# GNSS Training for ITS Developers

## 1 - EGNSS Principles

European Global Navigation Satellite Systems Agency

HORIZON 2020

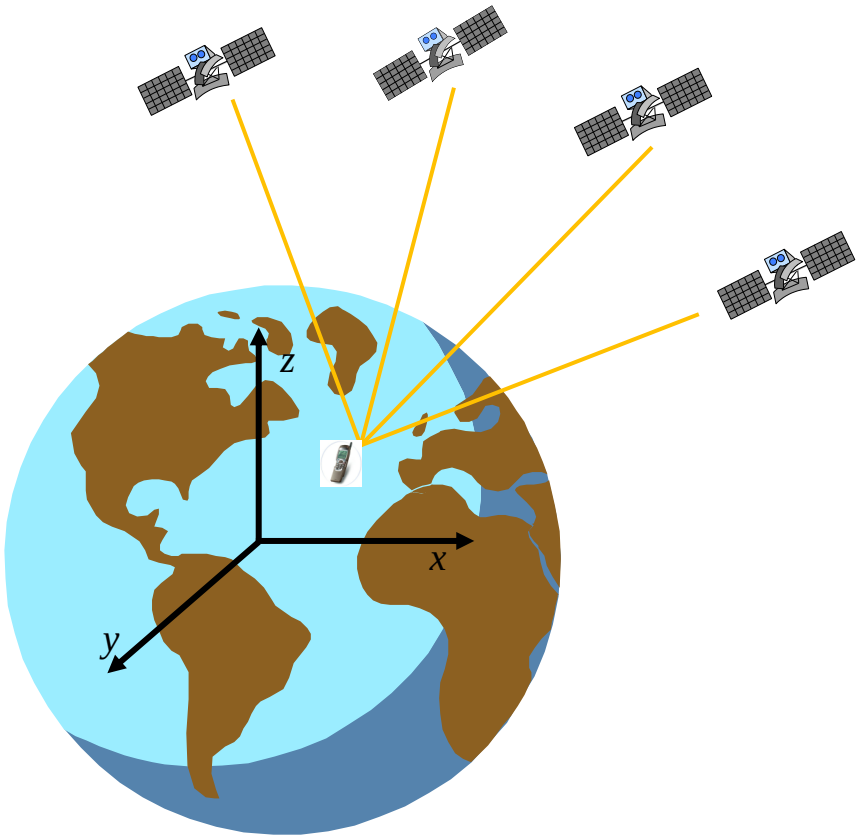
# Table of Content

**EGNSS Principles**

# Table of Content

EGNSS Principles

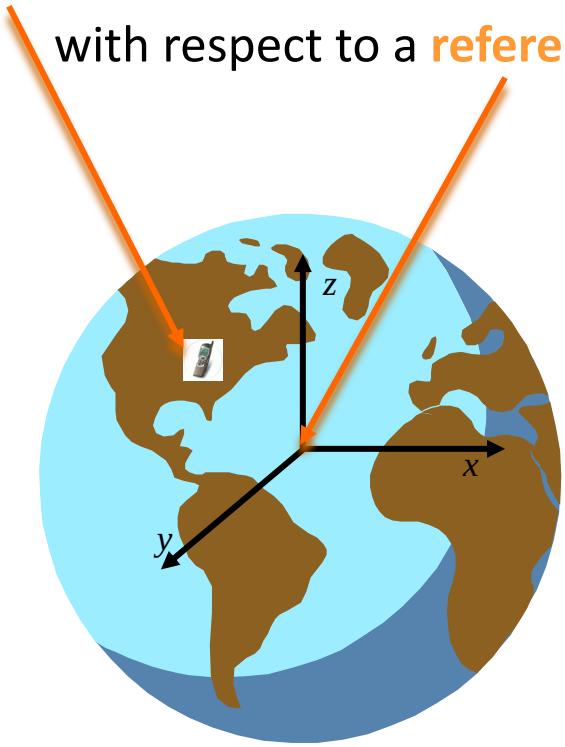
# Global Navigation Satellite Systems




**GNSS** enable users (on Earth surface or flying) to determine their position with respect to a **Reference Frame**

# Getting Started

**Addressed Problem:** To determine the **position** of an object (receiver) with respect to a **reference frame**.




SOLUTIONS

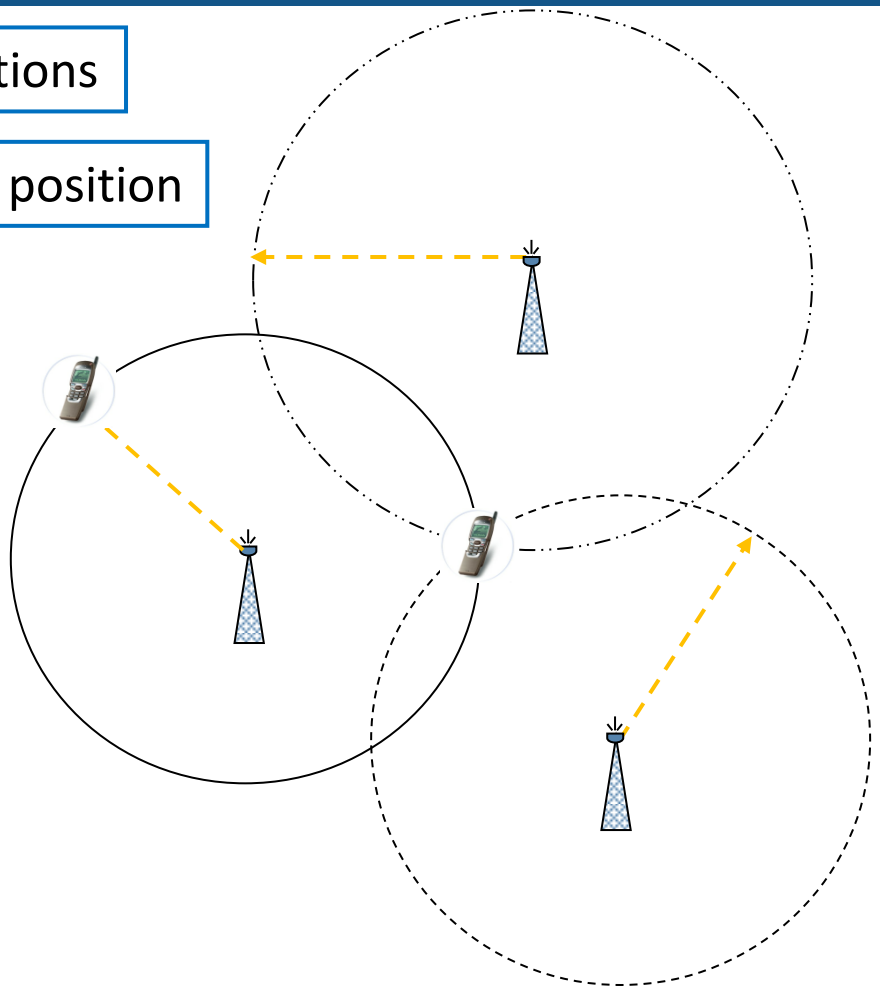
- The early navigators and mapmakers relied on **celestial observations**
- The science of **timekeeping** allowed for an improvement of navigation (especially at open sea)
- Dead reckoning with **inertial navigation systems**
- In modern era, **Radio-navigation** is the most widely used (Determination of **position** and **speed** of a moving object by means of the estimation of parameters of **electromagnetic signals** sent by transmitters)

# Trilateration

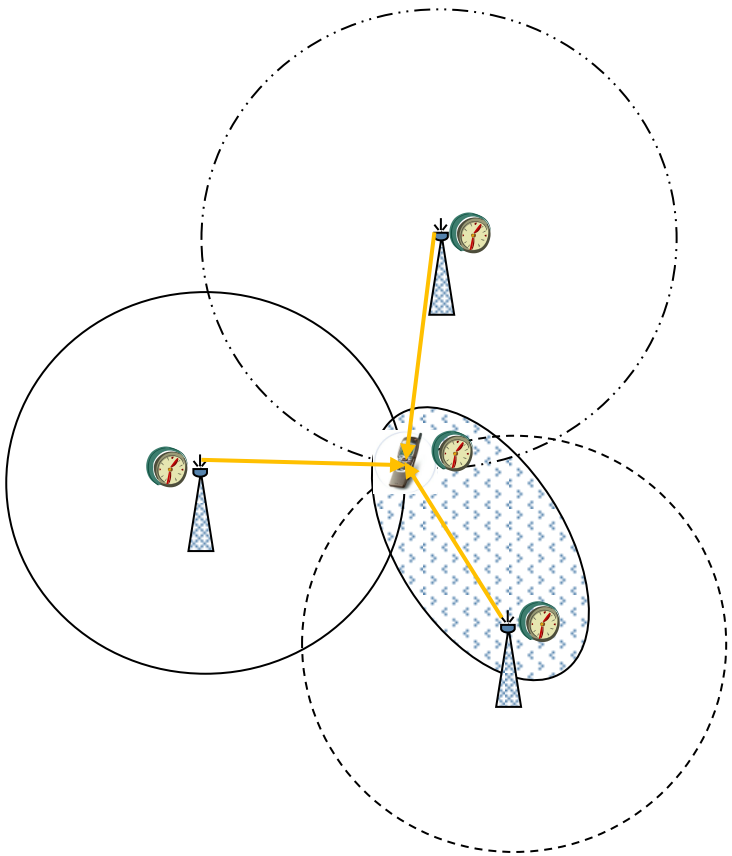
Transmitters are in **known** positions

The receiver is in an **unknown** position

The receiver is able to measure the TOA (*Time Of Arrival*) and *consequentially* the distances

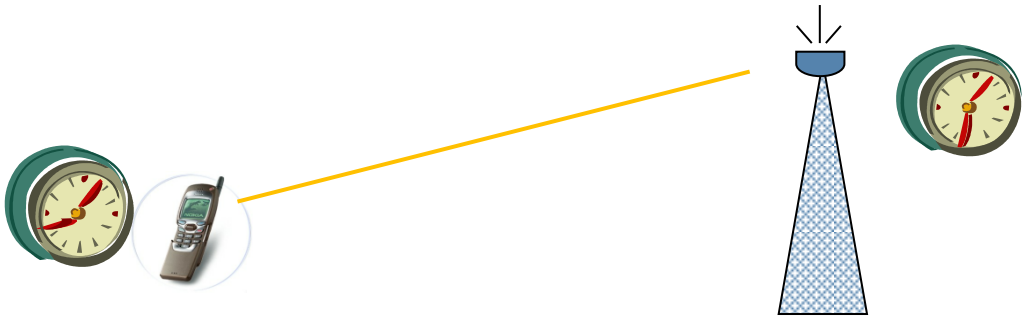


# The Basic Tool: the Clock



The observer measures the TOA (*Time Of Arrival*)
The time of departure is known (set by transmitter)
The travel time is their difference
The distance is the travel time multiplied by the speed of light.

<u>Transmitters</u> and <u>receivers</u> equipped with clocks.



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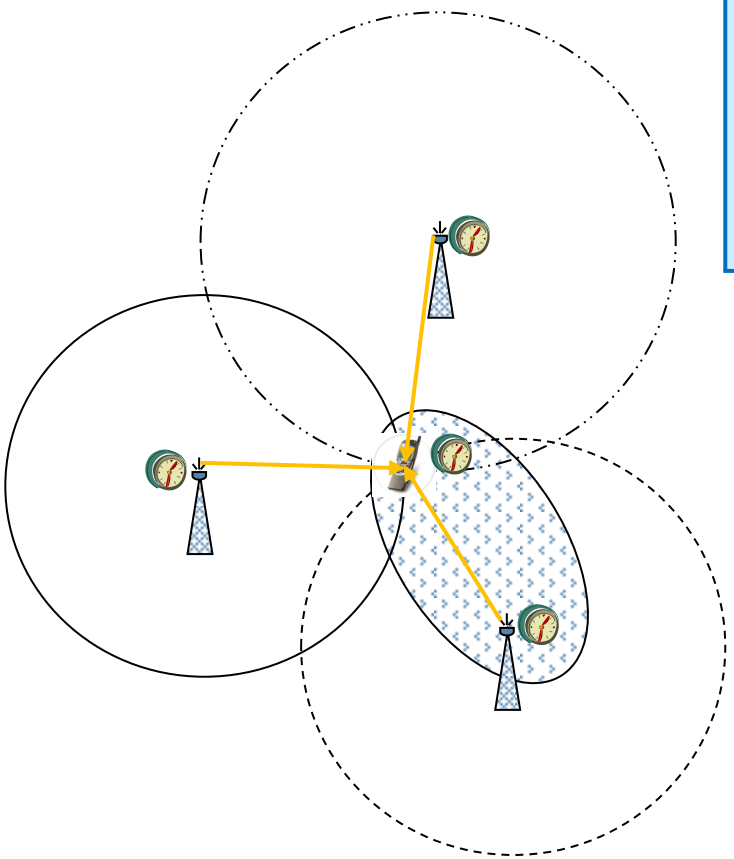


Time difference between TX and RX is the basis.

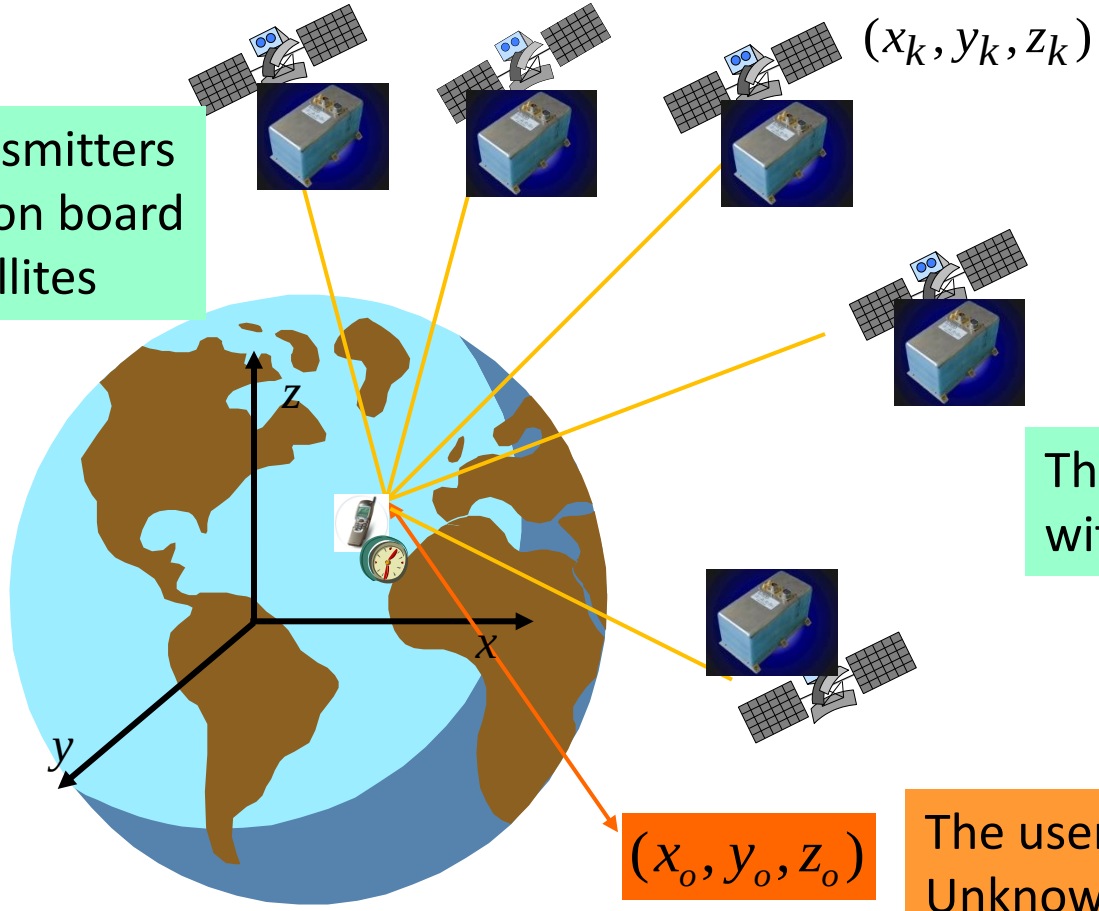
**TX and RX clocks must be synchronized**

Very onerous requirement!!

Synchronization error of **1µs** corresponds to an error distance of approx. **300 m**

# Trilateration by Satellites

Transmitters are on board satellites



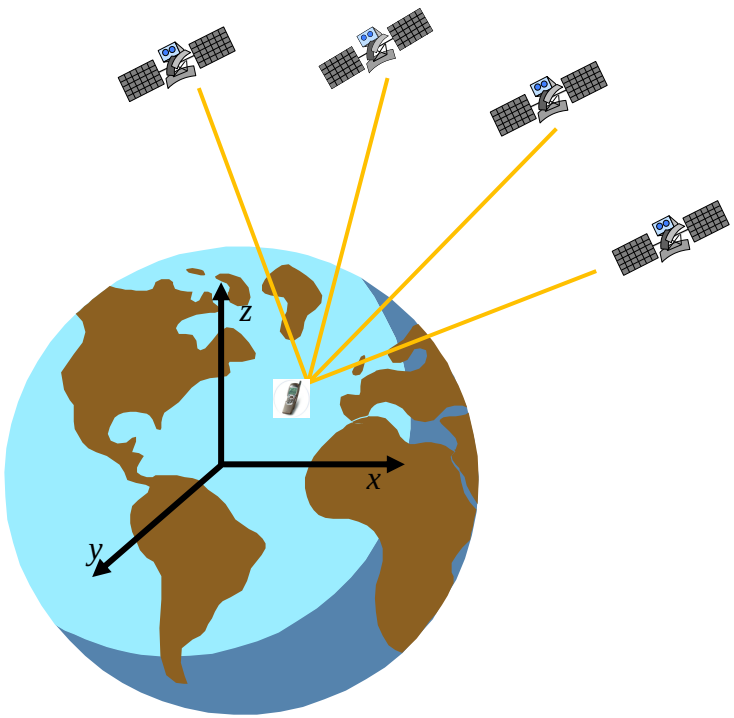

Satellites are at **known positions**, as we know the orbits and the **satellite time**

The satellites are equipped with **atomic clocks**

The user to be located (receiver)
Unknown position

# GNSS in One Slide

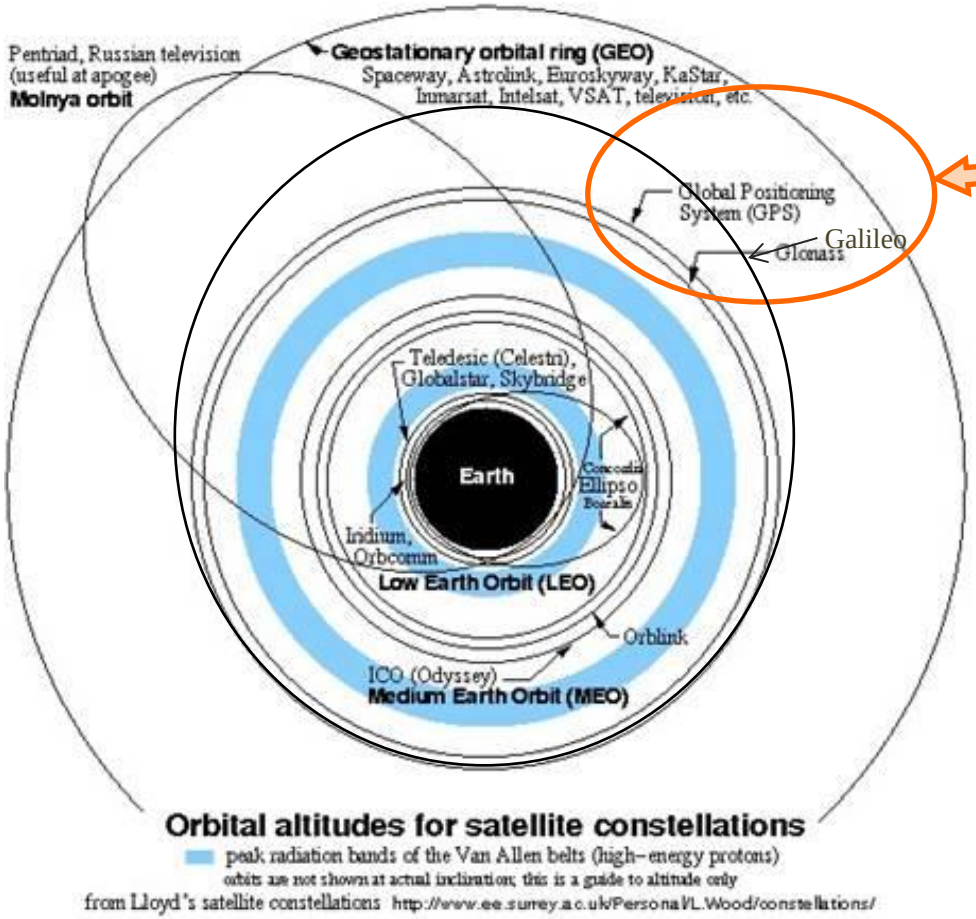
A **Global Navigation Satellite System** (**GNSS**) consists of a constellation of satellites with global coverage, whose payloads are especially designed to provide positioning of objects




GNSSs implement the **trilateration** method (spherical positioning systems)

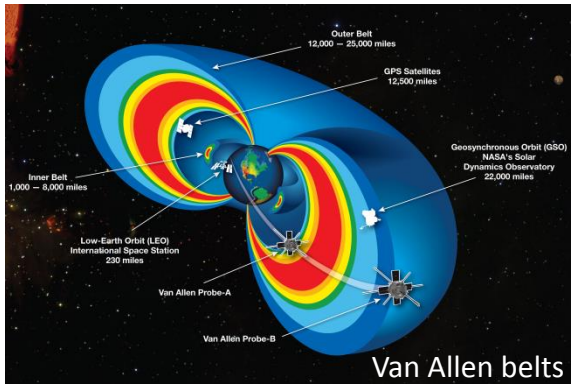
The satellites are at known positions, as we know satellite **orbits** and **time**

# Satellite Orbits




GNSS satellites orbit on Medium Earth Orbits (MEO)

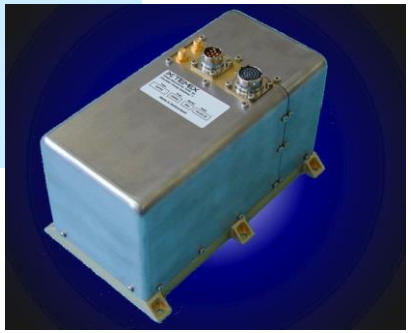
GPS orbit: 20,200 km
GLONASS orbit: 19,100 km
Galileo orbit: 23,222 km

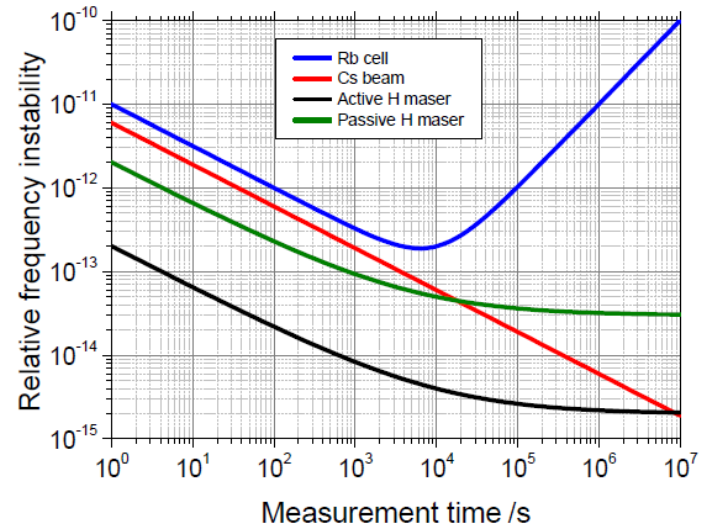


Van Allen belts

# On-board Satellite Clocks

Rubidium Atomic Frequency Standard
3.2 Kg mass
30 W power






Passive Hydrogen Maser
18 Kg mass
70 W power

**Rubidium**

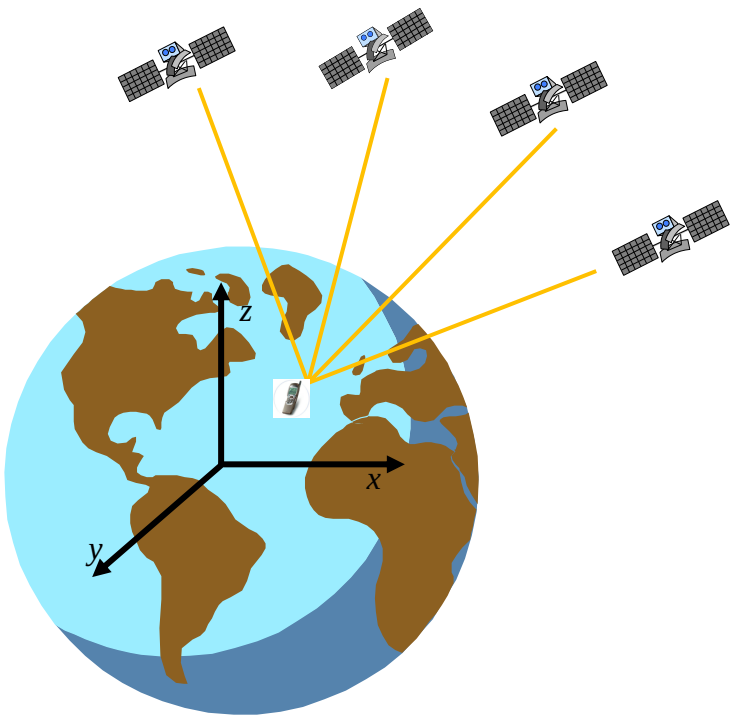
- Cheaper and Smaller
- Good short-term stability (less than 10 nsec/day)
- Subject to <u>larger frequency variation</u> caused by environmental conditions

**Passive H-Maser**

- Outstanding short-term and long term frequency stability (less than 1 nsec/day)
- Frequency drift

# GNSS in One Slide

A **Global Navigation Satellite System** (**GNSS**) consists of a constellation of satellites with global coverage, whose payloads are especially designed to provide positioning of objects



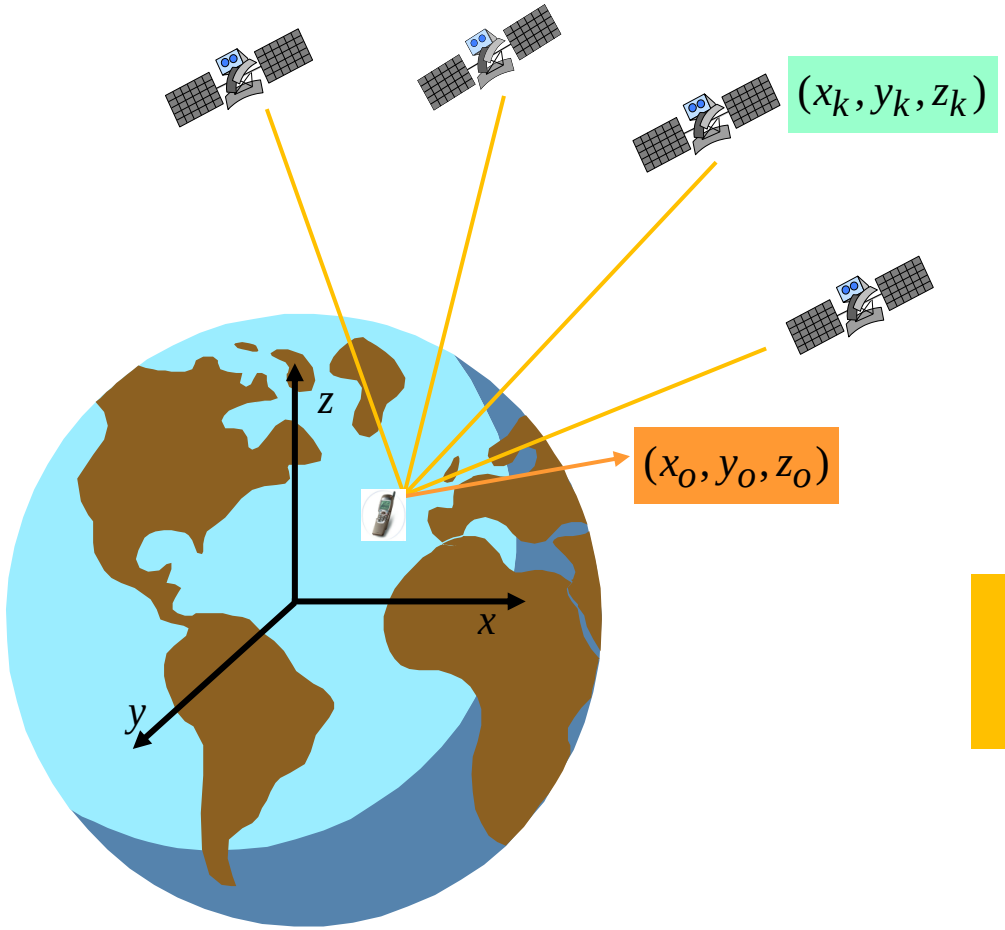

GNSSs implement the **trilateration** method (spherical positioning systems)

The satellites are at known positions, as we know satellite **orbits** and **time**

Reference Coordinate Systems and Frames

Time Scales

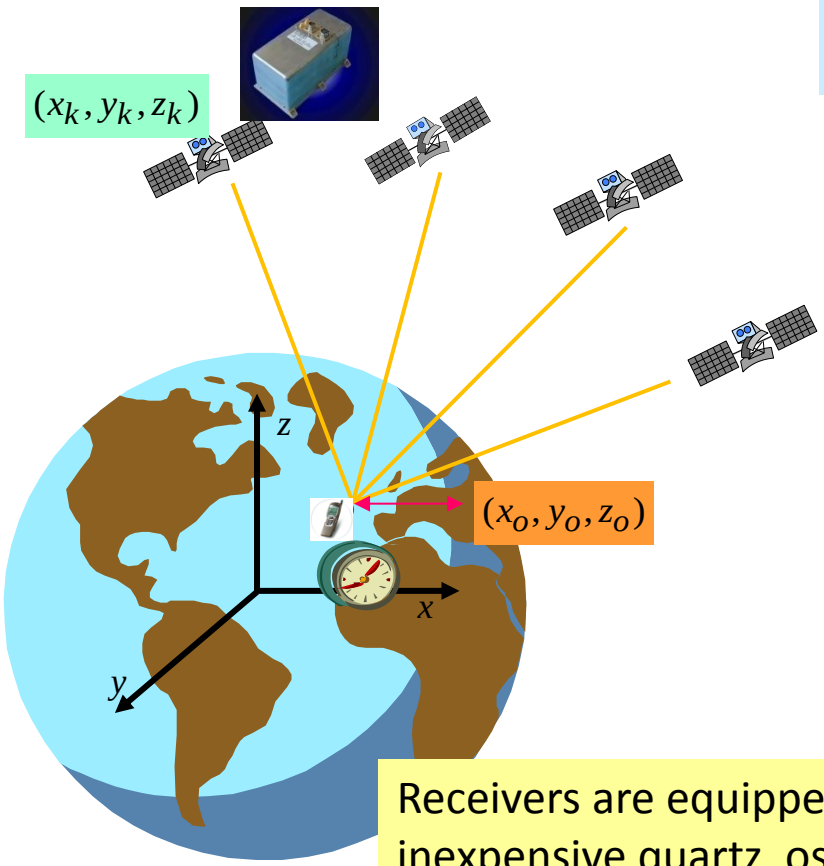
# How Many Satellites?




Why four satellites?

**To sidestep the synchronisation requirement**

# Ranges and Pseudoranges




Receivers are equipped with inexpensive quartz oscillators.

To sidestep the synchronisation requirement four satellites are needed

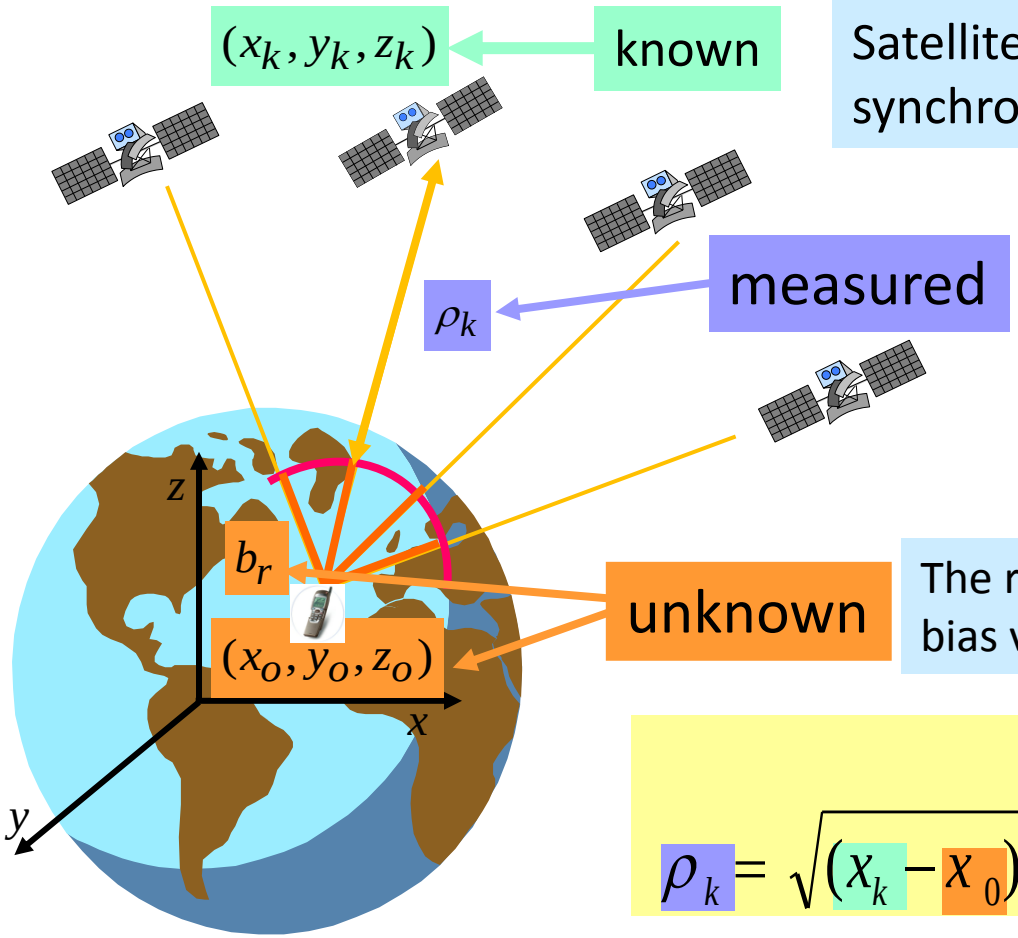
TOA measurements at the receiver are affected by the same clock bias $(b_c)$

$$(b_c) \longrightarrow (b_r)$$

The range bias $(b_r)$ becomes the fourth unknown to be estimated

Because of the bias $(b_r)$ **pseudoranges** are measured instead of **ranges**

# The Navigation Equation




Satellite clocks are synchronised

The receiver has a clock bias vs satellite clocks

$$\rho_k = \sqrt{(x_k - x_0)^2 + (y_k - y_0)^2 + (z_k - z_0)^2} - b_r$$

# The Navigation Equation

If we consider 4 satellites:

$$\begin{cases} \rho_1 = \sqrt{(x_{s1}-x_0)^2+(y_{s1}-y_0)^2+(z_{s1}-z_0)^2} - c\cdot\delta t_u \\ \rho_2 = \sqrt{(x_{s2}-x_0)^2+(y_{s2}-y_0)^2+(z_{s2}-z_0)^2} - c\cdot\delta t_u \\ \rho_3 = \sqrt{(x_{s3}-x_0)^2+(y_{s3}-y_0)^2+(z_{s3}-z_0)^2} - c\cdot\delta t_u \\ \rho_4 = \sqrt{(x_{s4}-x_0)^2+(y_{s4}-y_0)^2+(z_{s4}-z_0)^2} - c\cdot\delta t_u \end{cases}$$

measured

Known
(written in the
navigation message)

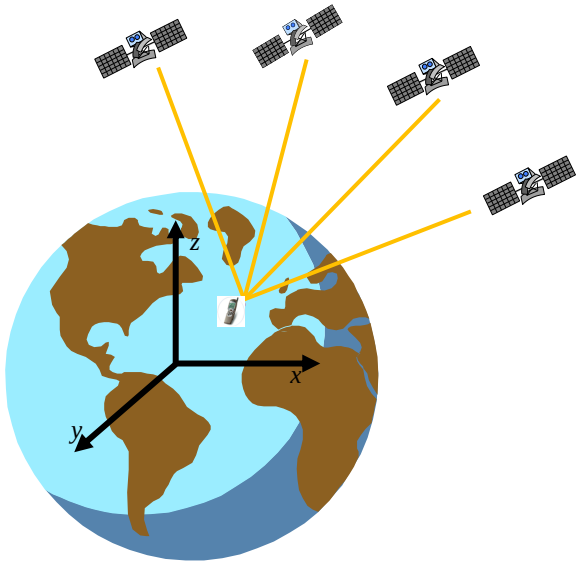
$x_0, y_0, z_0, \delta t_u$

**4 unknowns**

# The Navigation Equation

## REMARKS

- In order to estimate its position a receiver must have **at least four satellites** in view
- The satellites must be in **Line-of-Sight**
- If a larger number of satellites is in view a better estimation is possible. In the past the combination of four satellites giving the best performance was chosen
- Modern receivers use **several channels** in order to perform the position estimation



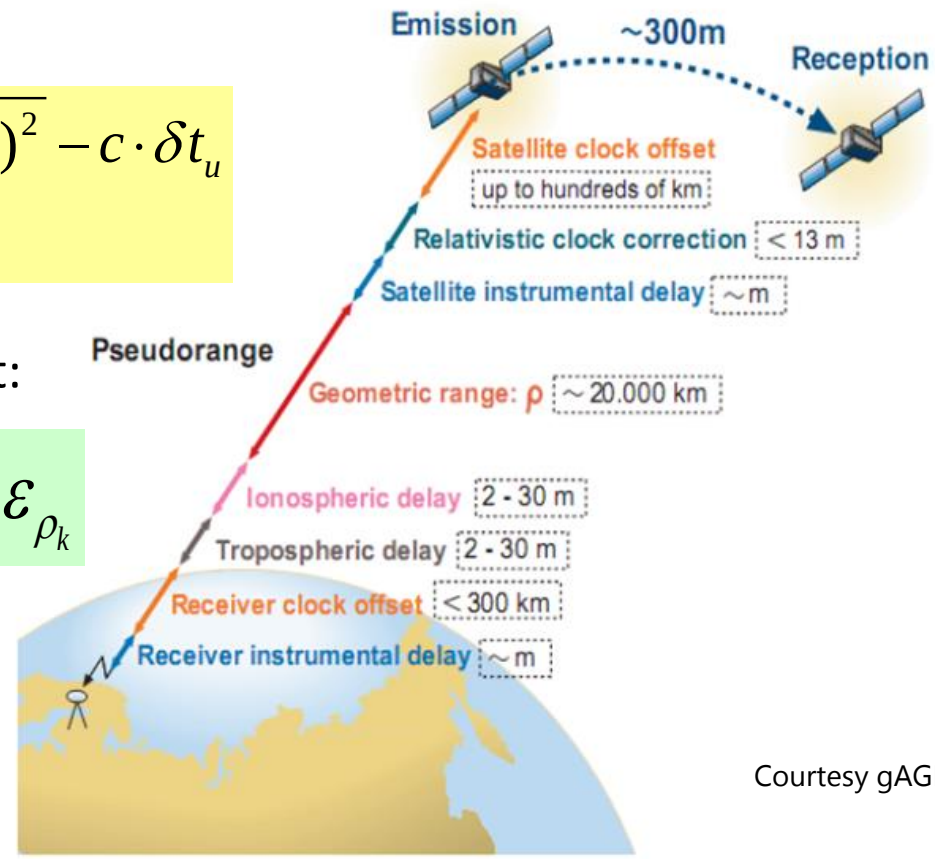
# Positioning Errors

Ideal measured pseudorange

$$\rho_k = \sqrt{(x_k - x_u)^2 + (y_k - y_u)^2 + (z_k - z_u)^2} - c \cdot \delta t_u$$
$$= \quad r_k - c \cdot \delta t_u$$

Other errors impact on the measurement:

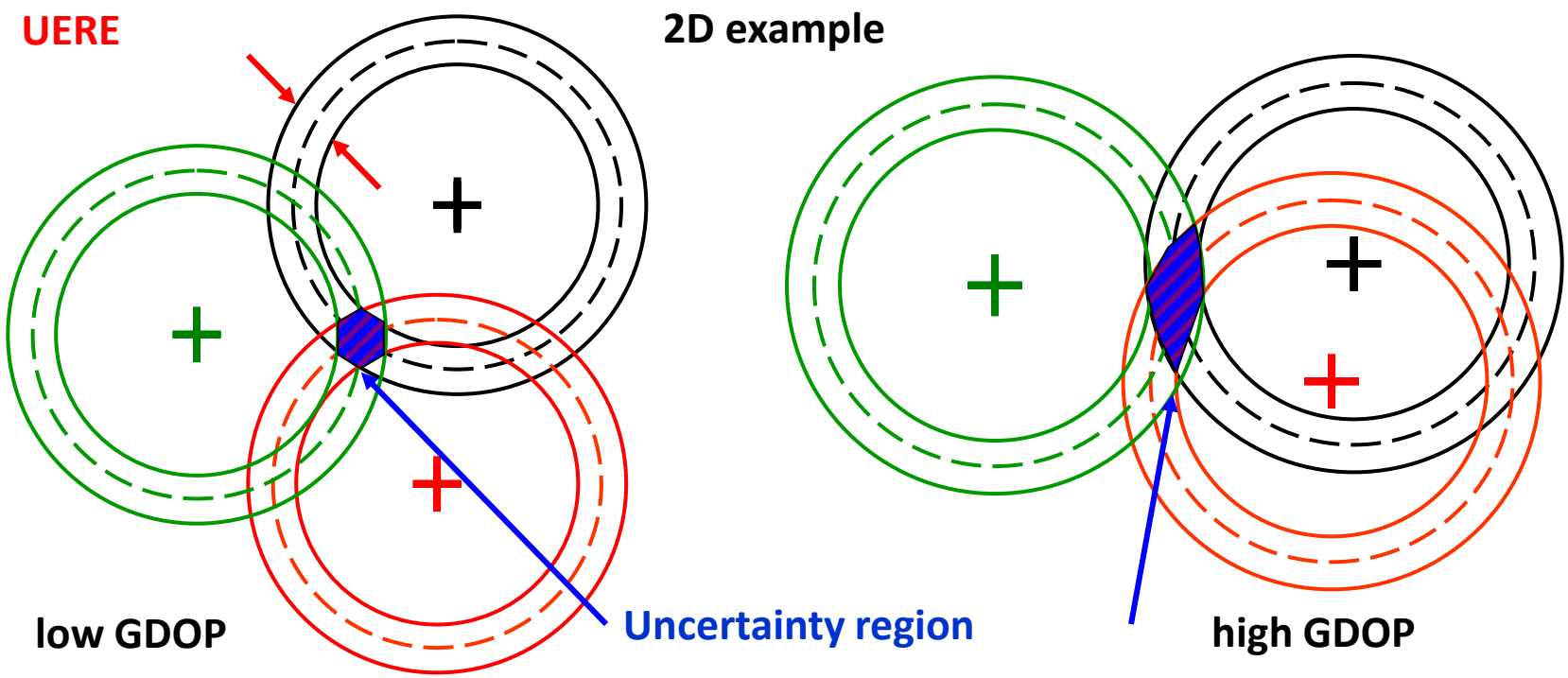
$$\rho_k = r_k + c \cdot (\delta t_k - \delta t_u) + I_{\rho_k} + T_{\rho_k} + \varepsilon_{\rho_k}$$




Courtesy gAGE

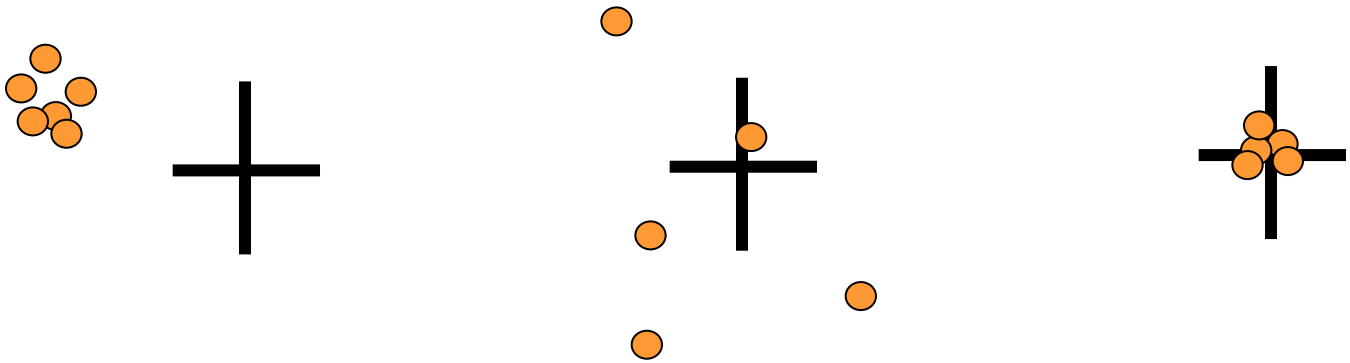
# The Geometrical Problem

The impact of the pseudorange error on the final estimated position depends on the displacement of the satellites (reference points)



# Accuracy and Precision

- **Accuracy:** measure of how close a point is to its true position
- **Precision:** measure of how closely the estimated points are in relation to each other



High Precision
Low Accuracy

Low Precision
Low Accuracy

High Precision
High Accuracy

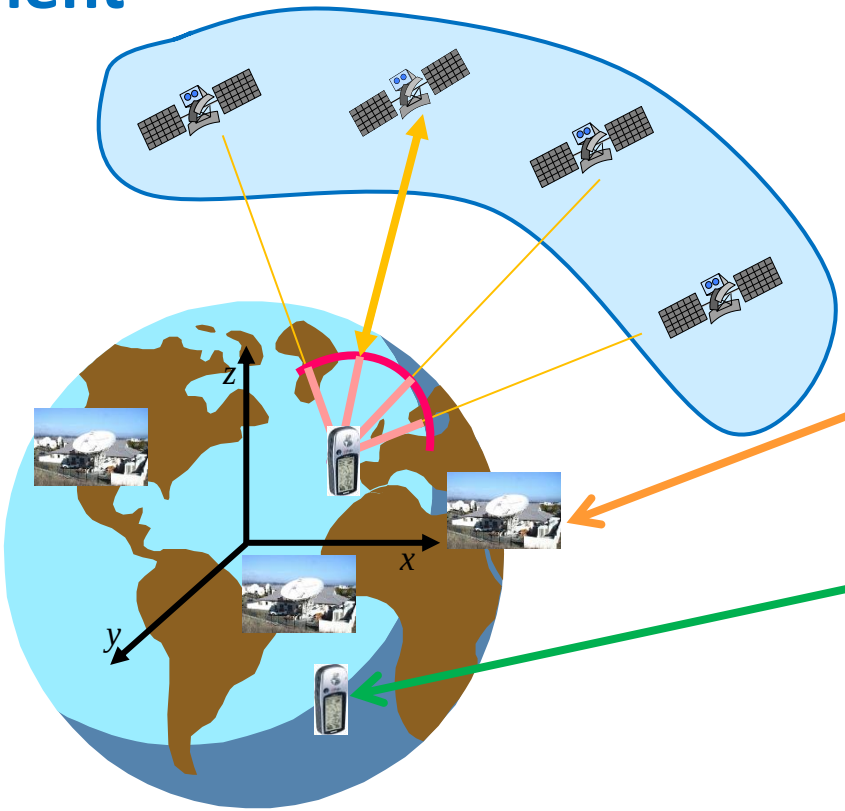
# Navigation Satellite Systems

**Space Segment**

Satellite constellation
Launching facilities

Monitoring Stations
Up-loading Stations
Master Station/Control Centre

**Control Segment**




**User Segment**

User Receivers
Applications

# Space Segment

Galileo (FM3)

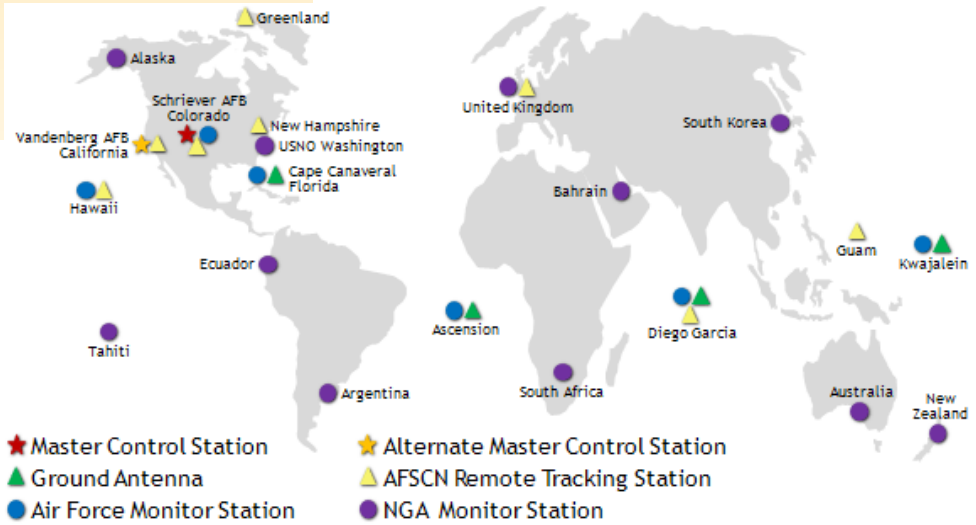
Figure 24 GPS IIRM Satellite (Artist's Rendition)

GPS (IIR-M)

GLONASS (K)

# Control Segment

- A network of stations distributed all around the planet
- Monitor the status of the satellites and of the signals
- Some ground stations are able to communicate to the satellites in order to control them and correct the signal generation




Example: GPS Control Segment

# User Segment


- It consists of a wide range of different receivers, with different performance levels
- The receiver estimates the position of the user on the basis of the signals transmitted by the satellites

- All receivers must:
  - Identify the satellites in view
  - Estimate the distance user-satellite
  - Perform trilateration

Additional functionalities aim at
  - easing and/or improving the position estimation (augmentations)
  - improve the user output interface
  - added value services (e.g. route calculation, integration with communication systems)

# User Segment GNSS Applications

## Mass Market

- Personal communication
- Personal navigation
- Cars / motorcycles
- Trucks & buses
- Light Commercial Vehicles
- Personal outdoor recreation

Low cost
Low power
Small size
User friendly

## Safety of Life

- Aviation
- Rail
- Maritime
- Inland waterways
- Ambulance
- Police / Fire
- Search and Rescue
- Personal Protection
- Traffic surveillance
- Dangerous goods transp.

Integrity
Continuity
Availability
Accuracy

## Professional

- Geodesy
- Oil and Gas
- Environment
- Fisheries / EEZ
- Land Survey / GIS
- Precision survey
- Precision Agriculture
- Fleet Management
- Asset Management
- Meteorological forecasting
- Construction / Civil Engineering
- Mining
- Timing
- Space

High precision
High accuracy
High reliability

# Existing Navigation Satellite Systems

- **GNSS** – Systems providing almost global coverage on Earth surface

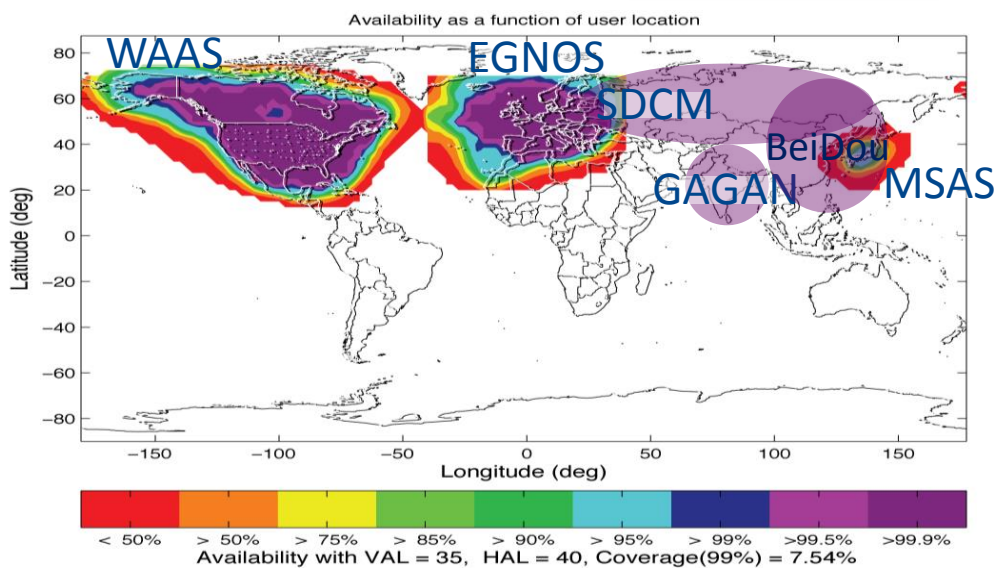
  **GPS, GLONASS, GALILEO, BEIDOU** (US,RU,EU,CN)

- **RNSS** – System whose coverage is limited to a Region

  **IRNSS, QZSS** (IN,JP)

## Space Based Augmentation Systems (SBAS)

- To improve availability, continuity and accuracy of GNSS
- To provide integrity information

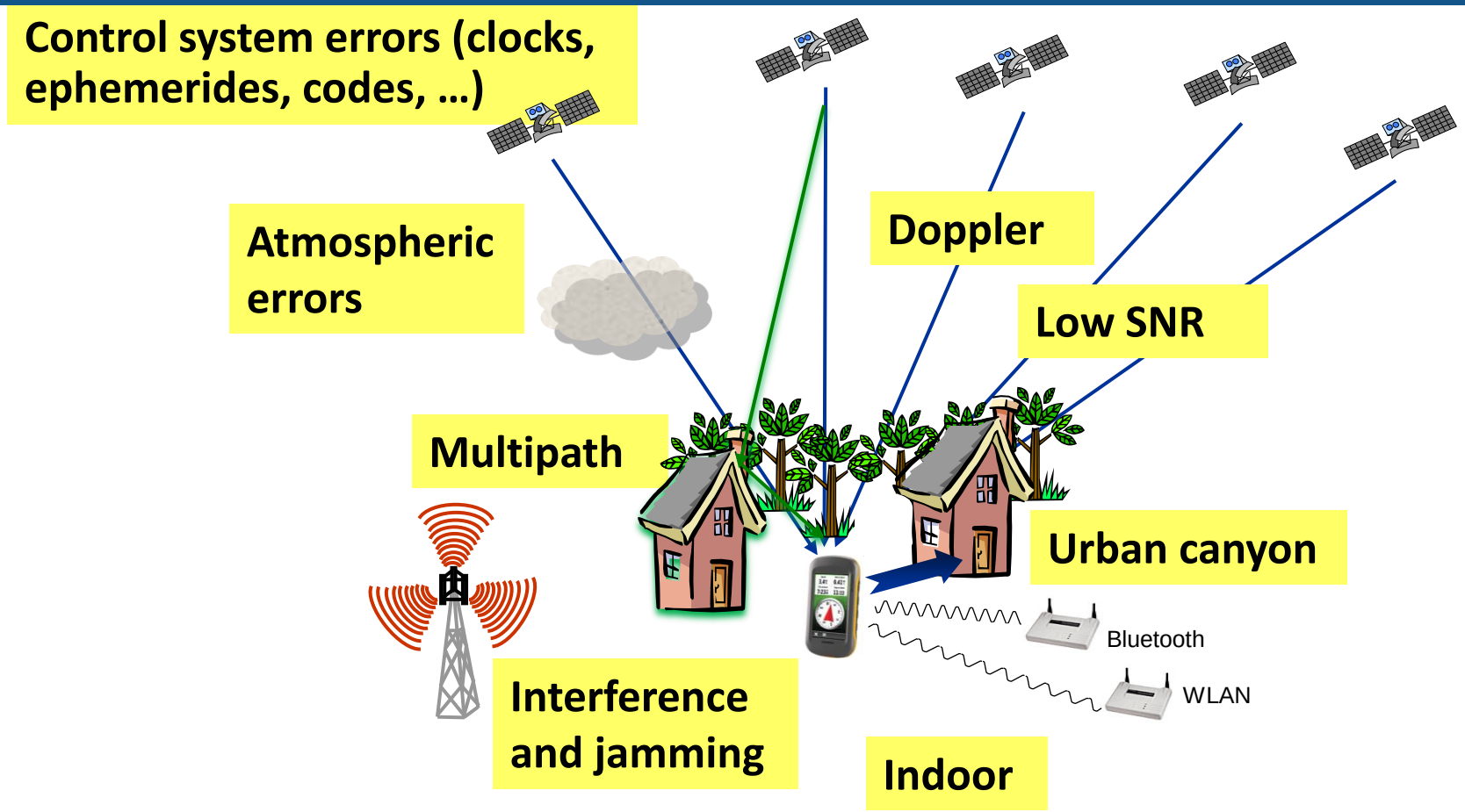



Source: Stanford University

# Table of Content

EGNSS Principles

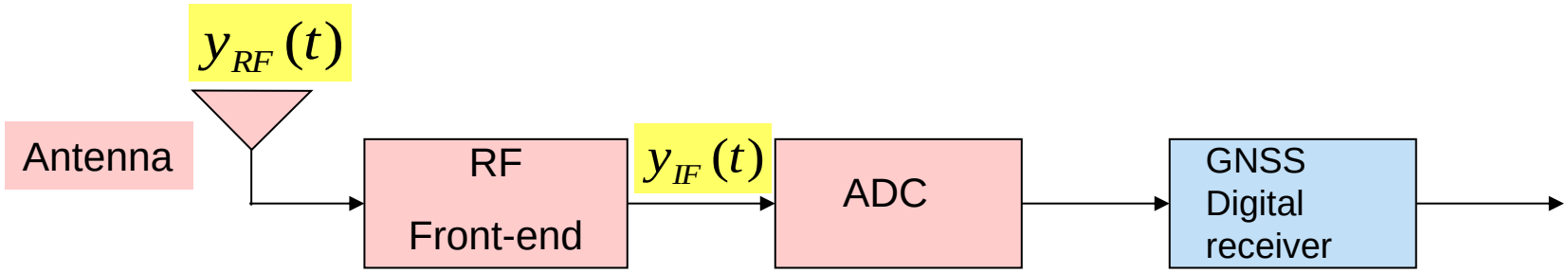
# The Hard Work of GNSS Receivers



# The Receiver Chain

Let us consider the SIS of a single SV (space vehicle)

SIS (Signal in Space)



# GNSS Receiver Operations

1 **Sky search** — Search for IDs of visible satellites

2 **Acquisition** — Code delay and Doppler estimates, rough alignment of code and carrier

3 **Tracking** — Refines code and carrier alignment

4 **Measurements** — Pseudorange and data demodulation

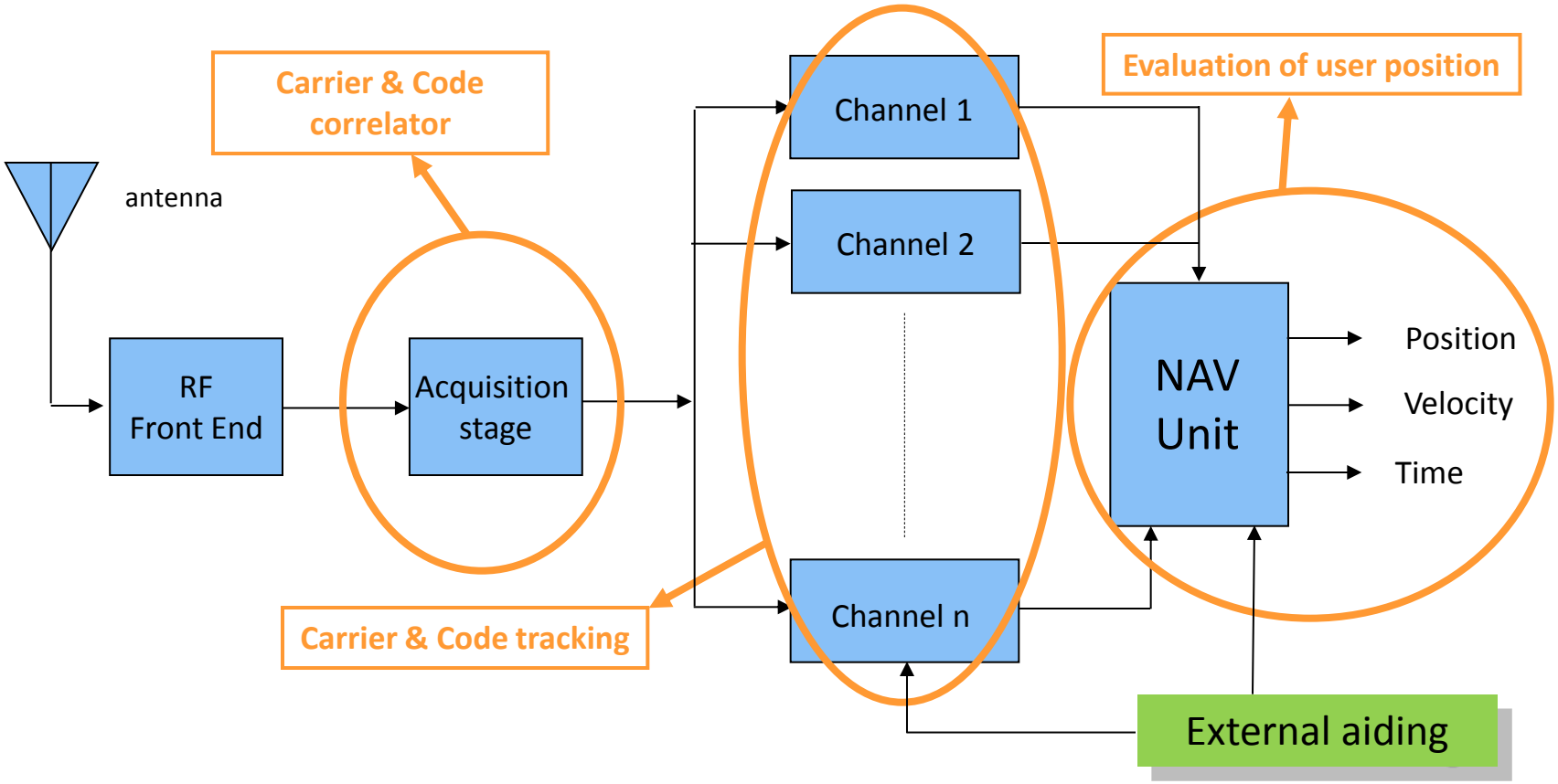
# GNSS Receiver Operations

5 **Computation** — Usually the PVT

6 **Integration with external info** — Not present in all receivers

7 **HMI** — Not present in all receivers

# GNSS Receiver Functionalities



# Receiver Performance

Receivers Classes

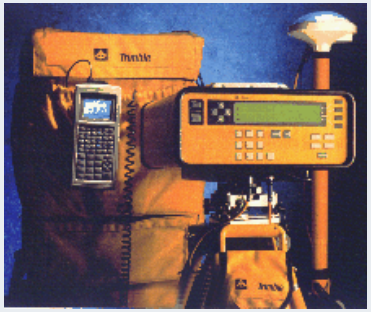
Receivers Specifications

# Receivers Classes

| | Description | Device Price [€] |
|---|---|---|
|  | Handheld receivers for hikers and sailors. Small size with latitude-longitude displays and maps. | 100 - 600 |
|  | Integrated GPS in mobile phones. Low cost and single frequency. | 50-600 |
|  | Maritime navigators. Fixed mount, large screens with electronics chart | 100-3000 |
|  | In-car navigation systems. Detailed street maps and turn-by-turn directions. These systems can be also handheld (e.g. PDA) | 100-2000 |

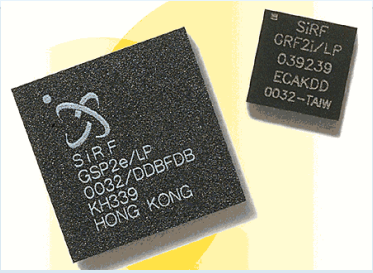
Price differences are due to reason independent from the embedded GNSS chip

# Receivers Classes

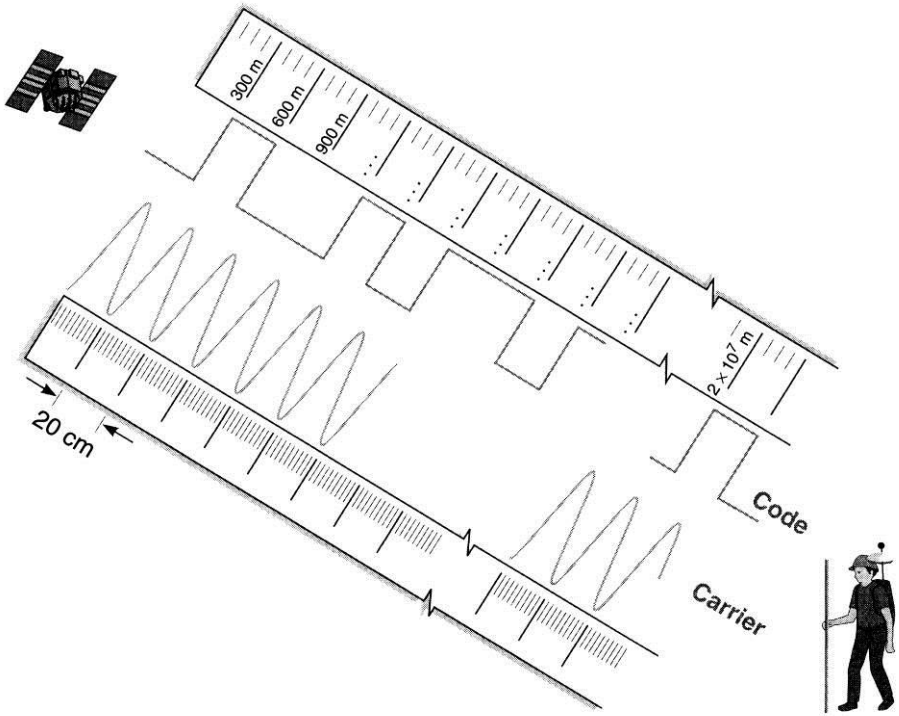
| | Description | Approx. Price [€] |
|---|---|---|
|  | Aviation receivers. FAA and EUROCONTROL certified, panel mounted with maps.<br><br>**INTEGRITY REQUIRED !** | >3000 |
|  | Survey and mapping professional receivers. Multi-frequency and differential GPS, centimeter accuracy | 1500 – 30000 |

Price differences are due to reason independent from the embedded GNSS chip

# GNSS Modules

| | Description | Approx. Price [€] |
|---|---|---|
|  | Plug-in modules.<br>Integrated receivers and antenna.<br>Employed in tracking systems | 30 – 700 |
|   | OEM boards.<br>Employed for integration in other complex systems. | 100 – 5000 |
|   | Chip sets.<br>Employed for integration, but all the circuitry is needed | 1 – 30 |

# Professional vs Mass-Market Receivers




Carrier Phase
vs
Code Phase?

Raw measurements availability and configurability

Configurability

DGNSS … RTK

# Receivers Classification: Market Segment

| Category | Receiver Characteristics |
|---|---|
| Consumer | Single frequency, cost driven, high volume, moderate performance, also multi constellation |
| Light Professional | Single frequency, multi constellation, cost driven, low volume, good performance, integration with external devices, professional features |
| Professional | Multi frequency, multi constellation, cost/requirements driven, low volume, high performance, advanced processing algorithms |
| Safety of Life | Double/ Multi frequency, multi constellation, requirements driven, low volume, high performance, high reliability, **integrity**, **certification** |
| P R S | Double frequency, low volume, high performance, high reliability, requirements driven, integrity, advanced processing algorithms |

# GNSS RX Features

- Constellation exploited
- Military or civil receiver
- PVT update rate
- Indoor operations or high multipath environment
- Interference mitigation
- Dynamic conditions (static or high dynamic)
- DGPS or WAAS/EGNOS capability (RTK input/ output)
- Storage of log data
- Shock and vibration tolerance
- Cartographic support
- INS integration or dead-reckoning systems
- Integration with COM systems
- Portability
- Usability
- Power consumption
- Cost

# Example of Technical Specification (1)

## Septentrio PolaRx4 PRO

- 264 hardware channels
- TRACK+: Septentrio's low-noise tracking algorithms,
- GPS L1/L2/L2C/L5,
- GLONASS L1/L2
- Galileo E1, E5a, E5b, E5 AltBOC and
- GLONASS CDMA L3
- experimental tracking of Beidou signals
- AIM+: Advanced Interference Monitoring and Mitigation
- APME+: extends Septentrio's patented A Posteriori Multipath Estimator to GLONASS, Galileo and Beidou signals
- ATrack+: is Septentrio's patented Galileo AltBOC tracking.

# Example of Technical Specification (2)

## Septentrio PolaRx4 PRO

| Pseudorange noise (not smoothed) | | Carrier Phase | |
|---|---|---|---|
| GPS L1 C/A | 16 cm | L1/E1 | <1 mm |
| GLONASS L1 open | 25 cm | L2 | 1 mm |
| Galileo E1 B/C | 8 cm | L5/E5 | 1.3 mm |
| Galileo E5 A/B | 6 cm | **Doppler** | |
| Galileo E5 AltBOC | 1.5 cm | L1/L2/L5 | 0.1 Hz |
| GPS L2 P(Y) | 10cm | | |
| GLONASS L2 (mil) | 10m | | |

# Example of Technical Specification (3)

## NovAtel 628

- 120 hardware channels
- GPS L1 L2 L2C L5
- GLONASS L1 L2
- Galileo E5a E5b E5 AltBOC
- Beidou B1 B2
- QZSS
- L-Band
- RT-2 (RTK algorithm)
- Pulse Aperture Correlator (PAC) multipath mitigation technology
- SPAN INS integration technology
- …

# Example of Technical Specification (4)

## NovAtel 628

| Pseudorange noise (not smoothed) | | Carrier Phase | |
|---|---|---|---|
| GPS L1 C/A | 4 cm | L1 GPS | 0.5 mm |
| GLONASS L1 open | 8 cm | L1 GLONASS | 1 mm |
| GPS L2 P(Y) | 8 cm | L2 | 1 mm |
| GPS L2C | 8 cm | L2C | 0.5 mm |
| GPS L5 | 3 cm | L5 | 0.5 mm |
| GLONASS L2 open | 8cm | | |
| GLONASS L2 mil | 8 cm | | |

# Example of Technical Specification (5)

## NovAtel 628

| Position Accuracy (RMS) | | Signal Reacquisition | |
|---|---|---|---|
| Single point L1 | 1.5 m | L1 | <0.5 s (typical) |
| Single point L1/L2 | 1.2 m | L2 | <1.0 s (typical) |
| SBAS (GPS) | 0.6 m | **Maximum Data Rate** | |
| DGPS | 0.4 m | Measurements | 100 Hz (20 SV) |
| L-band VBS | 0.6 m | Positions | 100 Hz (20 SV) |
| L-band XS | 15 cm | **Vibration** | |
| L-band HP | 10 cm | Random vibe | MIL-STD 810G (Cat 24, 7.7 g RMS) |
| RT-2 | 1 cm + 1ppm (BL) | Sine vibe | IEC 60068-2-6 |

# Receiver Output

The typical output from a GNSS receiver comes in two kind of formats:

- Proprietary binary
- NMEA (National Marine Electronics Association)

while the specific binary protocol for differential correction is the RTCM (Radio Technical Commission for Maritime services).

The RINEX (Receiver INdependent EXchange) format is textual an commonly used to log low level data (pseudorange measurement instead of positions) coming from professional receiver in order to enable data post-processing.

NMEA protocol can be considered universal even if can carry less information with respect to proprietary protocols. It is used by mass-market receiver.

# NMEA Format

- Maintained by the National Marine Electronics Association
- NMEA format is supported by several types of instruments (other than GNSS)
- NMEA enabled devices are designed as either talker or listener (or both)
- NMEA messages are ASCII strings. Logs are .txt files
- There is a set of standard messages for each type of instruments (Loran C, GPS, Integrated Instruments etc.)

# NMEA Sentences

- All data is transmitted in form of sentences
- Only printable ASCII characters are allowed, with exception for
  - carriage return (<CR>)
  - line feed (<LF>)
- Each sentence
  - starts with $
  - ends with <CR><LF>
- Three kind of sentences:
  - **talker**: data fields are defined for each sentence type, a sentence may contain up to 80 characters plus $, <CR>,<LF>
  - **query**: to be sent to the receiver in order to obtain specific information
  - **proprietary**: start with $P, user defined, constraints hold

# GPS NMEA

**NMEA GPS related messages are identified by the talker identifier GP**

Example: GPGGA Global Positioning System Fix Data.
Time, Position and fix related data for a GPS receiver

**$GPGGA,125455,4503.9174,N,00739.5418,E,2,06,1.7,270.9,M,48.3,M,0,1023*77**

**GP**= GPS device **GGA** format type

**Time** = 12h, 54 min, 55 sec (UTC)

**Latitude** = 45°3.9174’ North; **Longitude** = 7°39.5418’ East; Precision (1-4): 2;

number of satellites: 6; PDOP: 1.7;

**Altitude**: 270.9 meters; Geoidal separation: 48.3 meters;

Time since last DGPS update: 0; Station ID: 1023; Checksum: 77 hex

# GPS NMEA

Other messages:

- **$GPRMB**: Recommended minimum navigation info
- **$GPGSA**: GPS DOP and active satellites
- **$GPGLL**: Geographic Position (Lat/Lon)
- **$GPGSV**: Satellites in view
- **$GPRTE**: Routes
- …

# NMEA example

```
$GPGGA,092750.000,5321.6802,N,00630.3372,W,1,8,1.03,61.7,M,55.2,M,,*76
$GPGSA,A,3,10,07,05,02,29,04,08,13,,,,,1.72,1.03,1.38*0A
$GPGSV,3,1,11,10,63,137,17,07,61,098,15,05,59,290,20,08,54,157,30*70
$GPGSV,3,2,11,02,39,223,19,13,28,070,17,26,23,252,,04,14,186,14*79
$GPGSV,3,3,11,29,09,301,24,16,09,020,,36,,,*76
$GPRMC,092750.000,A,5321.6802,N,00630.3372,W,0.02,31.66,280511,,,A*43
$GPGGA,092751.000,5321.6802,N,00630.3371,W,1,8,1.03,61.7,M,55.3,M,,*75
$GPGSA,A,3,10,07,05,02,29,04,08,13,,,,,1.72,1.03,1.38*0A
$GPGSV,3,1,11,10,63,137,17,07,61,098,15,05,59,290,20,08,54,157,30*70
$GPGSV,3,2,11,02,39,223,16,13,28,070,17,26,23,252,,04,14,186,15*77
$GPGSV,3,3,11,29,09,301,24,16,09,020,,36,,,*76
$GPRMC,092751.000,A,5321.6802,N,00630.3371,W,0.06,31.66,280511,,,A*45
```

duration 1s

# RINEX File Example

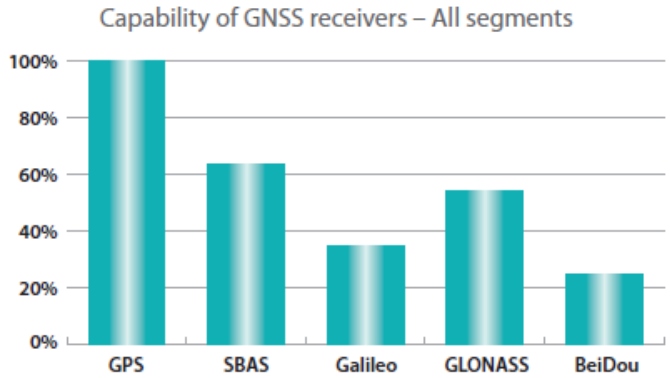
```
----|---1|0---|---2|0---|---3|0---|---4|0---|---5|0---|---6|0---|---7|0---|---8|0-

     3.00           OBSERVATION DATA    M                   RINEX VERSION / TYPE
G = GPS  R = GLONASS  E = GALILEO  S = GEO  M = MIXED        COMMENT
XXRINEXO V9.9       AIUB                20060324 144333 UTC PGM / RUN BY / DATE
EXAMPLE OF A MIXED RINEX FILE VERSIOIN 3.00                 COMMENT
The file contains L1 pseudorange and phase data of the      COMMENT
geostationary AOR-E satellite (PRN 120 = S20)               COMMENT
A 9080                                                      MARKER NAME
9080.1.34                                                   MARKER NUMBER
BILL SMITH          ABC INSTITUTE                           OBSERVER / AGENCY
X1234A123           GEODETIC            1.3.1               REC # / TYPE / VERS
G1234               ROVER                                   ANT # / TYPE
  4375274.       587466.      4589095.                      APPROX POSITION XYZ
         .9030         .0000         .0000                  ANTENNA: DELTA H/E/N
     0                                                      RCV CLOCK OFFS APPL
G    5 C1C L1W L2W C1W S2W                                  SYS / # / OBS TYPES
R    2 C1C L1C                                              SYS / # / OBS TYPES
E    2 L1B L5I                                              SYS / # / OBS TYPES
S    2 C1C L1C                                              SYS / # / OBS TYPES
    18.000                                                  INTERVAL
G APPL_DCB          xyz.uvw.abc//pub/dcb_gps.dat            SYS / DCBS APPLIED
DBHZ                                                        SIGNAL STRENGTH UNIT
  2006    03    24    13    10   36.0000000     GPS         TIME OF FIRST OBS
                                                            END OF HEADER
> 2006 03 24 13 10 36.0000000  0  5      -0.123456789012
G06  23629347.915            .300 8         -.353 4  23629347.158         24.158
G09  20891534.648           -.120 9         -.358 6  20891545.292         38.123
G12  20607600.189           -.430 9          .394 5  20607600.848         35.234
E11          .324 8          .178 7
S20  38137559.506      335849.135 9
```

file header

measurement for 1st epoch (1s)

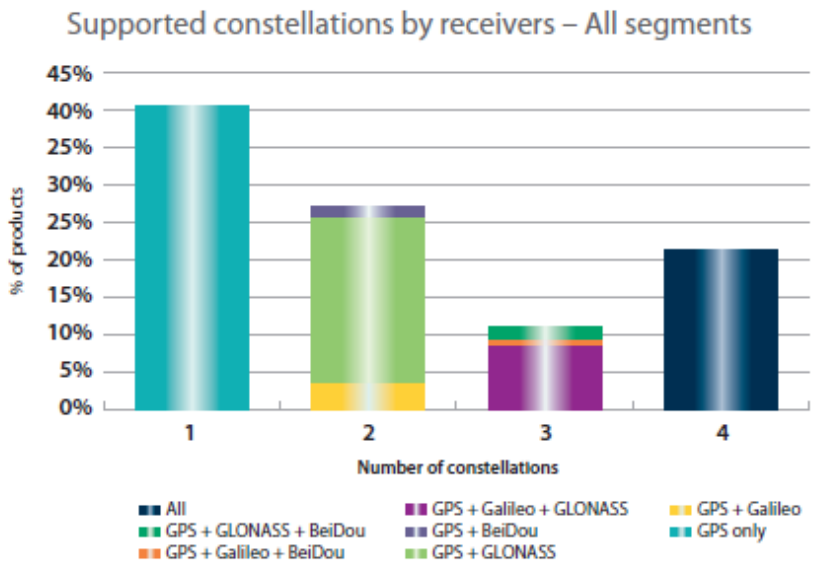
continuing…

# GNSS Receivers Capability




* Analysed manufacturers: CSR, Furuno, Hemisphere GNSS, Japan Radio Co., Leica Geosystems AG, Mediatek, NavCom Technology, Nottingham Scientific Ltd, NovAtel, Orolia, Septentrio, STMicroelectronics, Topcon, Trimble, U-blox, Avidyne, Broadcom, Esterline, Garmin, Honeywell, Infineon, Intel, John Deere, Kongsberg, Omnicom, Qualcomm, Rockwell Collins, SkyTraq Technology, Texas Instruments, THALES Avionics, Universal Aviation.

** Please note that the capability of GNSS devices presented in Market Report Issue 3 cannot be compared with the ones from the current edition due to different group of manufacturers used in the analysis.




GNSS Market Report 2015 - GSA

# Table of Content

EGNSS Principles

# EGNSS - Galileo

- Initiative of the European Union (EU) and the European Space Agency (ESA), in collaboration with European Industries
- Galileo is a **civil system under civil control**
- Military applications are not the main objective of the system
- Galileo offers **guaranteed services**
- Galileo is **compatible** and **interoperable** with GPS
- Galileo is open to **international cooperation**

# Why Galileo ?

The European point of view

**Economical**

- New job opportunities
- Foster competitiveness of European industry
- Gain global market shares

**Political**

- Independence
- Civil system
- Industrial policy

**Social**

- More efficient and new services for citizens
- Environmental benefits
- Development

**Technological**

- Promote European research in GNSS
- Achieve better performance

# Galileo Aims

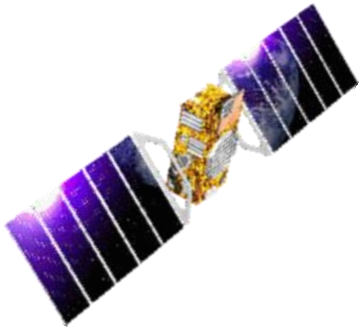
- To provide **wider range of services** to navigation users
- To promote **open markets** by facilitating the growth in trade of goods and services
- To provide a system **compatible** with existing GPS
- To **improve the global satellite navigation infrastructure** by providing an additional up to date system enabling more continuous, robust, and precise service for civilian users worldwide
- To provide an **alternative** to existing GNSS

# Galileo Adds-on

| | |
|---|---|
| Precision | • Improved by new modulation schemes |
| Availability | • Improved by specific orbit design * |
| Coverage | • Improved by specific orbit design * |
| Reliability | • Improved by Authentication service (CS) |
| Accuracy | • Improved by High Accuracy service (CS) |

* advantage also by multi constellation

# Galileo Implementation Plan

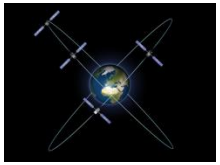


Galileo System Testbed v1
Validation of critical algorithms
2003

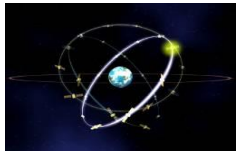
GALILEO
GSTB-V1

GIOVE A/B
2 test satellites
2005/2008

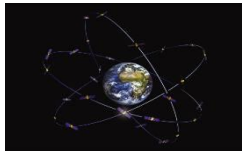
GALILEO
GIOVE



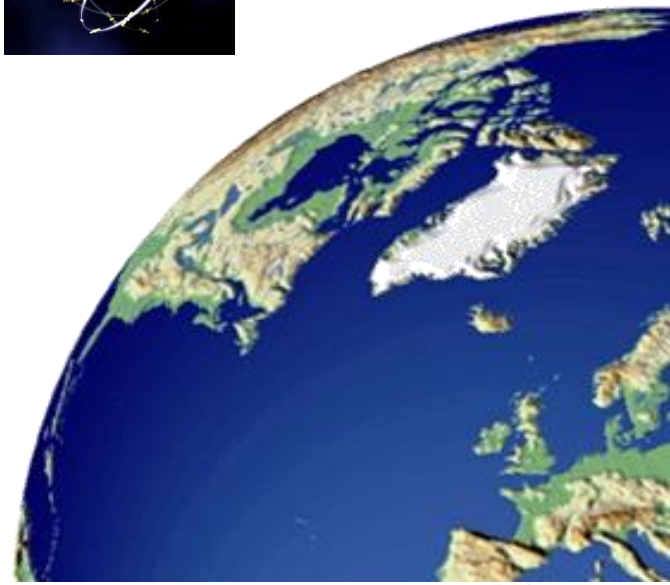
In-Orbit Validation
4 fully operational satellites
and ground segment
2013



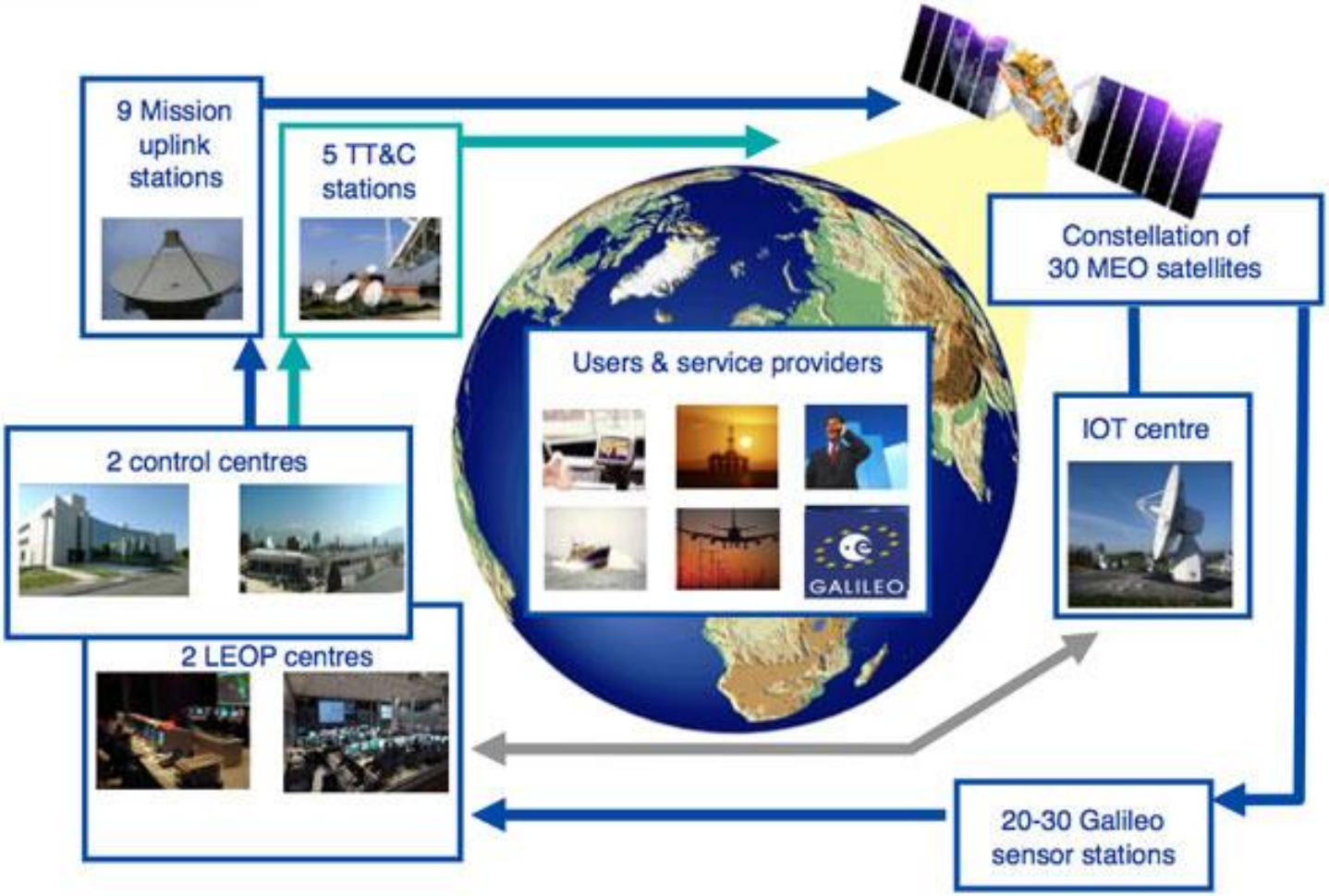
Initial Operational Capability
Early services for OS, SAR,
PRS
2015/2016



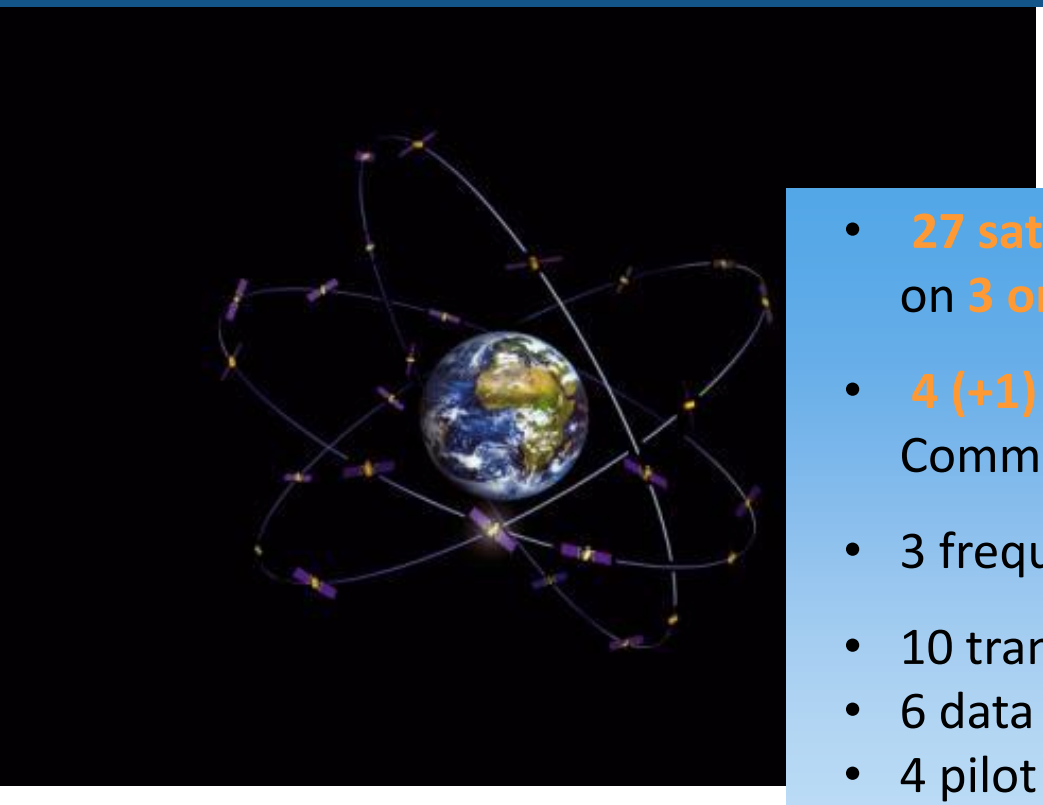
Full Operational Capability
Full services, 30 satellites
2020



# Galileo at a Glance

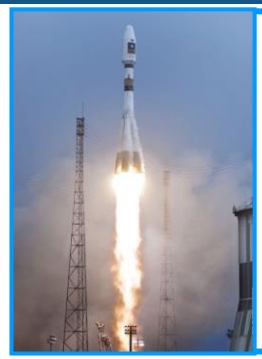


# Galileo at a Glance

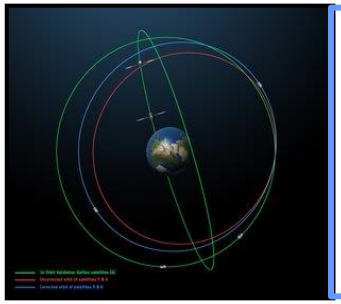


- **27 satellites** (and 3 spare ones) at 23222 km on **3 orbital planes**
- **4 (+1) services**: Open, Public Regulated, Commercial, Search&Rescue (+ SOL)
- 3 frequency **bands** (E5, E6 and E1)
- 10 transmitted **signals**
- 6 data channels (carrying data bits)
- 4 pilot channels (data-free)
- **Reference Frame**: within 3 cm w.r.t. ITRF96

# Galileo is Taking Off



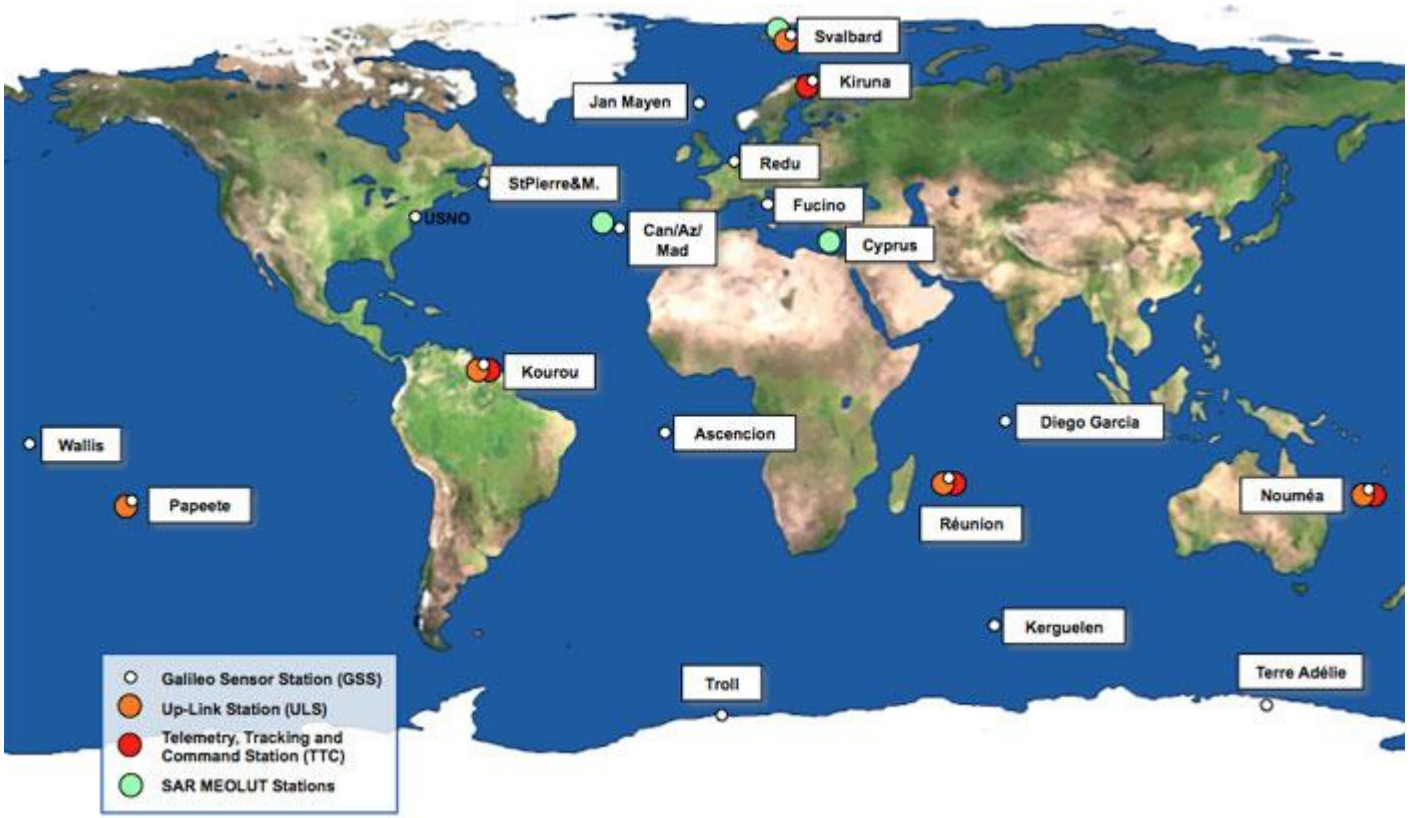
- First two **IOV operational satellites** launched on 21st October 2011
- Third and fourth Galileo satellites, completing the IOV **quartet**, launched on 12 October 2012
- On 12 March 2013, the first ever **position fix using only Galileo satellites and ground segment** was achieved.



- First two **FOC satellites** launched on 22nd August 2014
- Injection anomaly – lower and elliptical orbits
- By 13th March 2015, both sat moved to **corrected orbits** with repeat pattern of 20 days

- Two FOC **satellites** launched on 27th April 2015
- Galileo 7 & 8 satellites reached their orbit
- Current Galileo constellation: 4 IOV + 2 FOC + 2 FOC in corrected orbit

# Galileo Ground Segment



# Galileo Services

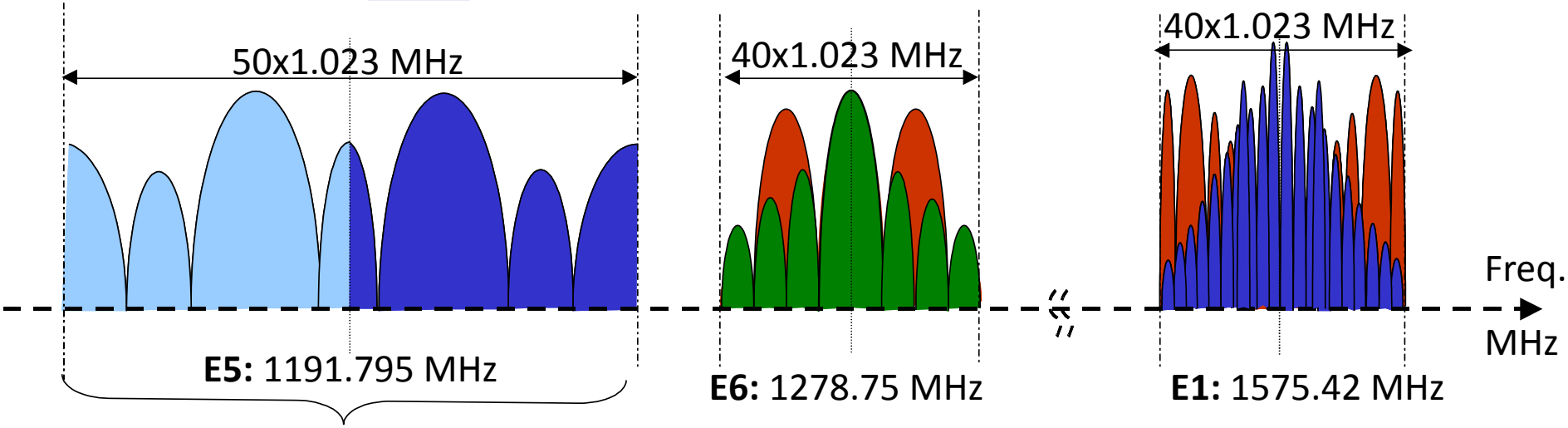
| | | |
|---|---|---|
| **Open Service (OS)** | Freely accessible service for positioning, navigation and timing |  |
| **Public Regulated Service (PRS)** | Encrypted service designed for greater robustness and higher availability |  |
| **Search and Rescue Service (SAR)** | Assists locating people in distress and confirms that help is on the way |  |
| **Commercial Service (CS)** | Delivers authentication and high accuracy services for commercial applications |  |

The former "Safety-of-Life" service is being re-profiled:

| | | |
|---|---|---|
| **Integrity Monitoring Service** | Provides vital integrity information for life-critical applications |  |

# Galileo Signals and Mapping to Services

| E5A Data+Pilot | E5B Data+Pilot | E6A | E6B-C | E1A | E1B-C |
|---|---|---|---|---|---|
| QPSK-like mod. | QPSK-like mod. | $BOC_{cos}(10,5)$ | BPSK(5) | $BOC_{cos}(15,2.5)$ | CBOC(6,1,1/11) |
| Rc = 10.23Mcps | Rc = 10.23Mcps | Rc = 5.115 | Rc = 5.115 | Rc = 2.5575 | Rc = 1.023 |
| Rs = 50 Mcps | Rs = 250 Mcps | Rs = - | Rs = 1000 | Rs = - | Rs = 250 |
| **Open Service** | **OS/CS** | **PRS** | **CS** | **PRS** | **OS/CS** |




AltBOC (15,10) mod.

CASM mod.

CASM mod.

# List of Galileo Satellites Tracked with NGene2 Navigation Software Receiver

- **NGene2** is a navigation fully software receiver developed by **NavSAS**: a ISMB – Politecnico di Torino joint research group.

| $SV_{ID}$ | Name | Launch date | Acquisition and Tracking | Used in PVT |
|---|---|---|---|---|
| 11 | Galileo-IOV PFM (*Thijs*) | 21/10/2011 | ✓ | ✓ |
| 12 | Galileo-IOV FM2 (*Natalia*) | 21/10/2011 | ✓ | ✓ |
| 19 | Galileo-IOV FM3 (*David*) | 12/10/2012 | ✓ | ✓ |
| 20 | Galileo-IOV FM4 (*Sif*) | 12/10/2012 | ✓ | ✓ |
| 18 | Galileo-FOC FM1 (*Doresa*) | 22/08/2014 | ✓ | * |
| 14 | Galileo-FOC FM2 (*Milena*) | 22/08/2014 | ✓ | * |
| 26 | Galileo-FOC FM3 (*Adam*) | 27/03/2015 | ✓ | * |
| 22 | Galileo-FOC FM4 (*Anastasia*) | 27/03/2015 | ✓ | * |

* Dummy navigation message

# Table of Content

EGNSS Principles

# Positioning Errors

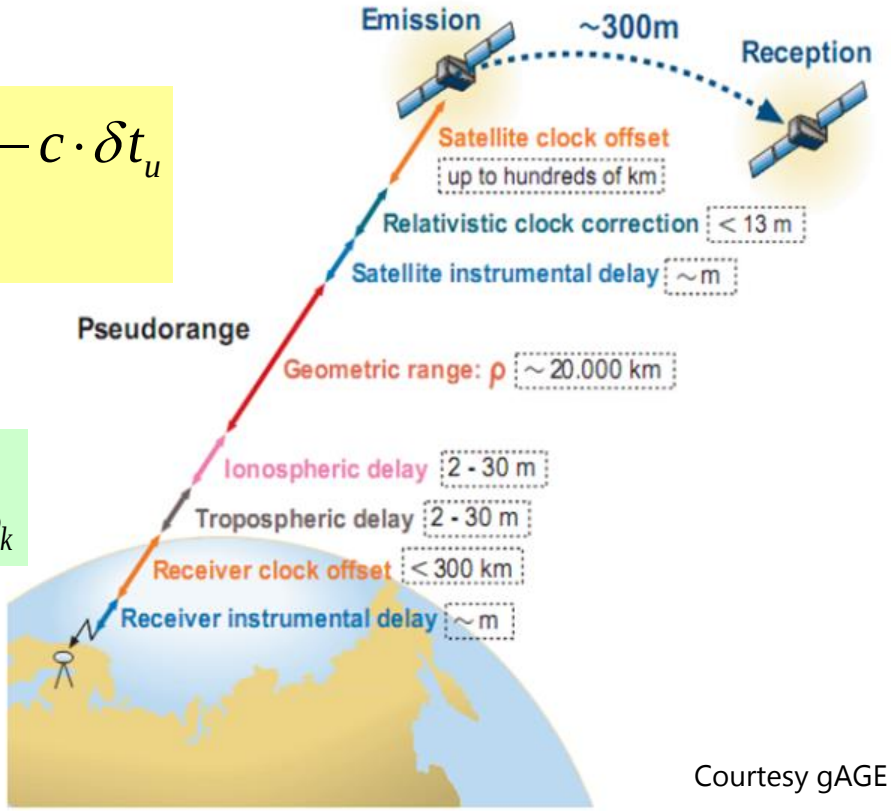
Ideal measured pseudorange

$$\rho_k = \sqrt{(x_k - x_u)^2 + (y_k - y_u)^2 + (z_k - z_u)^2} - c \cdot \delta t_u$$
$$= \quad r_k - c \cdot \delta t_u$$

Other errors impact on the measurement

$$\rho_k = r_k + c \cdot (\delta t_k - \delta t_u) + I_{\rho_k} + T_{\rho_k} + \varepsilon_{\rho_k}$$

Part of these errors cannot compensated by the system. Only systematic/ averaged errors and those measured by the control segment can be taken into account.




Courtesy gAGE

# Differential GNSS

- Differential GPS (DGPS) aims to **mitigate some errors** afflicting the measurements performed by GPS (now GNSS) receivers

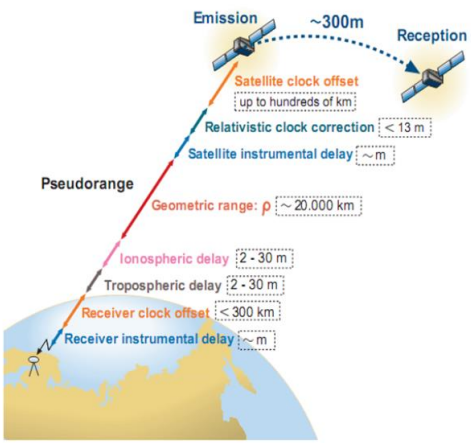
- **DGPS services enhances the performance of the current GNSS with additional information to:**
  - Improve **INTEGRITY** via real-time monitoring
  - Improve **ACCURACY** via differential corrections
  - Improve **AVAILABILITY** and **CONTINUITY**

- **Two groups:**
  - Local Area Augmentation Systems
    (or Ground Based Augmentation Systems)
  - Wide Area Augmentation Systems
    (or **Space Based Augmentation Systems**)

# Error Components (1)

The total error affecting the pseudorange measurement can be split in different components:

- **Satellite clock error**: the misalignment between satellite clock and GNSS time system
- **Satellite ephemeris error**: the error in the satellite position estimation
- **Ionospheric Delay**: the delay caused by the ionosphere on the signal due to the action of free electrons
- **Tropospheric Delay**: the delay introduced by the troposphere (humidity, temperature, pressure)
- **Multipath and Receiver noise**: local phenomenon



# Error Components (2)

Some among these error components are told to have a **high spatial correlation**: i.e. their effect varies slowly at location changes and two receivers not far apart experiments similar errors

- **Satellite clock errors** have the identical impact on each user
- **Ephemeris error** impacts varies slightly depending on the user position
- **Ionospheric and Tropospheric effects** are spatially correlated: a distance of several kilometers produces just small changes in pseudorange measurements.
- **Residual errors** are due to spatially uncorrelated sources of errors like noise, multipath or interference.

# Some Definitions

The following concepts are important to define the performances of a GNSS system in particular from the **safety** point of view

- **Availability**: ability of the system to perform its function at the initiation of the intended operation.
- **Continuity**: ability of the total system to perform its function without interruptions during the intended operation.
- **Accuracy**: degree of conformance between the computed user position and the true position.
- **Integrity**: ability of the system to provide timely warnings to users when it may not be used to navigate

# Satellite Based Augmentation Systems (SBAS)

The first SBAS to be conceived was the **American WAAS** developed by the Federal Aviation Administration to augment the GPS.

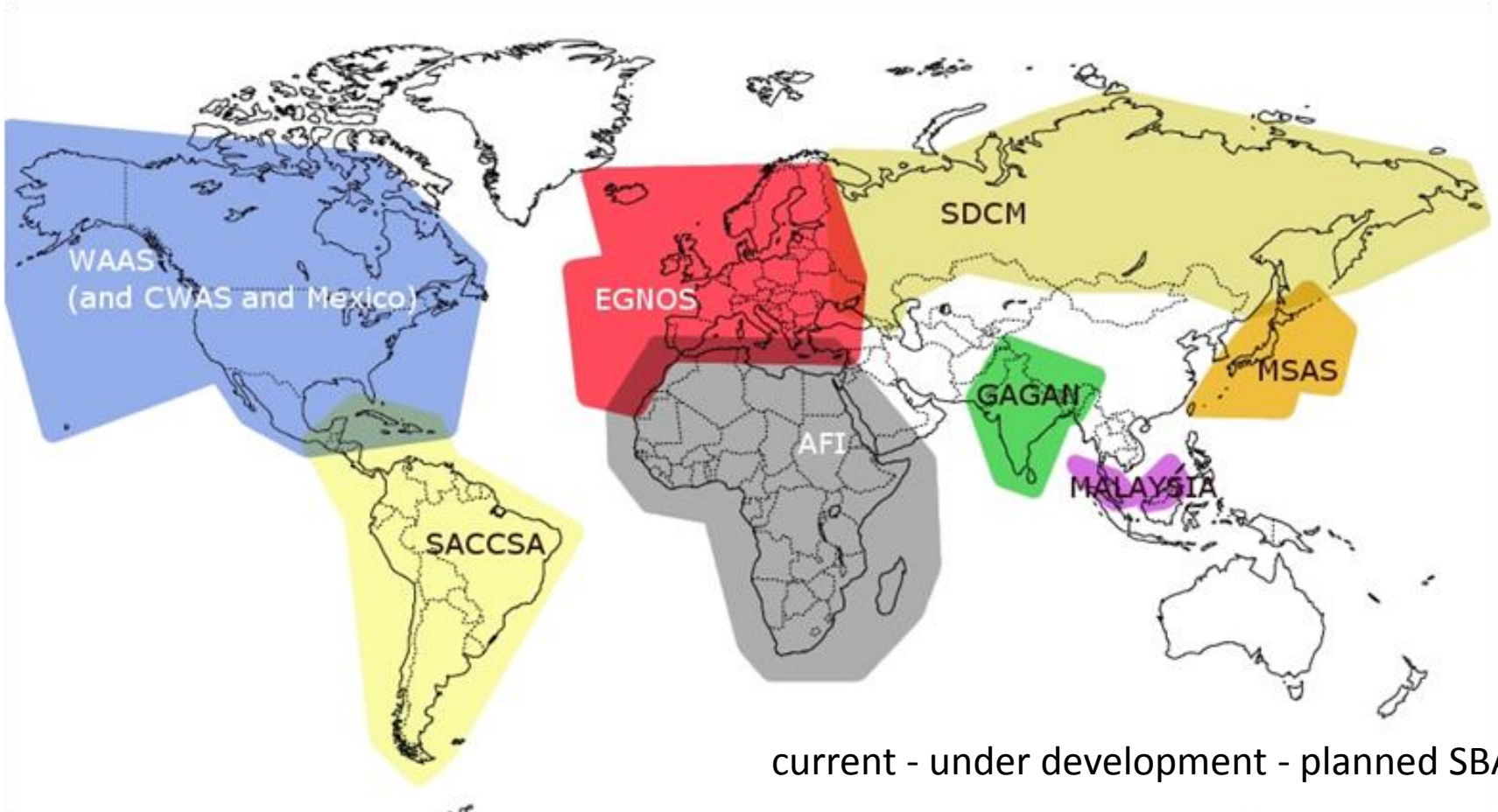
The goal was to **enable aircrafts to use GPS for all phases of flight**, from *en route* down to *precision approaches* to any airport within its coverage area.

This was achieved thanks to the **improvement of its accuracy, integrity, availability and continuity**.

RTCA DO-229 standard defines minimum performance, functions and features for SBAS-based sensors that provide position information to a multi-sensor system or separate navigation system.

**These standards are intended to be applicable to other SBAS providers**, such as European Geostationary Navigation Overlay Service (EGNOS) and Japan's Multi-functional Transport Satellite (MTSAT) Satellite-based Augmentation System (MSAS).

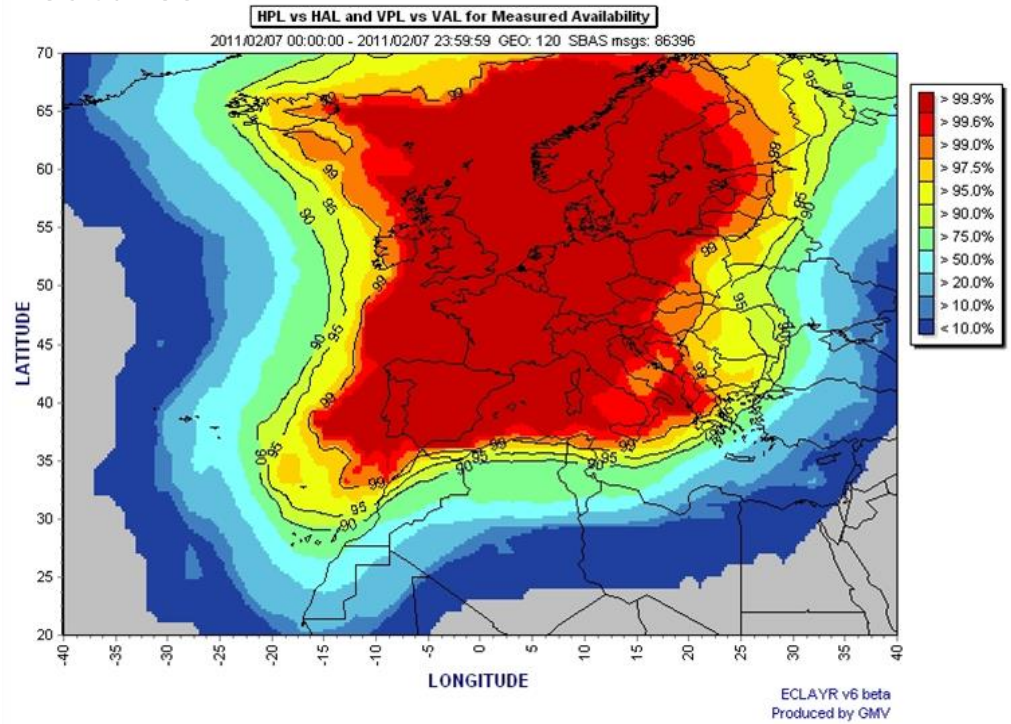
# Satellite Based Augmentation Systems



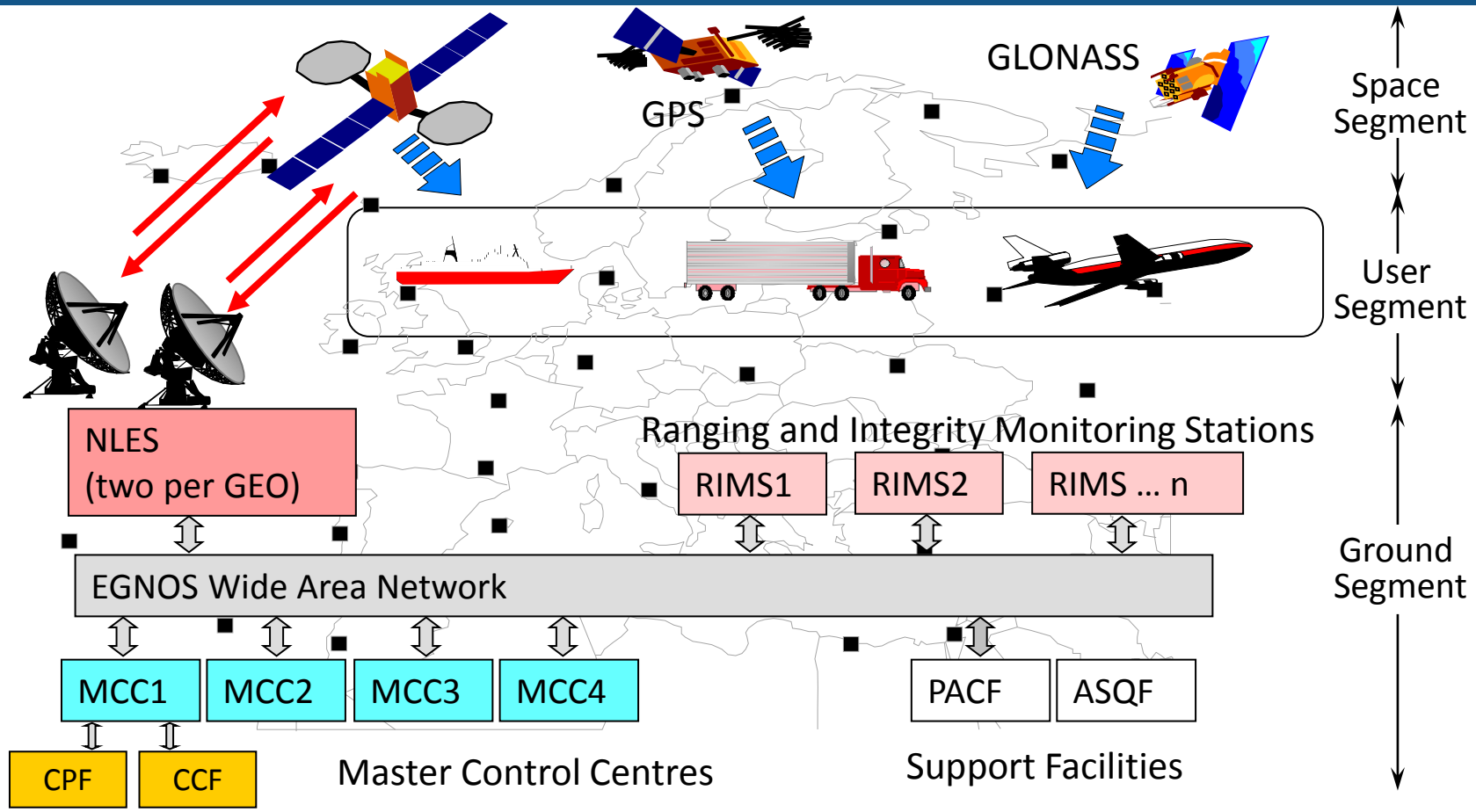

current - under development - planned SBAS

# EGNOS

- EGNOS had been implemented by EUROCONTROL, ESA, EC to increase the potentiality of GPS and GLONASS over the European continent.
- This is done thanks to three main features:
  - Wide Area Differential corrections
  - Integrity information
  - GPS-like ranging signals to increase the number of navigation satellites available (ranging-GEO function)
    It is no more supported due to poor advantages.



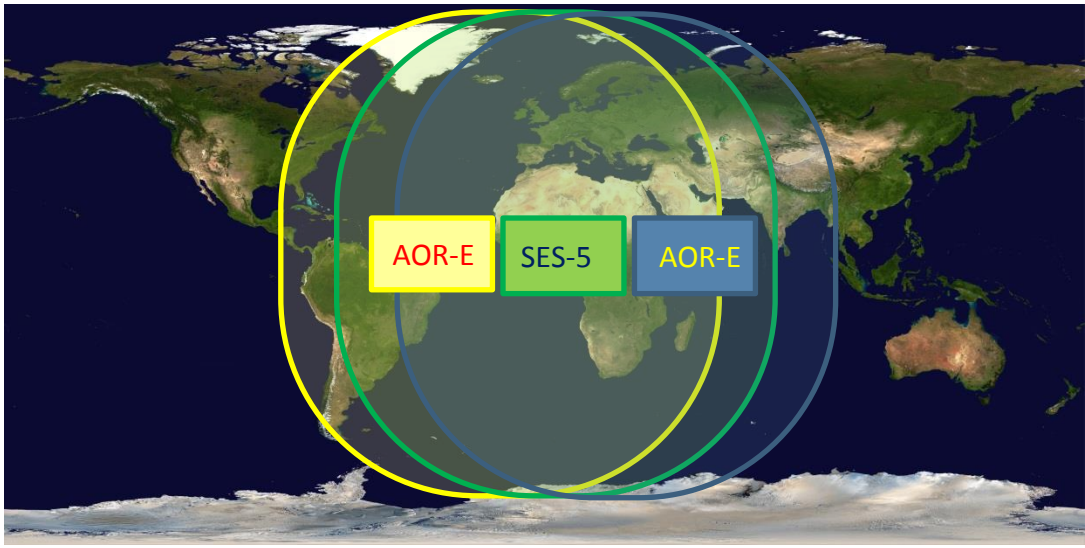
# System Architecture



# Space Segment

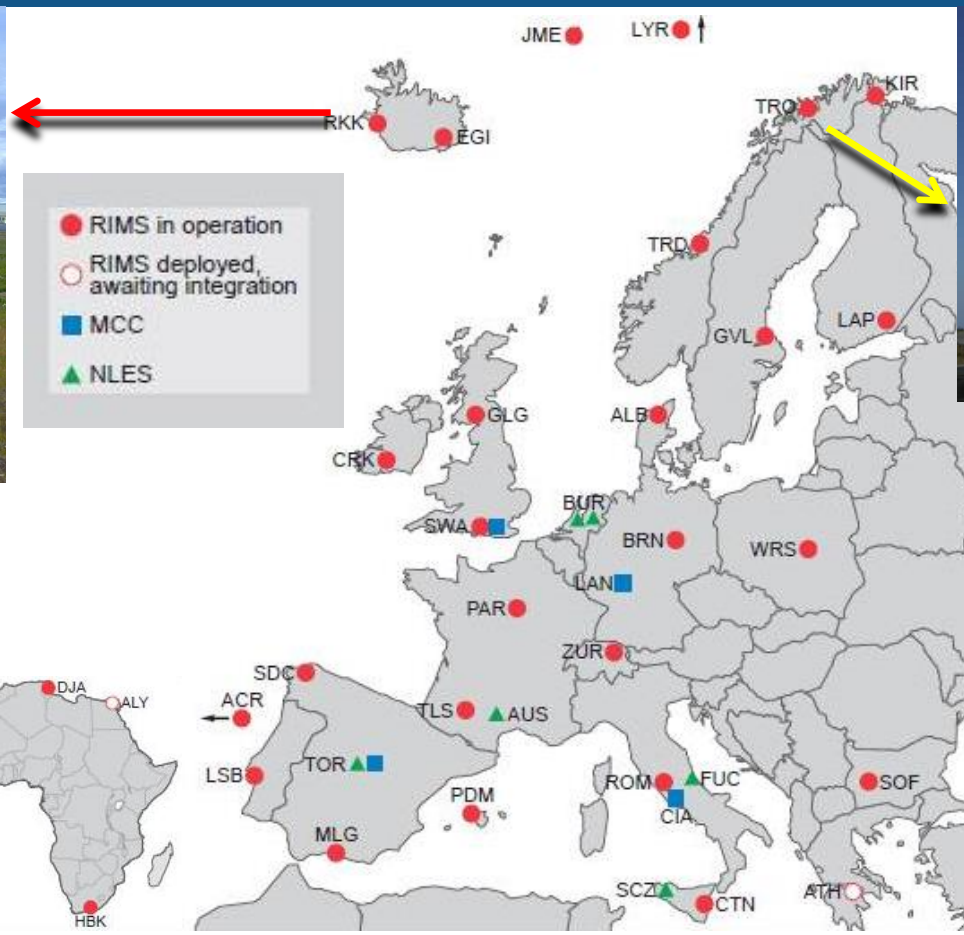
EGNOS data transmission primarily relies on three telecommunication geostationary satellites centred over Europe:

- Inmarsat-3 AOR-E (Atlantic Ocean Region East) stationed at 15.5° W. **PRN 120**
- Inmarsat-3 IOR-W (Indian Ocean Region West) stationed at 25.0°E. **PRN 126**
- SES-5 stationed at 5.2°E **PRN 136** under commissioning



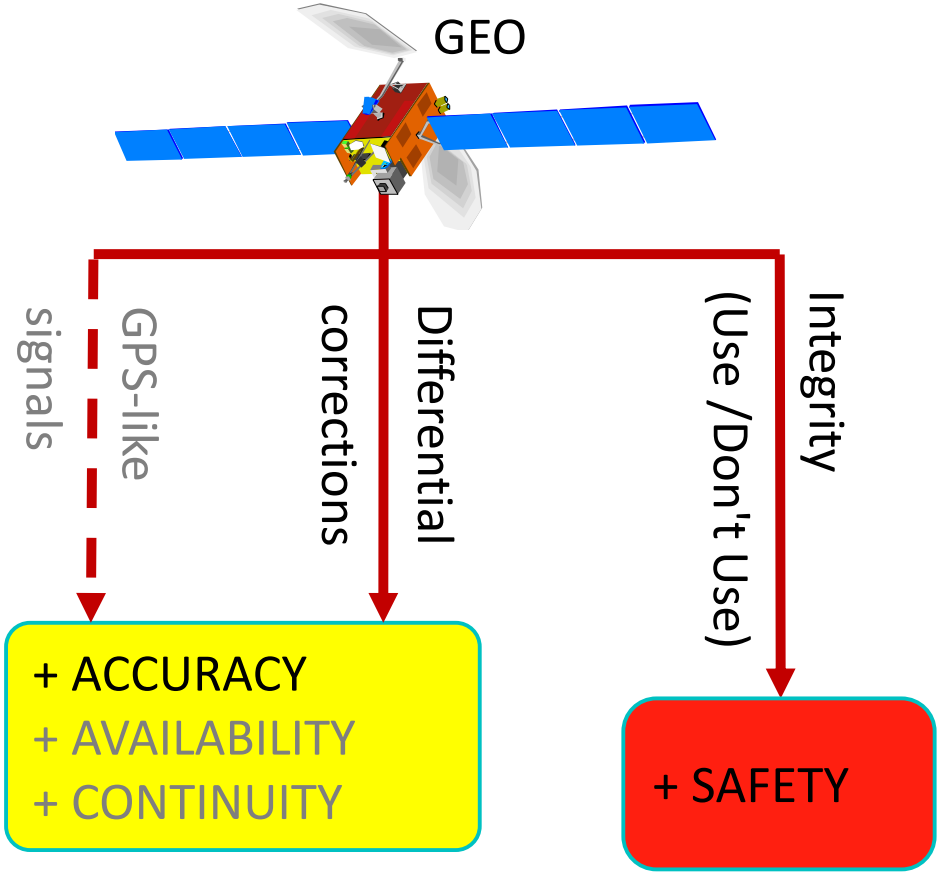
# RIMS


Reykjavik


RIMS in operation
RIMS deployed, awaiting integration
MCC
NLES
JME
LYR
KIR
TRO
RKK
EGI
TRD
GVL
LAP
GLG
ALB
CRK
BUR
SWA
BRN
WRS
LAN
PAR
ZUR
SDC
ACR
TLS
AUS
TOR
LSB
PDM
ROM
FUC
CIA
SOF
MLG
GOL
SCZ
CTN
ATH
MON
KOU
MAD
CNR
LPI
NOU
DJA
ALY
HBK


Trondheim

# Broadcast Information



# Table of Content

EGNSS Principles

# Galileo Services

- **Open Service (OS)**:
  - **Freely available service** for Mass-Market applications requiring simple positioning and no guarantee of service

- **Commercial Service (CS):**
  - It is for professional use requiring higher accuracy and it may offers a guaranteed service in return of a fee
    - broadcasting of supplementary data to foster *commercial applications*
    - signal *encryption/authentication*

# Galileo Services

- **Safety-of-Life (SoL) Service:**
  - Integrity service for transportation application
  - Recent official decision of re-profiling (descoping) as Integrity Monitoring Service

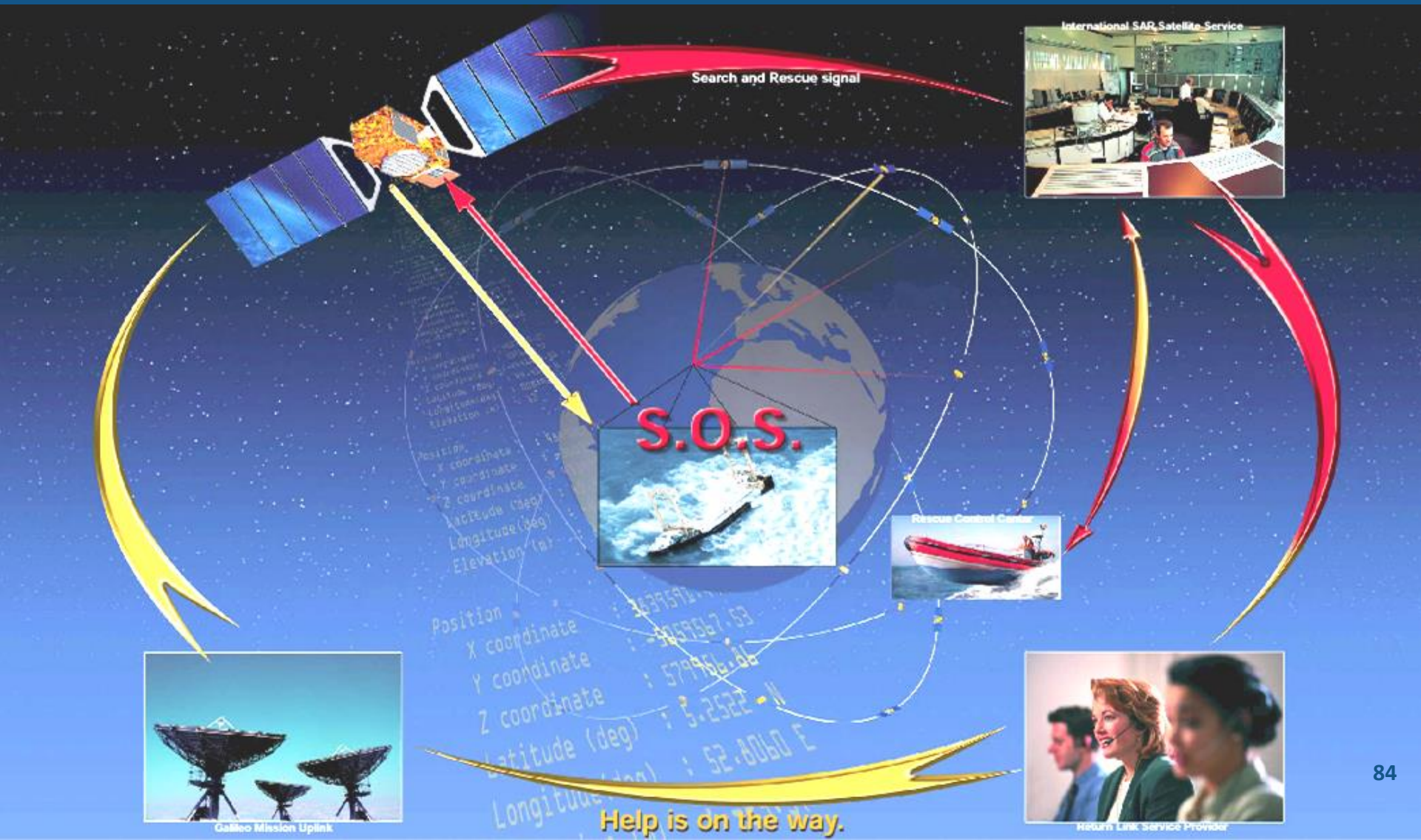
- **Search-And-Rescue (SAR) Service:**
  - Real-time detection of distress alarm
  - It is compatible with COSPAS-SARSAT
  - It needs a return link

- **Public Regulated Service (PRS):**
  - Reserved to government authorized-users only

# Galileo Services: Current Status

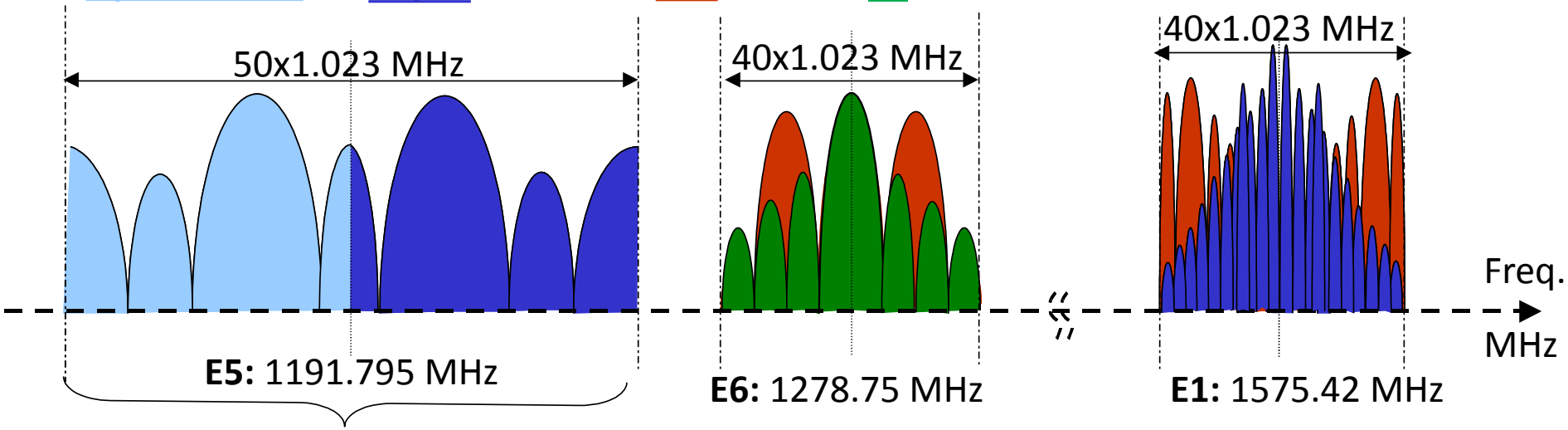
- Open Service: → available public documentation (ICD)
- Commercial Service: → under design
- Safety-of-Life Service: → being re-profiled
- Search-And-Rescue: → payload activated in Jan 2013
  (ground stations ready on October 2013)
- Public Regulated: → restricted ICD

# Galileo SAR:
# Instantaneous Localization with Communications



# Galileo Signals and Mapping to Services

| E5A Data+Pilot | E5B Data+Pilot | E6A | E6B-C | E1A | E1B-C |
|---|---|---|---|---|---|
| QPSK-like mod. | QPSK-like mod. | $BOC_{cos}(10,5)$ | BPSK(5) | $BOC_{cos}(15,2.5)$ | CBOC(6,1,1/11) |
| Rc = 10.23Mcps | Rc = 10.23Mcps | Rc = 5.115 | Rc = 5.115 | Rc = 2.5575 | Rc = 1.023 |
| Rs = 50 Mcps | Rs = 250 Mcps | Rs = - | Rs = 1000 | Rs = - | Rs = 250 |
| **Open Service** | **OS/CS** | **PRS** | **CS** | **PRS** | **OS/CS** |




AltBOC (15,10) mod.

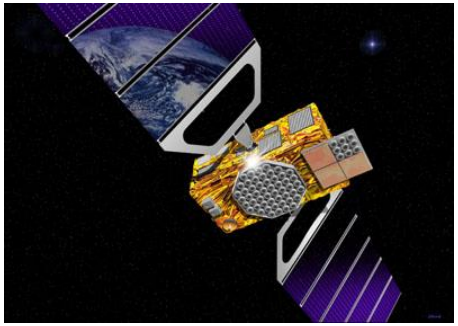
CASM mod.

CASM mod.

# Galileo and GPS

## US and EU Agreement in June 2004

- Adoption of a common signal for Galileo E1 and GPS III L1 open signals - BOC(1,1).
- Adoption of interoperable timing and geodesy standards to facilitate the joint use of Galileo and GPS
- Broadcast of GPS/Galileo time offset.
- Commitment to preserve National Security capabilities
- Non-restrictions of access to open service end-users



- **Interoperability**
- **Compatibility**

# Multi-GNSS Environment

Multi-GNSS environment → ? → System of Systems

More systems

More satellites

Better performance at user level?

# Compatibility and Interoperability

- **Compatibility** = ability of space-based PNT services to be used separately or together without interfering with each individual service or signal, and without adversely affecting national security

**First: Do not Harm**

- **Interoperability** = Combined use of two systems
  - Common center frequencies
  - Same Time Reference System
  - Same Coordinate Reference Frame

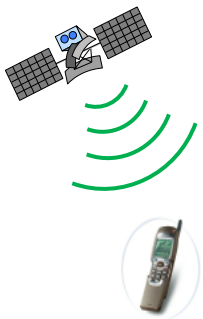
# Interoperability

Interoperability is the result of an **optimization process** and derives from weighted consideration of:

- Compatibility (without performance degradation)
- Simple user receiver design
- Market considerations
- Vulnerability (common failures)
- Independence
- Security

**COMPATIBILITY IS MANDATORY TO HAVE INTEROPERABILITY**

# Navigation Signal in Space



The signal broadcast by the navigation satellites must:

- Allow the user to **estimate the pseudorange** user-satellite
- Carry some **useful data**
- Be **robust** to the transmission through the atmosphere
- Identify in a **unique way** the satellites

**The SIS is characterised by:**

- Frequency Band
- Carrier Frequency
- Modulation Scheme
- Multiplexing Format
- Ranging Code
- Navigation Data Format
- Transmitted Power

Bands & Frequencies

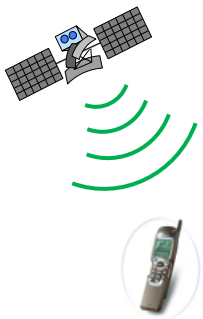
Modulation schemes

Multiplexing

Codes

Navigation Data

# Navigation Signal in Space



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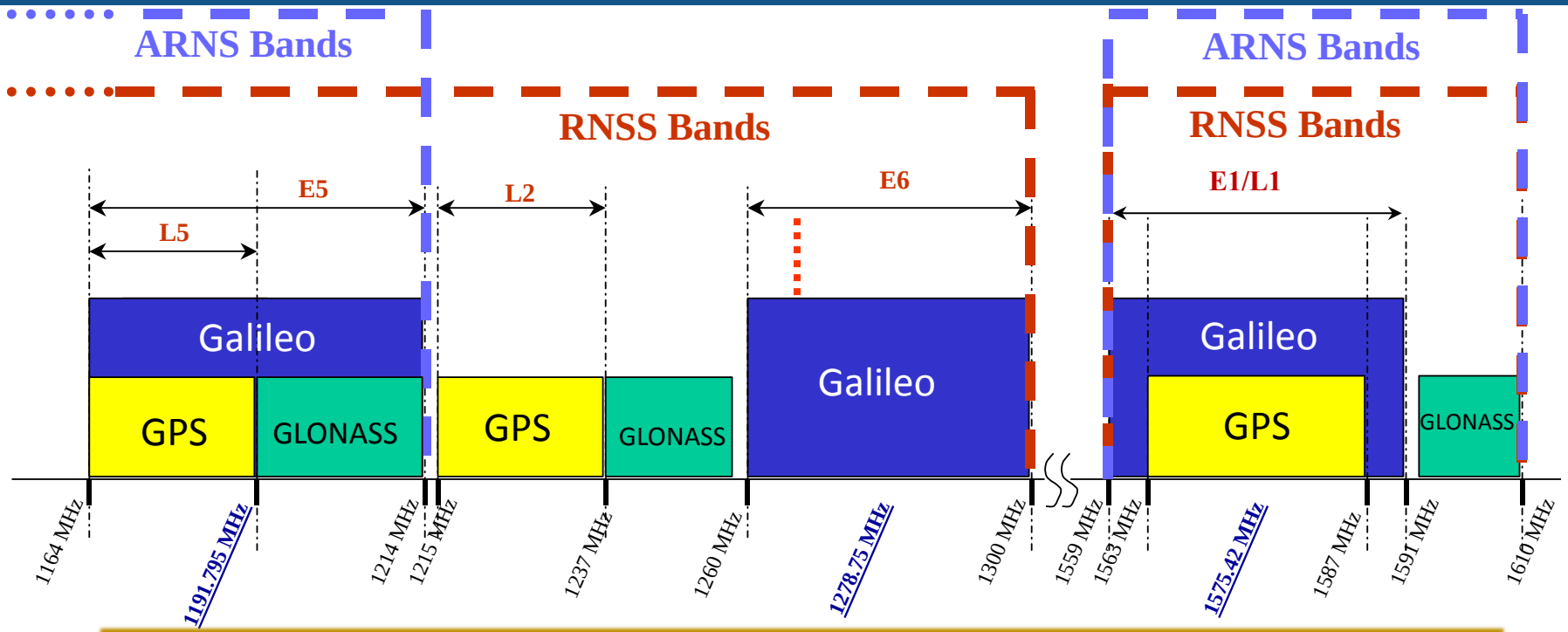
# Bands Allocation



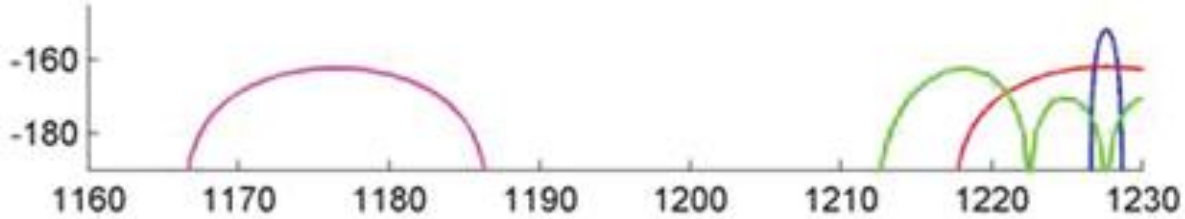

- At European level, **L1** band has been **renamed to E1 for Galileo**
- **E1/L1** and **E5a/L5** are common to GPS bands for **interoperability**

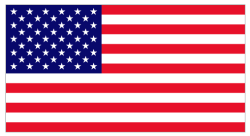
**ARNS: Aeronautical Radio Navigation Service**

**RNSS: Radio Navigation Satellite Services**

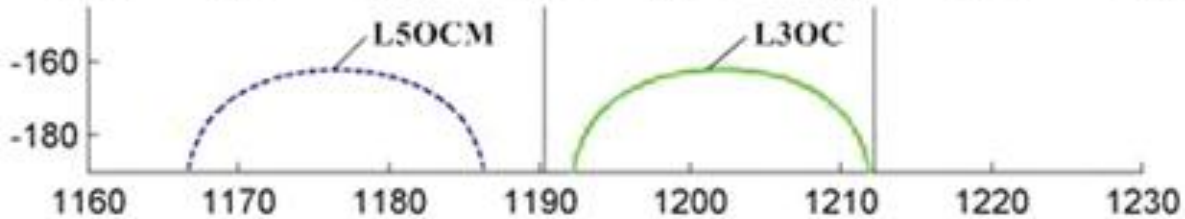
# GNSS Signals in L5 (E5)

**GPS**

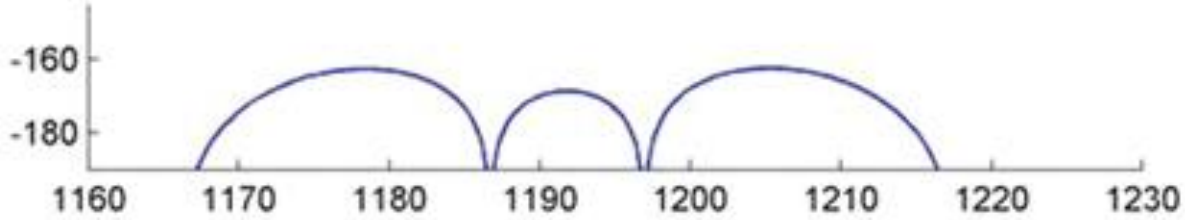


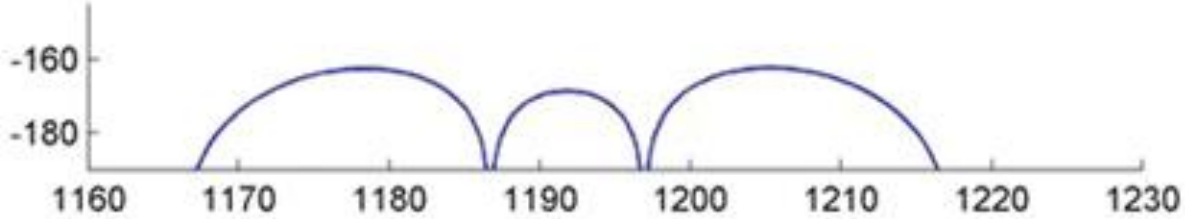
**GLONASS CDMA**




**GALILEO**




**COMPASS**




# GNSS Signals in L2 (E6)

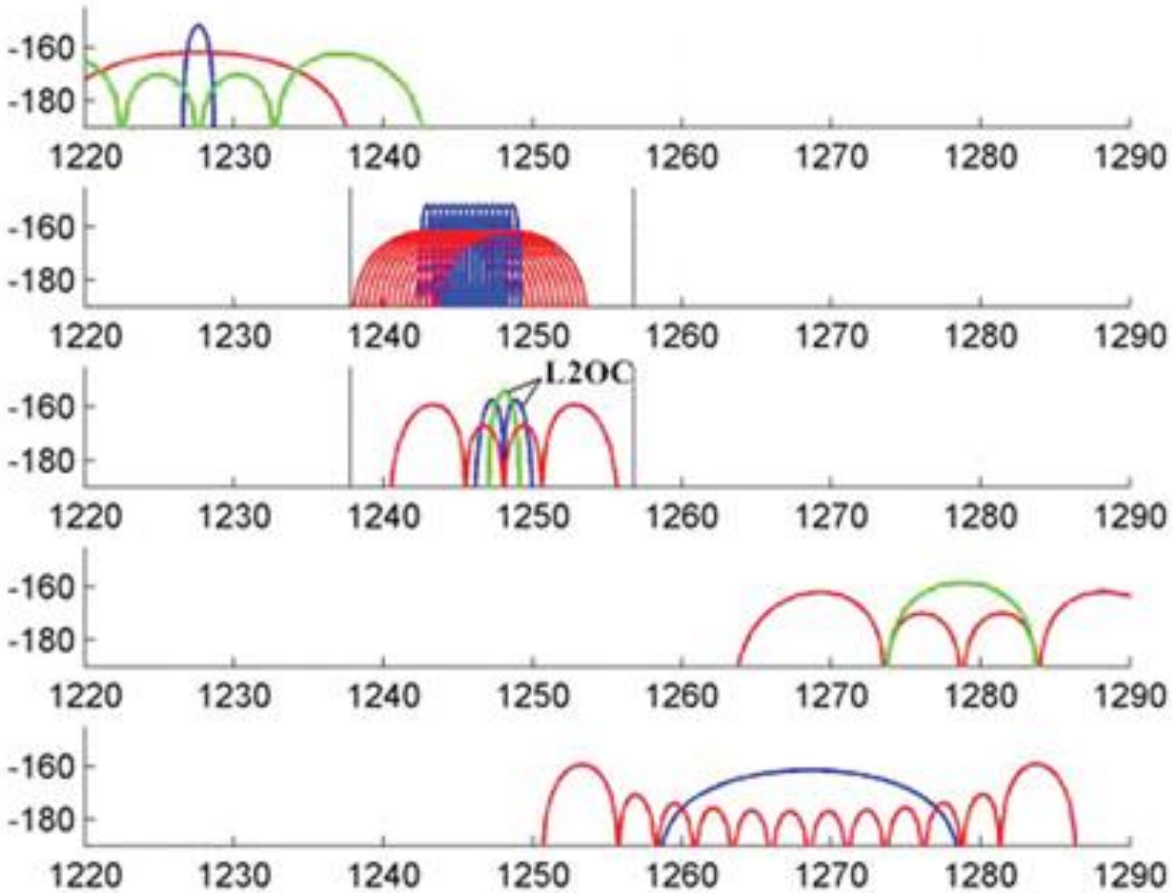
**GPS**

**GLONASS FDMA**

**GLONASS CDMA**

**GALILEO**

**COMPASS**



# GNSS Signals in L1 (E1)

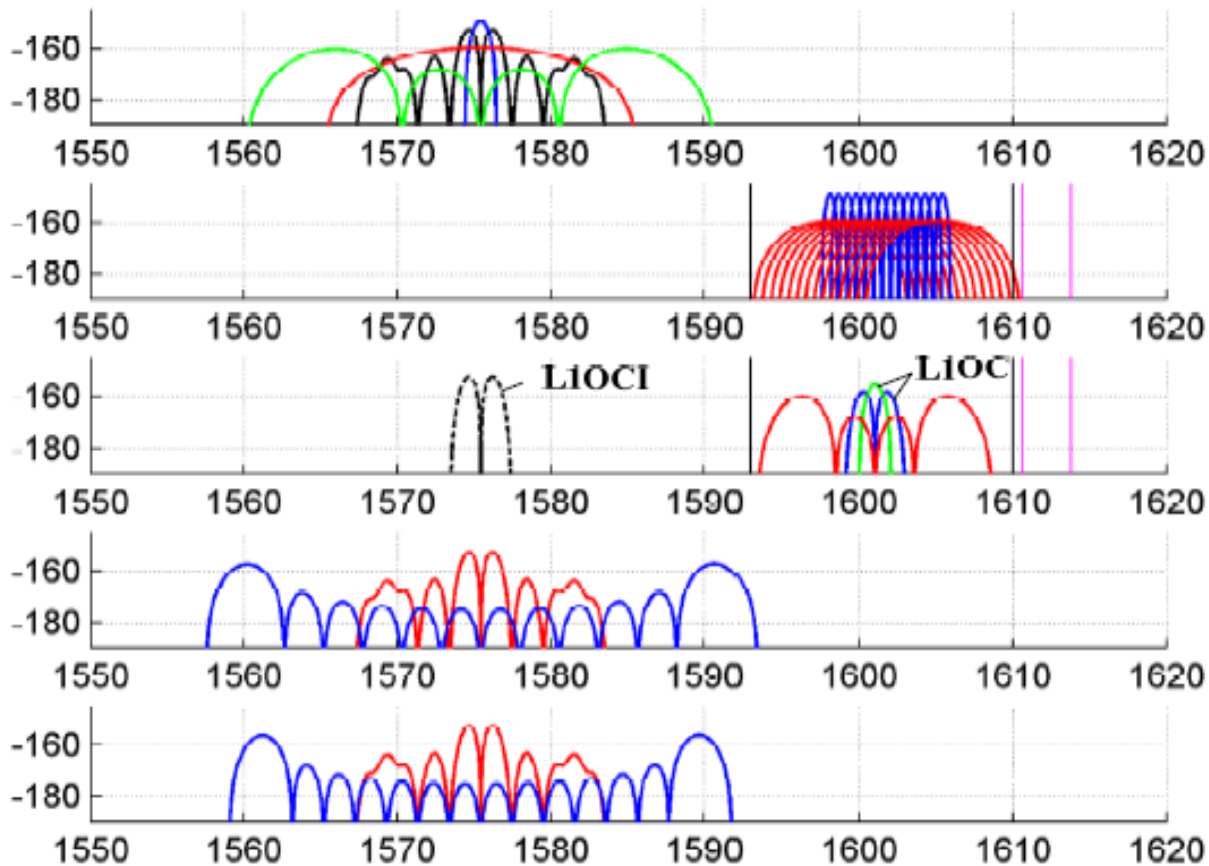
**GPS**

**GLONASS FDMA**

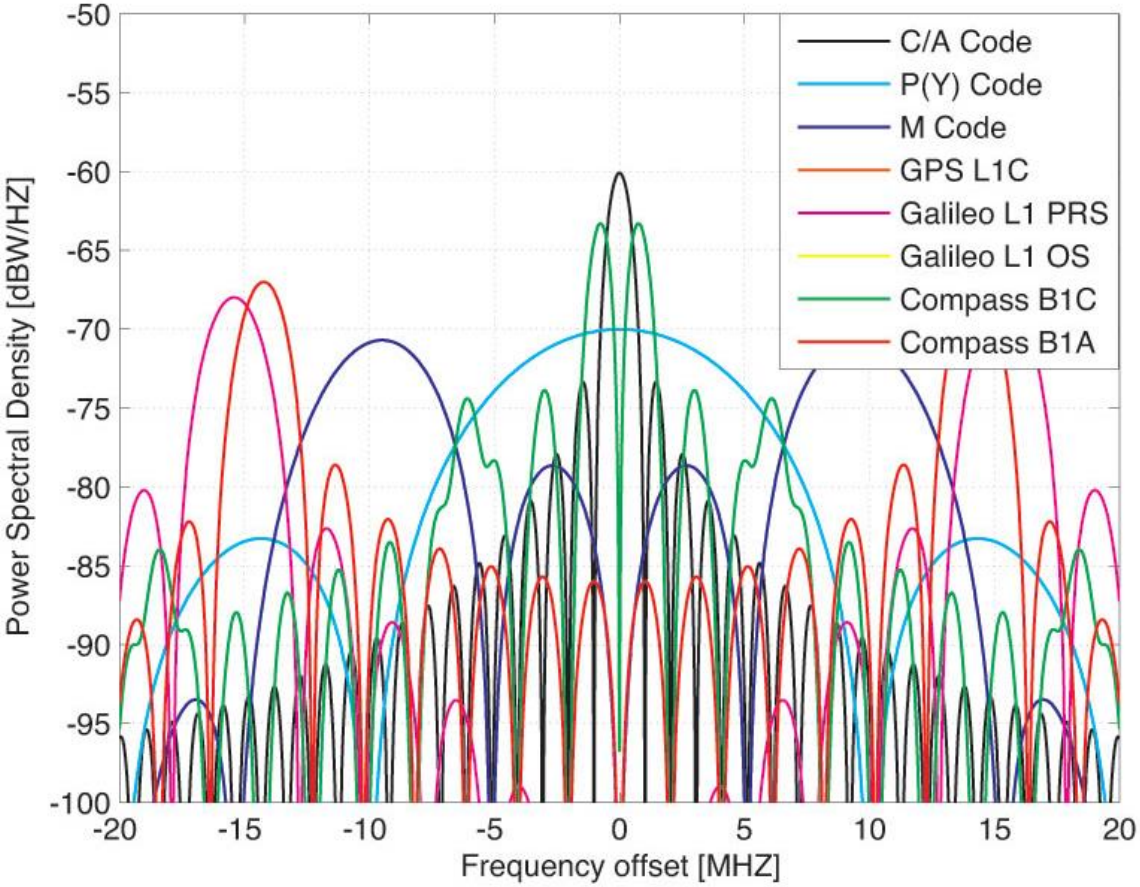
**GLONASS CDMA**

**GALILEO**

**COMPASS**

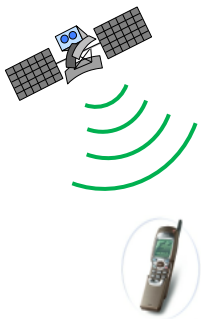



# GNSS Signals in L1 (E1)




+ RNSS signals!!!

# Navigation Signal in Space



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Modulation schemes

Multiplexing

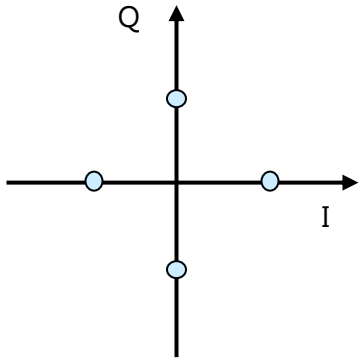
Codes

Navigation Data

# Navigation Signal in Space Modulation Schemes

Traditional modulation schemes used in navigation SISs are:

- BPSK
- QPSK

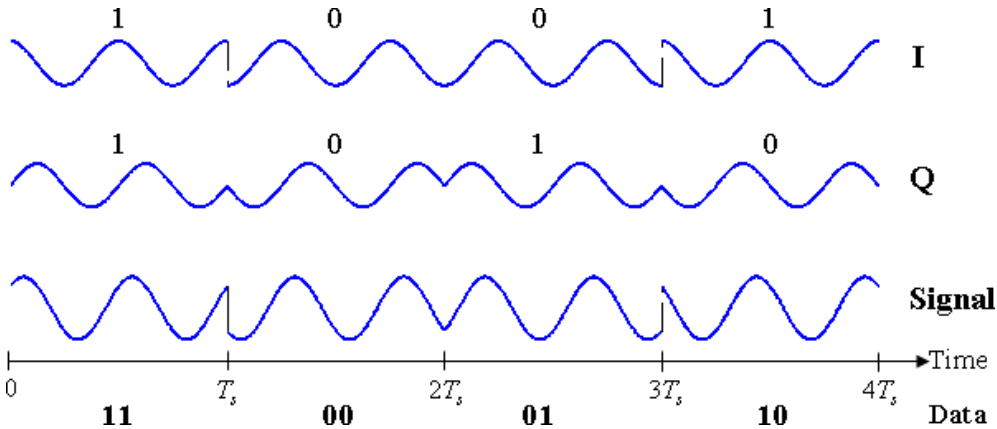




BPSK is the simplest form of phase shift keying (PSK).
It uses two phases which are separated by 180°.
Low data rate (1 bit/symbol)
Best BER performance among PSK modulations

QPSK can be obtained as the combination of 2 BPSK signals:

- one in-phase
- the other in quadrature (90° phase shift)

Data rate: 2 bits/symbol



# The L1 C/A GPS Signal Structure

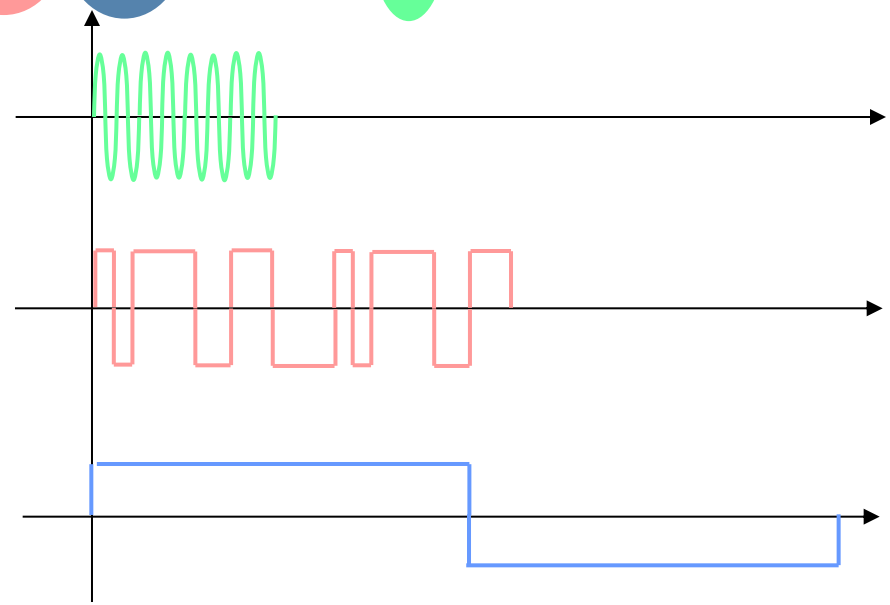
**BPSK modulation**

$$x_{RF}(t) = \sqrt{2P_c}\, c(t)\, d(t) \cos(2\pi f_L t + \theta_{L1})$$

Carrier

Ranging code: Pseudo-Random Noise (PRN) sequence of chips (typ. 1023 chips per ms)

Navigation data: sequence of bits (50 bits per second)



*Note: in the graphs the signal periods are not realistic (only pictorial)*

# The BOC SIS Components

**BOC modulation** (in new and modernized SISs, innovative modulation schemes have been proposed (BOC, MBOC, AltBOC…)

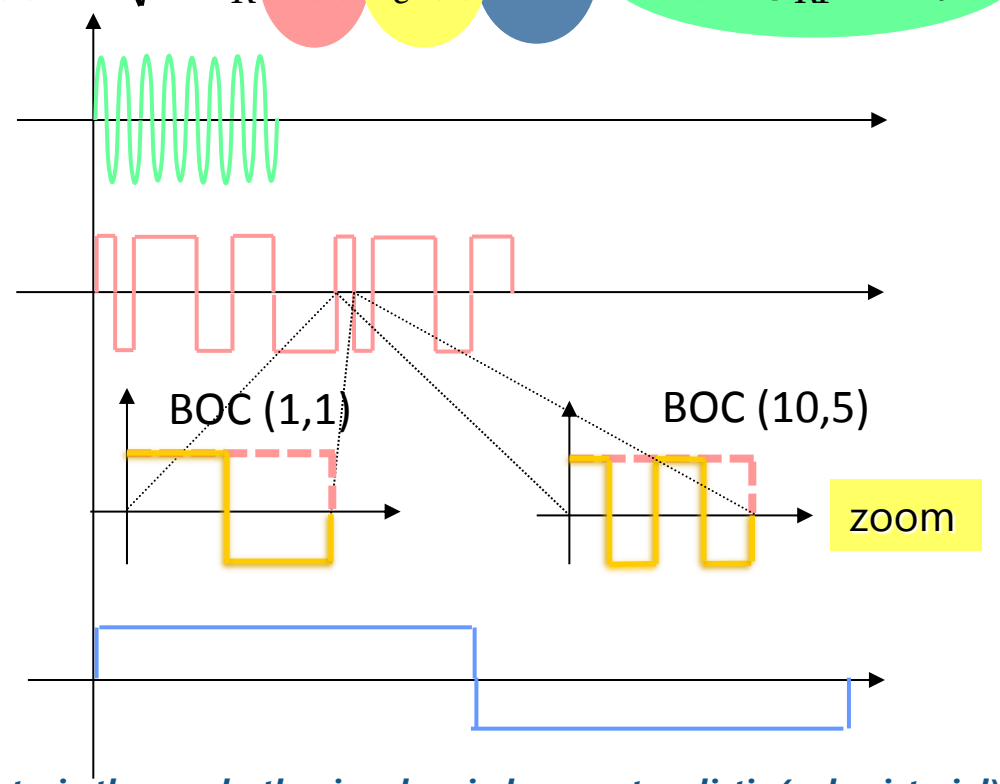
$$x_{RF}(t) = \sqrt{2P_R}\, c(t)\, s_c(t)\, d(t) \sin(2\pi f_{RF} t + \varphi)$$

Carrier

Ranging code: Pseudo-Random Noise (PRN) sequence of chips

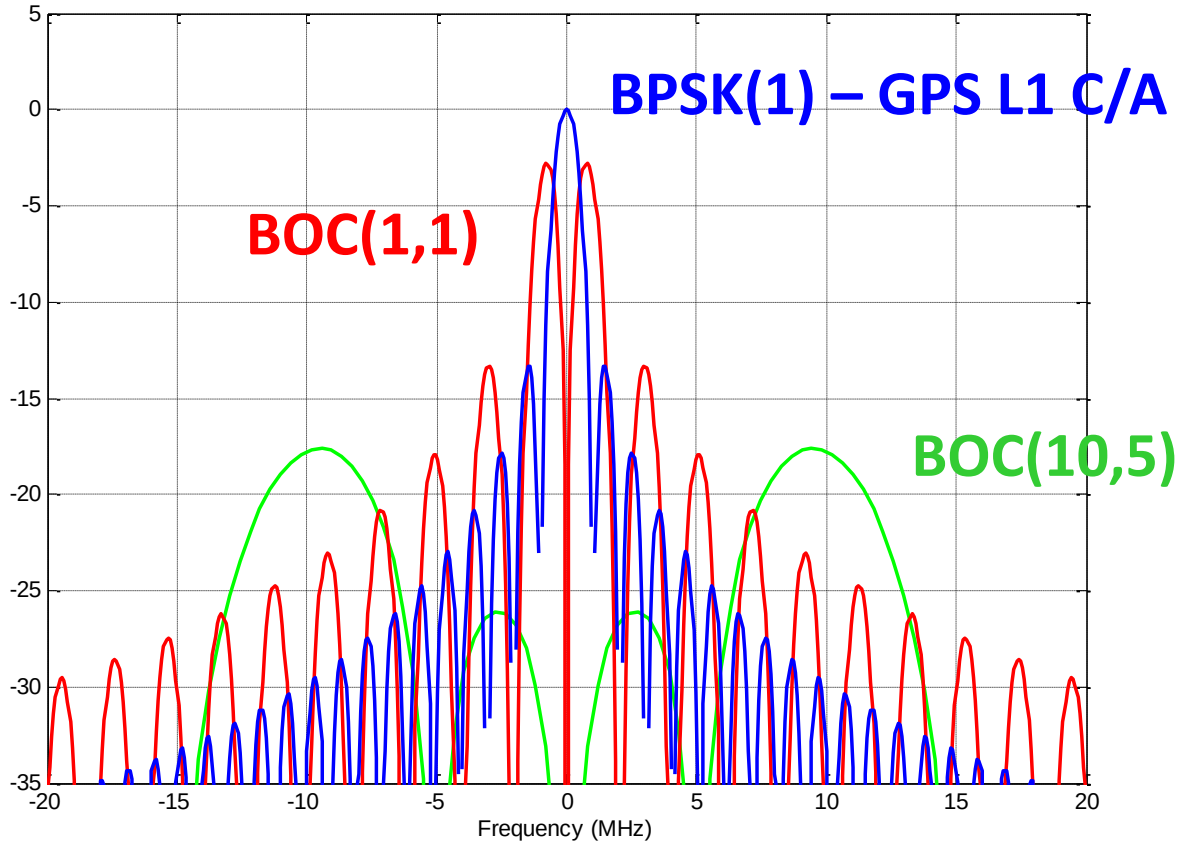
**Subcarrier waveform**

Navigation data: sequence of bits



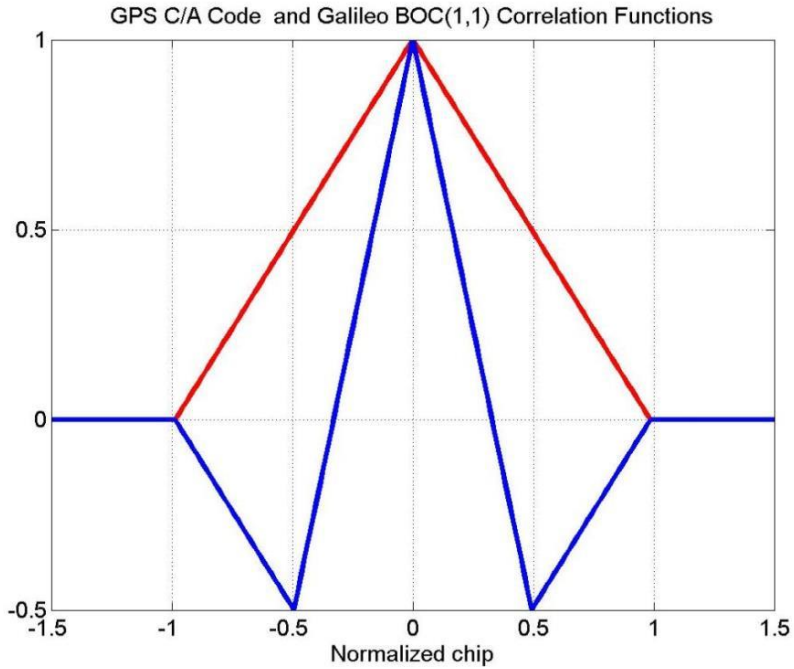

***Note: in the graphs the signal periods are not realistic (only pictorial)***

# Power Spectral Density (normalized)



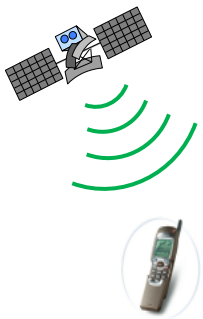
# Correlation Property of BOC Modulated Signals

- The autocorrelation of a **BPSK(1)** modulated code (GPS L1 C/A) has a **triangular shape** in the interval $[-T_r \;\; T_r]$
- The BOC signals have a **narrower correlation peak** around the origin, but **multiple side peaks**




- The **positioning performance** is related to the ability of identifying the main peak of the correlation function:
  - BOC signal can **potentially give better accuracy**
  - Due to the presence of the side peaks, the improvement is traded-off with the **complexity of the receiver** (false-lock mitigation needed)

# Navigation Signal in Space



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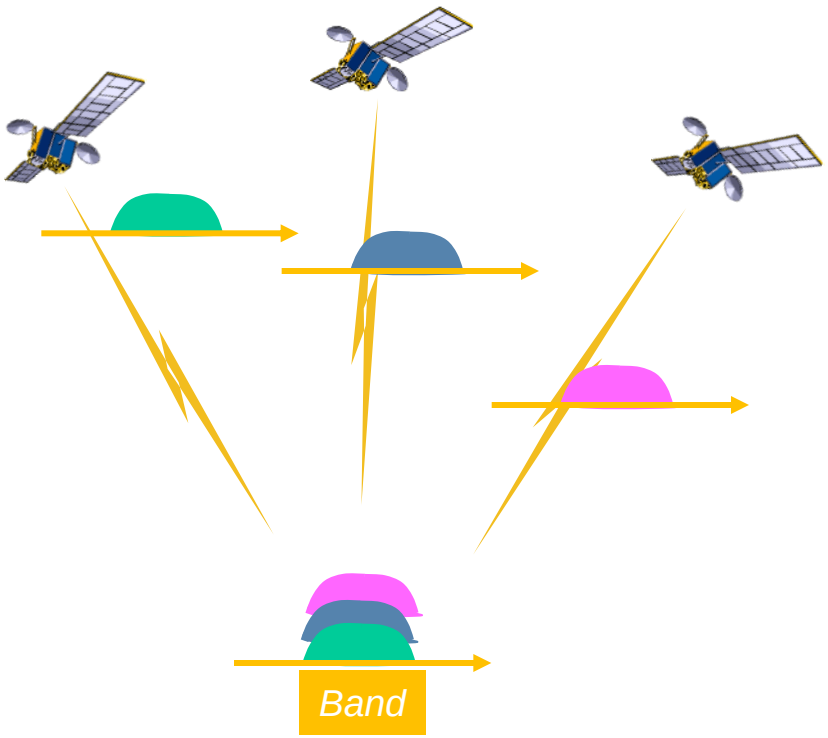
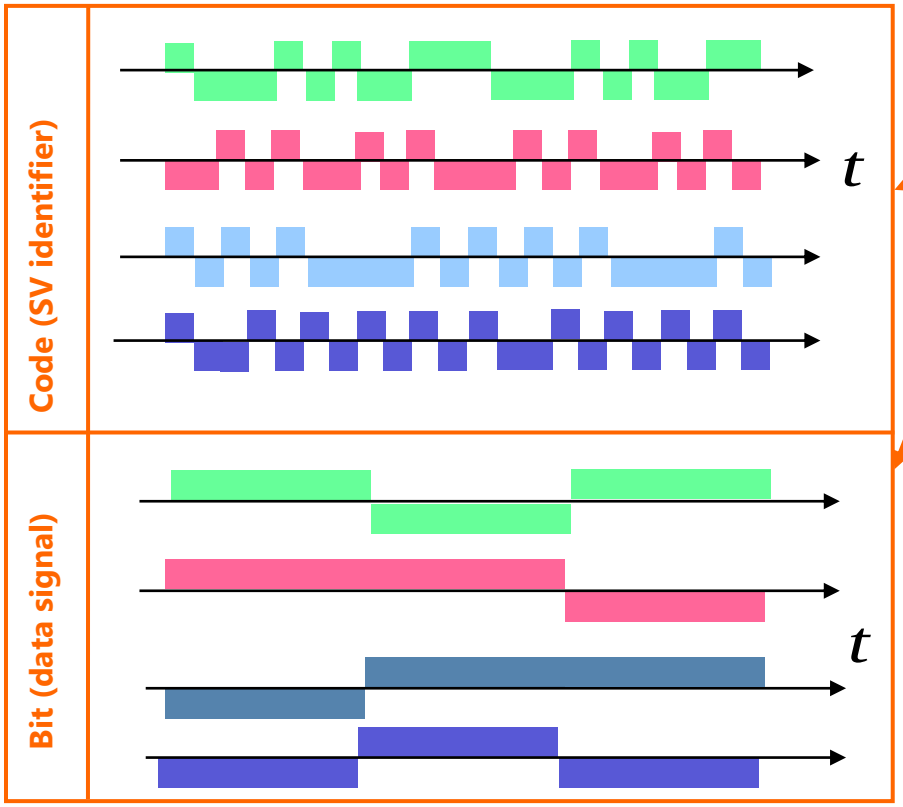
# Navigation Signal in Space Multiplexing

## CDMA technique

- Code Division Multiple Access (**CDMA**) is a multiple-access technique for transmitters sharing the same band
- The data-signal band is spread using a code, which is **unique for each transmitter**



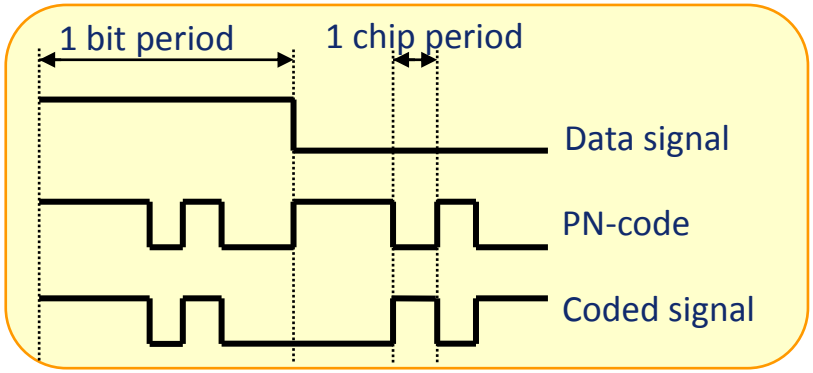
# Navigation Signal in Space
# Multiplexing




Each SV has to transmit:

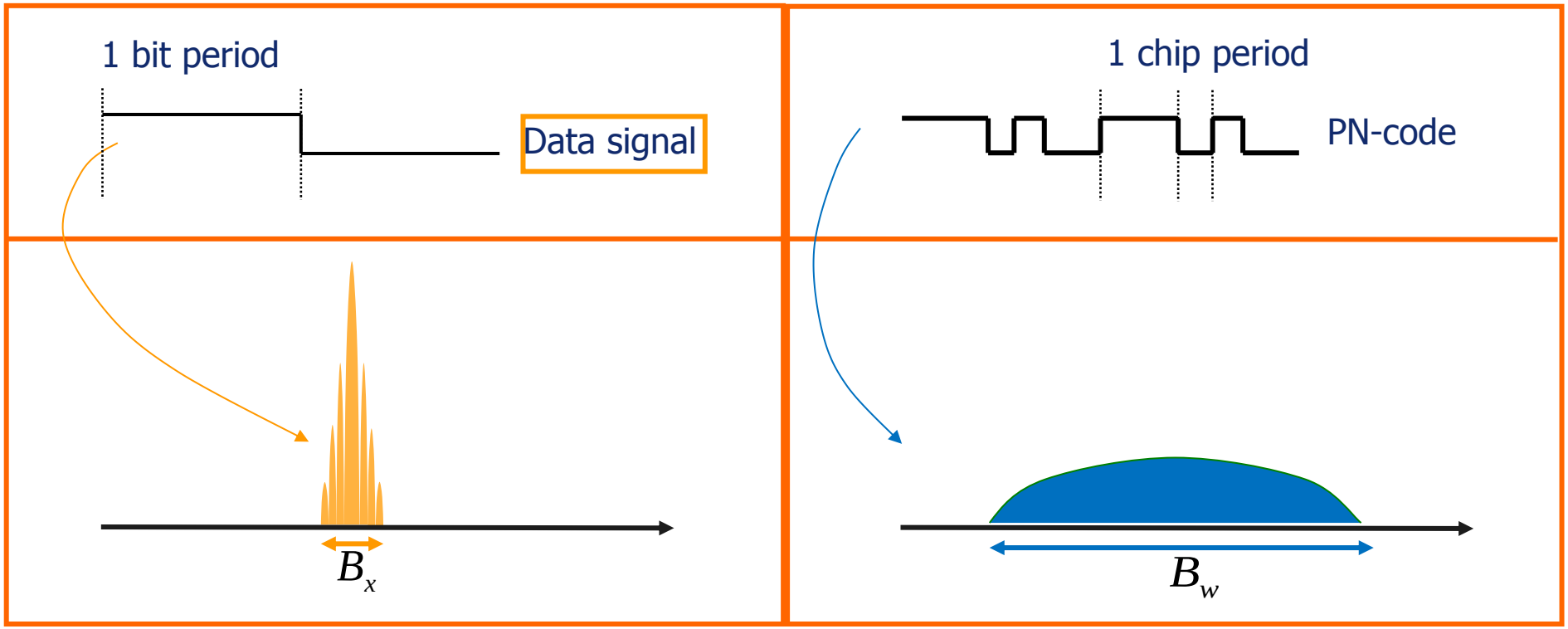
- its identifier
- its time and position

The data signal is multiplied by a pseudo random binary sequence (**PN-code**), generally referred to as <u>pseudo noise</u> (*PN*)



# Navigation Signal in Space
# Multiplexing

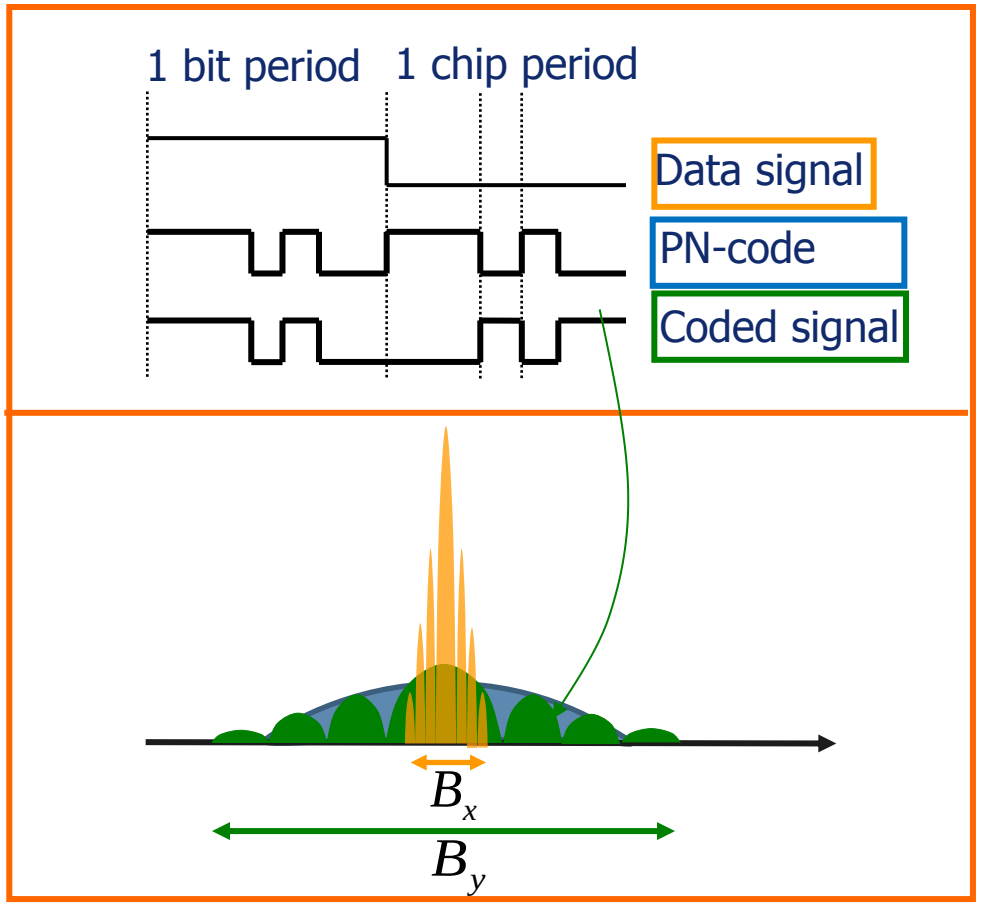
## CDMA as a Spread Spectrum Technique




If a signal with a narrowband $B_x$ is combined with a PN code: …

# Navigation Signal in Space Multiplexing

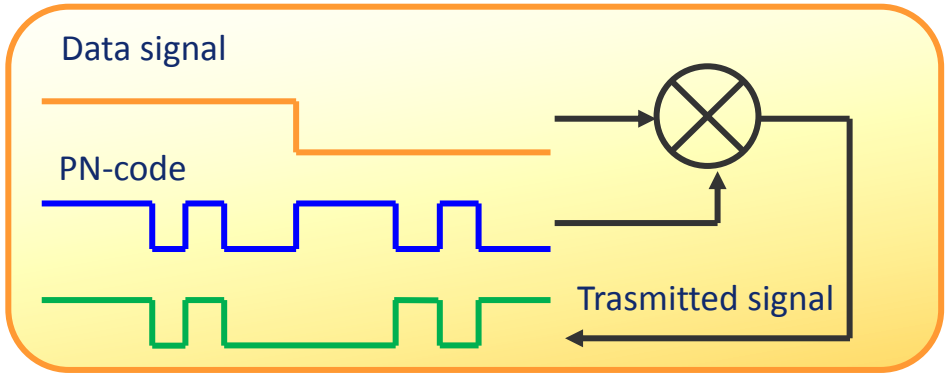
- The bandwidth $B_y$ of the resulting signal is the sum of band $B_x$ and the large band of the code $B_w$ (Fourier transform property)
- The total **transmitted power** stays equal
- The bandwidth $B_y$ of the resulting signal is **much greater** than $B_x$. The name "spread spectrum" indicates that the spectrum is spread
- The level of the power spectral density decreases

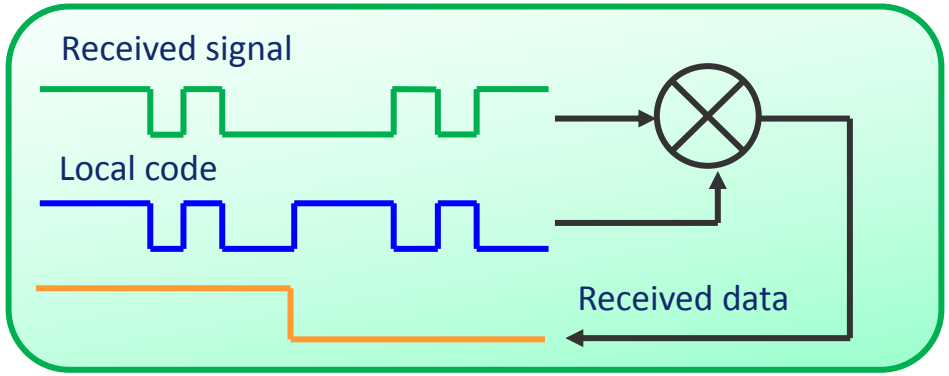


# Navigation Signal in Space
# Multiplexing

## Spreading and despreading (time domain)

TX

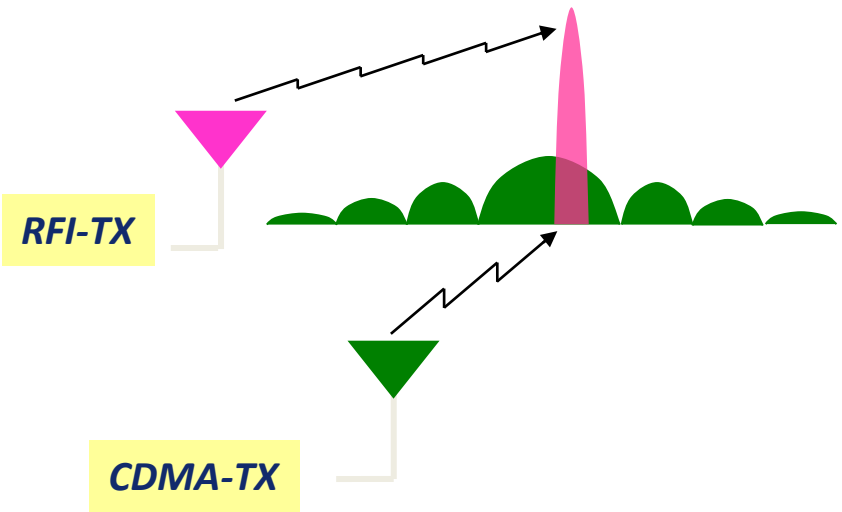



RX

# Navigation Signal in Space Multiplexing

## CDMA : Effects of Radio Frequency Interference (RFI)



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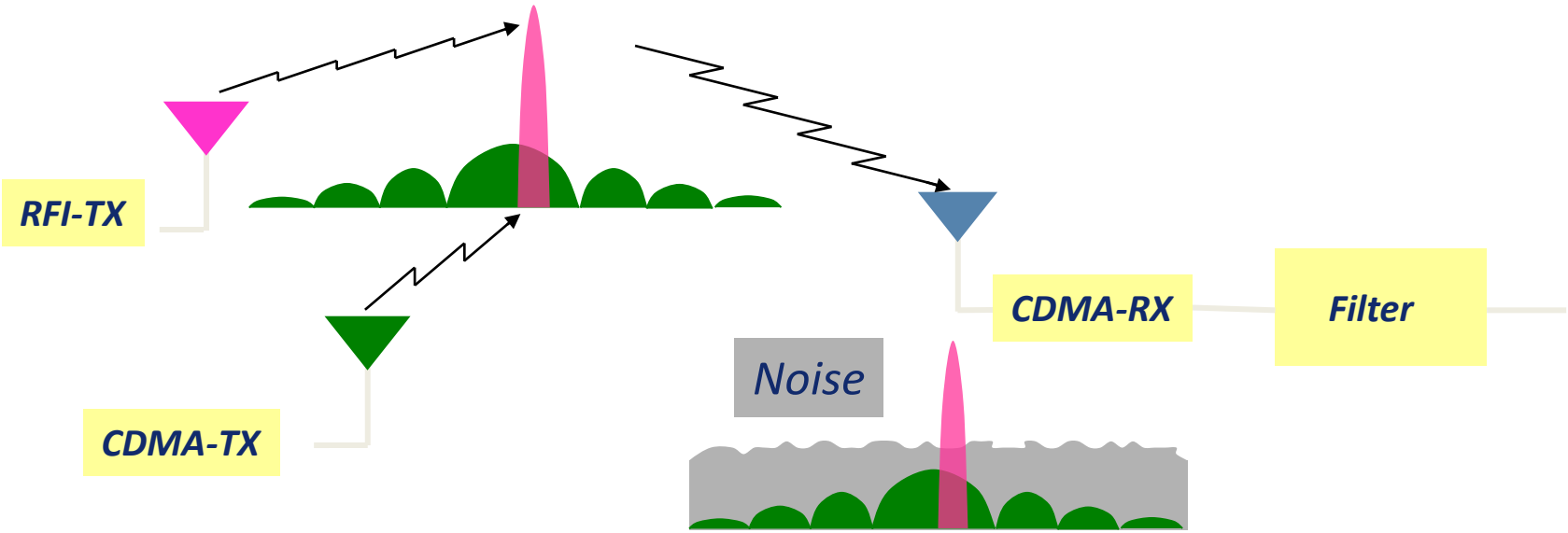

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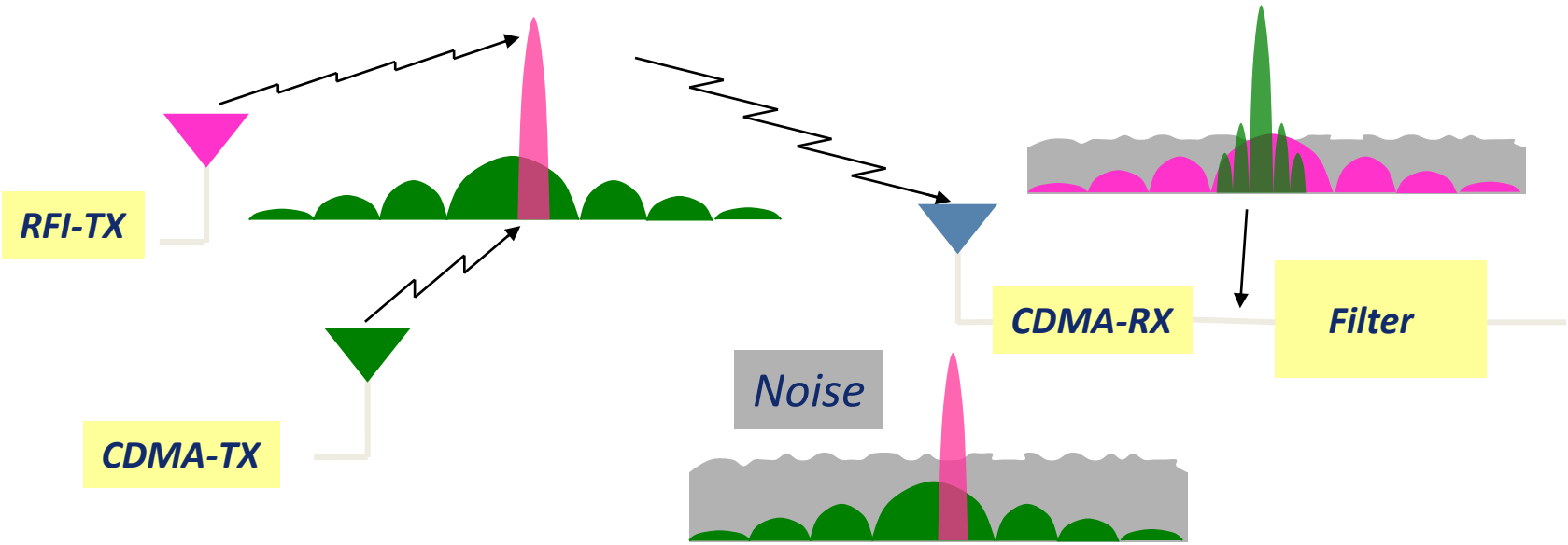

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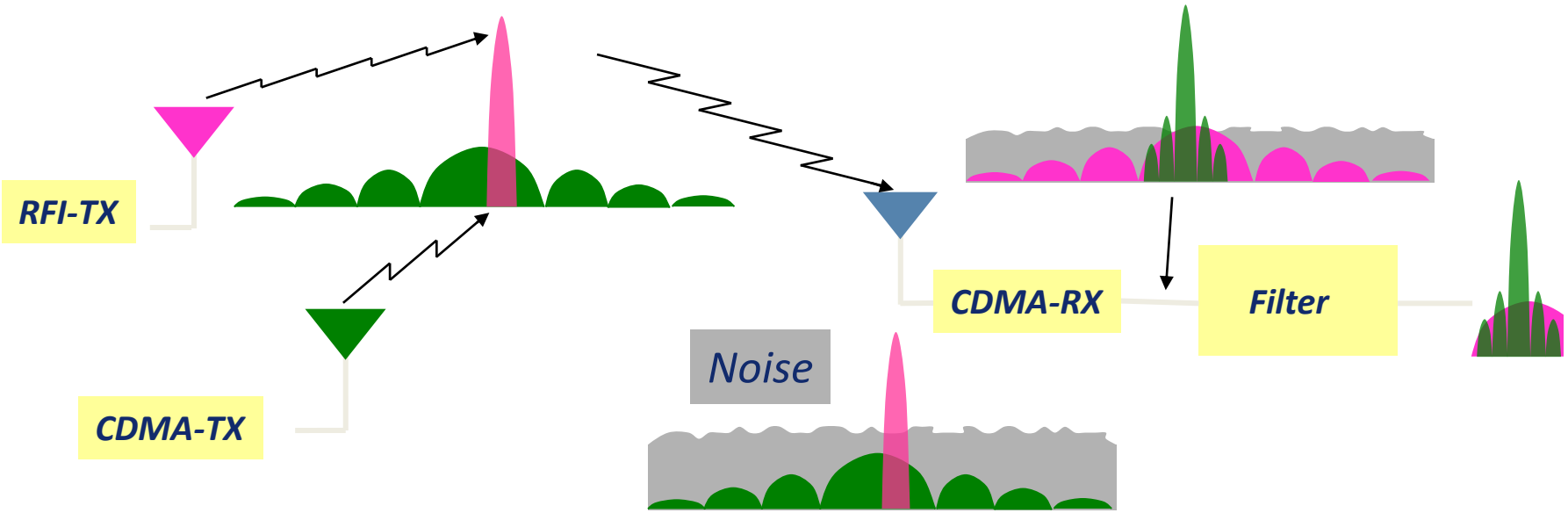
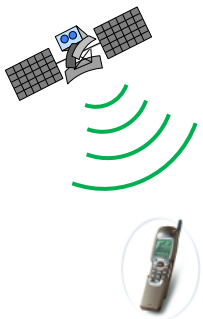


# Navigation Signal in Space



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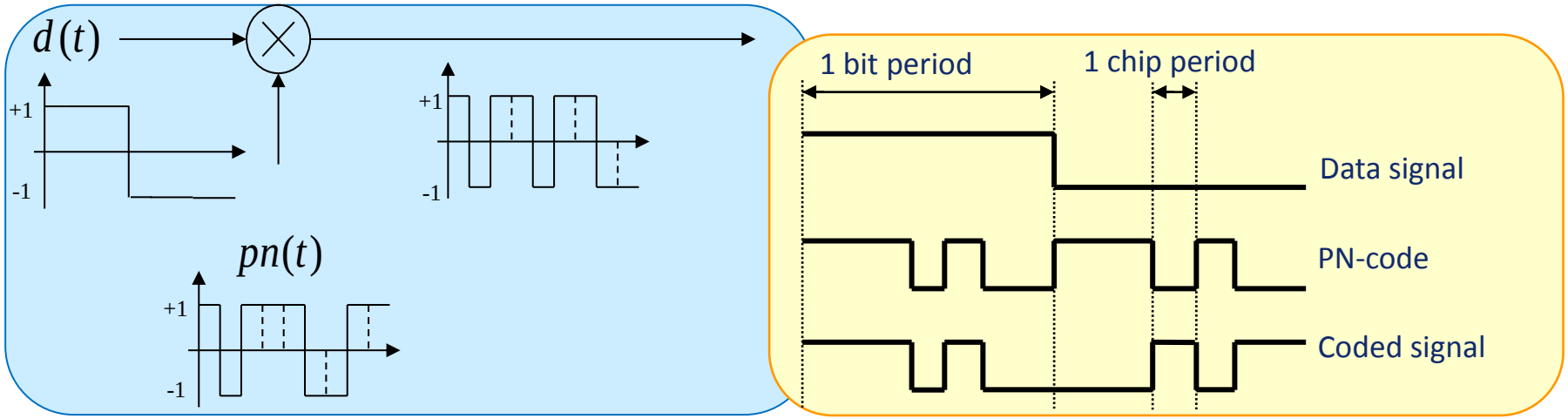
# Navigation Signal in Space
# PN-Code

## The PN-Code: a sequence of chips

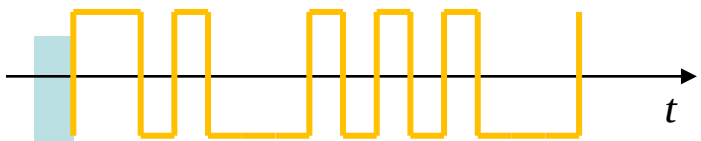
- The data signal is multiplied by a pseudo random binary sequence (**PN-code**), generally referred to as <u>pseudo noise</u> (*PN*)
- Such sequences have **noise-like properties** (spectral flatness, low cross-correlation values)



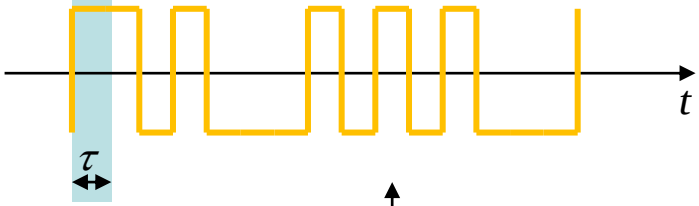
# Navigation Signal in Space
# PN-Code

## Code Correlation: Auto Correlation

- Code $c_i(t)$

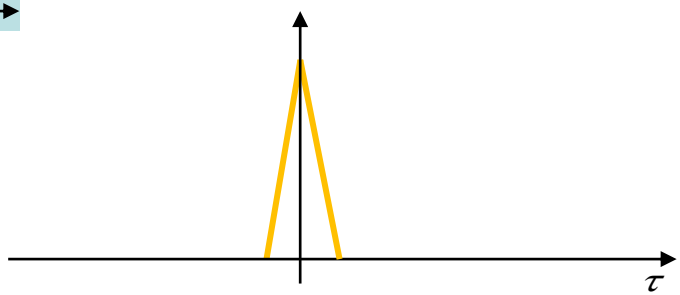



- Code translation $c_i(t+\tau)$




- Auto Correlation

$$R_i(\tau) = \int_{-\infty}^{+\infty} c_i(t) c_i(t+\tau) dt$$

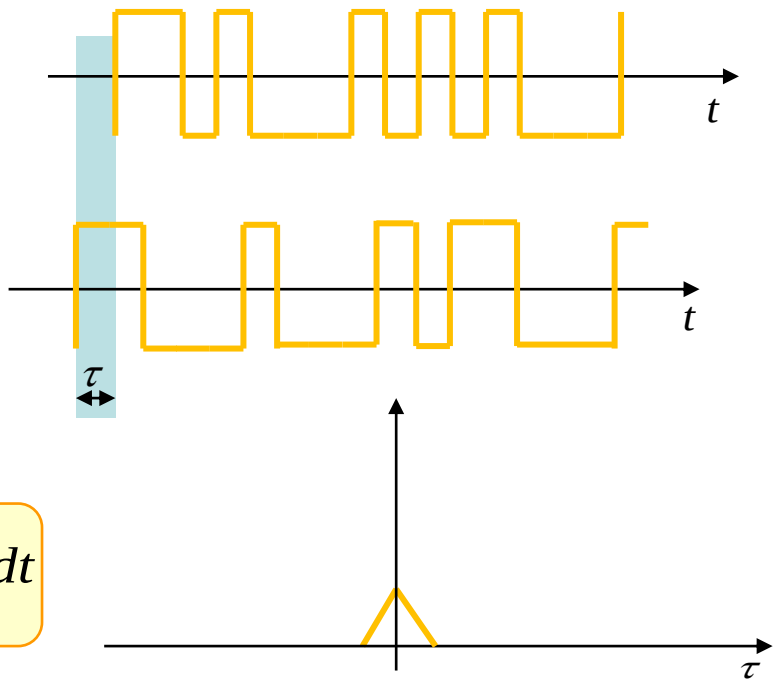


# Navigation Signal in Space
# PN-Code

## Code Correlation: Cross Correlation

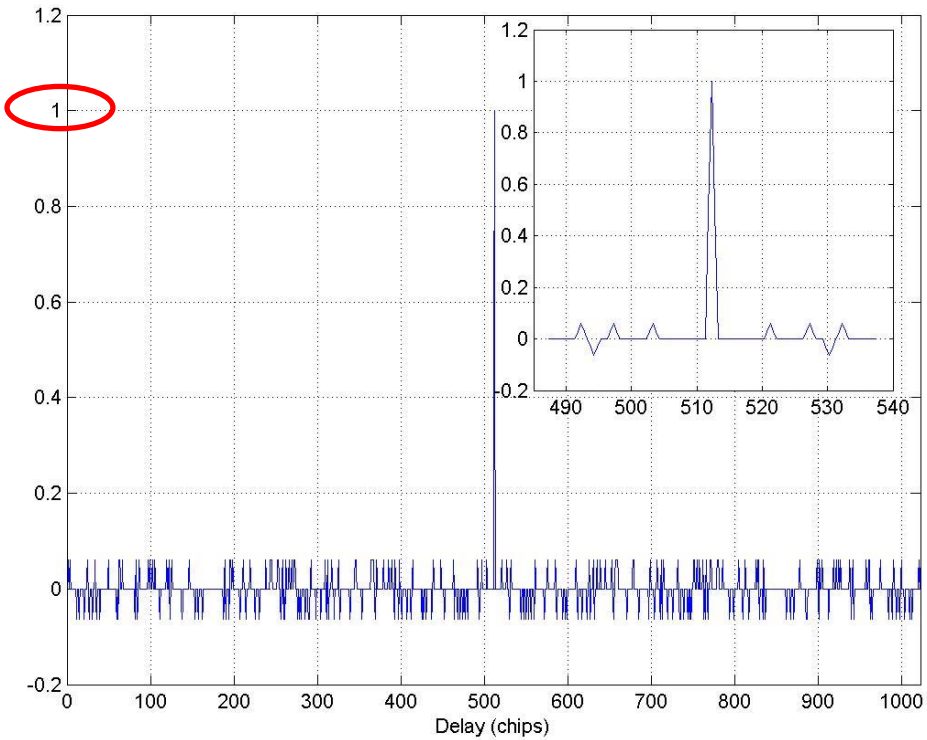
- Code $c_i(t)$
- Code translation $c_k(t+\tau)$
- Cross Correlation

$$R_{ik}(\tau) = \int_{-\infty}^{+\infty} c_i(t) c_k(t+\tau) dt$$

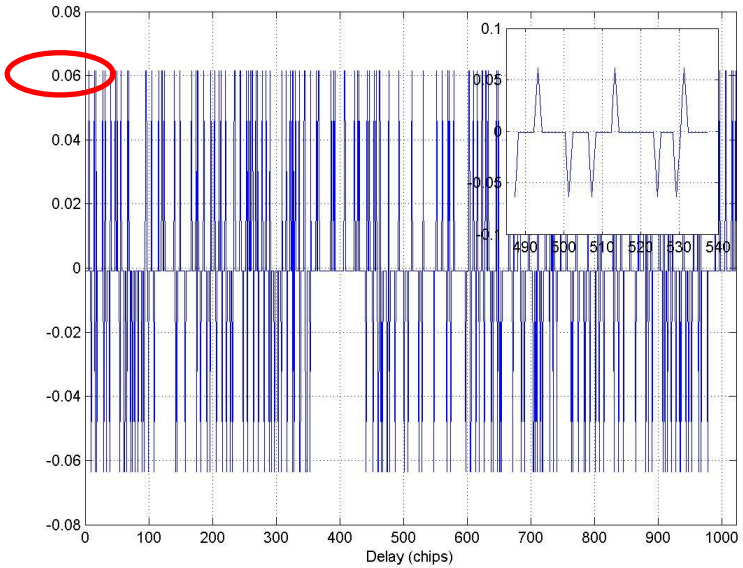


# Navigation Signal in Space
# PN-Code

## GPS C/A code

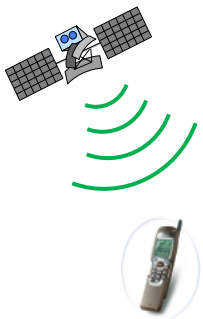



Autocorrelation of satellite 16




Cross-correlation between satellites 16 and 27

# Navigation Signal in Space



The signal broadcast by the navigation satellites must:

- Allow the user to estimate the pseudorange user-satellite
- Carry some useful data
- Be robust to the transmission through the atmosphere
- Identify in a unique way the satellites

The SIS is characterised by:

- Frequency Band
- Carrier Frequency
- Modulation Scheme
- Multiplexing Format
- Ranging Code
- Navigation Data Format
- Transmitted Power

Bands & Frequencies

Modulation schemes

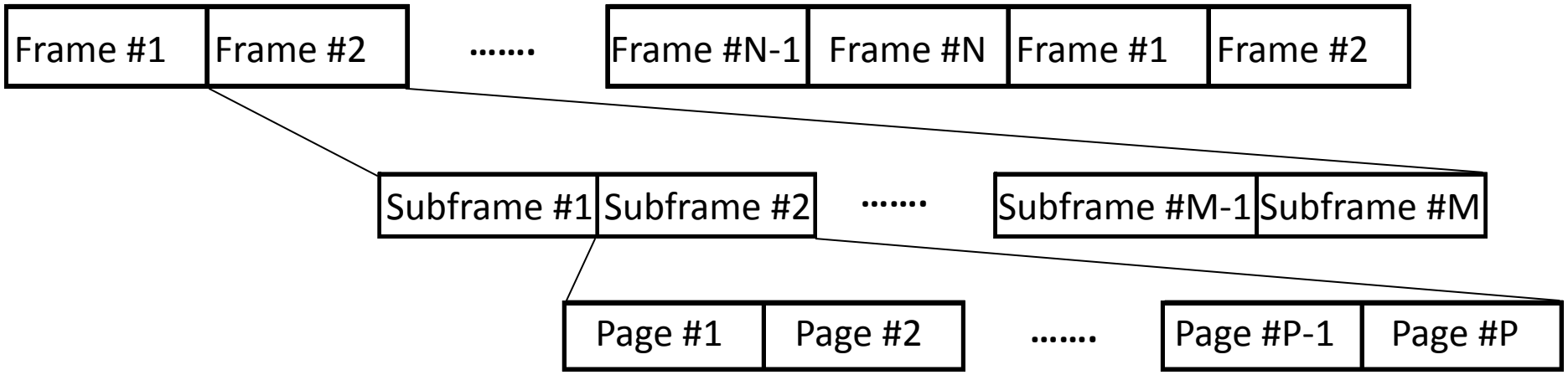
Multiplexing

Codes

Navigation Data

# Navigation Data Frame Structure

- **Galileo Message Data Stream**: the navigation message is transmitted in the data stream as a **sequence of frames**
- Each **frame** consists of a certain number of **subframes** (depending on the signal band)
- Each **subframe** consists of a number of **pages**



# Navigation Data Frame Structure

| Message | Signal | Data rate | Page duration | # Pages in a sub-frame | # Sub-frames in a frame |
|---|---|---|---|---|---|
| ***F/Nav*** | *E5a* | 50 sps | 10 s | 5 | 12 |
| ***I/Nav*** | *E5b E1B* | 250 sps | 2 s | 15 | 24 |
| ***C/Nav*** | *E6C* | 1000 sps | 1 s | 15 | 8 |
| ***G/Nav*** | *E6P E1P* | | | | |

The I/NAV message structures for the E5b-I and E1-B signals use the same page layout since the service provided on these frequencies is a dual frequency service, using frequency diversity. Only page sequencing is different, with page swapping between both components in order to allow a fast reception of data by a dual frequency receiver.

# EGNOS Signal and Messages

- EGNOS Signal Structure
- EGNOS Message Types
- Use of EGNOS information

All these topics are discussed in:

**Minimum Operational Performance Standards (MOPS) for Global Positioning System/Wide Area Augmentation System Airborne Equipment, RTCA/DO-229 D**

Issued by the Special Committee 159 of the

**Radio Technical Commission for Aeronautics**

# Signal Structure

- The signal broadcast via the SBAS GEOs to the SBAS users is designed to minimize standard GPS receiver hardware modifications: it is a GPS signal with a higher data rate.
  - Gold code from 120 to 138 are reserved for SBAS
  - Data rate will be 250 bits per second. The data are rate ½ convolutional encoded with a Forward Error Correction (FEC) code. Symbol rate that the SBAS receiver must process is 500 symbols per second (sps).
- Each 250 bits data block (1 second) contains a message.

# Message Types - Content

| | |
|---|---|
| **MSG 0** | Don't use this SBAS signal for anything (for SBAS testing) |
| **MSG 1** | PRN Mask assignments, set up to 51 of 210 bits |
| **MSG 2 to 5** | Fast corrections |
| **MSG 6** | Integrity information |
| **MSG 7** | Fast correction degradation factor |
| **MSG 8** | *Reserved for future messages* |
| **MSG 9** | GEO navigation message (*X*, *Y*, *Z*, time, etc.) |
| **MSG 10** | Degradation Parameters |
| **MSG 11** | *Reserved for future messages* |
| **MSG 12** | SBAS Network Time/UTC offset parameters |
| **MSG 13 to 16** | *Reserved for future messages* |
| **MSG 17** | GEO satellite almanacs |
| **MSG 18** | Ionospheric grid point masks |
| **MSG 19 to 23** | *Reserved for future messages* |
| **MSG 24** | Mixed fast corrections/long term satellite error corrections |
| **MSG 25** | Long term satellite error corrections |
| **MSG 26** | Ionospheric delay corrections |
| **MSG 27** | SBAS outside service volume degradation |
| **MSG 28** | Clock-ephemeris covariance matrix message format |
| **MSG 29 to 61** | *Reserved for future messages* |
| **MSG 62** | Internal Test Message |
| **MSG 63** | Null Message |

# Integrity: with/without Corrections

A given SBAS GEO can broadcast either **coarse integrity data** or both such data and **wide area corrections**.

- The coarse integrity data include **use/don't-use information** on all satellites in view of the applicable region, including the GEOs.
- **Correction data <u>include estimates</u> of the error after application of the corrections:**
  - $\sigma^2_{UDRE}$ is the variance of a Normal distribution associated with the **user differential range error** for a satellite after application of fast corrections and long term corrections, excluding atmospheric effects
  - $\sigma^2_{GIVE}$ is the variance of a Normal distribution associated with the residual **ionospheric vertical error** at an IGP for an L1 signal.

# Correction Types

There are three types of correction concerning errors originating from the satellite:

- Fast corrections:
  - for rapidly changing errors such as those due to Selective Availability
  - common to all users and broadcast as such (pseudorange difference)
- Long-term corrections:
  - for slower changing errors due to long term satellite clock parameters and ephemeris errors
  - the users are provided with satellite position and clock error estimates for each satellite in view.
- Ionospheric corrections
  - separately, a wide-area ionospheric delay model is provided and sufficient real-time data to evaluate the ionospheric delays for each satellite using that model.

# Modelling of Degradation Data

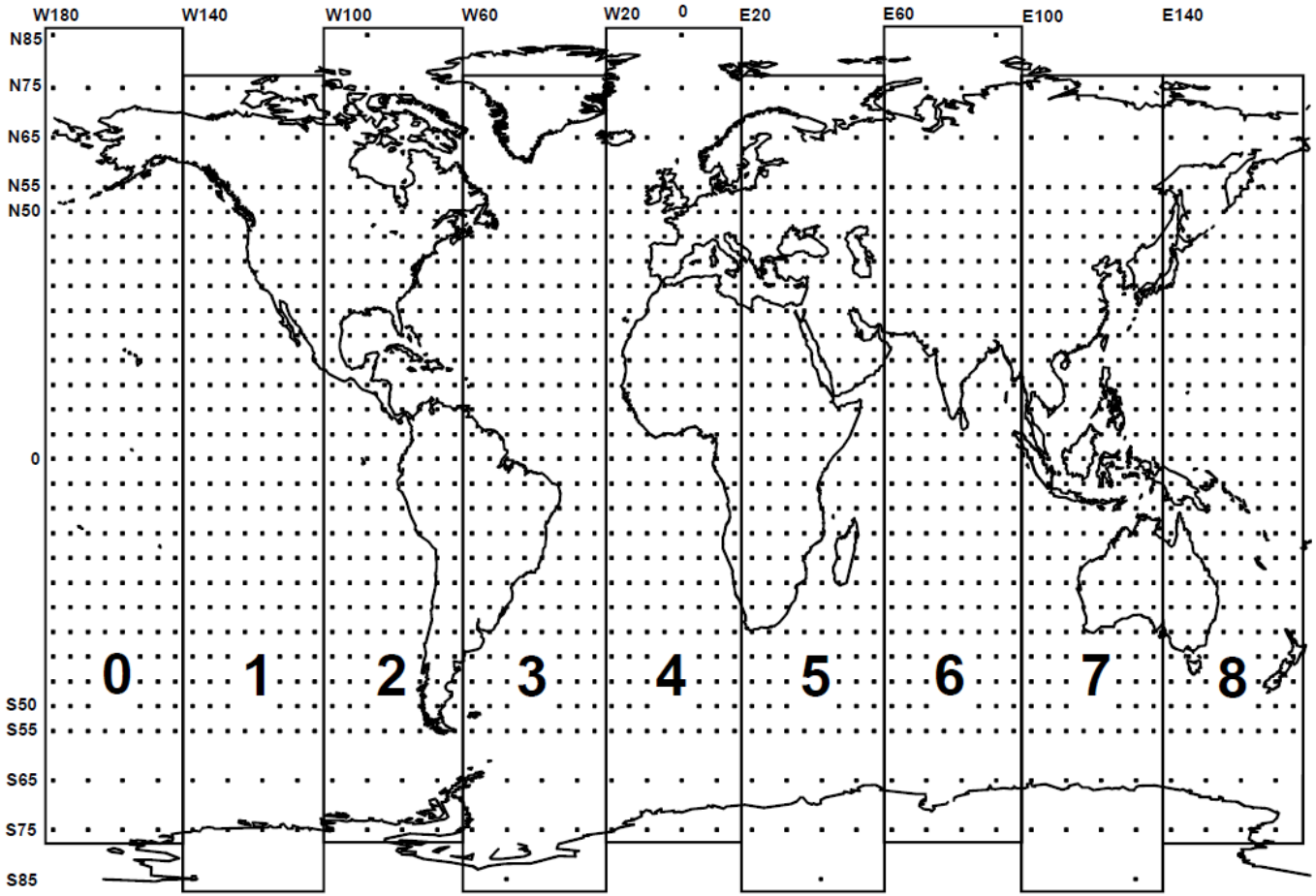
- The fast corrections, long-term corrections, and ionospheric corrections are all designed to provide the most recent information to the user.
- <u>However, there is always the possibility that the user will fail to receive one of these messages, either due to momentary shadowing or a random bit error.</u>
- In order to guarantee integrity, the user must apply models of the degradation of this information.

- Fast and Long-Term Correction Degradation is taken into account by the term

$$\boxed{\sigma^2_{flt}}$$

- The data for the computation of this term are broadcast by EGNOS

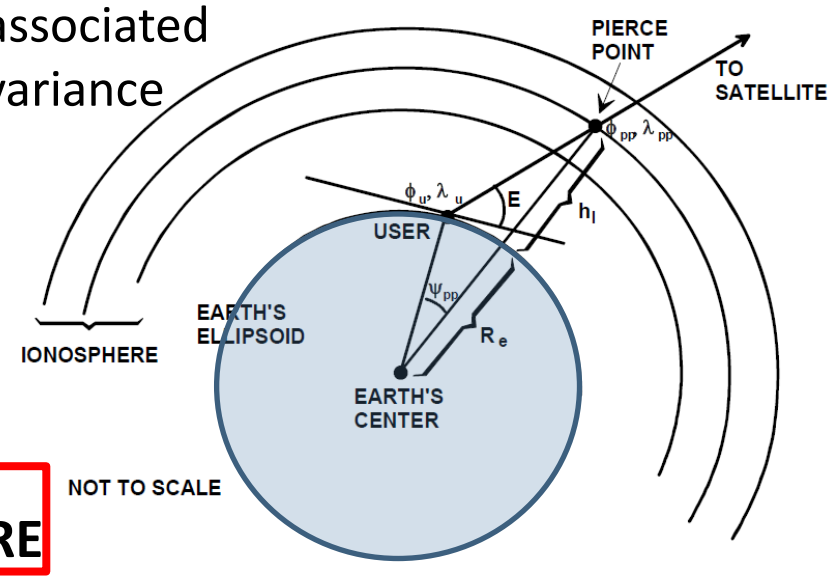
# Global Ionospheric Grid Points Map




NOTE: bands 9 & 10 are not shown

# Ionospheric Delays

- EGNOS through the Ionospheric Delay Corrections Message provides information about **vertical delays** and **<u>Grid</u> Ionospheric Vertical Error $\sigma^2$** at **IGP's**.
- These values must be interpolated by the user to the Ionospheric Piercing Points (IPP) of the observed satellites.
- The results are the vertical delays and the associated **<u>User</u> Ionospheric <u>Vertical</u> Error $\sigma^2$** (model variance for user ionospheric vertical error).
- These must be multiplied by the obliquity factor computed from the elevation angle to the satellite to obtain a **slant range correction** and the **User Ionospheric <u>Range</u> Error $\sigma^2$** or $\boxed{\sigma^2_{UIRE}}$



# Tropospheric Model

DO 229 include the definition of a tropospheric model enabling a receiver to take into account the average local tropospheric refraction.

All users will compute their own tropospheric delay correction for all the satellite *i* in use.

$$Tropospheric\ Delay_i = Vertical\ Delay_i \cdot f(Elevation_i)$$

The residual error variance $\sigma^2_{i,tropo}$ for the tropospheric delay correction for satellite *i*, based on the model is calculated from:

$$\boxed{\sigma^2_{i,tropo}} = \sigma_{TVE} \cdot f(Elevation_i)$$

the σ of the tropospheric vertical error **is $\sigma_{TVE}$ = 0.12 m** and $f(El_i)$ is the same tropospheric correction mapping function for satellite elevation used for the correction computation.

# Variance of Airborne Receiver Errors $\sigma^2_{air}$

- This variance takes into account all the other error sources affecting an airborne receiver.
- Different values are considered depending on the equipment class:
  - For Class 1 equipment $\sigma^2_{i,air} = 25m^2$
  - For Class 2, 3 and 4 equipment: $\sigma_{air}[i] = \left(\sigma^2_{noise}[i] + \sigma^2_{multipath}[i] + \sigma^2_{divg}[i]\right)^{1/2}$

  where
  - $\sigma_{multipath}$[i] takes into account the effects of multipath propagation
  - $\sigma_{divg}$ [i] takes into account the effect of ionospheric divergence on the receiver smoothing filter
  - $\sigma_{noise}$ [i] takes in account receiver noise, thermal noise, interference, inter-channel biases, time since smoothing filter initialization, processing errors...

# Residual Error Variance

For satellite *i*

$$\boxed{\sigma^2_i = \sigma^2_{i,flt} + \sigma^2_{i,UIRE} + \sigma^2_{i,air} + \sigma^2_{i,tropo}}$$

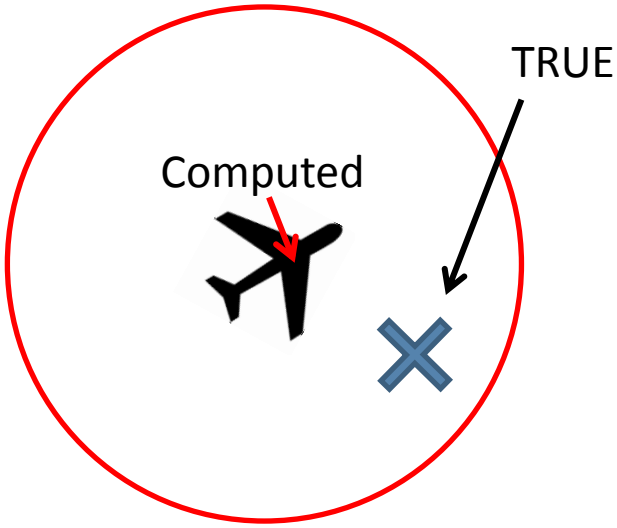
provides the pseudorange measurement residual error variance after the application of EGNOS corrections

But how to use this obtain ***integrity*** information?

# The Integrity Concept

**“I know I’m getting this accuracy, the system is not lying to me…”**

- During a specific flight operation the pilot must be aware that the plane true position is within a circle having its centre in the computed position




- The circle radius is called **Horizontal Protection Level** (Vertical PL is also defined)
- Integrity is assured if an alarm is raised in case the circle becomes too big
- HPL bound the error with a determined probability.

# High Level Integrity Requirements

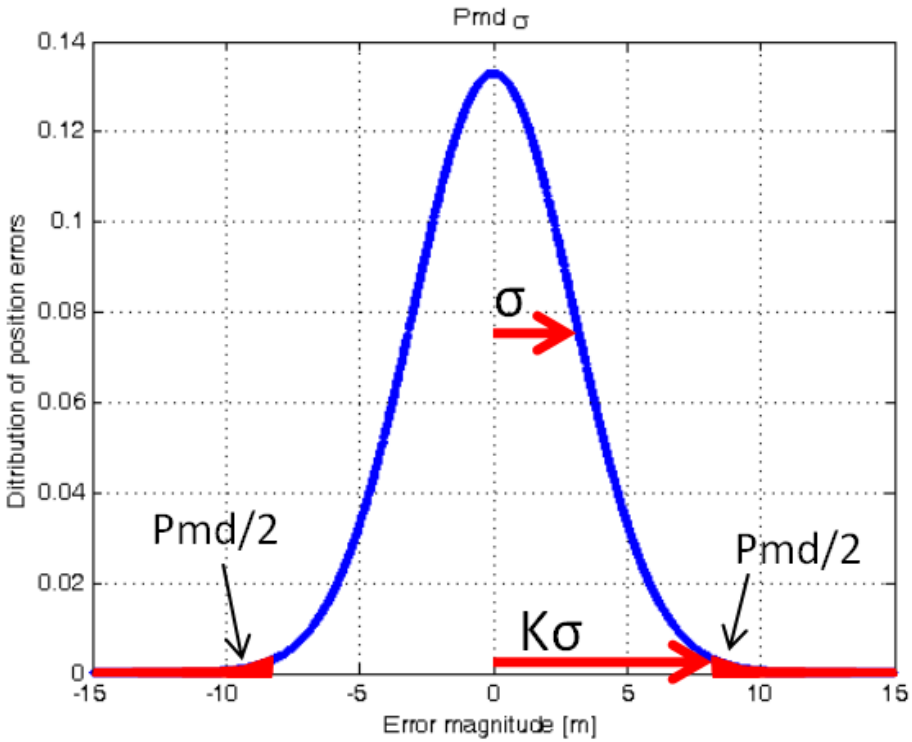
Integrity requirements involve:

- The limit maximum allowed circle radius: **Alarm Limit**
- The probability that a wrong information is provided (error>PL) without an alarm being raised: **Integrity Risk**
- The time within the above mentioned alarm must be raised: **Time to Alarm**

The three parameters vary depending on the different flight phases.

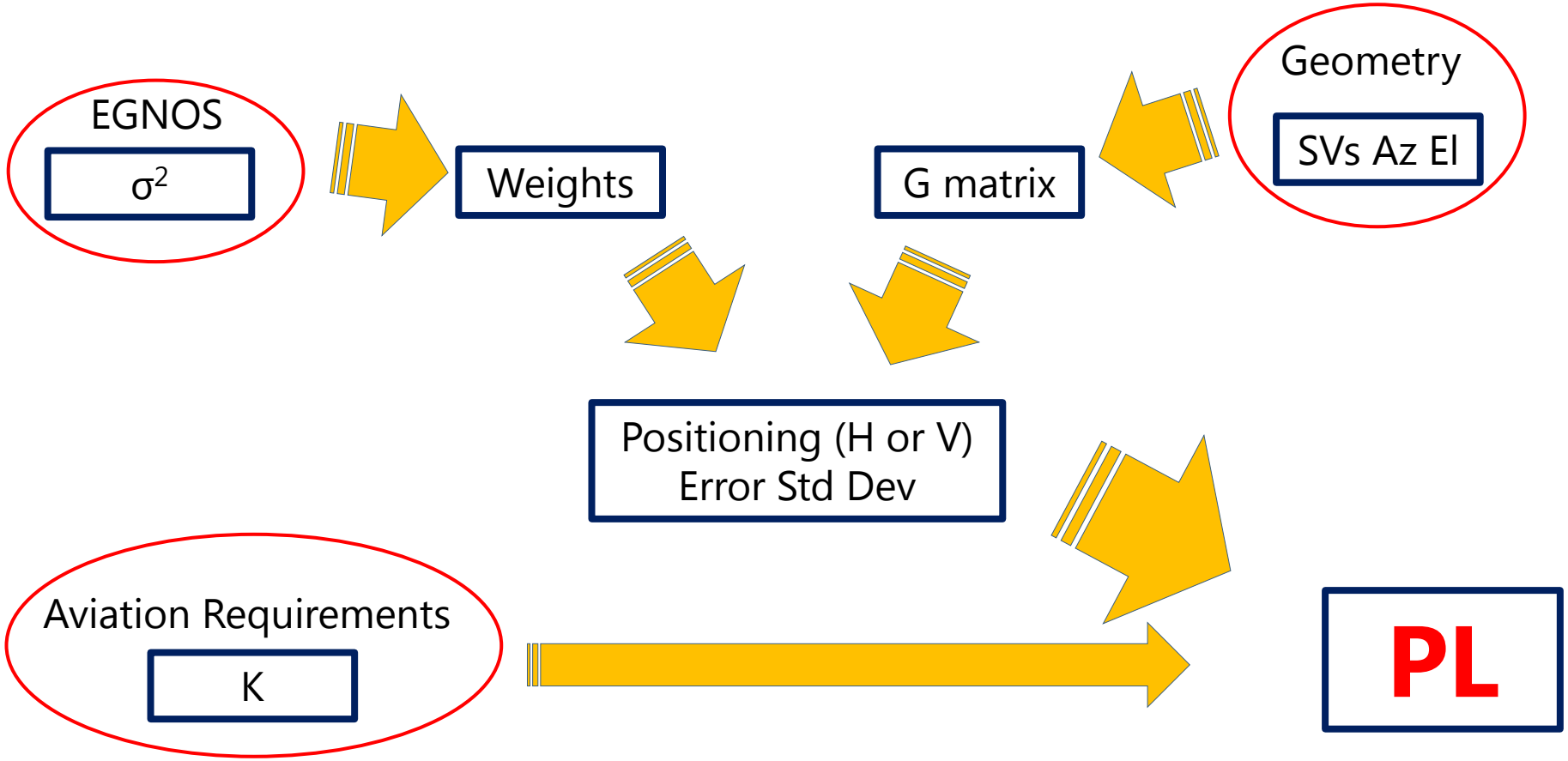
# How to obtain integrity information from σ?

- The error on measured pseudoranges affects the positional error
- In the same way the residual error estimate (variance) on pseudorange can be translated in the position error variance.
- Once the variance on the position is computed this is multiplied by a factor ***K*** in order to reduce the probability of a missed detection that correspond to the **integrity risk** requirement




Visualisation of the integrity risk as the area of a Gaussian distribution tails

# Protection Level Computation



# Contacts

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