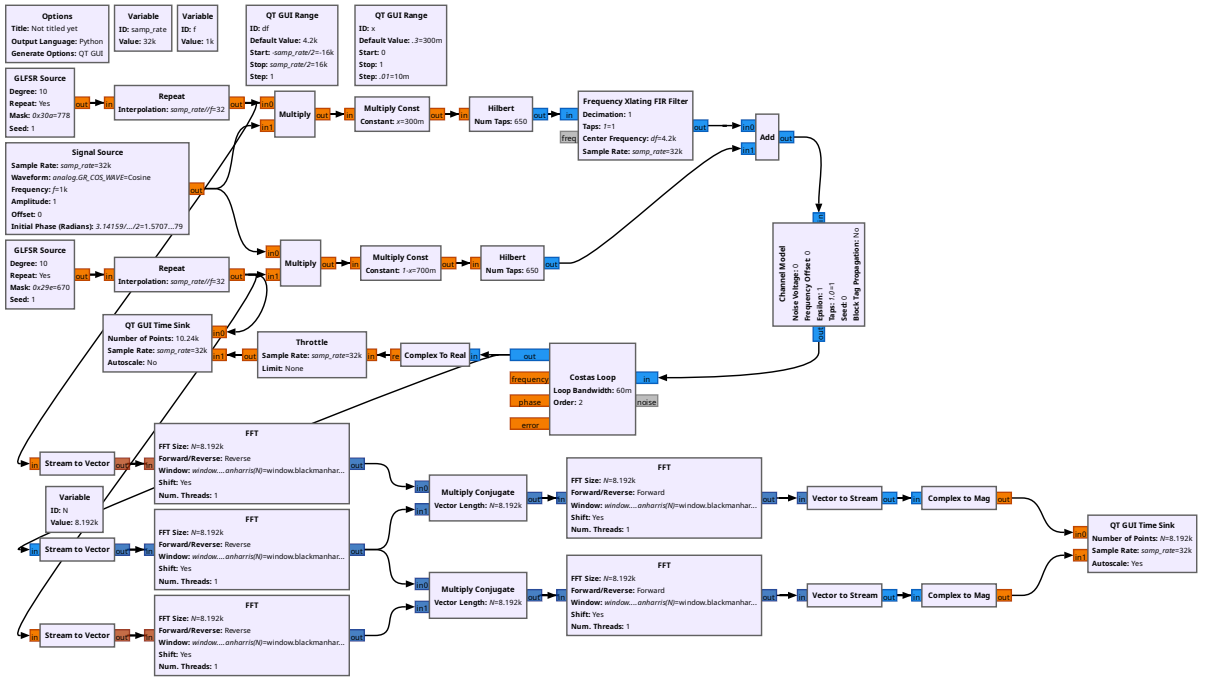
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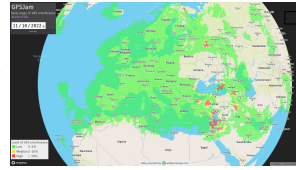
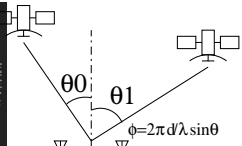
GNSS signal analysis using SDR

- Global Navigation Satellite Systems (GNSS): constellations of spaceborne microwave atomic clocks...
- ... broadcasting signals in the 1-2 GHz L-band
- subject to jamming and spoofing (MEO @ 20000 km)
- SDR has access to raw IQ information collected on multiple antennas

⇒ direction of arrival calculation



Dec. 2022



If directions of arrival (phases) of signals from all satellites are the same (phase of the squared signal to cancel BPSK modulation spectrum spreading), spoofing signal is detected ⇒ null steering for jamming/spoofing cancellation (CRPA[10])

Decode genuine signal using GNU Radio based `gnss-sdr` [11]

However, once the genuine signal is recovered, how to generate 1-PPS output?

[10] 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

[11] `https://github.com/oscimp/gnss-sdr-1pps/`

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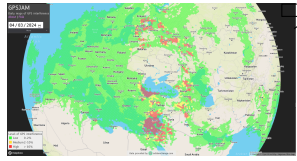
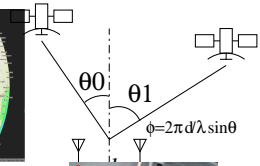


Apr. 2024



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GNSS signal analysis using SDR

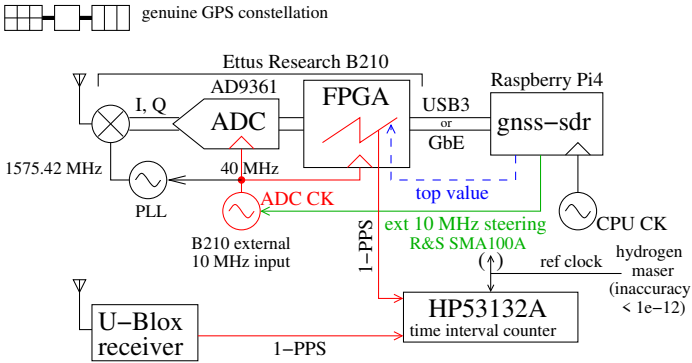
- `gnss-sdr` provides an **clock offset** information between GNSS time and local time

```
Current receiver time: 1 min 52 s
Position at 2001-Oct-12 06:25:15.500000 UTC using 4 observations is Lat = 47.251495868 [deg], Long = 5.993075579 [deg], Height = 360.117 [m]
init offset: 0.015487310819 [s]init LO frequ: 12.346229542937 [Hz]
Velocity: East: -0.282 [m/s], North: -1.510 [m/s], Up = -1.480 [m/s]
Position at 2001-Oct-12 06:25:16.000000 UTC using 4 observations is Lat = 47.251542192 [deg], Long = 5.993097609 [deg], Height = 377.010 [m]
Velocity: East: 0.249 [m/s], North: 0.922 [m/s], Up = 0.651 [m/s]
Current receiver time: 1 min 53 s
Position at 2001-Oct-12 06:25:16.500000 UTC using 4 observations is Lat = 47.251576137 [deg], Long = 5.993169968 [deg], Height = 373.085 [m]
Velocity: East: 0.289 [m/s], North: 0.988 [m/s], Up = 1.087 [m/s]
New GPS NAV message received in channel 0: subframe 5 from satellite GPS PRN 12 (Block IIR-M)
New GPS NAV message received in channel 2: subframe 5 from satellite GPS PRN 24 (Block IIF)
New GPS NAV message received in channel 3: subframe 5 from satellite GPS PRN 02 (Block IIR)
New GPS NAV message received in channel 4: subframe 5 from satellite GPS PRN 19 (Block IIR)
New GPS NAV message received in channel 5: subframe 5 from satellite GPS PRN 32 (Block IIF)
Position at 2001-Oct-12 06:25:17.000000 UTC using 4 observations is Lat = 47.251548923 [deg], Long = 5.993130850 [deg], Height = 363.682 [m]
Velocity: East: -0.154 [m/s], North: 0.483 [m/s], Up = 0.803 [m/s]
Current receiver time: 1 min 54 s
```

- the only known time is the sampling of the ADC, all other communication is asynchronous (block transfers through USB/Ethernet and by the GNU Radio scheduler)
- SDR **ADC clock steering**
- Full control of the complete signal processing chain
- Steer local oscillator to match incoming timing information

How to materialize timing information is 1-Pulse Per Second (1-PPS)?

Problem statement: sample timing

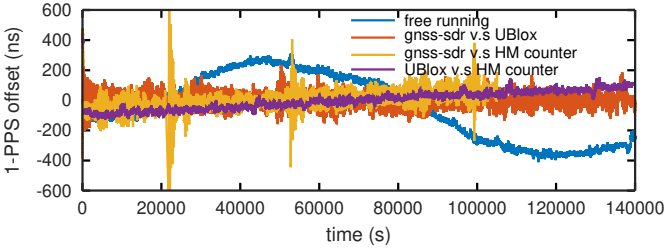


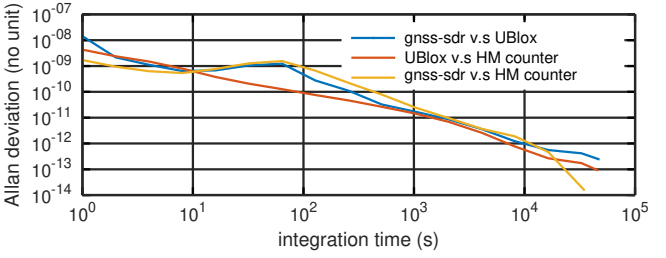
40 MHz is 4-times multiplication of reference 10 MHz input of B210
HM always clocks the HP53132A counter and might clock the B210

D. Rabus, G. Goavec-Merou, G. Cabodevila, F. Meyer, J.-M Friedt, *Generating a timing information (1-PPS) from a software defined radio decoding of GPS signals*, IFCS (2021)

- All communication between FPGA and GP-CPU hardware asynchronous
- Only ADC sampling time is known **assuming** continuous datastream at f_s
- Control the clock timing the AD9361 frontend ADC, which also clocks the FPGA
- Counter **in the FPGA** from 0 to $f_s - 1 \Rightarrow$ 1-PPS output
- Characterization: HP53132A time-interval counter clocked by Hydrogen Maser (HM) and reference 1-PPS from U-Blox NEO-M8P hardware receiver

1-PPS output: closed loop result





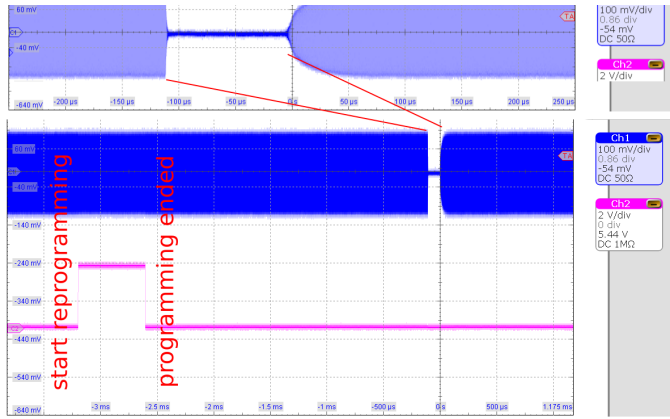
- Long term stability assessment
- Drift of the HM with respect to 1-PPS GNSS visible at $\geq X \cdot 10^4$ s
- Allan Time Deviation (MDEV) from 10^{-8} at 1 s (10 ns @ 1 s) $\searrow 1/\tau$
- Control loop time constant visible $\tau \in [10 - 100]$ s
- At the moment integrated within `gnss-sdr` $\Rightarrow$ move to an external client communicating with `gnss-sdr` through UDP link [a] including the Time of Week (ToW) to remove 20 ms uncertainty on 1-PPS edge... work in progress

[a] `https://github.com/acebrianjuan/gnss-sdr-pvt-monitoring-client`

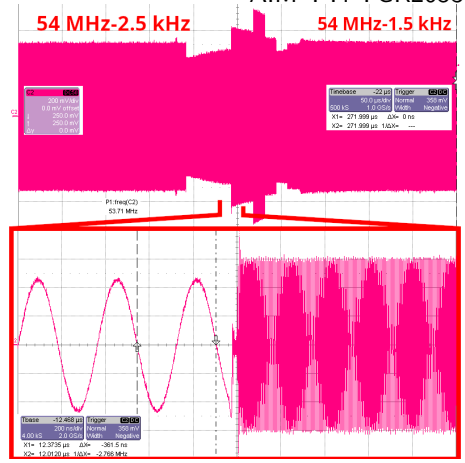
Problem of digital system clocked with tunable commercial synthesizers

Clocking a digital system (FPGA, Raspberry Pi) with a commercial synthesizer:

Rohde & Schwarz SMA100A

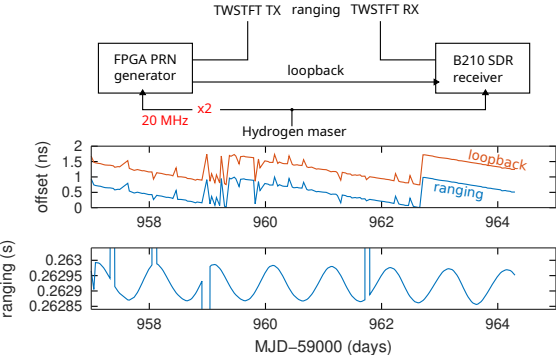


AIM-TTi TGR2053



⇒ dedicated hardware (ADi DDS) or PLL buffer

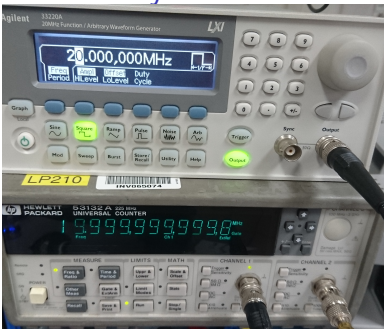
Problem of digital system clocked with tunable commercial synthesizers



1 ns delay over 40 h is $\frac{10^{-9}}{40 \cdot 3600} = 7 \cdot 10^{-15}$ or at 20 MHz a frequency offset of 14 nHz on **both** the reference and measurement channels (since offset on FPGA reference clock), visible on the hydrogen maser disciplined B210

J.-M Friedt *& al.*, *Development of an opensource, openhardware, software-defined radio platform for two-way satellite time and frequency transfer*, IFCS (2023)

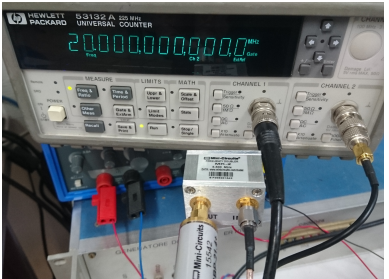
Agilent 33220A digital synthesizer (square wave output with offset) and counter clocked by hydrogen maser: claims 20 MHz but **erroneous** output frequency (last digit is 100 μHz) $\longrightarrow$



ADi DDS:

$$f_{out} = f_{clk} \times \frac{word}{2^{width}}$$

Counter clocked by hydrogen maser and doubled hydrogen maser (requires a sine wave to square wave conditioning circuit to clock the FPGA) $\longrightarrow$



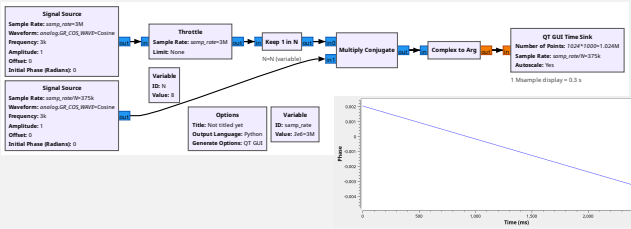
Problem of digital software: GNU Radio NCO implementation

- Never calculate $\cos(2\pi ft)$ since $t \to \infty$ will lead to inaccurate trigonometric calculation
- rather calculate $\cos(\varphi)$ with $\varphi = \varphi + 2\pi \times f/f_s$ at each time step, and $\varphi = \varphi - 2\pi$ if $\varphi \geq 2\pi$ to keep between $[0 : 2\pi]$ but π cannot be represented as a fraction ... $\exp(j\omega(t/8)) \cdot \exp^*(j(\omega/8)t) \neq 1$! $\downarrow$
- see `gnuradio-runtime/include/gnuradio/nco.h` at `https://github.com/gnuradio/gnuradio`

```
void set_freq(double angle_rate) { phase_inc = angle_rate; } // angle_rate is in radians / step

// increment current phase angle
void step(int n = 1)
{phase += phase_inc * n;
 if (fabs(phase) > GR_M_PI) {
    while (phase > GR_M_PI)  phase -= 2 * GR_M_PI;
    while (phase < -GR_M_PI) phase += 2 * GR_M_PI;
 }
}

// compute cos or sin for current phase angle
float cos() const { return std::cos(phase); }
float sin() const { return std::sin(phase); }
```

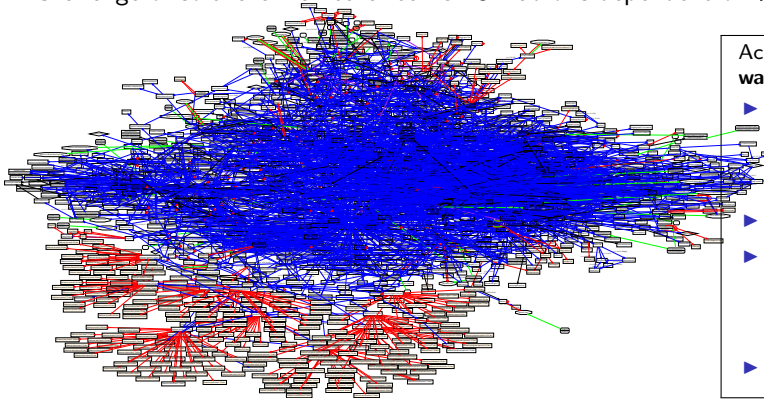


https://github.com/gnuradio/gnuradio/issues/6800

```
template <class o_type, class i_type>
void nco<o_type, i_type>::sin(float* output, int noutput_items, double ampl)
{for (int i = 0; i < noutput_items; i++) {
   output[i] = (float)(sin() * ampl);
   step();
 }
}
```

Conclusion & issues

- Usage of SDR in the context of time and frequency dissemination
- Challenge of software maintenance: GNU Radio is dependent on >700 packages under GNU/Linux



Acknowledgement: the **free, opensource software/gateware** development community:

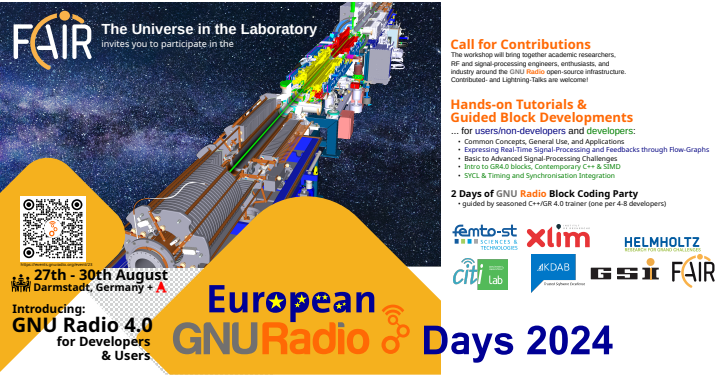
- `gnss-sdr` at `github.com/gnss-sdr/` by the Centre Tecnològic Telecomunicacions Catalunya (CTTC, Spain): C. Fernández-Prades and J. Arribas
- GNU Radio at `github.com/gnuradio/`
- Ettus Research FPGA gateware at `github.com/ettusresearch/fpga` and USRP Hardware Driver (UHD) Software at `github.com/ettusresearch/uhd`
- Buildroot at `https://buildroot.org/`

- SDR ideally suited for distributed coherent systems when used with **White Rabbit**: join us at European GNU Radio Days 2024 at GSI in Darmstadt (Germany) last week of August

Slides available at
jmfriedt.free.fr

Conclusion & issues

- Usage of SDR in the context of time and frequency dissemination
- Challenge of software maintenance: GNU Radio is dependent on >700 packages under GNU/Linux



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- `gnss-sdr` at `github.com/gnss-sdr/` by the Centre Tecnològic Telecomunicacions Catalunya (CTTC, Spain): C. Fernández-Prades and J. Arribas
- GNU Radio at `github.com/gnuradio/`
- Ettus Research FPGA gateware at `github.com/ettusresearch/fpga` and USRP Hardware Driver (UHD) Software at `github.com/ettusresearch/uhd`
- Buildroot at `https://buildroot.org/`

- SDR ideally suited for distributed coherent systems when used with **White Rabbit**: join us at European GNU Radio Days 2024 at GSI in Darmstadt (Germany) last week of August

Slides available at
`jmfriedt.free.fr`