

# Galileo is here – Update and G1 Evolutions, ESA activities

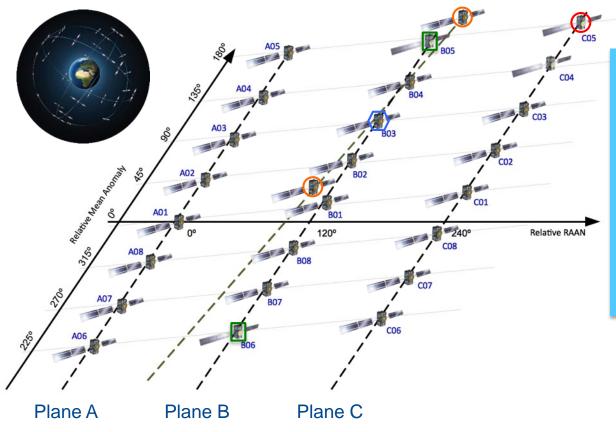
Dr. Jörg Hahn – European Space Agency Hd Galileo G1 System Engineering Service

ITSF Online, 4 November 2020

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#### **Galileo Constellation Status: STABLE**





**Navigation (22 in service) Search and Rescue (24 in service)** 

26 satellites in orbit





1 spare



1 unavailable



2 no SAR (by design)

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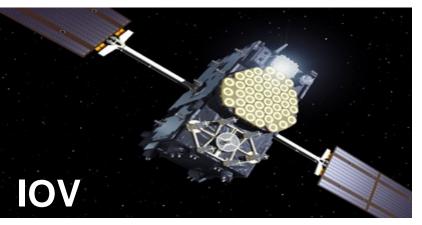






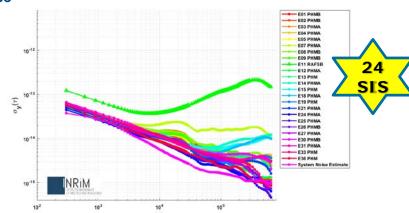
#### **Constellation Satellites**





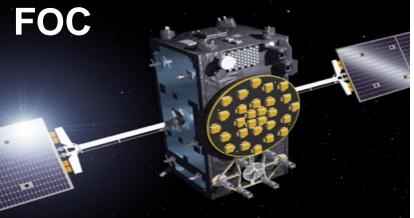






Satellite Clock Allan Deviation drmv vs IENG

**Embarked Clocks: Rubidium Atomic Frequency Standard Passive Hydrogen Maser** 



**OHB Systems GmbH SSTL Ltd** 22 satellites

+ 12 under production































#### Galileo Resilience



- July 2019 Event Inquiry Board recommendations
- Substantial Programme steering
  - Maintain navigation in case of multiple element failure graceful degradation
  - Improve upgrade deployment capabilities
  - Review redundancy for some elements of the service delivery in the light of existing and new services
  - Review operational processes and procedures
  - Continuous reinforcement of cyber security
- Robust Timing service under definition
- Overarching principle for G2G (infrastructure, signals...)















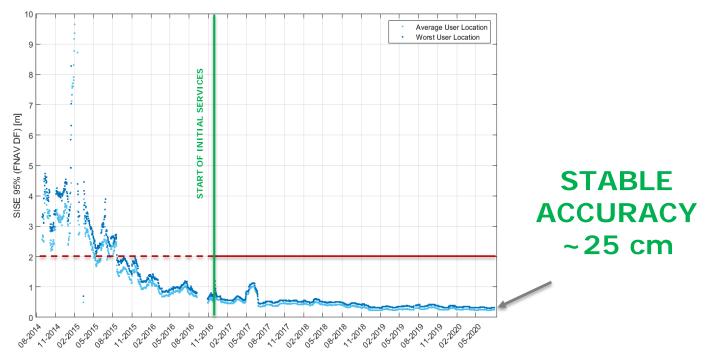






## **Excellent As-observed Ranging Performance**





- Decreasing Ranging Error trend due to increasing number of Satellites and G/S improvements
- Ranging accuracy (95%) 0.25 m all satellites in July 2020 (FNAV)

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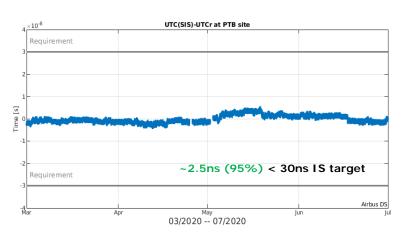


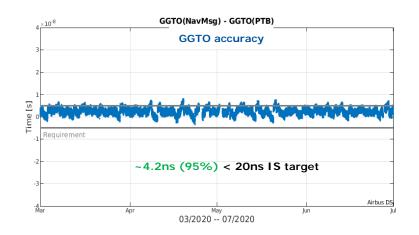


#### Galileo Timing Performance STABLE



#### **Broadcast UTC** Offset





- Evaluated with calibrated timing GPS/Galileo receiver operated in UTC(k) laboratory (PTB, INRIM)
- Deployment of new V2B.08.01.00 in all 4 GSS PTFs, including GRCPs
- GSSPTFs delay calibration complete for GRCNs and GRCPs















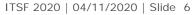












# **High Availability of Signals for Timing Applications**

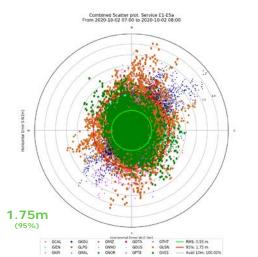


Operational Satellites :

Availability of H. Accuracy < 10 m

Global PDOP <=6 availability

Availability for Timing Service

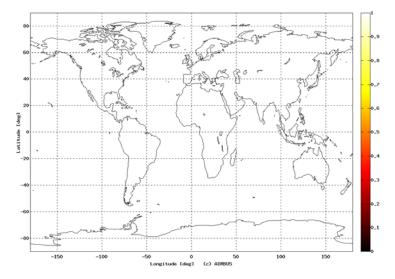


22

**100%** (Average User Location)

99.99% (Average User Location)

100%



Availability of Horizontal Position Accuracy < 10 m for 22 satellites

Measured Horizontal Positioning Accuracy (TGVF-X)

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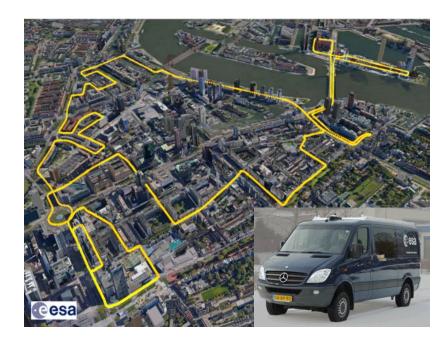
March 2020 – Mass Market Receiver Test Campaign in Urban Environment

Good: Single Frequency in 2017

Better: Single Frequency in 2020

#### Best: Dual Frequency in 2020!

Figure of Merit	MM SF Aggregated 2017	MM SF 2020	MM DF 2020
Horiz. Perc-95 [m]	6.40	4.68	2.51
Vert. Perc-95 [m]	7.90	5.60	4.03
3D Perc-95 [m]	10.90	6.36	4.44
Availability [%]	100.00	100.00	100.00
Total #epochs	46804	9981	9981



























#### Galileo G1G Evolutions



- OS Navigation Message Authentication (OS-NMA)
- **Commercial Authentication Service (CAS)**

- High Accuracy Service (HAS)
- Open Service I/Nav message improvements
- SAR Full Operational Capability





# **Authentication and High Accuracy**

esa

- AUTHENTICATION will be based on:
  - ★ Navigation Message Authentication Integrated in E1 OS.
     Consumer users, free of charge
  - ★ Commercial Authentication Service E6C Spreading Code Encryption
- ★ High ACCURACY based on PPP over E6B

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## **OS Navigation Message Authentication**



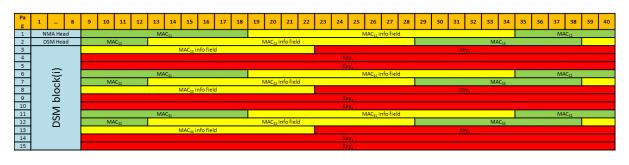
ZZZZ

EDBS

Galileo Core

"Authentication frame" i+1

- Layer on top of OS (Free of charge)
- Building block of authenticated PVT
- E1B External Data Broadcast Service (one page every 2 s) to provide authentication data to the user
- Reuse of 40 bits of previous External Region Integrity Status (ERIS)
- Protocol based on an adaptation of TESLA protocol [IETF RFC 4082]
- Asymmetry provided by delayed key



MAC: Message Authentication Code DSM: Digital Signature Message

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 $= \mathbf{n}$ 

































& transmitted

module

"Authentication frame" i

# **High Accuracy Service**

- Galileo has been designed to allow for broadcast of value added data, such as **high accuracy** and **authentication**.
- The Galileo High Accuracy Service will be:
  - Broadcast globally and free of charge to Galileo users
  - using the E6 signal to broadcast corrections to Galileo Navigation messages enabling PPP techniques, and
  - Enable fast PPP for regional users through additional corrections.
- The European Commission's goal with offering a free High Accuracy signal is to allow **innovation** to flourish in both consolidated and emerging **markets**, while **minimising** as far as possible any **disruption** to the current business models of established providers.





- 448 bits per Satellite per sec on E6b
- 20 cm (H) / 40 cm (V)
- Sub NS timing performance
- Global (SL1) and Regional (SL2)























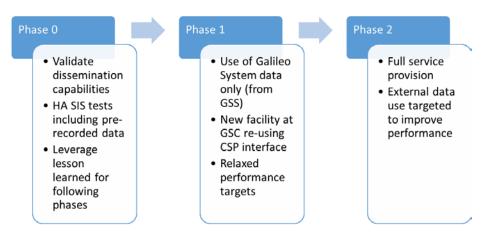






## **High Accuracy Service Path**





- **HAS Phase 0:** SIS Tests ongoing.
- **HAS Phase 1:** HA Data Generator under procurement by GSA.
  - Based on existing infrastructure.
  - Focus on regional provision of corrections with relaxed performances.
- **HAS Phase 2:** Under design. Global (SL1), full accuracy service, including ionospheric information to improve convergence regionally (SL2).





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## I/Nav (Improving Galileo E1-OS)



#### I/Nav is Evolving:

- After Galileo SoL re-profiling important message spare capacity available in I/NAV
- Use such spare capacity to improve data timeliness and robustness
- Software now under procurement for satellite upload
- Enables fast reconstruction of Galileo System Time (GST)
- Backward compatible fully transparent to already deployed Galileo receivers

#### What is REDCED, SSP and RS and why are they important?

- Reduced Clock and Ephemeris (RedCED): CED compressed to only 1 I/Nav word = FAST
- Reed Solomon (RS): additional coding gain for CED = **ROBUST**
- Secondary Synchronisation Pattern (SSP): time sync w/o NAV decoding = FAST + SIMPLE



























#### Optimized Galileo I/NAV Message on E1-B



T <sub>0</sub> (GST <sub>0</sub> sync.)		E1-B content						
1 s	H	CED	2 (1/2	2)				Even
2 s		CED 2 (2/2)	Res	SAR	Spare	CRC	SSP1	Odd
3 s	l	CED	4 (1/2					Even
4 s	l	CED 4 (2/2)	Res	SAR	Spare	CRC	SSP2	Odd
5 s	l		JTC (1					Even
6 s		GST-UTC (2/2)	Res	SAR	Spare	CRC	SSP3	Odd
7 s		Alma	nac (1	(2)				Even
8 s		Almanac (2/2)	Res		Spare	CRC	SSP1	Odd
9 s		Alma	nac (1	(2)				Even
10 s		Almanac (2/2)	Res		Spare	CRC	SSP2	Odd
11 s		RS CED	1 or 2	(1/2)				Even
12 s		RS CED 1 or 2 (2/2)	Res	SAR	Spare	CRC	SSP3	Odd
13 s		RS CED	3 or 4	(1/2)				Even
14 s		RS CED 3 or 4 (2/2)	Res		Spare	CRC	SSP1	Odd
15 s	ll	Reduce	CED	(1/2)				Even
16 s	l	Reduced CED (2/2)	Res		Spare	CRC	SSP2	Odd
17 s	H	Reser	ved (1.	/2)				Even
18 s		Reserved (2/2)	Res	SAR	Spare	CRC	SSP3	Odd
19 s		Reser	ved (1,	/2)				Even
20 s		Reserved (2/2)	Res		Spare	CRC	SSP1	Odd
21 s		CED	1 (1/2	2)				Even
22 s		CED 1 (2/2)	Res		Spare	CRC	SSP2	Odd
23 s		CED	3 (1/2					Even
24 s		CED 3 (2/2)	Res	SAR	Spare	CRC	SSP3	Odd
25 s		Iono, BG	D, GS	Γ (1/2)				Even
26 s		Iono, BGD, GST	Res		Spare	CRC	SSP1	Odd
27 s		Resei	ved (1	/2)				Even
28 s		Reserved (2/2)	Res		Spare	CRC	SSP2	Odd
29 s		Reduce	d CED	(1/2)				Even
30 s		Reduced CED (2/2)	Res	SAR	Spare	CRC	SSP3	Odd

#### Fully Backward Compatible

• No change to already defined I/NAV words (CED, Almamanc, GST-UTC, Iono/BGD/GST)

#### Reduced CED (redCED)

- Compression of CED information from 4 words into 1 word
- Time to CED (95%) for a vehicular user in an urban environment reduced significantly (down to 16 sec)
- Reduced PVT accuracy (< 40 m) until demod. of all 4 CED words

# legacy I/NAV subframe layout no CED available I/NAV with Reduced CED and Reed-Solomon codes (RS2+RedCED) no CED available reduced accuracy nominal accuracy 1 time<sub>395%</sub> [s]

#### Reed Solomon (RS-CED)

- Correction of residual errors <u>AND</u> recovery of erased information
- Any four different error free RS-CED or CED words recover CED
- Benefit for timeliness and robustness

#### CED 2 CED 3





incl. RS-CED contribution



#### Secondary Synchronisation Pattern (SSP)

- Correlation with SSP pattern allows to resolve Rx time ambiguity of +/- 3 sec
- Enables fast GST recovery (modulo 6 seconds) at symbol level

	SSP1	SSP2	SSP3
Plain SSP configurations	00000100	00101011	00101111
Encoded SSP configurations (last 16 symbols of the I/NAV E1 pages, after FEC encoding of the 8 plain SSP bits + 6 tails bits)	1110100100100101	0110110001001110	1101000000111110

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# **Opportunities** and other ESA activities on GNSS Timing



- Timing for 5G
- Absolute Calibration in ESTEC
- NAVISP







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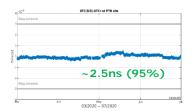








#### Galileo for 5G timing







- GNSS continue to be used as time synchronisation source at the network edge
  - deployment of 5G Massive MIMO requires → relative Time Error <65 ns. Network operators could use GNSS in several deployment schemes
- GNSS continue to be used as time reference for the ePRTC/stratum 0 netclock
- GNSS is used for enabling sidelink synchronisation in Vehicle-to-everything (V2X) communications (exchange of information from a vehicle to its technological environment)
- 5G-based (terrestrial) accurate (<10 m) **positioning** requires a dense network deployment and time synchronisation accuracy <10 ns (network/transmitters relative synchronisation), at this moment this may be only achieved by GNSS sites at transmitting points.
- timing requirements evolve in new generations (e.g., ultra-low latency comms, use of higher frequency bands mm-waves-). Besides better accuracy, **resilience** towards interference and spoofing is key for GNSS time based solutions.

5G Sync function	Time
Turiction	Synch Accuracy
Network synch	1.5 us
Massive MIMO	<65ns (relative
IVITIVIO	antenna
	element)
Location (OTDOA)	<10ns
V2X Sidelink	<400 ns
Factories of future – motion control	< 100 ns

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#### **Absolute Calibration at ESTEC laboratory**



- Absolutely calibrated chains are operating continuously at ESA/ESTEC
- Two full chains were calibrated for the BIPM using the ESA/ESTEC procedure:





		Anten	Antenna APC		Cable		Receiver		TOTAL	
	GNSS Signal	Value	Uncer.	Value	Uncer.	Value	Uncer.	Value	Uncer.	
	Li C/A	20.89	0.54	140.75	0.26	9.48	0.74	171.12	0.95	
oo	Li P	20.88	0.53	140.75	0.26	9.38	0.52	171.01	0.79	
GPS	L2 P	17.93	0.43	140.76	0.25	10.28	0.53	168.97	0.73	
	L5	20.22	0.53	140.76	0.25	10.66	0.46	171.64	0.74	
Galileo	E1 BC	20.90	0.54	140.75	0.26	9.75	0.47	171.40	0.76	
	E6 BC	20.65	0.48	140.76	0.25	7.99	0.55	169.40	0.77	
	E5a	20.30	0.51	140.76	0.25	10.58	0.48	171.64	0.74	
S	E5b	17-75	0.49	140.76	0.25	6.89	0.79	165.40	0.96	
	E5 (AltBOC)	18.06	0.41	140.76	0.25	8.59	0.48	167.41	0.68	
	G1 C (centre)	21.41	0.53	140.75	0.26	6.26	0.78	168.42	0.98	
0	G1 P (centre)	21.40	0.53	140.75	0.26	6.90	0.55	169.05	0.81	
GLO	G2 C (centre)	17.23	0.55	140.76	0.25	11.38	1.34	169.37	1.47	
	G2 P (centre)	17.23	0.55	140.76	0.25	10.29	0.60	168.28	0.85	
0	Bı	19.93	0.44	140.75	0.26	5.95	0.62	166.63	0.80	
BD	B2	17.85	0.51	140.76	0.25	6.81	0.59	165.42	0.82	

NISG



	GNSS Signal	Antenna APC		Cable		Receiver		TOTAL	
		Value	Uncer.	Value	Uncer.	Value	Uncer.	Value	Uncer
GPS	Li C/A	19.98	0.44	311.28	0.33	11.70	0.64	342.96	0.84
	L1 P	20.01	0.43	311.28	0.33	11.22	0.49	342.51	0.73
	L2 P	18.36	0.43	311.28	0.31	11.20	0.50	340.84	0.73
	L5	20.74	0.46	311.28	0.31	11.96	0.47	343.98	0.73
Galileo	E1 BC	19.98	0.44	311.28	0.33	11.86	0.45	343.12	0.71
	E6 BC	19.38	0.45	311.28	0.31	9.83	0.57	340.49	0.79
	E5a	20.78	0.44	311.28	0.31	11.87	0.47	343-93	0.71
	E5b	19.18	0.46	311.28	0.31	7.68	0.75	338.14	0.93
	E5 (AltBOC)	19.97	0.42	311.28	0.31	9.56	0.46	340.81	0.70
	G1 C (centre)	22.18	0.46	311.28	0.33	5.32	0.91	338.78	1.07
0	G1 P (centre)	22.19	0.46	311.28	0.33	6.23	0.78	339.70	0.96
GLO	G2 C (centre)	18.32	0.59	311.28	0.31	12.71	1.46	342.31	1.60
	G2 P (centre)	18.31	0.59	311.28	0.31	11.24	0.92	340.83	1.14
BD	B1	19.67	0.44	311.28	0.33	4.51	0.61	335-46	0.82
	B2	19.13	0.48	311.28	0.31	7.63	0.56	338.04	0.80

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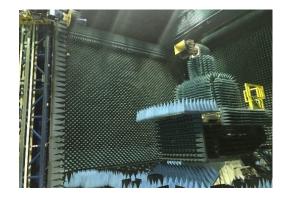




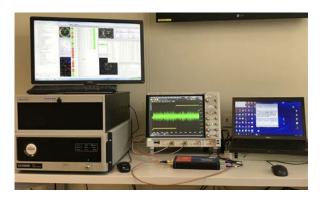


# Absolute Calibration at ESTEC laboratory (cont'd) esa

- Accuracy at sub-ns level
- Hardware delays are estimated using simulated signals
  - → Antenna: anechoic chamber + VNA
  - → Antenna cable: VNA
  - → Receiver: GNSS simulator + scope + SDR correlator + PR differences







E. Garbin, P. Defraigne, P. Krystek, R. Piriz, B. Bertrand, P. Waller, "Absolute calibration of GNSS timing stations and its applicability to real signals" 2019, *Metrologia* **56** 015010

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# Navigation Innovation and Support Programme (NAVISP)

In parallel to the development of the systems, ESA has a programme to support innovation in the wide-field of Position, Navigation and Time.

The programme is articulated among 3 Elements:

- Element 1: support PNT innovation, mid/long term
- Element 2: support to industry PNT competitiveness
- Element 3: support to national PNT projects

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# **NAVISP Timing-Related Projects**



- Demonstration of Pulsar Time-Scale
- Quantum-based sensing for PNT
- Atomic clocks based on laser-cooled atoms
- Advanced concepts for chip-scale atomic clocks
- Complementary PNT infrastructure in LEO orbits
- High altitude pseudo-satellites for PNT
- GNSS for precise timing of indoor small cells
- Secure and reliable time-transfer techniques
- Timing and synchronization for aviation systems and networks
- Advanced digital modem for satellite two-way time-transfer
- Advanced timing devices for smart power grids
- High stability clock time distribution via optical-fiber

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#### Conclusions



- Excellent and stable Galileo System performance
- Outstanding timing performance for GNSS & clock stability demonstrated with UTC (SIS) better than 5 ns
- Batch 3 of 12 satellites under production for deployment starting in 2021 providing in-orbit spares
- New System capabilities under development:
  - OS-NMA, CAS, High Accuracy Services
  - Faster and more robust Time To Fix (I/NAV)
- Galileo is a full reality in Mass-Market devices:

#### Are your products up to date?



