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FUNTIMES

Future Navigation and Timing Evolved Signals

M. Anghileri, J. J. Floch, *Airbus Defence and Space, Germany*

D. Margaria, B. Motella, *ISMB, Italy*

A. Garcia-Peña, O. Julien, C. Macabiau, R. Chauvat, *ENAC, France*

M. Paonni, *EC-JRC, Italy*



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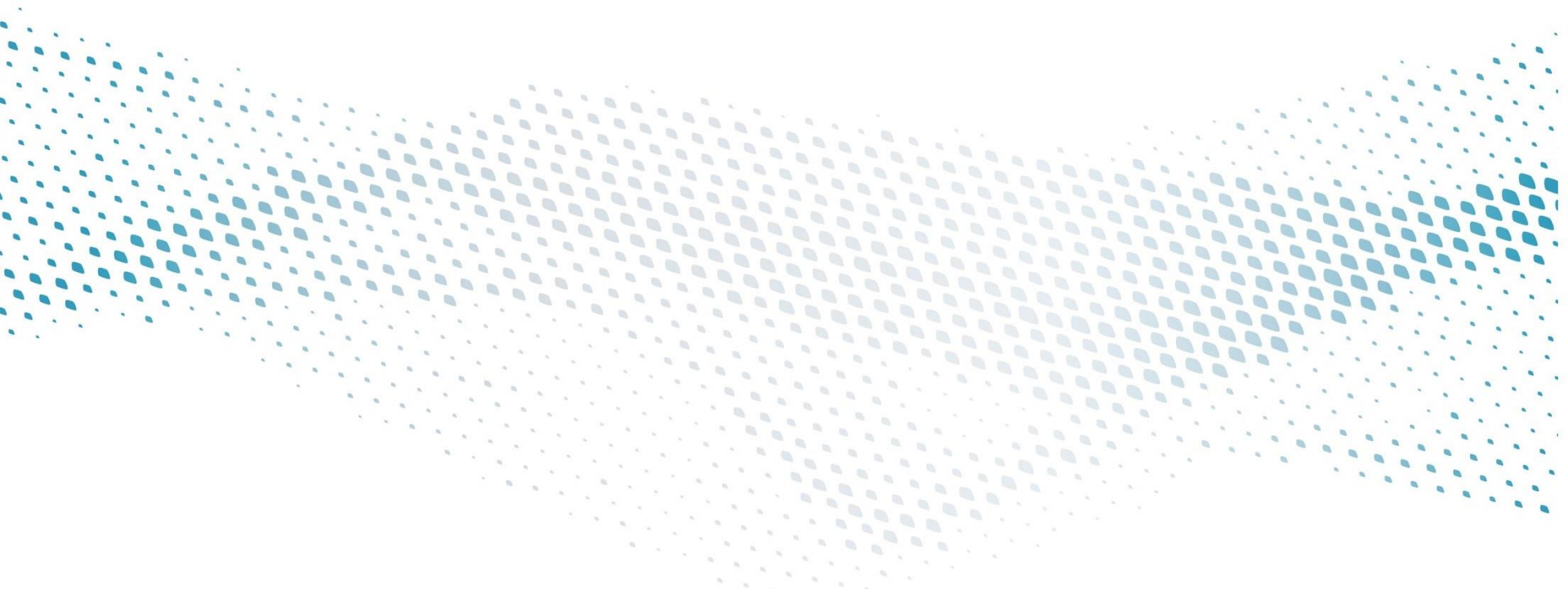
This presentation shows some findings of FUNTIMES - Future Navigation and Timing Evolved Signals, a project funded by the European Union under the Horizon 2020 Framework Program.

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The content represents the view of the authors that prepared it and is not related to any decision of the European Commission or of the Galileo Programme.

Outline

- Project Overview
- Signal User Requirements
- PNT Signal R&D Activity
- Conclusions and Perspectives



Project Overview



Future Navigation and Timing Evolved Signals - FUNTIMES

The Future Navigation and Timing Evolved Signals (FUNTIMES) project is a European GNSS mission evolution study funded by the European Commission within the Horizon 2020 Framework for Research and Development.

It aimed at preliminary supporting the definition, design and implementation of the future generation of Galileo signals

- Considering the **lessons learned from Galileo**
- Combining solutions that **optimize the current system and signals** with the introduction of **innovation elements answering to the needs of the various GNSS user communities.**

Duration: 24 months (January 2016 – January 2018)

Budget: €600 000

Project Coordinator:

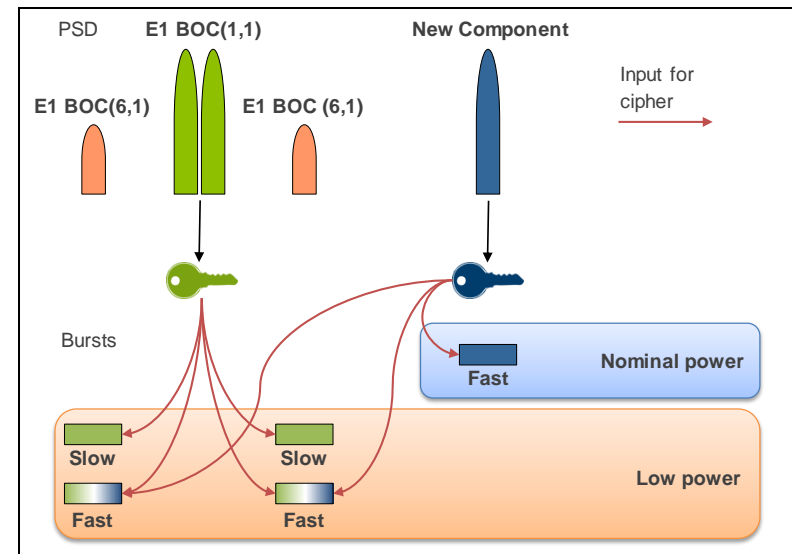
Marco Anghileri marco.anghileri@airbus.com

European Commission Project Manager:

Dominic Hayes dominic.hayes@ec.europa.eu

European Commission (JRC) Technical Officer:

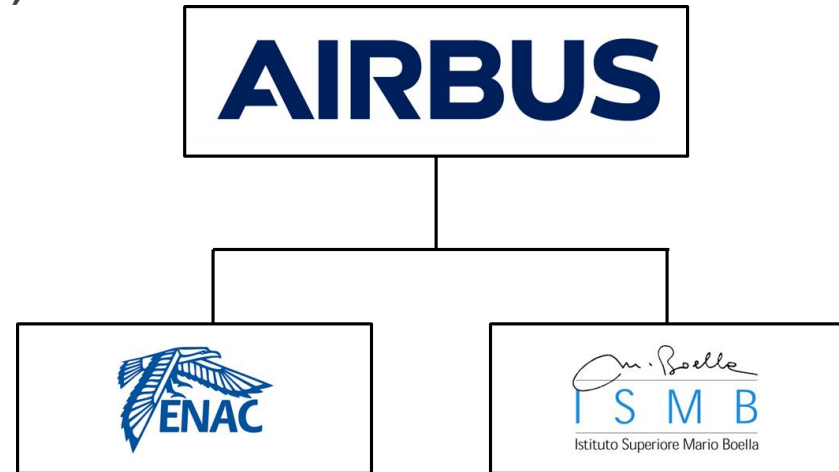
Matteo Paonni matteo.paonni@ec.europa.eu



The FUNTIMES Project Team

The FUNTIMES study was led by **Airbus** as prime contractor, supported by its subcontractors:

- **Ecole Nationale de l'Aviation Civile (ENAC)**
- **Istituto Superiore Mario Boella (ISMB)**

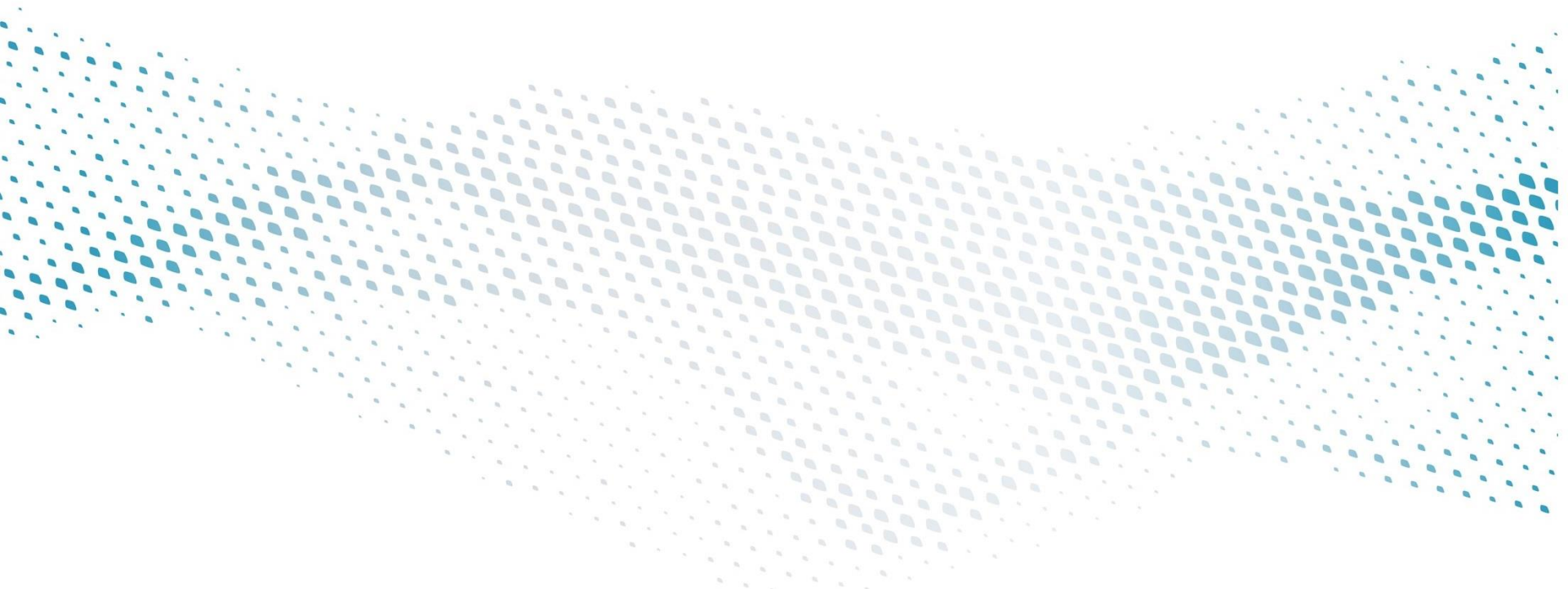


- **Airbus Defence and Space**

- World leader in the space industry
- Major contributions to the design, development, implementation and verification of EGNOS and Galileo
- More than 15 years of experience in signal design and evolution in support of ESA, EC and GSA

- **ENAC and ISMB** from the academic/research sectors

- Both with several years of research activities in the field of satellite navigation
- Know-how in other fields and technologies (e.g. communication)
- Background on the provision of services with higher reliability (e.g. signal and message authentication)
- Past and ongoing activities involving user communities, standardization entities and fora, service providers and chipset manufacturers for the definition of new signal user requirements



Signal User Requirements Survey



Signal User Requirements

7 GNSS user communities investigated:

- “Traditional” Safety-of-Life (Civil aviation, Rail)
- UAV/RPAS
- Automotive
- Mobile Location-Based Services (LBS)
- High Accuracy
- Timing
- Emergency Services



User communities	Safety of Life		Automotive		Mobile LBS	High Accuracy		Timing	Emergency		UAV/RPAS
Applications	Civil Aviation	Rail (Train Control)	Location-Based Charging	Vehicle Motion Sensor (VMS)	Smart Phone	Surveying	Automated Farming → VMS	Telecom Infrastructure	SAR	Emergency Warning	UAV/RPAS

Questionnaire on Signal User Requirements

Signal User Requirements		Timeframe	
Generic Category	Specific Parameters	<10 years	>10 years
High-level Performance Requirements	PVT performance requirement		
	Main threats		
	Time-to-service		
Compatibility / Interoperability	Backward compatibility		
	New GNSS frequency band		
	Interop. with other GNSS		
	Complementarity with other technologies		
Receiver Basic Performance and Features	Need for carrier phase measurement		
	Accuracy		
	Sensitivity (Acq, Tracking)		
	Need of Nav data through signal		
Detailed Signal Characteristics for Improved Performance	Ranging Integrity		
	Ranging Continuity and Availability		
	Authentication		
	New data/additional information		
	Robustness to Specific Sources of Errors		
Current Issues	Signal related issues and limitations		

Main Outcome of the User Survey (1/4)

- **Improved resistance to RFI**
 - Important for most of the applications.
 - Growing threat due to increase of background noise and proliferation of unintentional / intentional jamming sources
 - ➔ Desired signal features: frequency diversity, signal bandwidth, spreading modulation (sharp correlation function), signal power, secondary codes or ability to do long correlations.
- **Ability to generate robust carrier phase measurements**
 - Recognized benefits for smoothing or for RTK/PPP techniques
 - ➔ Desired signal features: pure pilot signal, signal power or longer wavelength.

Main Outcome of the User Survey (2/4)

- **Improved TTFF (in warm or cold start) and acquisition sensitivity**
 - Main reasons for this request are:
 - Poor reception conditions in specific application environments
 - Need for early access to some pseudoranges and for initializing other sensors
 - A dedicated acquisition signal could be used to then transition to accurate tracking on a different signal
 - Ideally not requiring significantly higher receiver resources

➔ Desired signal features: medium-length and easy-to-generate PRN codes, additional pilot signal, more signal power, wide correlation peak
- **Robustness against multipath and NLOS situations:**
 - Most applications would require more natural robustness against MP and NLOS due to the increasing number of users in challenging environments

➔ Desired signal features: signal bandwidth, sharp and narrow correlation function, long correlation durations

Main Outcome of the User Survey (3/4)

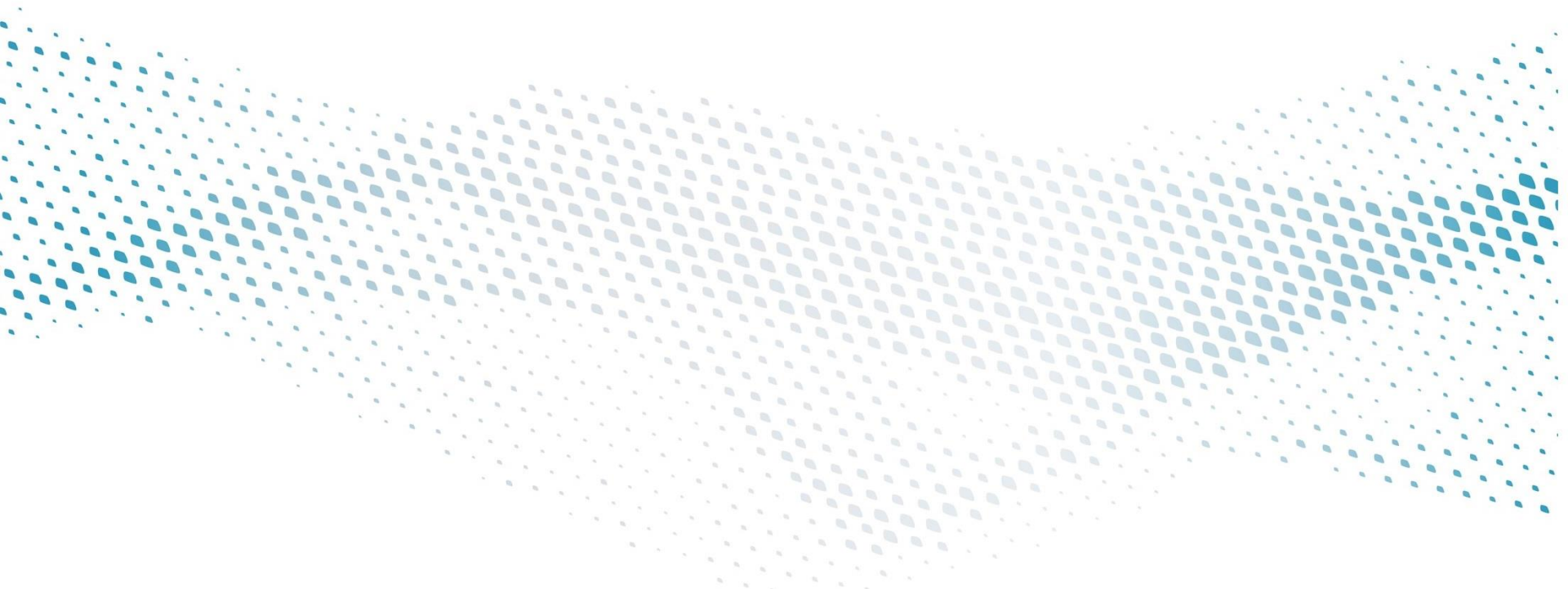
- **Provision of an authentication service**
 - Feature desirable in many applications, although the short-term need is not always very clear as the threat awareness is not really spread.
 - To strengthen the robustness of critical applications that have short time-to-alert.
 - A posteriori authentication would be sufficient for a number of applications
 - The main concerns of receiver manufacturers and service providers is the overhead required to manage safely the cryptographic keys.
- ➔ Desired signal features: spreading code and navigation message authentication, use of alternative data channels

Main Outcome of the User Survey (4/4)

- **Access to Navigation message from Signal-In-Space**

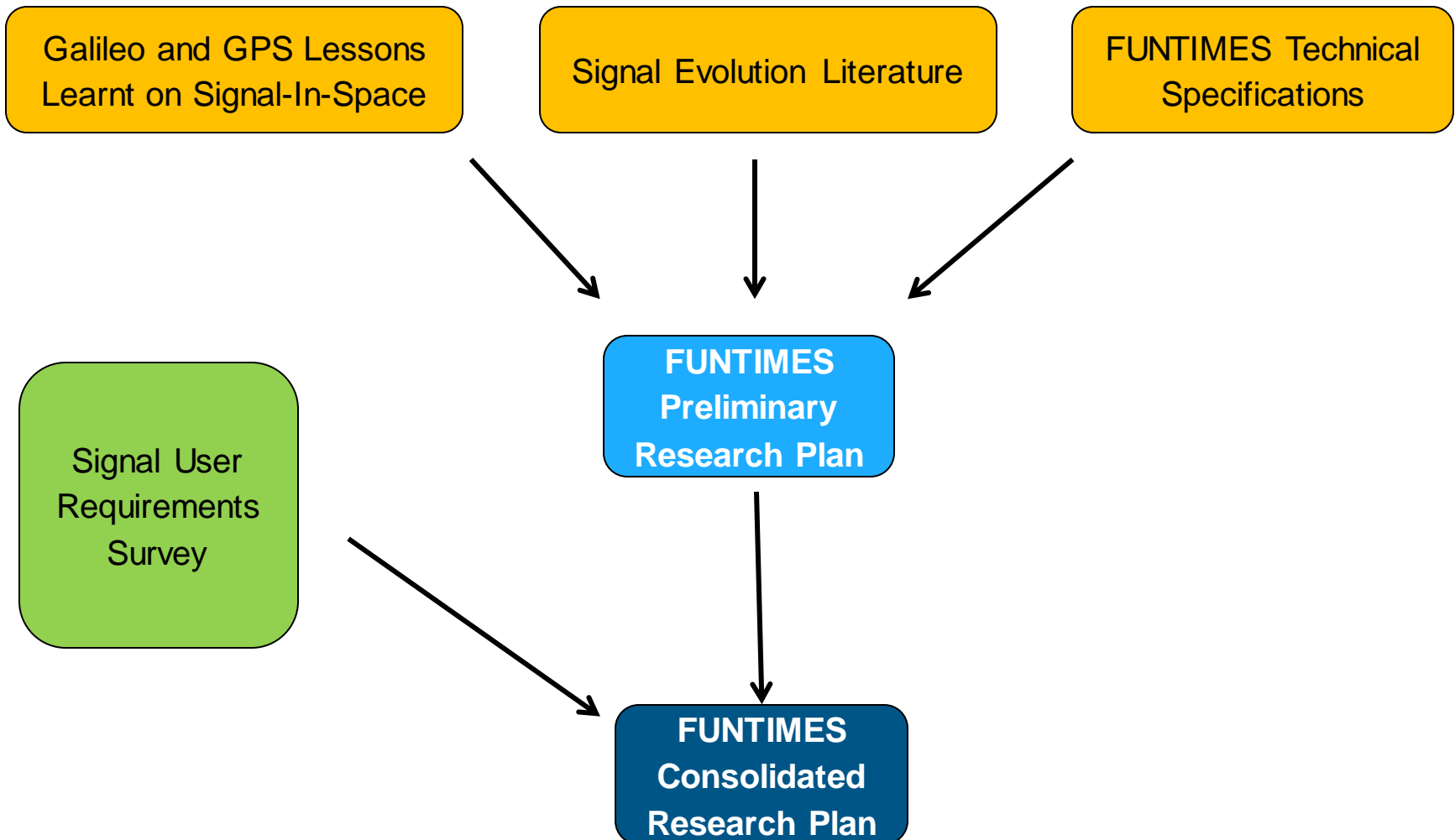
- All user communities still require the access to the navigation message through the satellite link (essentially to cover corner cases).
- There are 2 categories of needs:
 - For critical applications and for users that can be in challenging environments: preference to have a signal that can ensure a good data demodulation of the key message parameters (low to medium data rate)
 - For users that need high accuracy, there is a strong interest in having more information such as PPP or extra atmospheric information through an open channel, preferably aligned with L1 or L5 frequencies.
- Other desired features are:
 - more frequent transmission of timing information
 - reference time offsets with all GNSS including the integrity of this information

➔ Desired signal features: improved encoding scheme, fast access to CED and system time, higher data rate, optimized navigation message content and structure



PNT Signals R&D Activity

FUNTIMES R&D Work Logic



FUNTIMES R&D Work Logic

FUNTIMES Consolidated Research Plan

Topics Investigated

- Signal Authentication Techniques
- LDPC Codes for Future GNSS Signals
- Usage of CSK for GNSS Data Delivery
- Adding New Components to a Legacy Signal

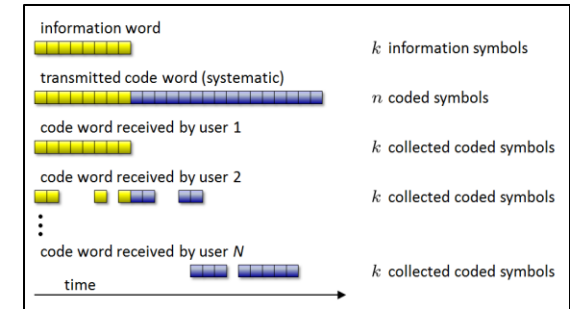
Proposed Technical Solutions

- Reed Solomon Codes for the Improvement of the I/NAV Message
- Spreading code and Navigation data based Authentication Protocol
- Multi-Purpose TDM Signal Component
- Robust High Data Rate Signal Component

RS Codes for Improving the I/NAV Message

A technical solution for reducing the Time to First-Fix for non connected users was evaluated:

- Use of Reed-Solomon (RS) codes at the Link Layer (outer encoding)
 - MDS “Joker” property
 - Erasure correction capability
 - Error correction capability
 - Systematic implementation to ensure backward compatibility
- Example application to the Galileo I/NAV message was assessed
 - Time to CED performance in AWGN and 2-state LMS channel
 - Assessment of RS algorithm complexity



Outcomes of the assessment:

- Significant improvement of Time-to-CED (50% to 60%) especially in urban environment
- Full backward compatibility with legacy receivers
- Low added complexity at transmitter and receiver side

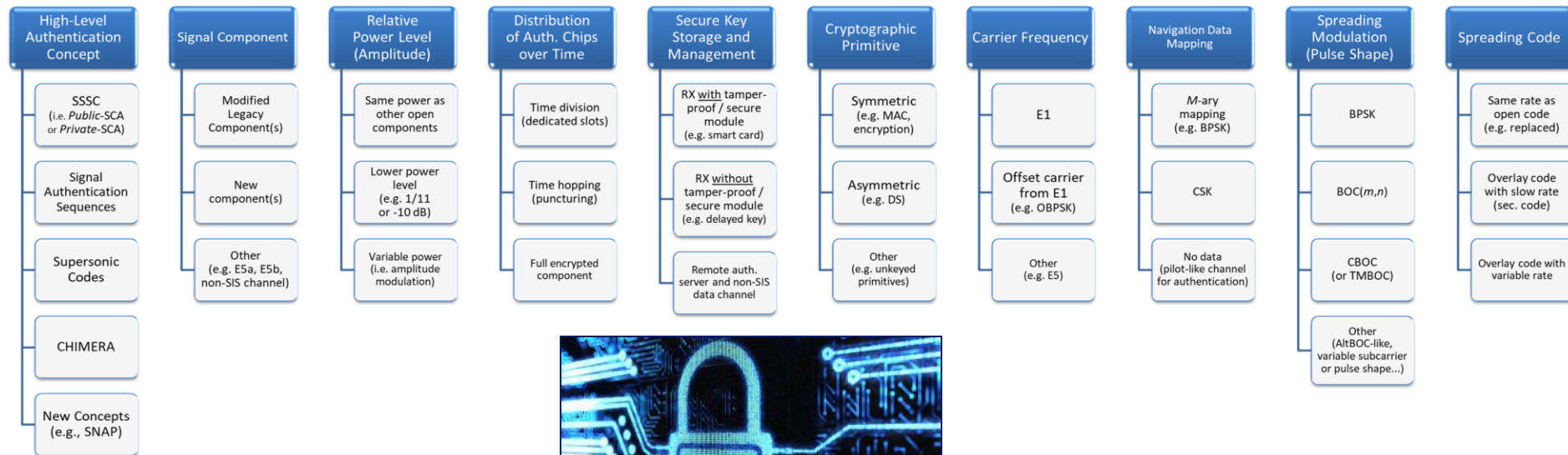
T_0 in sec.	I/NAV on E1-B RS4
1	CED 2/4
3	CED 4/4
5	RS CED 1
7	RS CED 2
9	
11	
13	
15	
17	RS CED 3
19	RS CED 4
21	CED 1/4
23	CED 3/4
25	
27	
29	
min. TTFFD	8.000 s
av. TTFFD	13.933 s
95% TTFFD	17.625 s
max. TTFFD	18.000 s

Signal Authentication Techniques

Objective:

Improve the PNT signal's reliability by providing an enhanced authentication service based on **both** navigation message authentication (**NMA**) and spreading code authentication (**SCA**), in such a way that the two solutions can take advantage of their combination

Signal authentication design trade-offs:

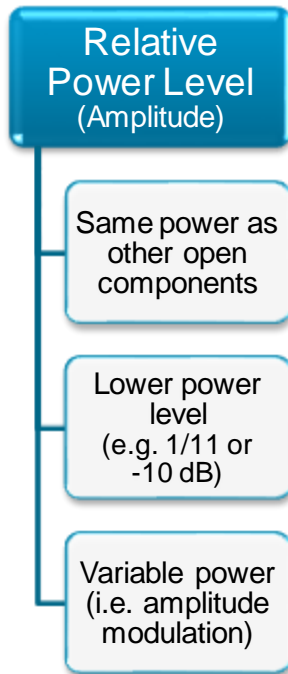


Impact of Single Design Aspects

Signal Component

Authentication schemes can be basically implemented:

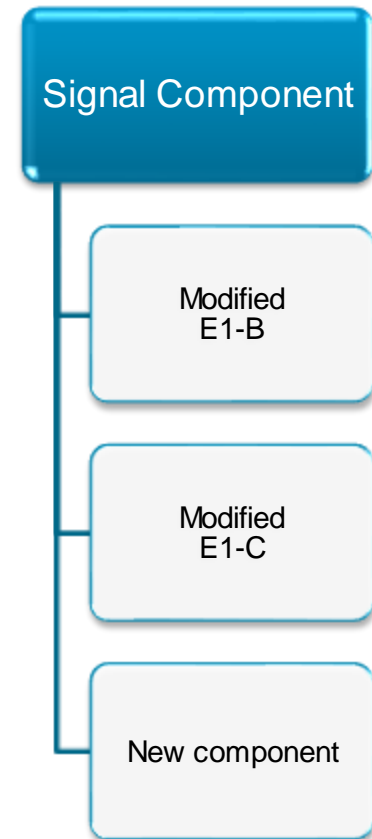
- By modifying an **existing signal component** (e.g., E1-B, E1-C, E5a, E5b)
 - Possible performance degradations for non-participant users ($\Delta C/N_0$)
- Introducing a **new component**
 - More flexibility in the design of the authentication scheme, thus reducing some constraints related to the backward compatibility



The choices for the **Relative Power Level** of the authentication component basically are:

- **Same power** as other open components
- **Lower power** level (e.g. 1/11)
- **Variable power** (i.e. amplitude modulation)
 - Low power level options tend to increase the robustness against some spoofing attacks (i.e., requiring directional antennas with higher gain)
 - However the power level can affect the achievable authentication performance for participant receivers (e.g., TBA, TTA, reduced effective C/N_0)

→ **Trade-off** among these aspects **has to be performed**



The SNAP Solution: High-Level Concept

• High-level idea

- Possible re-use of E1-B OS NMA data → Additional protection to OS NMA (“time binding” concept^[1])
- Initially inspired from SSSC^[2], Supersonic Codes^[3], and Signature-Amortization^[4] concepts



CSK_S “Low rate” SCA bursts: a-posteriori verification with latency around 10 s (i.e. TBA ≈ 10 s)

CSK_F “High rate” SCA bursts: intended to reduce Time Between Authentications (e.g. TBA ≈ 2 s)

- “High rate” bursts for all satellite signals generated from **same code chips**, by using a **future NMA key** (k_{j+1}):

$$\text{crypto key}_m \propto \text{Hash} \{ k_{j+1} \mid \text{GST}_m \}$$

- **Different CSK shifts** applied to each burst, depending on **Sat. ID**, **previous key** (k_j), and **next NMA bits**:

$$\text{shift}_m \propto \text{Hash} \{ \text{Sat. ID} \mid k_j \mid \text{next 'Reserved 1' field} \}$$

- **Suitable to a 2-step verification procedure** at the receiver (see next slide):

- **1st step** based on a codeless correlation of CSK_F bursts from different satellite signals
- **2nd step** with a-posteriori verification of both CSK_S and CSK_F bursts (as soon as k_{j+1} is disclosed)

Two-steps Authentication at the Receiver

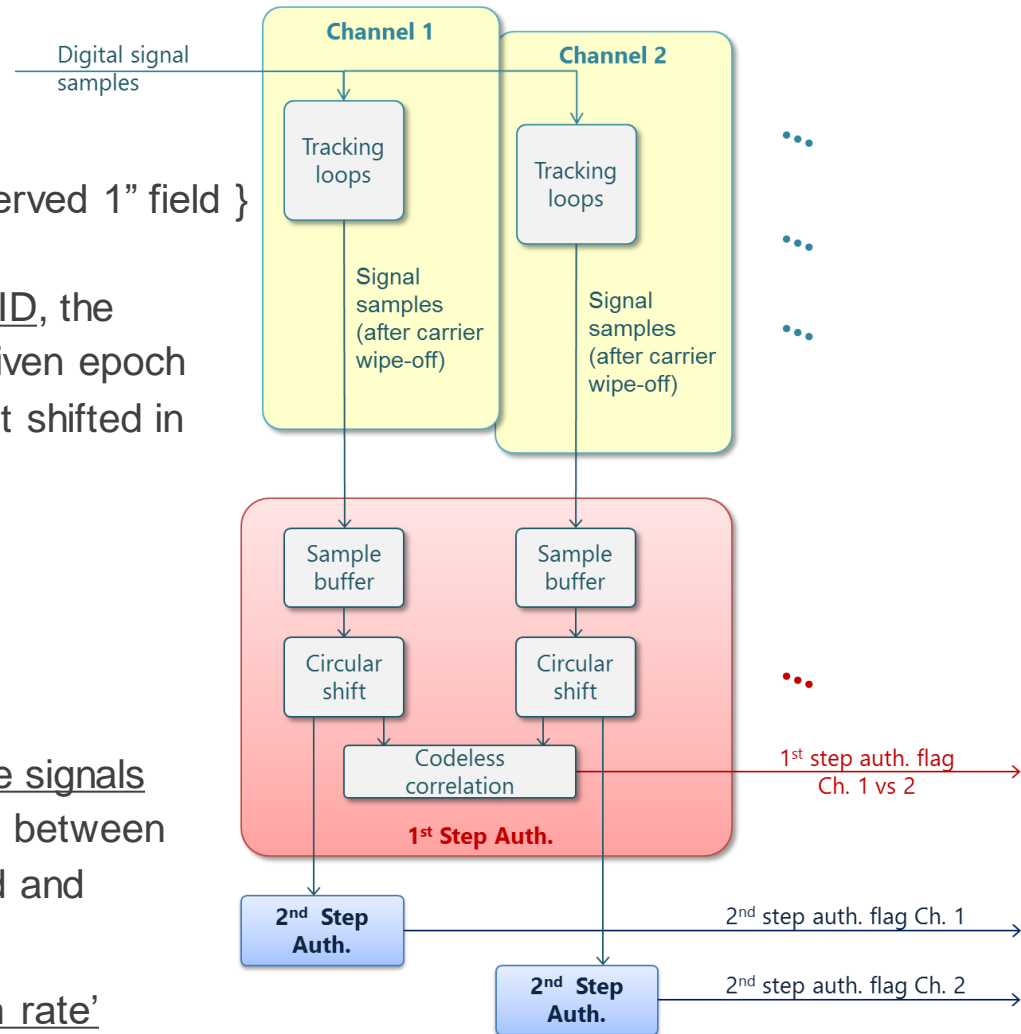
- **crypto key_m** $\propto \text{Hash} \{ k_{j+1} \mid \text{GST}_m \}$
- **shift_m** $\propto \text{Hash} \{ \text{Sat. ID} \mid k_j \mid \text{next "Reserved 1" field} \}$

Being the crypto key independent of the Sat. ID, the bursts received from different satellites at a given epoch consist of the same code chips sequence, just shifted in a different way for every satellite.



The **receiver** is able to:

1. first cross-authenticate couples of satellite signals by applying a **codeless CSK correlation** between bursts from two satellites, properly shifted and aligned \rightarrow **first step**;
2. a-posteriori verify both 'low rate' and 'high rate' bursts with a **correlation**, as soon as k_{j+1} is disclosed \rightarrow **second step**.



Main Trade-off Aspects

The proposed high-level concept is still open to **different implementation alternatives and optimizations**. In details, such open choices are related to:

1. Inputs for the SCA bursts generation

- Only bits from a legacy component, e.g. E1-B **OS NMA bits** (TESLA keys and MACs)
- only bits transmitted on a **new data signal component** (e.g., CSK modulated)
- an **intermediate solution**, using bits from OS NMA plus few additional bits from a new component

2. Signal component for the SCA bursts allocation

- on a modified version of the **E1-B** component
- on a modified version of the **E1-C** component
- on a new signal component

3. Allocation of high rate and low rate SCA bursts

- on a **single component** (joint allocation)
- on **multiple signal components**

4. Power level of each component carrying authentication features

- at **nominal value** (referred to as 0 dB)
- at **-10 dB** from nominal power

Code Shift Keying (CSK) Modulation for GNSS Signals

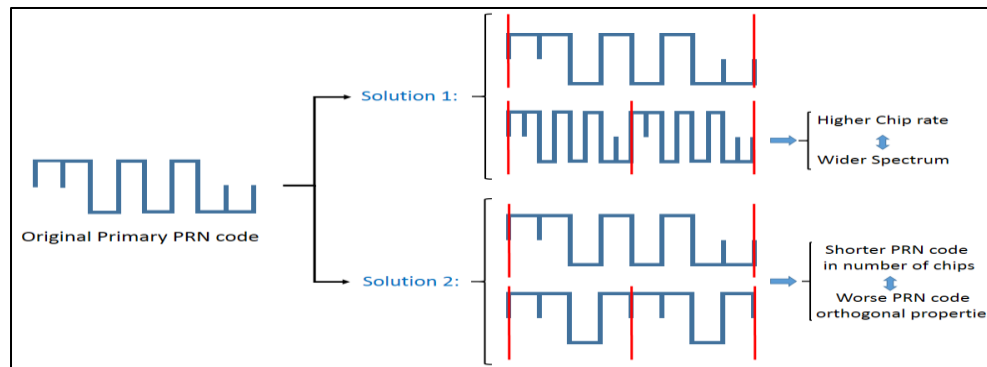
Background

- Several problems are addressed with the implementation of a CSK modulation on the GNSS signal data component:

1) Amount of data which can be currently broadcasted by a GNSS signal is limited.

This limitation is imposed by the DS-SS structure of a GNSS signal:

- increasing the chip rate increases the signal bandwidth
- decreasing the PRN code length degrades the PRN code correlation properties

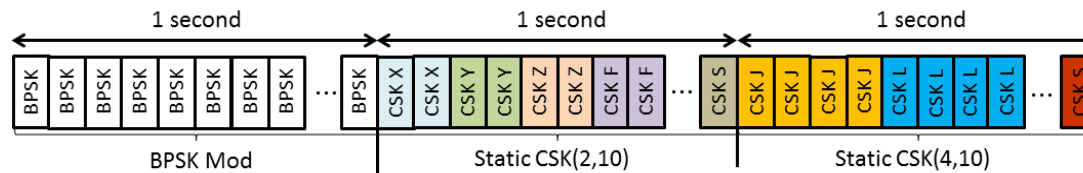


- 2) Data component of current GNSS signals is designed as a communication signal without taking into account the GNSS specificities: data has different degrees of relevance for the receiver and variable data rates could be of high interest.
- 3) In urban environments, the data demodulation becomes difficult to achieve due to the harsh reception conditions particularly affecting the signal carrier tracking up to a PLL loss-of-lock.

Code Shift Keying (CSK) Modulation for GNSS Signals

Expected benefits

- 1) Bit rate increase of a DS-SS signal without:
 - increasing the PRN code number of chips, and without increasing the signal chip rate (bandwidth constraint).
- 2) Flexibility of the data rate:
 - allows to dynamically change the number of CSK symbols.
 - Different levels of robustness / timeliness can be achieved



- 3) Possibility of implementing a non-coherent demodulation
 - More robust access to data in urban environment and/or for high dynamic users.

Possible issues and drawbacks

- 1) CSK signals are not suitable for ranging: the receiver does not know which cyclic shift of the fundamental PRN code is expected at each correlation epoch.
- 2) Complexity of the receiver is significantly increased: advances in receiver technologies should mitigate this (e.g. FT/IFT demodulator, cloud processing, improved chipset performance/efficiency)

CSK Example Implementations Studied

DATA MODULATION

Identifier	BPSK	CSK(4,1)	CSK(6,1)	CSK(8,1)	CSK(10,1)	CSK(12,1)
Modulation	BPSK	CSK	CSK	CSK	CSK	CSK
Number of bits per symbol (B)	1	4	6	8	10	12
Number of PRN codes per Symbol (U)	1	1	1	1	1	1
Codeword length (bits)	1200					
Interleaver	40x30					
Channel Code	LDPC Codes					

DATA COMPONENT CHARACTERISTICS

Identifier	BPSK	CSK(4,1)	CSK(6,1)	CSK(8,1)	CSK(10,1)	CSK(12,1)
Bit rate (bits/s)	100	400	600	800	1000	1200
Codeword length (s)	12	3	2	1.5	1.2	1
Number of data message in 12s	1	4	6	8	10	12

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DEMODULATOR BLOCK

Type of Modulation	BPSK	CSK			
Demodulation Method	Coherent	Coherent		Non-Coherent	
Decoding Method	---	Classic	Iterative	Classic	Iterative

CSK Example Implementations Studied

Low Dynamic User

		Time to Data 95% Value (s)		
		30	35	40
Coh Dem – Classic Deco	Case 1a			
	C/N ₀ [dBHz]	30	35	40
	BPSK	36	12	12
	CSK(4,1)	21	9	6
	CSK(6,1)	18	6	4
	CSK(8,1)	18	6	4.5
Coh Dem – Iterative Deco	Case 1b			
	C/N ₀ [dBHz]	30	35	40
	CSK(4,1)	18	9	6
	CSK(6,1)	18	6	4
	CSK(8,1)	16.5	6	3
	CSK(10,1)	16.8	6	3.6
CSK(12,1)	16	5	3	

Dynamic User

		Time to Data 95% Value (s)		
		30	35	40
Coh Dem – Classic Deco	Case 2a			
	C/N ₀ [dBHz]	30	35	40
	BPSK		100	100
	CSK(4,1)		100	12
	CSK(6,1)		20	10
	CSK(8,1)		16.5	10.5
Non-Coh-DDCP- Classic Deco	Case 2b			
	C/N ₀ [dBHz]	30	35	40
	CSK(4,1)		12	6
	CSK(6,1)		10	6
	CSK(8,1)		9	4.5
	CSK(10,1)		8.4	4.8
CSK(12,1)		8	4	

High Dynamic User

		Time to Data 95% Value (s)		
		30	35	40
Non-Coh-DDCP- Classic Deco	Case 3			
	C/N ₀ [dBHz]	30	35	40
	CSK(4,1)		12	9
	CSK(6,1)		10	6
	CSK(8,1)		9	4.5
	CSK(10,1)		8.4	4.8
CSK(12,1)		8	4	

COMMENTS:

- Low Dynamic User: Time to Data reduced by 2x or 4x depending on the C/N₀ and CSK implementation
- Dynamic User: Time to Data reduced by 12x to 25x
- High Dynamic User: Only CSK demodulation possible, still very rapid access to data

Multi-Purpose TDM Signal Component

General Objective:

- To design a signal component targeting several functionalities, e.g.:
 - 1) Fast/Low complexity Acquisition
 - 2) Fast access to Clock and Ephemeris Data
 - 3) Authentication
- Allowing continuous or partial non-coherent processing

Time Division Multiplexing:

- TDM was chosen for the following reasons:
 - Reduced complexity implementation at satellite payload
 - higher efficiency of multiplexing

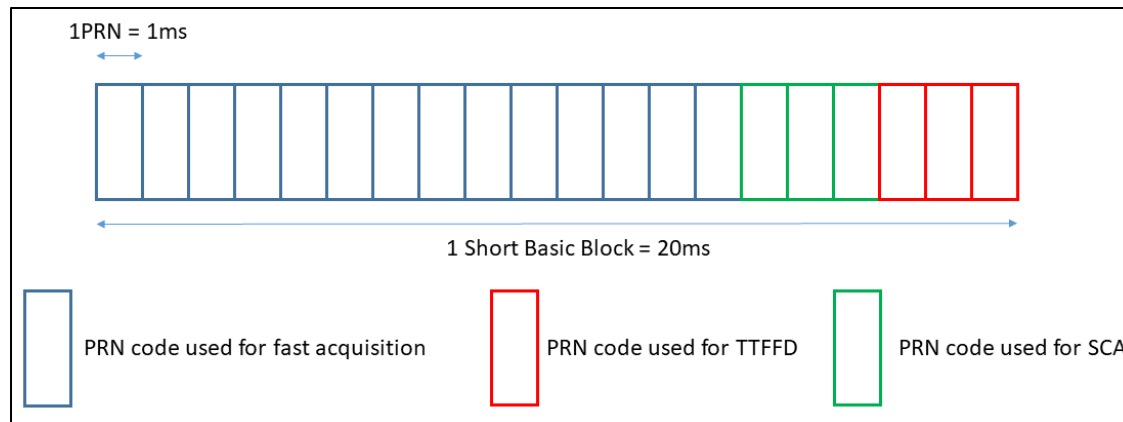
Multi-Purpose TDM Signal Component

Time Division Multiplexing:

- TDM considered at PRN code level: each PRN code is associated to a different functionality
- TDM signal structure is defined from Short basic blocks and Advanced blocks.

Short basic block:

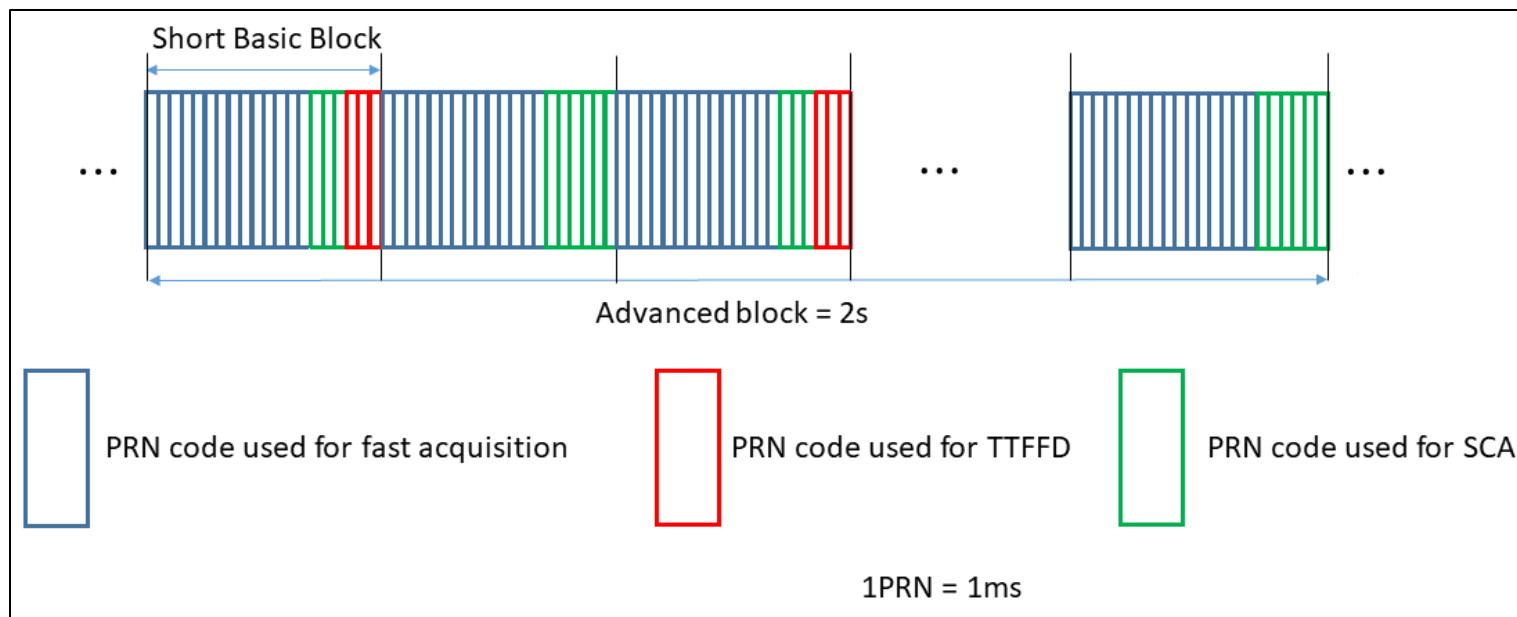
- A small number of PRN codes constitute the basic block of e.g. 20 ms:
- Each PRN code is associated to a different functionality
- PRN codes are chosen equal to 1ms or multiples of 1ms



Multi-Purpose TDM Signal Component

Advanced blocks:

- An advanced block is made of several basic blocks
- The signal periodic structure is guaranteed by the advanced blocks.



- Example duration of an advanced block in the order of 2 to 3 seconds
- An advanced block allows for more flexibility in the combination of short basic blocks

Multi-Purpose TDM Signal Component

Targeted Use Cases for Signal Design

Low complexity: signal for low-power consumption (e.g. IoT devices or cheap mass-market receivers)

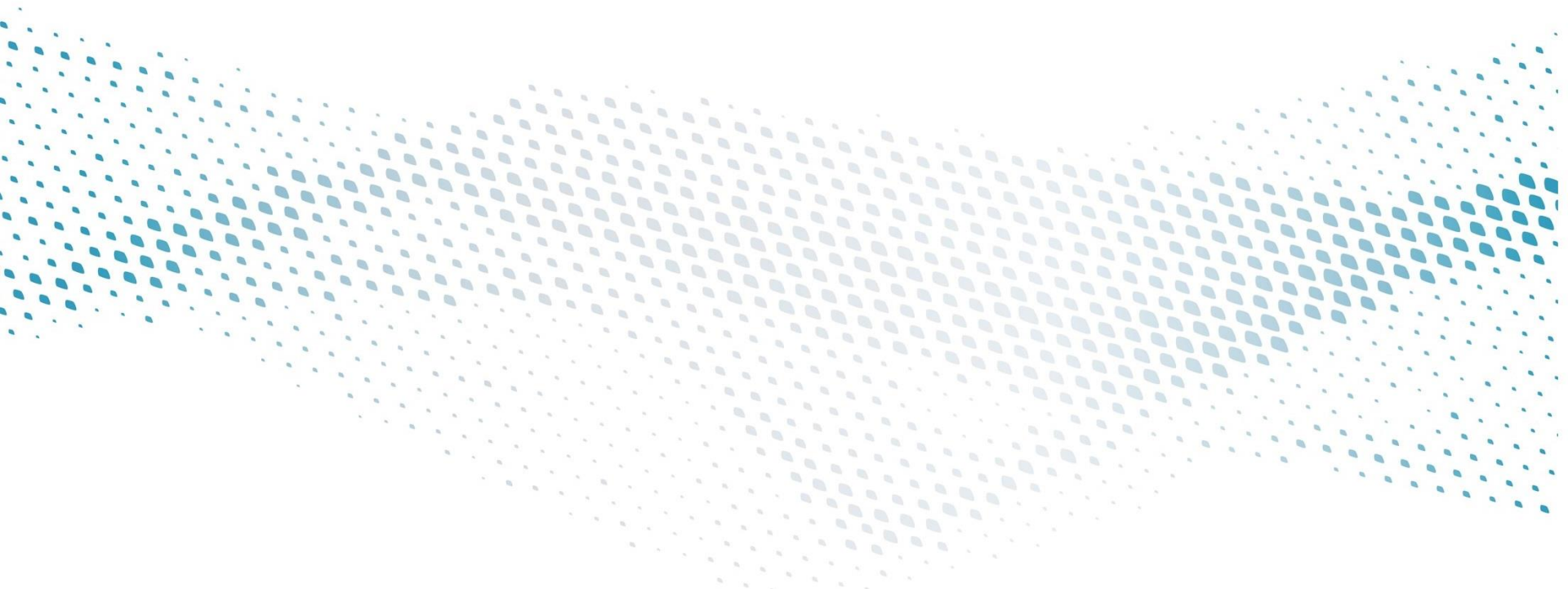
High Performance – No CED: users targeting the best possible performance without putting constraints to the receiver complexity (e.g. autonomous cars or high sensitivity receivers). In this scenario it is assumed that CED is recovered either using a legacy signal or an external source.

High Performance – CED: Same as previous but with clock and ephemeris data from the TDM signal component.

High Dynamic users: users with high dynamics which could require to use the non-coherent processing mode to ensure a high continuity or availability of the service.

Signal design options and **performance results** are available in a dedicated paper:

Garcia-Pena A., Julien O., Anghileri M., Floch J.J., Paonni M., *Multi-purpose TDM Component for Galileo E1 OS*, ION GNSS+ 2018



Conclusions and Perspectives

Conclusions and Perspectives

The project allowed to:

- study **new elements in the field of GNSS signal engineering**
- **consolidate solutions that were already investigated in the recent literature**, paving the way to the evolution of the Galileo signals

The proposed ideas present different levels of maturity:

- In some cases the solutions are **ready to be implemented in the currently deployed systems**
- In other cases they would require a corresponding **evolution of the space and/or ground segments.**

The **technical solutions** offered have been mainly investigated focusing on the current Galileo Open Service signals, but **can be also adopted by any other GNSS.**

For the way forward, it is recommended to **support the R&D activity** with early implementation and prototyping, especially at the **user receiver side**. Many of the proposed solutions are mature enough for this next step.

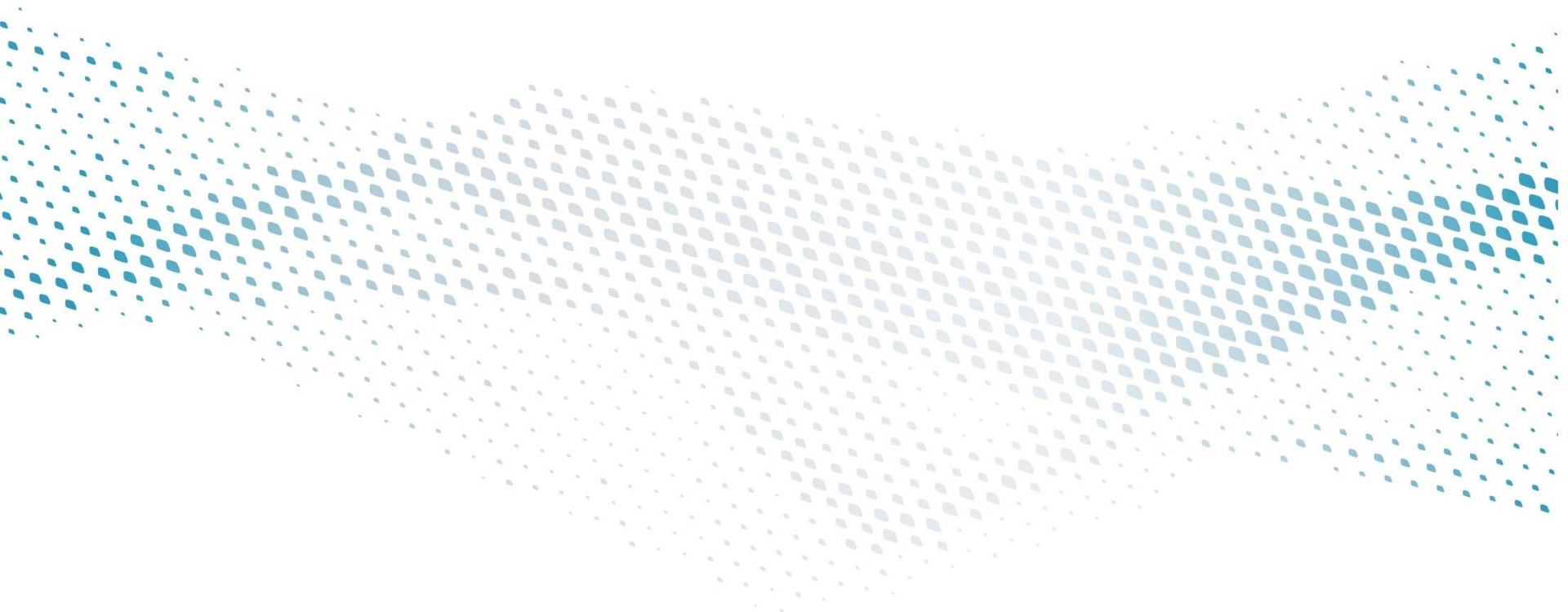
Thanks for your Attention

FUNTIMES Related Publications

- Margaria D., Motella B., Anghileri M., Floch J.J., Fernández-Hernández I., Paonni M., *Authentication Solutions for Civil GNSS Signals: Recent Developments and Perspectives*, IEEE Signal Processing Magazine Special Issue on Advances in Signal Processing for GNSS
- Schotsch B., Anghileri M., Ouedraogo M., Burger T., *Joint Time-to-CED Reduction and Improvement of CED Robustness in the Galileo I/NAV Message*, ION GNSS+ 2017
- Margaria D., Motella B., Paonni M., *SNAP: an Authentication Concept for the Galileo Open Service*, ION/IEEE PLANS 2018, Conference Proceedings
- Garcia-Pena A., Julien O., Anghileri M., Floch J.J., Paonni M., *Multi-purpose TDM Component for Galileo E1 OS*, ION GNSS+ 2018
- Chauvat R., Garcia-Pena A., Anghileri M., Floch J.J., Paonni M., *Ultra-Sparse Binary LDPC Codes with CSK Signals for Increased Data Rate in GNSS Signals*, IEEE Proceedings, Navitec 2018

References in this Presentation

- [1] Anderson, J. and al., "Chips-Message Robust Authentication (CHIMERA) for GPS Civilian Signals," *Proceedings of the 30th International Technical Meeting of The Satellite Division of the Institute of Navigation (ION GNSS+ 2017)*, Portland, Oregon, September 2017, pp. 2388-2416.
- [2] L. Scott, "Anti-Spoofing & Authenticated Signal Architectures for Civil Navigation Systems," Proc. of ION GPS/GNSS 2003, September 2003.
- [3] O. Pozzobon et al., "Supersonic GNSS Authentication Codes," Proc. ION GNSS+ 2014, September 2014.
- [4] G. Caparra et al., "Design Drivers and New Trends for Navigation Message Authentication Schemes for GNSS Systems," Inside GNSS, Sept./Oct. 2016.



Back-up Slides

SUR Survey Outcome per Application (1/2)

	Acq. And Tracking Sensitivity	Measurement quality	Additional RF resistance	Authentication	Additional multipath resistance	Backward compatibility	Nav. message	Compl. with other techno.
Civil Aviation Navigation	Potentially interesting for surface navigation	Carrier phase robustness for carrier smoothing No possibility of biased measurements (integrity)	Grow ing observed threat Greater resistance to background noise	Desirable in the long term Short TTAut (few sec) Should not require database manipulation for the keys	Interesting for surface navigation	Mandatory. Legacy users should not suffer from new signals	Access to nav. Message is essential ARAIM ISM through nav. Message Complete UTC year	INS
Train Control	Important for urban scenarios	Carrier phase robustness for carrier smoothing/RTK No possibility of biased measurements	Important	Important for long term. Short TTAut (~sec)	Critical	Mandatory Legacy users should not suffer from new signals	Access to nav. Message is essential ARAIM ISM through nav. Message	Track data base, computer vision, visual odometry, etc.
Automotive LBC and VMS	very important for acq and tracking (basis for high availability) early access to velocity information	Carrier phase robustness for carrier smoothing/RTK No possibility of biased measurements	Very important due to challenging RF environment	Short term against simple spoofing resilience Long term against intermediate spoofing TTAut of a few sec.	Important	Important	Access to nav. Message is important for corner cases PPP info on L1 or L5	V2X ranging, radar, lidar, camera, inertial sensors, database, new communication systems, A-GNSS
Mobile LBS	very important for acq and tracking (basis for high availability) early access to initialize other sensors	Carrier phase robustness for carrier smoothing/RTK No possibility of biased measurements (integrity)	Very important due to challenging RF environment	Interesting to enable some applications, even if a posteriori	Depends upon the application	Important	Access to nav. Message is important for corner cases Reasonable data rate	Sensors inside cell phone, A-GNSS

SUR Survey Outcome per Application (2/2)

	Acq. And Tracking Sensitivity	Measurement quality	Additional RFI resistance	Authentication	Additional multipath resistance	Backward compatibility	Nav. message	Compl. with other techno.
Surveying	At least as good as now	Carrier phase robustness in challenging environments No possibility of biased measurements (integrity)	Important but not necessarily the main concern currently	A posteriori authentication is also interesting	Very important to maintain performance in challenging environment	Mandatory	Access to nav. Message is very important Time information more frequently PPP info on L1 and/or L5 Atmosphere information	INS
Timing and Sync.	At least same as now	Carrier phase robustness for carrier smoothing No possibility of biased measurements (integrity)	Critical	Very important Short TTAut	Important	Mandatory	Mandatory reference time offset to all GNSS integrity of reference time offset	External source of timing
Search and Rescue	Important in case of beacon affected by masking	OK with current performance	Important but not necessarily the main concern currently	Already protected by NMA	Not critical	Mandatory: Legacy users should not suffer from new signals	current RLS and RLM answer the need possibly pass more information about the rescue center	Autonomous
RPAS Navigation	At least same as now	Carrier phase robustness for carrier smoothing/RTK	Very important due to challenging RFI environment	Will become key for traffic monitoring concepts Few sec.	Important	Mandatory	no special need maybe ARAIM ISM through nav. Message	At least INS and vision sensors