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Galileo System Update and Open Service Evolution

Space SUITE Training

26 June 2024

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This presentation is divided into two sections:

1. Galileo System Update
2. Open Service Evolution

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1. Galileo System Update

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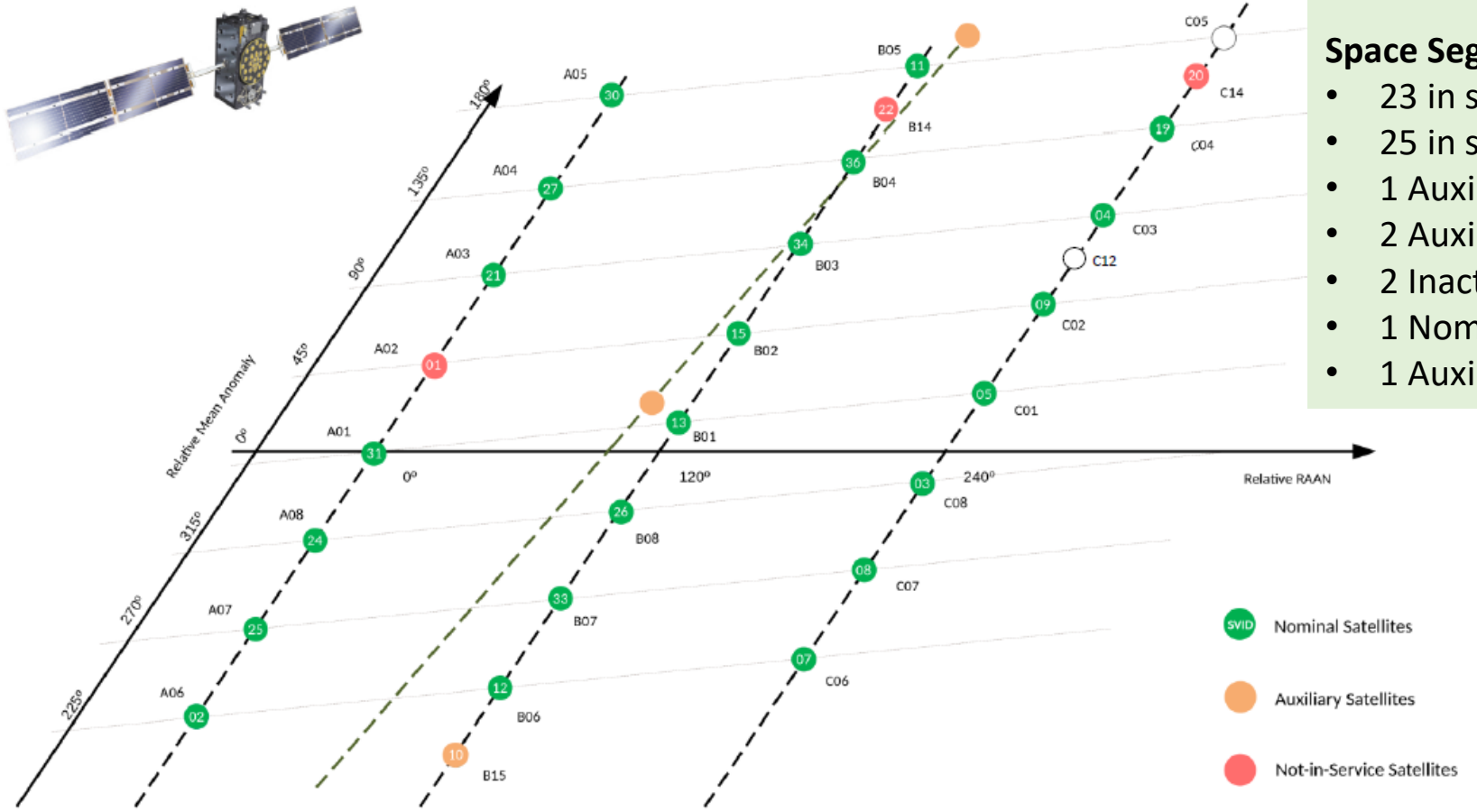
GALILEO Space segment status



Current Status

Space Segment: 28 satellites in Orbit

- 23 in service for Navigation
- 25 in service for Search and Rescue
- 1 Auxiliary in service for Navigation/SAR
- 2 Auxiliary in service for SAR only
- 2 Inactive Spare
- 1 Nominal slot under commissioning
- 1 Auxiliary slot under commissioning

Galileo Services – now, then and next

Open Service (OS)

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

Public Regulated Service (PRS)

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

Search and Rescue (SAR) - contribution

- Forward link + acknowledgement "return link“

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

Road to FOC:

- Currently delivering "Enhanced Services" (OS SDD 1.3 and OS SiS ICD 2.1, Nov 23)
- Space Segment
  - Successful L12 commissioning (Q3 24)
  - Successful L13 launch and commissioning (End 24)
  - Plan for next launches (to maintain capability) under consolidation
- Ground Segment
  - Successful migration to next major release completed and operational as of March 24
  - No impact on service

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OSNMA

- **Full document set for Service Phase available at GSC (4 documents)**
  - Test signals on continuous broadcast since 3 August 2023, following the **service phase configuration**
  - Test PKI certificates available for download
  - Test vectors available enable the assessment of a receiver capabilities to support different OSNMA configurations

  - Performance of test phase published in quarterly reports
  - Work continues towards service declaration with associated commitments

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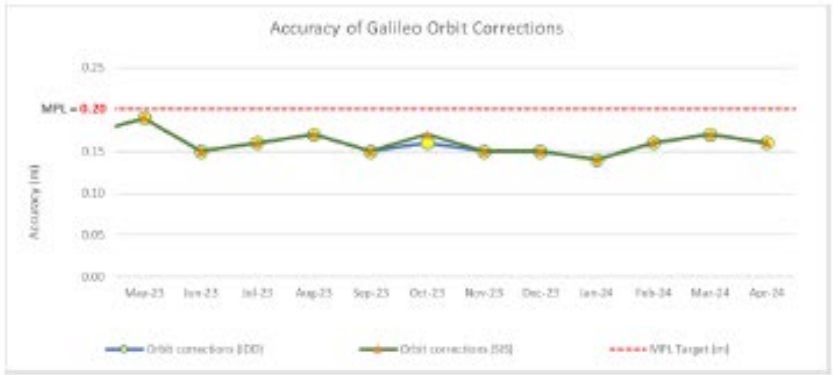
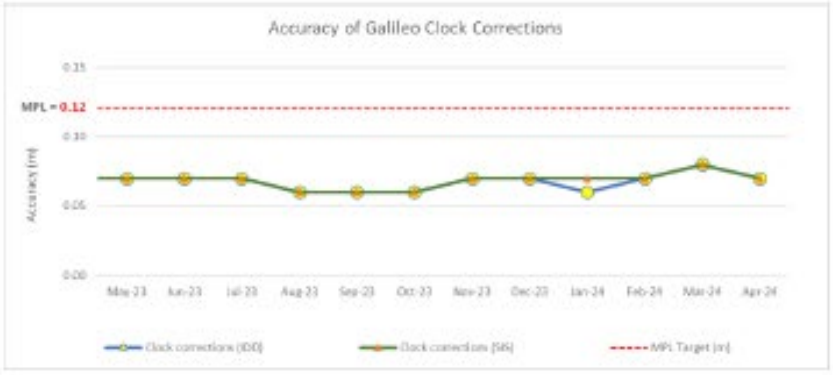
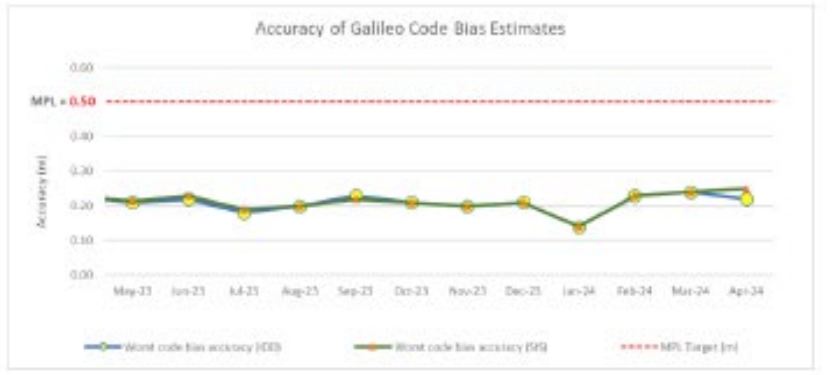
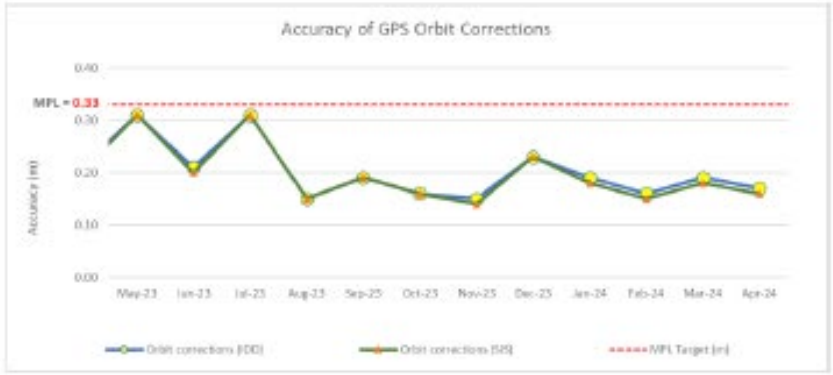
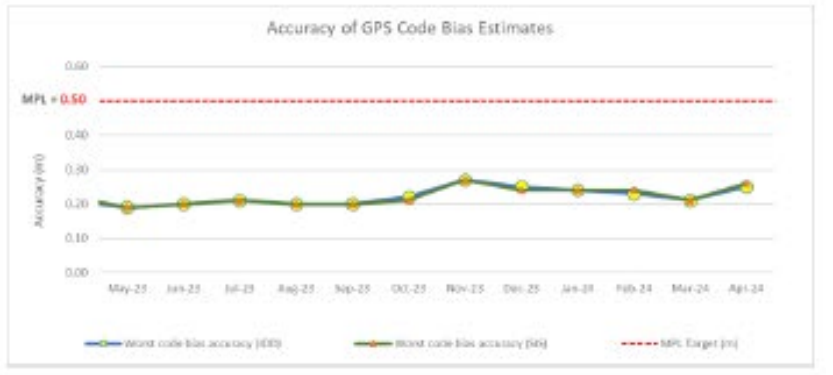
High Accuracy Service Performance











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Other Services on the way

- **Search and Rescue:** 4th MEOLUT in La Reunion deployed
  - Service Validation campaign running, findings addressed
  - **Extending SAR/Galileo coverage to Indian Ocean in 2024**

- **Emergency Warning Service:** Initial Service implementation starting in 2024

- **Timing Service:** Message Definition published in April 2024

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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

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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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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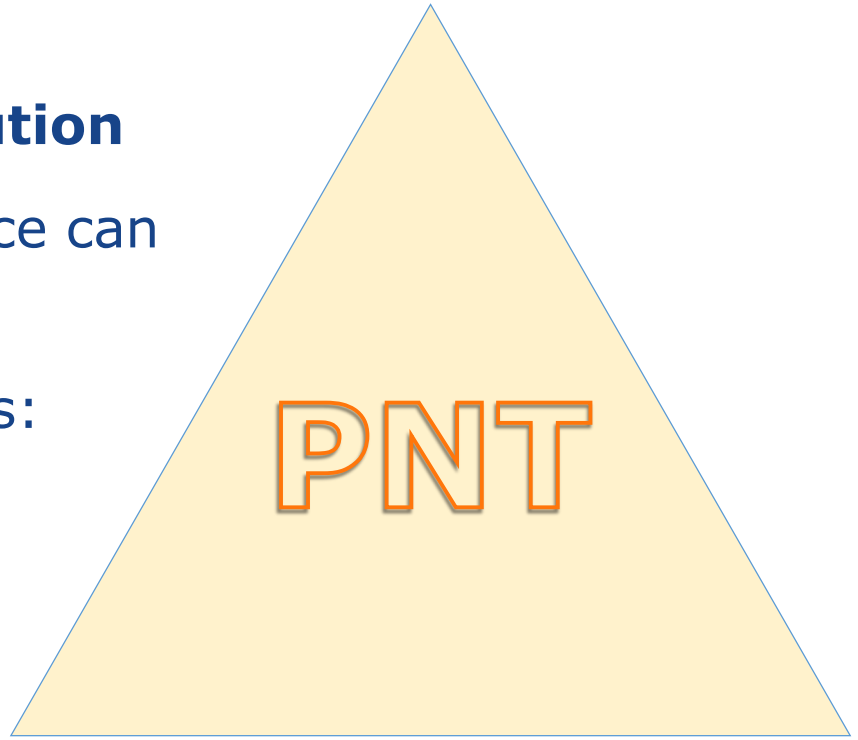
GNSS Backbone for User PNT

- 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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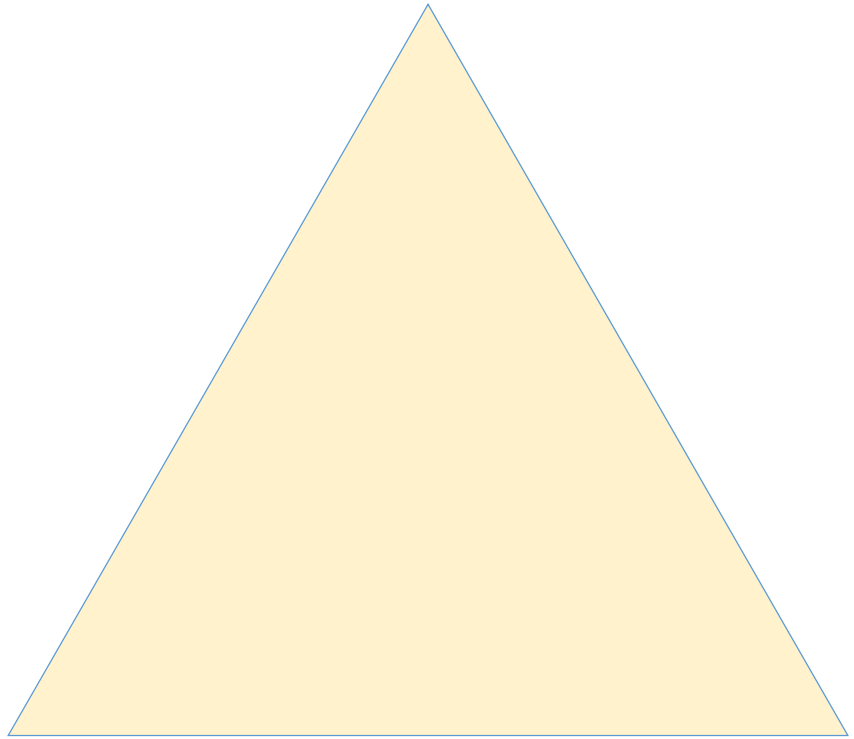
The 3 (+ 1) Dimensions of GNSS Performance



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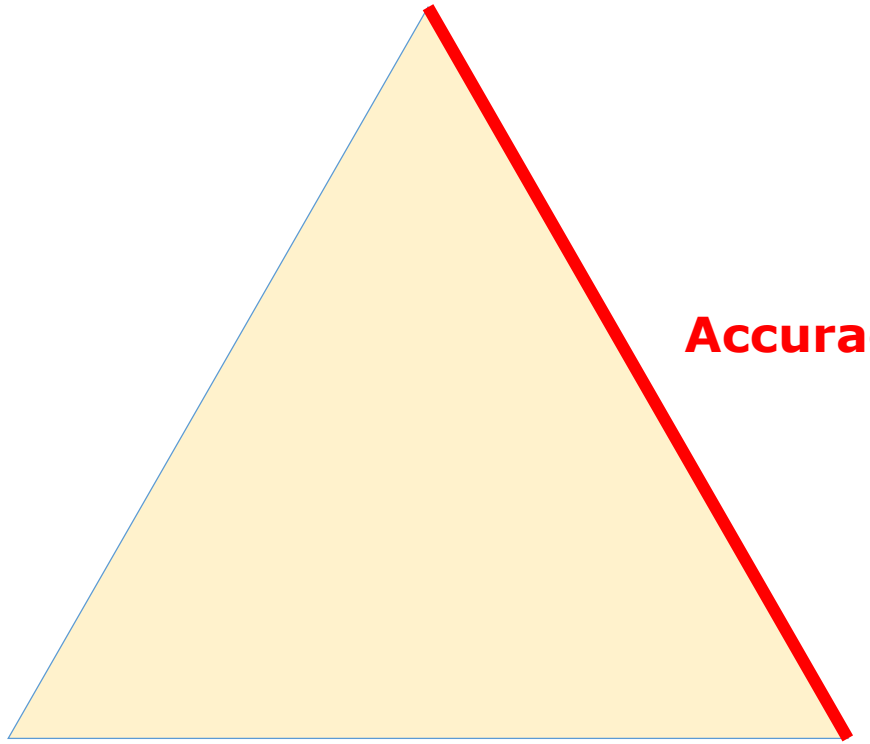

Accuracy

What matters ultimately!

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

Accuracy has to be delivered!

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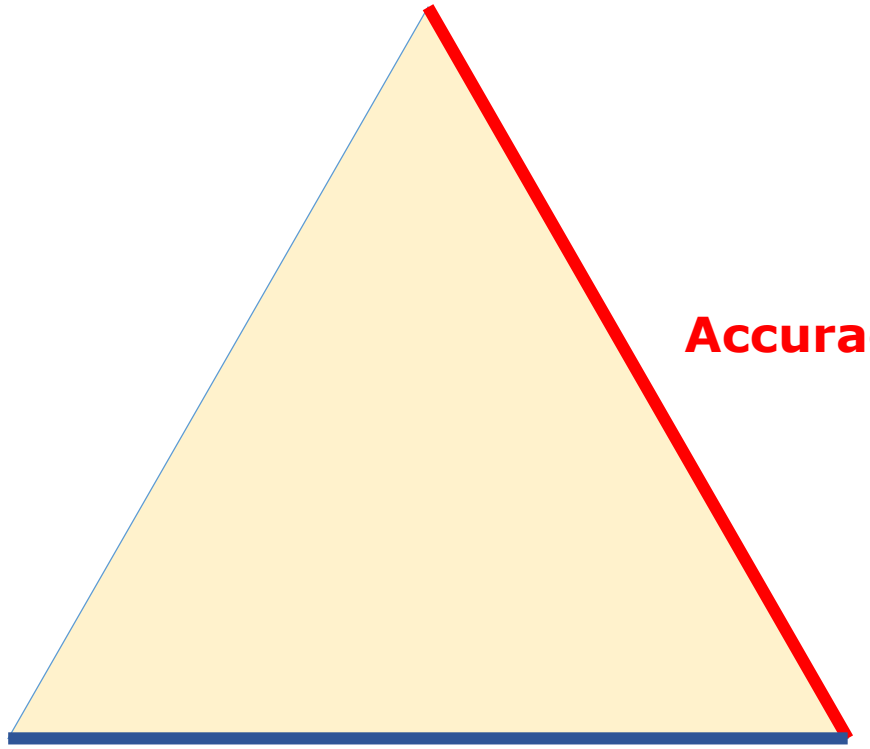

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Qualifies the conditions at which accuracy is delivered (and kept)

Minimum required C/N_0

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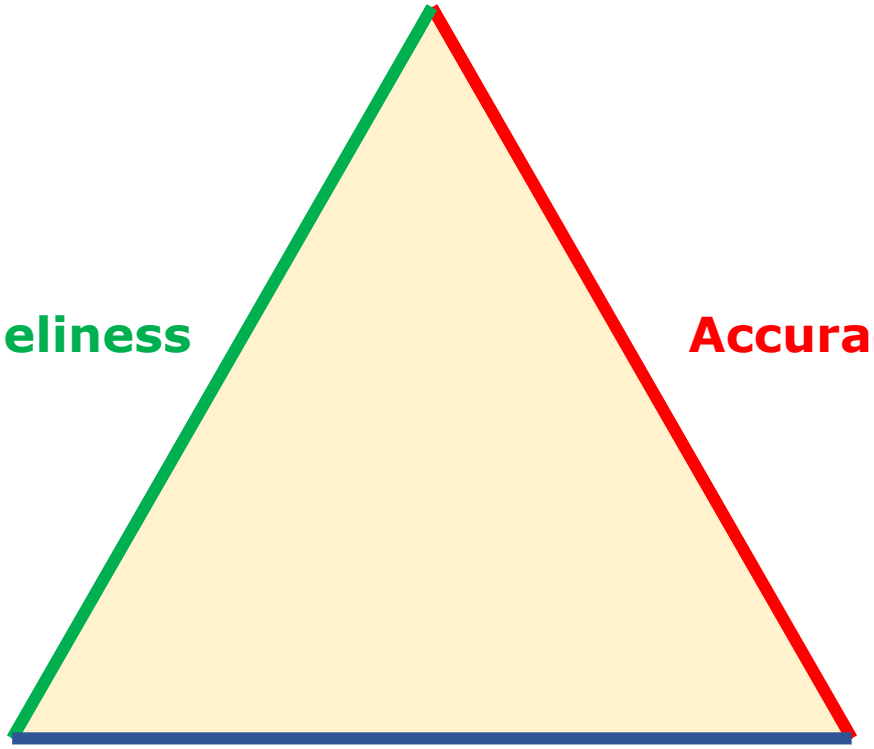

Timeliness

How long does it take?

Time-To-First-Fix

Key for stand-alone

Increasing impact on performance perception

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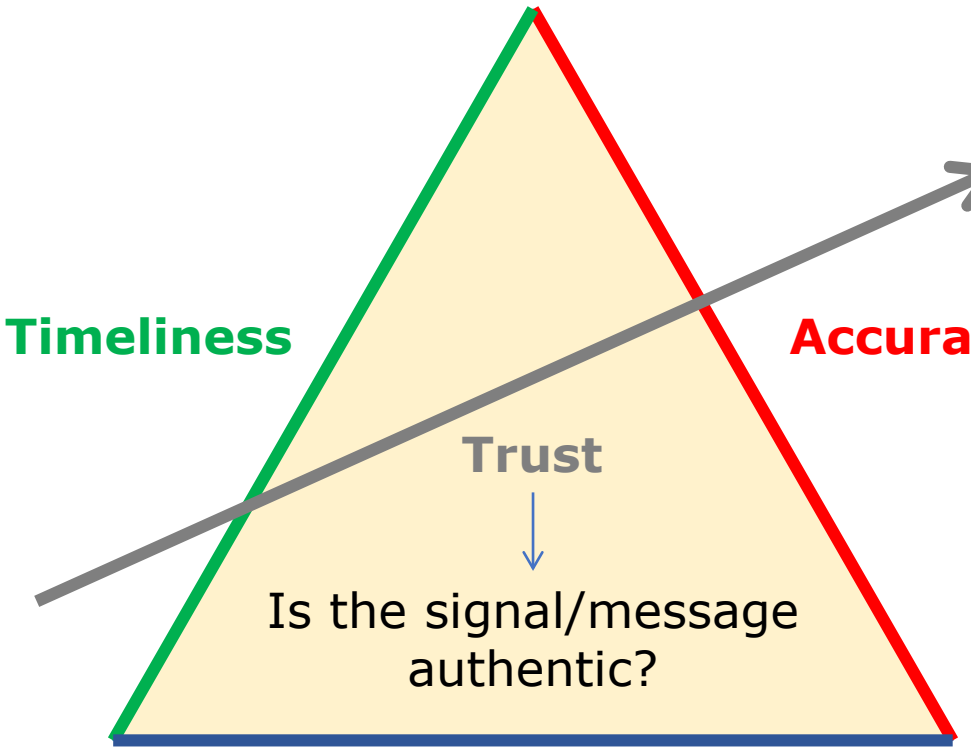

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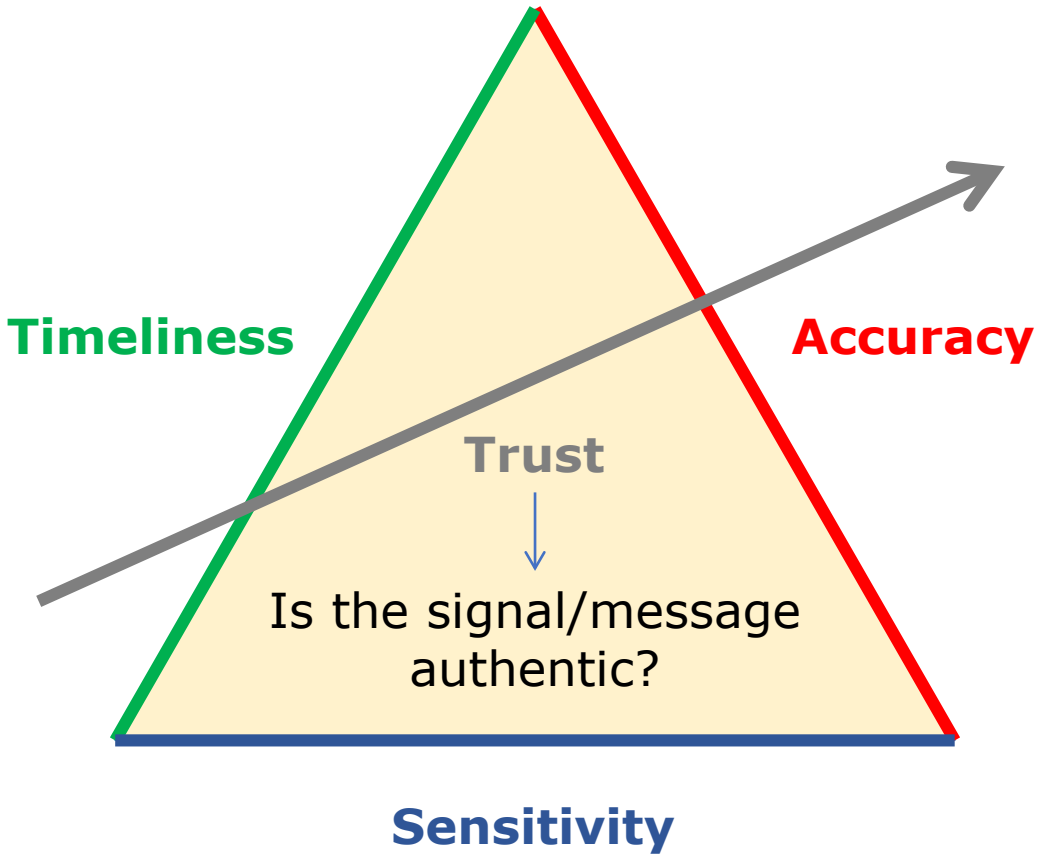
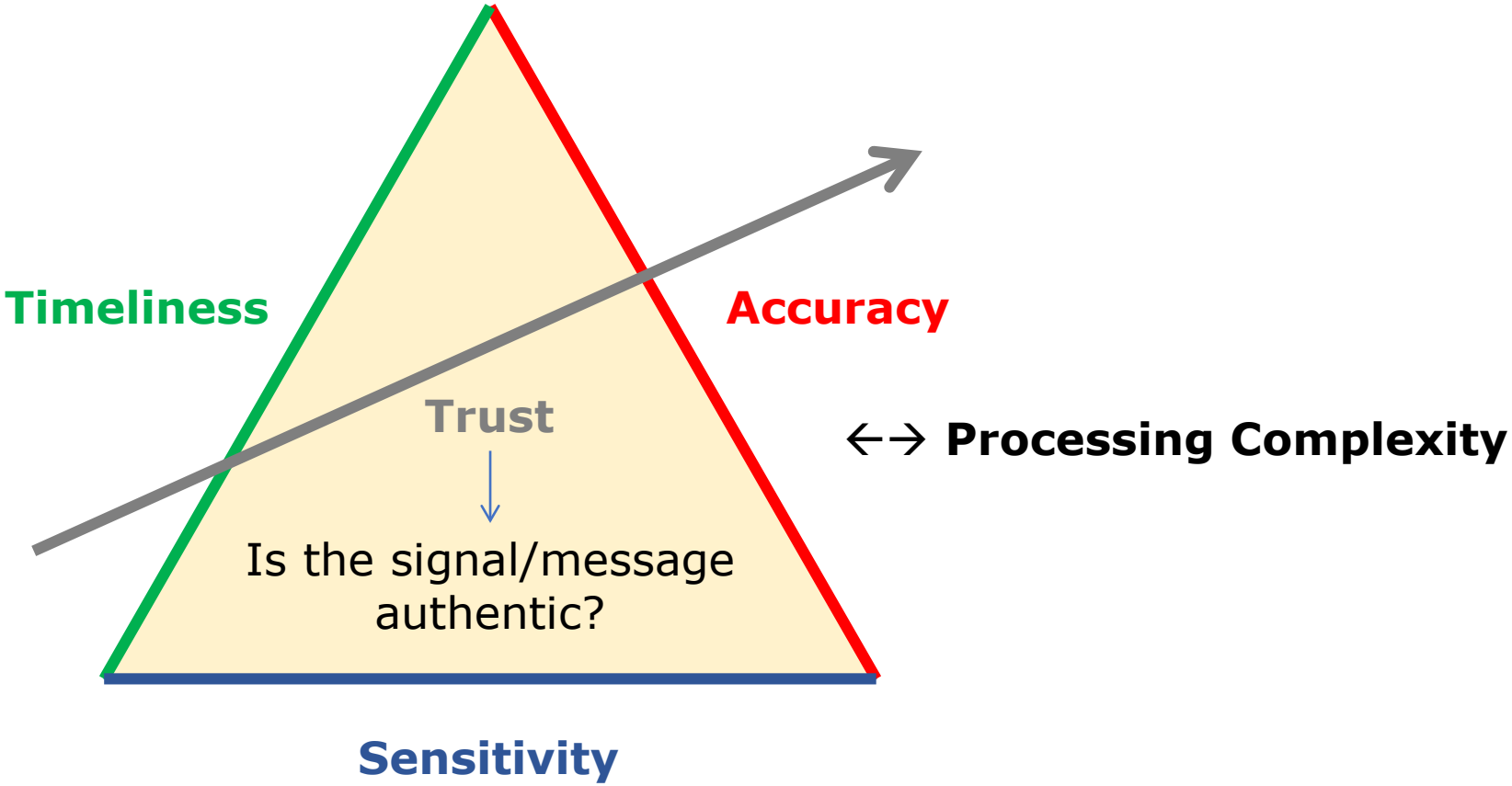


Signal design is a **trade-off** exercise targeting **specific user demand** and considering those **key performance indicator**

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 2.1

- A new issue of the OS SIS ICD released in Nov. 2023

- Major updates introduced in 2021 with Issue 2.0 adding **three new features** to the **I/NAV message** transmitted within the **E1 OS** signal
  - ✓ Reduced Clock and Ephemeris
  - ✓ Reed-Solomon Outer Forward Error Correction
  - ✓ Secondary Synchronization Pattern

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 OS SIS ICD
- 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

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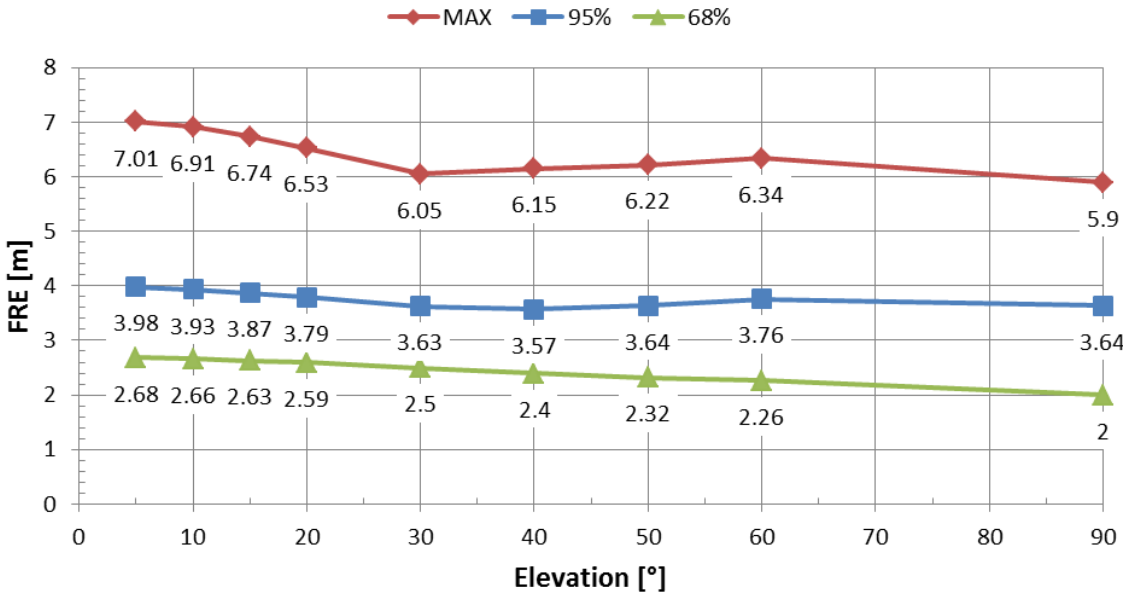
Reduced Clock and Ephemeris Data - RedCED (2/2)

- Reduced CED Fitting Range Error (FRE)

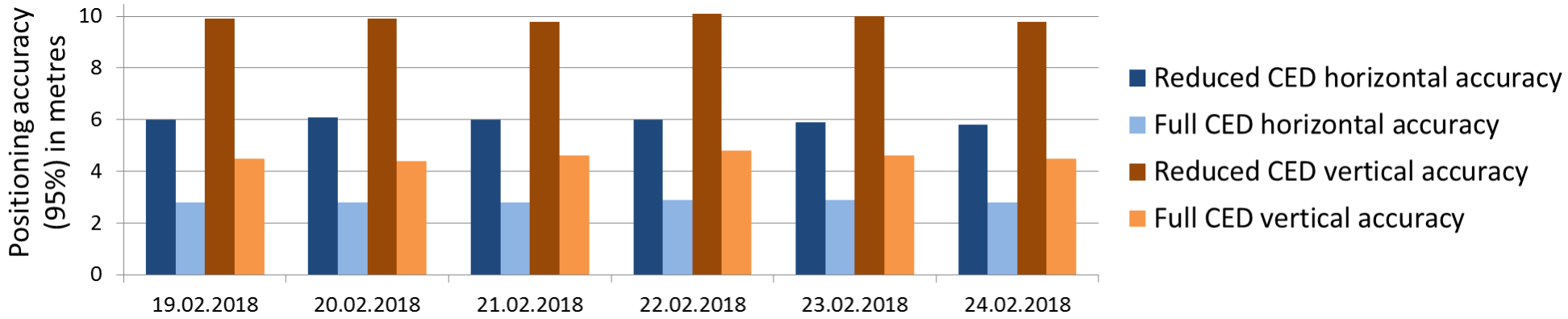
$$FRE(E) = |\Delta T_{ClkRadial}(E)| + \Delta X_{Tangential} \cdot \frac{R_{earth}}{R_{orbit}} \cos(E)$$

  - ✓ 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 performance

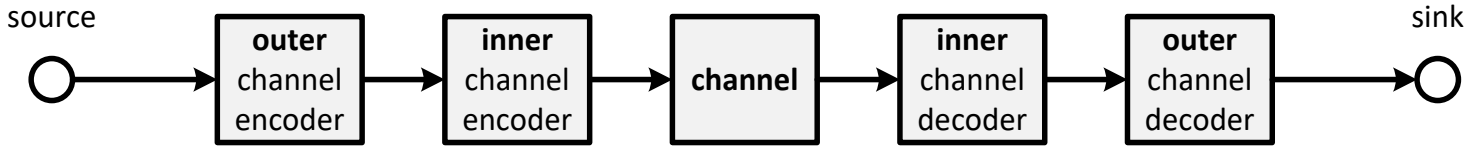


- Dual Frequency E1-E5b User Positioning Performance (global average over 159 IGS stations)



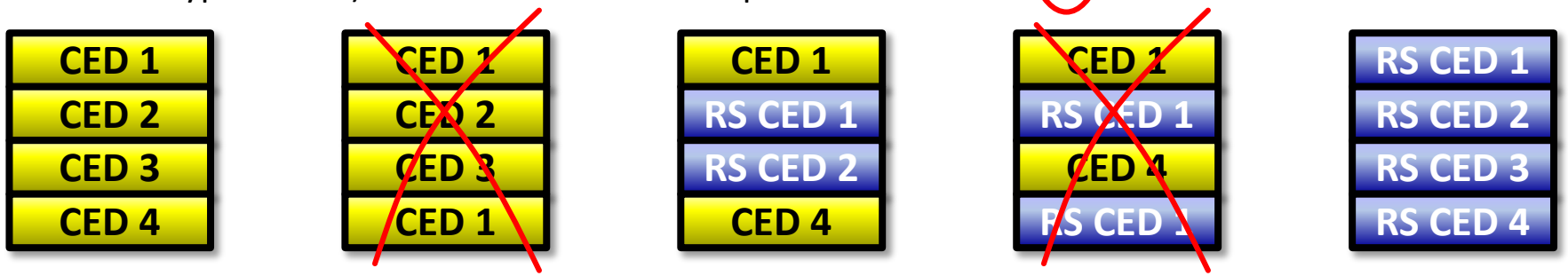
Reed-Solomon Outer Forward Error Correction

- 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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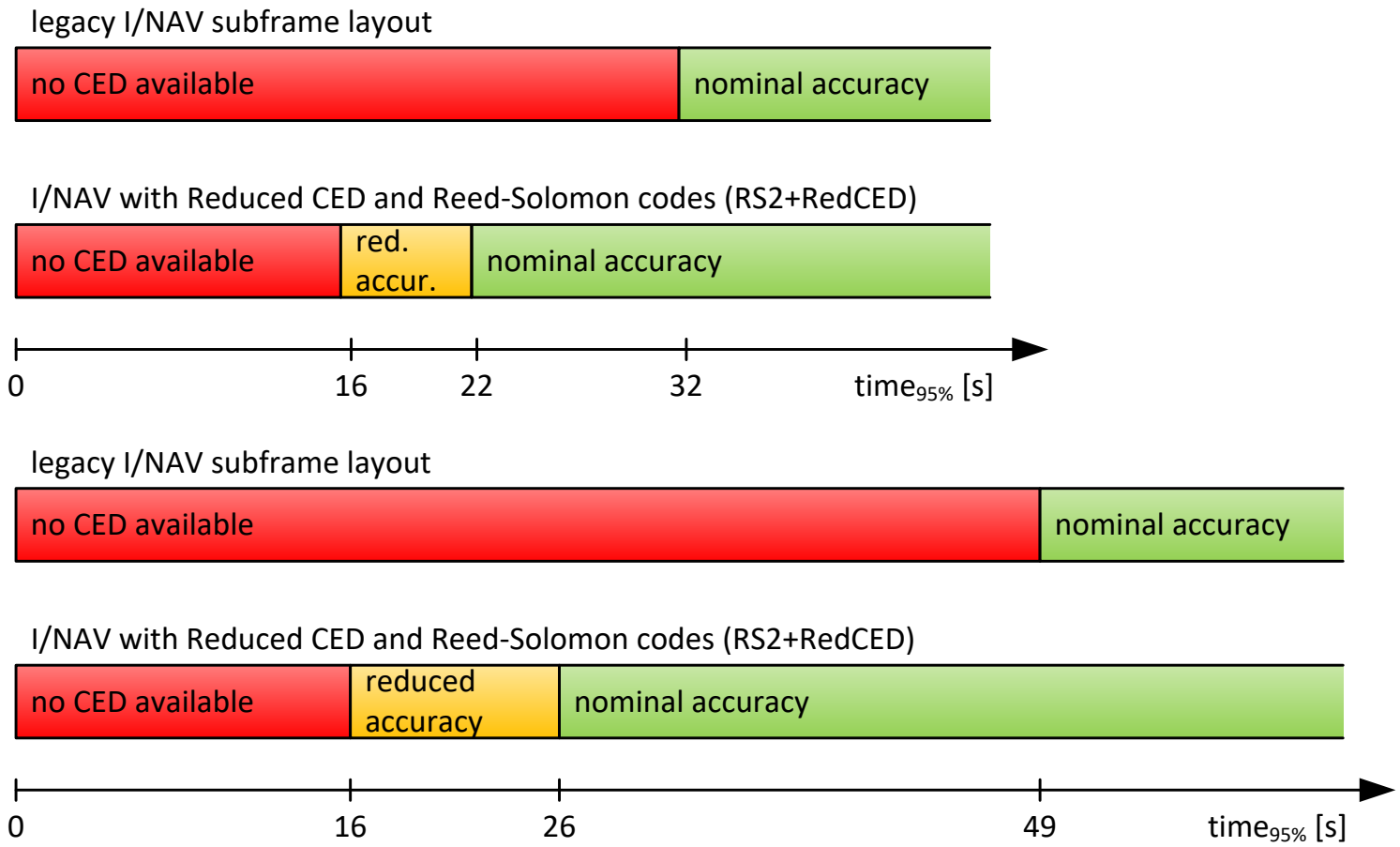
“Time to Clock and Ephemeris Data” Improvement



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 → TOW modulo 6s = 1s
  - SSP2 detected → TOW modulo 6s = 3s
  - SSP3 detected → TOW modulo 6s = 5s

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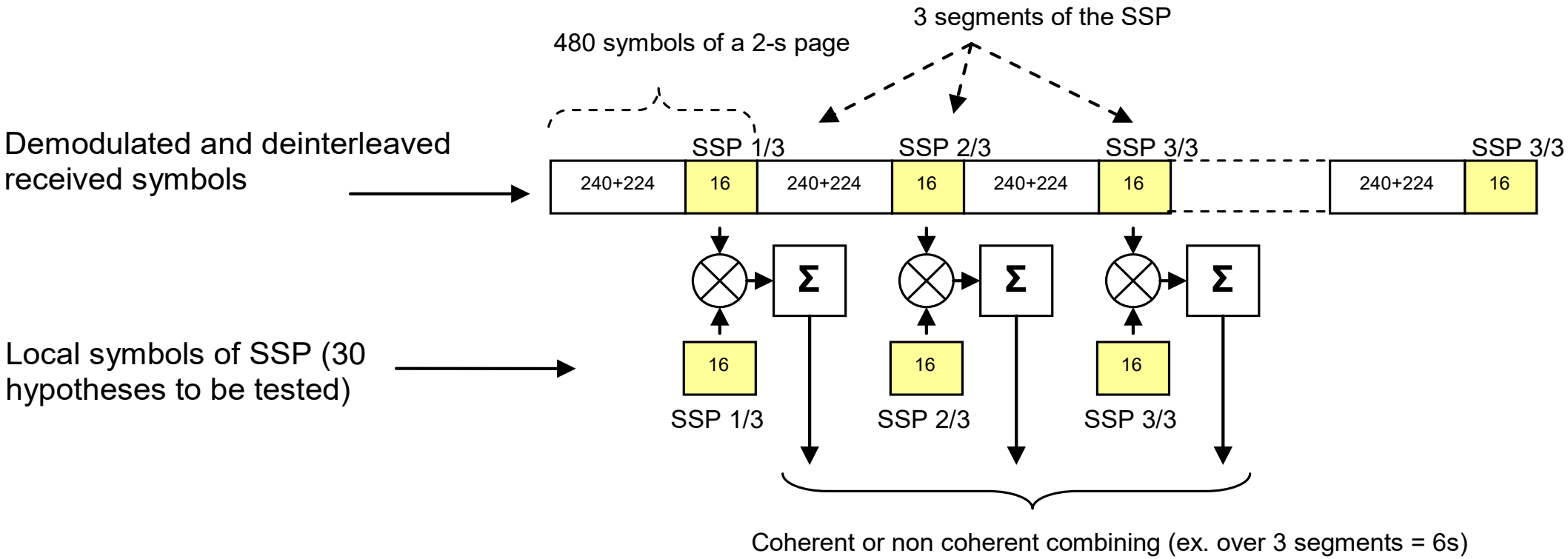
Secondary Synchronization Pattern (SSP) – 2/2

- 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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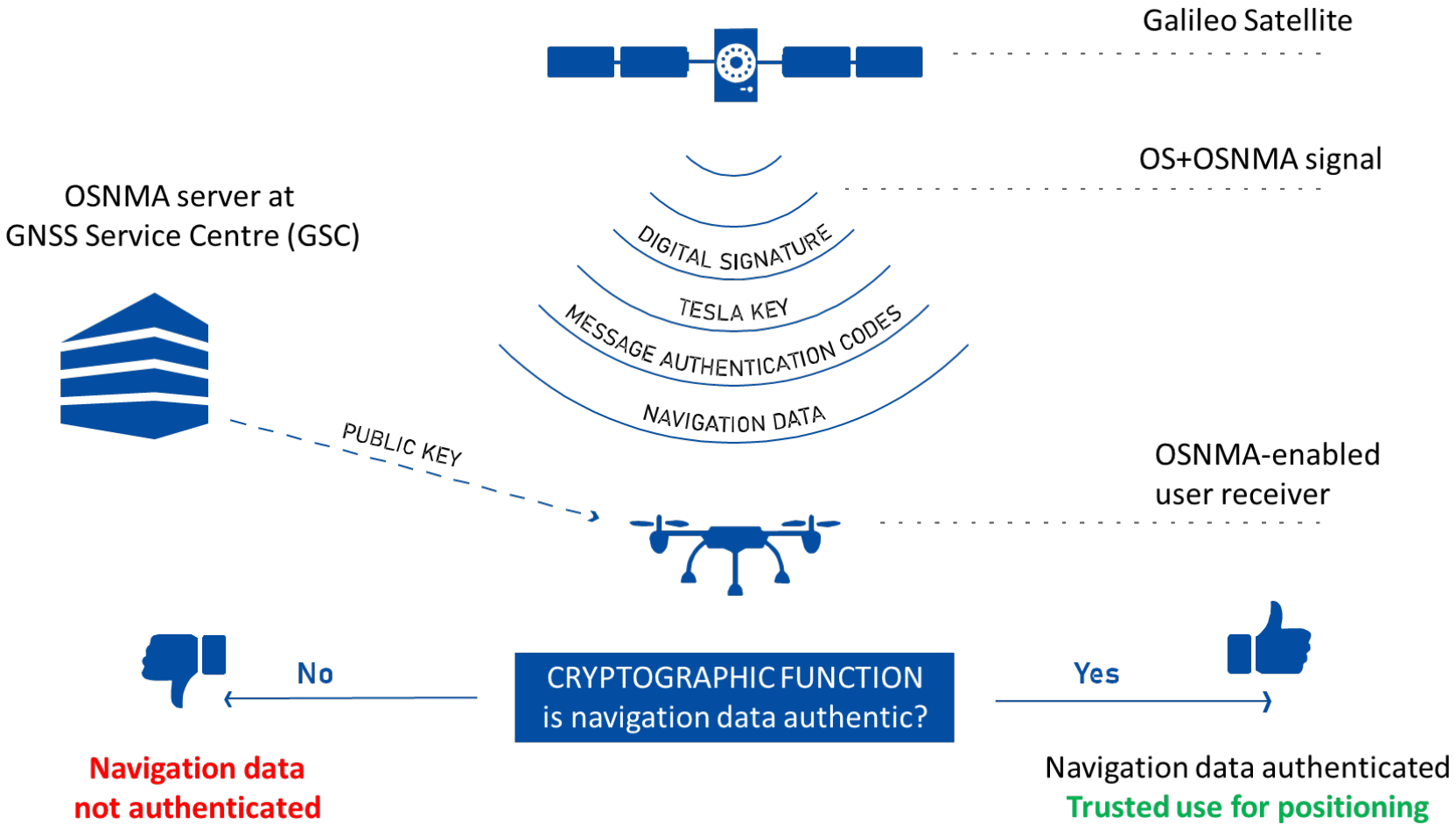
Galileo Open Service Navigation Message Authentication

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



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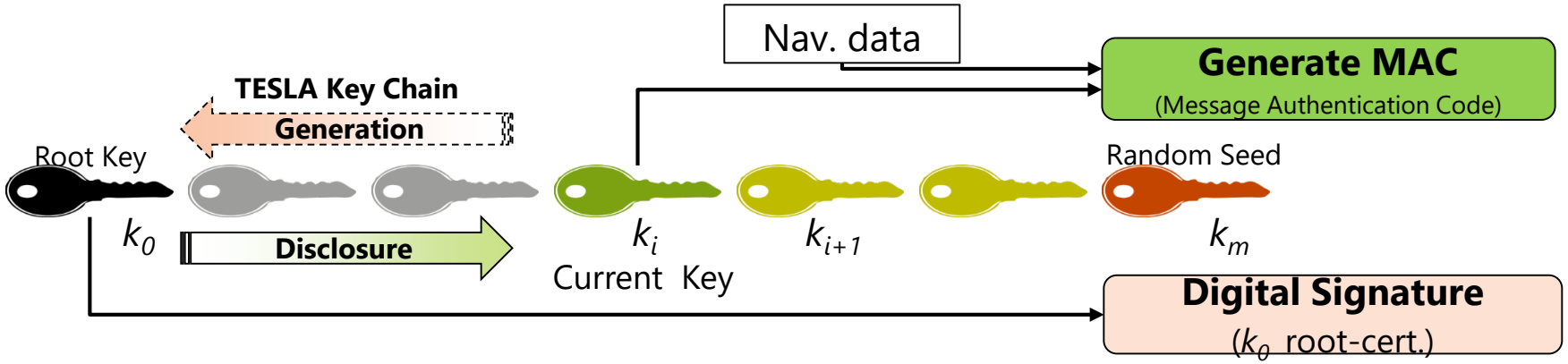
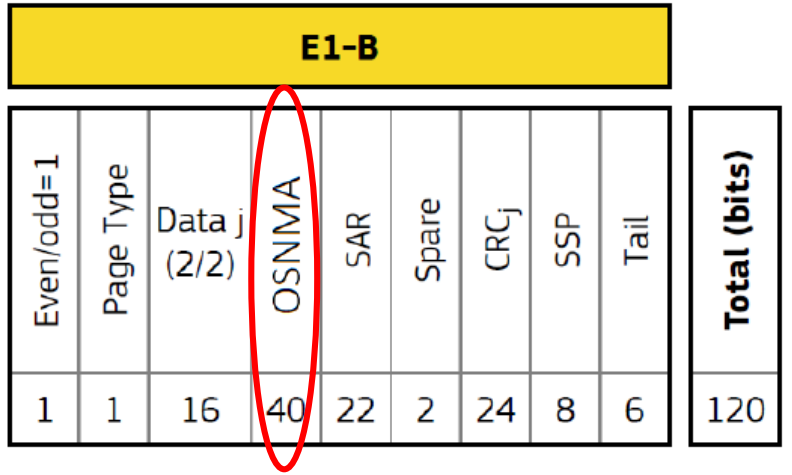
Galileo OSNMA Basics

- 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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Moving Towards G2G!

- I/NAV Improvements up and running
- Signal design for G2G continues under the same principle
- New signal elements being considered to further optimize "3-D (+1)" Galileo performance
  - ✓ Quasi-pilot concept
  - ✓ Data capacity
  - ✓ Authentication
- Still, NEVER FORGET, major optimisation capacity in the hands of receiver manufacturers

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THANK YOU

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