Software defined radio receiver for multi-band GNSS reception

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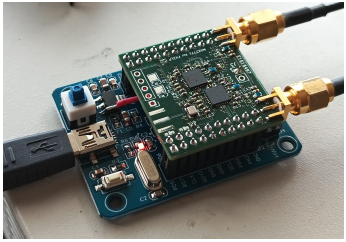
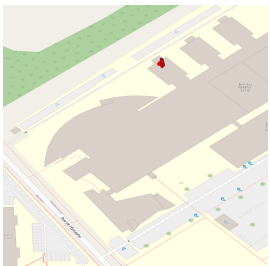
From



to

```
> 2024 08 14 16 03 19.0000000 0 4
G13 26677805.858 7 140192817.566 7 3590.334 7 43.512
G14 28295834.916 6 148695547.549 6 4209.469 6 40.300
G30 25101222.820 8 131907837.064 8 1254.211 8 51.110
G20 24951215.267 7 131119518.199 7 896.314 7 47.843
> 2024 08 14 16 03 20.0000000 0 4
G13 26677119.759 7 140189224.429 7 3587.690 7 43.779
G14 28295031.757 6 148691334.164 6 4214.389 6 40.656
G30 25100981.910 8 131906580.351 8 1253.806 8 51.314
G20 24951039.364 7 131118617.388 7 896.117 7 47.906
> 2024 08 14 16 03 21.0000000 0 4
G13 26676437.663 7 140185631.373 7 3592.389 7 43.679
G14 28294218.270 6 148687120.773 6 4212.169 6 40.532
G30 25100742.929 8 131905324.028 8 1255.340 8 51.420
G20 24950866.874 8 131117717.063 8 898.874 8 48.169
> 2024 08 14 16 03 22.0000000 0 4
G13 26675749.902 7 140182037.428 7 3590.930 7 43.974
G14 28293419.650 6 148682906.377 6 4210.729 6 40.439
G30 25100500.429 8 131904067.112 8 1253.217 8 50.693
```

to



December 9, 2025

Direction of arrival measurement[1]

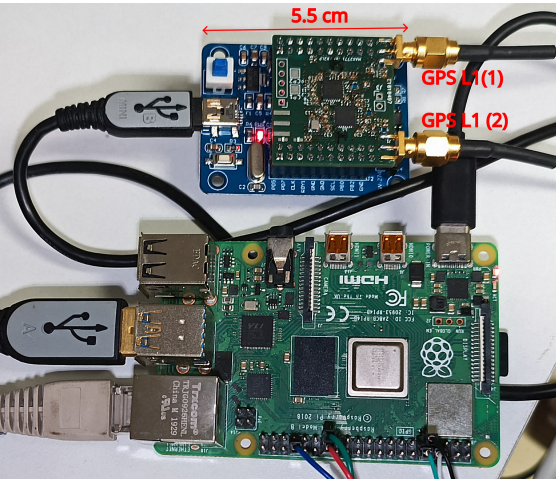
- Condition for jamming/spoofing[a] cancellation: direction of arrival measurement...
- ... through phase analysis.
- Common clock driving all MAX2771...
- ... but internal PLL converting 24 MHz to targeted LO frequency

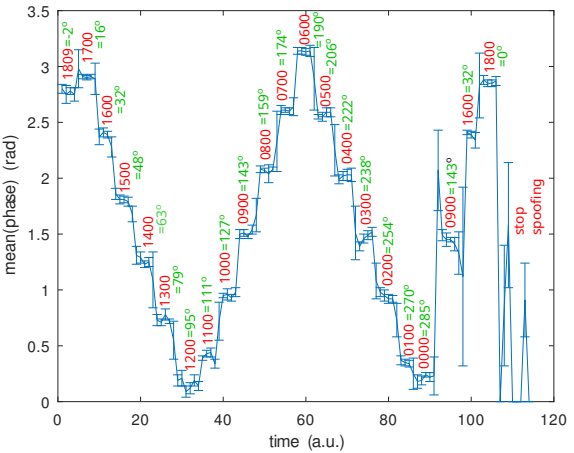
[a] `https://developer.android.com/develop/sensors-and-location/sensors/gnss-spoof-jam` for single antenna jamming/spoofing indicators through AGC and SNR variations

[1] `https://www.404media.co/ukraine-is-jamming-russias-superweapon-with-a-song/`

Local oscillator drift

- 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

Local oscillator drift

- DoA drift from PLL warming up[2]
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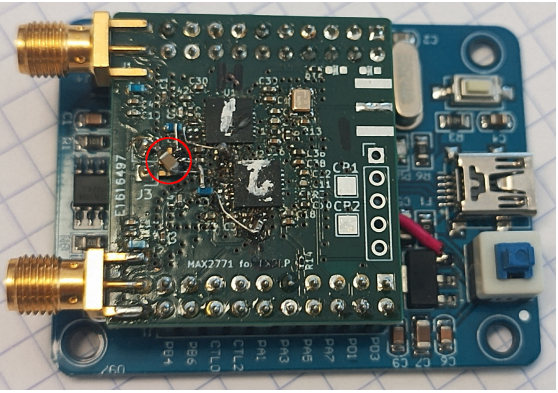
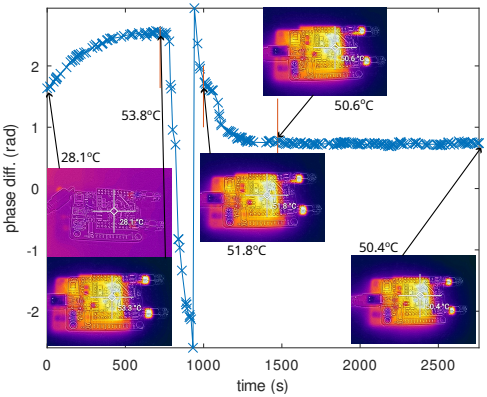




[2] https://github.com/jmfriedt/max2771_fx2lp/tree/main/250610_calibrate_phase

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

RINEX file format

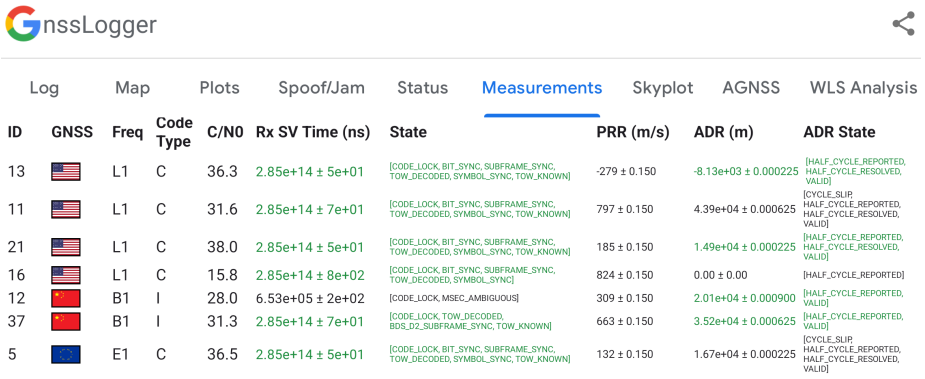
Standardized file format (Receiver INdependent EXchange): header indicates which signal are broadcast followed by time ending with number of satellites and data ⇒ `convbin -od -os file.ubx` from a Zed-F9P UBlox receiver

```
     3.04           OBSERVATION DATA    M: Mixed            RINEX VERSION / TYPE
CONVBIN demo5 b34g 20251203 070021 UTC                      PGM / RUN BY / DATE
...
  1208001.6727   260605.8262  6236716.5069                  APPROX POSITION XYZ
        0.0000        0.0000        0.0000                  ANTENNA: DELTA H/E/N
G    4 C1C L1C C2X L2X                                      SYS / # / OBS TYPES
E    4 C1X L1X C7X L7X                                      SYS / # / OBS TYPES
  2025    09    30    11    26   28.0000000     GPS         TIME OF FIRST OBS
  2025    09    30    11    31   31.0000000     GPS         TIME OF LAST OBS
G L1C                                                       SYS / PHASE SHIFT
G L2X  0.00000                                              SYS / PHASE SHIFT
E L1X  0.00000                                              SYS / PHASE SHIFT
E L7X  0.00000                                              SYS / PHASE SHIFT
  0                                                         GLONASS SLOT / FRQ #
 C1C    0.000 C1P    0.000 C2C    0.000 C2P    0.000       GLONASS COD/PHS/BIS
                                                            END OF HEADER
> 2025 09 30 11 26 28.0000000  0 14
G05  21543121.518   113209866.8311
G07  22097456.951   116122919.1171
G09  22543808.581   118468513.3161
G16  22091705.362   116092693.9951
G21  21380460.846   112355079.4831
G27  24252145.735   127445885.0791
G29  24424801.384   128353197.0911
G30  23176153.781   121791509.6201
G26  24573984.906   129137161.0671
E08  25912171.769   136169381.3341
E05  24686094.961   129726303.8851
E03  24086786.604   126576917.0841
E16  26626116.477   139921185.7561
E24  25598232.306   134519618.2891
> 2025 09 30 11 26 29.0000000  0 14
G05  21542911.578   113208763.016
G07  22097219.518   116121671.135
G09  22544436.507   118471812.575
G16  22091930.488   116093876.158
```

```
     3.04           OBSERVATION DATA    M: Mixed            RINEX VERSION / TYPE
CONVBIN demo5 b34g 20251203 070152 UTC                      PGM / RUN BY / DATE
...
  1208001.6727   260605.8262  6236716.5069                  APPROX POSITION XYZ
        0.0000        0.0000        0.0000                  ANTENNA: DELTA H/E/N
G    8 C1C L1C D1C S1C C2X L2X D2X S2X                      SYS / # / OBS TYPES
E    8 C1X L1X D1X S1X C7X L7X D7X S7X                      SYS / # / OBS TYPES
  2025    09    30    11    26   28.0000000     GPS         TIME OF FIRST OBS
  2025    09    30    11    31   31.0000000     GPS         TIME OF LAST OBS
G L1C                                                       SYS / PHASE SHIFT
G L2X  0.00000                                              SYS / PHASE SHIFT
E L1X  0.00000                                              SYS / PHASE SHIFT
E L7X  0.00000                                              SYS / PHASE SHIFT
  0                                                         GLONASS SLOT / FRQ #
 C1C    0.000 C1P    0.000 C2C    0.000 C2P    0.000       GLONASS COD/PHS/BIS
                                                            END OF HEADER
> 2025 09 30 11 26 28.0000000  0 14
G05  21543121.518   113209866.8311       1105.702        47.000
G07  22097456.951   116122919.1171       1249.700        48.000
G09  22543808.581   118468513.3161      -3297.664        46.000
G16  22091705.362   116092693.9951      -1180.309        45.000
G21  21380460.846   112355079.4831      -1199.540        48.000
G27  24252145.735   127445885.0791       3252.296        42.000
G29  24424801.384   128353197.0911      -3235.472        40.000
G30  23176153.781   121791509.6201       2941.070        44.000
G26  24573984.906   129137161.0671      -3493.472        40.000
E08  25912171.769   136169381.3341       2539.786        43.000
E05  24686094.961   129726303.8851      -2827.162        43.000
E03  24086786.604   126576917.0841       -193.588        48.000
E16  26626116.477   139921185.7561       2588.755        48.000
E24  25598232.306   134519618.2891       1417.756        46.000
> 2025 09 30 11 26 29.0000000  0 14
G05  21542911.578   113208763.016        1102.126        47.000
G07  22097219.518   116121671.135        1246.281        48.000
G09  22544436.507   118471812.575       -3300.825        46.000
G16  22091930.488   116093876.158       -1183.954        45.000
```

Raw GNSS from Android [5] [6]

- Google GNSSLogger stores raw information from visible satellites (pseudo-range, C/N0, Doppler...)
- `https://github.com/jorgeho1995/geagnss` for converting raw GNSSLogger files to RINEX[4] (see the `geagnss/tools/raw_android_to_rinex` subdirectory)



ID	GNSS	Freq	Code Type	C/N0	Rx SV Time (ns)	State	PRR (m/s)	ADR (m)	ADR State
13		L1	C	36.3	2.85e+14 ± 5e+01	[CODE_LOCK, BIT_SYNC, SUBFRAME_SYNC, TOW_DECODED, SYMBOL_SYNC, TOW_KNOWN]	-279 ± 0.150	-8.13e+03 ± 0.000225	[HALF_CYCLE_REPORTED, HALF_CYCLE_RESOLVED, VALID]
11		L1	C	31.6	2.85e+14 ± 7e+01	[CODE_LOCK, BIT_SYNC, SUBFRAME_SYNC, TOW_DECODED, SYMBOL_SYNC, TOW_KNOWN]	797 ± 0.150	4.39e+04 ± 0.000625	[CYCLE_SLIP, HALF_CYCLE_REPORTED, HALF_CYCLE_RESOLVED, VALID]
21		L1	C	38.0	2.85e+14 ± 5e+01	[CODE_LOCK, BIT_SYNC, SUBFRAME_SYNC, TOW_DECODED, SYMBOL_SYNC, TOW_KNOWN]	185 ± 0.150	1.49e+04 ± 0.000225	[HALF_CYCLE_REPORTED, HALF_CYCLE_RESOLVED, VALID]
16		L1	C	15.8	2.85e+14 ± 8e+02	[CODE_LOCK, BIT_SYNC, SUBFRAME_SYNC, TOW_DECODED, SYMBOL_SYNC]	824 ± 0.150	0.00 ± 0.00	[HALF_CYCLE_REPORTED]
12		B1	I	28.0	6.53e+05 ± 2e+02	[CODE_LOCK, MSEC_AMBIGUOUS]	309 ± 0.150	2.01e+04 ± 0.000900	[HALF_CYCLE_REPORTED, VALID]
37		B1	I	31.3	2.85e+14 ± 7e+01	[CODE_LOCK, TOW_DECODED, BDS_D2_SUBFRAME_SYNC, TOW_KNOWN]	663 ± 0.150	3.52e+04 ± 0.000625	[HALF_CYCLE_REPORTED, VALID]
5		E1	C	36.5	2.85e+14 ± 5e+01	[CODE_LOCK, BIT_SYNC, SUBFRAME_SYNC, TOW_DECODED, SYMBOL_SYNC, TOW_KNOWN]	132 ± 0.150	1.67e+04 ± 0.000225	[CYCLE_SLIP, HALF_CYCLE_REPORTED, HALF_CYCLE_RESOLVED, VALID]

[4] J.H. Olcina *& al*, *Python toolbox for android GNSS raw data to RINEX conversion*, GPS Solutions **28**95 (2024)

[5] GSA, *Using GNSS raw measurements on Android Devices (2017)* at `https://galileognss.eu/wp-content/uploads/2018/05/Using-GNSS-Raw-Meaurements-on-Android-devices.pdf`

[6] `https://developer.android.com/develop/sensors-and-location/sensors/gnss-analyze-raw`

Raw GNSS from Android [7] [8] [9]: dual frequency GNSS?

Xiaomi MI10 (no L1C/L5C)

```
     3.05                OBSERVATION DATA    M                   RINEX VERSION / TYPE
Android RINEX 1.1        UPV                 2025-11-23 18:25:12 PGM / RUN BY / DATE
GNSS00LOG                                                        MARKER NAME
...
GNSSLogger                                                       OBSERVER / AGENCY
                         M2007J17G           v2.0.0.1            REC # / TYPE / VERS
NONE                     NONE                                    ANT # / TYPE
        0.0000           0.0000         0.0000                   APPROX POSITION XYZ
        0.0000           0.0000         0.0000                   ANTENNA: DELTA H/E/N
G    8 C1C L1C D1C S1C C5Q L5Q D5Q S5Q                           SYS / # / OBS TYPES
R    4 C1C L1C D1C S1C                                           SYS / # / OBS TYPES
C    8 C2I L2I D2I S2I C5P L5P D5P S5P                           SYS / # / OBS TYPES
E    8 C1C L1C D1C S1C C5Q L5Q D5Q S5Q                           SYS / # / OBS TYPES
  2025    11    23    16    53    21.437459     GPS             TIME OF FIRST OBS
                                                                 END OF HEADER

> 2025 11 23 16 53 21.4374590  0 23
G12    23358459.413          -3114.539   29.600
G25    20541751.922          -1823.846   31.800    20539399.144       -1361.942    26.100
G28    20844050.629            587.900   26.300    20841700.224         439.019    29.800
G29    20400835.969            467.875   29.400
G31    21979772.713           2480.350   23.900
G26                                                23409762.286        2384.795    26.200
R14    19807427.951           1867.550   27.300
R22    22756753.780          -3731.700   17.800
...
```

Ulefone (with L1C)

```
     3.05                OBSERVATION DATA    M                   RINEX VERSION / TYPE
Android RINEX 1.1        UPV                 2025-11-23 18:25:44 PGM / RUN BY / DATE
GNSS00LOG                                                        MARKER NAME
...
GNSSLogger                                                       OBSERVER / AGENCY
                         Power Armor 19T GNSSv3.1.1.1            REC # / TYPE / VERS
NONE                     NONE                                    ANT # / TYPE
        0.0000           0.0000         0.0000                   APPROX POSITION XYZ
        0.0000           0.0000         0.0000                   ANTENNA: DELTA H/E/N
G    4 C1C L1C D1C S1C                                           SYS / # / OBS TYPES
C    4 C2I L2I D2I S2I                                           SYS / # / OBS TYPES
R    4 C1C L1C D1C S1C                                           SYS / # / OBS TYPES
E    4 C1C L1C D1C S1C                                           SYS / # / OBS TYPES
  2025    11    23    16    53    22.000000     GPS             TIME OF FIRST OBS
                                                                 END OF HEADER

> 2025 11 23 16 53 22.0000000  0 19
G29    20368277.335   22732.374   -1174.150   32.910
G28    20811463.224   20673.754   -1055.922   27.857
G31    21946993.712                 841.117   23.248
G25    20509425.920   63010.045   -3466.093   29.077
G11    23441642.589               -3161.024   20.836
G32    24083496.442               -4747.681   21.668
G26    23379250.382                1552.319   26.493
G18    25211231.428                2081.765   20.324
...
```

[7] V. Renaudin *& al.*, *Positionnement GNSS précis sur smartphone : une réalité proche ?* (2020) à `https://cnig.gouv.fr/IMG/documents_wordpress/2020/11/4_VRenaudin_GNSS_smartphone.pdf`

[8] T. Purfürst, *Evaluation of Static Autonomous GNSS Positioning Accuracy Using Single-, Dual-, and Tri-Frequency Smartphones in Forest Canopy Environments*, MDPI Sensors **22**(3) 1289 (2022)

[9] U. Robustelli *& al.*, *Assessment of Dual Frequency GNSS Observations from a Xiaomi Mi 8 Android Smartphone and Positioning Performance Analysis*, MDPI Electronics **8**(1) 91 (2019)

Raw GNSS from LuGRE [13]

- https://zenodo.org/records/16411687 and https://github.com/NavsasPolito/LuNART
- Galileo time to GPS time offset[10], GGTO, is broadcast with an accuracy better than 5 ns
- $\Rightarrow$ Galileo and GPS pseudoranges can be mixed in finding the PVT solution
- videos of the LuGRE data release workshop [11] in /home/jmfriedt/LuGRE (4 half-days [12])

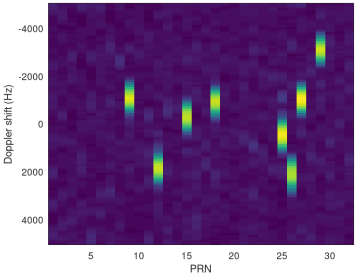
[10] https://www.esa.int/Applications/Satellite_navigation/Galileo_and_GPS_synchronise_watches_new_time_offset_helps_working_together

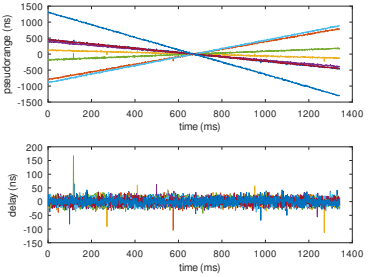
[11] https://www.asi.it/en/event/lunar-navigation-and-exploration/

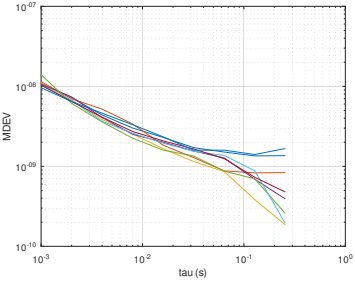
[12] https://www.polito.it/en/polito/communication-and-press-office/poliflash/lugre-mission-nasa-and-asi-release-landmark-lunar-experiment

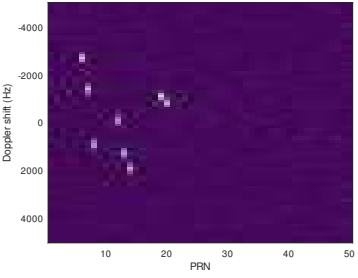
[13] LuGRE sets another record: first GNSS signals detected in lunar orbit (21 February 2025) at https://www.asi.it/en/2025/02/lugre-sets-another-record-first-gnss-signals-detected-in-lunar-orbit/

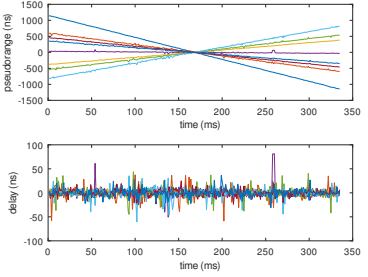
Raw GNSS time transfer: manual xcorr v.s gnss-sdr pseudo ranges

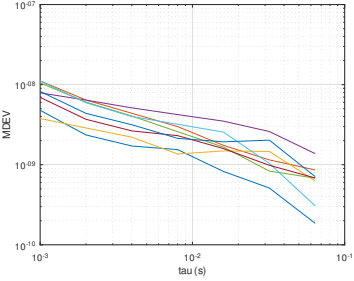








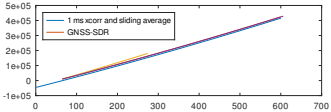


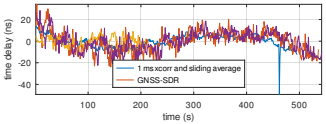


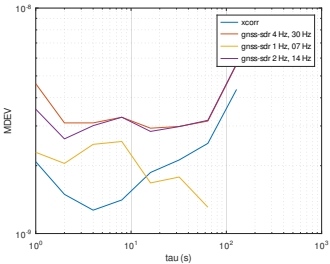
Manual xcorr calculation v.s. gnss-sdr pseudoranges

900 s long record, 16 bit samples collected by 2-X310s clocked by HM and 1-PPS, sampling @ 5 MS/s

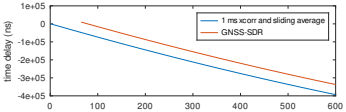
PRN25:

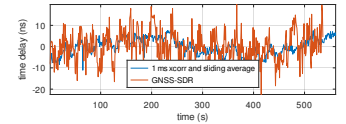


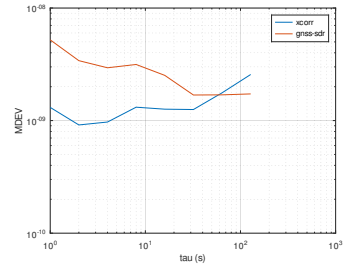




PRN29:







- At the beginning, acquisition for coarse Doppler shift estimate for visible SVs
- GPS L1: cross-correlate 1-ms long batches, oversample ($\times 3$ by zero-padding) and parabolic fit of cross-correlation peak magnitude
- sliding average over 1000 estimates (1-s long equivalent): top
- remove parabolic fit of SV trajectory (top to middle)
- compare with `gnss-sdr` pseudo-range for the same SV ($/3 \cdot 10^8 \times 10^9$ ns) (bottom for modified Allan deviation result):

```
Tracking_1C.implementation=GPS_L1_CA_DLL_PLL_
Tracking_1C.pll_bw_hz=30.0;
Tracking_1C.dll_bw_hz=4.0;
Tracking_1C.order=3;
Tracking_1C.early_late_space_chips=0.5;
```