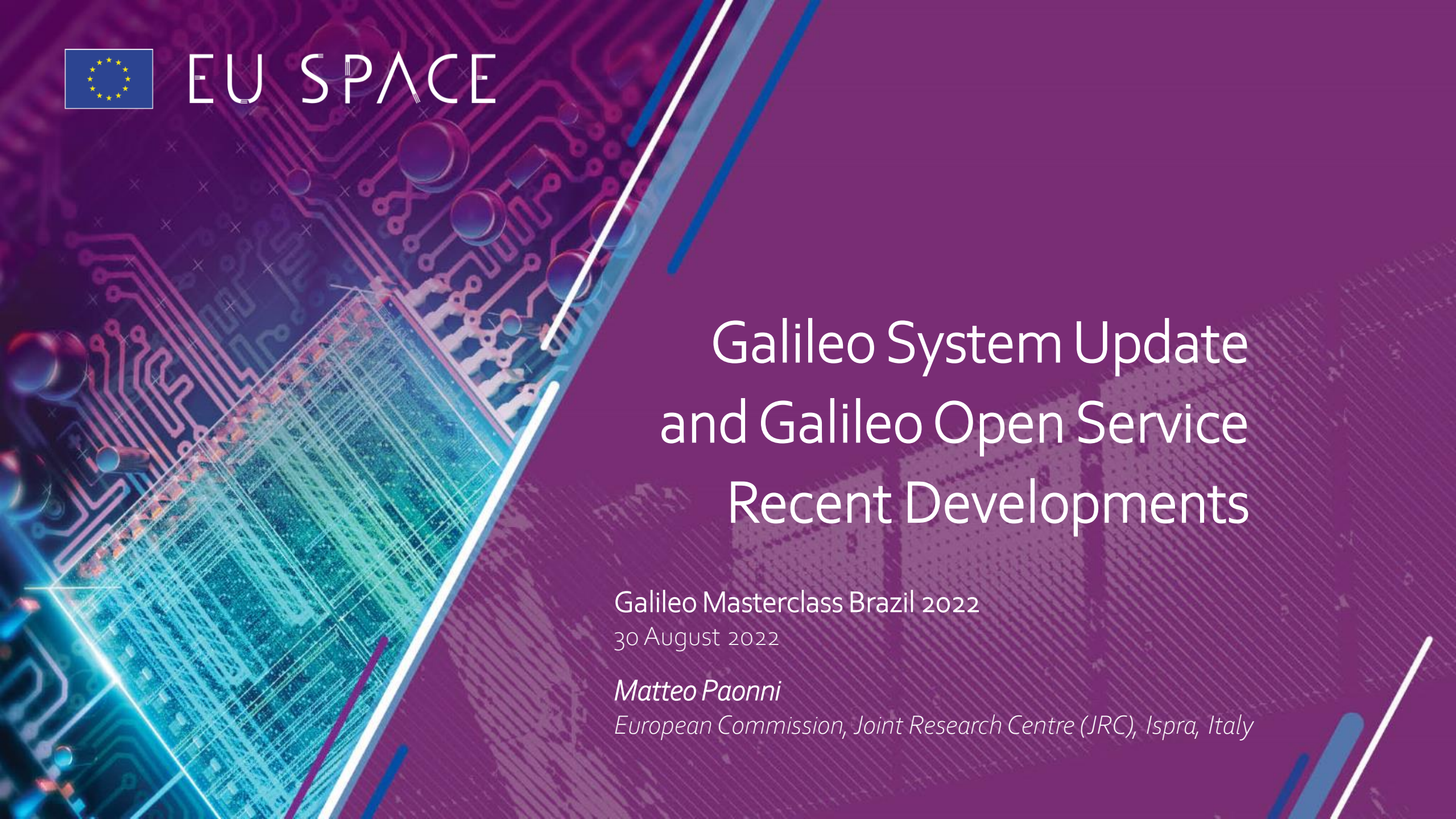

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Galileo System Update and Galileo Open Service Recent Developments

Galileo Masterclass Brazil 2022

30 August 2022

Matteo Paonni

European Commission, Joint Research Centre (JRC), Ispra, Italy

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This presentation is divided into two sections:

1. Galileo System Update
2. Galileo Open Service Development

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1. Galileo System Update

Galileo Services – now, then and next

Open Service (OS)

- Free and Open Positioning Navigation & Timing (3 frequencies)
- Emergency Warning Service + Advanced timing + SSV

Public Regulated Service (PRS)

- Encrypted, more robust, unlimited & uninterrupted access
- PRS evolutions

Search and Rescue (SAR) - contribution

- Forward link + acknowledgement "return link“ + TWC + RBA + DPS

High Accuracy and Authentication

- Free High accuracy services + OSNMA
- Advanced signal authentication services

Safety-of-Life (SoL) - contribution

- Multilateral Workplan for aviation adoption (ARAIM+EGNOSv3)

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Open Service

Programme Objective:

- Full Operational Capability declaration initially planned in Q4 2022
- 2 additional launches are required (L12/L13) to ensure at least one spare satellite per plane, but deferred following ROSCOSMOS unilateral decision to withdraw from Kourou

Status

- Today service availability is in the range of 98-99%, which is compliant with the SDD commitment in-force
- Discussion on-going with Arianespace to update launch schedule
- Assessment on-going for an updated OS SDD, taking into account revised launch manifest.

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OSNMA

Test Campaigns

- **Internal** Test Phase conducted during 2021: Validation of performance and operational procedures
- **Public** Test Phase on-going, targeting Rx manufacturers, application developers and research institutions, started on 15 November 2021.
  - ✓ OSNMA signal provided globally and continuously with very good availability
  - ✓ More than 120 participants subscribed.
  - ✓ 1st authentication test signal provided by a GNSS ever enabled now by Galileo worldwide !

Next phase

- Public Observation phase to be followed by declaration of **Initial Operational Capability**

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Commercial Authentication Services (CAS)

Principle: encrypted code (E6-C) and OSNMA authenticated NAV data (E1-B)

- Approach: deliver first an Assisted version of the concept (***ACAS***), based on server connection (offline), free of charge.
- Initial operability: Q1 2024
- Full capability: Q2 2025

Next phase

- Assess the feasibility of a fee-based Standalone CAS (***SCAS***), based on market analyses and ACAS adoption. Requires the possession in the receiver of a symmetric key (real-time authentication). Assessment phase starting now.
- For Galileo 2nd Generation, the performance of these Authentication capabilities will be enhanced, also addressing E1 and E5 ranging authentication(***OSRA***).

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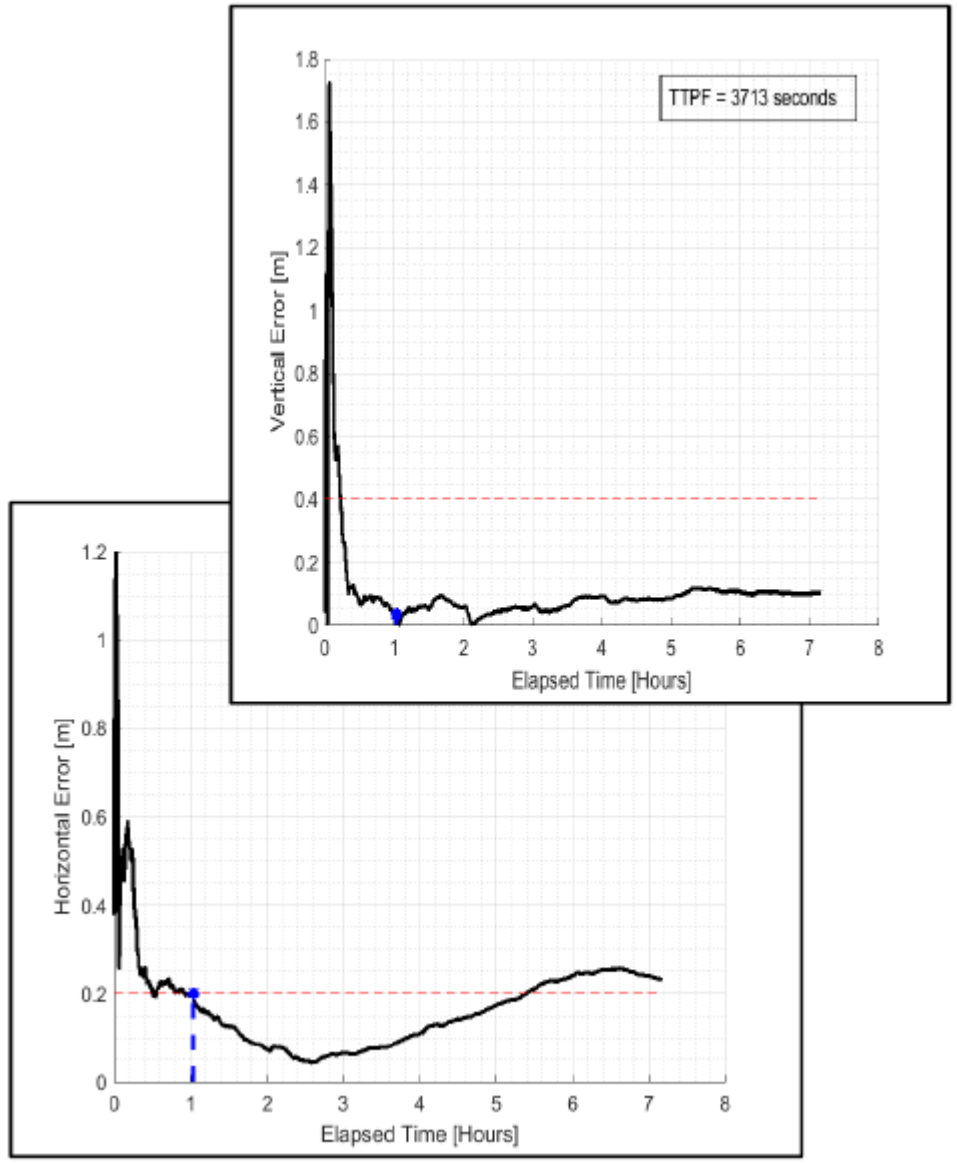
High Accuracy Service

Approach

- Open-access and free service based on the provision of corrections to the Galileo signals and data transmitted in the Galileo E6 signal

Test Campaigns

- Multiple internal test campaigns since 2020
- HAS Signal in Space testing: Promising early results (position accuracy at decimeter level)
- Key stakeholders from multiple Member States involved (15 companies + 4 EUSPA funded projects)
- 1st HAS Signal-in-Space ICD published online



SIS corrections testing achieved and Service validation planned Q4 2022

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Search and Rescue

Status

- Service is performing extremely well, both ***forward link*** (since Dec. 2016) and ***return link*** (since Jan. 2021)
- EU Coverage with 3 MEOLUT
- Extension to Indian Ocean with the 4th MEOLUT in Q1 2023

Programme Objectives

- **Remote activation of SAR beacons** via the Galileo Return Link Service (2023)
- **Two Way Communication**: ensure Com link between person in distress and Rescue Coordination Centre (RCC), enabled by the *long Return Link Message*
- **Distress Position Sharing**: RCC can contact Galileo to share the position of a beacon user in distress with other nearby users

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Emergency Warning Service

Galileo
Emergency
Warning
Service

Programme Objective

- On-demand broadcast (L1 band) of alerts and guidance to population at threat
- Alert activation decided by national civil protection
- Public demonstration phase Q1 2023 to Q3 2023
- Service declaration 2024

Advantage of Galileo EWS

- Reaches population at large scale in ~ 1 minute
- No specific equipment needed. Simply a user terminal with Galileo chipset in it
- Available also when terrestrial alert systems are down (collapsed or saturated)

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PRS Initial services

Towards Initial Operational Capability (IOC)

- IOC planned Q2 2024
- Launch 12 and 13 deferred do NOT impact the IOC phase

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Other Services in the making

- **Advanced timing service**
- **Space service volume**
- **ARAIM**
- **Contribution to ionosphere prediction**

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Support to users

- **Service notice, NAGUs, Helpdesk, training, support to startups**
  - ✓ Galileo Service Centre (GSC)
- **Performance monitoring and reporting**
  - ✓ Galileo Reference Centre (GRC)
- **Testing lab for new services and features**
  - ✓ Joint Research Centre (JRC)
- **Receiver developments**
  - ✓ Fundamental elements programme
  - ✓ Bilateral agreements with manufacturers
- **Market development and user consultation platforms**
  - ✓ EUSPA

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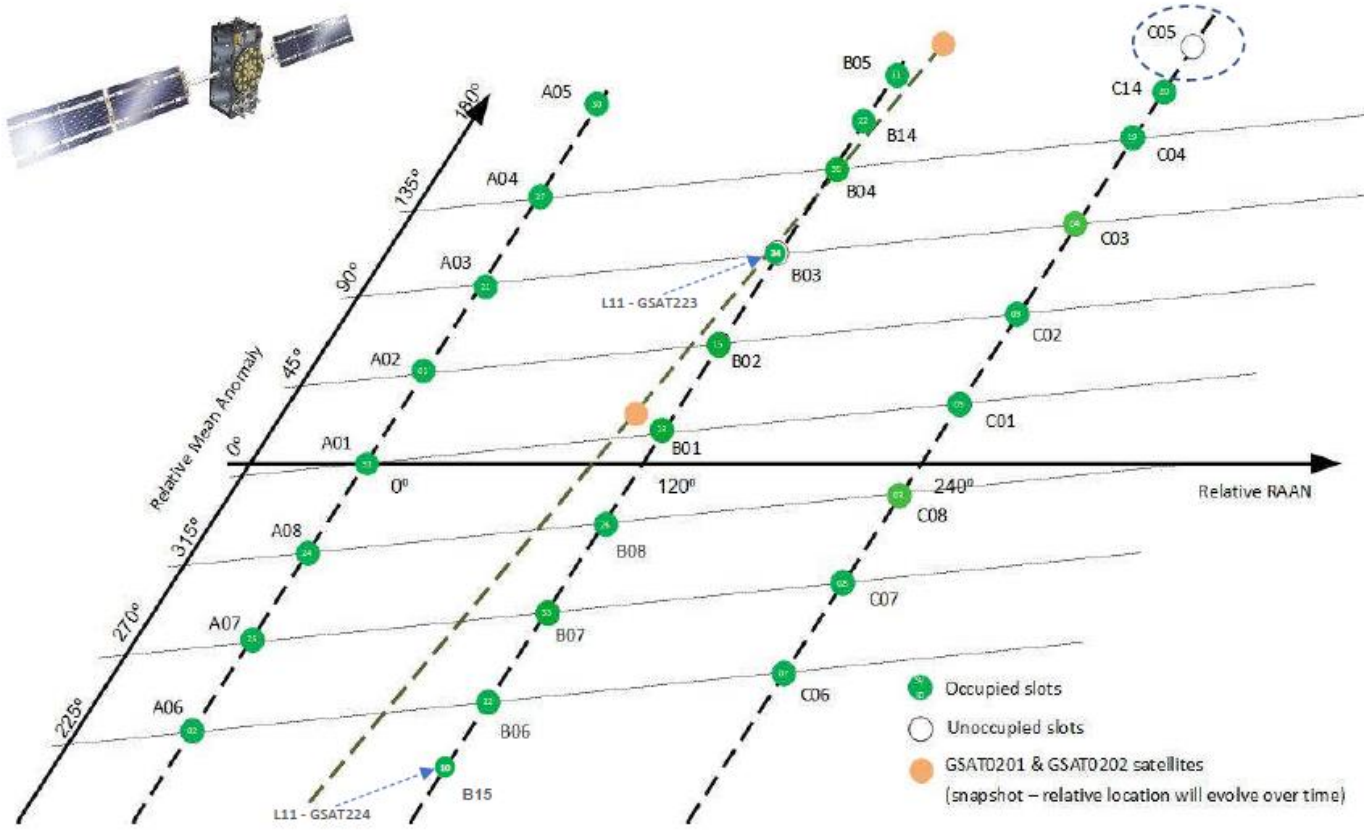
GALILEO Space segment status



Plane A	Plane B	Plane C
L13	✓ L11	L12

Current Status

Space Segment: 28 satellites in Orbit

- 24 in service for Navigation
- 26 in service for Search and Rescue
- 2 Auxiliary not in service (L3)
- 1 Inactive spare
- 1 Nominal Slot not occupied (L12)

Status compared to OS FOC

- Plan A: 1 spare missing (L13)
- Plan B: status GREEN with L11 in service
- Plan C: 1 nominal + 1 spare missing (L12)

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G1G Space Segment Deployment

- **28 Galileo G1G satellites have been launched so far with a combination of Soyuz and Ariane-5 launches – 24 operational in nominal slots**
- **10 Galileo G1G satellites have been produced and remain to be launched:**
  - ✓ 4 satellites to reach full operational capability (all nominal slots filled up and 1 spare in plane for robustness)
  - ✓ 6 additional satellites to maintain the constellation until the ramp up of G2G satellites
- **L12 campaign in March/April 2022 was interrupted following the unilateral decision from Roscosmos to withdraw from CSG**
  - Satellites have been put in storage in Kourou, waiting for return flight back to Europe
- **L13 on Soyuz initial foreseen in September 2022 will not take place either**
- **Ariane-6 is the baseline launcher for Galileo**
  - ✓ Availability for Galileo is expected by end of 2023
  - ✓ Constellation performances as provided today can be maintained until at least end 2024

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A look into the Future: G2G satellites

Credits: ThalesAleniaSpace

Main Characteristics

- New satellites class: +2 tons (vs. 750 kg in G1G), 32 m in deployed panel conf. (vs 16 m), on-board power multiplied by 3-4
- More signals + auth., more power and more on-board flexibility
- Inter-satellite links
- All-Electric propulsion transfer to MEO < 180 days
- 15 year service life (vs. 12 years), EOL Graveyarding and passivation
- 5 atomic clocks (PHM-II, RAFS-II) + experimental clocks + experimental payload(s)

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2. Open Service Developments

Improving Galileo Open Service Resilience and Performance (with No Compromise!)

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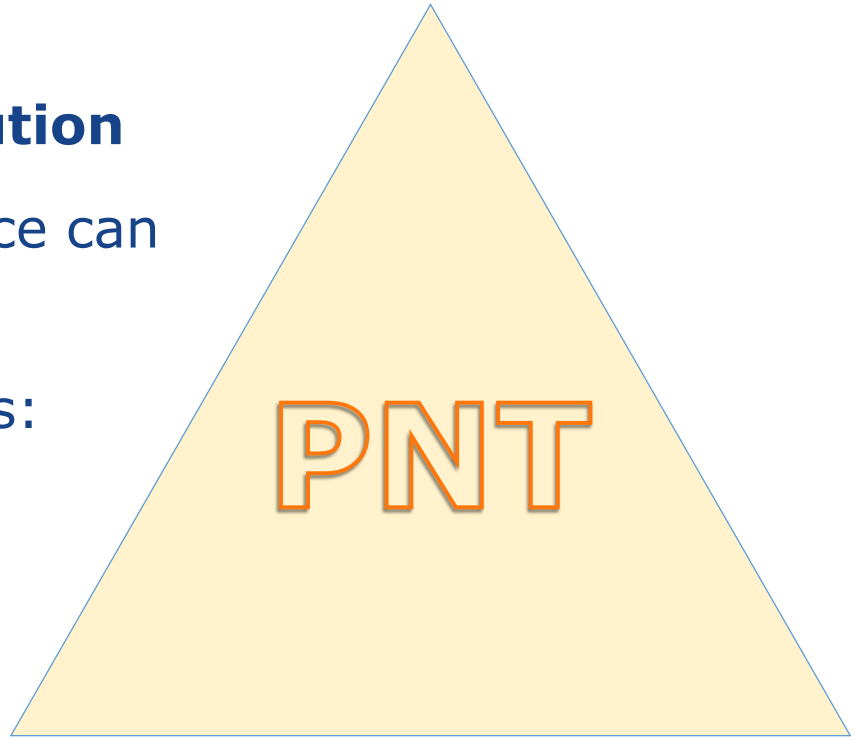
GNSS Backbone for User PNT

- GNSS provides key **contribution** to user **PNT solution**
- Depending on specific **application** user performance can depend more or less on GNSS
- GNSS performance mainly depends on three factors:
  - ✓ **System design** (constellation, signals, …)
  - ✓ **Propagation**
  - ✓ **Receiver implementation**



- These three factors strongly relates with each other and impact all **dimensions of GNSS performance**

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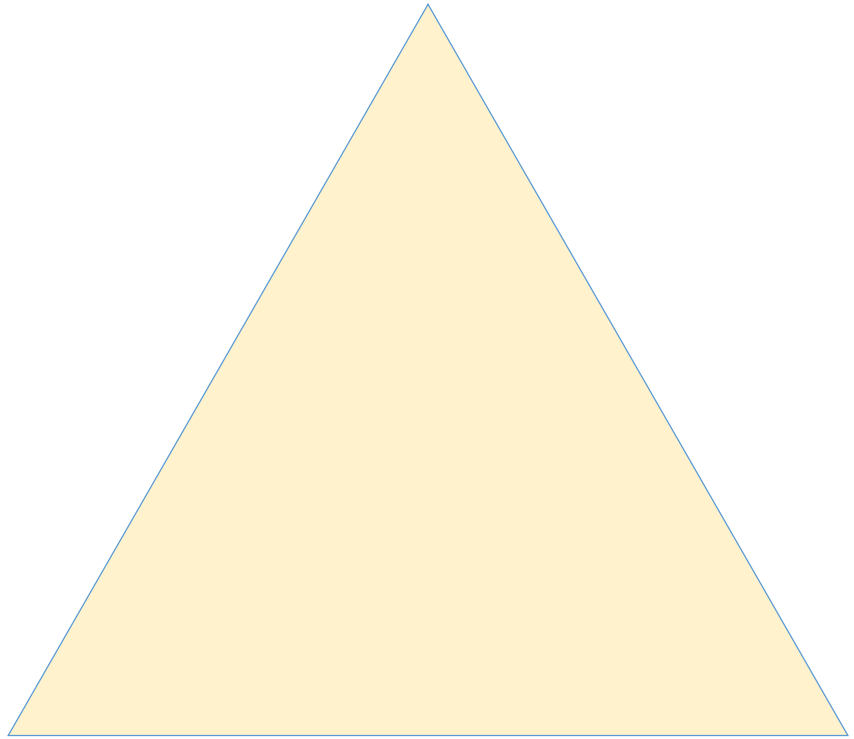
The 3 (+ 1) Dimensions of GNSS Performance



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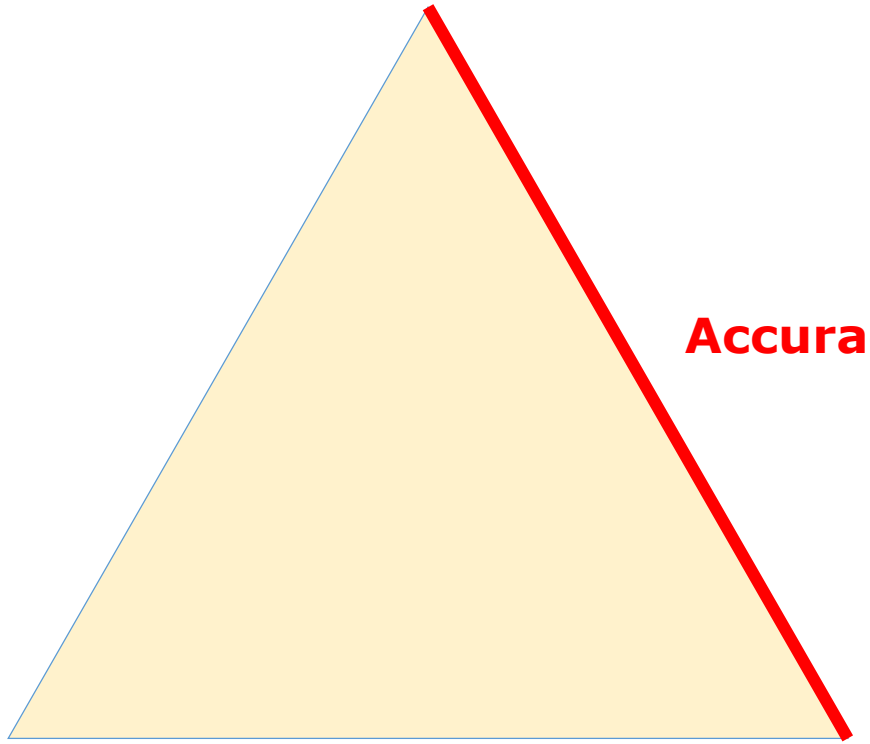

Accuracy

What matters ultimately!

Depends on all factors
- ✓ Accurate signals
- ✓ Channel is critical…
- ✓ …as well receiver!

Accuracy has to be delivered!

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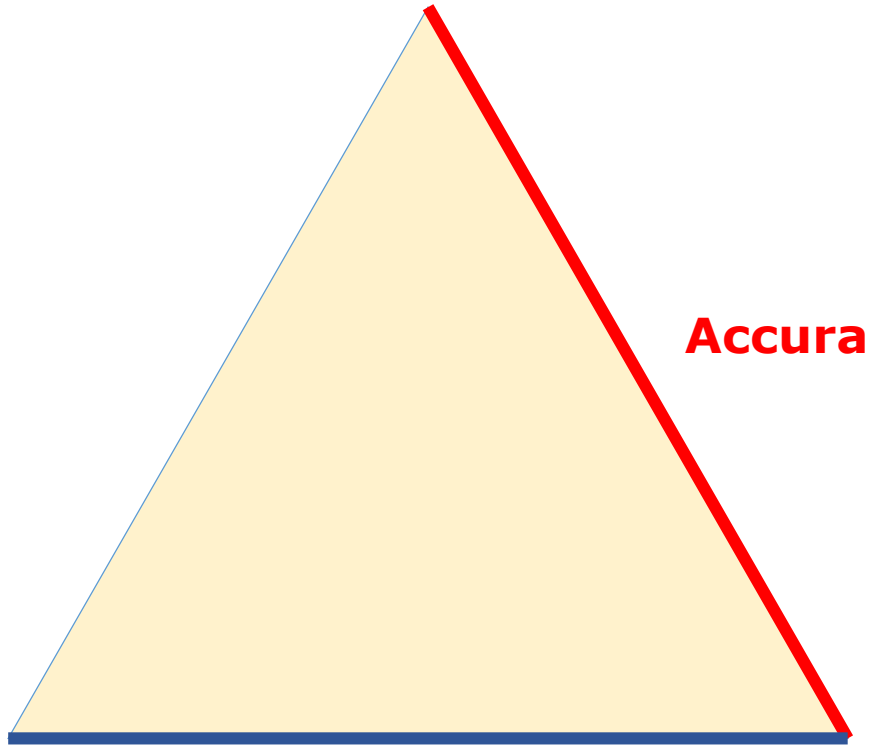
The 3 (+ 1) Dimensions of GNSS Performance



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Qualifies the conditions at which accuracy is delivered (and kept)

Minimum required C/N_0

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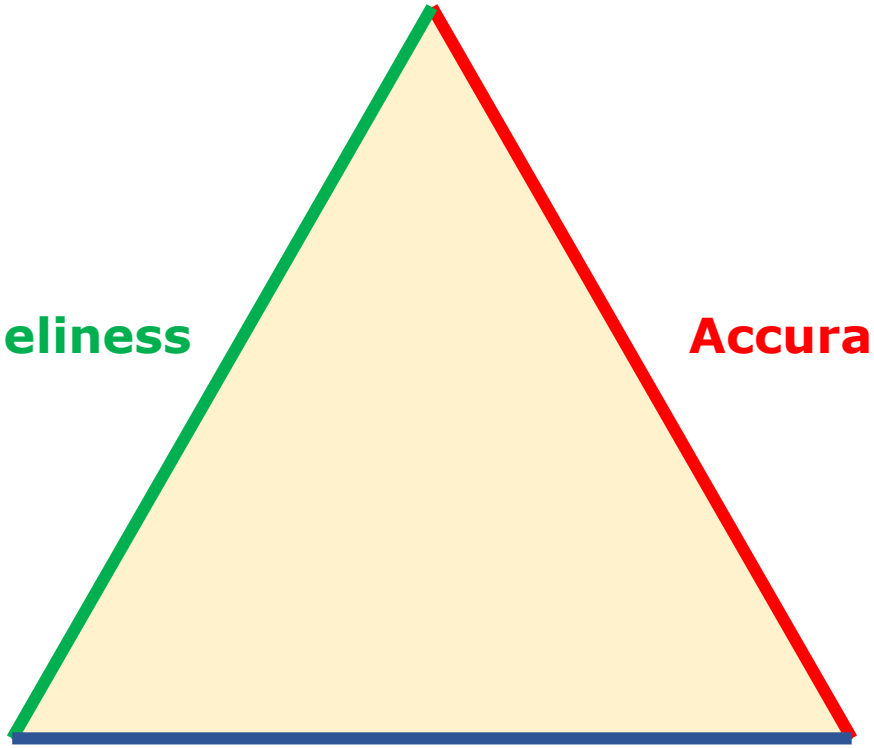
The 3 (+ 1) Dimensions of GNSS Performance



Timeliness

How long does it take?

Time-To-First-Fix

Key for stand-alone

Increasing impact on performance perception

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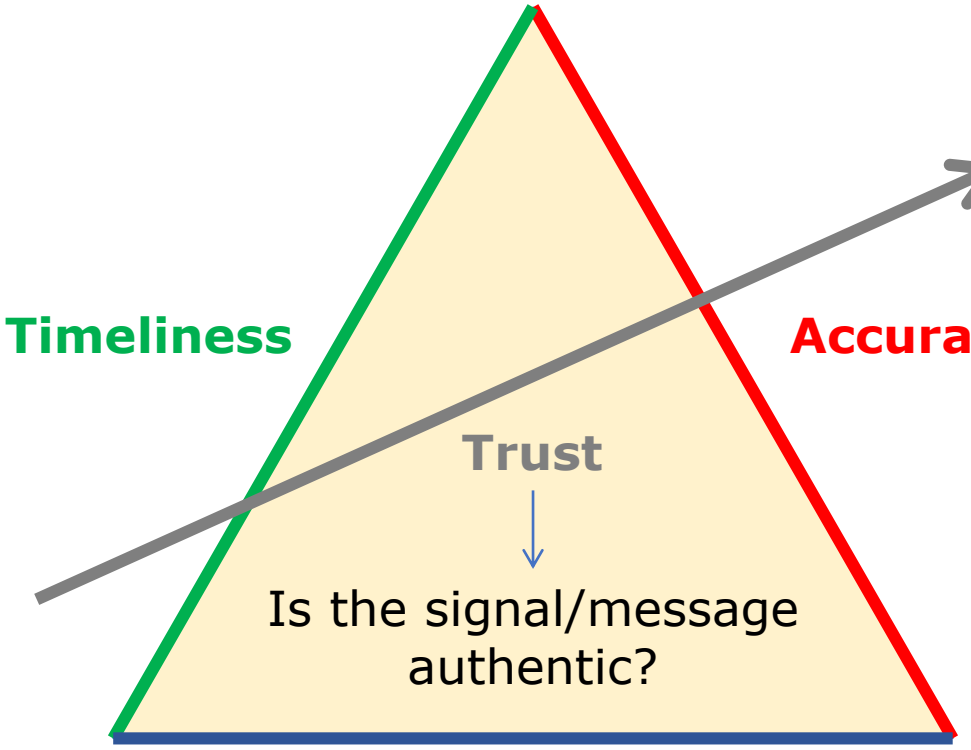

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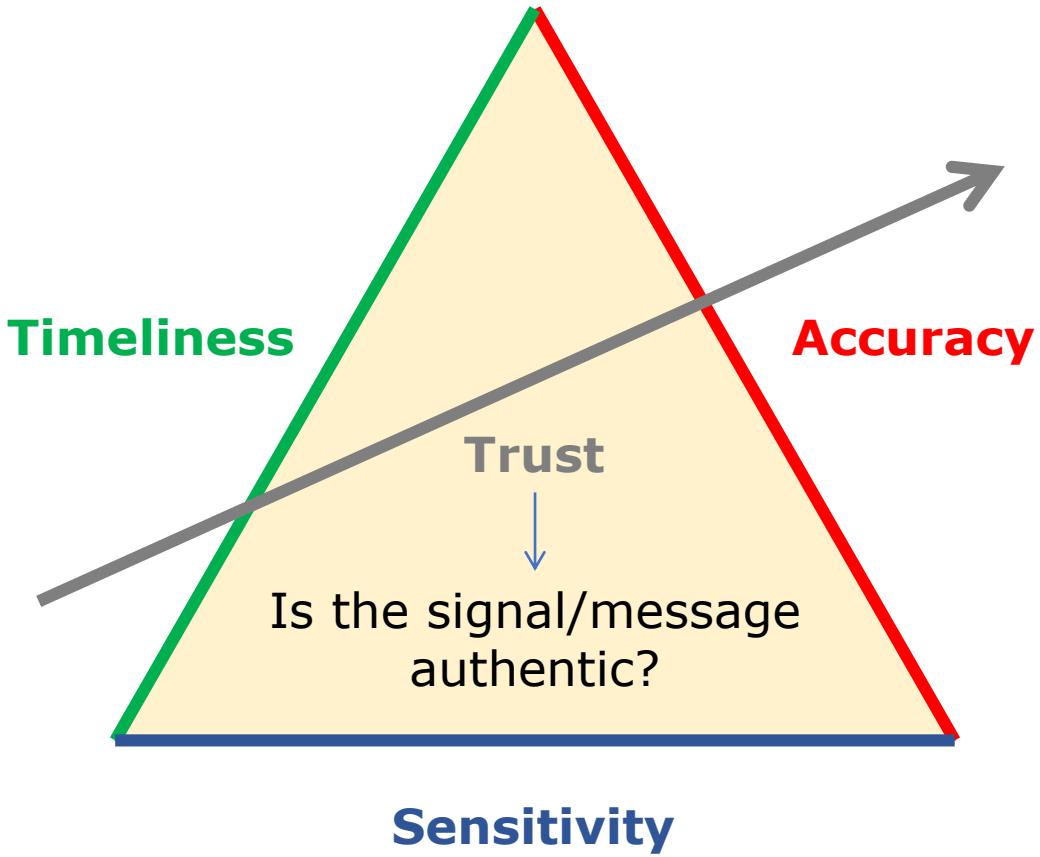

Signal design is a **trade-off** exercise targeting **specific user demand** and considering those **key performance indicator**

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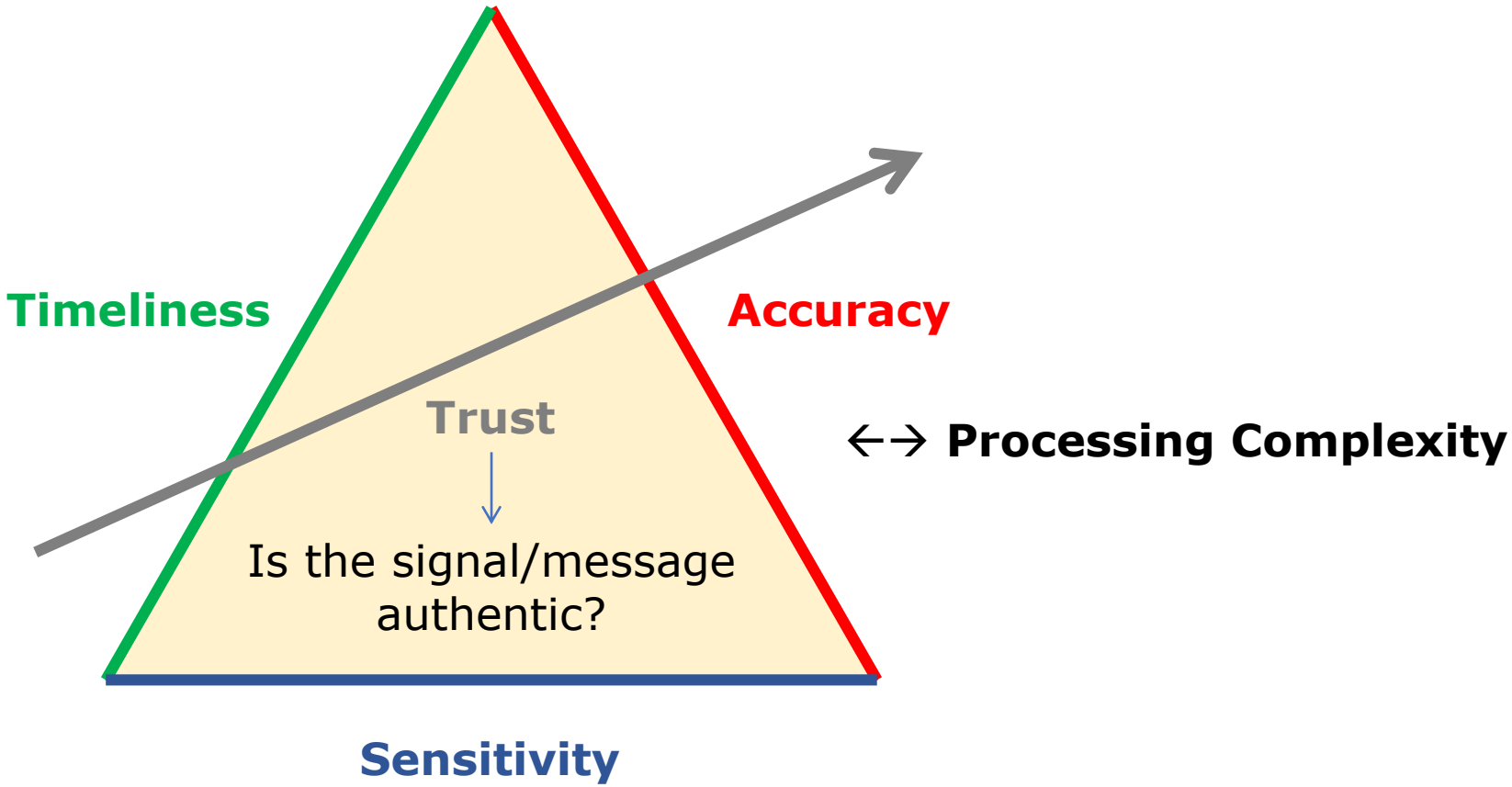
The 3 (+ 1) Dimensions of GNSS Performance



Signal design is a **trade-off** exercise targeting **specific user demand** and considering those **key performance indicator**

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The case of Galileo Open Service

- Galileo delivers top-class **accuracy**
- In the last years substantial work performed to improve **Galileo Open Service (OS)** performance in terms of **sensitivity** and **TTFF** and to add **authentication** functions:
  - ✓ **Optimization** of **I/NAV** message (following SoL reprofiling)
  - ✓ Introduction of **Open Service Navigation Message Authentication** (OSNMA)
- The main objective is to serve **new user needs** and **emerging applications**
  - ✓ **Low power/low complexity** applications (e.g. IoT, snapshot), safety-critical applications, higher robustness
- Further work ongoing under **G2G** and considering evolved/new signals and functionalities, including OS
- Any optimization and/or evolution is obviously constrained to be **backward compatible**
  - ✓ Legacy signals and receivers

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Galileo OS SIS ICD Issue 2.0

- A new issue of the OS SIS ICD released in Jan. 2021

- Major update adding **three new features** to the **I/NAV messag** transmitted within the **E1 OS** signal
  - ✓ Reduced Clock and Ephemeris
  - ✓ Reed-Solomon Outer Forward Error Correction
  - ✓ Secondary Synchronization Pattern

- Few other minor updates

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Motivation

- Improvement of **the Galileo E1 Open Service performance** in terms of **Robustness** and **TTFF**, especially in challenging environments
  - Enable **fast retrieval of Clock and Ephemeris Data** (CED)
  - Enable **fast reconstruction of the Galileo System Time** (GST)
- **Backward compatibility** guaranteed
  - Introduction of **new I/NAV words** in addition to the provision of **legacy message**
  - Exploiting **currently unused message capacity**
  - **Low complexity** implementation within OS receivers
  - **No impact** to legacy or non-participative receivers

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NAV Message Processing within the Receiver

- The conditions to **access and process Galileo OS NAV messages** are clearly specified within the Galileo OSSISICD
- It is key that those provisions are respected and the receivers are implemented with the necessary **flexibility**

> For all message types, only the message pages include a 'type' marker to identify the content of each page received by the user. There is no management data transmitted within the navigation message to indicate subframe and frame structures, and indeed these higher level structures should be considered as the typical flow of pages reflecting the current Galileo navigation message design, which may evolve together with future evolutions of Galileo. This evolution may also involve the inclusion of additional new page types beyond the types defined in this version of the Galileo OS SIS ICD. A user receiver is expected to be able to recognise page types and to react properly and in a well controlled manner to page types unknown to its software as well as to variations in the order of received pages.

OS SIS ICD section 4.1.2

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Optimized Galileo I/NAV Message on E1-B

T_0 (GST_0 sync.)	E1-B content (*nominal sub-frame layout*)						E1-B page
1 s	I/NAV Word 2 – **CED**						Even
2 s	I/NAV Word 2	Res	SAR	Spare	CRC	**SSP1**	Odd
3 s	I/NAV Word 4 – **CED**						Even
4 s	I/NAV Word 4	Res	SAR	Spare	CRC	**SSP2**	Odd
5 s	I/NAV Word 6						Even
6 s	I/NAV Word 6	Res	SAR	Spare	CRC	**SSP3**	Odd
7 s	I/NAV Word 7 or 9						Even
8 s	I/NAV Word 7 or 9	Res		Spare	CRC	**SSP1**	Odd
9 s	I/NAV Word 8 or 10						Even
10 s	I/NAV Word 8 or 10	Res		Spare	CRC	**SSP2**	Odd
11 s	I/NAV Word 17 or 18 - **RS CED**						Even
12 s	I/NAV Word 17 or 18	Res	SAR	Spare	CRC	**SSP3**	Odd
13 s	I/NAV Word 19 or 20 - **RS CED**						Even
14 s	I/NAV Word 19 or 20	Res		Spare	CRC	**SSP1**	Odd
15 s	I/NAV Word 16 - **Reduced CED**						Even
16 s	I/NAV Word 16	Res		Spare	CRC	**SSP2**	Odd
17 s	I/NAV Word 0						Even
18 s	I/NAV Word 0	Res	SAR	Spare	CRC	**SSP3**	Odd
19 s	I/NAV Word 0						Even
20 s	I/NAV Word 0	Res		Spare	CRC	**SSP1**	Odd
21 s	I/NAV Word 1 – **CED**						Even
22 s	I/NAV Word 1	Res		Spare	CRC	**SSP2**	Odd
23 s	I/NAV Word 3 – **CED**						Even
24 s	I/NAV Word 3	Res	SAR	Spare	CRC	**SSP3**	Odd
25 s	I/NAV Word 5						Even
26 s	I/NAV Word 5	Res		Spare	CRC	**SSP1**	Odd
27 s	I/NAV Word 0						Even
28 s	I/NAV Word 0	Res		Spare	CRC	**SSP2**	Odd
29 s	I/NAV Word 16 - **Reduced CED**						Even
30 s	I/NAV Word 16	Res	SAR	Spare	CRC	**SSP3**	Odd

Backward compatibility

Provision of “legacy” CED: I/NAV Words 1 to 4

Time to CED improvement (full accuracy)

Provision of RS encoded CED: I/NAV Words 17 to 20

Time to CED improvement (reduced accuracy)

Provision of Reduced CED: I/NAV Word 16

Time to GST improvement

Provision of Secondary Synchronization Patterns

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Reduced Clock and Ephemeris Data - RedCED (1/2)

- RedCED is a compact set of satellite orbit and clock correction information, transmitted twice every 30 s within **1 single I/NAV word** (new Word Type 16)
- Keeping the discretization errors as small as possible:
  - ✓ Tailored set of equinoctial elements for near circular orbit
  - ✓ Provision of Clock minus Radial Error Correction Coefficients
- Transformation to Keplerian orbit elements:
  - ✓ Eccentricity: $e = \sqrt{e_x^2 + e_y^2}$
  - ✓ Argument of perigee: $\omega = \tan^{-1}\left(\frac{e_y}{e_x}\right)$
  - ✓ Mean anomaly: $M_0 = \lambda_0 - \tan^{-1}\left(\frac{e_y}{e_x}\right)$
- Reduced CED reference time: $t_{or} = \text{modulo}\left(30 * \left\lfloor \frac{TOT_{RedCED}}{30} \right\rfloor + 1s, 604800s\right)$

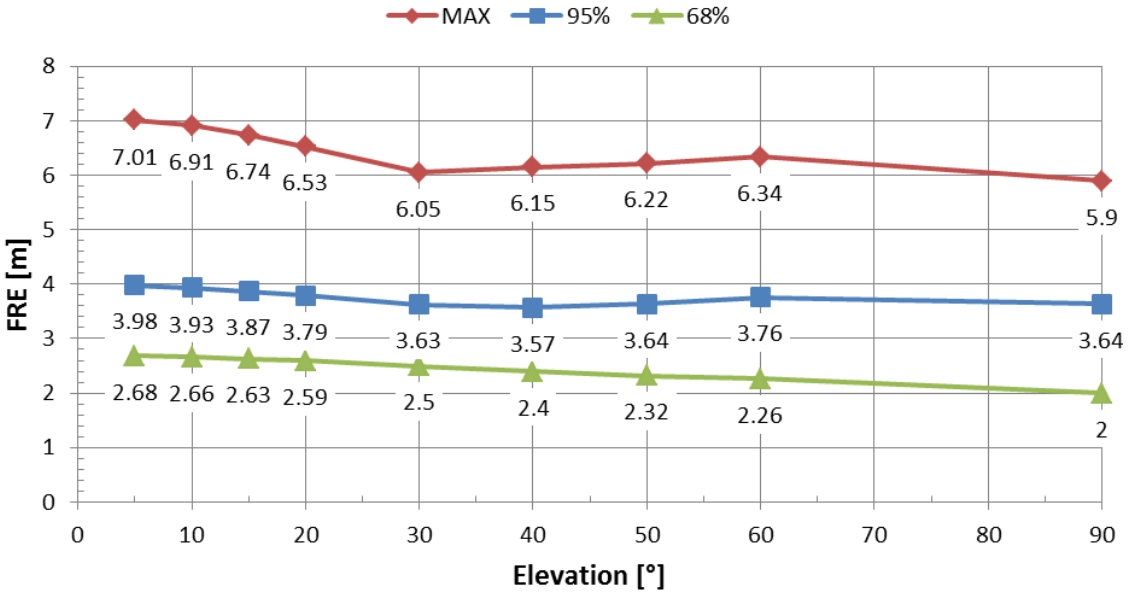
Type=16	Reduced CED parameters								Total (bits)
	ΔA_{red}	e_{xred}	e_{yred}	Δi_{0red}	Ω_{0red}	λ_{0red}	a_{f0red}	a_{f1red}	
6	5	13	13	17	23	23	22	6	128

Reduced Clock and Ephemeris Data - RedCED (2/2)

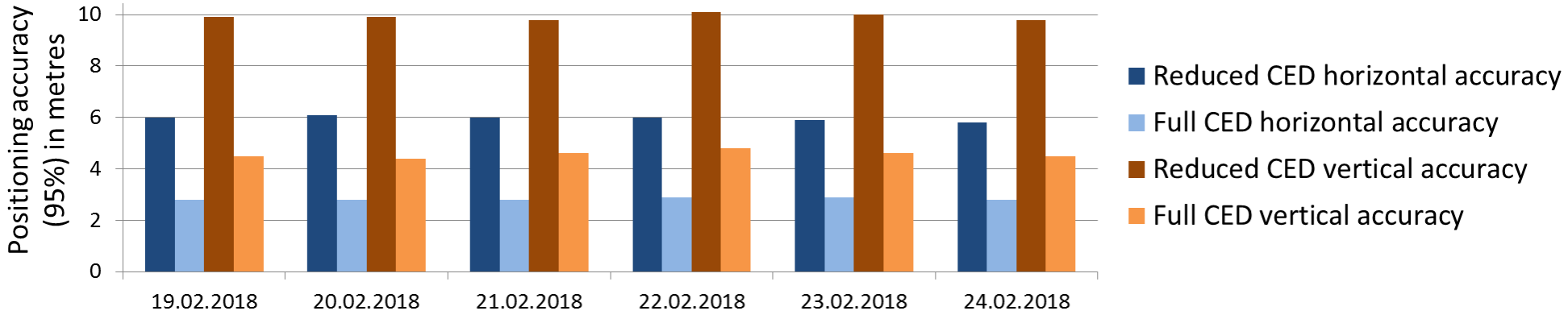
- Reduced CED Fitting Range Error (FRE)

$$FRE(E) = |\Delta T_{ClkRadial}(E)| + \Delta X_{Tangential} \cdot \frac{R_{earth}}{R_{orbit}} \cos(E)$$

  - ✓ 10 minutes validity duration with very remarkable ranging and positioning performance
  - ✓ Galileo satellites set to transmit RedCED only if signal are healthy (SHS=0, DVS=0, SISA≠NAPA)
- Remarkable ranging and positioning performanc

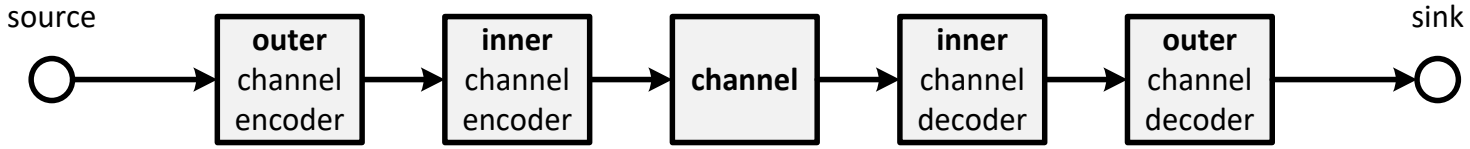


- Dual Frequency E1-E5b User Positioning Performance (global average over 159 IGS stations)



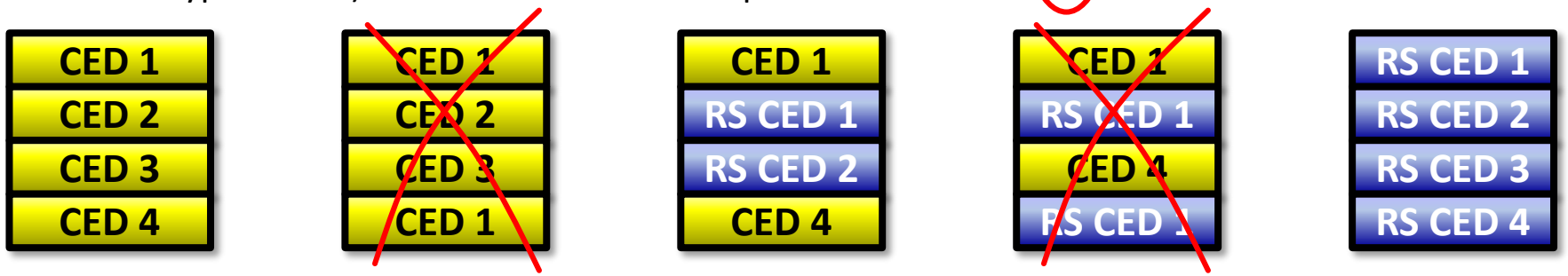
Reed-Solomon Outer Forward Error Correction

- Reed-Solomon (RS) Outer Forward Error Correction (FEC2) providing correction of residual errors AND recovery of erased information



- The “Joker Property”
  - ✓ RS codes are non-binary maximum distance separable (MDS) codes
  - ✓ **any set of four different error free words** received being either **legacy CED** (I/NAV Word Types 1-4) or newly introduced **RS CED** (I/NAV Word Types 17-20) recovers the clock and ephemeris data

Type= 17, 18, 19, 20	FEC2 Reed-Solomon for CED (1/2)	LSB(IOD_{nav})	FEC2 Reed-Solomon for CED (2/2)	Total (bits)
6	8	2	112	128



- **2 dB** improved **data demodulation robustness** in **open sky**
- **5 dB** improved **data demodulation robustness** in **urban environment**

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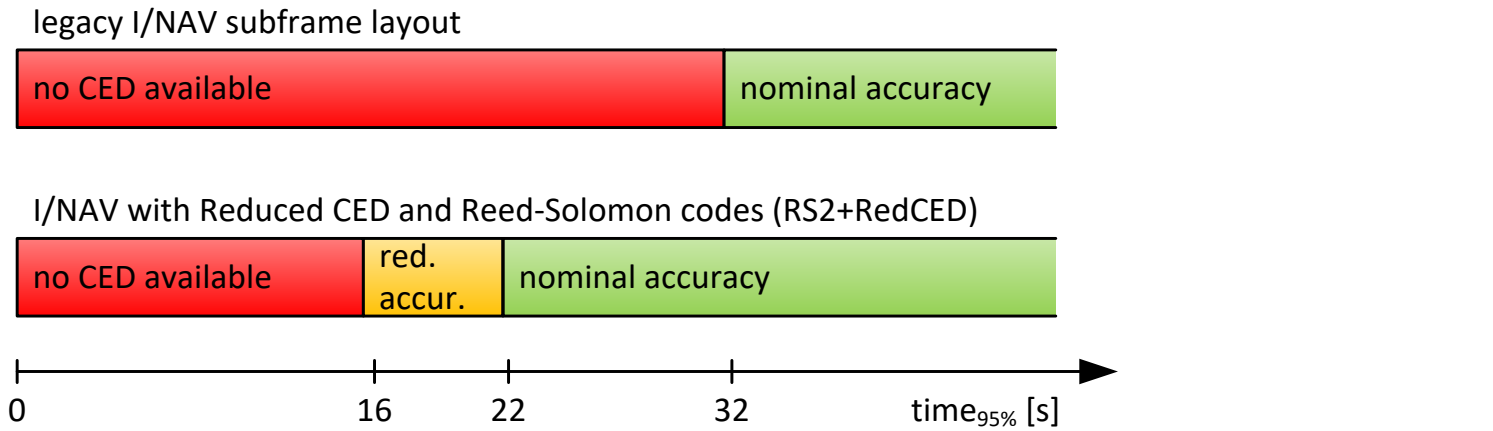
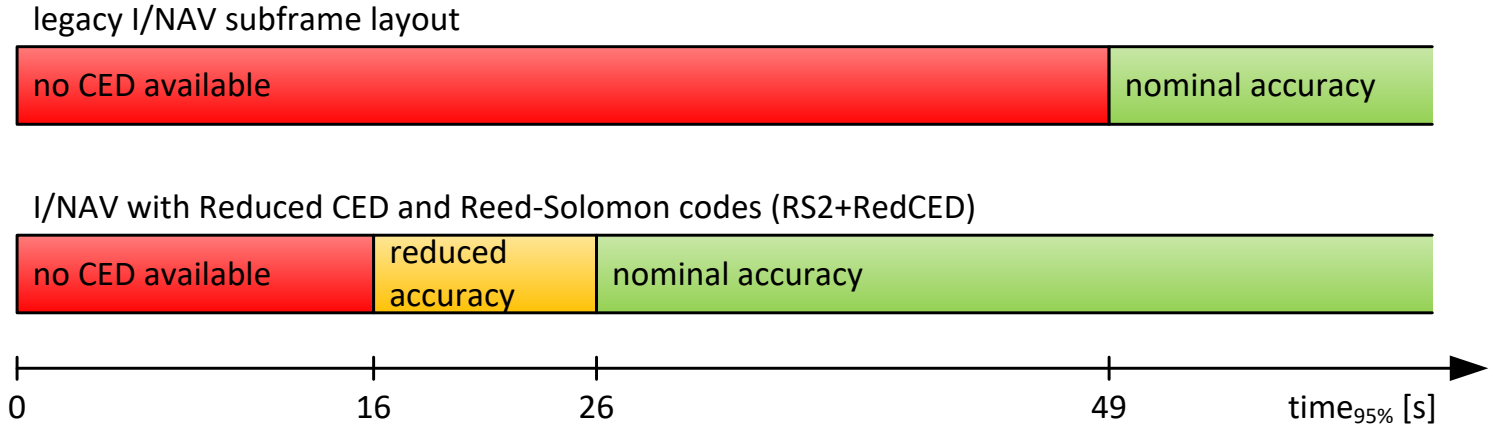
“Time to Clock and Ephemeris Data” Improvement



Time to CED (95%) for a user in *open sky*



Time to CED (95%) for a user in *urban* environment

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Secondary Synchronization Pattern (SSP) – 1/2

- SSP replaces reserved bits on I/NAV E1-B
- SSP enables the reconstruction of the GST
  - ✓ performing a correlation operation on the encoded symbols

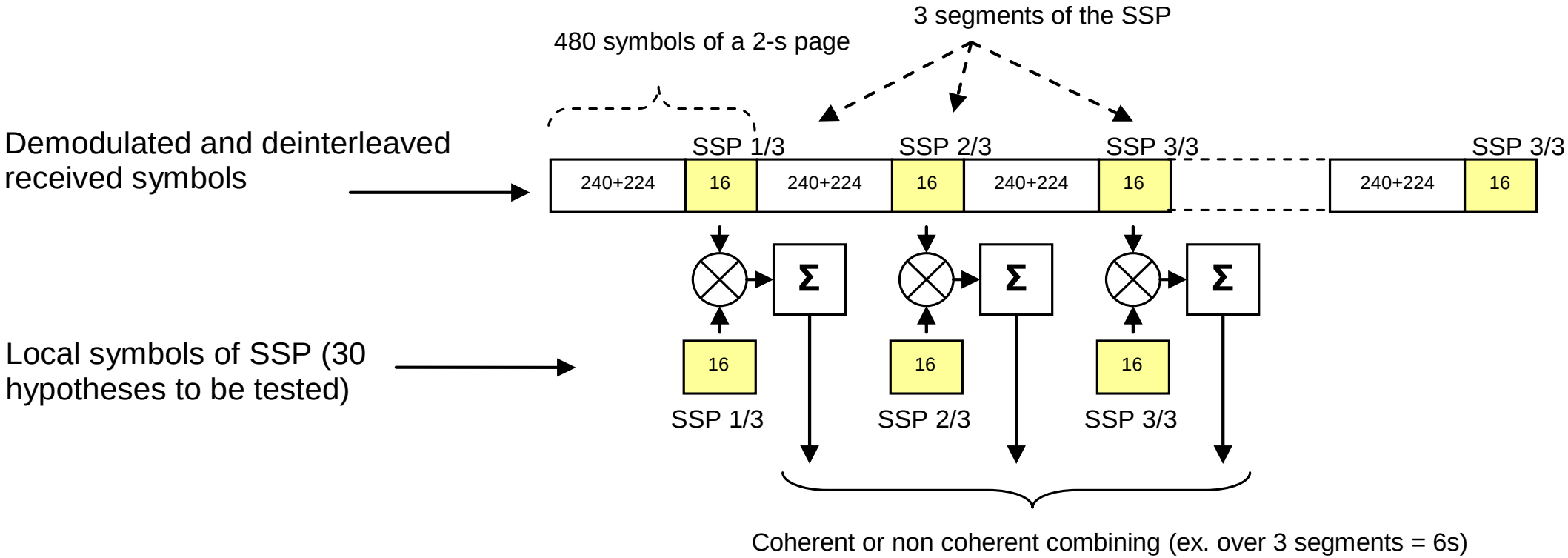
E1-B									
Even/odd=1	Page Type	Data j (2/2)	Reserved 1	SAR	Spare	CRC_j	SSP	Tail	**Total (bits)**
1	1	16	40	22	2	24	8	6	120

	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

- Required level of coarse synchronisation: GST ± 3 sec
- Ambiguous Time Of Week (TOW) information can be retrieved
  - SSP1 detected → $\mathrm{TOW\ modulo\ 6s} = 1s$
  - SSP2 detected → $\mathrm{TOW\ modulo\ 6s} = 3s$
  - SSP3 detected → $\mathrm{TOW\ modulo\ 6s} = 5s$

Secondary Synchronization Pattern (SSP) – 2/2

- Exemplary receiver implementation: synchronization through correlation at symbol level



- Reconstruct Galileo System Time using weak signals
- No need to demodulate the navigation message

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Implementation Roadmap and Receivers Testing Campaign

- All technical details relevant for INAV improvements implementation in a receiver are provided within **OS SIS ICD Issue 2**, including **test vectors**
- **Target performance** widely discussed within technical literature[1]
- The system set to transmit the new I/NAV capabilities already in **2022** and complete deployment to all satellites by **2023**
- The Programme is supporting receiver manufacturers with a **dedicated testing campaign** on implementation of the new I/NAV capabilities
  - ✓ **Laboratory tests** through simulated signals under realistic scenarios
  - ✓ **Open call for testing** announced by EUSPA[2]

[1] M. Paonni et al., *Improving the Performance of Galileo E1-OS by Optimizing the I/NAV Navigation Message*, Proceedings of ION GNSS+ 2019

[2] https://www.euspa.europa.eu/newsroom/news/euspa-re-opens-testing-campaign-inav-improvements-implementation

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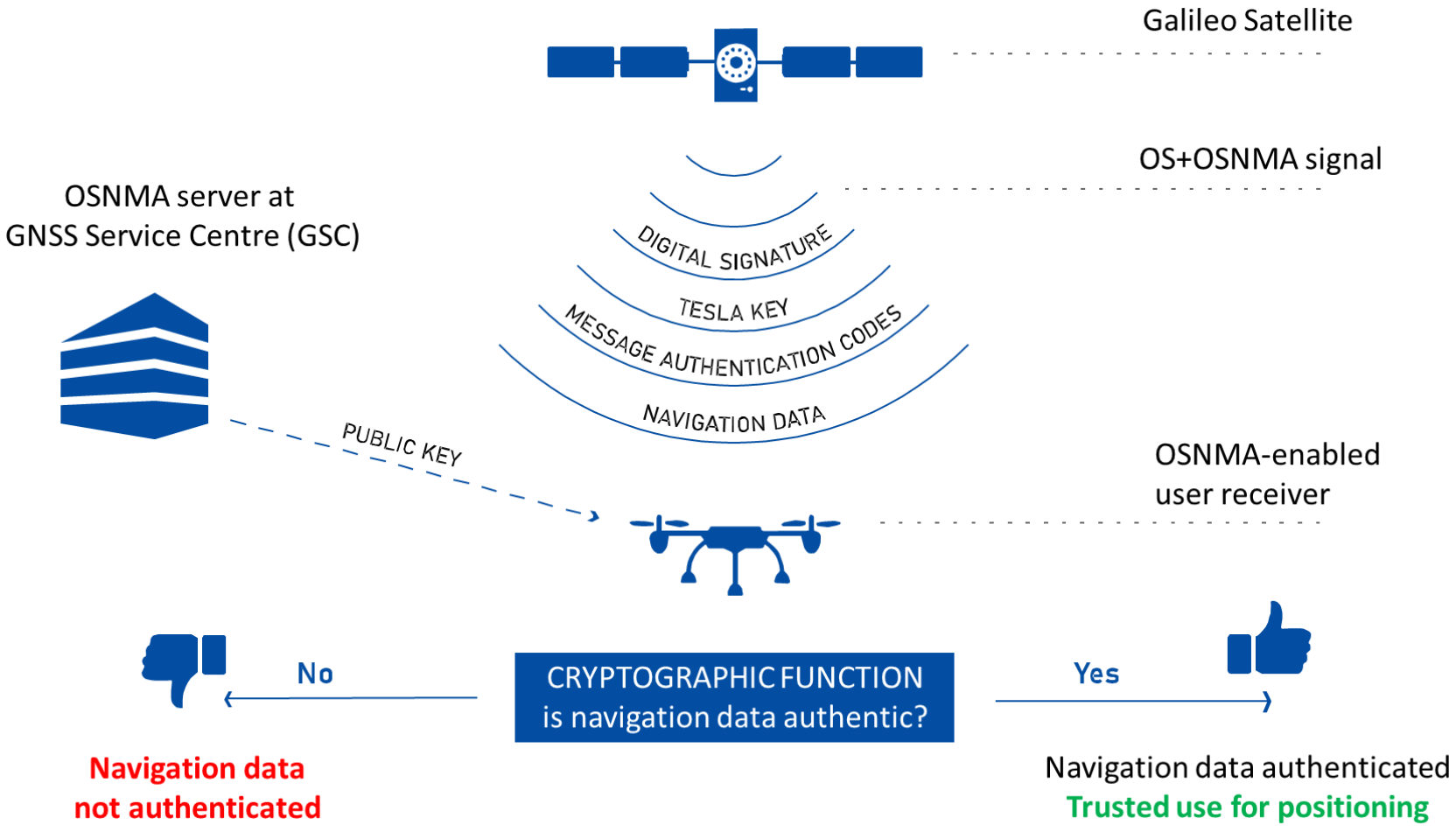
Galileo Open Service Navigation Message Authentication

- OSNMA is another step from the Galileo program to increase the **resilience** of the user navigation solution



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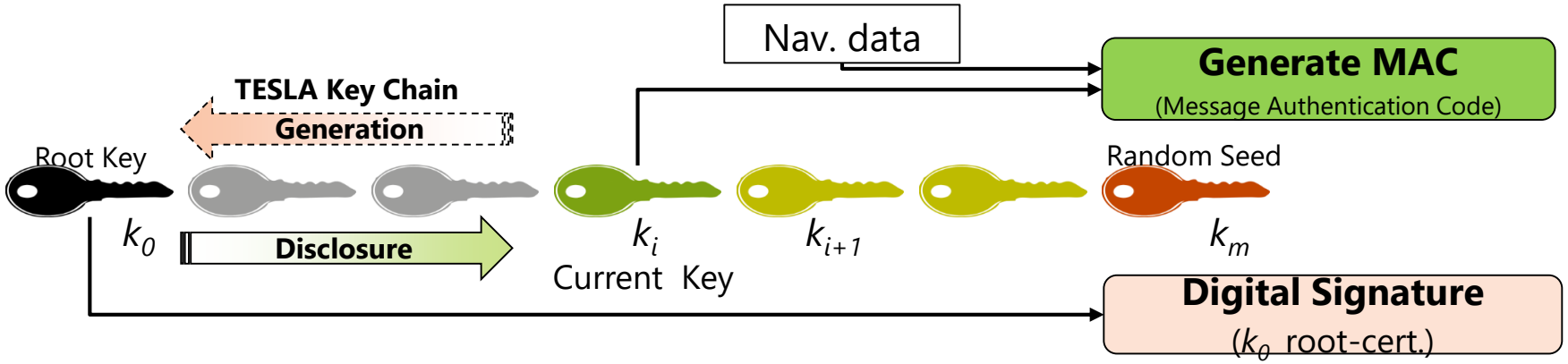
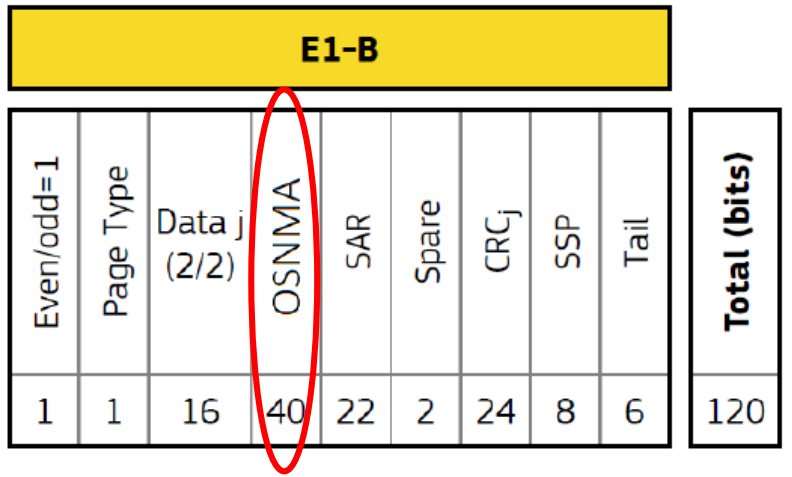
Galileo OSNMA Basics

- OSNMA implemented making use of spare bits within **I/NAV E1-B** (Reserved 1 field)
- **TESLA protocol** (Timed Efficient Stream Loss-Tolerant Authentication) adapted to Galileo



- **Chain of keys** generated through a **one-way** function
  - ✓ *Message Authentication Code* (MAC) to authenticate a specific portion of the navigation message
  - ✓ Current key (used to compute MAC) released with a delay
- ✓ Single one-way chain for all satellites
- ✓ Root key (k_0) signed with a public-private signature scheme



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OSNMA Public Observation OPEN!

- OSNMA Test Signal is available globally
- Open access for receiver manufacturers and app developers (following registration process at GSC to get access to key material)
- Relevant documentation published at GSC*:
  - OSNMA User ICD for the Test Phase
  - OSNMA Receiver Guidelines for the Test Phase
  - OSNMA Typical Performance presentation

* https://www.gsc-europa.eu/electronic-library/programme-reference-documents#OSNMA

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Conclusions

- Galileo is introducing a number of technical solutions to enable improved performance for the Open Service users
- Increased data retrieval and position fix robustness and timeliness thanks to I/NAV improvements introduced in OS SIS ICD 2.0
  - ✓ I/NAV improvements being deployed, testing opportunities offered through EUSPA
- Increased positioning resilience thanks to the progressive introduction of authentication functions
  - ✓OSNMA Public observation phase ongoing, initial service planned for 2023
- All those innovations introduced making an efficient use of spare bandwidth within the I/NAV message
- Guarantee **backward compatibility is paramount**…
- …**look forward to continue improvement** as well!

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THANK YOU

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