

# Lecture 2

# GNSS Architecture



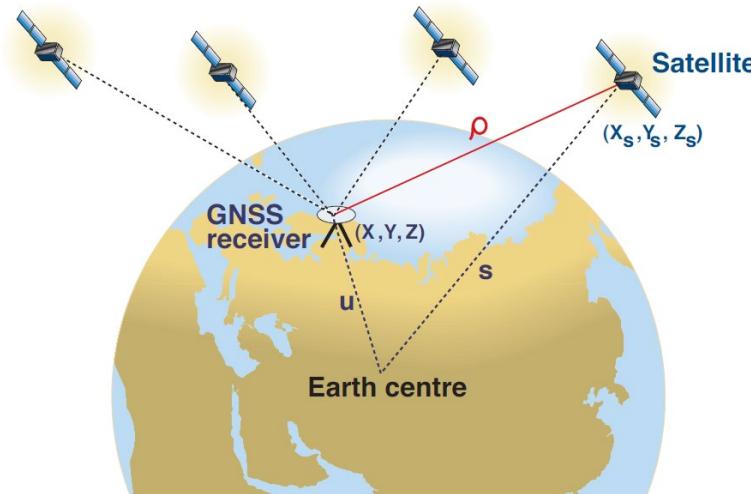
Professors: Dr. J. Sanz Subirana, Dr. J.M. Juan Zornoza  
and Dr. A. Rovira-García

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1. Introduction: GNSS Concept and Historical Review
2. GNSS segments: Galileo Segments
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4. GNSS signals
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6. Performance of Galileo Req. for Galileo Services
7. Comparison between the different GNSSs
8. The more satellites the better?

# Introduction: GNSS Concept

Global Navigation Satellite System (GNSS) is a generic term denoting a satellite navigation system (e.g. GPS, GLONASS, Galileo and Beidou) that provides continuous positioning over the globe.



# Introduction: Historical Review

**1957: Sputnik was launched on 4th of October**



1973: Conceptual phase of Global Positioning System (GPS)

1984: Begin of civilian use of GPS

**1995: Full operational capability of GPS**



**1996: Full operational capability of GLONASS**

1999: First concept for Galileo

2000 May: Final deactivation of the selective availability

**2000: BeiDou (COMPASS) is initiated**

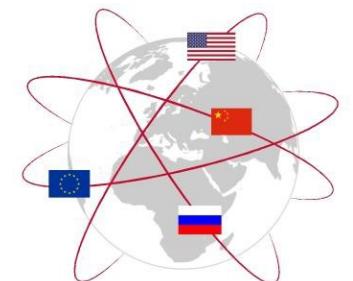
**2002: Galileo programme was officially started.**

2004: Launching of the 50<sup>th</sup> GPS satellite

2005 December: Launch of 1<sup>st</sup> Galileo test satellite GIOVE-A

2008 April: Launch of 2<sup>nd</sup> Galileo test satellite GIOVE-B

2011-2016: Launch of 14 Galileo satellites (troubles for two of them)



Main GNSS program countries  
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# Current and Planned Global Navigation Satellite Systems



**GPS**

1995 FOC



**GLONASS**

1996 FOC



**BeiDou**

2020 FOC?



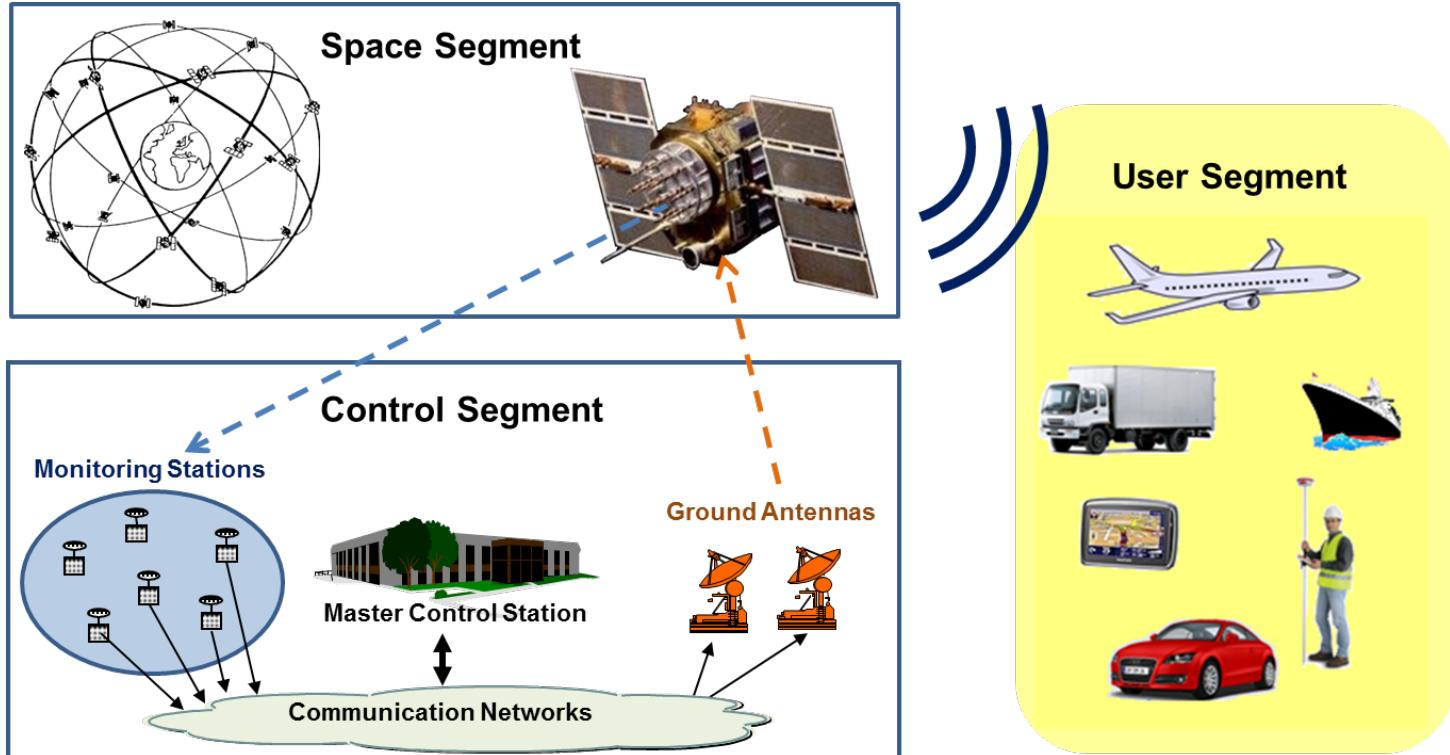
**Galileo**

2020 FOC ?

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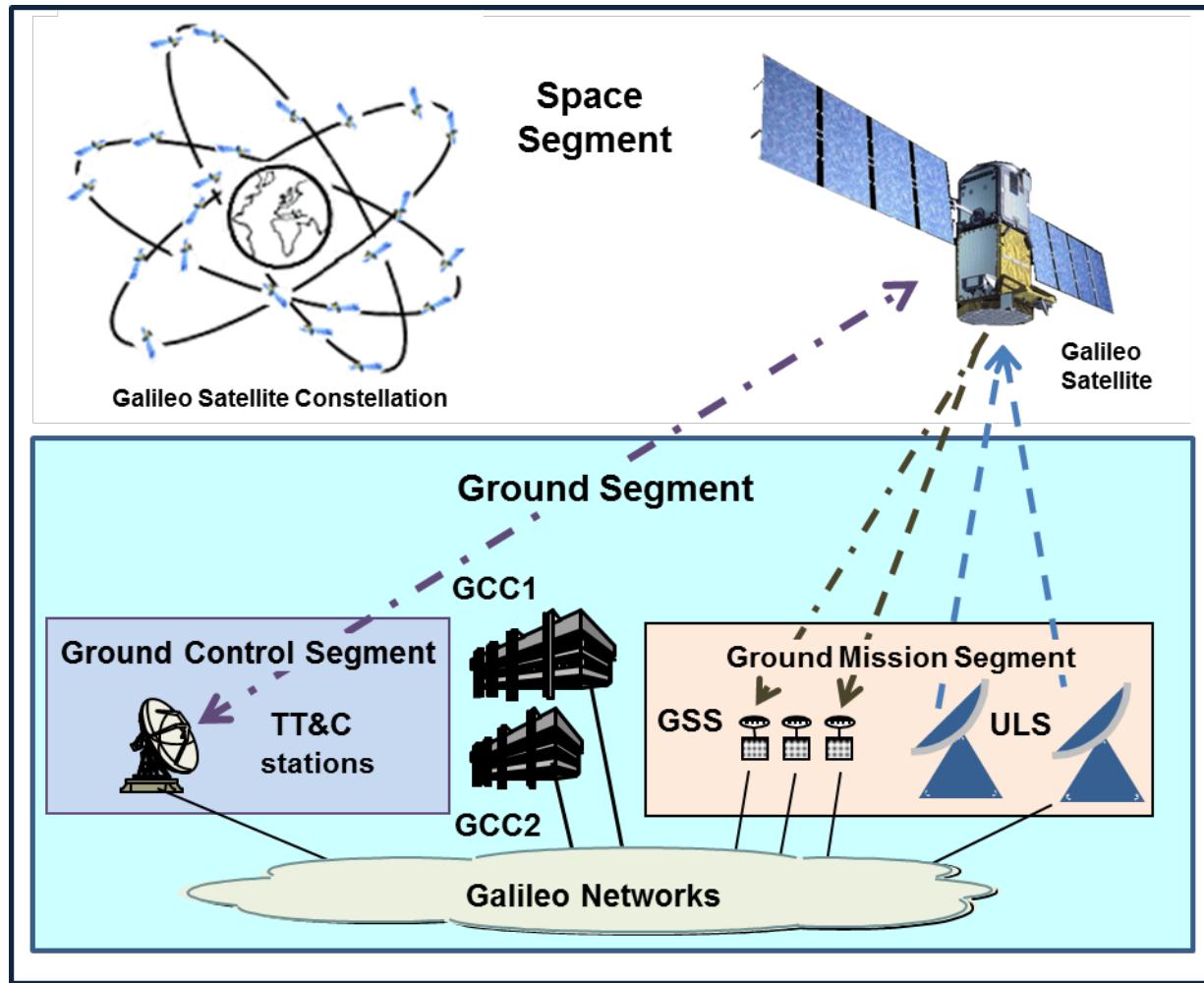
# GNSS Segments



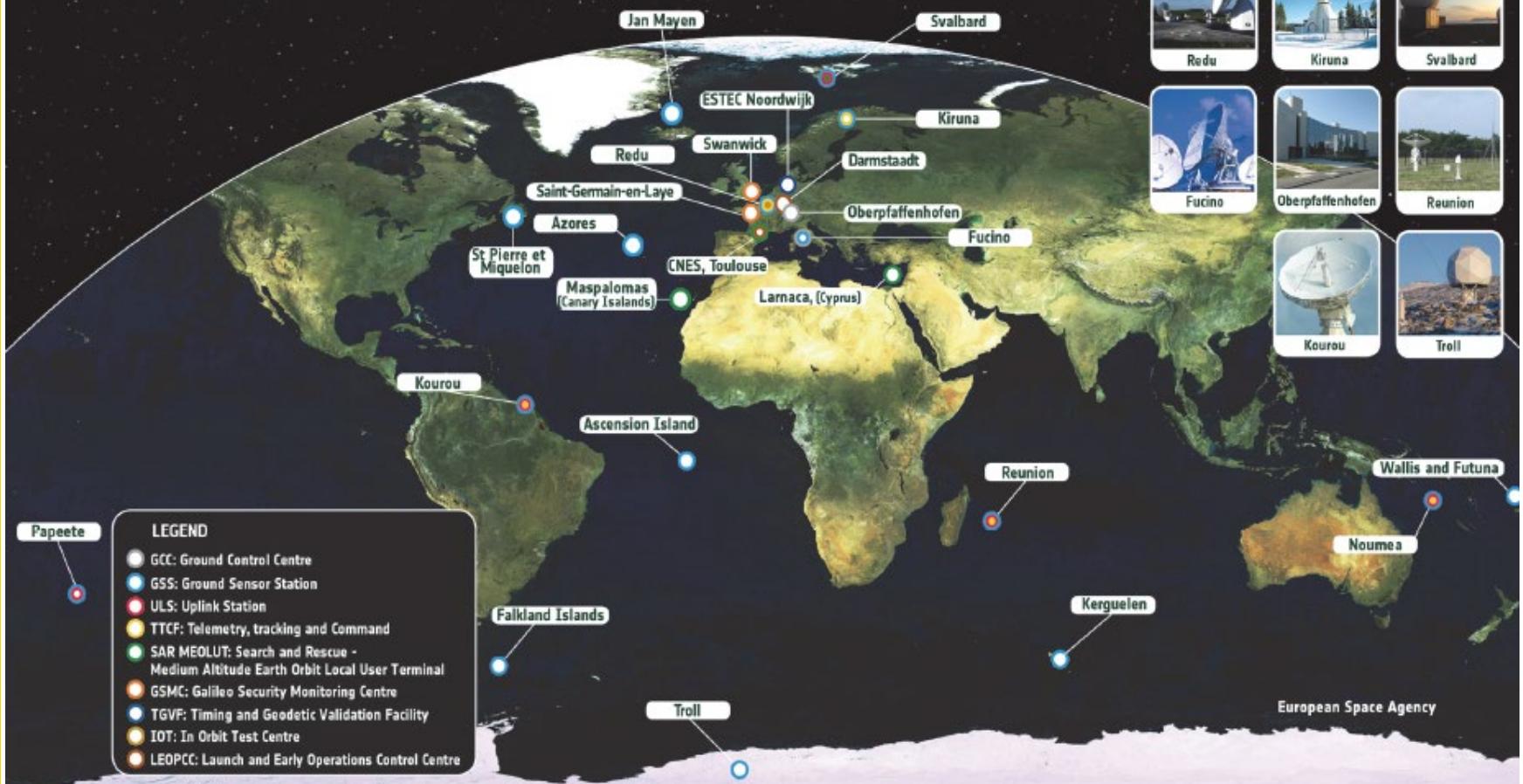
A GNSS basically consists of 3 main segments:

- Space segment: comprises the satellites
- Control (ground) segment: responsible of the proper operation of the system
- User segment: includes the GNSS receivers providing positioning, velocity and precise timing to users

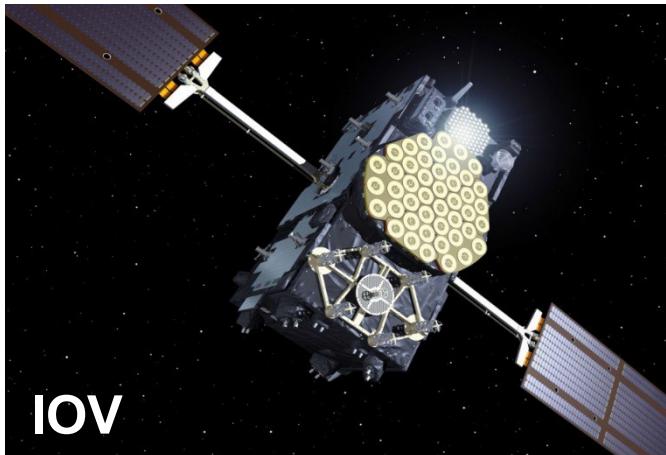
# Galileo Segments



## → GALILEO GROUND SEGMENT OVERVIEW



# Galileo Space Segment

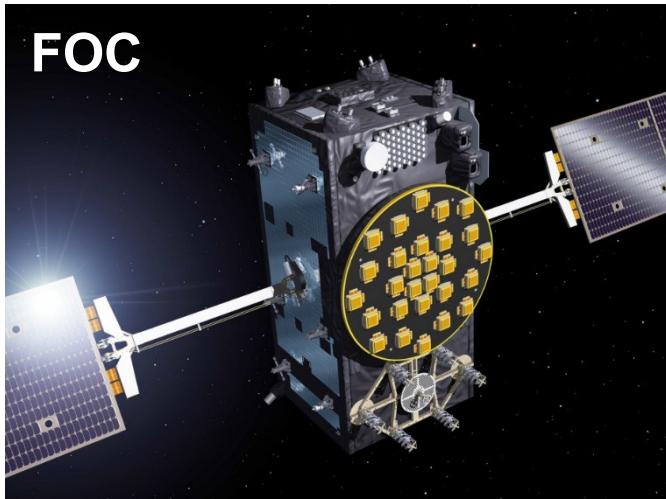


IOV

Spacecraft Prime Contractor Astrium GmbH  
(now Airbus Defence & Space)

**4 satellites – 4 In-Orbit (2011-2012)**

Mass at Launch	700 kg
Power Consumption	1.420 W
Dimensions	2,7 x 1,6 x 14,5 m
Orbit Injection	Direct into MEO orbit
Attitude Profile	Yaw Steered



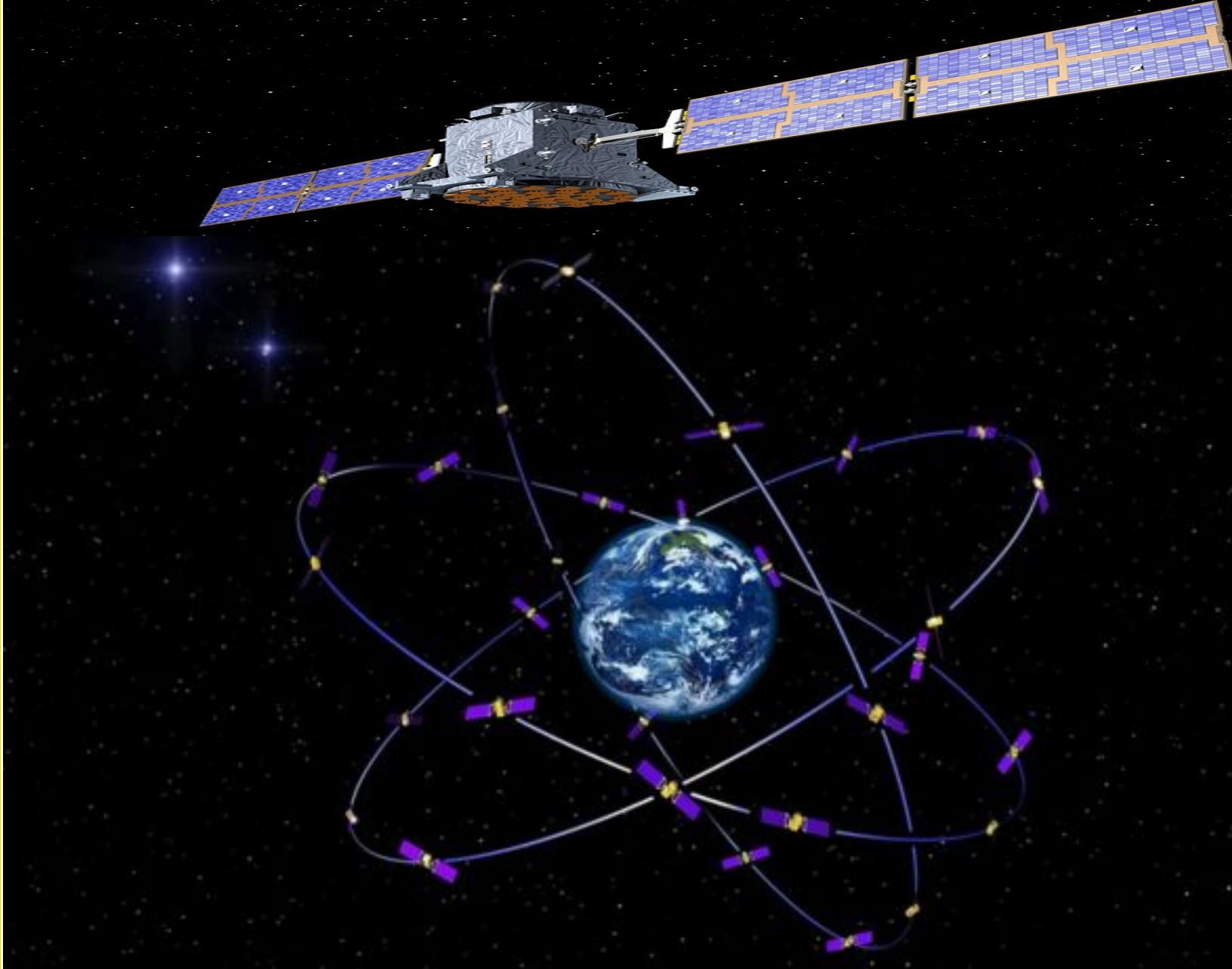
FOC

Spacecraft Prime Contractor OHB Systems GmbH  
Payload Prime Contractor SSTL Ltd

**26 satellites – 26 In-Orbit (2014-2019)**

Mass at Launch	733 kg
Power Consumption	1.900 W
Dimensions	2,5 x 1,1 x 14,7 m
Orbit Injection	Direct into MEO orbit
Attitude Profile	Yaw Steered

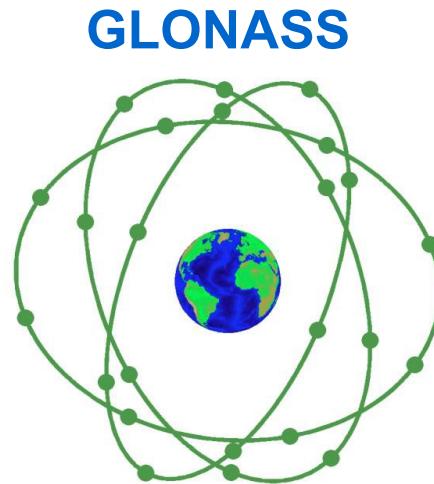
*Note: Medium Earth Orbiter (MEO)  
are at altitude of 23.222 km*



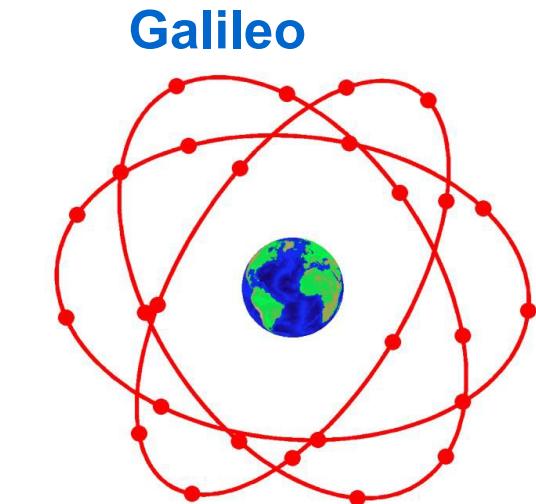
# Nominal constellations



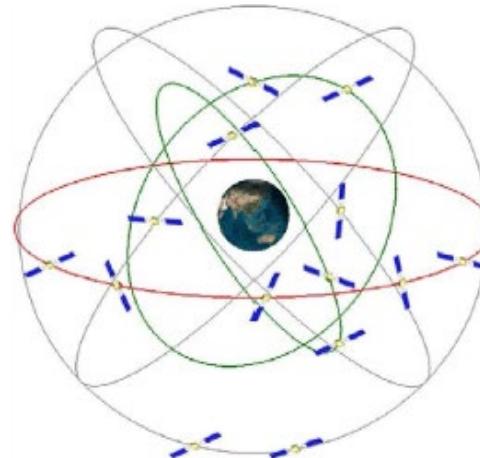
6 planes,  
4 sats each



3 planes,  
8 sats each

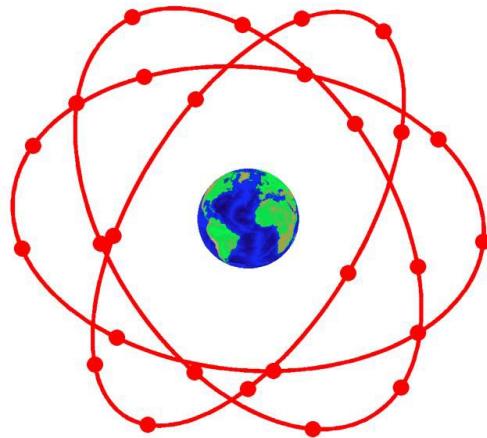


3 planes,  
9 sats each

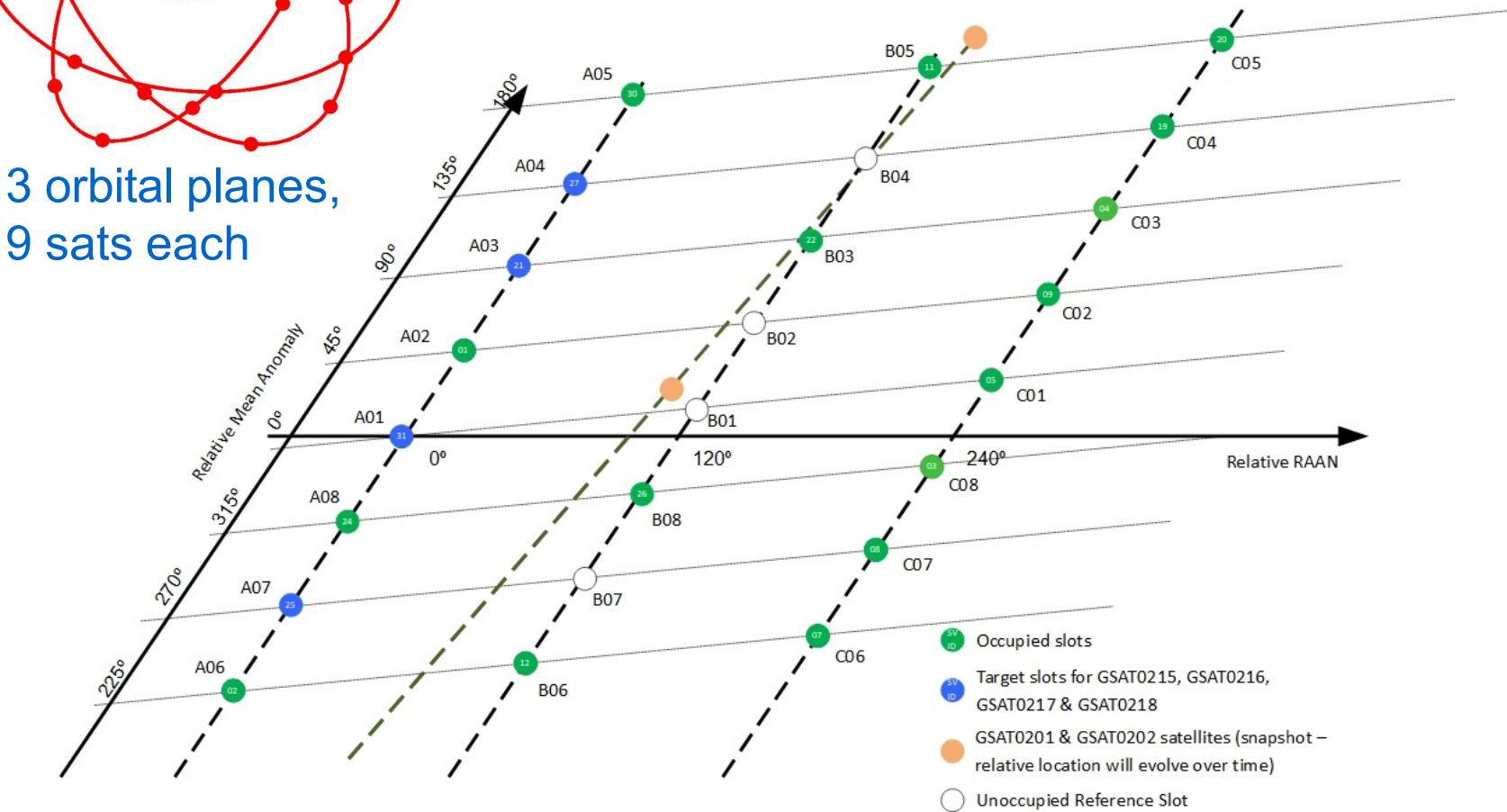


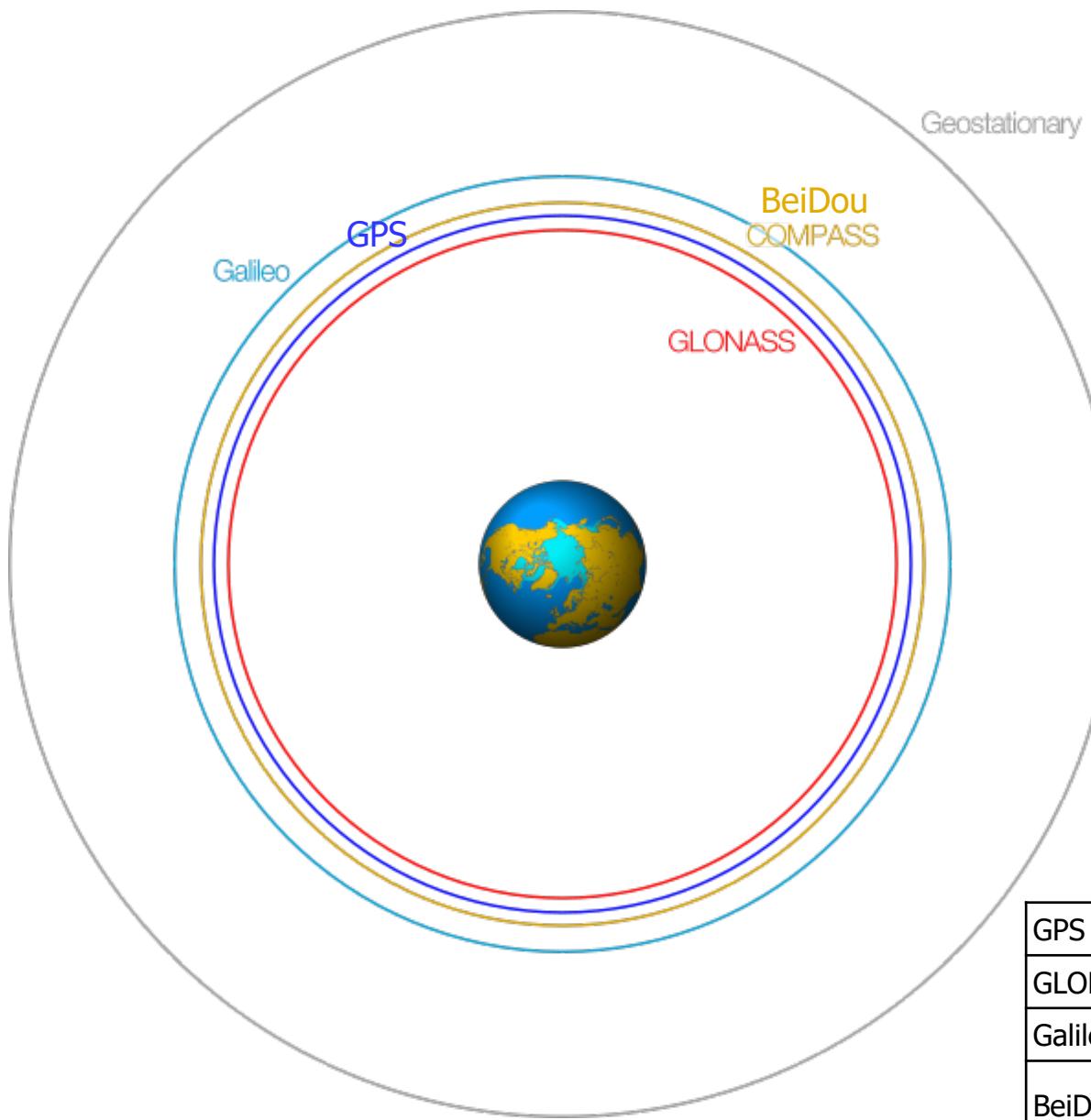
**BeiDou (COMPASS)**  
MEO: 3 planes,  
9 sats each  
IGSO: 3 planes  
1 sat each  
GEO: 5 GEO

# Galileo constellation



3 orbital planes,  
9 sats each





	Semi-Major Axis (km)	Orbit Period (h/m/s)
GPS	26 560	11h 58' 02"
GLONASS	25 460	11h 15' 44"
Galileo	29 582	14h 04' 45"
BeiDou	27 888 42 164	12h 53' 00" 23h 56'

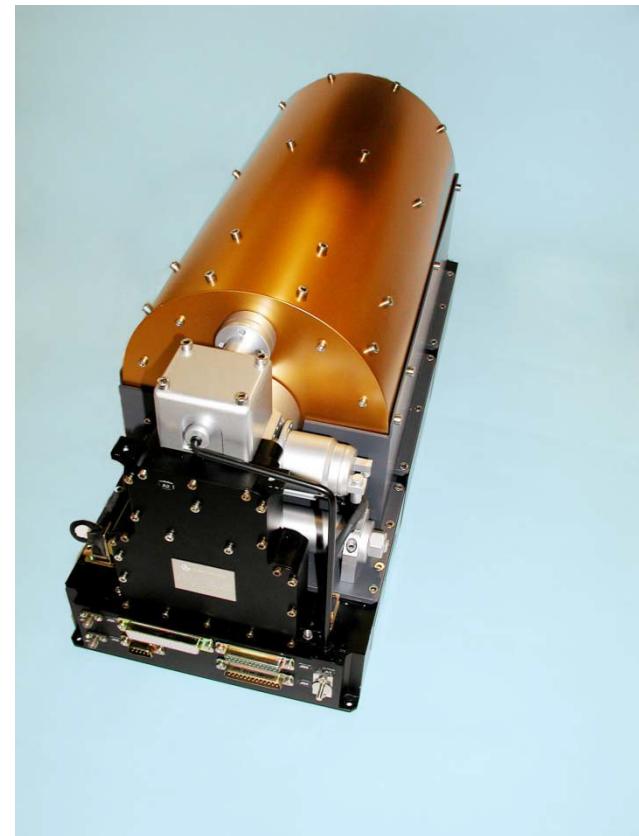
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# Galileo Clocks in Space

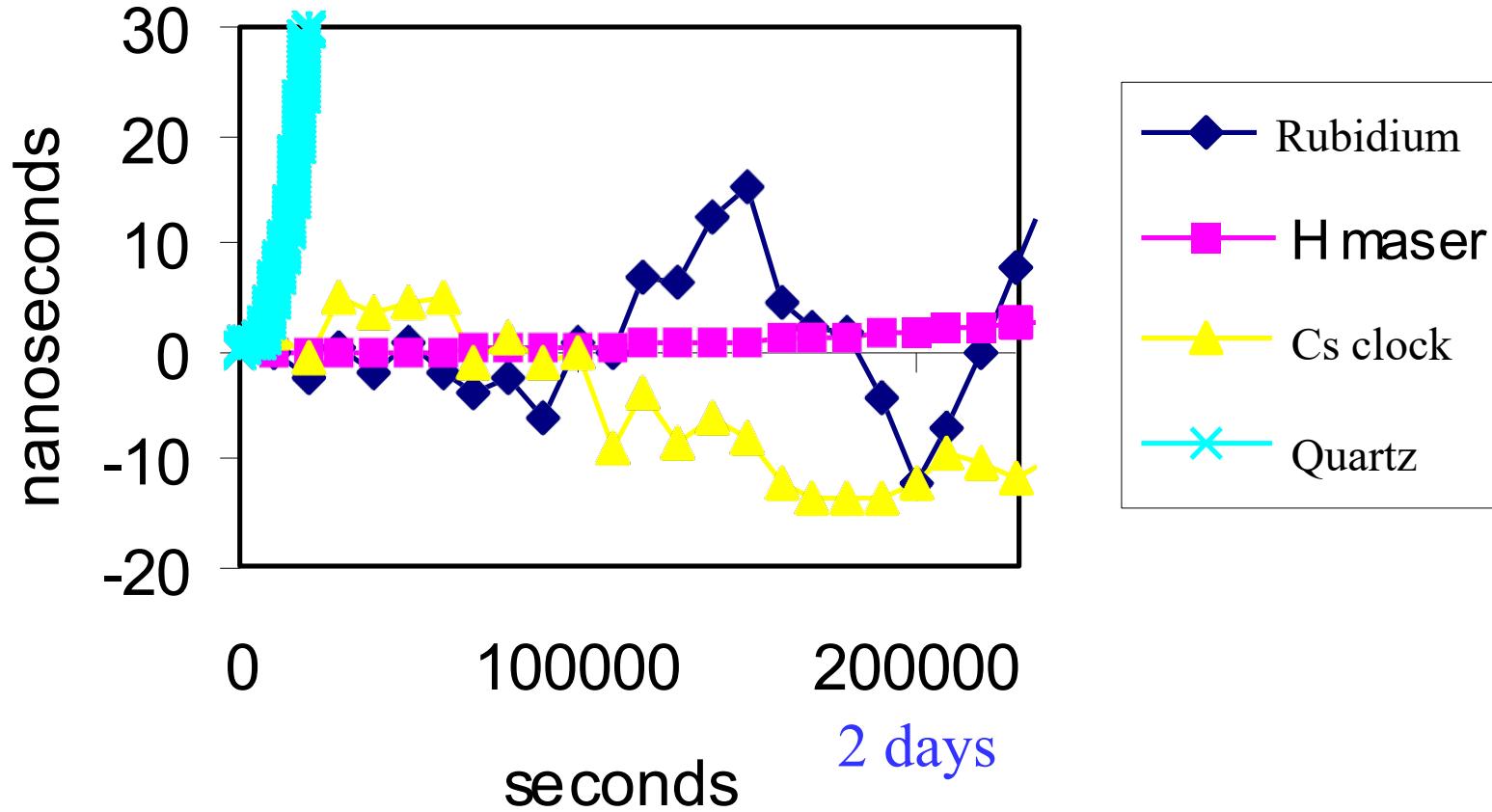


Rubidium Atomic  
Frequency Standard



FIRST Space Passive  
H-Maser

# Clocks stability



# Relativity effects can be measured with atomic clocks on board of satellites

- High velocity slows down clock
- Small gravitational potential (high altitude) accelerate clock

On board GPS/Galileo at 20.000 km

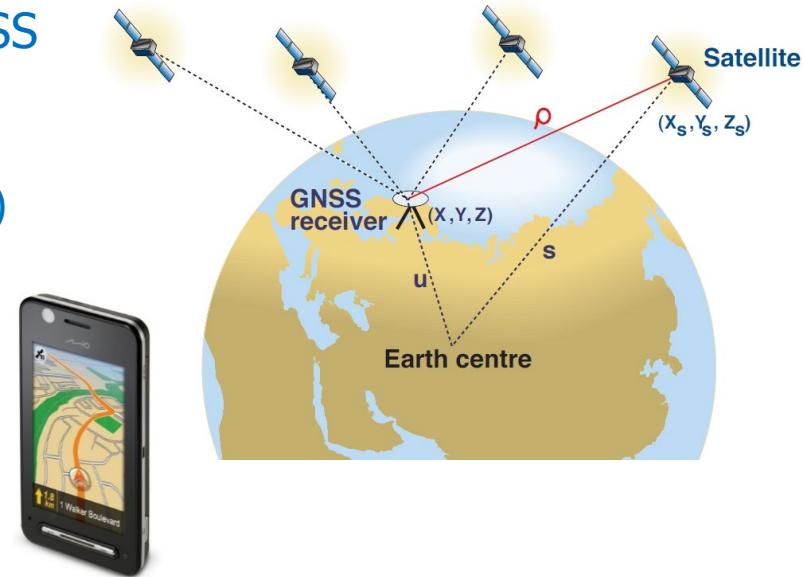
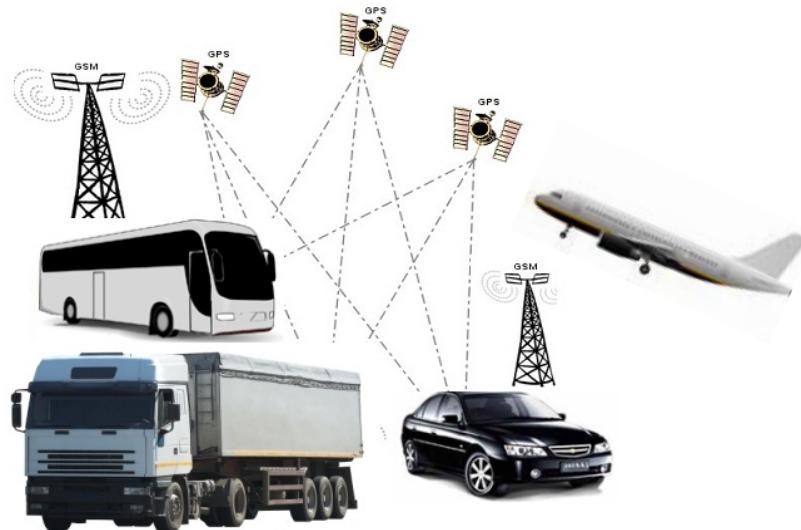
The effect is  $10^{-10}$  which means 1 millisecond / year

$$\frac{f'_0 - f_0}{f_0} = \frac{1}{2} \left( \frac{v}{c} \right)^2 + \frac{\Delta U}{c^2} = -4.464 \cdot 10^{-10}$$



# User Segment

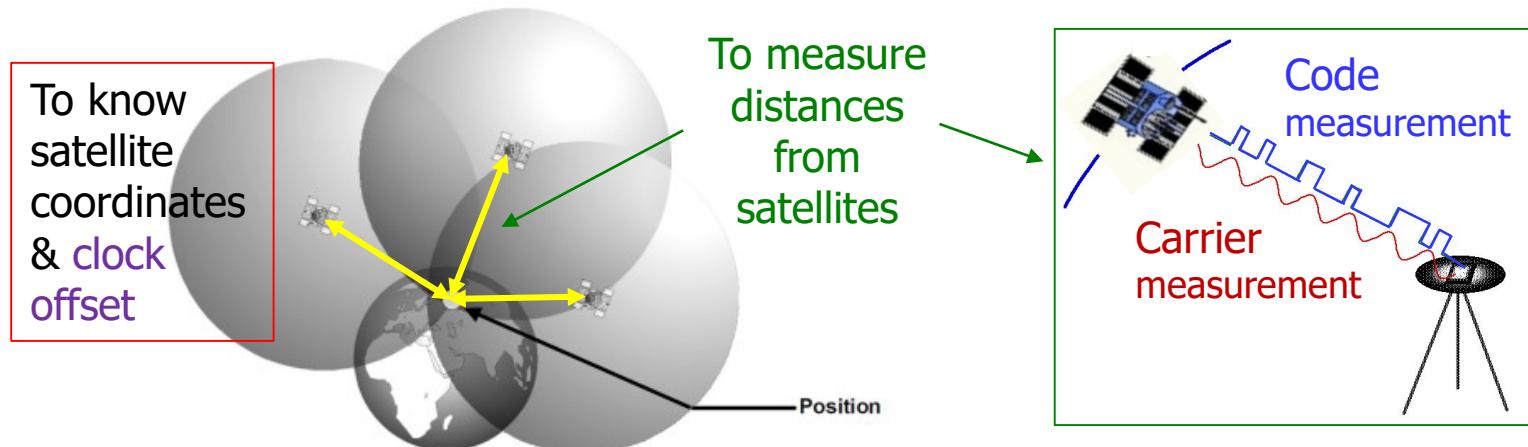
The user segment is composed of GNSS receivers. Their main function is to receive GNSS signals, determine pseudoranges (and other observables) and solve the navigation equations in order to obtain the coordinates and provide a very accurate time.



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# GNSS positioning concept



This picture is from <https://gpsfleettrackingexpert.wordpress.com>

- GNSS uses technique of “triangulation” to find user location
- To “triangulate” a GNSS receiver needs:
  - To know the satellite coordinates and **clock synchronism errors**:  
→ Satellites broadcast orbits parameters and clock offsets.
  - To measure distances from satellites:  
→ This is done measuring the **traveling time** of radio signals:  
("Pseudo-ranges": **Code** and **Carrier** measurements)  
→ Measurements must be corrected by several error sources:  
Atmospheric propagation, relativity, clock offsets, instrumental delays...

# Contents

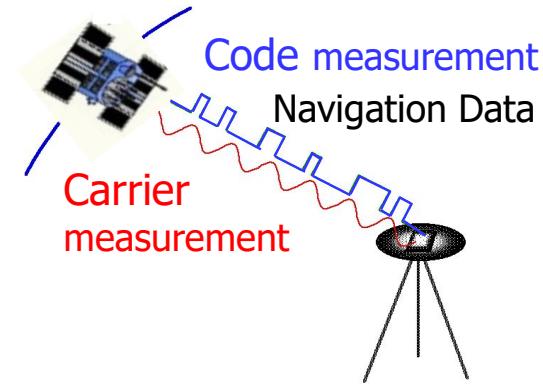
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# GNSS Signals

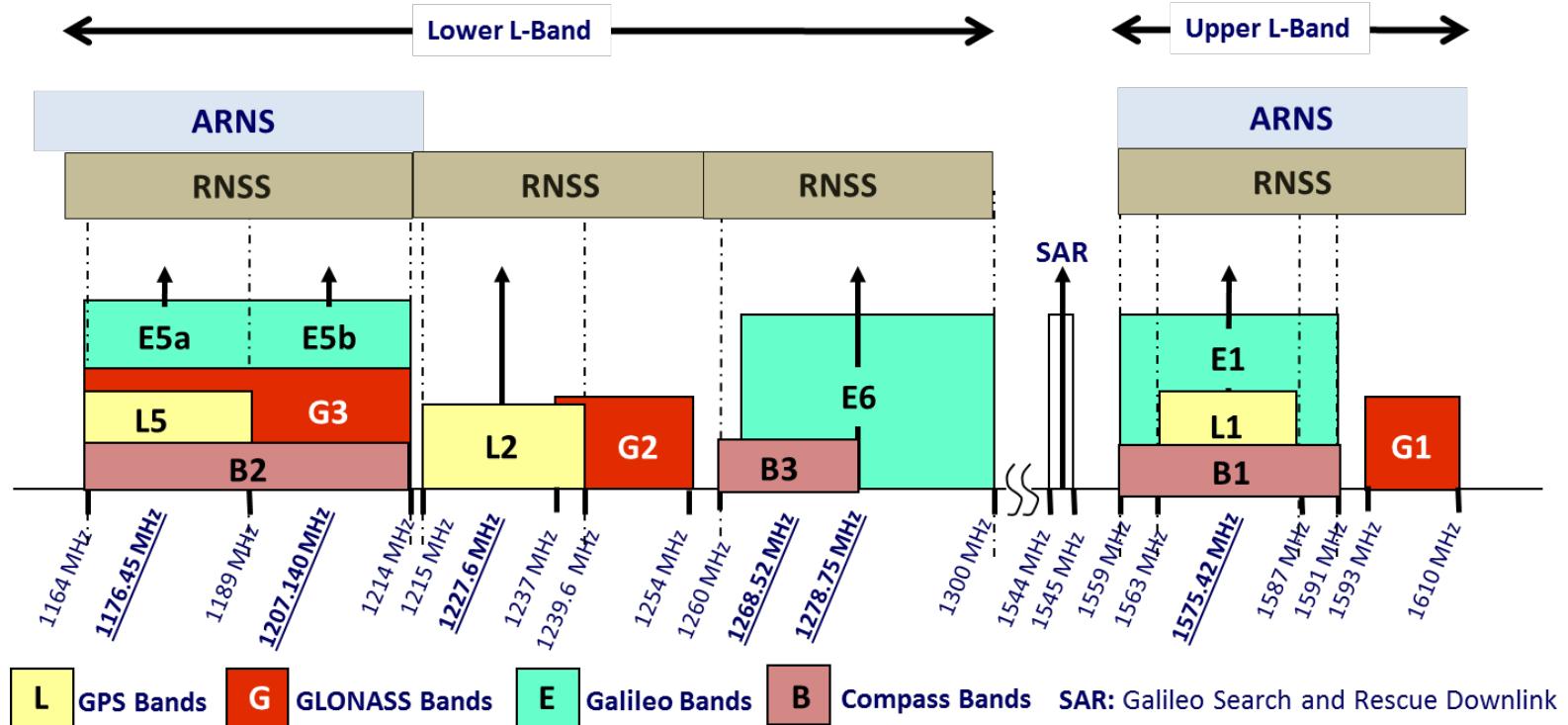
GNSS satellites continuously transmit navigation signals at two or more frequencies in L band.

These signals contain ranging codes and navigation data to allow users to compute both the travel time from the satellite to the receiver and the satellite coordinates at any epoch. The main signal components are described as follows:

- **Carrier:** Radio frequency sinusoidal signal at a given frequency.
- **Ranging code:** Sequences of zeros and ones which allow the receiver to determine the travel time of the radio signal from the satellite to the receiver. They are called Pseudo Random Number (PRN) sequences or PRN codes.
- **Navigation data:** A binary-coded message providing information on the satellite ephemeris (pseudo-Keplerian elements or satellite position and velocity), clock bias parameters, almanac, satellite health status and other complementary information.



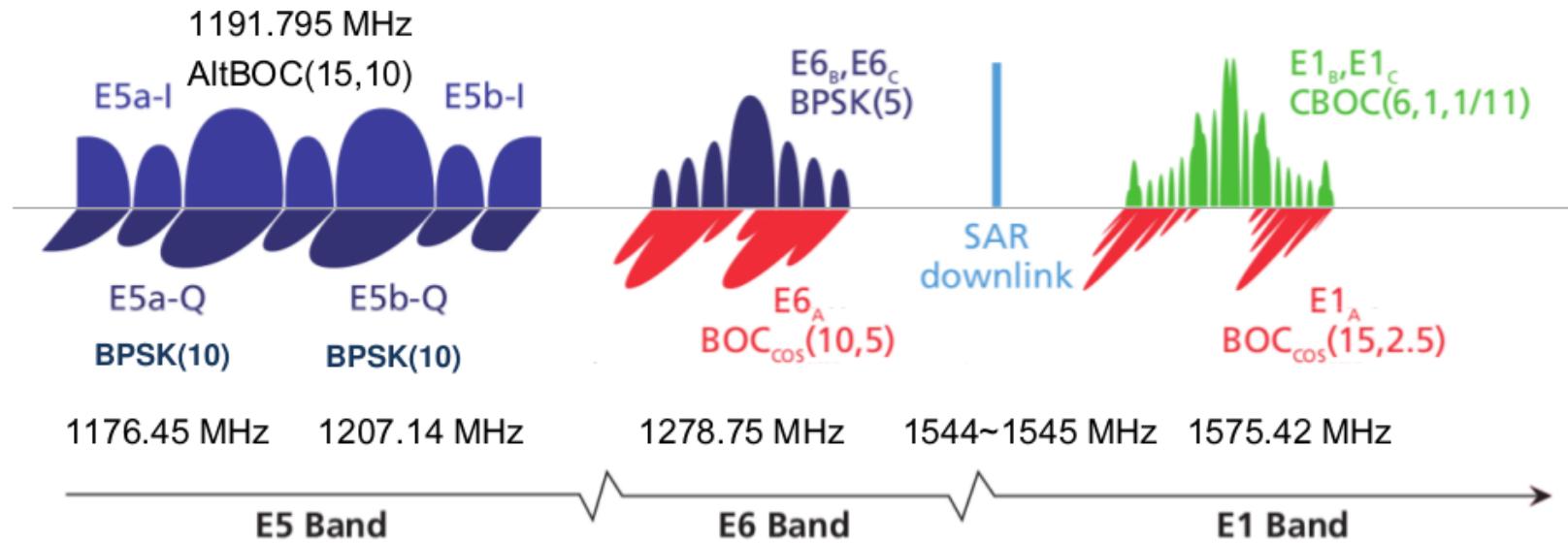
# GNSS Signals



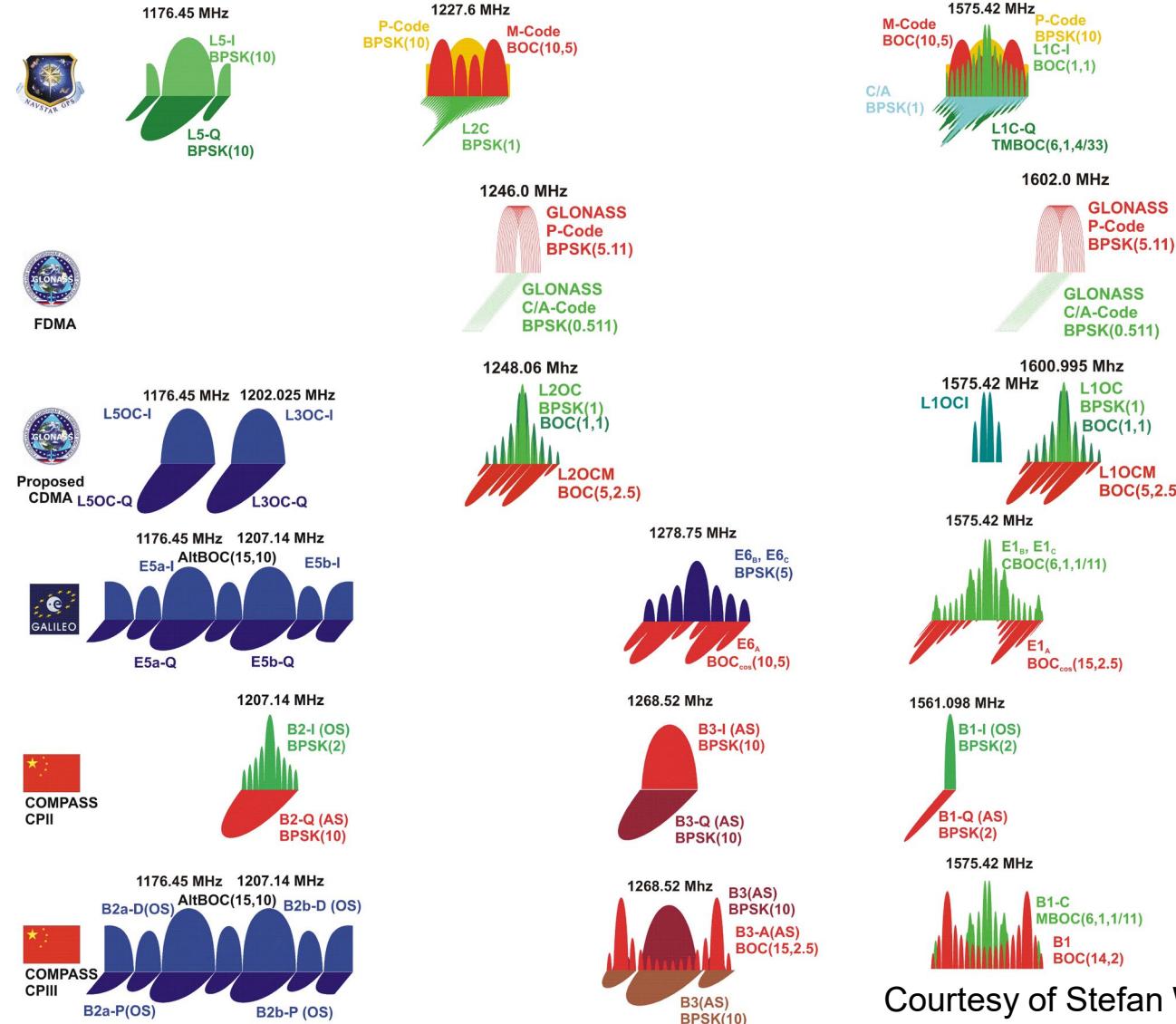
**ARNS:** Aeronautical Radio Navigation Service

**RNSS:** Radio Navigation Satellite Service

# Galileo Signals



# Signals and modulations implementations



Courtesy of Stefan Wallner

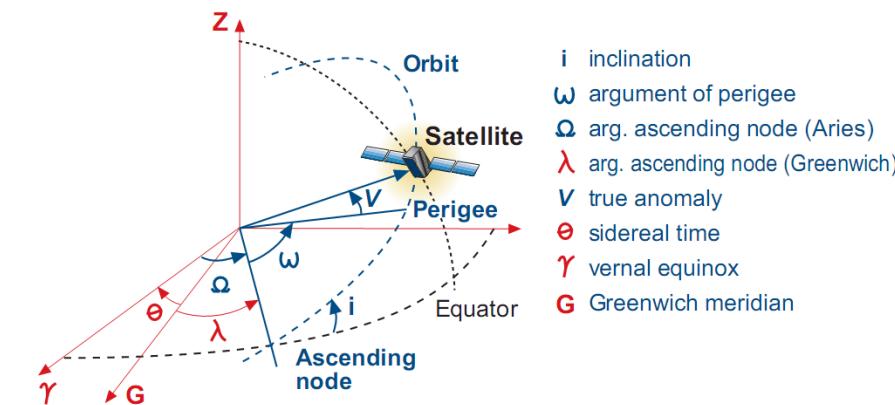
# Galileo Services

<b>Open Access</b>	Free (as GPS) Mass market	
<b>Public Regulated</b>	Controlled access to government authorized-users only High Availability	
<b>Commercial</b>	Under development Access controlled by CS provider High Accuracy	
<b>Search &amp; Rescue</b>	Near real-time relay of distress alarms to improve existing search & rescue serv. Return link feasible	

# GNSS Navigation Data

GPS/Galileo/Beidou broadcast ephemeris and clock message parameters.

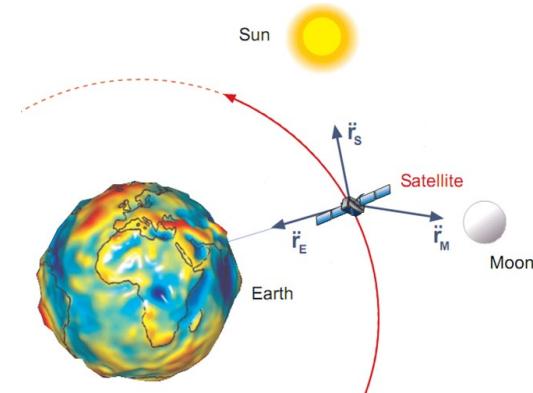
Parameter	Explanation
$t_{oe}$	Ephemerides reference epoch in seconds within the week
$\sqrt{a}$	Square root of semi-major axis
$e$	Eccentricity
$M_o$	Mean anomaly at reference epoch
$\omega$	Argument of perigee
$i_o$	Inclination at reference epoch
$\Omega_0$	Longitude of ascending node at the beginning of the week
$\Delta n$	Mean motion difference
$\dot{i}$	Rate of inclination angle
$\dot{\Omega}$	Rate of node's right ascension
$c_{uc}, c_{us}$	Latitude argument correction
$c_{rc}, c_{rs}$	Orbital radius correction
$c_{ic}, c_{is}$	Inclination correction
$a_0$	Satellite clock offset
$a_1$	Satellite clock drift
$a_2$	Satellite clock drift rate



Glonass broadcast ephemeris and clock message parameters.

Parameter	Explanation
$t_e$	Ephemerides reference epoch
$x(t_e)$	Coordinate at $t_e$ in PZ-90
$y(t_e)$	Coordinate at $t_e$ in PZ-90
$z(t_e)$	Coordinate at $t_e$ in PZ-90
$v_x(t_e)$	Velocity component at $t_e$ in PZ-90
$v_y(t_e)$	Velocity component at $t_e$ in PZ-90
$v_z(t_e)$	Velocity component at $t_e$ in PZ-90
$X''(t_e)$	Moon and Sun acceleration at $t_e$
$Y''(t_e)$	Moon and Sun acceleration at $t_e$
$Z''(t_e)$	Moon and Sun acceleration at $t_e$
$\tau_n(t_e)$	Satellite clock offset
$\gamma_n(t_e)$	Satellite relative frequency offset

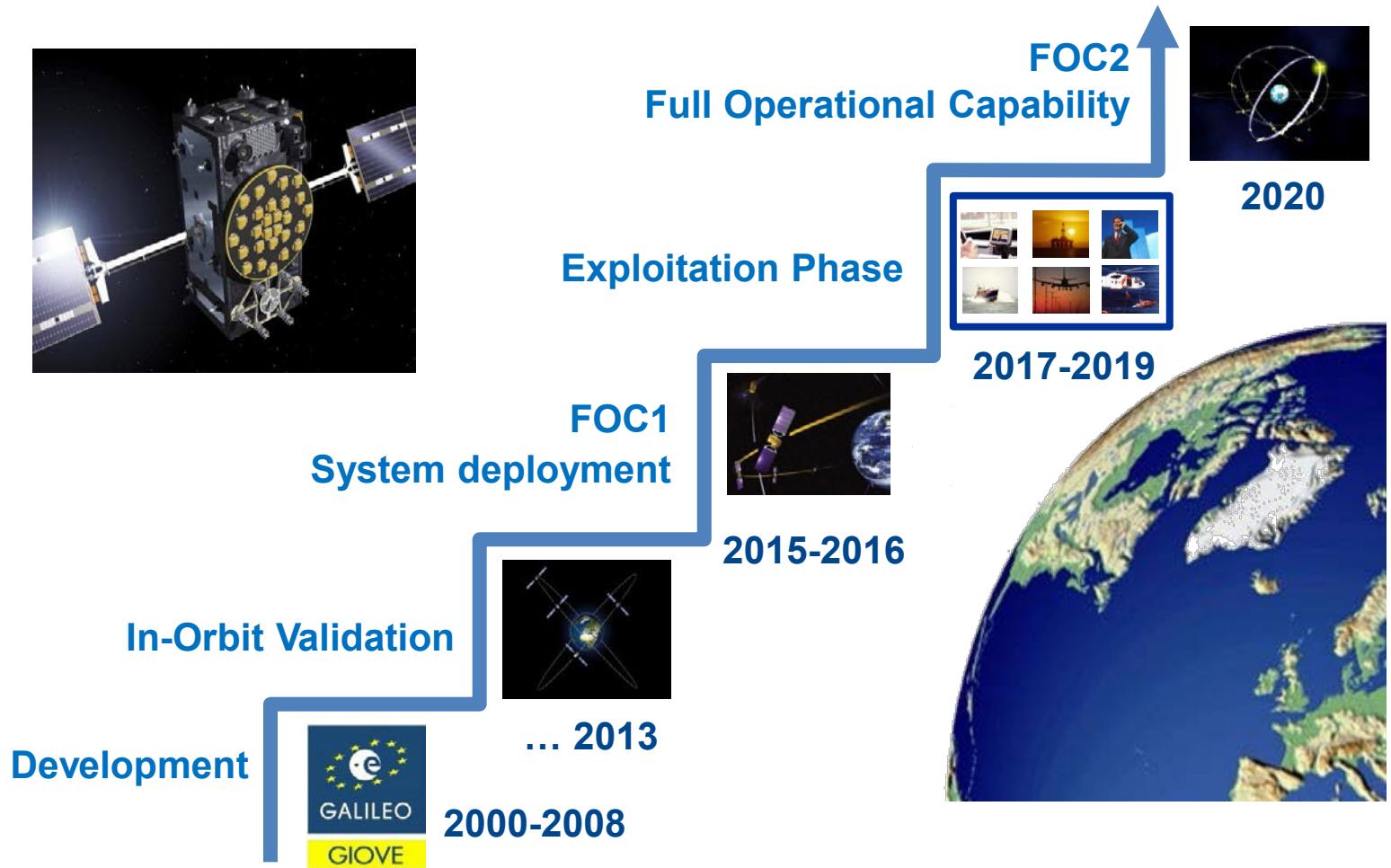
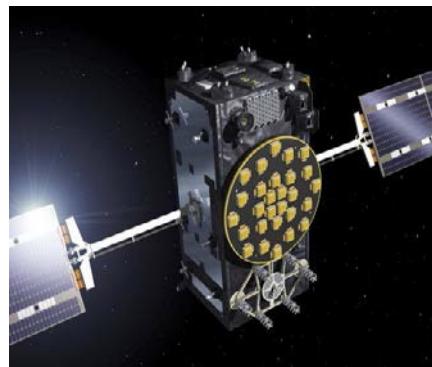
Fourth-order Ruge-Kutta orbit integration



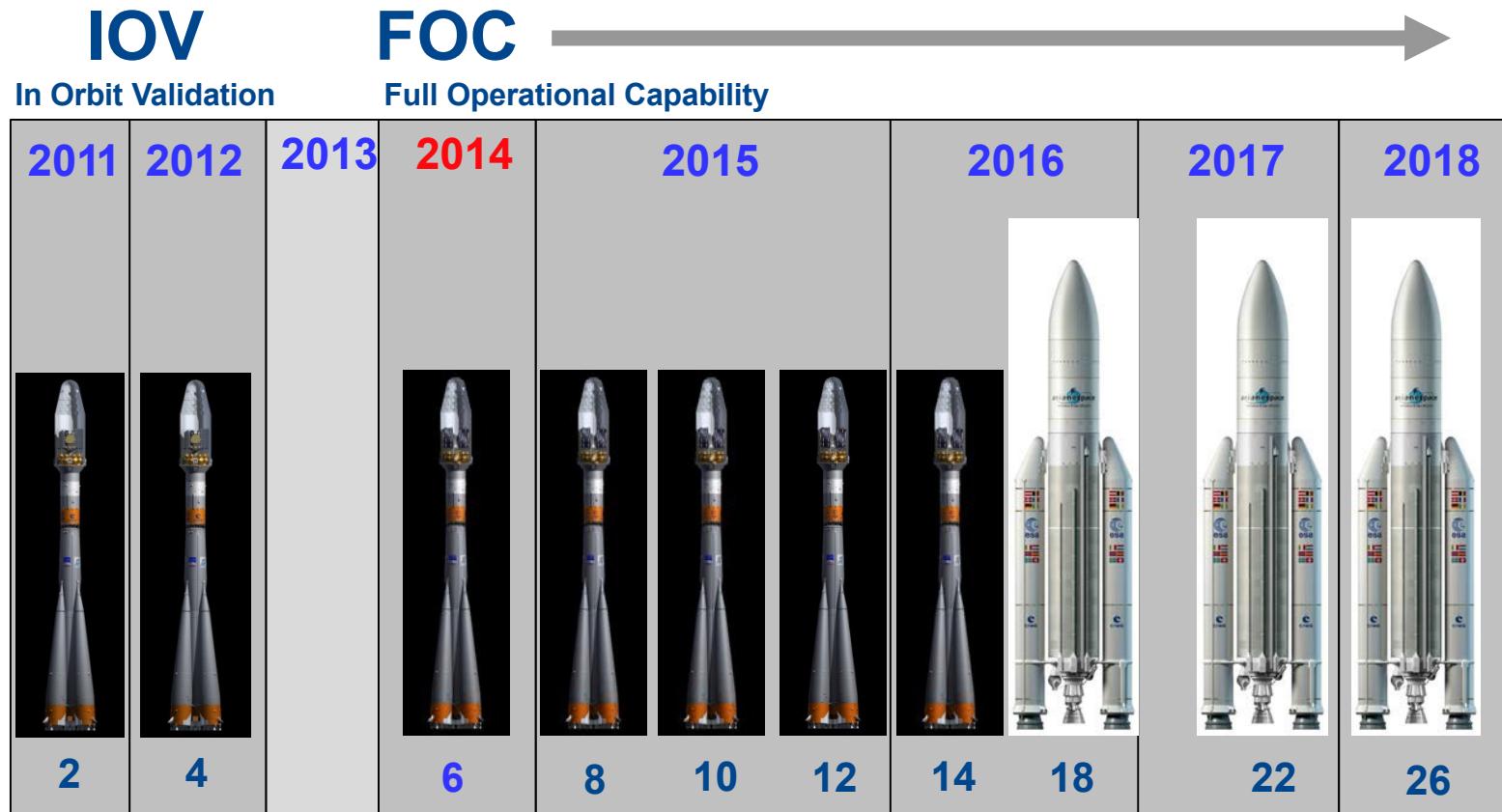
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# Deployment and exploitation of Galileo



# Galileo launch plan



# Galileo Constellation Status

15.03.18

Common Name	SVN	Int. Sat. ID	NORAD ID	NORAD Name	PRN Notes
IOV-1, Galileo PFM	E101	2011-060A	37846	GALILEO-PFM	E11 Slot B05
IOV-2, Galileo FM2	E102	2011-060B	37847	GALILEO-FM2	E12 Slot B06
IOV-3, Galileo FM3	E103	2012-055A	38857	GALILEO-FM3	E19 Slot C04
IOV-4, Galileo FM4	E104	2012-055B	38858	GALILEO-FM4	E20 Slot C05 Not available from 05/07/2014
FOC-1	E201	2014-050A	40128	GALILEO 5 (261)	E18 Orbit injection failure ( $i=49.7^\circ$ $e=0.23$ )
FOC-2	E202	2014-050B	40129	GALILEO 6 (262)	E14 Orbit injection failure ( $i=49.7^\circ$ $e=0.23$ )
FOC-3	E203	2015-017A	40544	GALILEO 7 (263)	E26 Slot B08
FOC-4	E204	2015-017B	40545	GALILEO 8 (264)	E22 Slot B03
FOC-5	E205	2015-045A	40889	GALILEO 9 (205)	E24 Slot A08 Not usable PLANNED OUTAGE
FOC-6	E206	2015-045B	40890	GALILEO 10 (206)	E30 Slot A05
FOC-8	E208	2015-079B	41174	GALILEO 12 (269)	E08 Slot C07
FOC-9	E209	2015-079A	41175	GALILEO 11 (268)	E09 Slot C02
FOC-10	E210	2016-030B	41550	GALILEO 13 (26A)	E01 Slot A02
FOC-11	E211	2016-030A	41549	GALILEO 14 (26B)	E02 Slot A06
FOC-7	E207	2016-069A	41859	GALILEO 15 (267)	E07 Slot C06
FOC-12	E212	2016-069B	41860	GALILEO 16 (26C)	E03 Slot C08
FOC-13	E213	2016-069C	41861	GALILEO 17 (26D)	E04 Slot C03
FOC-14	E214	2016-069D	41862	GALILEO 18 (26E)	E05 Slot C01
FOC-15	E215	2017-079A	43055	GALILEO 19 (2C5)	E21 Slot A03
FOC-16	E216	2017-079B	43056	GALILEO 20 (2C6)	E25 Slot A07
FOC-17	E217	2017-079C	43057	GALILEO 21 (2C7)	E27 Slot A04
FOC-18	E218	2017-079D	43058	GALILEO 22 (2C8)	E31 Slot A01
FOC-19	E219	2018-060C	43566	GALILEO 23 (2C9)	E36 Slot B04
FOC-20	E220	2018-060D	43567	GALILEO 24 (2C0)	E13 Slot B01
FOC-21	E221	2018-060A	43564	GALILEO 25 (2C1)	E15 Slot B02
FOC-22	E222	2018-060B	43565	GALILEO 26 (2C2)	E33 Slot B07 Not usable UNTIL FURTHER NOTICE

[http://mgex.igs.org/IGS\\_MGEX\\_Status\\_GAL.php](http://mgex.igs.org/IGS_MGEX_Status_GAL.php)

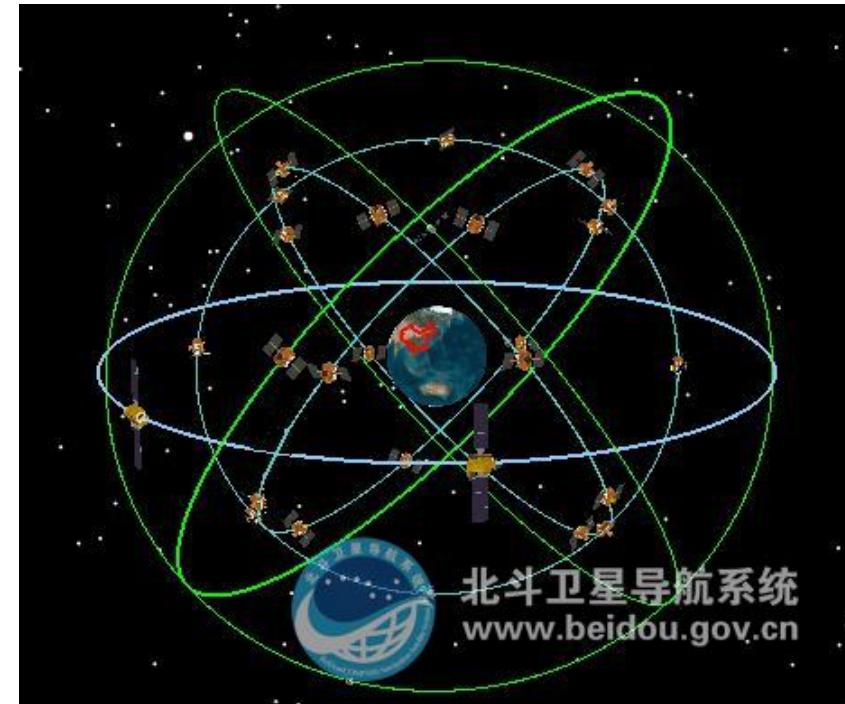
# BeiDou Constellation Status

At May 2019, 34 satellites are operational:

- 6 in geostationary orbits,
- 7 in 55-degree inclined geosynchronous orbits
- 21 in medium Earth orbits.

The full constellation is scheduled to comprise 35 satellites.

FOC planned for year 2020.



<https://www.glonass-iac.ru/en/BEIDOU/>

# GPS and GLONASS Constellation Status

## GPS CONSTELLATION STATUS, 10.05.2019

Total satellites in constellation	32
<b>Operational</b>	<b>31</b>
In commissioning phase	-
In maintenance	1
In decommissioning phase	-

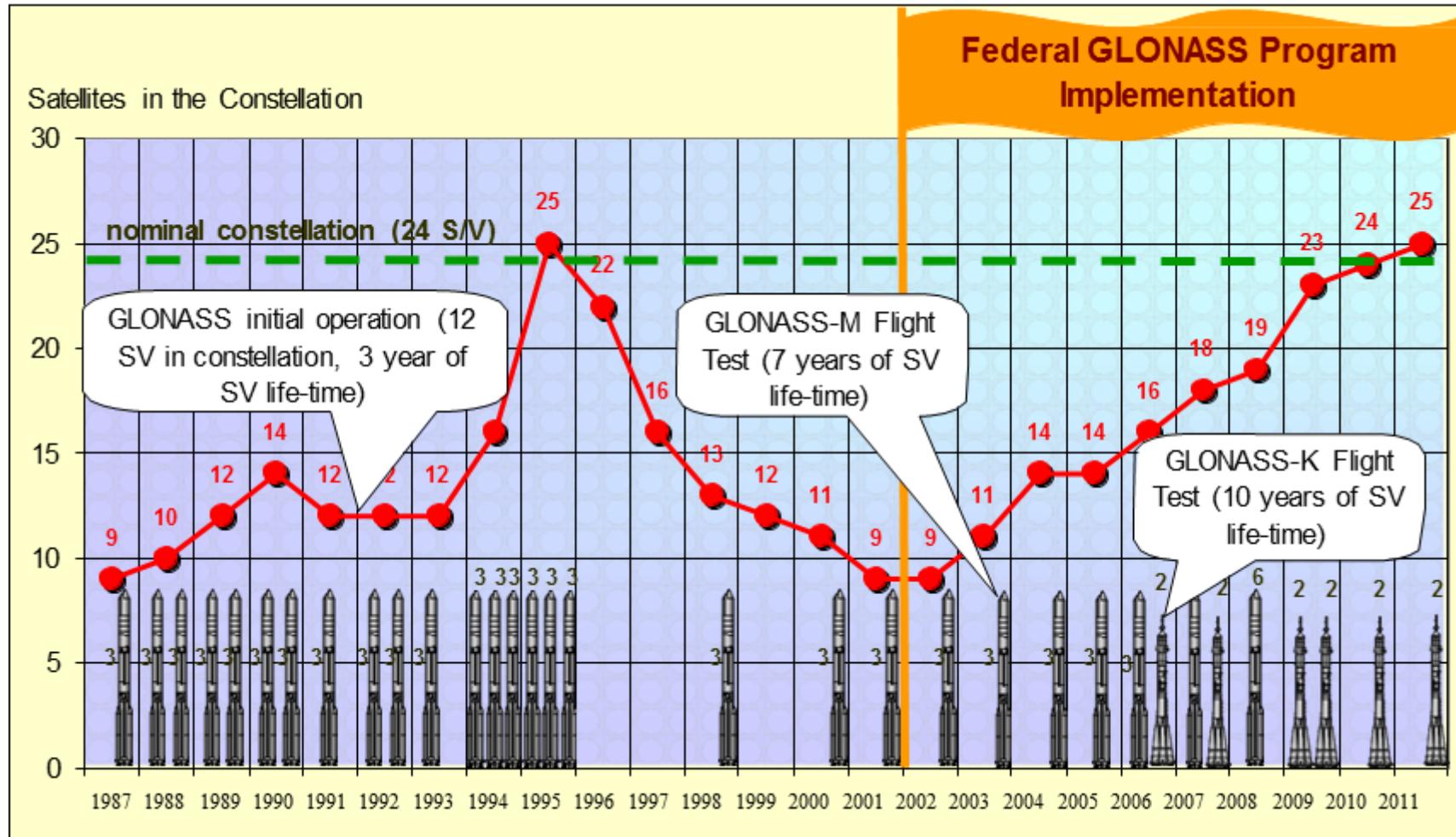
<https://www.glonass-iac.ru/en/GPS/>

## GLONASS CONSTELLATION STATUS, 10.05.2019

Total satellites in constellation	26
<b>Operational</b>	<b>24</b>
In commissioning phase	-
In maintenance	-
Under check by the Satellite Prime Contractor	-
Spares	1
In flight tests phase	1

<https://www.glonass-iac.ru/en/GLONASS/>

# GLONASS Constellation Evolution



By 2010 has achieved again 100% coverage of Russia's territory and in October 2011 the full orbital constellation of 24 satellites was restored, enabling full global coverage

GLONASS Program is in progress and has been extended to 2020 by which time the system is scheduled to have all satellites transmitting both the new CDMA and legacy FDMA signals.

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# Performance requirements for Galileo Services

Satellite-only Service	Open Service	Commercial Service	Public Regulated Service
Coverage	Global	Global	Global
Accuracy (95%) Single-freq. <sup>(1)</sup> Dual-freq.	15 m/24 m H; 35 m V 4 m H; 8 m V		15 m/24 m H; 35 m V 6.5 m H; 12 m V
Timing accuracy (95%) <sup>(2)</sup>	30 ns	30 ns	30 ns
Service availability	99.5%	99.5%	99.5%
Access control	Free open access	Controlled access of ranging codes and navigation data message	Controlled access of ranging codes and navigation data message
Certification and service guarantees	–	Guarantee of service possible	Built for accreditation and guarantee of service

(1) Single-frequency accuracy depends on which frequency is used.

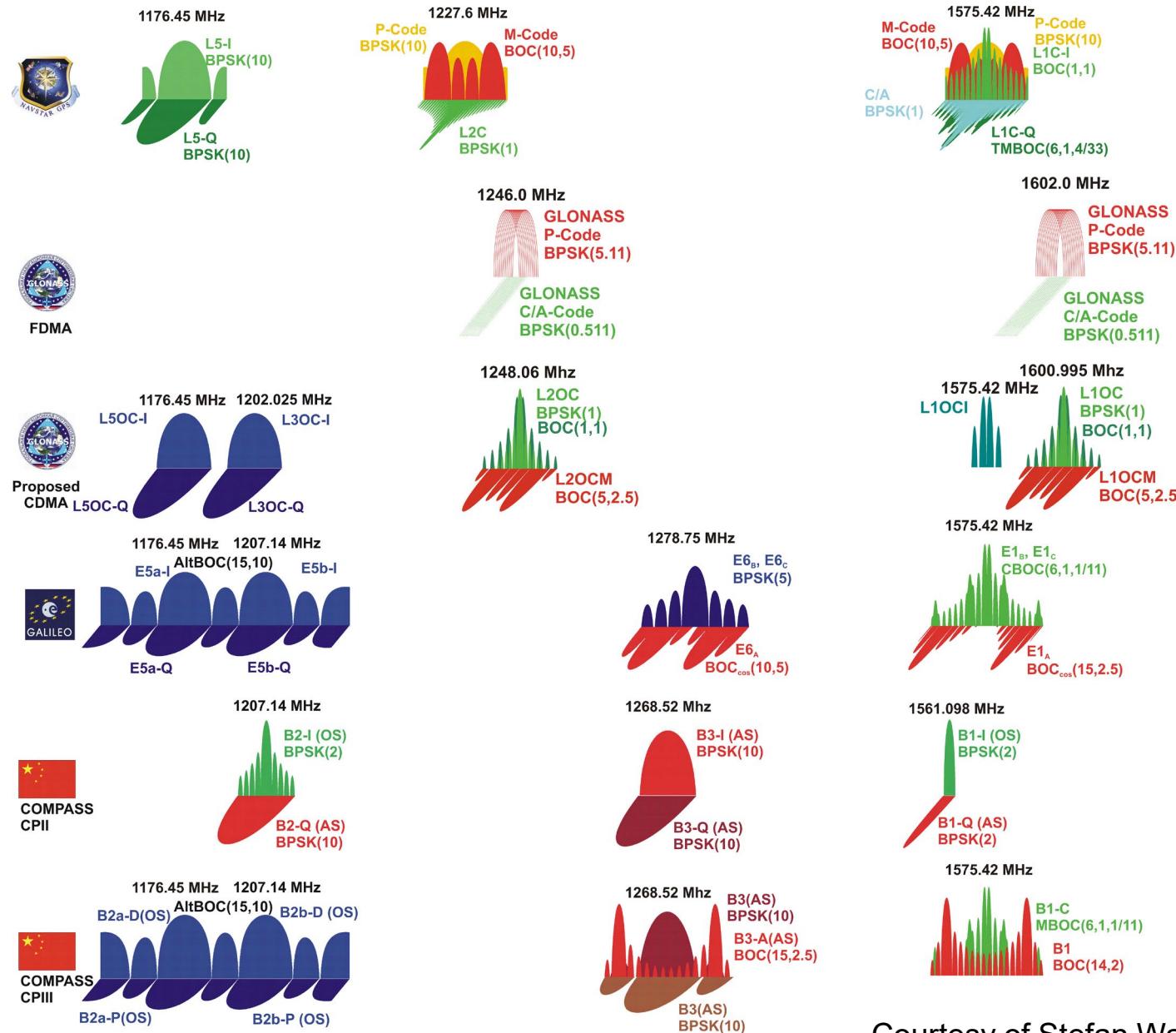
(2) Offset Galileo to UT over 24 h.

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# GNSS Systems Comparison

System	GPS	GLONASS	BeiDou	Galileo
Owner	United States	Russian Fed.	China	European Union
Coding	CDMA	FDMA (CDMA)	CDMA	CDMA
Orbit Height	20,180 km	19,130 km	21,150 km (MEO) 35,786 km	23,222 km
Period	11 h 58 m	11 h 16 m	12 h 38 m (MEO) 23h 56m	14 h 5 m
Revolutions / sidereal days	2/1	17/8	17/9 (MEO) 1/1	17/10
Number of Satellites	24	24	27(MEO) 3 (ISGO), 5 (GEO)	27
Accuracy	3,5 - 7,8 m	5-10 m	10 m	1-5 m
Frequency (RINEX Notation)	L1,L2,L5	L1, L2, (L5)	L1,L2,L6,L7	L1, L5, L6,L7,L8
Status	Operational	Operational	Deploying	Deploying

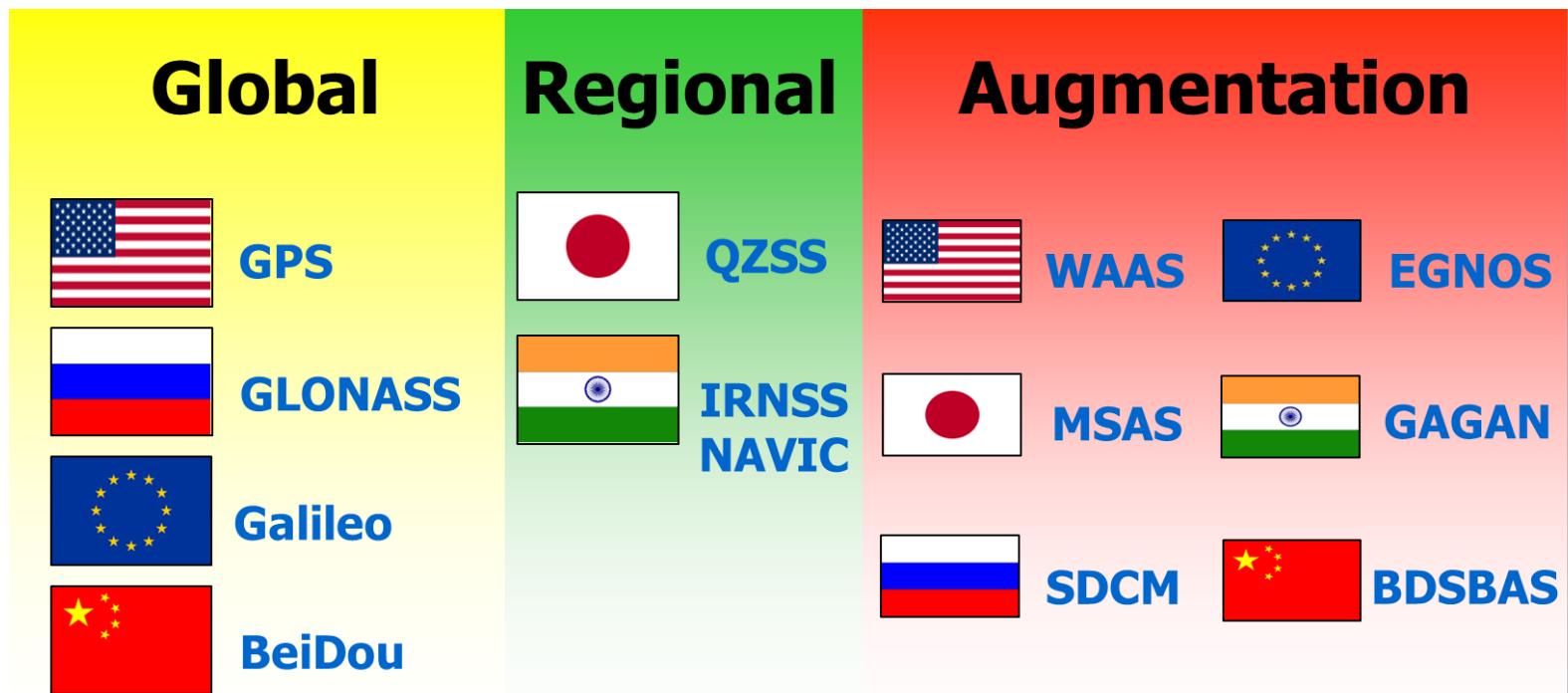


Courtesy of Stefan Wallner

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  - 2.1 Galileo Ground and Space Segments. Satellite Constellations
  - 2.2 Galileo Clocks in space: Clocks stability
3. GNSS positioning Concept
4. GNSS signals
  - 3.1 Galileo signals and services
5. Deploy and Exploitation of Galileo
6. Performance of Galileo Req. for Galileo Services
7. Comparison between the different GNSSs
8. The more satellites the better?

# Current and Planned Navigation Satellite Systems



Source: Guenter W. Hein  
ESA/JRC International Summer School on GNSS 2016

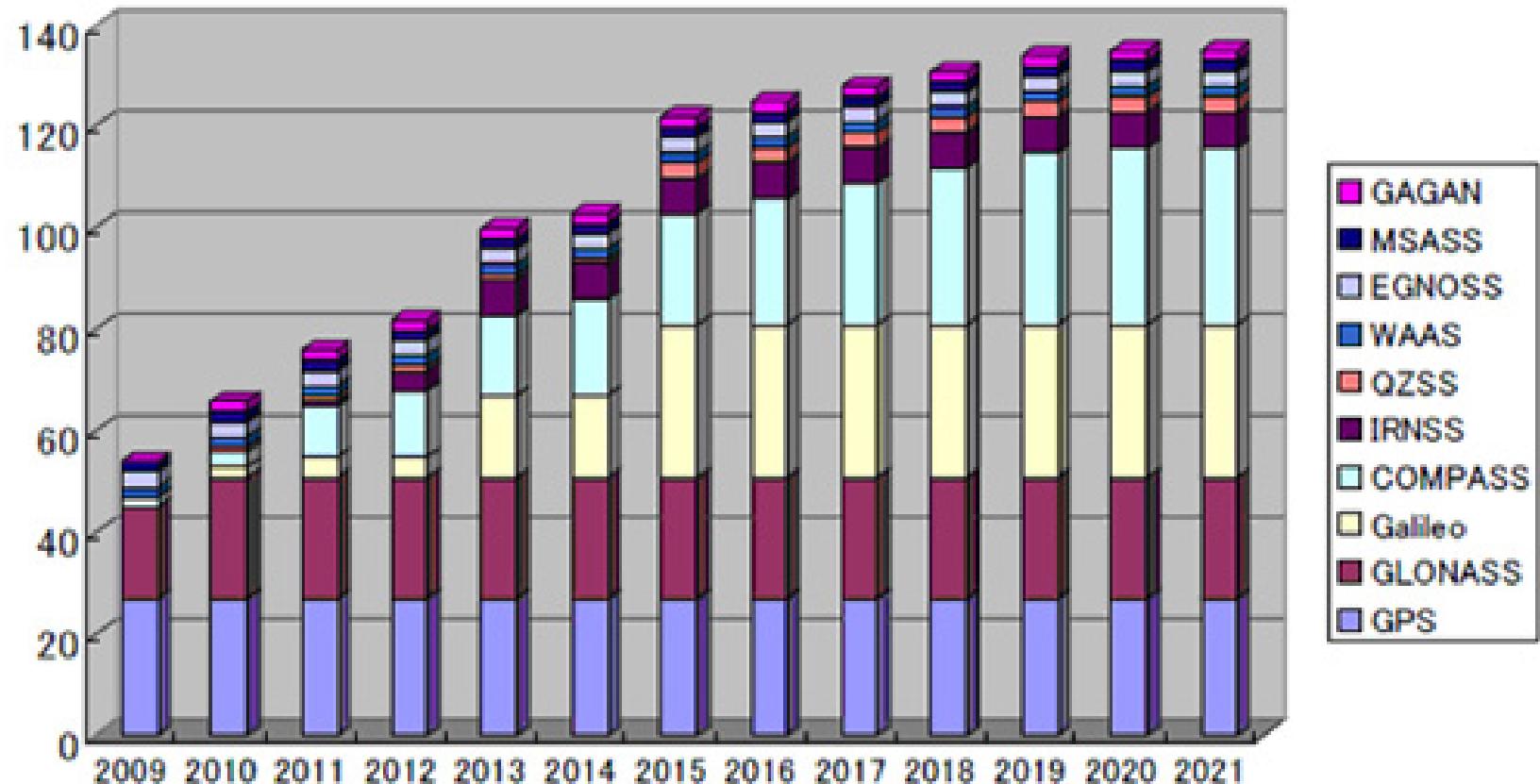
# Nominal Number of Satellites

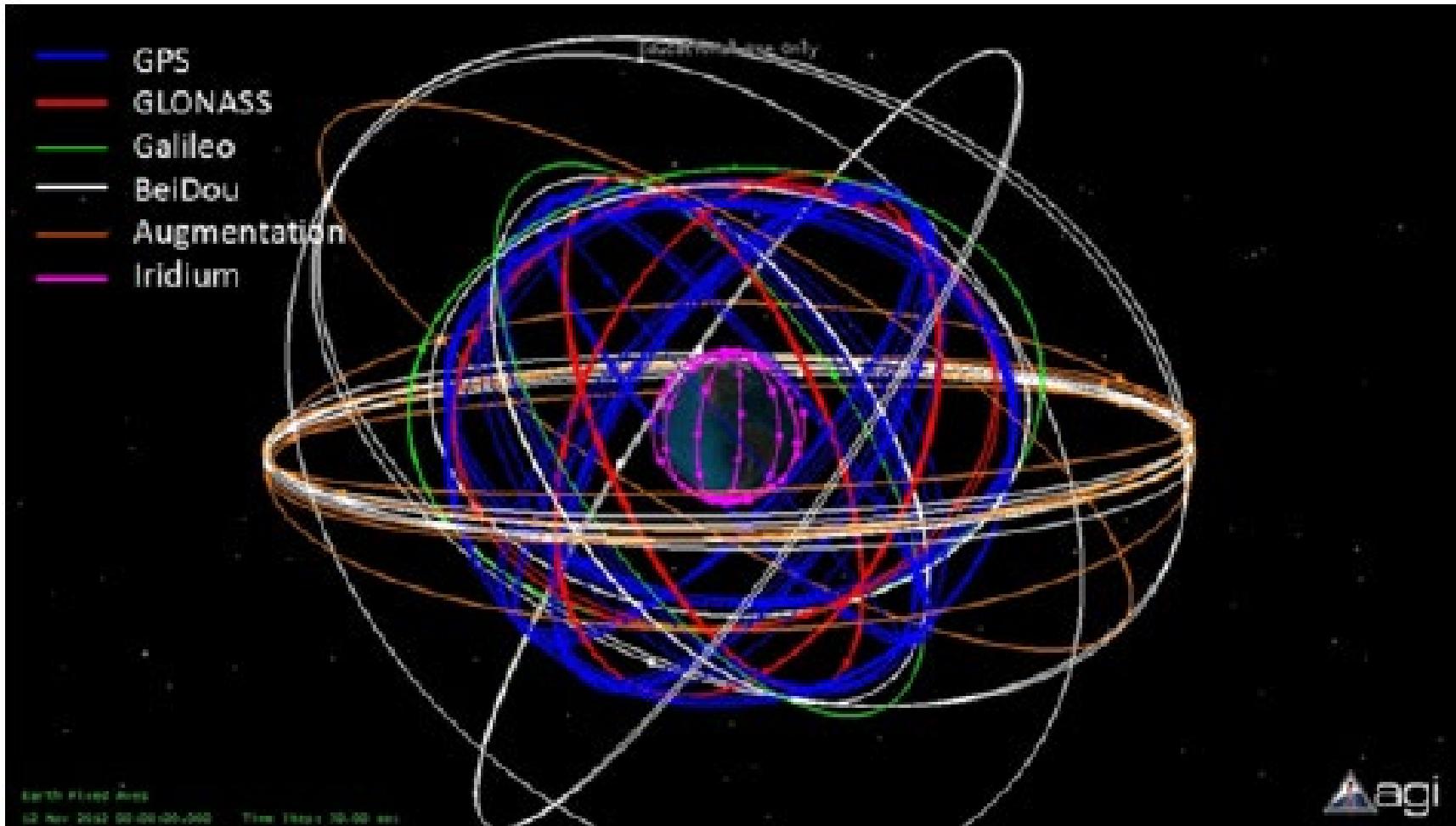


Source: Guenter W. Hein  
ESA/JRC International Summer School on GNSS 2016

<b>GLOBAL CONSTELLATIONS</b>	
GPS	24+3
GLONASS	24+2
Galileo	27+3
BeiDou	
27MEO+3	IGSO+5 GEO
<b>REGIONAL CONSTELLATIONS</b>	
QZSS	4+3
NAVIC (IRNSS)	7
SBAS (GEOS)	
WAAS	3
MSAS	2
EGNOS	3
GAGAN	2
SDCM	3
BDSBAS	3

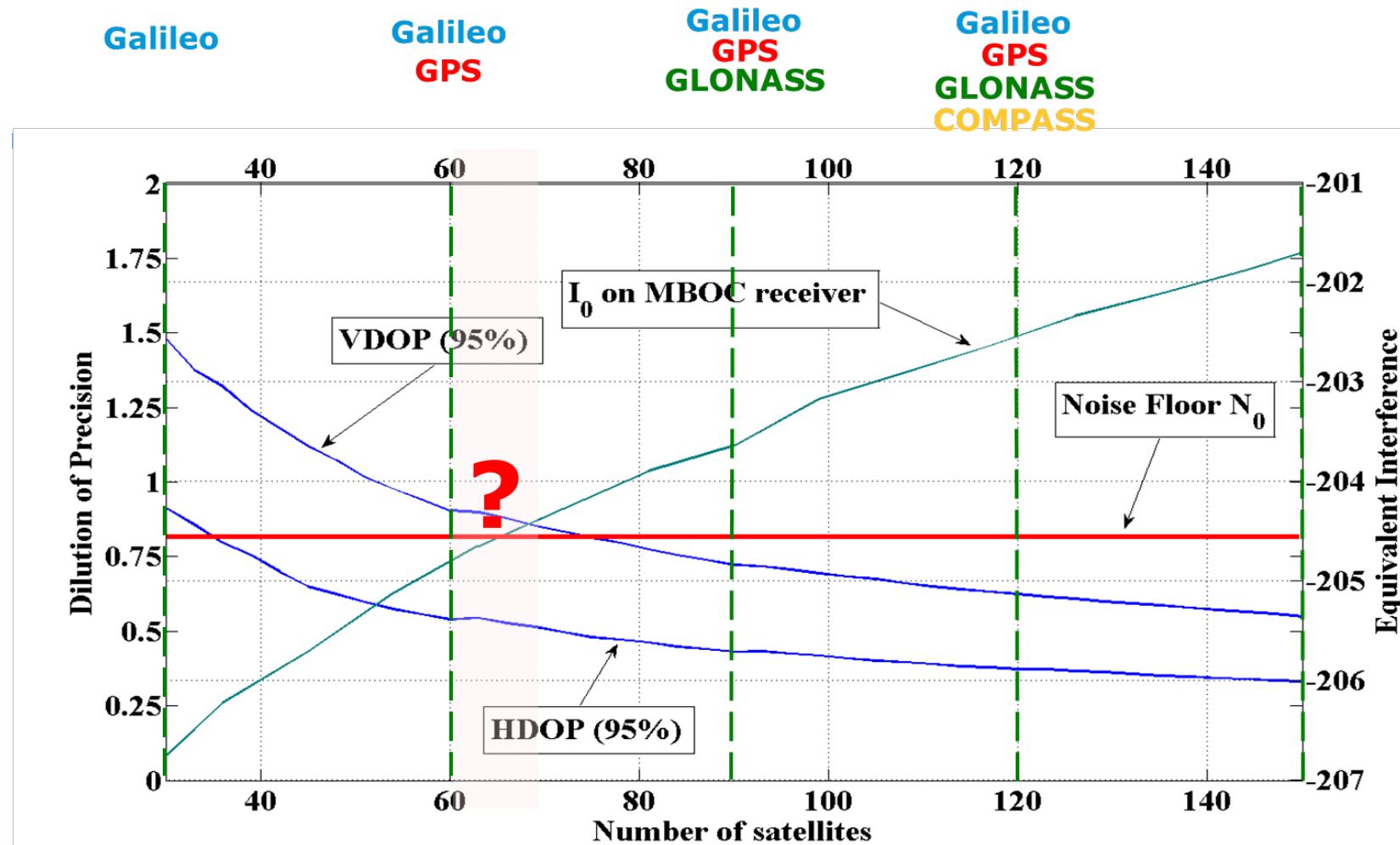
## The number of SVs in multi GNSS systems





# The More satellites the better?

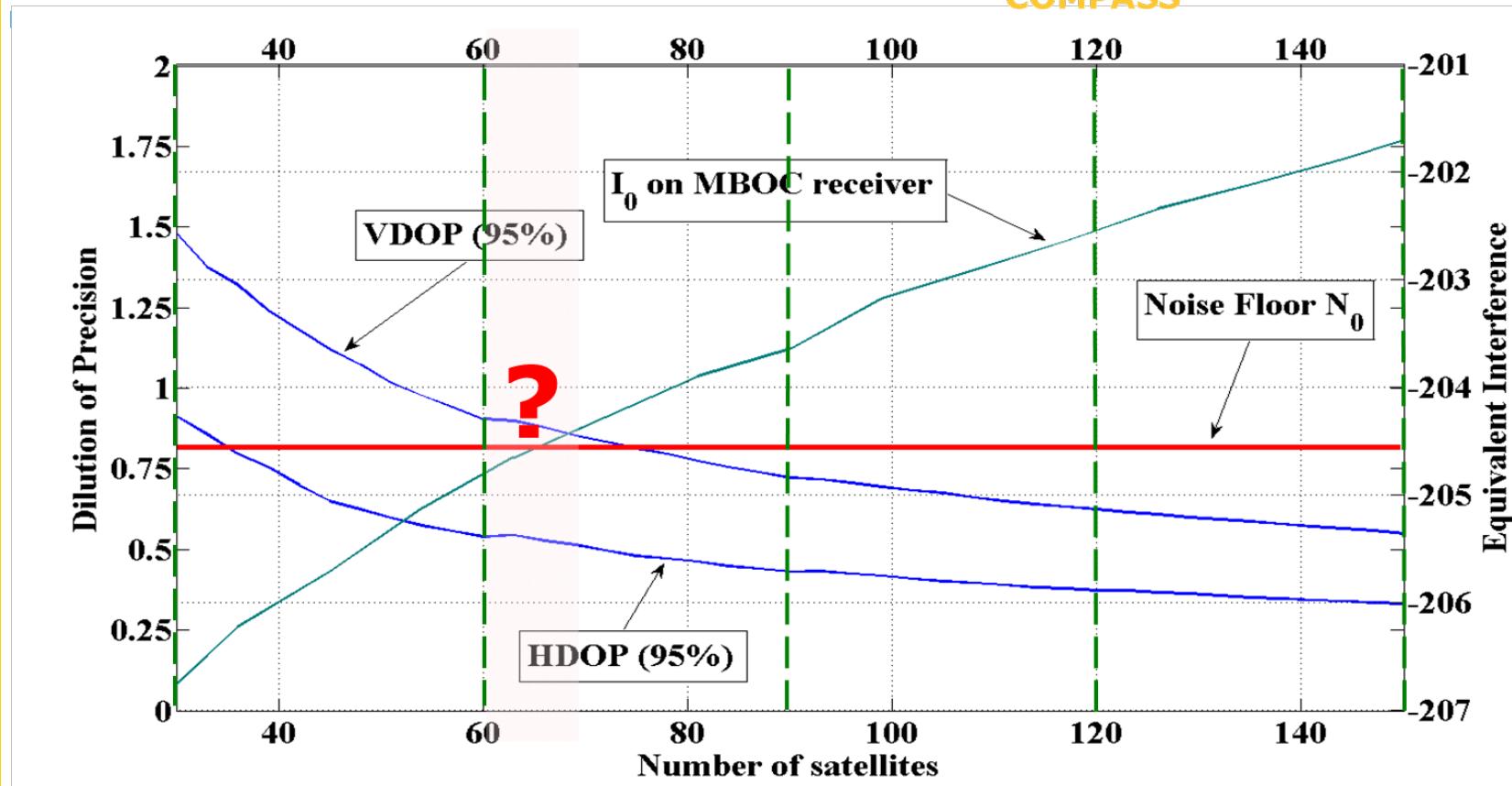
Source: Guenter W. Hein  
ESA/JRC International Summer School on GNSS 2016



GDOP decreases as the inverse square root of the number of satellites

$$GDOP \propto \frac{1}{\sqrt{N_{sat}}}$$

Galileo      Galileo GPS      Galileo GPS GLONASS      Galileo GPS GLONASS COMPASS



Once GNSS interference is dominant, noise floor increases linearly proportional to the number of satellites  $I_{\text{intra}} \propto N_{\text{sat}}$

# References

- [RD-1] J. Sanz Subirana, J.M. Juan Zornoza, M. Hernández-Pajares, GNSS Data processing. Volume 1: Fundamentals and Algorithms. ESA TM-23/1. ESA Communications, 2013.
- [RD-2] J. Sanz Subirana, J.M. Juan Zornoza, M. Hernández-Pajares, GNSS Data processing. Volume 2: Laboratory Exercises. ESA TM-23/2. ESA Communications, 2013.
- [RD-3] Pratap Misra, Per Enge. Global Positioning System. Signals, Measurements, and Performance. Ganga-Jamuna Press, 2004.
- [RD-4] B. Hofmann-Wellenhof et al. GPS, Theory and Practice. Springer-Verlag. Wien, New York, 1994.
- [RD-5] ESA/JRC International Summer School on GNSS 2016. Presentation Booklet. Ispra (Italy), 18-29 July 2016.

# Thank you

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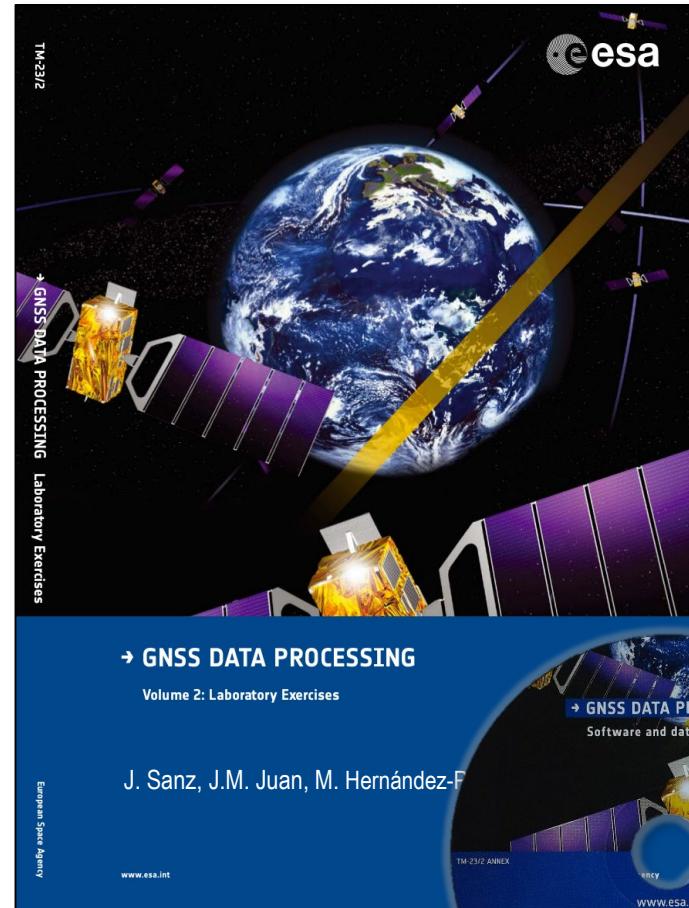
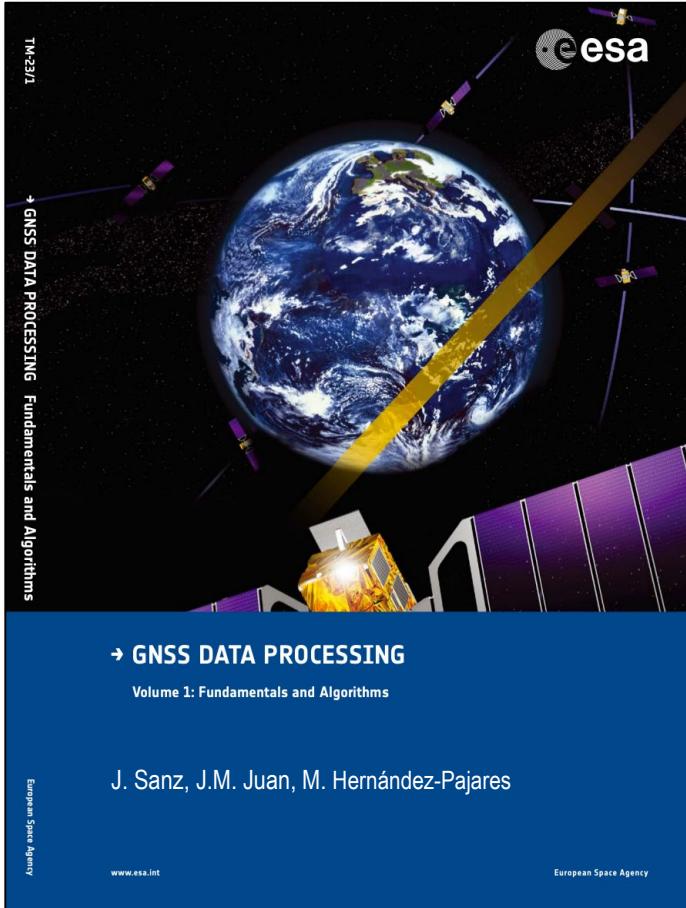
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**GNSS Data Processing, Vol. 2: Laboratory exercises.**

Galileo navigation signals. The two signals located in the E5a and E5b bands respectively are modulated onto a single E5 carrier frequency of 1191.795 MHz using the AltBOC technique: AltBOC(15,10).

Band	Carrier freq. (MHz)	Channel or sig. comp.	Modulation type	Code rate (Mcps)	Data rate (bps)	Services	
E1	1575.420	E1-A data	BOC <sub>cos</sub> (15,2.5)	2.5575	N/A	PRS	
		E1-B data	MBOC(6,1,1/11)	1.023	125	OS, CS	
		E1-C pilot			—		
E6	1278.750	E6-A data	BOC <sub>cos</sub> (10,5)	5.115	N/A	PRS	
		E6-B data	BPSK(5)		500	CS	
		E6-C pilot			—		
E5a	1176.450	E5a-I data	BPSK(10)	10.23	25	OS	
		E5a-Q pilot			—		
E5b	1207.140	E5b-I data	BPSK(10)	10.23	125	OS, CS	
		E5b-Q pilot			—		

