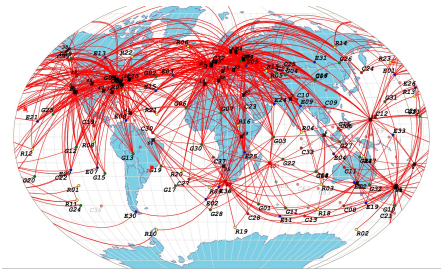
The GALMON.EU
Open Source & Open Data
GNSS monitoring project

@PowerDNS_Bert / bert@hubertnet.nl (presentation)
& many contributors & station operators



High level goals

- Provide highly transparent, easily accessible data on all the world's Global Navigation Satellite Systems (GNSS)
- Use this data to provide real-time monitoring of performance
  - Including sending out actionable alerts
- Make available our data in relevant forms, both for monitoring and research:
  - Raw frames/words/strings/messages
  - Time-series database
  - Pre-configured dashboards and graphs
  - Live coverage/DOP maps of the world
- Perform post-processing to create daily, weekly, monthly reports of targets like DOP, System-in-Space/Ranging error
- All this in hopes to increase the quality of the world's GNSS.

Current status

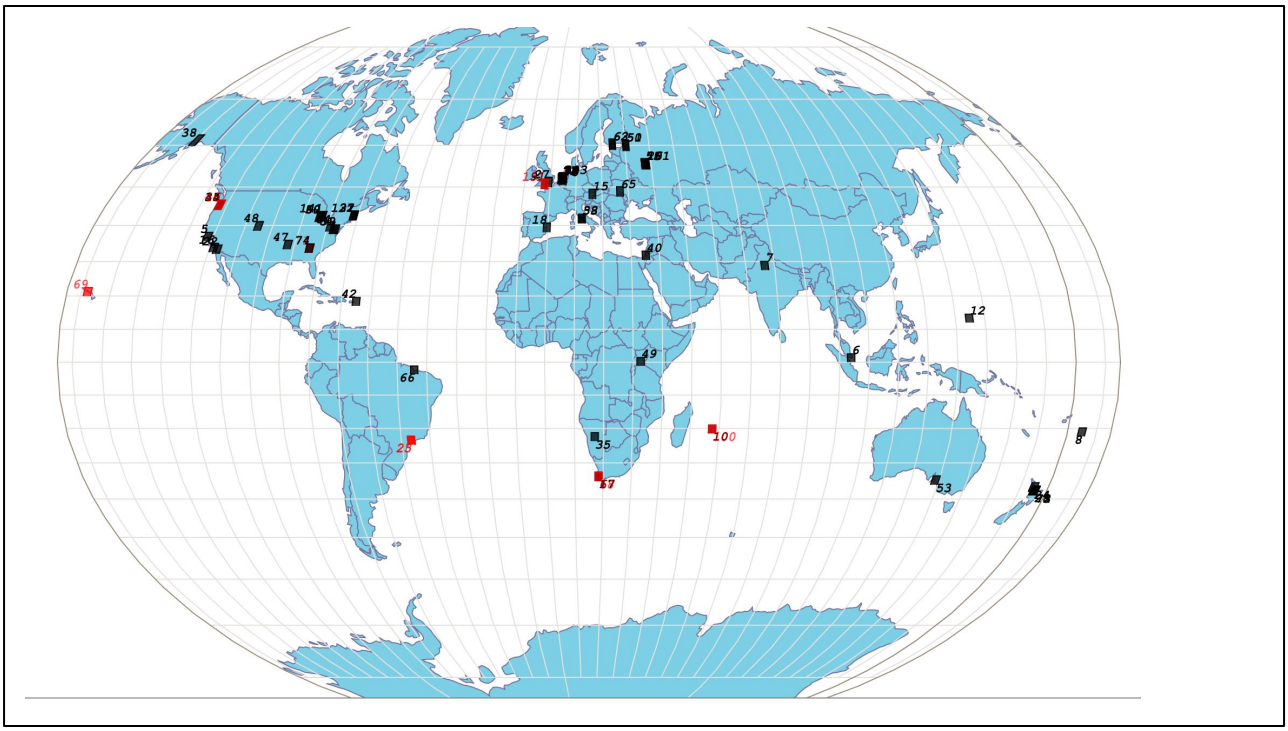
- >60 receivers around the world (Europe, Americas, Oceania, Asia, Africa, Tonga, Mauritius, Reunion, Hawaii, Guam)
- Increasing number of dual band timing receivers (>12)
- Products:
  - **All** receivers deliver “RINEX+”/RTCM+ data
    - Plus CNR, signal quality status
  - In addition, a full binary copy of each and every GNSS frame/message/word/string received
  - Time-series database of all parameters
  - Live alerting of GNSS issues (SISA/URA/URAI/FT changes, health, loss of signal)
- Status display on galmon.eu: per-SV stats, live *DOP map, live coverage map
- Graphs available on https://public.galmon.eu/ (user: guest, password: guest)
- **Non-RTCM data is freely available to everyone**
- RTCM data needs **privacy** agreement (not yet in place)

Current status: software

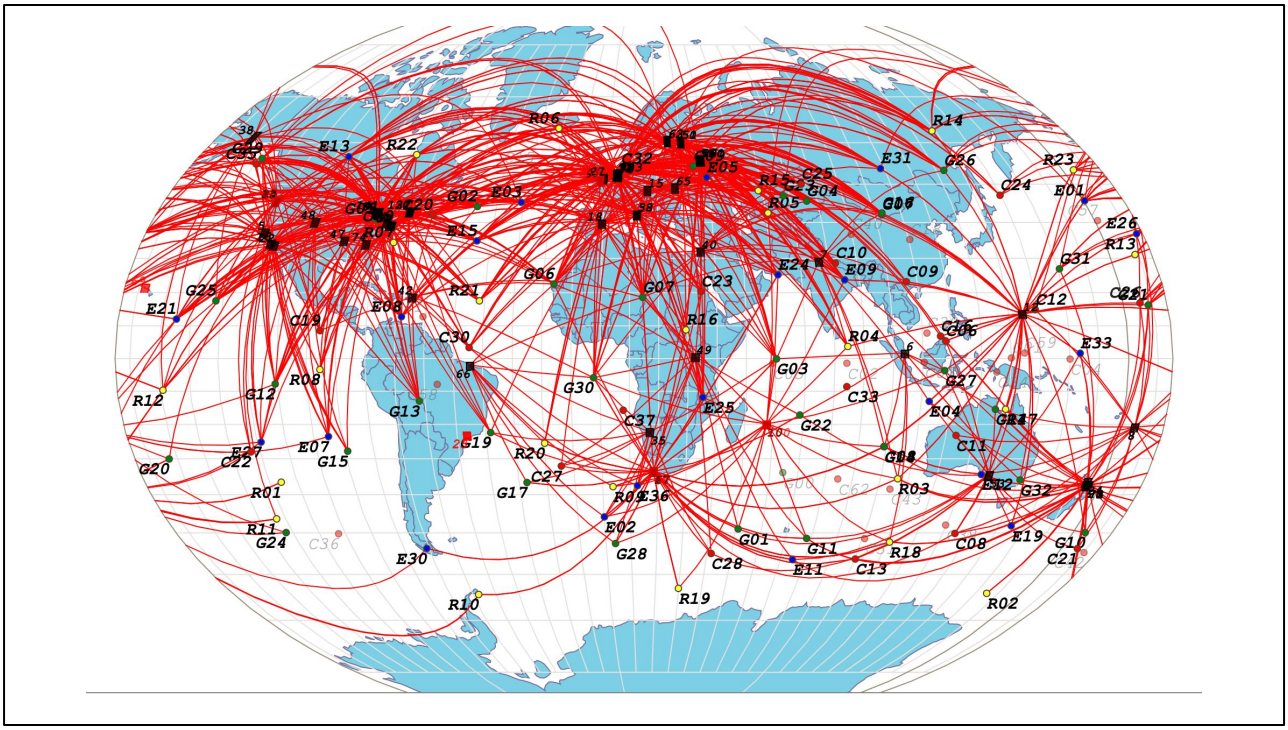
- Very lightweight receiver driver, running on every Linux/UNIX/OSX platform, favorite is Pi Zero W
- Large scale data store (50GB/week growth currently, total since August 2019 > 500GB)
- Analysis of ephemeris discontinuities (in time & space)
- Comparison of determined range & Doppler offset to ephemeris
- SP3 post-processing comparison
- Streaming analysis of all data to a time-series database
  - All parameters (clock corrections, ionospheric model, orbit elements, UTC/GPS time offsets)
- Graphing dashboard that feeds off the time-series database
- Stateful analysis for alerting (galmonmon)

Galmon.eu is a coordinated, crowd-sourced, **open-source** project, driven by **wonderful volunteers & contributors.**

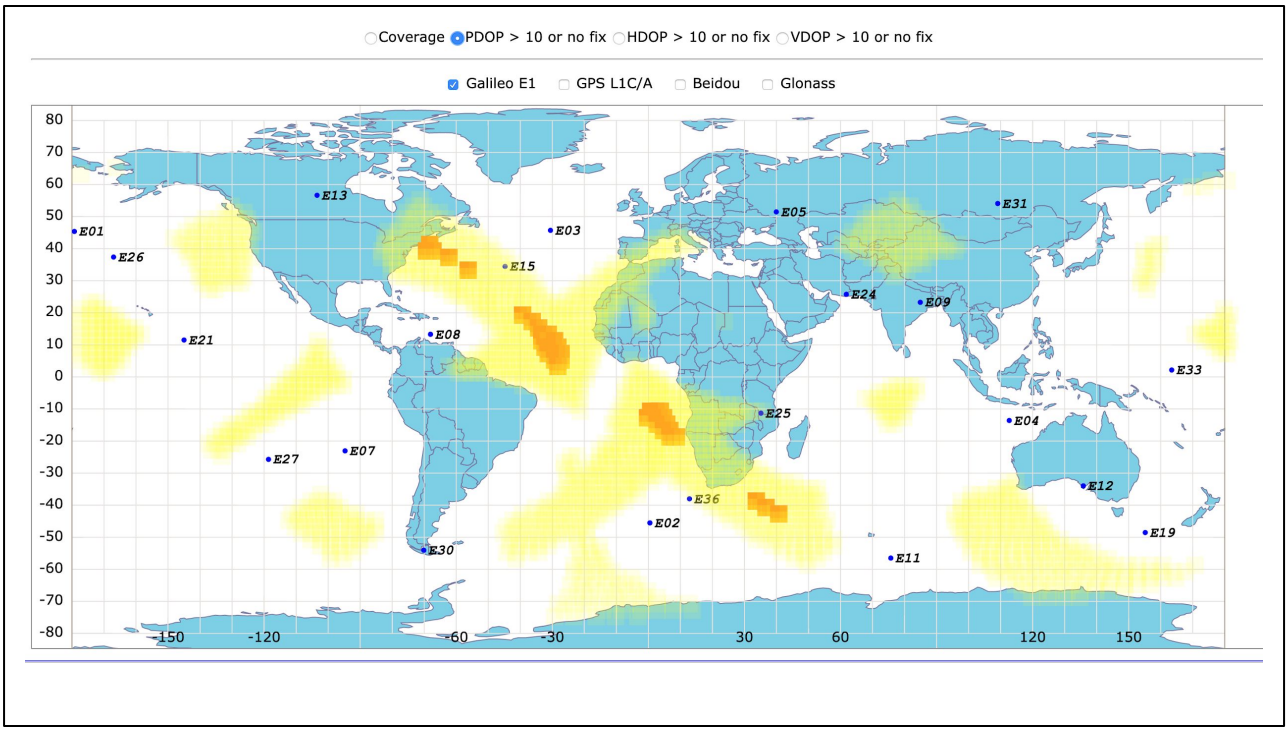
Bert Hubert may head the project, but it would be nothing without the operators, volunteers and contributors.



Stations. Some of the red ones are not down but are multiple stations in one place, and a testing node there might be down. https://galmon.eu/geo/



This is the “show everything” view connects all stations with all monitored satellites.
https://galmon.eu/geo/



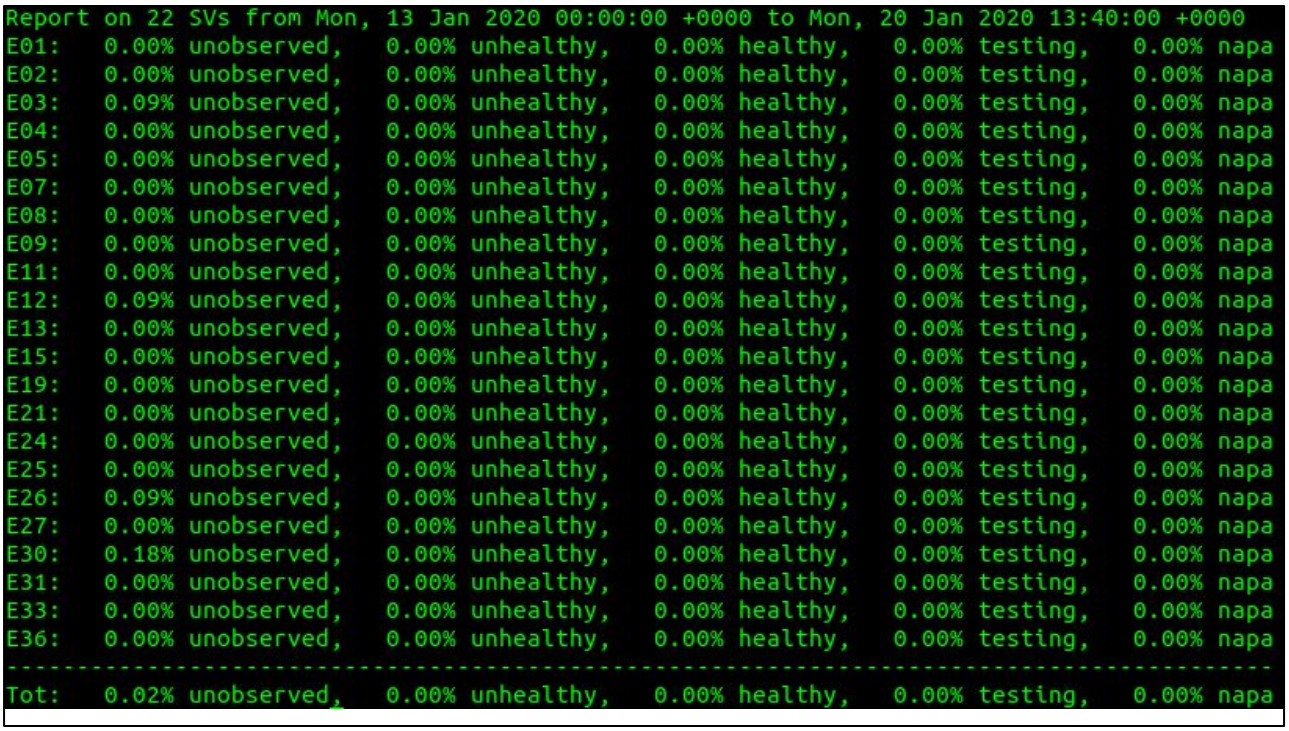
This is a live HDOP/VDOP/PDOP or coverage map. The colors are for different views of the horizon. Red (not shown) means PDOP > 10 even with a 5 degree view of the horizon, yellow 20 degree. https://galmon.eu/geo/coverage.html

Last update: a few seconds ago. More information about this Galileo/GPS/BeiDou/Glonass open source monitor can be found here. Live observer map here, status (coverage, DOP) map here. **Experimental Grafana dashboard on public.galmon.eu (user: guest, password: guest)**.

☑ Galileo E1 ☐ Galileo E5b ☐ BeiDou B1I ☐ BeiDou B2I ☐ Glonass L1 ☐ Glonass L2 ☐ GPS L1C/A ☐ GPS L2C

sv	best-tle	iod	eph-age-m	latest-disco	time-disco	sisa	health	alma-dist	ΔUTC ns	sources	hqsources	db	ΔHz	prres	elev	last-seen-s
E01@1	GSAT0210 (PRN E01)	104	85 minutes ago	8.7 cm	0.1 ns	312 cm	ok/ok/val/val	3.2 km	0.0 +0.0/d	17	4	15 - 47	-9.38	-1.52	5 - 61	a few seconds
E02@1	GSAT0211 (PRN E02)	109	35 minutes ago	8.1 cm	0.0 ns	312 cm	ok/ok/val/val	0.8 km	0.0 +0.0/d	5	3	26 - 46	0.46	0.43	20 - 68	a few seconds
E03@1	GSAT0212 (PRN E03)	111	15 minutes ago	2.0 cm	0.1 ns	312 cm	ok/ok/val/val	2.4 km	0.0 +0.0/d	33	20	25 - 47	203.32	0.65	6 - 66	a few seconds
E04@1	GSAT0213 (PRN E04)	104	85 minutes ago	4.3 cm	0.2 ns	312 cm	ok/ok/val/val	1.0 km	0.0 +0.0/d	4	3	23 - 42	-26.11	0.17	18 - 51	a few seconds
E05@1	GSAT0214 (PRN E05)	105	75 minutes ago	7.6 cm	0.0 ns	312 cm	ok/ok/val/val	2.1 km	0.0 +0.0/d	23	12	26 - 47	47.75	-1.97	3 - 84	a few seconds
E07@1	GSAT0207 (PRN E07)	111	15 minutes ago	8.0 cm	0.0 ns	312 cm	ok/ok/val/val	1.5 km	0.0 +0.0/d	9	0	21 - 35			4 - 21	a few seconds
E08@1	GSAT0208 (PRN E08)	111	15 minutes ago	5.8 cm	0.0 ns	312 cm	ok/ok/val/val	1.2 km	0.0 +0.0/d	24	11	24 - 47	3.84	-0.75	9 - 83	a few seconds
E09@1	GSAT0209 (PRN E09)	111	15 minutes ago	4.8 cm	0.1 ns	312 cm	ok/ok/val/val	2.3 km	0.0 +0.0/d	17	5	25 - 45	138.27	1.40	5 - 78	a few seconds
E11@1	GSAT0101 (PRN E11)	104	85 minutes ago	5.1 cm	-0.1 ns	312 cm	ok/ok/val/val	0.9 km	0.0 +0.0/d	4	3	29 - 42	-17.22	-0.40	11 - 35	a few seconds
E12@1	GSAT0102 (PRN E12)	104	85 minutes ago	5.5 cm	-0.2 ns	312 cm	ok/ok/val/val	0.3 km	0.0 +0.0/d	4	3	25 - 38	0.08	-0.13	32 - 87	a few seconds
E13@1	GSAT0220 (PRN E13)	111	15 minutes ago	5.1 cm	0.0 ns	312 cm	ok/ok/val/val	2.9 km	0.0 +0.0/d	31	18	20 - 50	6.18	0.78	10 - 69	a few seconds
E14@1	GSAT0202 (PRN E14)	111	15 minutes ago	5.3 cm	-0.1 ns	312 cm	test/test/val/val		0.0 +0.0/d	3	0	27 - 42			42 - 44	a few seconds
E15@1	GSAT0221 (PRN E15)	111	15 minutes ago	20.4 cm	0.1 ns	312 cm	ok/ok/val/val	0.7 km	0.0 +0.0/d	31	16	9 - 47	1.02	0.17	13 - 62	a few seconds
E18@1	GSAT0201 (PRN E18)	106	65 minutes ago	13.9 cm	0.0 ns	312 cm	test/test/val/val		0.0 +0.0/d	4	0	27 - 49			16 - 64	a few seconds
E19@1	GSAT0103 (PRN E19)	111	15 minutes ago	3.9 cm	-0.1 ns	312 cm	ok/ok/val/val	3.5 km	0.0 +0.0/d	2	0	26 - 33			15 - 45	a few seconds
E21@1	GSAT0215 (PRN E21)	111	15 minutes ago	2.7 cm	0.0 ns	312 cm	ok/ok/val/val	1.4 km	0.0 +0.0/d	14	5	16 - 48	-4.47	0.16	7 - 49	a few seconds
E24@1	GSAT0205 (PRN E24)	111	15 minutes ago	3.6 cm	-0.1 ns	312 cm	ok/ok/val/val	1.6 km	0.0 +0.0/d	20	12	24 - 46	-256.14	-4.13	5 - 60	a few seconds
E25@1	GSAT0216 (PRN E25)	106	65 minutes ago	9.0 cm	0.1 ns	312 cm	ok/ok/val/val	0.1 km	0.0 +0.0/d	13	4	21 - 47	-16.91	-4.13	7 - 76	a few seconds
E26@1	GSAT0203 (PRN E26)	108	45 minutes ago	2.8 cm	0.0 ns	312 cm	ok/ok/val/val	0.9 km	0.0 +0.0/d	15	4	25 - 43	-9.06	-1.02	9 - 58	a few seconds
E27@1	GSAT0217 (PRN E27)	109	35 minutes ago	3.8 cm	0.1 ns	312 cm	ok/ok/val/val	2.7 km	0.0 +0.0/d	4	1	28 - 37			2 - 27	a few seconds
E30@1	GSAT0206 (PRN E30)	106	65 minutes ago	8.9 cm	0.0 ns	312 cm	ok/ok/val/val	1.0 km	0.0 +0.0/d	2	0	35 - 36			5 - 16	a few seconds
E31@1	GSAT0218 (PRN E31)	105	75 minutes ago	7.7 cm	0.1 ns	312 cm	ok/ok/val/val	2.2 km	0.0 +0.0/d	21	14	17 - 44	107.29	-0.61	7 - 41	a few seconds
E33@1	GSAT0222 (PRN E33)	111	15 minutes ago	9.1 cm	0.0 ns	312 cm	ok/ok/val/val	1.3 km	0.0 +0.0/d	5	3	20 - 47	0.44	-1.30	36 - 63	a few seconds
E36@1	GSAT0219 (PRN E36)	111	15 minutes ago	3.5 cm	0.1 ns	312 cm	ok/ok/val/val	4.1 km	0.0 +0.0/d	4	2	24 - 45			15 - 82	a few seconds

This is the main page, on https://galmon.eu/ - in this page several outlier stations have not yet been filtered, causing large Dleta Hz values. Normally these track within <1Hz. Note that many SVs are observed by >10 receivers at a time.

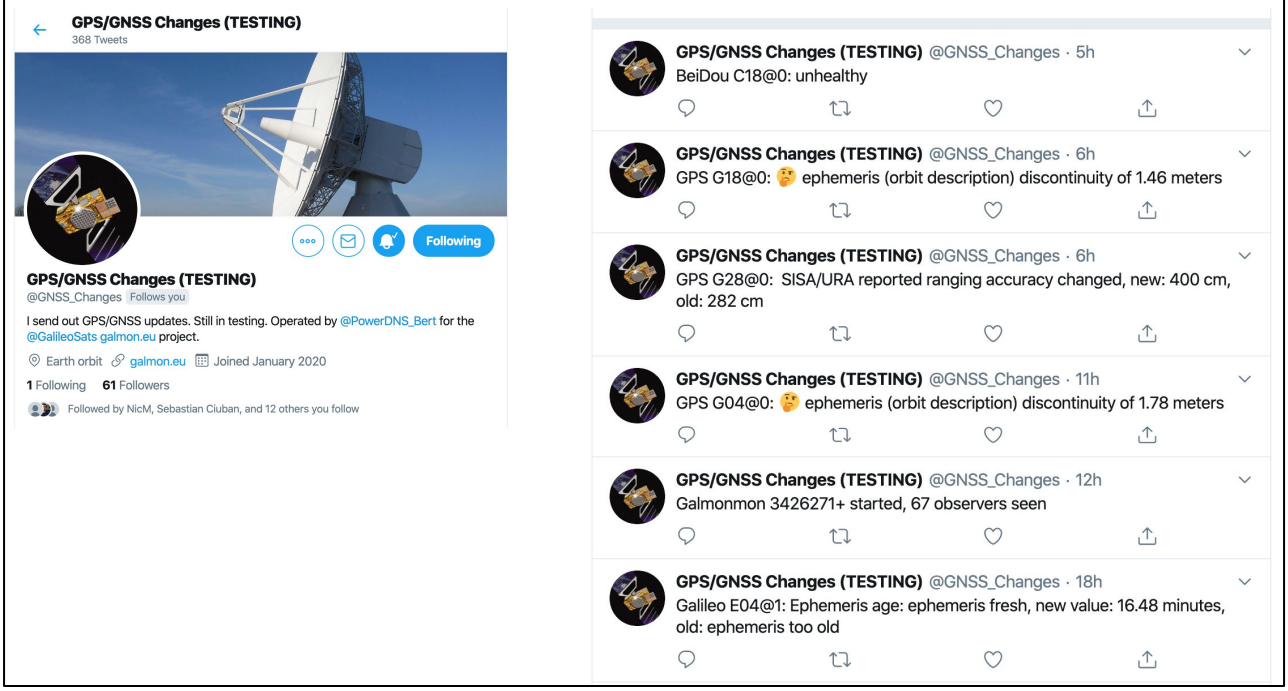


```
Report on 22 SVs from Mon, 13 Jan 2020 00:00:00 +0000 to Mon, 20 Jan 2020 13:40:00 +0000
E01:   0.00% unobserved,   0.00% unhealthy,   0.00% healthy,   0.00% testing,   0.00% napa
E02:   0.00% unobserved,   0.00% unhealthy,   0.00% healthy,   0.00% testing,   0.00% napa
E03:   0.09% unobserved,   0.00% unhealthy,   0.00% healthy,   0.00% testing,   0.00% napa
E04:   0.00% unobserved,   0.00% unhealthy,   0.00% healthy,   0.00% testing,   0.00% napa
E05:   0.00% unobserved,   0.00% unhealthy,   0.00% healthy,   0.00% testing,   0.00% napa
E07:   0.00% unobserved,   0.00% unhealthy,   0.00% healthy,   0.00% testing,   0.00% napa
E08:   0.00% unobserved,   0.00% unhealthy,   0.00% healthy,   0.00% testing,   0.00% napa
E09:   0.00% unobserved,   0.00% unhealthy,   0.00% healthy,   0.00% testing,   0.00% napa
E11:   0.00% unobserved,   0.00% unhealthy,   0.00% healthy,   0.00% testing,   0.00% napa
E12:   0.09% unobserved,   0.00% unhealthy,   0.00% healthy,   0.00% testing,   0.00% napa
E13:   0.00% unobserved,   0.00% unhealthy,   0.00% healthy,   0.00% testing,   0.00% napa
E15:   0.00% unobserved,   0.00% unhealthy,   0.00% healthy,   0.00% testing,   0.00% napa
E19:   0.00% unobserved,   0.00% unhealthy,   0.00% healthy,   0.00% testing,   0.00% napa
E21:   0.00% unobserved,   0.00% unhealthy,   0.00% healthy,   0.00% testing,   0.00% napa
E24:   0.00% unobserved,   0.00% unhealthy,   0.00% healthy,   0.00% testing,   0.00% napa
E25:   0.00% unobserved,   0.00% unhealthy,   0.00% healthy,   0.00% testing,   0.00% napa
E26:   0.09% unobserved,   0.00% unhealthy,   0.00% healthy,   0.00% testing,   0.00% napa
E27:   0.00% unobserved,   0.00% unhealthy,   0.00% healthy,   0.00% testing,   0.00% napa
E30:   0.18% unobserved,   0.00% unhealthy,   0.00% healthy,   0.00% testing,   0.00% napa
E31:   0.00% unobserved,   0.00% unhealthy,   0.00% healthy,   0.00% testing,   0.00% napa
E33:   0.00% unobserved,   0.00% unhealthy,   0.00% healthy,   0.00% testing,   0.00% napa
E36:   0.00% unobserved,   0.00% unhealthy,   0.00% healthy,   0.00% testing,   0.00% napa
-------------------------------------------------------------------------------------------
Tot:   0.02% unobserved,   0.00% unhealthy,   0.00% healthy,   0.00% testing,   0.00% napa
```

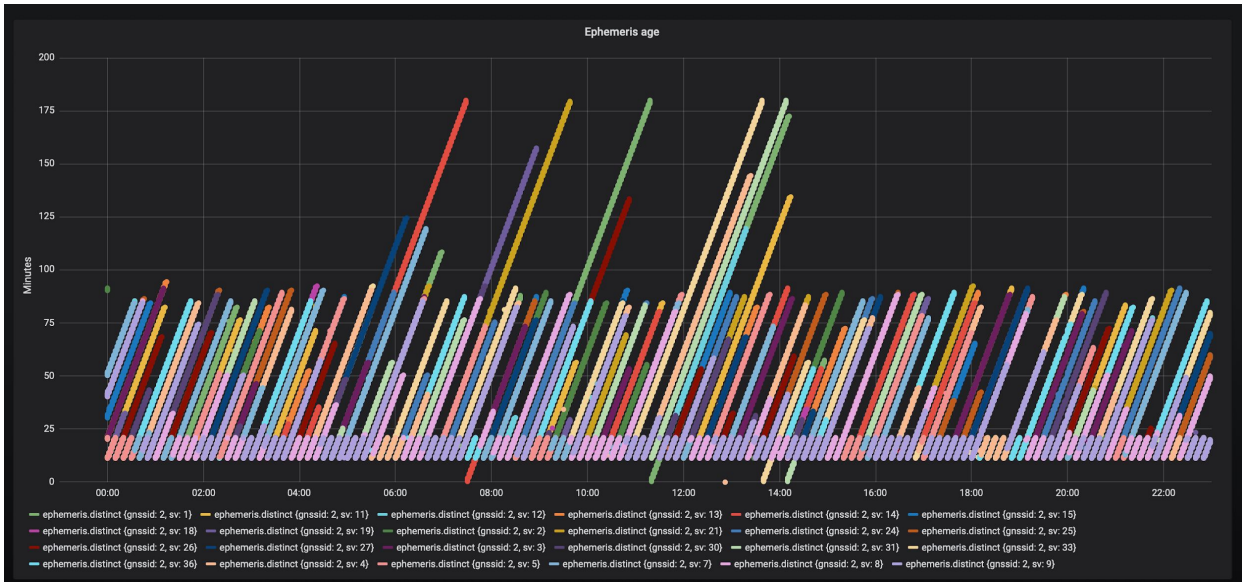
This is “the weekly Galileo report” generated by the “reporter” tool. It can make reports over arbitrary time periods.

Tight integration with Matplotlib & the data processing ecosystem.

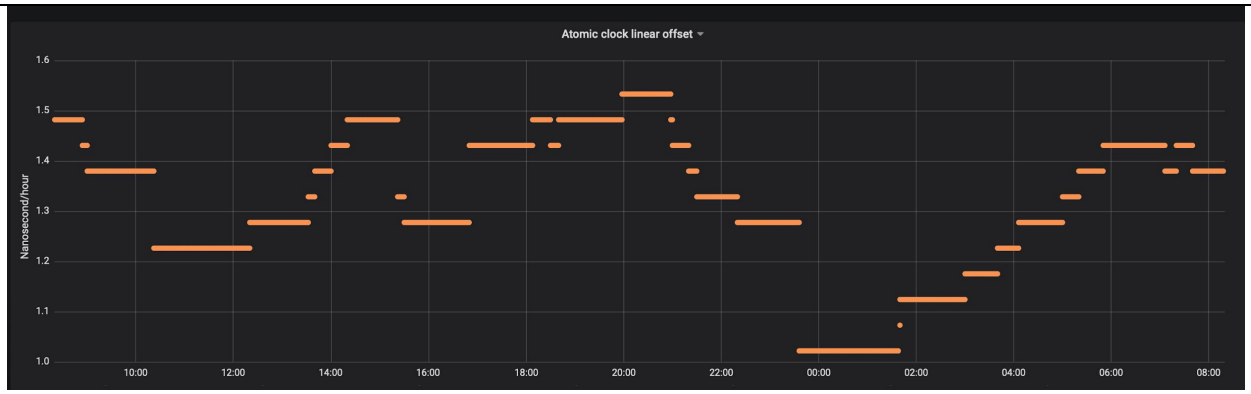
This movie, generated with Matplotlib and our time-series database integration, shows the distribution of the Doppler residual and range-residual with respect to the broadcast orbit. It is clear all dots move around (0,0) which is good.



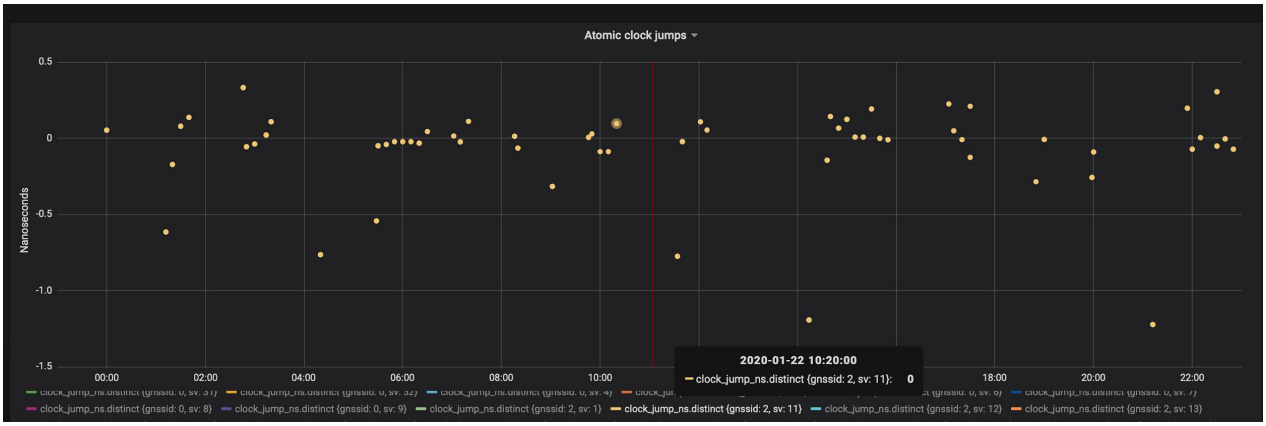
These alerts are generated by ‘galmonmon’, which in turn is connected to Twitter. The https://twitter.com/gnss_changes account tweets out live updates when GNSS conditions change. It is calibrated to send out a few alerts per (normal) day. On a bad day there are many more alerts.



This is a sample graph from our graphing server on https://public.galmon.eu/ (user: guest, password: guest). This shows a day in which Galileo was somewhat late uploading new ephemerides and some SVs reached 3 hour old data. It can also be seen that four times an SV got issued a somewhat exceptional ephemeris, starting with an age of 0. This was the 22nd of January 2020. Note that our graphs are for GPS, GLONASS, BeiDou and Galileo, even though most examples in this presentation are Galileo.

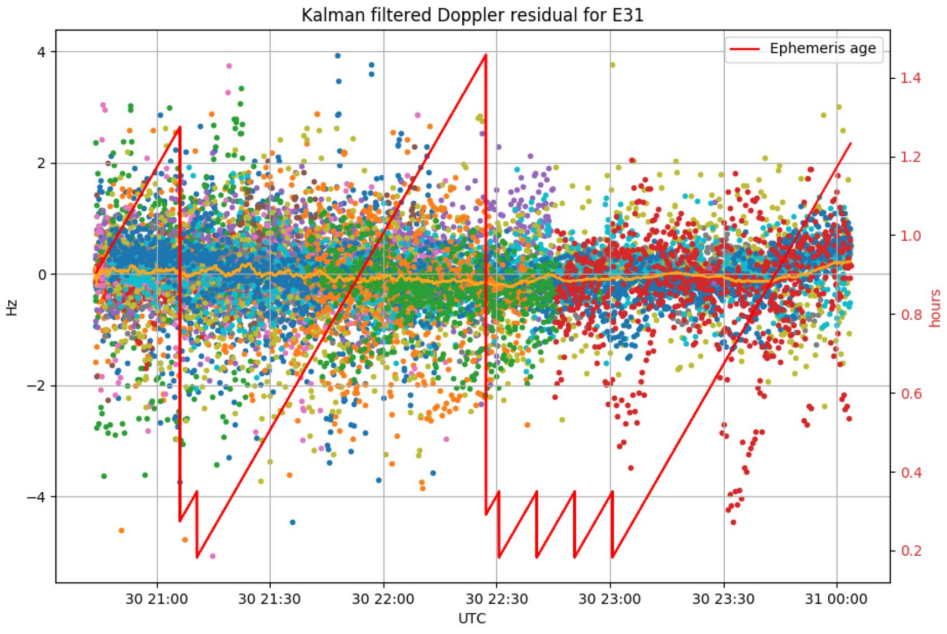


Another graph from https://public.galmon.eu (user:guest, password: guest), showing the somewhat mysterious oscillation in the af1 clock drift parameter.


Atomic clock jumps
0.5
0
-0.5
-1.0
-1.5
Nanoseconds
00:00
02:00
04:00
06:00
08:00
10:00
18:00
20:00
22:00
2020-01-22 10:20:00
clock_jump_ns.distinct {gnssid: 2, sv: 11): 0
clock_jump_ns.distinct {gnssid: 0, sv: 8}
clock_jump_ns.distinct {gnssid: 0, sv: 9}
clock_jump_ns.distinct {gnssid: 2, sv: 1}
clock_jump_ns.distinct {gnssid: 2, sv: 11}
clock_jump_ns.distinct {gnssid: 2, sv: 12}
clock_jump_ns.distinct {gnssid: 2, sv: 13}

- ephemeris, updated every frame (so, a lot)
  - iod-live: current IOD number
  - eph-age: age of this ephemeris (distance from t0e)
- sisa, updated every frame
  - value: raw Galileo SISA value
- gpsura, updated every frame
  - value: raw GPS URA value
- beidouurai, updated every frame
  - value: raw BeiDou URAI value (more or less same as GPS)
- FT, GLONASS specific FT value (SISA)
- clock, clock information, updated every frame
  - offset_ns: time offset of this clock wrt GST/GPS time/Beidou time
  - t0c: t0 of the clock parameters
  - af0, af1, af2: clock polynomial parameters, in Galileo raw units, even for non-galileo SVs
- clock_jump_ns
  - value: number of nanoseconds jump in clock correction from this ephemeris to the previous one
- iono, ionospheric parameters
  - ai0, ai1, ai2: Galileo NeQuick parameters
  - sf1-sf5: The as yet unused 'storm flags'
- galbgd, Galileo Broadcast Group Delay
  - BGDE1E5a in raw galileo values
  - BGDE1E5b in raw galileo values
- galhealth, Galileo-specific health bits, values according to ICD
  - e1bhs
  - e5bhs
  - e1bdvs
  - e5bdvs
- gpshealth, GPS-specific health bits
  - value
- beidouhealth, BeiDou-specific health bits
  - sath1
- glohealth, GLONASS-specific health bits
  - Bn
- glo_taun_ns, GLONASS-specific TauN
  - value, in nanoseconds
- FT, GLONASS specific FT value
- utcoffset, for GPS, Galileo, Beidou
  - a0, in Galileo units
  - a1, in Galileo units
  - delta, in nanoseconds
  - t0t, in seconds
- gpsoffset, for Galileo, BeiDou does not fill this out. GPS doesn't need to
  - a0g, in Galileo units
  - a1g, in Galileo units
  - delta, in nanoseconds
  - t0g, in seconds
- eph-disco, statistics about ephemeris transitions
  - x,y,z: ECEF coordinates according to new ephemeris at new t0e
  - oldx,oldy,oldz: ECEF coordinates according to old ephemeris at new t0e
  - iod, oldiod: new and old IOD

This is an overview of all metric stored in the time-series database. Our data goes back to August 2019. All these numbers can easily be plotted or analysed from Jupyter/Python/Matplotlib/Pandas.

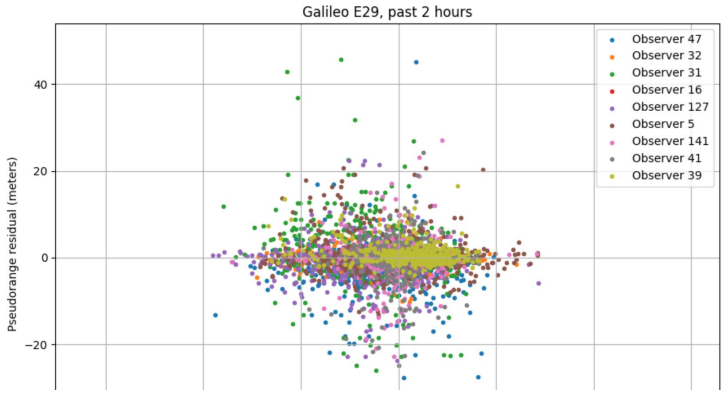


This is a sample Matplotlib graph showing the Kalman filtered Doppler residual (in orange) versus the noisy measurements. In red the ephemeris age, The colors of the dots reflect different receivers.

```
plt.figure()
sv="29"
part = corr.loc[(corr.sv==sv) & (corr.gnssid=="0")]
print(part.describe())
srcs = part.src.unique()

for src in srcs:
        plt.scatter(part[part.src==src].delta_hz_cor, part[part.src==src].prres, label="Observer "+src, marker='.')
plt.legend()
plt.xlabel("Doppler residual (Hz)")
plt.ylabel("Pseudorange residual (meters)")
plt.title("Galileo E"+sv+", past 2 hours")
plt.grid()
```

```
<IPython.core.display.Javascript object>
```



Some sample source code showing how data can be processed. The timeseries database is influxdb which has a Pandas connector.

Receivers range from €15 to many kilo-euros:

Our stations span three orders in magnitude in price. A favorite is a $8 AliExpress u-blox 8 receiver, coupled with a Raspberry Pi Zero running the receiver software. Shown right one of the best stations contributing data to the project.

Offline capabilities

- The software can post-process its data once SP3 files are available
- This allows for determination of SISE/URE for all constellations
- Further processing makes it possible to graph global or WUL SISE numbers

- Similarly, data can be post-processed to show distribution of xDOP values for all constellations and combinations.

Why??

- Why compete with IGS, CORS, GRC?
- Honest explanation: I didn't know
  - Not easy to find, not easy to understand. I did look before I started!
  - Proprietary standards (NTRIP, RTCM, EGNOS/WAAS) do not help
- Now that we exist, our unique contributions:
  - **Full streaming and live copy of each and every GNSS satellite around the world, every message (archive available)**
  - We strongly focus on not "reporting what the receiver thinks" (RINEX) but try to report each and every bit (although we also generate RINEX)
  - Live alerts
  - Reporting
  - Software platform with easy access to all data using "big data" standard protocols

Next steps

- **Our focus is on completing our role as a third party “GNSS Reference Centre”**
- We can currently only measure relative time and orbit errors (from one ephemeris to the next)
  - Lack of (UTC) time standard
- Work is ongoing to improve our orbital analysis, its current sensitivity (~2 meter) is not sensitive enough to be useful
  - Missing tropospheric model
- Expand beyond Ublox 8/9.

More information

- Twitter: https://twitter.com/GalileoSats, https://twitter.com/GNSS_Changes
- Some background on the “why”: https://berthub.eu/articles/posts/update-2019-powerdns-galileo-ripe-doh/

The GALMON.EU
GNSS monitoring project

@PowerDNS_Bert / bert@hubertnet.nl (presentation)
& many contributors & station operators