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GENESIS - GALILEO INNOVATIVE SPACE SERVICE SOLUTION

H2020 MAS WORKSHOP

EUROPEAN COMMISSION, 16/02/2022

PROGRAMME PRESENTATION

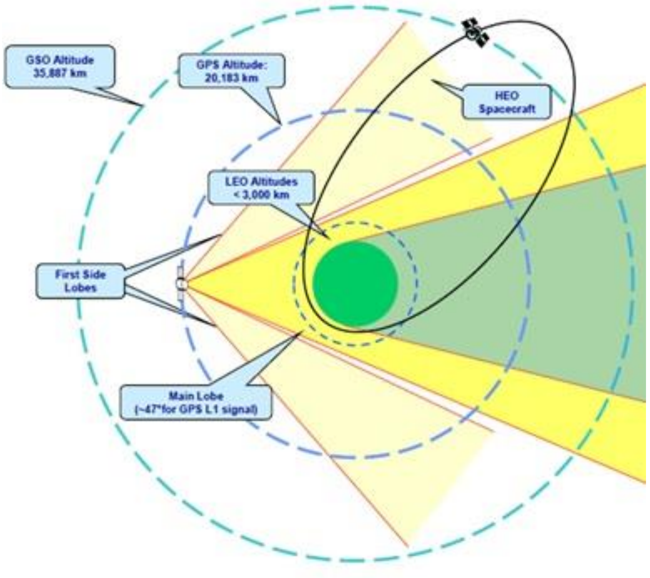
In the last 40 years, the **use of GNSS (GPS at first) for LEO orbit mission** and launchers has been widely exploited; GNSS can complement/replace the legacy orbit/attitude determination systems (ground-based ranging, star trackers, etc.)

The use of GNSS at increasing orbits (up to GEO and even lunar missions) has been proposed: in this context, the use of navigation **antennas's secondary lobes** can provide an increase of signals' availability

In this context, since 2006 EC participate to the Working Group B of the International Committee on Global Navigation Satellite Systems where the GNSS community is working towards the definition of Global interoperable GNSS Space Service Volume.

European Commission retains the Galileo Space Service one of the most promising services for the implementation in next generation GALILEO. Space Service provided to users that are located in space, in orbits well above the surface of the Earth, as well as other satellites or launchers; this is expected to:

- Enlarge Galileo Users community;
- Push European receivers manufactures towards a promising new market sector such as mega constellations



Source: *Enabling a Fully Interoperable GNSS Space Service Volume* - James J. Miller, 6th *International Committee on GNSS (ICG) --Tokyo, Japan, September 5-9, 2011*

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PROGRAMME PRESENTATION

In this context, EC launched in 2016 the ITT for «Innovative Mission Concepts: R&D for a Galileo Space Service» with the following main objective:

- **Characterize the GNSS Space Users and their Requirements in terms of GNSS**
- **Characterize the GALILEO and the Multi-GNSS Space Service Volume**
- **Provide Technical Support to the European Initiatives in the context of International Coordination towards an Interoperable SSV and Awareness actions**
- **Study the best to perform measurements towards the full characterization of the emissions of GALILEO satellites exploitable by space receivers and perform an initial measurement campaign**
- **Contribute to the definition of mission and user level requirements for the second generation of GALILEO**
- **Propose and Engineer Advanced Signal Processing techniques and algorithms for GNSS Receivers tailored for space service applications**

Contract has been award to Consortium led by Thales Alenia Space and SpaceTec Partners (as co-prime, responsible of market analysis and GNSS space users and requirements characterizarion) for **GENESIS** (**G**alil**E**o i**N**novativ**E** **S**pace serv**I**ce **S**olution) programme, in Early 2017

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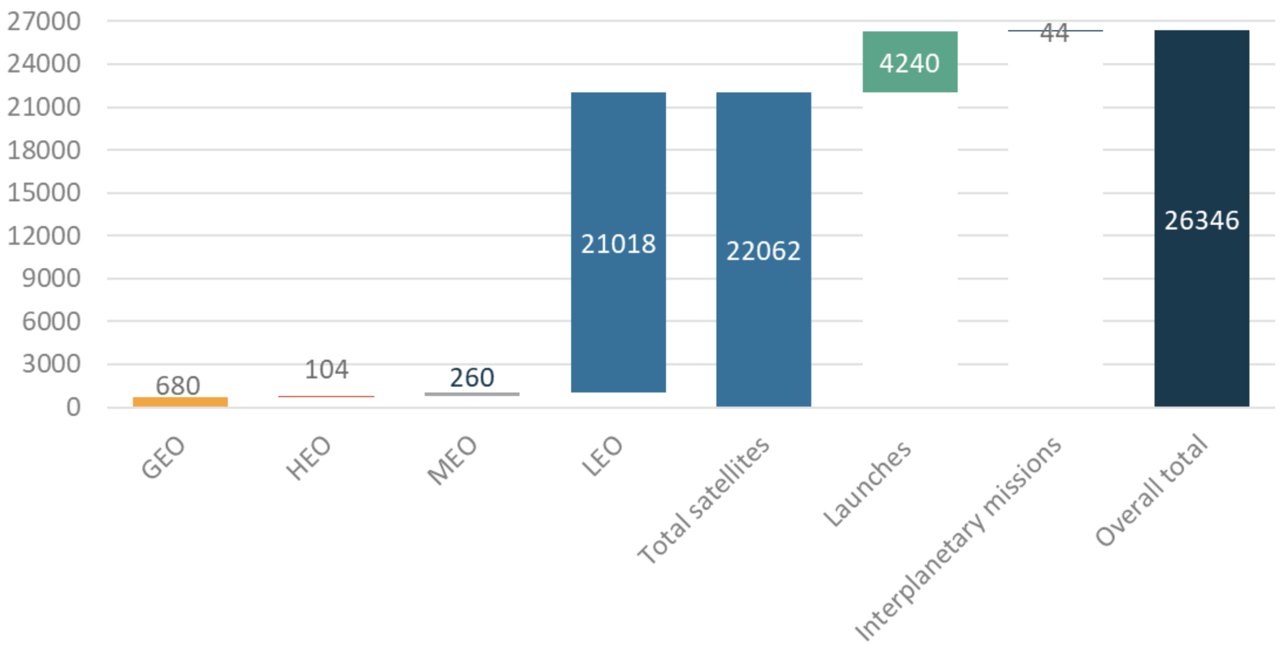

Forecasted Total Potential Addressable Market (TAM) by GNSS Space Applications
(Number of Spacecraft/Launchers to be Launched in 2017-2036 incl. LEO)

NOTE: Figures are from programme conclusions (2019), but are still indicative of the trend

LEO satellites constitute the majority of forecasted missions and offer the largest market segment for space borne GNSS technology

Nevertheless, applications in GEO missions, as well as in launchers and interplanetary missions are also of growing interest.

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MARKET ANALYSIS – GNSS SPACE USERS AND THEIR REQUIREMENTS

Dedicated user/stakeholder workshop with a selected number of representative target organisations has been organized

/// In total 24 organisations have been consulted during the project (excluding the EC and JRC), including a representative sample of different key stakeholder categories

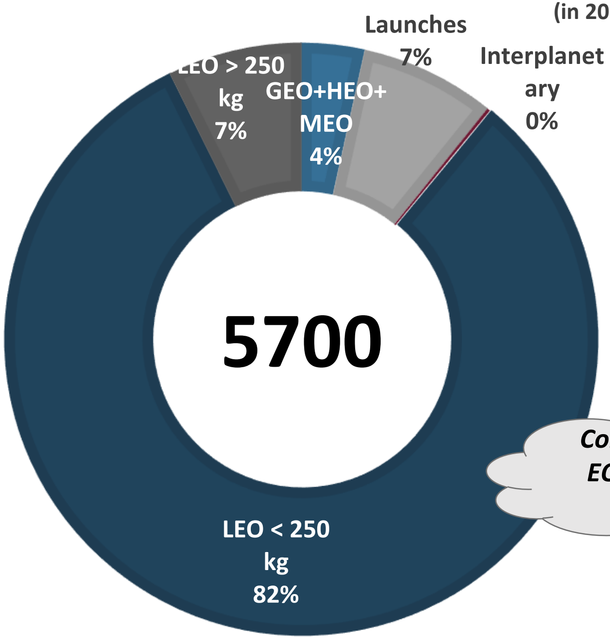
Stakeholder category	Entity Name
European institutions	DG GROW
	JRC
	Eurpean GNSS Agency (GSA)
Space Agencies, Space Offices Research and Technology Centres and Funding Agencies	European Space Agency (ESA)
	The Italian Space Agency (ASI)
	National Centre for Space Studies (CNES)
	Austrian Research Promotion Agency (FFG)
	Estonian Space Office
	Finnish Funding Agency for Technology and Innovation (TEKES)
	INTA
	Centre for the Development of Industrial Technology (CDTI)
	Aalto University

Stakeholder category	Entity Name
Space System Manufacturers	Thales Alenia Space (TAS)
	Airbus D&S
	OHB
	GMV
	Surrey Satellite Technology Ltd. (SSTL)
	RUAG
Space service providers and operators (incl. Launch)	Arianespace
	Eutelsat
Space borne Receiver Manufacturers	Thales Alenia Space (TAS)
	RUAG
	Airbus D&S
	DEIMOS Engenharia
	GMV
	Septentrio

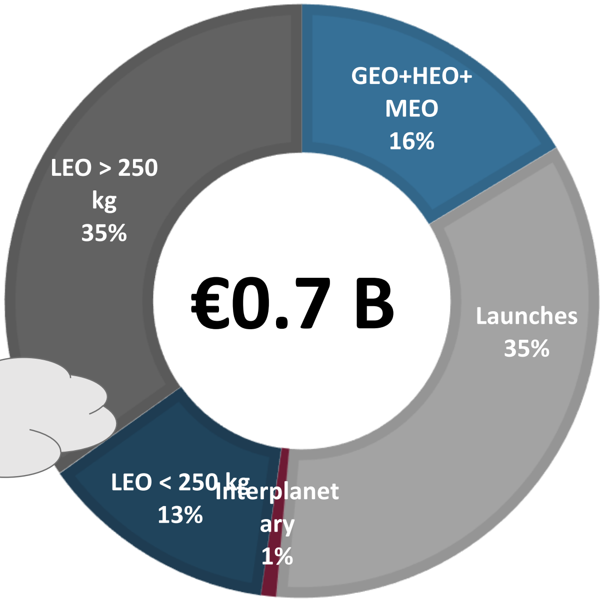
MARKET ANALYSIS – GNSS SPACE USERS AND THEIR REQUIREMENTS

Setting a **target position accuracy for Galileo in space of 3.5 m (95% sphere, 3D)** will address the requirements of EO applications in LEO, as well as the needs of >3000 km missions

Forecasted EGNSS Space Addressable Market Satisfied by Target Galileo Performances
-GNSS Spaceborne Receivers-
(in 2017-2036 period, % of total)



Considering only EO/RO missions In LEO



Source: STP Analysis

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GALILEO FEATURES FOR SPACE SERVICE

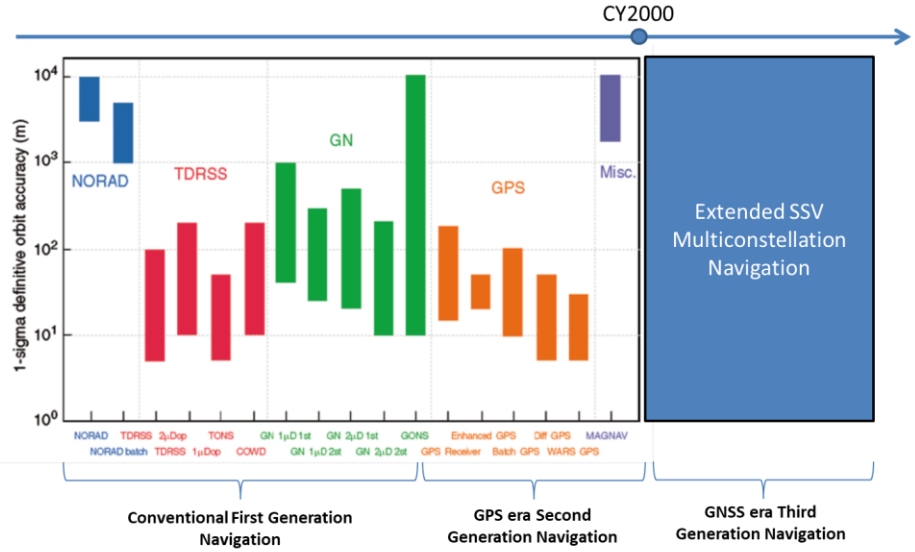
Orbital Determination vs Orbital Navigation (state of art)

ORBITAL DETERMINATION (OD)

- Determine the state of a satellite in order to support mission operations**:**
  - Post-flight processing generally integrates high fidelity propagation of spacecraft dynamic model with a set of observations and measurements collected by ground-based tracking stations
- Different precision on Orbital Determination**:**
  - **IOD:** preliminary Initial orbit determination
  - **POD:** Precise orbit determination

ORBITAL NAVIGATION (ON)

- As OD but real time spacecraft positioning by the direct on-board processing of avionic sensor and auxiliary observables
- To support platform autonomous operations as trajectory and attitude control tasks
- Payload and data handling can benefit of a precise position and time tag.



OD/ON Generations:

- 1st (or Standard approach) not considering GNSS availability
- 2nd (or Conventional approach) using baseline GNSS solutions
- 3rd (or Enhanced approach) using extended GNSS solutions

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GALILEO FEATURES FOR SPACE SERVICE

GNSS enhanced

GNSS introduces:

- A significant accuracy improvement
- Enhanced on-board synchronization capabilities relying on the common stable time reference

MAIN Challenges:

- High orbit utilization (it is used up to now only for LEO application)
- Complex and expensive architecture

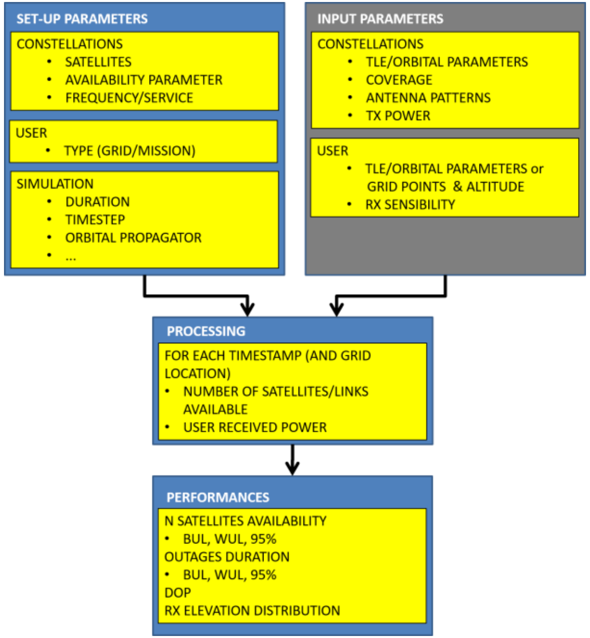
A 3rd navigation era can be defined as one that aims at improving GNSS constellation service, receivers and platform avionics in order to enable the following capabilities:

- Compatibility with on-board wide range orbit regime (LEO, MEO, GEO, GTO) by enhanced multi GNSS Space Service Volume exploitation (increased constellation elements, sidelobes exploitation)
- Implementation of Multi-constellation/Multi-frequency/Multi-antenna GNSS receivers for extended service availability
- Readiness for the tremendous expected impact of space missions commercialization (nano/micro-satellites trend of next 20 years) by improving navigation flexibility, miniaturizing the electronics and minimizing hardware complexity

GALILEO SSV CHARACTERIZATION

TAS-I SSV simulator has been developed and modified during the course of the programme, in order to assess the key Space Service parameters:

- Multi constellation/multi frequencies
- Receiver antenna flexibility
- User location/orbit



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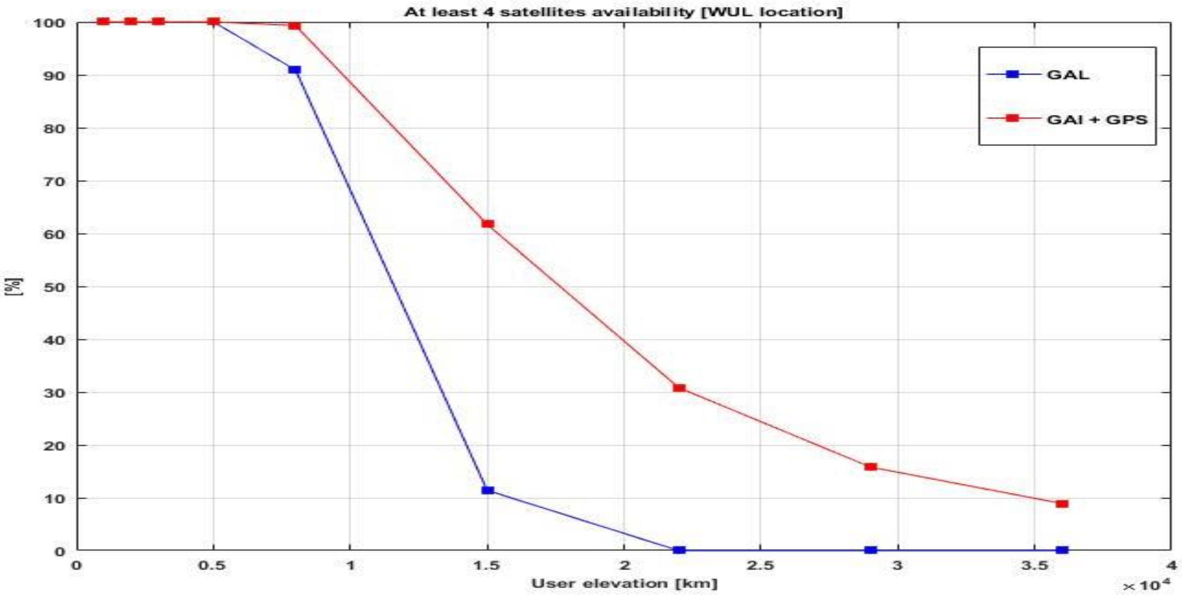
GALILEO SSV CHARACTERIZATION

At least 4 satellites availability (main lobe) – GAL E1-BC & GPS L1 C/A



The Availability is considered at WUL, over 10 days

Up to about 5000 km the number of available satellites increases w.r.t. ground user

Above 5000 km, GNSS main lobe limitation starts to decreases the number of available satellites

GALILEO only positioning is possible (with high availability) up to 5000 km; but the geometrical limitation impacts the PDOP above 4000 km

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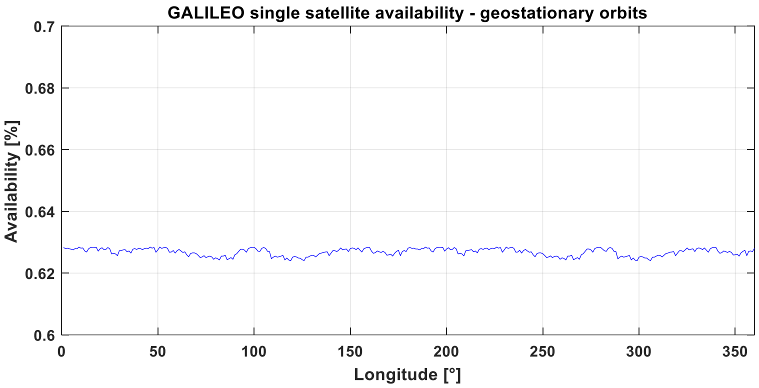
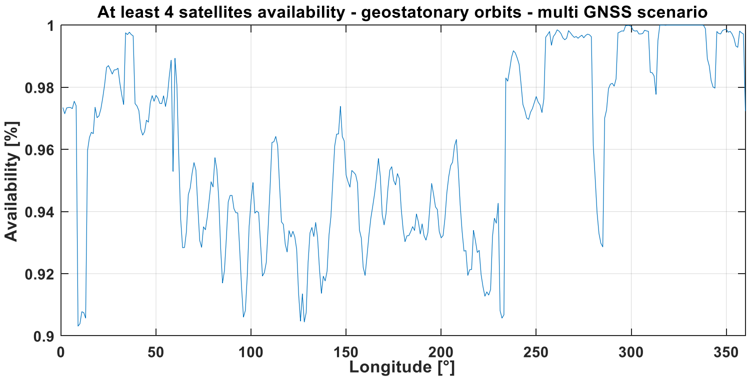
GALILEO SSV CHARACTERIZATION

4 links availability – GEO Orbits





- Multi-GNSS 4 satellites availability is above 90%
- GALILEO single satellite availability has to be at least 60%
- The exploitation of secondary lobes has not been considered

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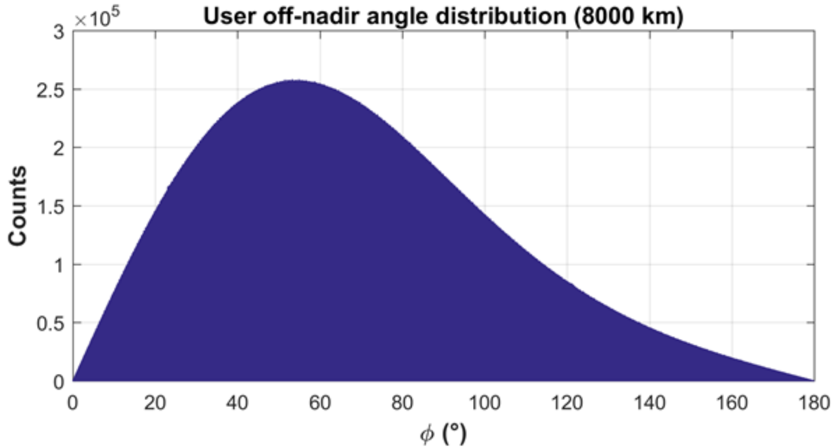
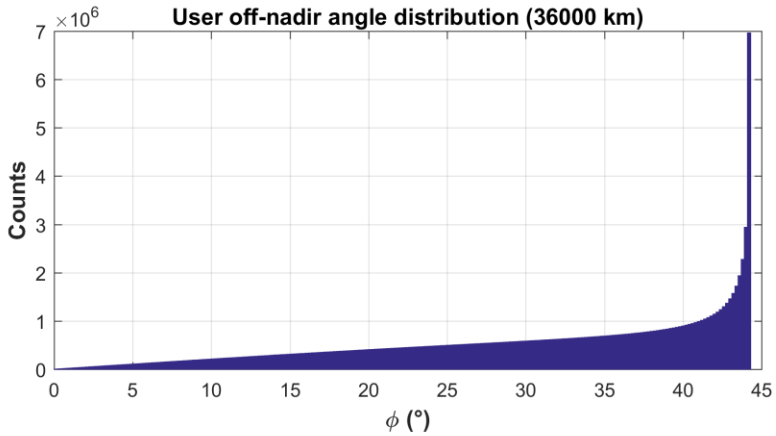
GALILEO SSV CHARACTERIZATION

User antenna needs

It is already intuitive that Low elevation users will have links available both from zenith and nadir (i.e. from the other side of the Earth), while GEO users will always see GNSS satellites around nadir





- Up to 8000 km of altitude, omnidirectional signal reception is required; this can be achieved both with omnidirectional antenna, or with nadir and zenith pointing antennas (in this case the user must ensure received signals relative calibration w.r.t. power and delays)
- for GEO altitude, only nadir pointing is necessary

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SPACE SERVICE: POSITIONING ERROR BUDGET

- A simplified method to verify that reference requirement set can be fulfilled combining high level information provided by SSV simulator (availability, average GDOP, maximum outage) and first order indexes representative of the exploited GNSS filter.
  - The following missions have been analyzed:
  - CSG agile satellite on-board POD (LEO)
  - SABRINA Mission Bistatic SAR formation flying (LEO)
  - Galileo Second Generation Low Thrust Autonomous EOR (LEO to MEO)
  - TLC Low Thrust EOR and Station Keeping (LEO to GEO)
  - Small satellite multiple launch and orbit acquisition (LEO)

- **The position errors** are in the **order of meters,** except for high and medium orbits in LEO to MEO orbital transfer due to a low visibility availability of GNSS satellites

- In the **LEO satellite** case, the number of GNSS satellites is always enough to keep the **position error within the requirement**

- DOP degrades above 4000km

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G2G SPACE SERVICE MISSION AND USER LEVEL REQUIREMENTS

- **Mission requirements:** deriving the GALILEO mission needs to support the above commitments
  - Space Service Through **Open Service**
  - Minimum Signal Power ≥-182.5 [dBW]
  - Off-Boresight Angle ≥ *20.5*° (E1, most stringent)
  - Services granted in nominal system configuration
  - Support to multi GNSS Space Service
  - Commitment on **GALILEO antenna patterns provision** to users

- **"Lower Space Service":** minimum up to 4000 km
  - Positioning: 3.5 m accuracy (3-D, 95% confid.), WUL
    - **Dual Frequencies** Users
    - Assumption: SISE 0.2m (1-sigma)
  - Timing: 40 ns UTC accuracy (95% confid.), WUL
    - **Dual Frequencies** Users
    - Assumption: UTC-GST accuracy of 10 ns (1-sigma)
  - User with **omnidirectional** antenna (or nadir + zenith pointing antennas)
  - Availability: ≥ 95%
- **"Upper Space Service":** geostationary orbits
  - **Single Frequencies** Users
  - Single satellite availability : >= 60%
  - User with **Nadir pointing** antenna

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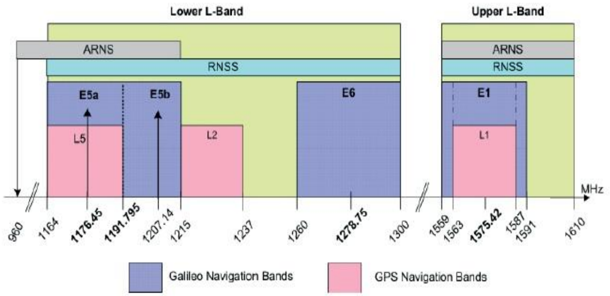
CHARACTERIZATION OF GALILEO SATELLITES EMISSIONS

Payload Definition

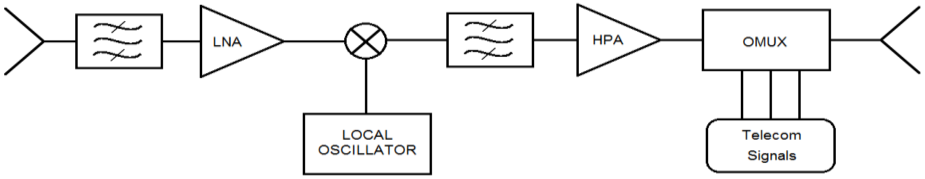
/// Transparent Payload

- Reduces the MVC budget as no de/coding chain is needed on board
- Simplifies the architecture
- Allows a more powerful and customizable signal processing at Ground Stations
- Is more suitable to be used as a Hosted Payload

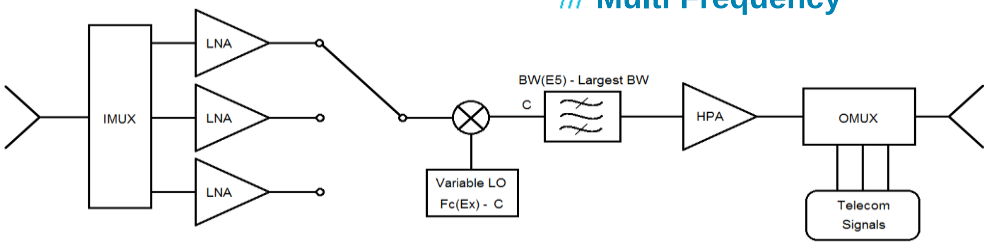


/// Two architecture approaches

/// Single Frequency



/// Multi Frequency



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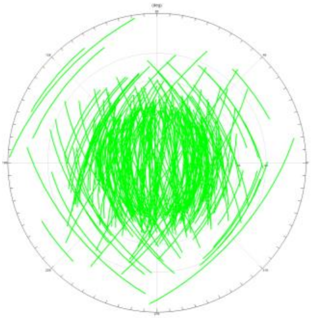
CHARACTERIZATION OF GALILEO SATELLITES EMISSIONS

Mission analysis and Simulations

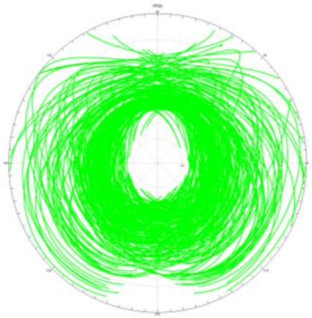
Determine the best type of mission / orbit insertion for characterisation of GALILEO satellite emissions

Analyses performed:

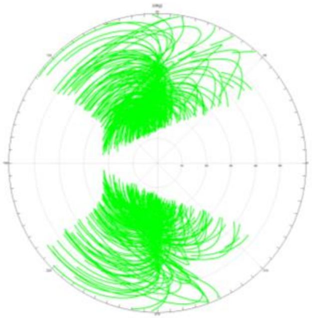
- Orbit and satellite Geometrical Parameters
- Line of sight simulation
- Receiver accommodation and Field of view
- Whole GALILEO constellation considered (planes A,B and C)



X face on rising satellite



Y face on rising satellite:
solar panels direction



Z face on rising satellite:
velocity direction

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CHARACTERIZATION OF GALILEO SATELLITES EMISSIONS

Conclusion

/// GEO mission

- Similar to NASA's ACE mission
- GNSS signal sampling for the whole satellite lifetime
- As hosted payload is dependent on systems and schedules unrelated from GALILEO

/// LEO to GEO mission

- Can be seen as a complement of the GEO mission
- Depending on the insertion orbit chosen it might need an additional antenna
- Chemical propulsion shortens the rising time, thus limiting added value

/// HEO mission

- Highly configurable
- Good survey of B and C planes
- Long measurements lead to high angular resolution (due to orbit relative slight drift)

/// MEO mission

- Can establish a Line of Sight on a wide Field of View
- Could be hosted by a 3th generation GALILEO satellite

/// LEO to MEO mission

- Long measurement time, RAAN variation and slow altitude increase provide:
  - High angular resolution
  - Wide field of view
- Could be hosted by a 3th generation GALILEO satellite

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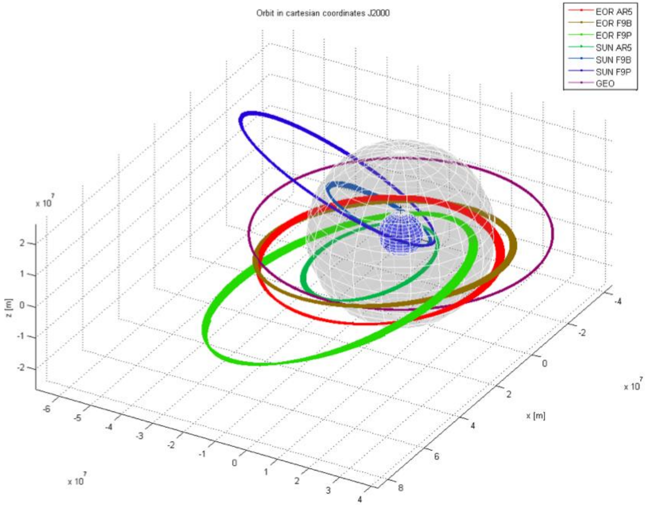
SPACE SERVICE: SIGNAL PROCESSING

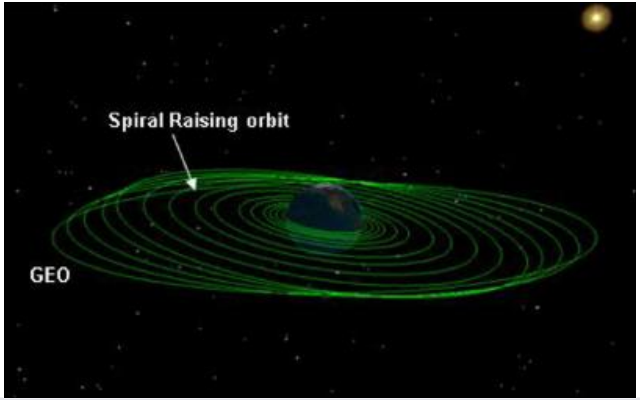
- /// Missions towards **GEO altitude** are increasing: full exploitation of the SSV
- /// **Orbits are higher than the GNSS Constellation and on-board Receiver <u>intersects</u> several times the "GNSS Sphere".**
- /// The RX shall be very **high sensitive in a high signal power dynamics,**

Near-Far problem is a well-known issue caused by **high signal dynamics** and **limited GNSS codes "isolation"** in CDMA systems

- ***New Signals*** → ***up to 30 dB*** *(i.e. Galileo and Modernized GPS)*
- ***Legacy*** → *approx.* ***22-23 dB*** *for GPS L1 C/A codes*



- /// **Near-far issue (intra-system interference or MAI) affects signal acquisition & tracking capabilities**
  - *Difficult discrimination of desired weak signal w.r.t. strong interfering signals* ➔ ***CROSS-CORRELATION***
  - *IF weak signals are detected, measurements are not accurate impacting* ***PVT accuracy***
  - *IF weak signals from SVs in view are not detected, impacting PVT continuity (few SVs in visibility)*



SPACE SERVICE: SIGNAL PROCESSING

Weak Signal Miss Detection without mitigation approach

/// GNSS Bit-True Signal Simulator

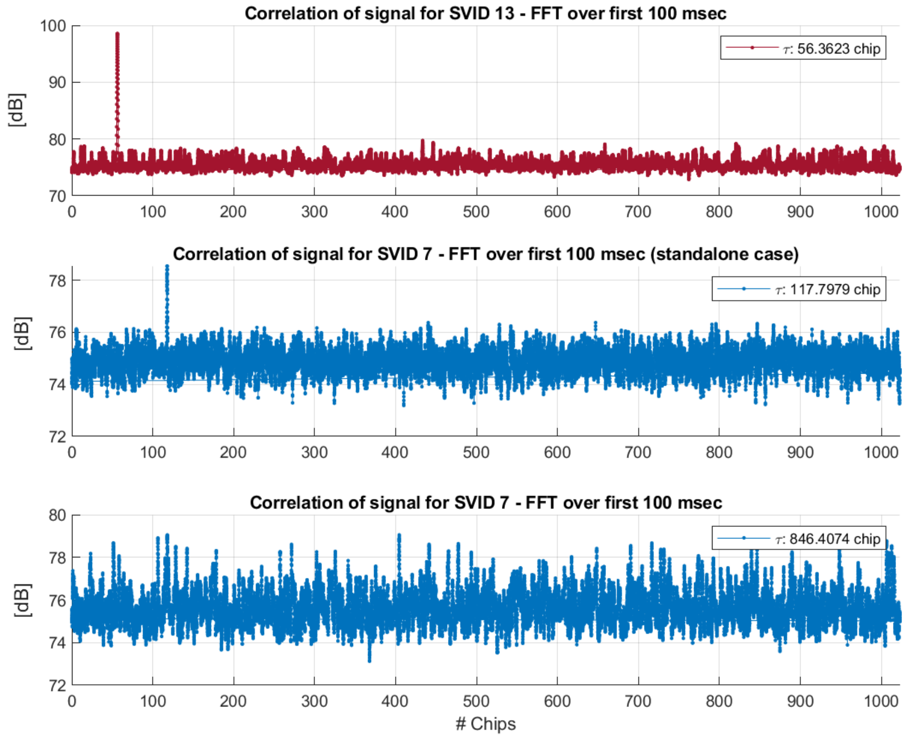
- generation of I&Q digital IF data stream
- 2-bit quantization from a noise-threshold controlled process
- data stream storing in a binary file

  (**weak standalone** and **signal pair** case)

$$y(nt_s) = \sum_{l}^{\{7\ 13\}} \left[\sqrt{Pow_l} * jc_l(nt_s) * e^{\left(j2\pi\left(f_{D_l} + f_{IF}\right)nt_s + \varphi_l\right)} + v(nt_s) \right]$$

Weak SIS MISS DETECTION in presence of MAI

TARGET : ACQ&TRK of the Weak Signal also in presence of MAI



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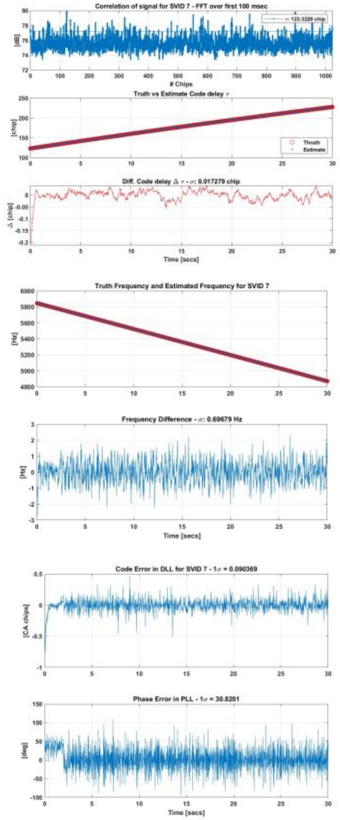
SPACE SERVICE: SIGNAL PROCESSING

DPIC - Results

Advanced Signal Processing Techniques available (*Successive Interference Cancellation (SIC)*, *Parallel Interference Cancellation (PIC)*, *Sub-space projection)*.

- /// **TRADE-OFF:** Algorithms performance **&** constraints of nowadays state-of-art GNSS Spaceborne RX architectures
- /// **MOST PROMISING ALGORITHM:** ***DELAYED PARALLEL INTERFERENCE CANCELLATION (DPIC)***
  - ➢ *subtractive **post-correlation** technique; **based on channel slaving ;***
  - ➢ *suitable for current GNSS Space Receiver architecture (i.e. flexible channels, **Software Defined Radio - SDR** approach)*
- /// Test Configuration (**30 sec**)
  - PRN 13 → “**Attacker” @ 52 dB-Hz**
  - PRN 7 → **Weak Signal @ 22 dB-Hz**
  - SIS Power difference → **27 dB**



- **Successful Weak Signal Tracking**
- **Code, Frequency and Phase Loop errors are dependent on the weak power but also on MAI estimation process**

SPACE SERVICE: SIGNAL PROCESSING

CONCLUSIONS

- **DPIC algorithm** is considered interesting for **reduced HW resources** necessary, matching space RX capabilities
- **Future implementation of the DPIC** in a real Spaceborne SW Receiver testing in a typical GNSS scenario
- Work developed under the GENESIS contract and Presented at ION GNSS+ 2019, Miami, FL

Mitigating the Near-Far Interference Problem in the GNSS Space Applications

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F. Paggi, *Thales Alenia Space Italia, Via Saccomuro 24, Rome, Italy*
C. O'Driscoll, *Independent Consultant*
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BIOGRAPHIES

Alberto Zin holds a PhD degree in Space Science and Technologies, from University of Padova, 2001. In 2002 he joined Thales Alenia Space Italia (formerly LABEN S.p.As.) in the GPS Products and Systems Group as Software Engineer. Now he is a System Engineer involved in different GNSS Programs and Applications, covering several ground-based and space-based applications. His fields of expertise cover GNSS radio occultation, autonomous space-borne navigation, GNSS-based ionospheric monitoring and timing/calibration applications.

Andrea Piccolo received the Master of Science degree in Telecommunications Engineering at the Politecnico di Milano in December 2014. Since 2015 he has joined the Navigation group of Thales Alenia Space Italia as GNSS Navigation Engineer in SW development integration and verification for multi-frequency multi-constellation GNSS space-borne receiver. He is currently working on several GNSS Programs and Application concerning space-based and ground-based applications.

Andrea Emmanuele received the B.E and M.E. degrees (cum laude) in telecommunications engineering and the Ph.D. degree in information engineering from the University of Pisa, Italy, in 2006, 2008 and 2012, respectively. His Ph.D. and post-doc research activities up to 2014 concerned design and performance analysis of advanced signal and coding techniques for future GNSS (G2G), in the frame of several ESA projects. Since 2014 he joined TASI in the Navigation group as Radio Navigation System and SW DSP engineer, working on the design of new generation EGNOS RIMS & TUR, G2G TUR, Monitoring receivers.

Luca Siniscalco received the Master of Science degree in Telecommunications Engineering at the University of Pisa, Italy in 2011. In the same year he joined Thales Alenia Space Italy as DSP Engineer for the industrial unit ground. His background and current activities are focused on GNSS signals performance, algorithm design and SW development for both ESA and ASI new generation of Ground and Space-Borne Receivers.

Francesco Paggi received M. Sc. In Aerospace Engineering from "La Sapienza" University of Rome and M. Sc. In Advanced Systems of Satellite Communication and Navigation from "Tor Vergata" University of Rome. He works since 2009 in Thales Alenia Space Italy as GNSS System Engineer; his activities covered GIOVE and GALILEO signal design and performances, GNSS signal processing, GALILEO system design, development, and evolution, and SAR/Galileo Service design and deployment. He's currently working on GALILEO Services deployment and GALILEO 2nd Generation services and signal definition.

Cillian O'Driscoll received his M.Eng.Sc. and Ph.D. degrees from the Department of Electrical and Electronic Engineering, University College Cork, Ireland. He was a senior research engineer with the Position, Location and Navigation (PLAN) group at the Department of Geomatics Engineering in the University of Calgary from 2007 to 2010. He was with the European Commission from 2011 to 2013, first as a researcher at the JRC, and later as a policy officer with the European GNSS Programmes Directorate in Brussels. From January 2014 to June 2017, Dr O'Driscoll was a research fellow at University College Cork. He is currently an independent consultant. His research interests are in all areas of GNSS signal processing.

Matteo Paonni is a Scientific Officer within the Directorate for Space, Security and Migration at Joint Research Centre of the European Commission in Ispra, Italy. Under his position Matteo provides technical and policy support to the EU Satellite Navigation Programmes Directorate within the European Commission and also to the European GNSS Agency. Matteo's main focus is on GNSS signal design and optimization, GNSS compatibility and GNSS signal processing. From 2007 to 2013 he was a

SPACE SERVICE: SIGNAL PROCESSING

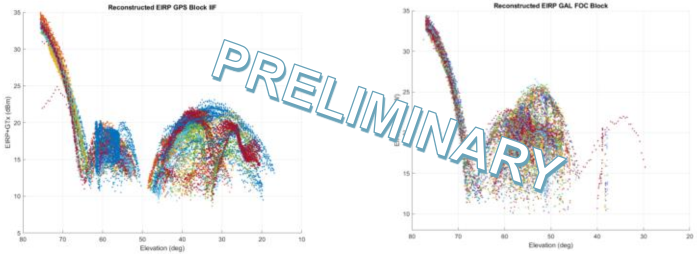
Recent results

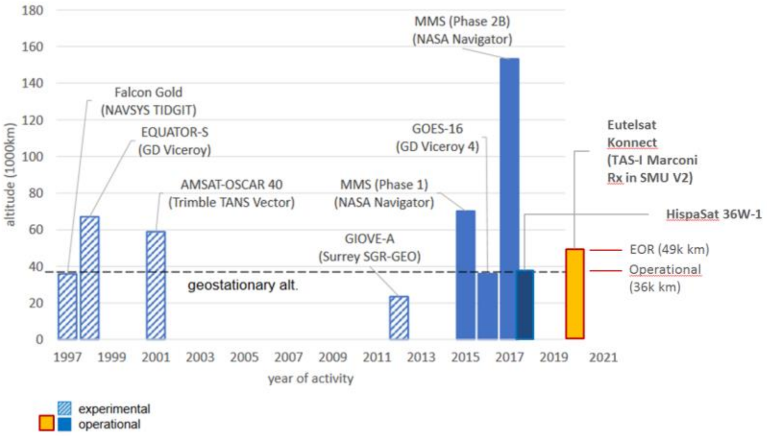
- In Europe, the Eutelsat Konnect is the first platform to house a **non-experimental, new generation, multi-constellation** GNSS receiver for its operations, i.e. a receiver which is used operationally in a commercial mission

- TAS-I GNSS Rx based on AGGA-4 board set important records in SSV (Geostationary orbit):
  - **first tracking of the GALILEO signal above the GALILEO constellation** (and above the GEO orbit as well).
  - According to the authors knowledge, the receiver marked the record of **tracking altitude** for an European GNSS receiver, with an altitude of approx 49000 km)

- The availability of Rx data from geostationary orbit allowed a reconstruction of GPS and GALILEO patterns. These results will be presented at NAVITEC 2022 conference.

- Anticipation of results:





Reaching and Navigating in Geostationary Orbit with a GNSS Receiver: challenges and in-flight results

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CONCLUSIONS 1/2

///Why to support GALILEO Space Services Introduction

- The Space Service has demonstrated as a very promising introduction for GALILEO
- GNSS approach will improve the automation of critical on-board operations and platform performances, enabling also in the next future novel scenarios.
- Considering the selected user needs and derived requirements, potential total addressable market for European GNSS space borne receivers of ca. 0.7 Billion Euro cumulatively in the 2017-2036 reference period can be captured for users up to 4500 km.

///The need to support multi GNSS SSV

- The availability of signals quickly decreases above 8000 km of altitude
- For higher elevations, multi GNSS receivers are necessary

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CONCLUSIONS 2/2

/// The need of navigation antenna characterization

- Users are interested in the GALILEO antenna information; providing it will grant advantage to GALILEO usage
- Within the antenna characterization possibilities, base-based missions have been analysed.
  - **LEO-to-MEO transfer orbit** appears promising: due to mission duration RAAN variation and slow altitude increase provide respectively a Line of Sight on a wide Field of View and a high angular resolution.
  - **HEO mission** proved to be also a good candidate for GNSS antenna characterisation, particularly for GALILEO satellites on B and C planes. Thanks to the relative orbit drift, a high angular resolution can be achieved with a long time measurements.

/// Future work areas to study enhancements for GALILEO Space Service

- The main limitations of GALILEO w.r.t. GPS in the Space Service provisions are:
  - **Limited main lobe aperture**: the relaxation of E1 main lobe aperture would increase signals availability
  - Current GALILEO signal design is not optimized for Space Services, both in terms of PRN codes length and modulation: results show the current gap of GALILEO w.r.t. GPS for acquisition.
  - **A “Coarse/acquisition” signal component** would limit the gap

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