EU SPACE

Galileo High Accuracy Service

Ignacio Fernández Hernández
European Commission
6 Sept 2022

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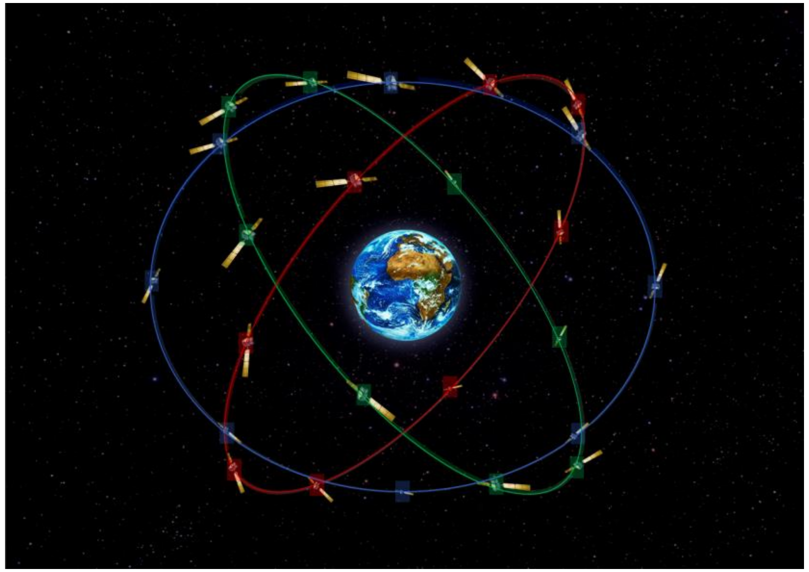
Galileo Constellation

Medium **E**arth **O**rbit (MEO) between **L**ow **E**arth **O**rbit (LEO) and **G**eosynchronous **E**arth **O**rbit (GEO)

→**Satellites altitude: 23,222 km**



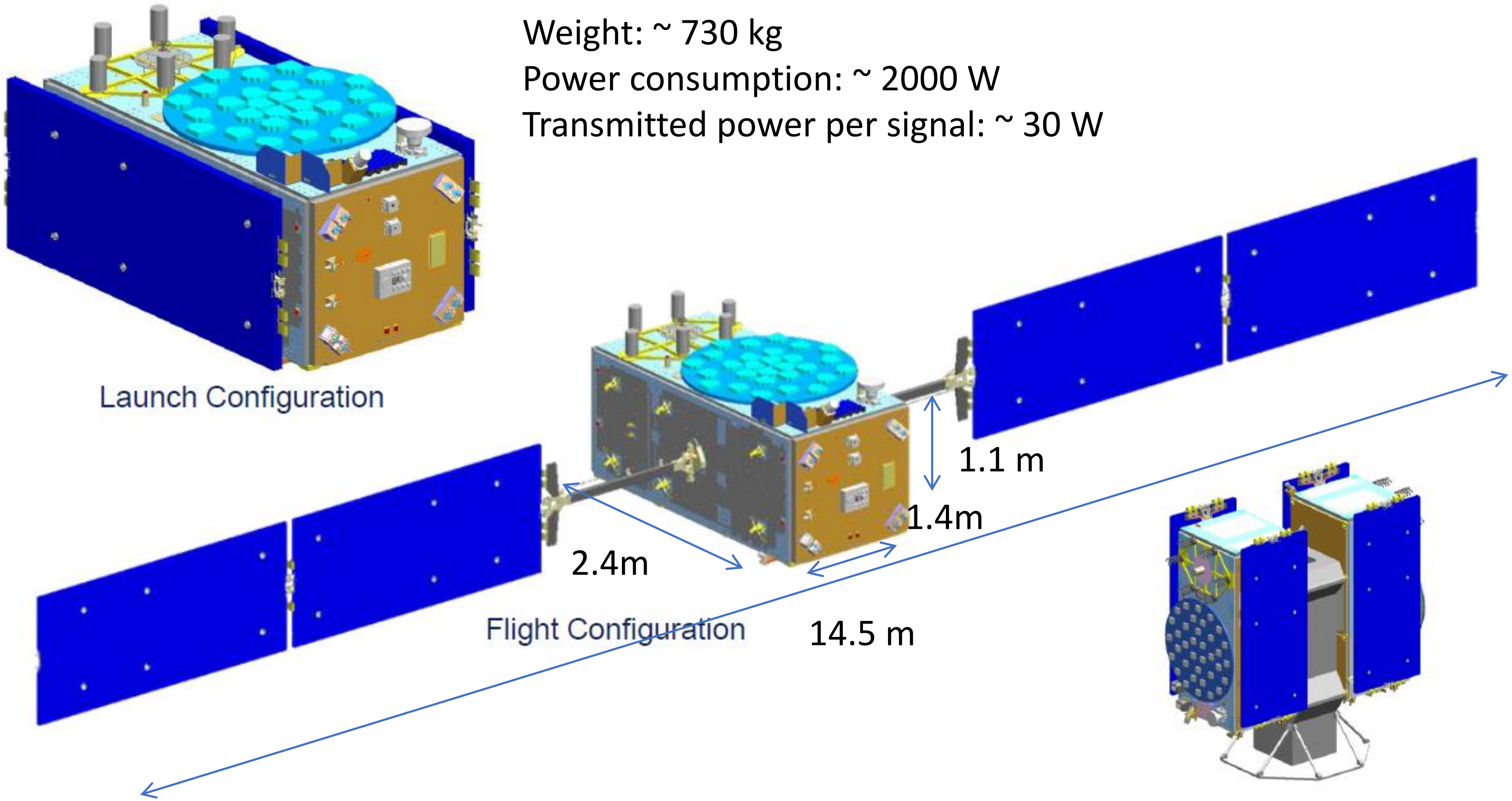
Walker Constellation 24/3/1

24 satellites

3 planes
8 satellites (+ 2 spares)/ plane
56° Inclination

Phasing between planes $\frac{1\cdot 360}{24} = 15°$

Galileo Satellite Dimensions



Launch Configuration

Weight: ~ 730 kg
Power consumption: ~ 2000 W
Transmitted power per signal: ~ 30 W

Flight Configuration

Satellites on Dispenser

~12 years lifetime

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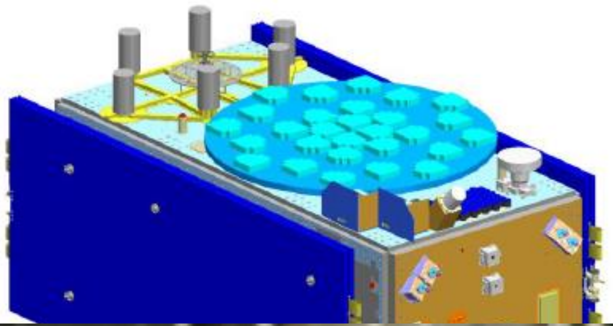

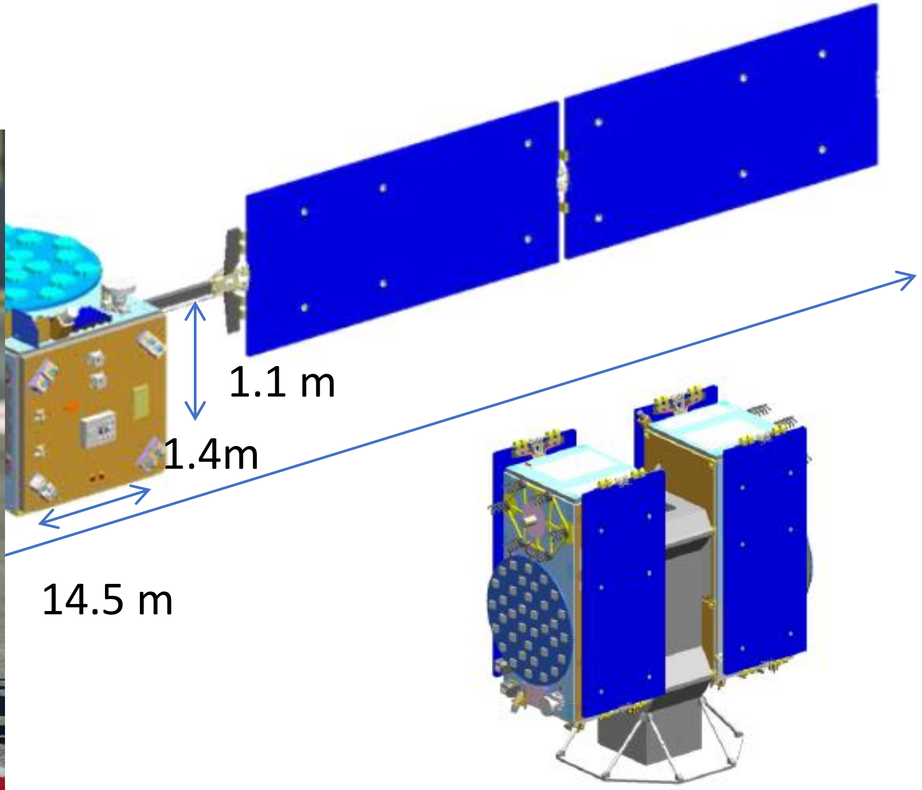

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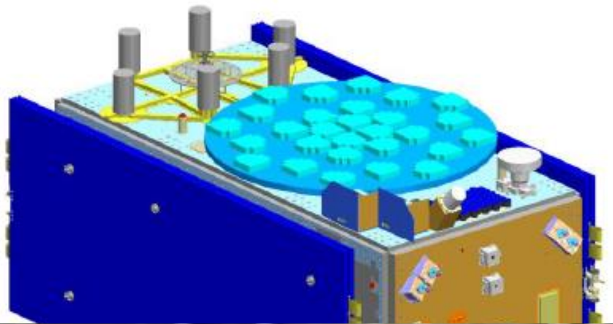

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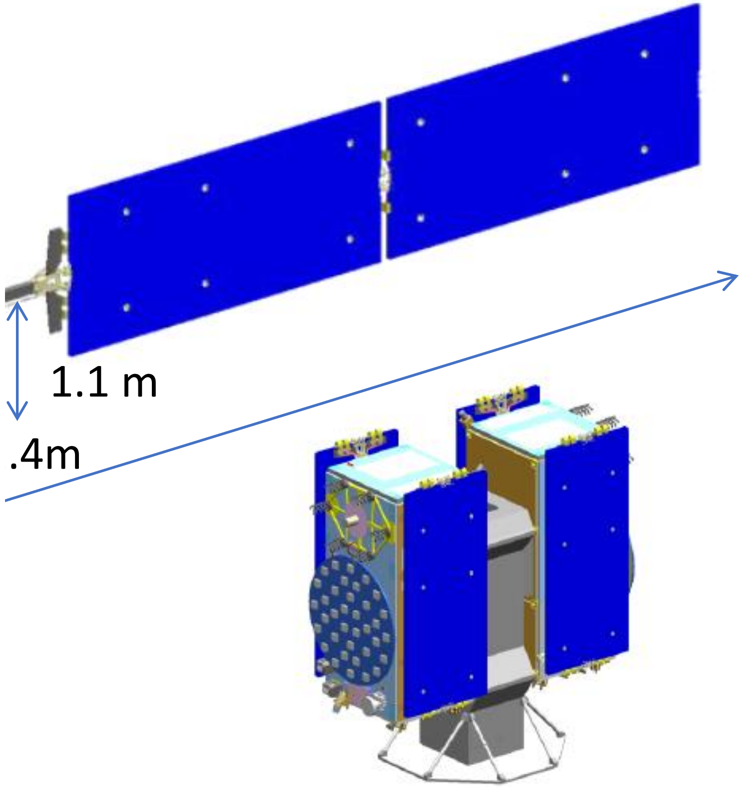

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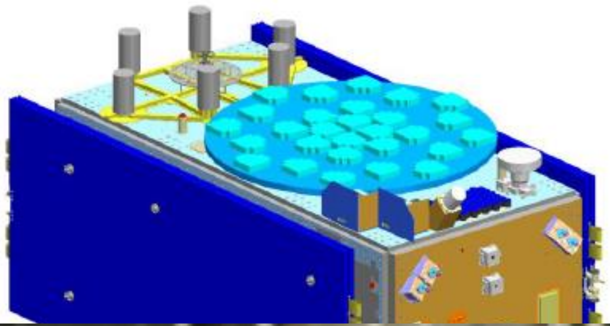

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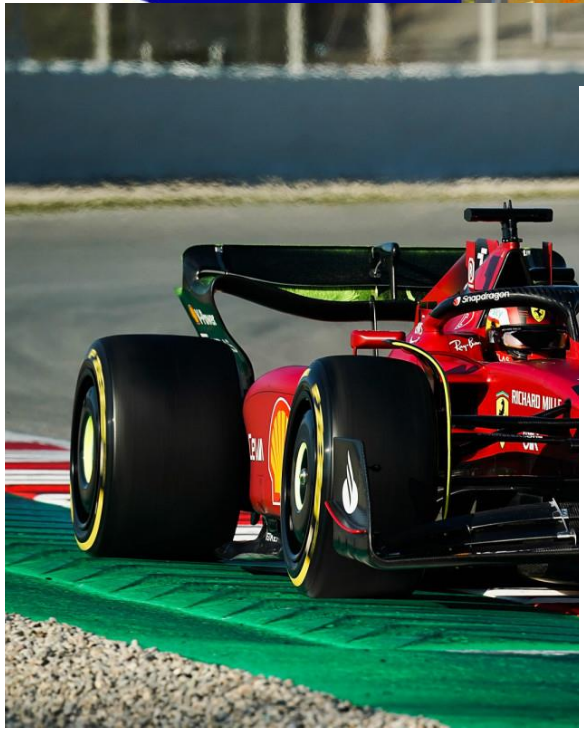
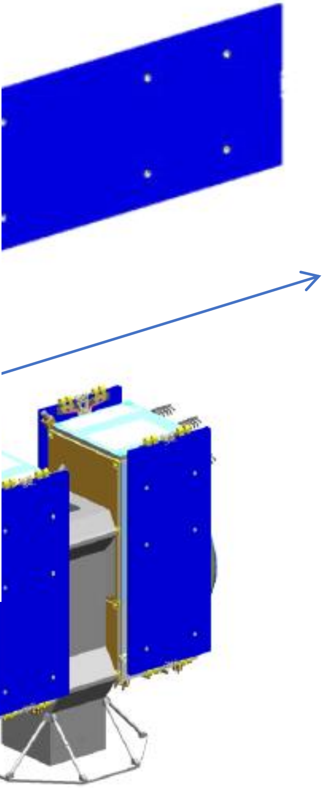




Satellites on Dispenser

~12 years lifetime

Galileo Satellite Clocks

Galileo is using two types of Ultra-Stable Atomic Clocks:

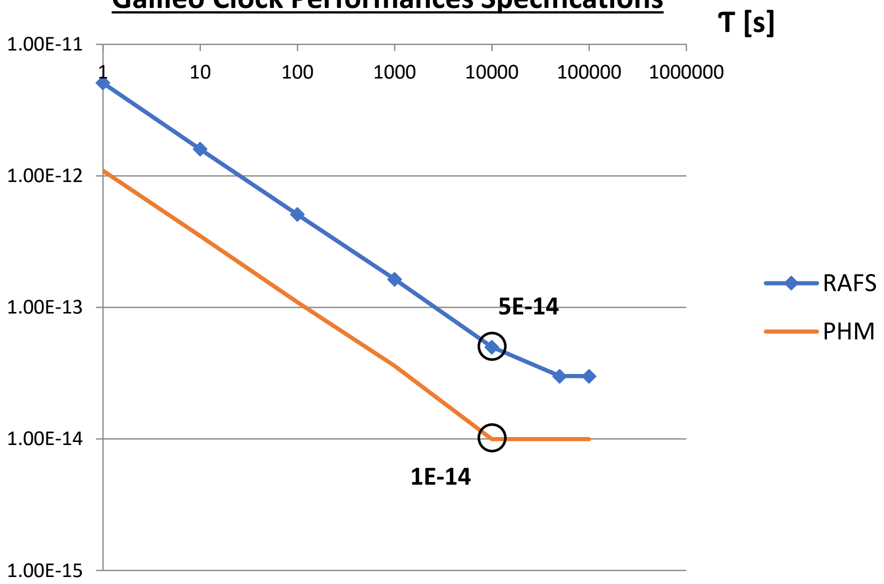
Passive Hydrogen Maser

18kg

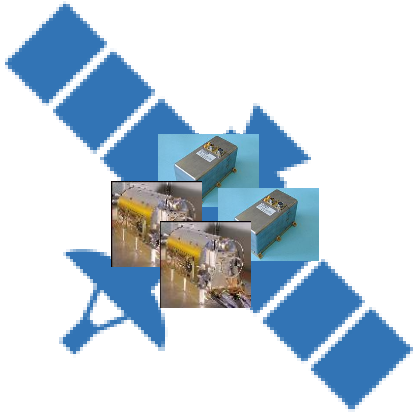
Rubidium Atomic Frequency Standard

5.5kg

Galileo Clock Performances Specifications

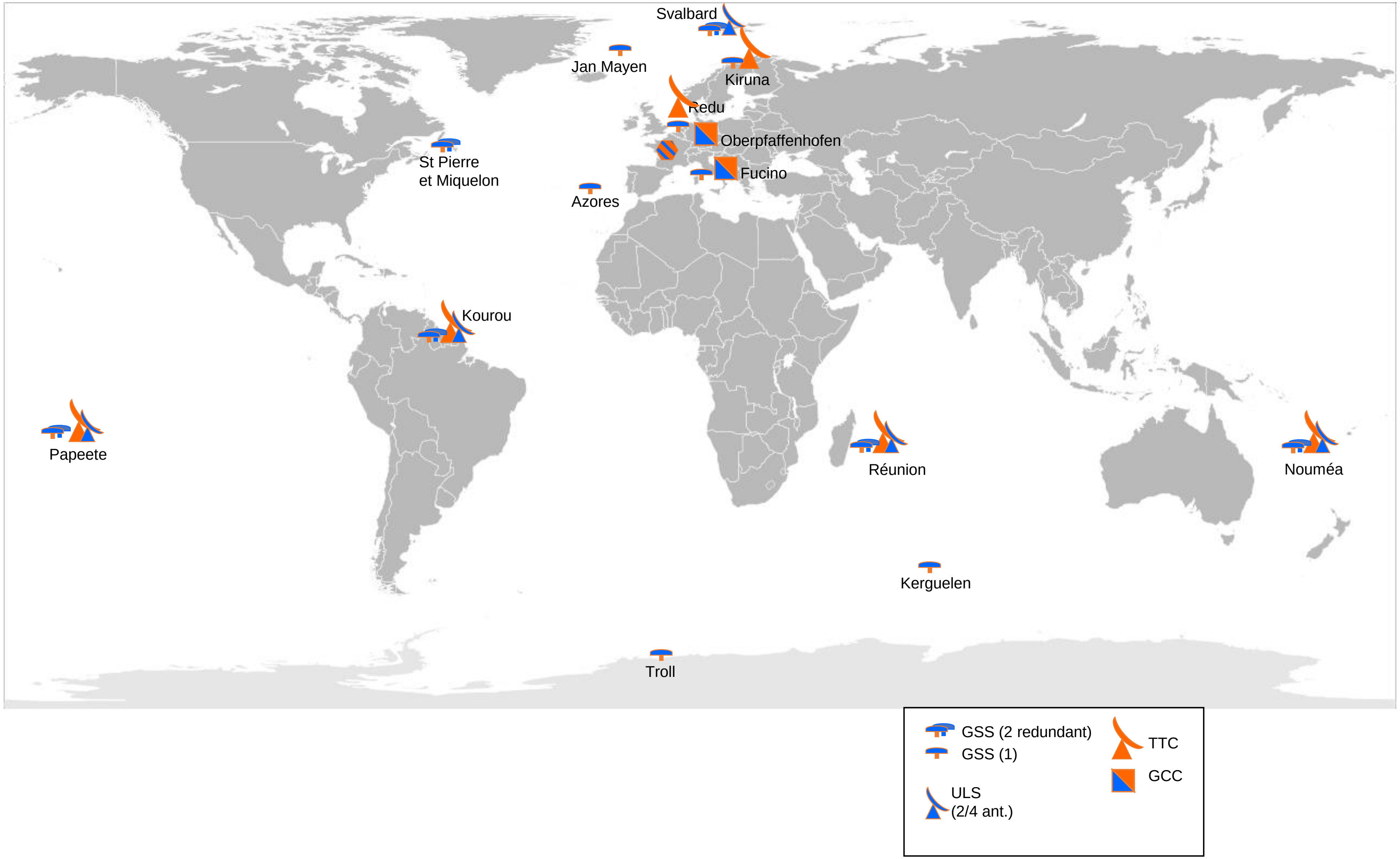


Allan Deviation = Measure of clock stability



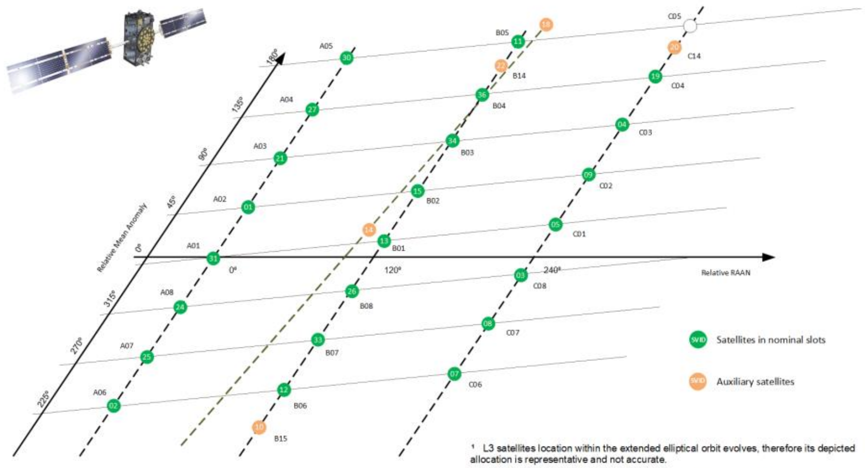
5ns = 1.5m Ranging Error (!)

Galileo Ground Segment



Galileo Up-to-Date Information

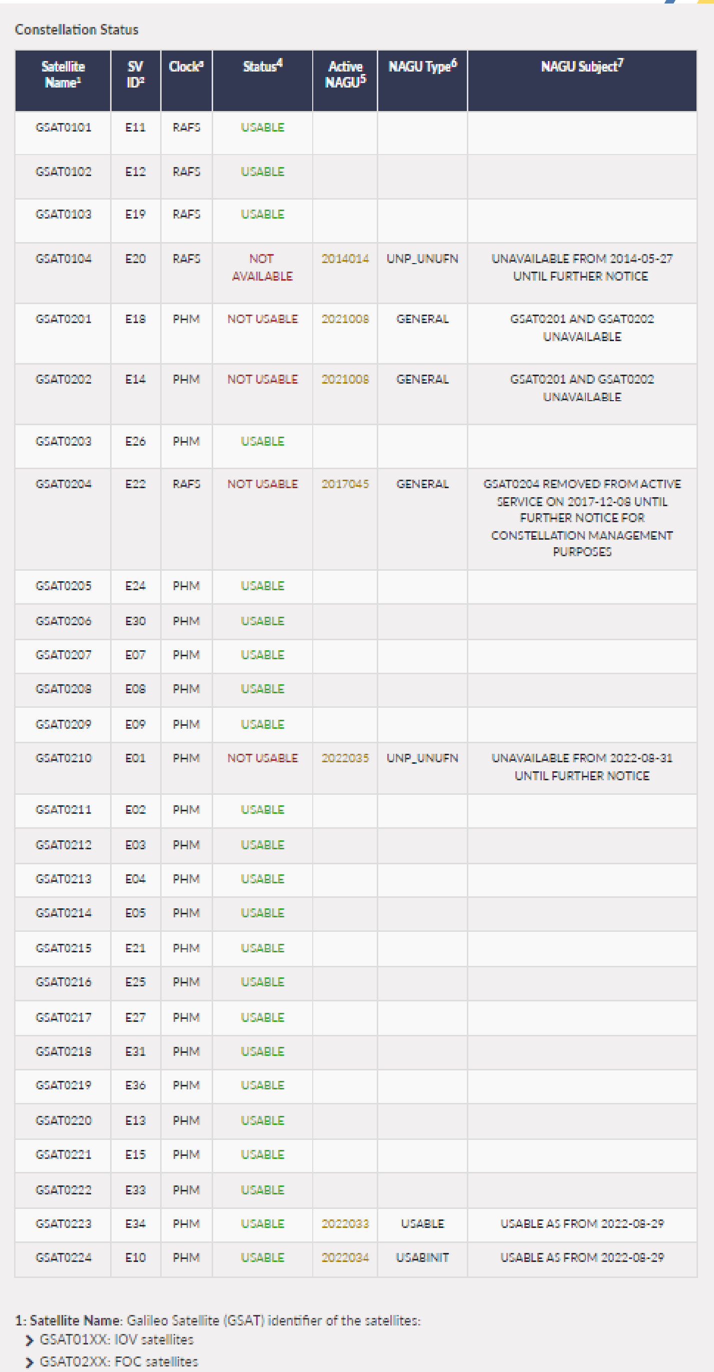
- https://www.gsc-europa.eu/system-service-status/constellation-information
- Currently:
  - 23 usable sats.
  - 5 not usable/not available
- Website includes
  - Orbital parameters
  - NAGUs/Service Notices



[1] L3 satellites location within the extended elliptical orbit evolves, therefore its depicted allocation is representative and not accurate.

[2] The plot represents the relative Mean Anomaly and RAAN with respect to slot A1. It does not correspond to a specific date.

- https://www.gsc-europa.eu/support-to-developers/galileo-satellite-metadata



Constellation Status

Satellite Name[1]	SV ID[2]	Clock[3]	Status[4]	Active NAGU[5]	NAGU Type[6]	NAGU Subject[7]
GSAT0101	E11	RAFS	USABLE			
GSAT0102	E12	RAFS	USABLE			
GSAT0103	E19	RAFS	USABLE			
GSAT0104	E20	RAFS	NOT AVAILABLE	2014014	UNP_UNUFN	UNAVAILABLE FROM 2014-05-27 UNTIL FURTHER NOTICE
GSAT0201	E18	PHM	NOT USABLE	2021008	GENERAL	GSAT0201 AND GSAT0202 UNAVAILABLE
GSAT0202	E14	PHM	NOT USABLE	2021008	GENERAL	GSAT0201 AND GSAT0202 UNAVAILABLE
GSAT0203	E26	PHM	USABLE			
GSAT0204	E22	RAFS	NOT USABLE	2017045	GENERAL	GSAT0204 REMOVED FROM ACTIVE SERVICE ON 2017-12-08 UNTIL FURTHER NOTICE FOR CONSTELLATION MANAGEMENT PURPOSES
GSAT0205	E24	PHM	USABLE			
GSAT0206	E30	PHM	USABLE			
GSAT0207	E07	PHM	USABLE			
GSAT0208	E08	PHM	USABLE			
GSAT0209	E09	PHM	USABLE			
GSAT0210	E01	PHM	NOT USABLE	2022035	UNP_UNUFN	UNAVAILABLE FROM 2022-08-31 UNTIL FURTHER NOTICE
GSAT0211	E02	PHM	USABLE			
GSAT0212	E03	PHM	USABLE			
GSAT0213	E04	PHM	USABLE			
GSAT0214	E05	PHM	USABLE			
GSAT0215	E21	PHM	USABLE			
GSAT0216	E25	PHM	USABLE			
GSAT0217	E27	PHM	USABLE			
GSAT0218	E31	PHM	USABLE			
GSAT0219	E36	PHM	USABLE			
GSAT0220	E13	PHM	USABLE			
GSAT0221	E15	PHM	USABLE			
GSAT0222	E33	PHM	USABLE			
GSAT0223	E34	PHM	USABLE	2022033	USABLE	USABLE AS FROM 2022-08-29
GSAT0224	E10	PHM	USABLE	2022034	USABINIT	USABLE AS FROM 2022-08-29

[1] **Satellite Name:** Galileo Satellite (GSAT) identifier of the satellites:
- GSAT01XX: IOV satellites
- GSAT02XX: FOC satellites

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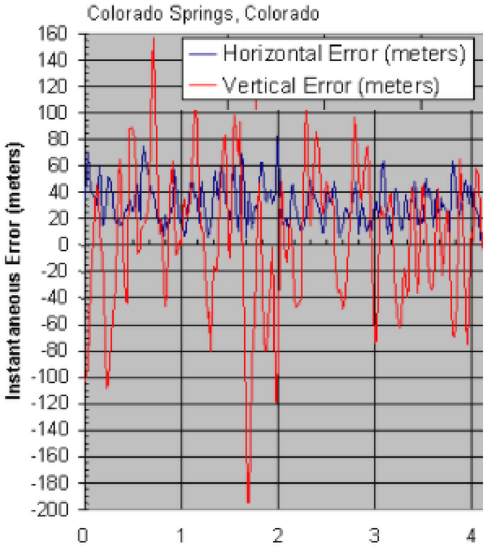
- Galileo
- GNSS Accuracy
- High Accuracy
  - RTK
  - PPP
- Galileo HAS (High Accuracy Service)

GNSS Accuracy

	Standalone	Augmented	
	Absolute positioning (global)	Absolute positioning	Differential positioning
Spreading code positioning (error >~ 1m)	- 1990s: GPS with Selective Availability **(~100m)**		
Carrier phase positioning (~1-20 cm)			

Accuracy and baseline lengths are approximate



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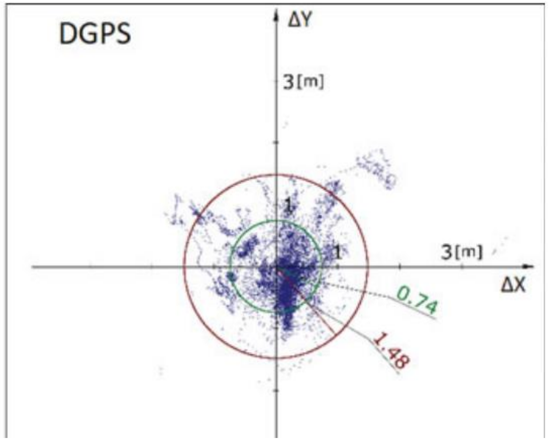

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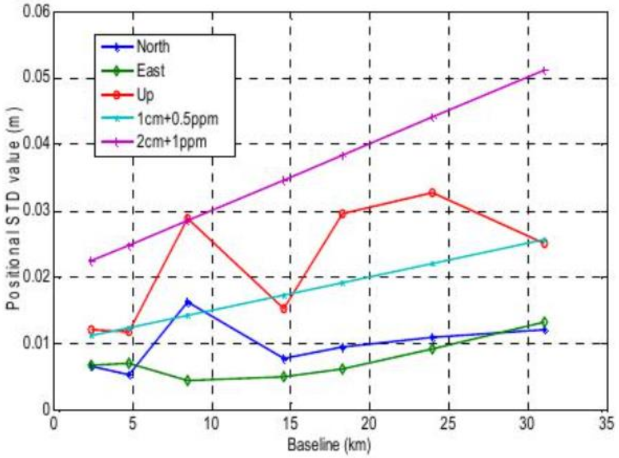

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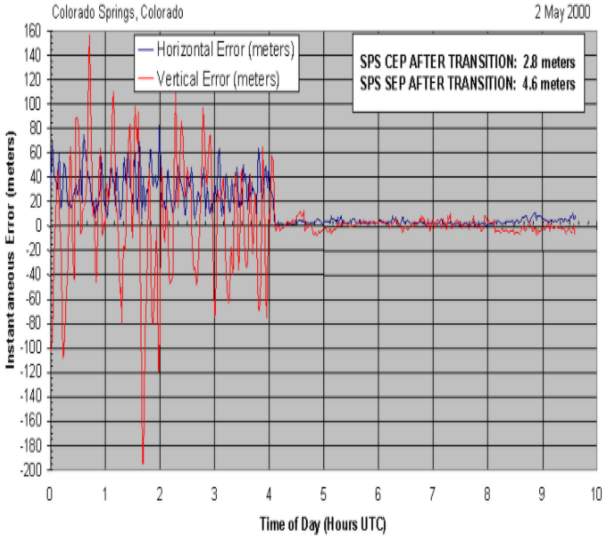

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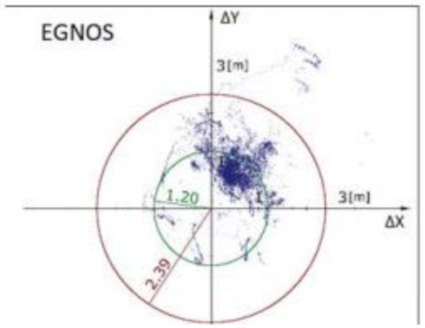

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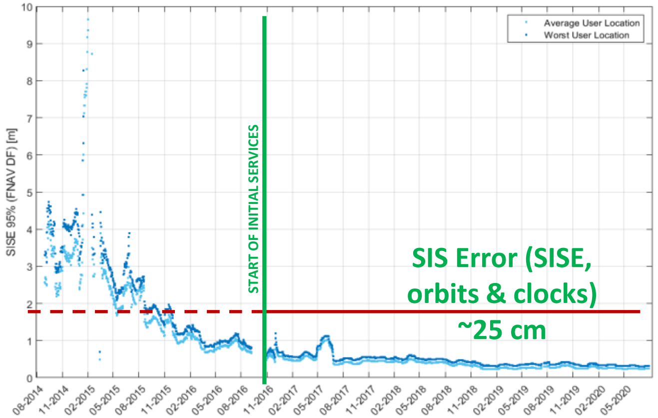
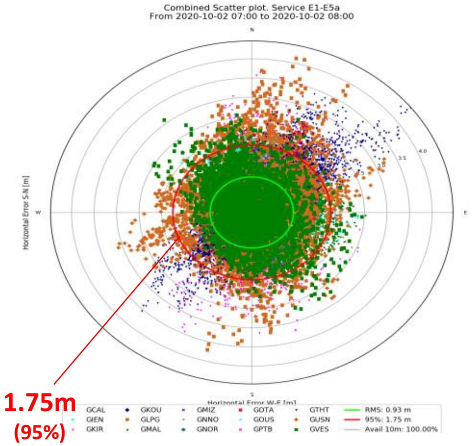


SIS Error (SISE, orbits & clocks)

~25 cm



1.75m
(95%)

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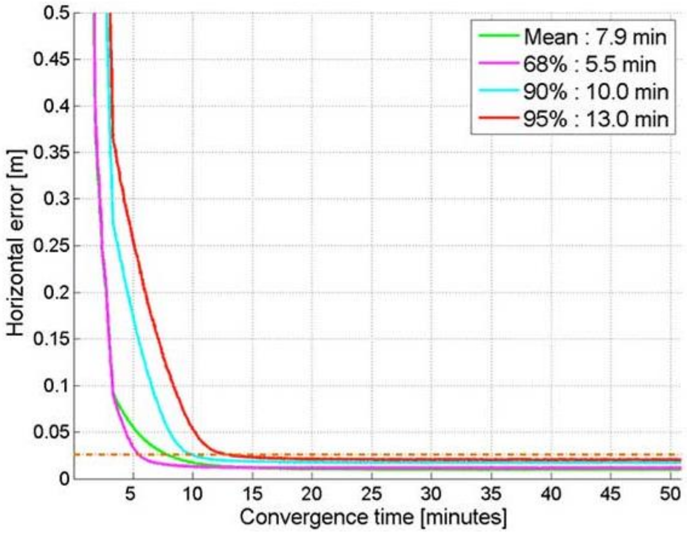

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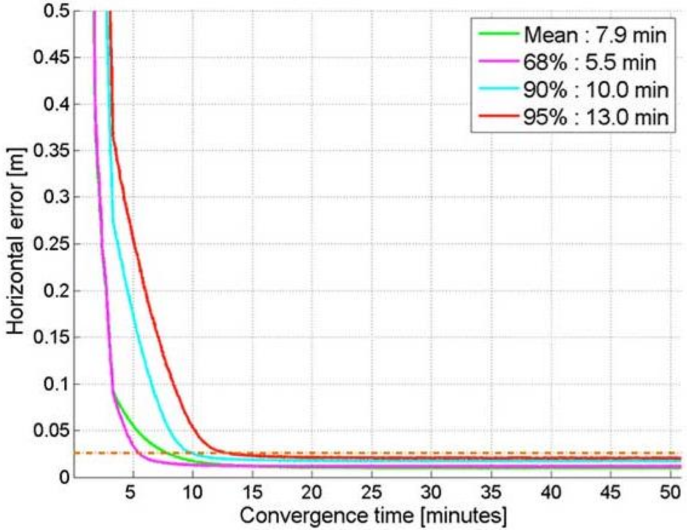

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Carrier phase positioning (~1-20 cm)	- 2020s: PPP from GNSS **(?-20cm)**: Precise orbits/clocks/biases (/ionosphere?) from GNSS. Lower convergence time with multi-frequency, multi-GNSS, ionosphere correction.	- 2010s: PPP **(~1-20cm)**, post-processing, then real time. Long (some mins in principle) convergence time. Needs satellite/ground link. - 2010s: PPP-RTK: model error contributions (mainly iono/tropo) with RTK networks -> short convergence.	- 1980s-90s: Static, then kinematic survey, post-processing, then kinematic survey in real-time (RTK). **(~1cm)**. Need base station some km away and ground link.

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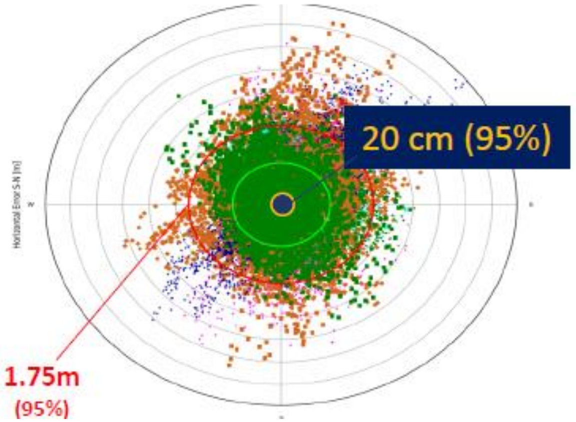

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Carrier Phase Measurements

- Pseudorange measurement equation:

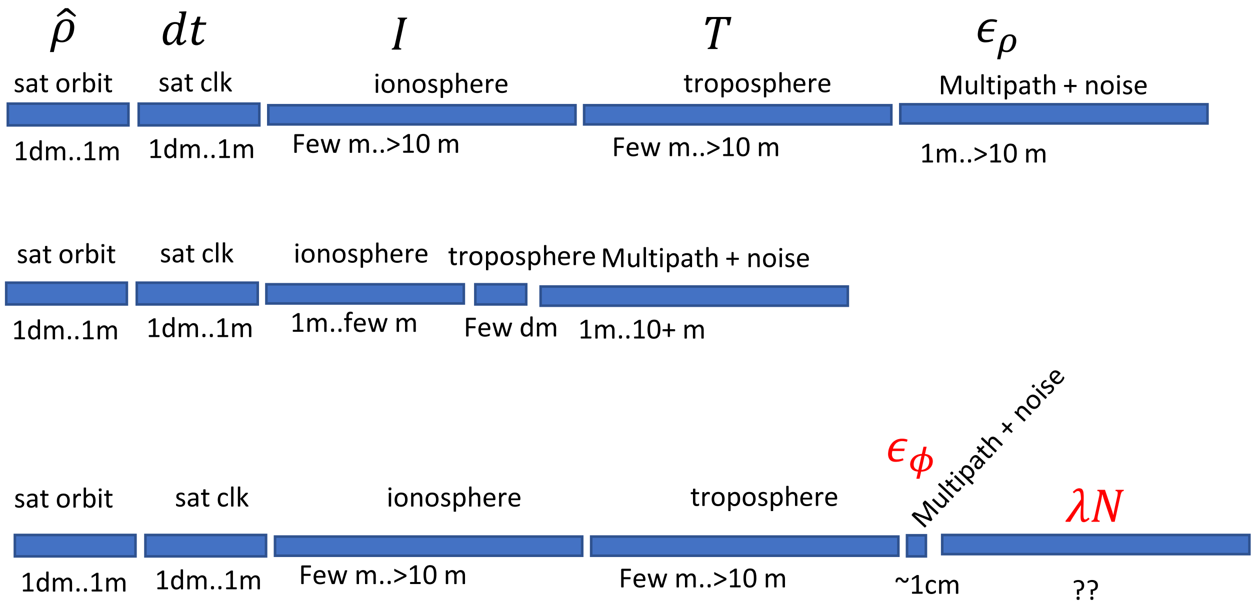
$$\rho = r + I + T + c(b - dt) + \epsilon_\rho$$

- Corrected pseudorange:

$$\rho_{corr} = r + I_{corr} + T_{corr} + c(b - dt) + \epsilon_\rho$$

- Carrier phase measurement equation:

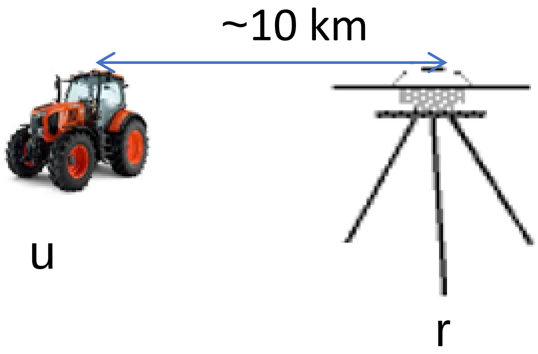
$$\phi = r - I + T + c(b - dt) + \lambda N + \epsilon_\phi$$



- Our objective is to reduce all errors as much a possible (cm level) so we can solve the carrier phase ambiguity
- Options:
  - Get more accurate corrections (PPP)
  - Cancel what we can through measurement linear combinations (RTK,PPP)

Real Time Kinematics

- Assume you have a reference station nearby (10km)
- You have synch’ed measurements from both your user receiver/rover (u) and the reference station (r)



- **Single difference:**

$$\phi_u = r_u - I_u + T_u + c(b_u - dt) + \lambda N_u + \epsilon_\phi$$

$$\phi_r = r_r - I_r + T_r + c(b_r - dt) + \lambda N_r + \epsilon_\phi$$

$$\phi_u - \phi_r = \phi_{ur} = r_{ur} + cb_{ur} + \lambda N_{ur} + \sqrt{2}\epsilon_\phi$$

- Iono, tropo, sat clk out. If N_r and N_u integer, N_{ur} integer. But noise error x $\sqrt{2}$

NB satellite index omitted

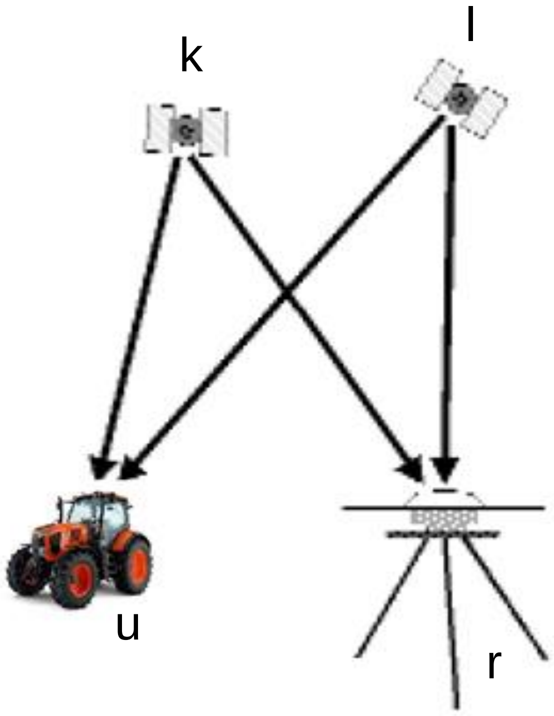
Real Time Kinematics

- Next objective: get rid of receiver biases with another linear combination.
- **Double difference**: subtract the single difference for one satellite (l) from that from another satellite (k)

$$\emptyset_{ur}^{kl} = \emptyset_{ur}^{k} - \emptyset_{ur}^{l} = r_{ur}^{kl} + N_{ur}^{kl} + 2\epsilon_{\phi}$$

- Now, satellite clock bias is cancelled. Noise error multiplied again by $\sqrt{2}$. No problem, still cm-level

- Remaining unknown: N_{ur}^{kl}



Real Time Kinematics

- How to remove N_{ur}^{kl}?
  - Observables at (sufficiently) different times -> geometric diversity. **Triple difference**
  - Requires continuous phase tracking (no cycle slips), so $N_{ur,t1}^{kl} = N_{ur,t2}^{kl}$

$$\emptyset_{ur,t2}^{kl} - \emptyset_{ur,t1}^{kl} = \emptyset_{ur,2,1}^{kl} = r_{ur,2,1}^{kl} + 2\sqrt{2}\epsilon_{\phi}$$

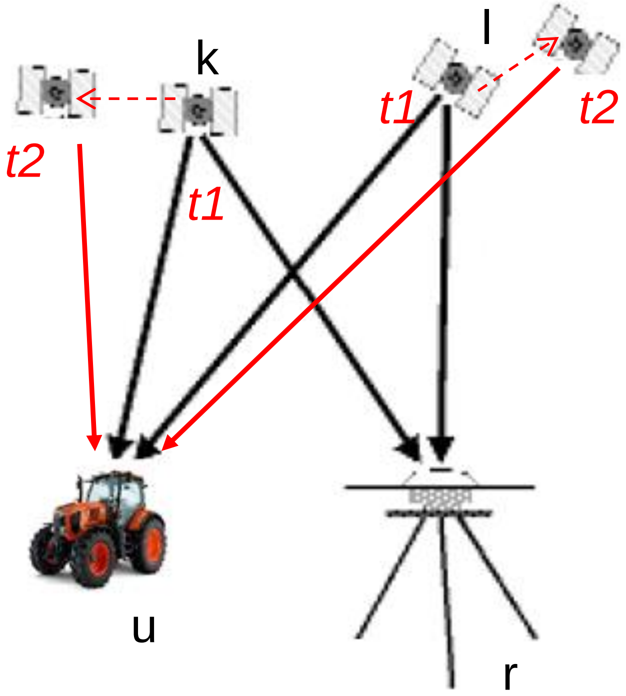
- -> all errors gone (except cm-level noise)

- Main disadvantage: waiting time

- Not exploited/discussed:
  - Linear combinations between frequencies of the same satellite (iono-free, widelane, narrow lane, geometry free)
    - https://gssc.esa.int/navipedia/index.php/Combination_of_GNSS_Measurements
  - Linear combinations of range and carrier phase (Melbourne-Wubbena)
    - https://gssc.esa.int/navipedia/index.php/Detector_based_in_code_and_carrier_phase_data:_The_Melbourne-W%C3%BCbbena_combination
  - Resolve ambiguities as a set. E.g.: LAMBDA method

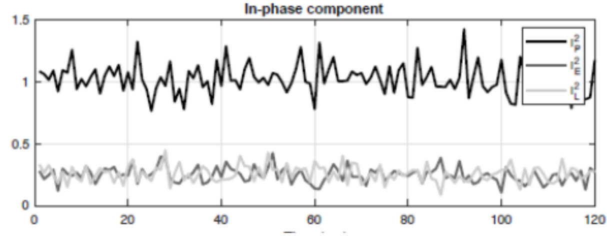
- Today’s RTK applications provide almost instantaneous convergence to cm-level position

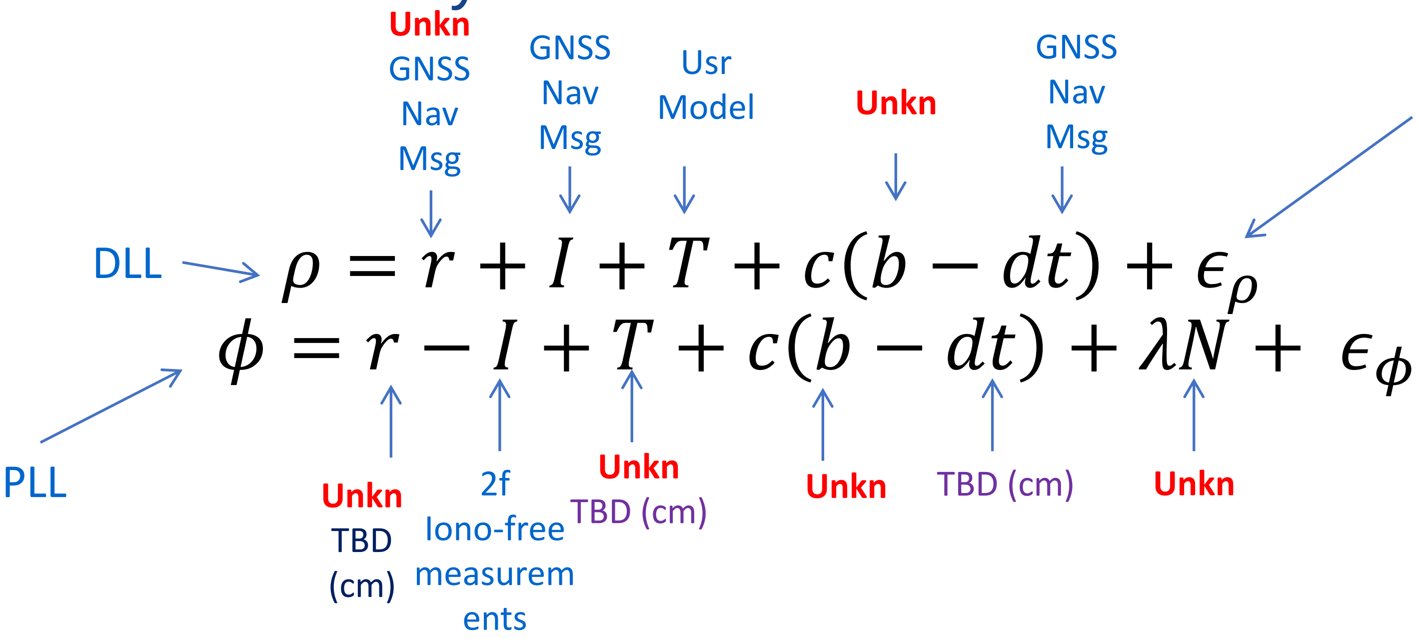
- Another ref: http://gpspp.sakura.ne.jp/rtklib/rtklib.htm



Precise Point Positioning (PPP)

- Absolute positioning with carrier phase measurements
- No reference station nearby needed





Unkn GNSS Nav Msg → r

GNSS Nav Msg → I

Usr Model → T

Unkn → b

GNSS Nav Msg → dt

DLL →

$$\rho = r + I + T + c(b - dt) + \epsilon_\rho$$

$$\phi = r - I + T + c(b - dt) + \lambda N + \ \epsilon_\phi$$

PLL →

r: **Unkn** TBD (cm)

I: 2f Iono-free measurements

T: **Unkn** TBD (cm)

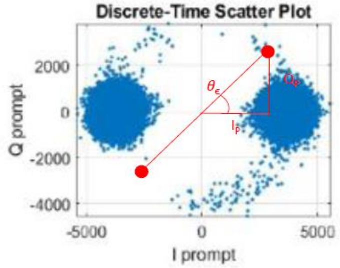
b: **Unkn**

dt: TBD (cm)

N: **Unkn**

$$\sigma^2_{\hat{\tau},\mathrm{EML}} \approx \frac{B_L \delta}{2\frac{C}{N_0}} \qquad (\mathrm{chips}^2)$$

$$\sigma^2_{\hat{\theta}} = \frac{B_\mathrm{L}}{\frac{C}{N_0}}\left(1 + \frac{1}{\underbrace{2\frac{C}{N_0}T}_{\text{SNR}}}\right) \qquad (\mathrm{rad}^2)$$



- Problems: remove/estimate I, T, dT, dt, N with a cm-level error
- Solution: iono-free (I), trilaning (N), tropospheric model or additional unknown (Tz), high accuracy satellite orbits (ρ) and clocks (dt), and biases for multiple frequencies

Precise Point Positioning (PPP)

- Iono-free measurements: remove 1st order iono error (99.9%)

$$I = \frac{40.3\,TEC}{f^2} \qquad \emptyset_{IF} = \frac{f_1^2\emptyset_1 - f_2^2\emptyset_2}{f_1^2 - f_2^2} \qquad p_{IF} = \frac{f_1^2 p_1 - f_2^2 p_2}{f_1^2 - f_2^2}$$

- Problem of iono-free:
  - multiplies code error by >2 depending on the frequency combination
  - Makes N non-integer
  - Therefore, accurate ionospheric corrections still useful

- Tropospheric Zenith Delay (TZD): based on mapping function and real time corrections, or estimated in the receiver (just 1 extra unknown, very stable)

- cm-level orbits and clocks require:
  - Precise models for satellite solar radiation pressure, antenna phase centre, centre of mass, phase wind-up, Earth rotation, tides…
  - A real-time monitoring and communication system. Several hundred bps needed

Kouba, J., & Héroux, P. (2001). Precise point positioning using IGS orbit and clock products. *GPS solutions*, *5*(2), 12-28.

Precise Point Positioning (PPP)

- Typical PPP solution state vector (iono-free)

$$X = (x, y, z, v_x, v_y, v_z, b_{IF}, T_Z, N^1, \dots, N^K)$$

- Typical PPP solution: Kalman Filter
  - Prediction phase: estimate state vector based on previous state
  - Correction phase: adjust based on new measurements

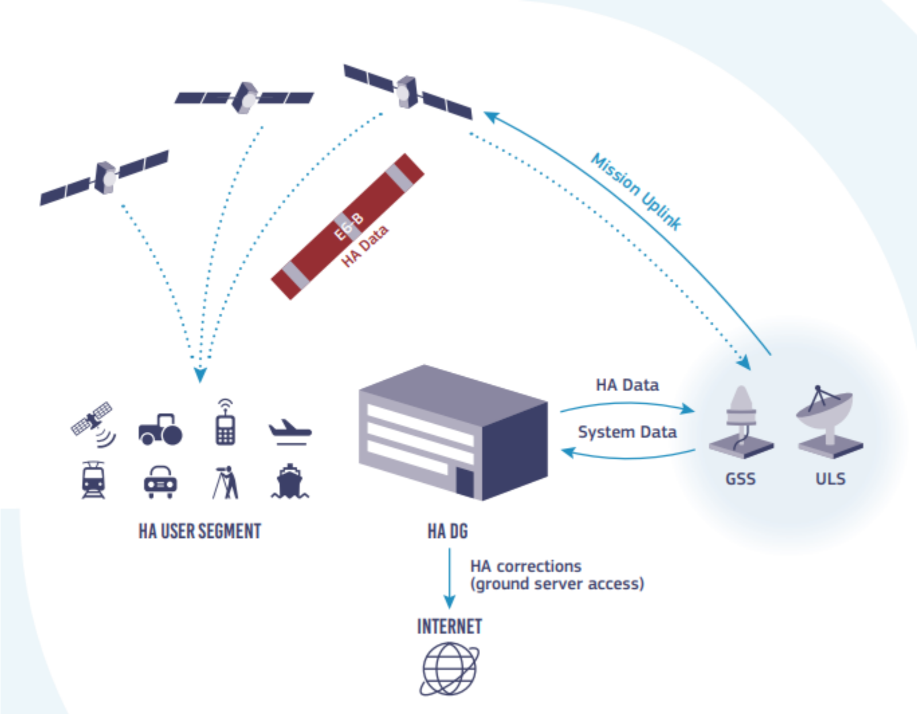
- Still, very accurate satellite (orbits, clocks, inter-freq. Biases) information required -> objective of PPP services, like Galileo HAS

Kouba, J., & Héroux, P. (2001). Precise point positioning using IGS orbit and clock products. *GPS solutions*, *5*(2), 12-28.

Table of Contents

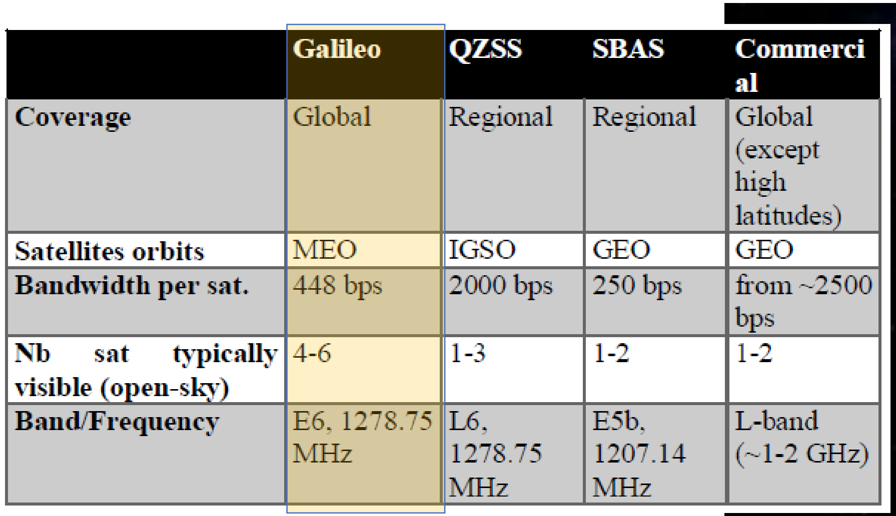
Overview of Galileo High Accuracy Service (HAS)

- Galileo High Accuracy Service provides orbit, clock, code and phase biases for Galileo and GPS (I/NAV & CNAV iono-free and Galileo E1, E5a,E5b, E6B/C and GPS L1C/A, L2C, L2P signals)
- Ionospheric corrections in Europe to be provided in the future (2024+)
- Ground dissemination channel through a real-time connection in RTCM-like format
- High update rate and dissemination delay of few seconds
- Users informed if a satellite shall not be used for PPP solution

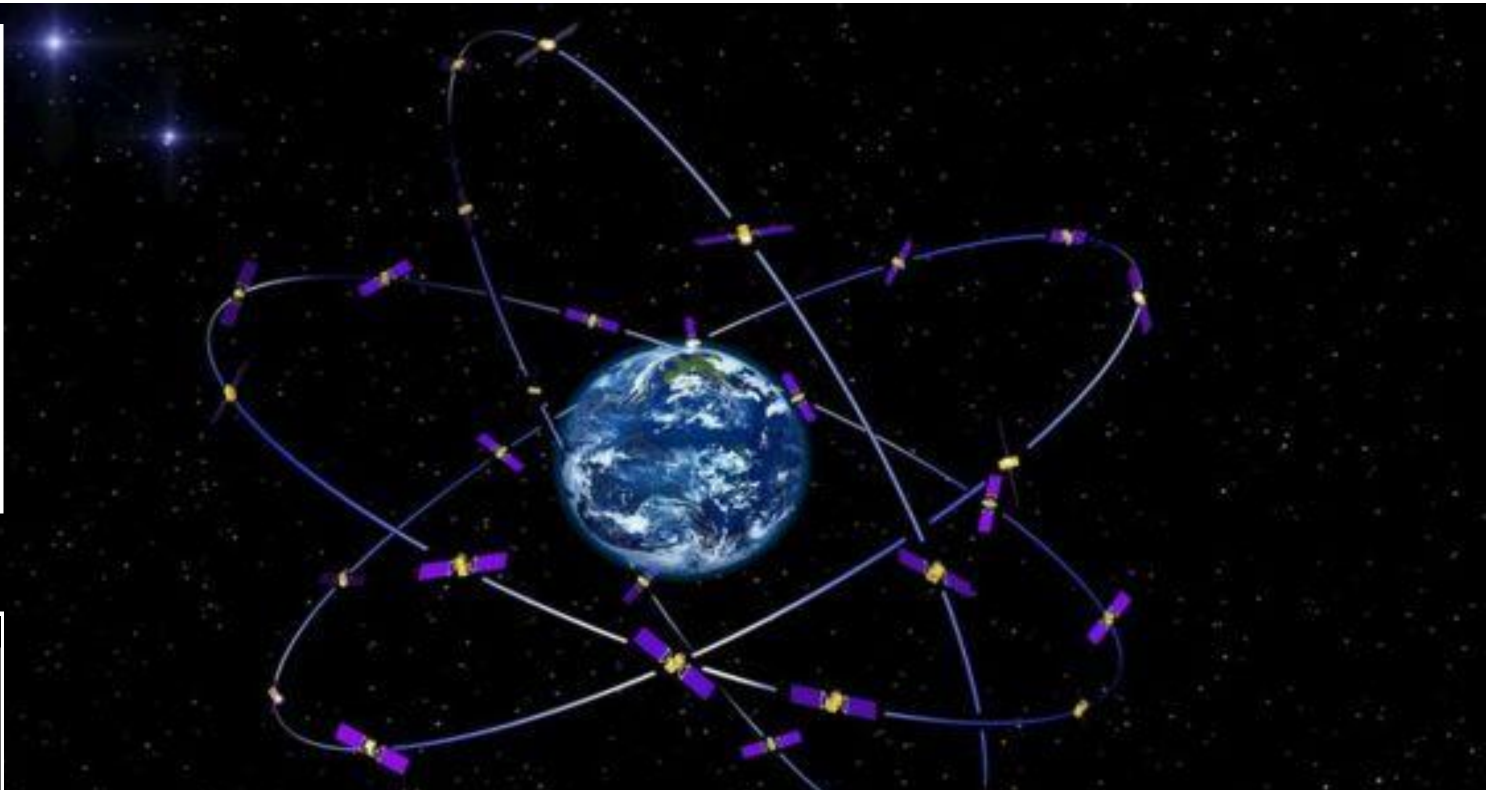


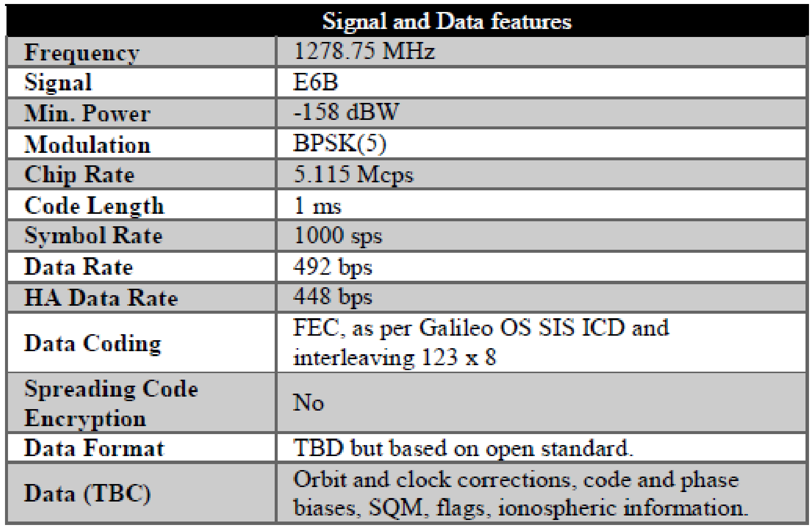
European Union Agency for the Space Program (EUSPA), "Information Note on Galileo High Accuracy Service," 2020. [Online]. Available: https://www.gsc-europa.eu/sites/default/files/sites/all/files/Galileo_HAS_Info_Note.pdf.
European Union, "E6-B/C Signal-In-Space Technical Note," 2019. [Online]. https://www.gsc-europa.eu/sites/default/files/sites/all/files/E6BC_SIS_Technical_Note.pdf.
HAS Signal In Space ICD
I. Martini, IONGNSS+ 2022

Galileo HAS Signal

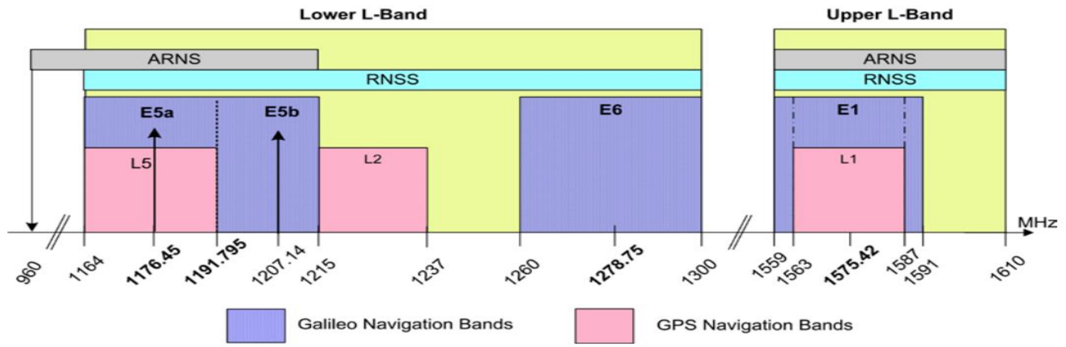


	Galileo	QZSS	SBAS	Commercial
Coverage	Global	Regional	Regional	Global (except high latitudes)
Satellites orbits	MEO	IGSO	GEO	GEO
Bandwidth per sat.	448 bps	2000 bps	250 bps	from ~2500 bps
Nb sat typically visible (open-sky)	4-6	1-3	1-2	1-2
Band/Frequency	E6, 1278.75 MHz	L6, 1278.75 MHz	E5b, 1207.14 MHz	L-band (~1-2 GHz)

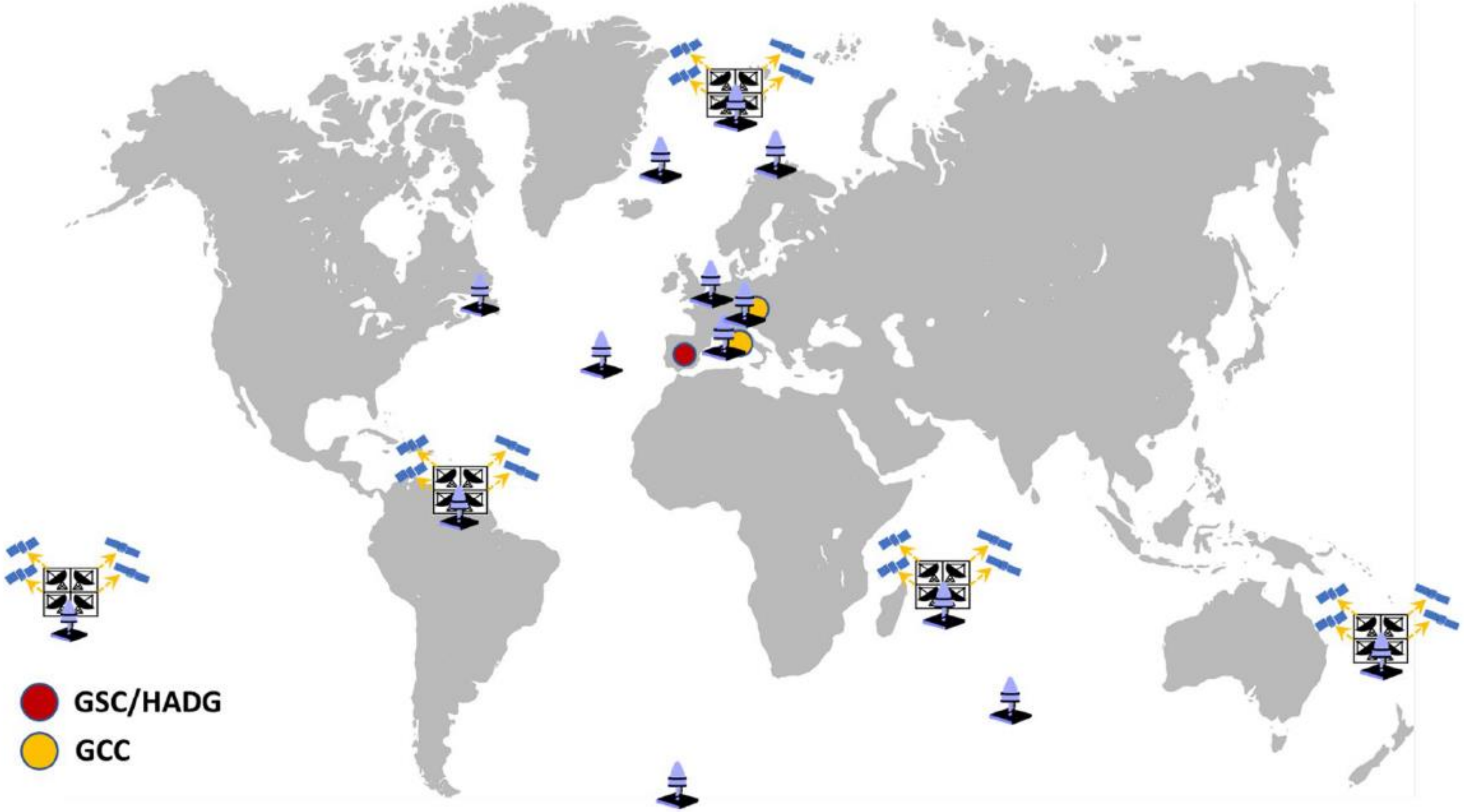




Signal and Data features	
Frequency	1278.75 MHz
Signal	E6B
Min. Power	-158 dBW
Modulation	BPSK(5)
Chip Rate	5.115 Mcps
Code Length	1 ms
Symbol Rate	1000 sps
Data Rate	492 bps
HA Data Rate	448 bps
Data Coding	FEC, as per Galileo OS SIS ICD and interleaving 123 x 8
Spreading Code Encryption	No
Data Format	TBD but based on open standard.
Data (TBC)	Orbit and clock corrections, code and phase biases, SQM, flags, ionospheric information.



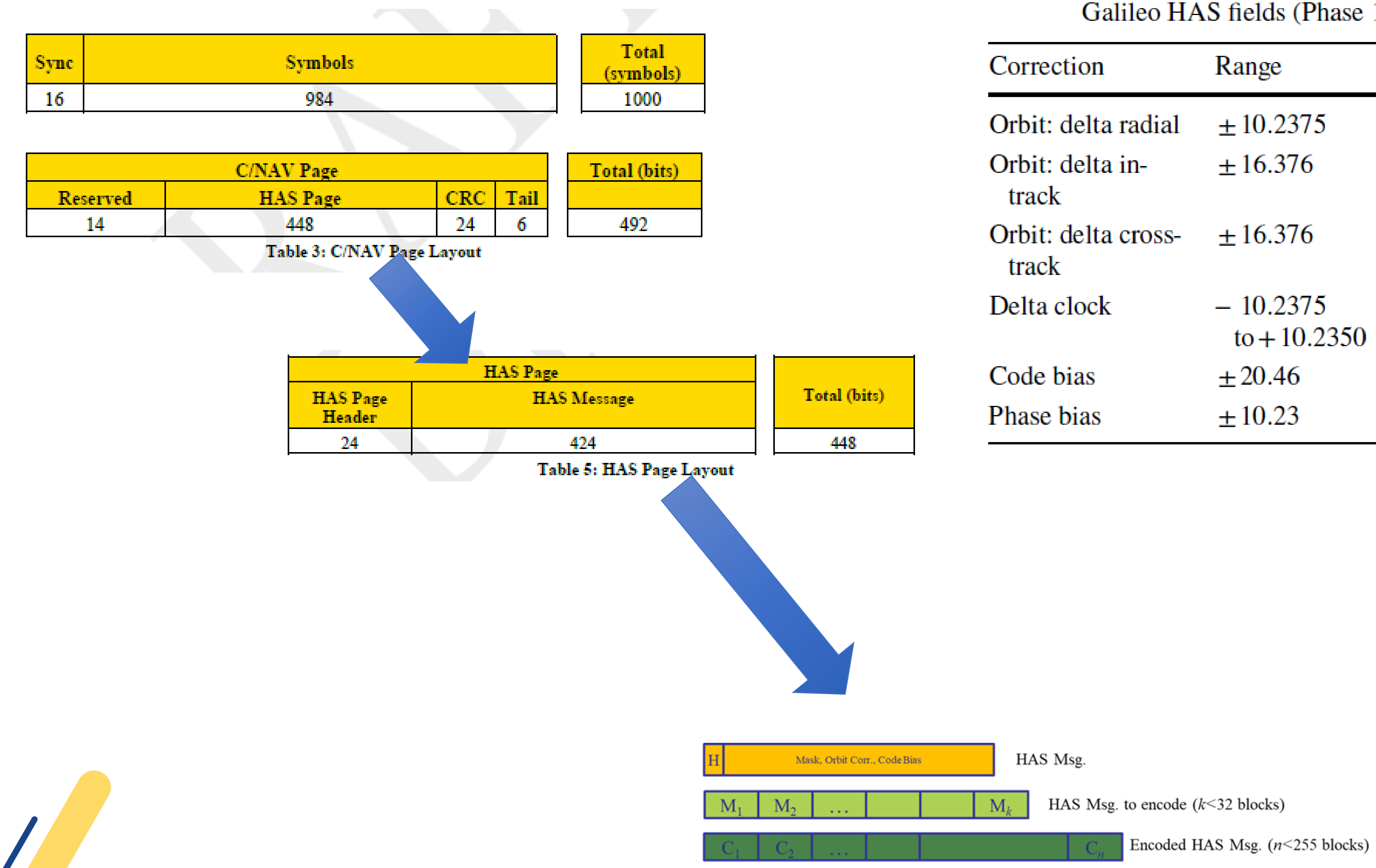
Galileo HAS infrastructure



Galileo HAS Phase 1 architecture. The 14 GSS (Galileo Sensor Stations) are depicted with a single antenna, and the five ULS (Up-Link stations) are depicted with four antennas

Fernandez-Hernandez, I., Chamorro-Moreno, A., Cancela-Diaz, S., Calle-Calle, J. D., Zoccarato, P., Blonski, D., ... & Mozo, A. (2022). Galileo high accuracy service: initial definition and performance. *GPS Solutions*, *26*(3), 1-18

HAS SIS ICD message structure



Sync	Symbols	Total (symbols)
16	984	1000

C/NAV Page				Total (bits)
Reserved	HAS Page	CRC	Tail	
14	448	24	6	492

Table 3: C/NAV Page Layout

HAS Page		Total (bits)
HAS Page Header	HAS Message	
24	424	448

Table 5: HAS Page Layout

HAS Msg.

HAS Msg. to encode (k<32 blocks)

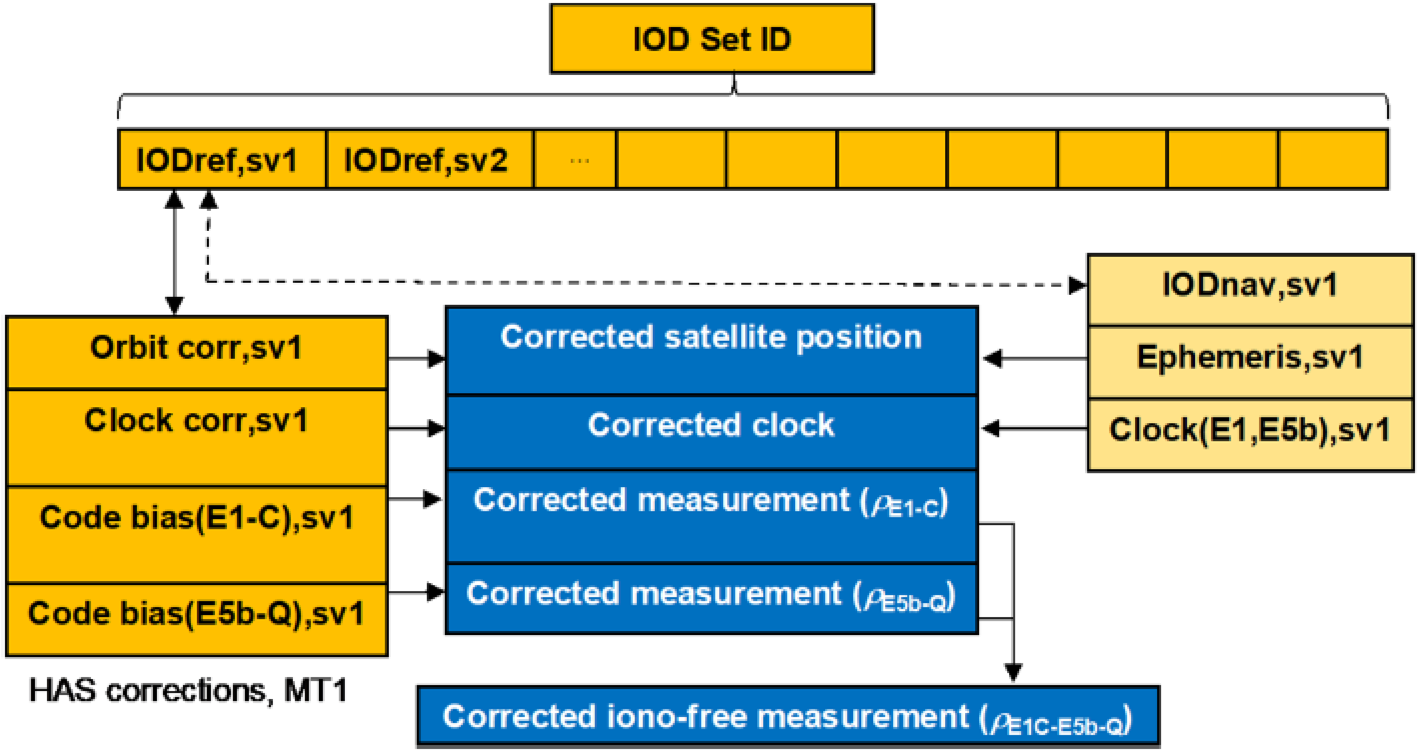
Encoded HAS Msg. (n<255 blocks)

Galileo HAS fields (Phase 1)

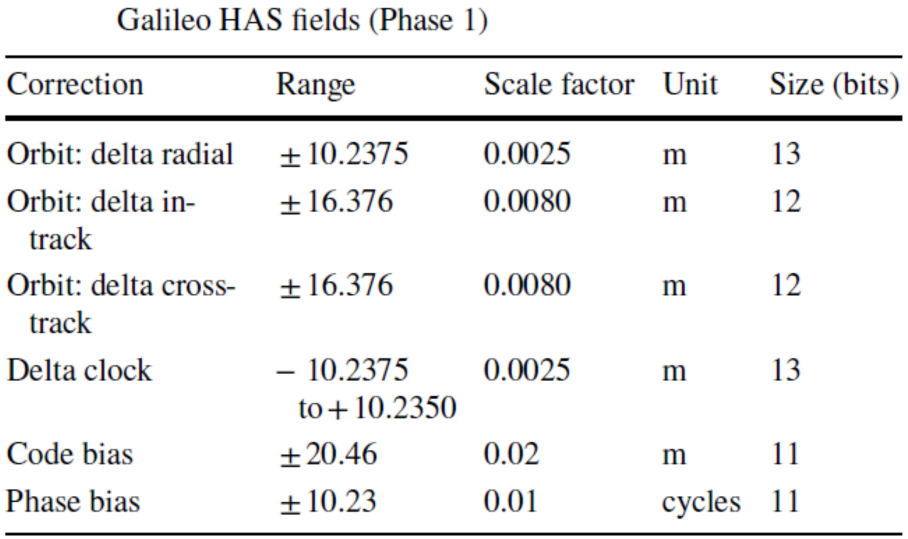
Correction	Range	Scale factor	Unit	Size (bits)
Orbit: delta radial	±10.2375	0.0025	m	13
Orbit: delta in-track	±16.376	0.0080	m	12
Orbit: delta cross-track	±16.376	0.0080	m	12
Delta clock	− 10.2375 to + 10.2350	0.0025	m	13
Code bias	±20.46	0.02	m	11
Phase bias	±10.23	0.01	cycles	11

NEW
GALILEO
HAS SIS ICD
PUBLISHED

HAS SIS ICD message structure



HAS corrections, MT1



Galileo HAS fields (Phase 1)

Correction	Range	Scale factor	Unit	Size (bits)
Orbit: delta radial	± 10.2375	0.0025	m	13
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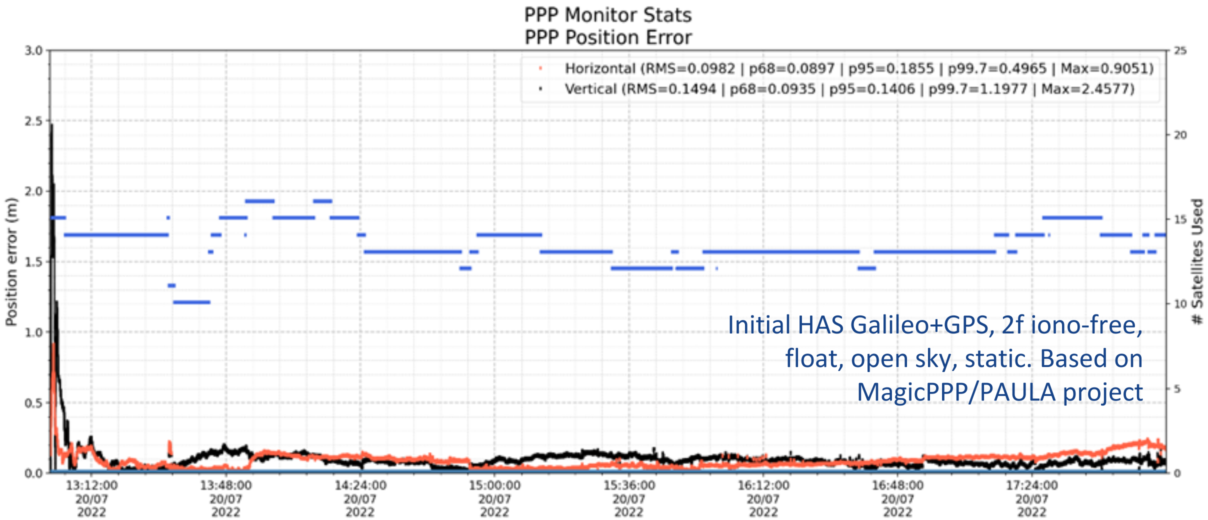
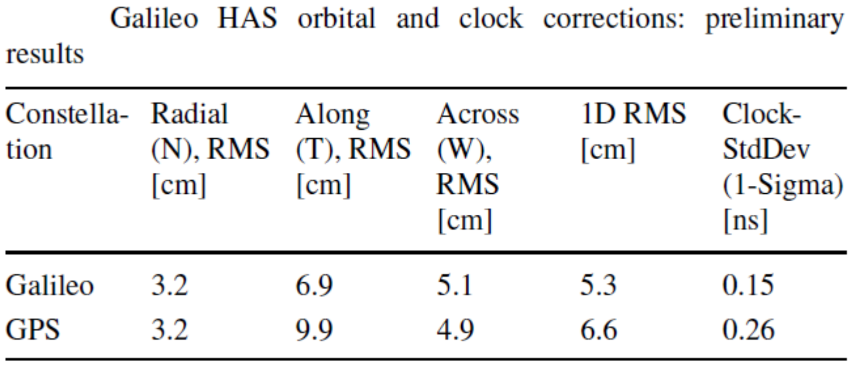
Orbit: delta cross-track	± 16.376	0.0080	m	12
Delta clock	− 10.2375 to + 10.2350	0.0025	m	13
Code bias	± 20.46	0.02	m	11
Phase bias	± 10.23	0.01	cycles	11

HAS Status and Plans

- HAS SIS ICD available since May 22
- Since July 22, HAS signal also available worldwide with orbit and clock corrections and biases for Galileo (E1, E5a/b, E6) and GPS (L1C/A, L2C)
- **Still in validation phase, but very high performance already!**
- Initial Service declaration foreseen for end'22, including an internet-based correction distribution service



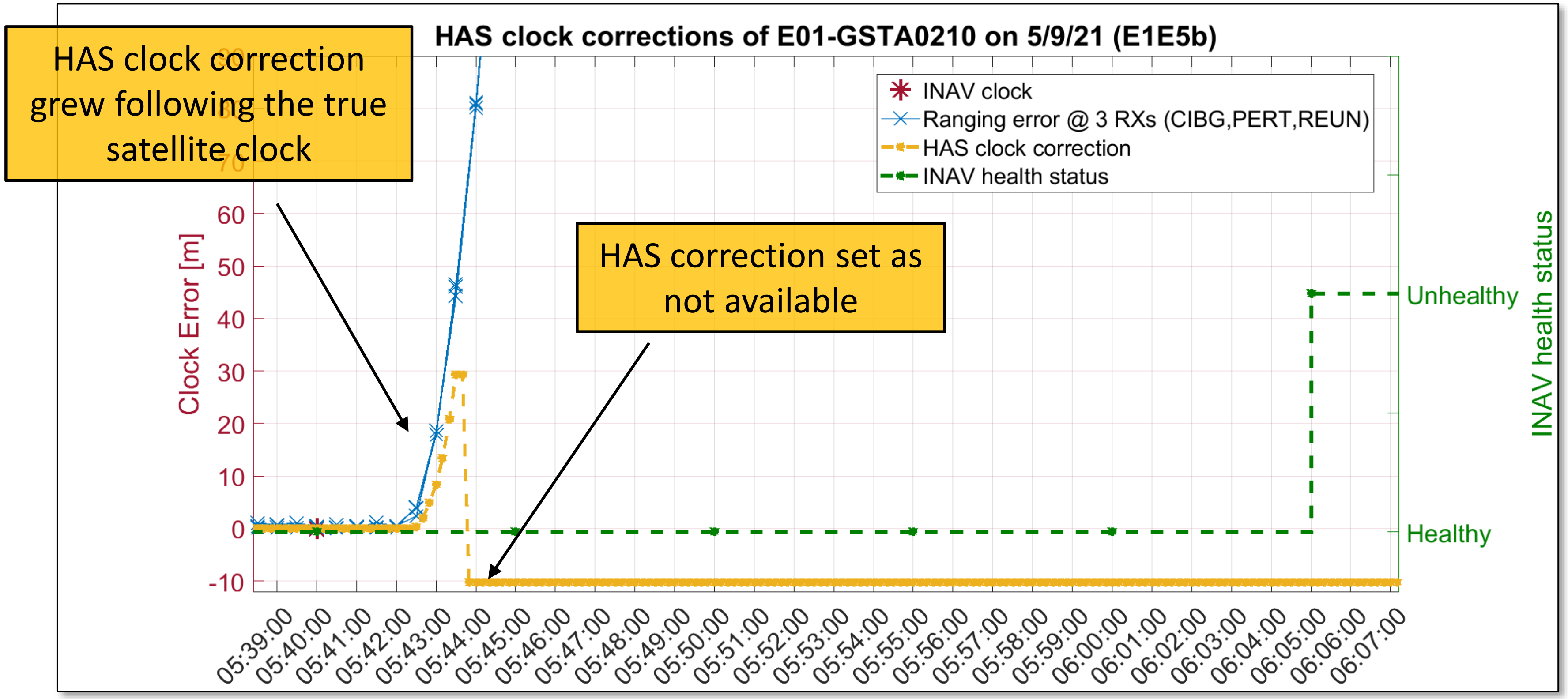
Initial HAS Galileo+GPS, 2f iono-free, float, open sky, static. Based on MagicPPP/PAULA project


Galileo HAS orbital and clock corrections: preliminary results

Constellation	Radial (N), RMS [cm]	Along (T), RMS [cm]	Across (W), RMS [cm]	1D RMS [cm]	Clock-StdDev (1-Sigma) [ns]
Galileo	3.2	6.9	5.1	5.3	0.15
GPS	3.2	9.9	4.9	6.6	0.26

HAS and fault detection

- If the HAS correction value grows and shows a degradation of the orbit and/or clock error, the user excludes the satellite to avoid impact on the position performance
- In addition, the HAS message informs the user that the satellite shall not be used

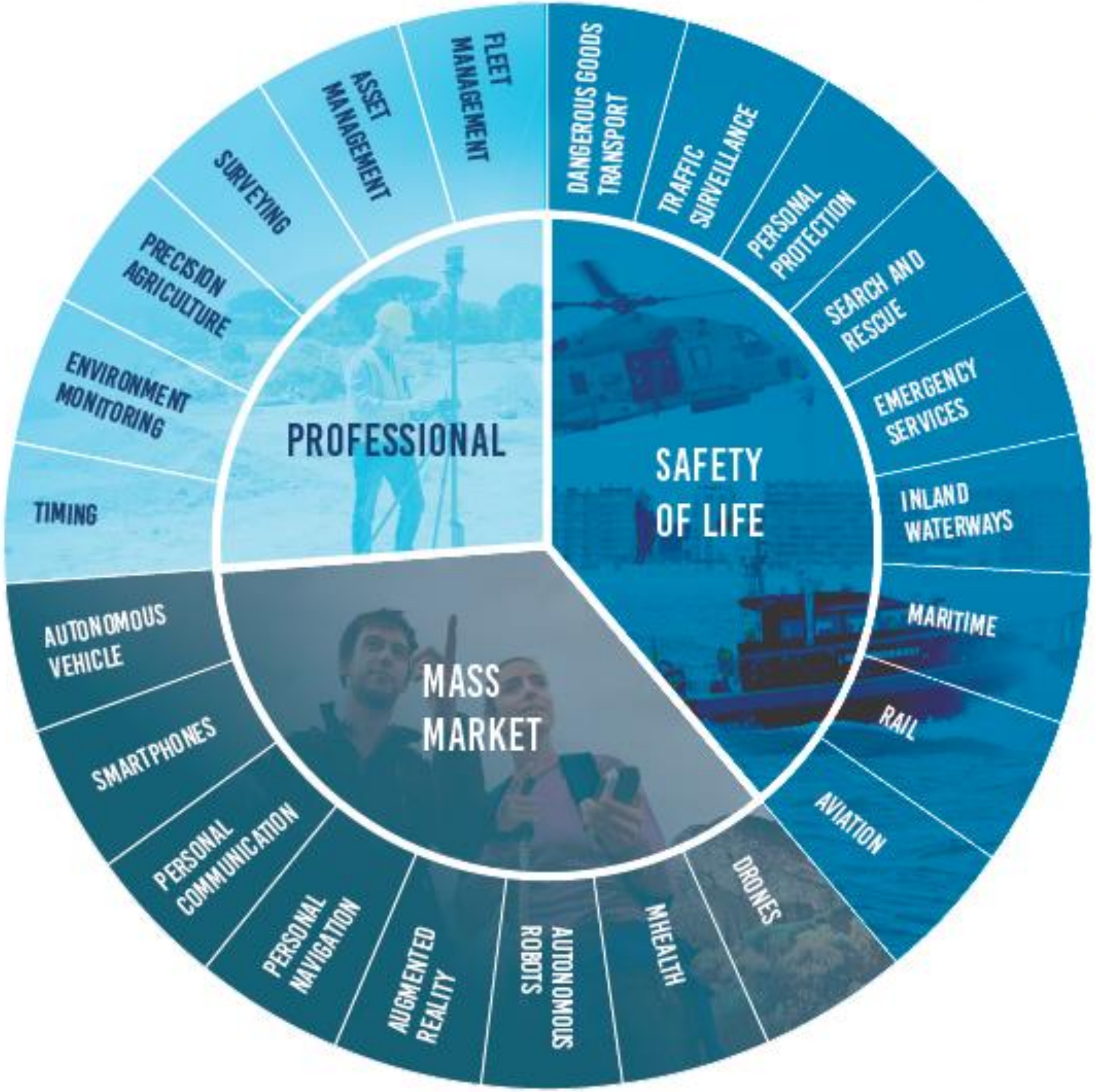


HAS clock correction grew following the true satellite clock

HAS correction set as not available

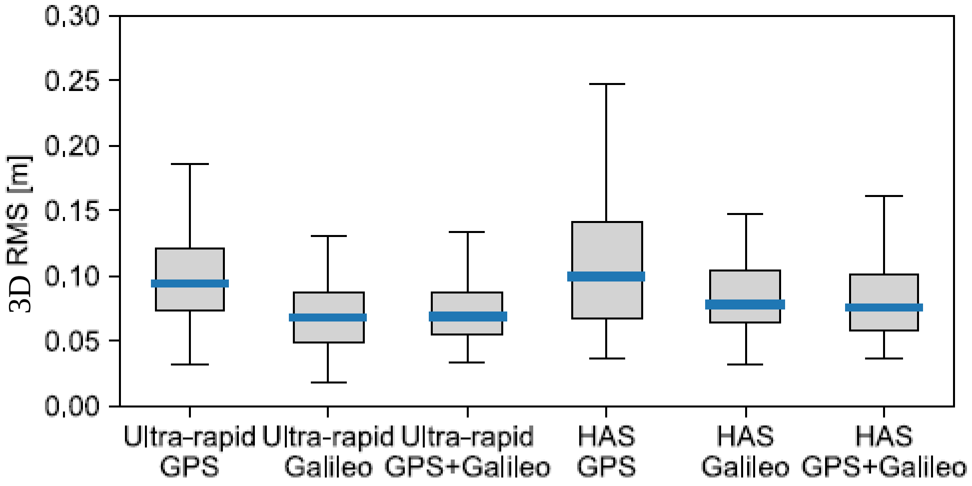
I. Martini et al. “Satellite Anomaly Detection with PPP Corrections: A Case Study with Galileo’s High Accuracy Service” ION ITM January 2022

Galileo HAS Applications



Galileo HAS Applications

- Recent example: using HAS for Sentinel 6A positioning (LEO, 1340km altitude)
- Main advantage: real time, no ground assistance



Hauschild, A., Montenbruck, O., Steigenberger, P., Martini, I., & Fernandez-Hernandez, I. (2022). Orbit determination of sentinel-6A using the galileo high accuracy service test signal. *GPS Solutions*, *26*(4), 1-13

EU SPACE

Thank you for your attention!

Galileo
High Accuracy Service

Ignacio Fernández Hernández
European Commission
6 Sept 2022

Acknowledgements: Galileo HAS team