Keynote Lecture: Galileo

Marco FALCONE – European Space Agency

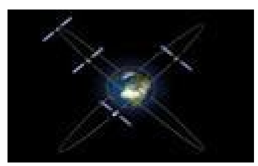
IGS Workshop 2017, Paris – July 3-7 2017

Deployment / Exploitation Plan

Development
GIOVE A & B

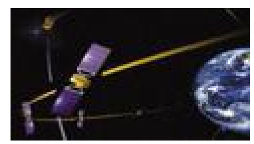
2005 & 2008

In-Orbit Validation



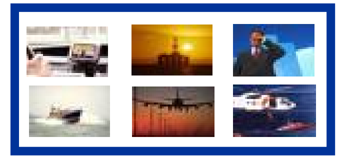
2011-2013

FOC1
Initial Services



2014-2016

Exploitation Phase

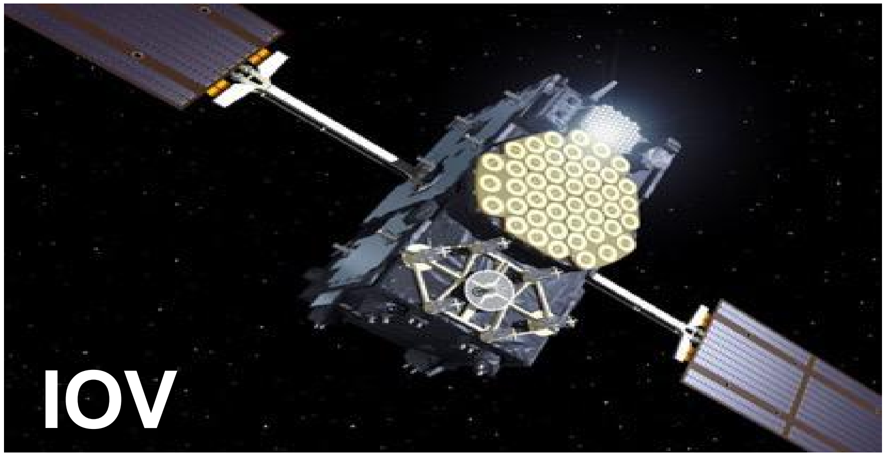


2017-2019

FOC2
Full Services

2020

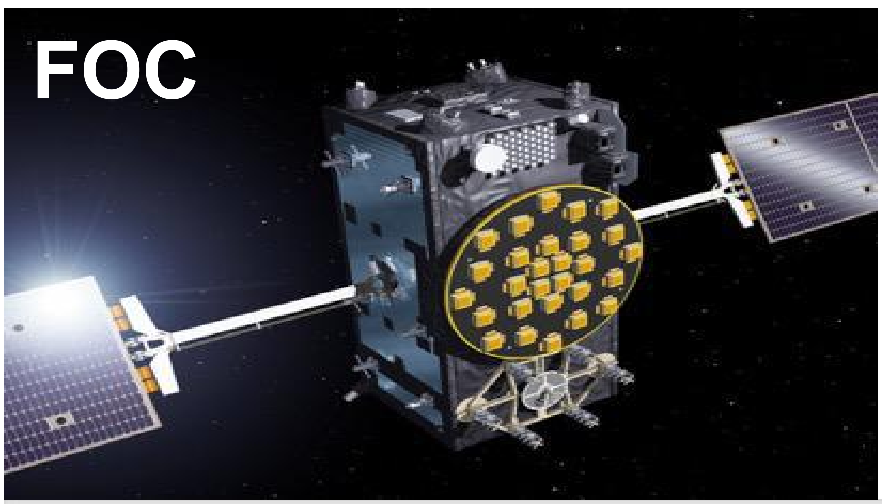
Constellation Satellites



S/C Prime Contractor Astrium GmbH (now Airbus Defence & Space)

4 satellites – 4 In-Orbit

Mass at Launch	700kg
Power Consumption	1420W
Dimensions	2.7 x 1.6 x 14.5 m
Orbit Injection	Direct into MEO orbit
Attitude Profile	Yaw Steered



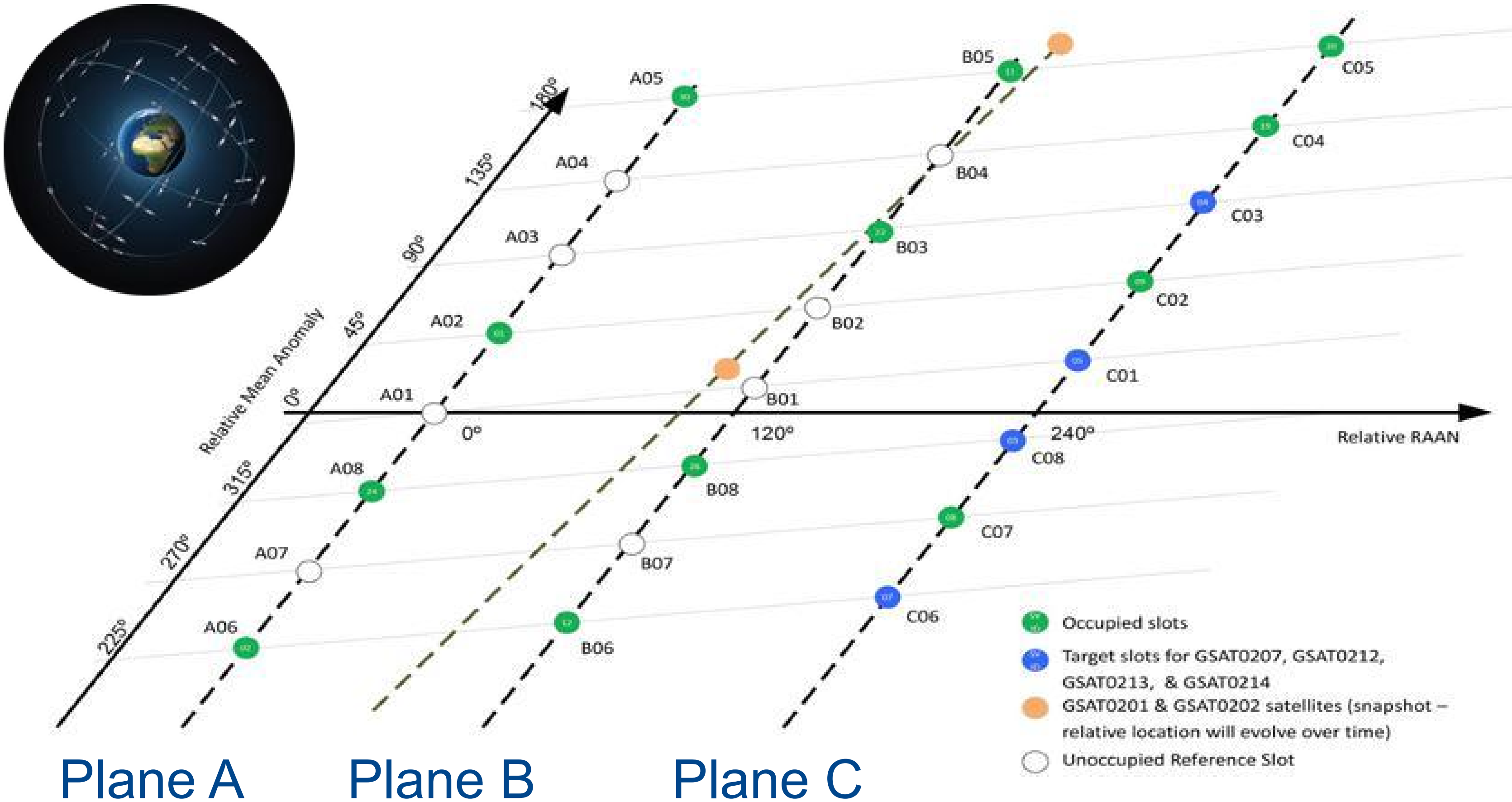
S/C Prime Contractor OHB Systems GmbH

P/L Prime Contractor SSTL Ltd

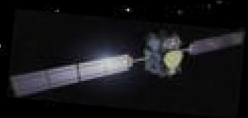
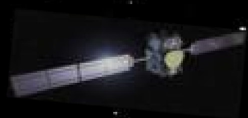
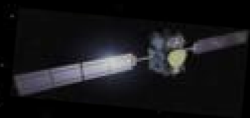
22 satellites – 14 In-Orbit

Mass at Launch	733kg
Power Consumption	1900 W
Dimensions	2.5 x 1.1 x 14.7 m
Orbit Injection	Direct into MEO orbit
Attitude Profile	Yaw Steered

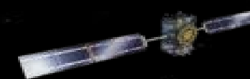
Current FOC1 constellation: 18 spacecraft



Constellation Status (30 June 2017)

	 GSAT0101	 GSAT0102	 GSAT0103	 GSAT0104	 GSAT0201	 GSAT0202
Launch Date	21 Oct. 2011	21 Oct. 2011	12 Oct. 2012	12 Oct. 2012	22 Aug. 2014	22 Aug. 2014
SV ID	11	12	19	20	18	14
Orbital Slot	B05	B06	C04	C05	Ext01	Ext02
Clock	RAFS	PHM	PHM	RAFS	PHM	PHM
Technical Status	Nominal	Nominal	Nominal	Unavailable (NAGU 2014014)	Testing (NAGU 2016029)	Testing (NAGU 2016030)
EIRP (wrt Public OS SIS ICD)	All bands aligned	All bands aligned	All bands in temporary back-off	E1 only E5 + E6 permanently unavailable	All bands aligned	All bands aligned
SAR Transponder	N/A	N/A	Nominal	Nominal	Nominal	Nominal

Constellation Status (30 June 2017)

	GSAT0203	GSAT0204	GSAT0205	GSAT0206	GSAT0208	GSAT0209
Launch Date	27 Mar. 2015	27 Mar. 2015	11 Sep. 2015	11 Sep. 2015	17 Dec. 2015	17 Dec. 2015
SV ID	26	22	24	30	08	09
Orbital Slot	B08	B03	A08	A05	C07	C02
Clock	PHM	RAFS	PHM	PHM	PHM	PHM
Technical Status	Nominal	Nominal	Nominal	Nominal	Nominal	Nominal
EIRP (wrt Public OS SIS ICD)	← All bands aligned →					
SAR Transponder	Nominal	Nominal	Nominal	Nominal	Nominal	Nominal

Constellation Status (30 June 2017)

	GSAT0210	GSAT0211	GSAT0207	GSAT0212	GSAT0213	GSAT0214
Launch Date	24 May 2016	24 May 2016	17 Nov. 2016	17 Nov. 2016	17 Nov. 2016	17 Nov. 2016
SV ID	01	02	07	03	04	05
Orbital Slot	A02	A06	C06	C08	C03	C01
Clock	PHM	PHM	PHM			PHM
Technical Status	Nominal	Nominal	Nominal	← Under Commissioning (NAGU 2016050) →		Nominal
EIRP (wrt Public OS SIS ICD)	All bands aligned	All bands aligned	All bands aligned			All bands aligned
SAR Transponder	Nominal	Nominal	Nominal			Nominal

Launch 8 In-Orbit Testing (IOT)

1st Signal in Space from pair 1:

GSAT0207: 2nd March 2017

GSAT0214: 3rd March 2017

Successful ITR on 4th May 2017

GSAT0207/0214 in service since 29 May 2017

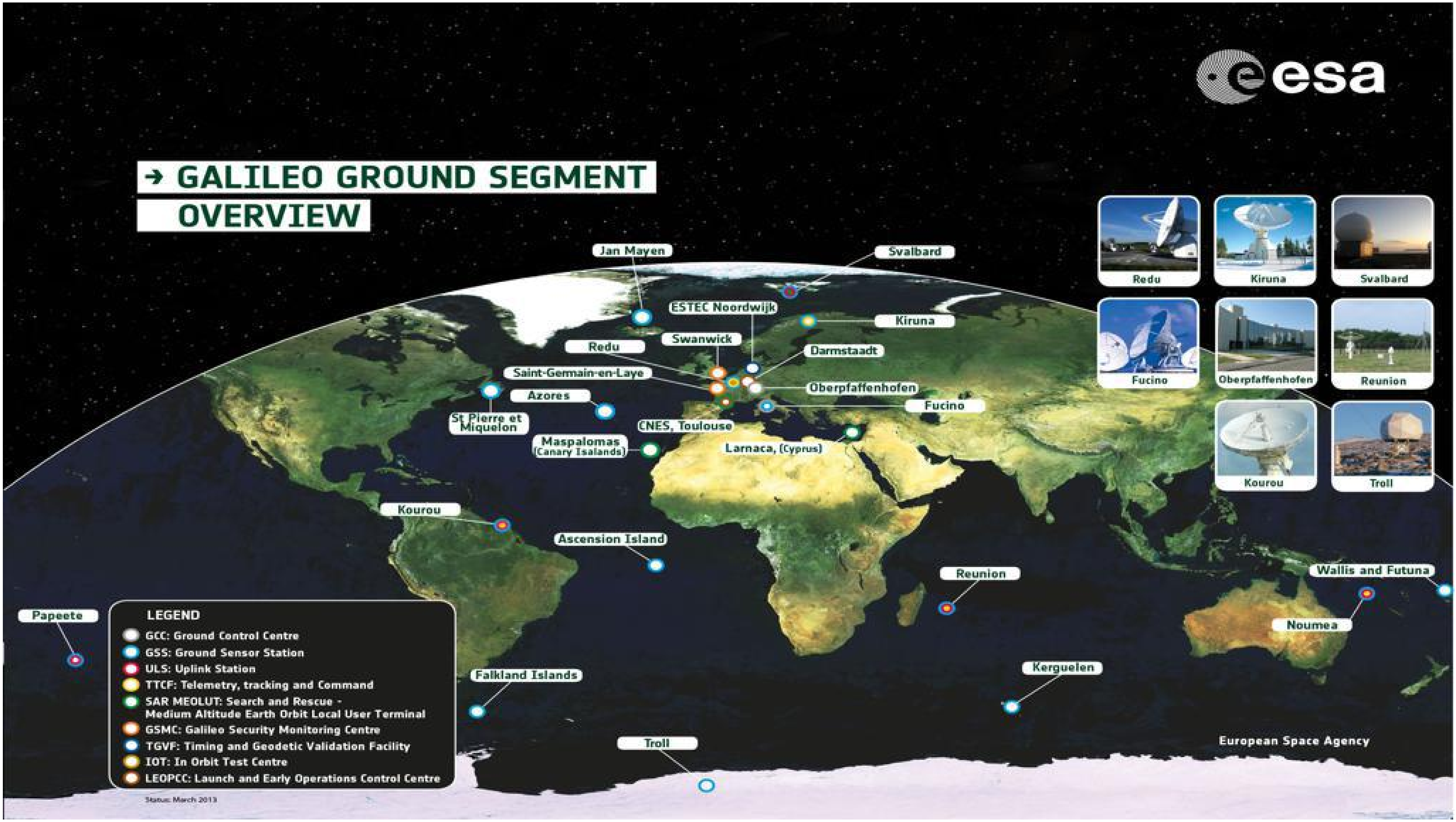
1st Signal in Space from pair 2:

GSAT0212: 22nd April 2017

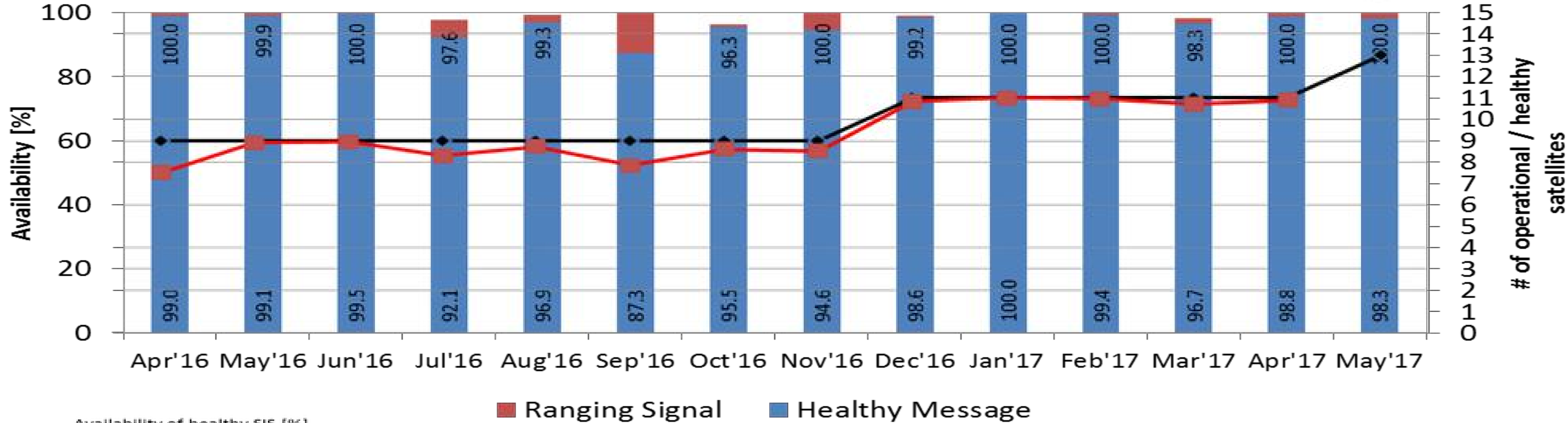
GSAT0213: 22nd April 2017

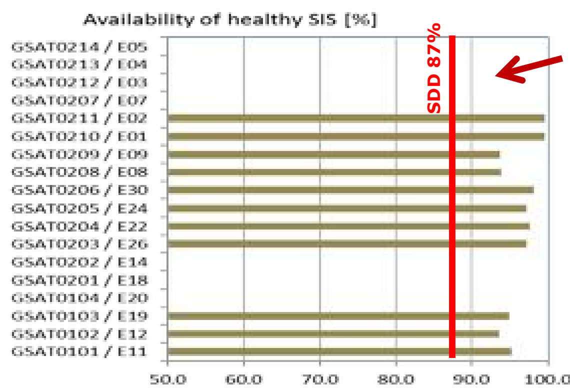
Successful ITR on 20th June 2017

GSAT0212/0213 planned in service: begin July 2017


esa
→ GALILEO GROUND SEGMENT
OVERVIEW
Jan Mayen
Svalbard
ESTEC Noordwijk
Kiruna
Swanwick
Redu
Darmstaadt
Saint-Germain-en-Laye
Oberpfaffenhofen
Fucino
Azores
St Pierre et Miquelon
CNES, Toulouse
Maspalomas (Canary Isalands)
Larnaca, (Cyprus)
Kourou
Ascension Island
Reunion
Wallis and Futuna
Noumea
Papeete
Falkland Islands
Kerguelen
Troll
Redu
Kiruna
Svalbard
Fucino
Oberpfaffenhofen
Reunion
Kourou
Troll
LEGEND
GCC: Ground Control Centre
GSS: Ground Sensor Station
ULS: Uplink Station
TTCF: Telemetry, tracking and Command
SAR MEOLUT: Search and Rescue - Medium Altitude Earth Orbit Local User Terminal
GSMC: Galileo Security Monitoring Centre
TGVF: Timing and Geodetic Validation Facility
IOT: In Orbit Test Centre
LEOPCC: Launch and Early Operations Control Centre
Status: March 2013
European Space Agency

High Signal Availability





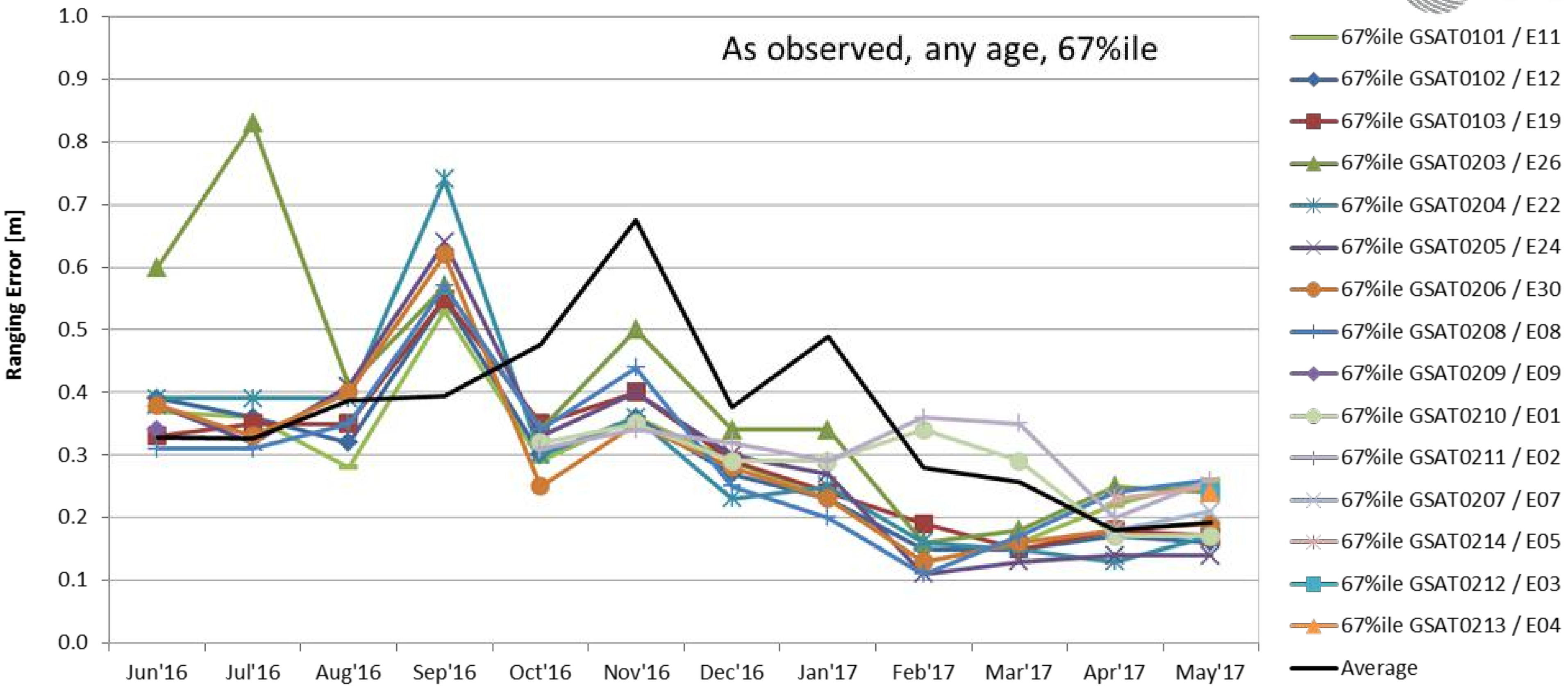
GSAT0207/0214 set healthy end of May

Availabilities reported since first complete month in operation.

Availability reduced by

- On Board S/W upgrades
- On Board Clocks maintenance
- Station keeping manoeuvre

As-observed Ranging Performance



- Decreasing Ranging Error trend due to increasing no. of satellites
- Ranging accuracy (67%) 0.53m all satellites 0.84m worst satellite

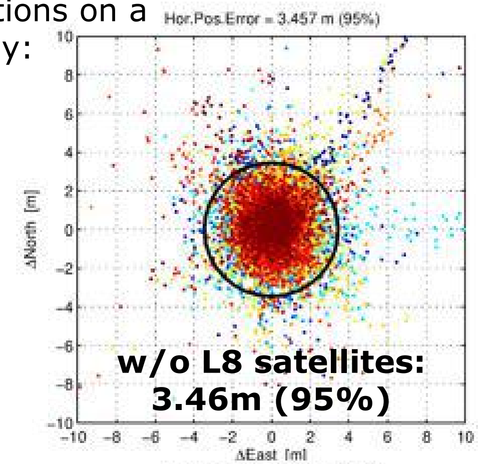
Ranging Accuracy including L8 Satellites

L8 Satellites

DF 100 min prediction accuracy																				
GSAT	0210	0211	0212	0213	0214	0207	0208	0209	0101	0102	0202	0201	0103	0204	0205	0203	0206	
SVID	E01	E02	E03	E04	E05	E07	E08	E09	E11	E12	E14	E18	E19	E22	E24	E26	E30	Cumulative
Run 1 DF OS (E5a-E1)																		
Orbit RMS error @WUL [m]	0.37	0.46	0.38	0.39	0.54	0.33	0.39	0.42	0.37	0.38	3.01	3.13	0.27	0.33	0.43	0.43	0.35	1.12
Clock RMS error [m]	0.24	0.26	0.25	0.27	0.25	0.19	0.26	0.30	0.22	0.24	0.23	0.27	0.15	0.27	0.19	0.31	0.24	0.25
Ranging 95%-ile error @WUL [m]	0.75	1.04	0.86	0.92	1.05	0.79	0.87	1.00	0.67	0.70	1.34	2.88	0.55	0.96	0.85	0.96	0.78	0.93
Ranging 95%-ile error @AUL [m]	0.56	0.70	0.62	0.61	0.74	0.53	0.66	0.75	0.40	0.50	0.92	1.71	0.37	0.66	0.56	0.75	0.58	0.68
Run 2 DF OS (E5b-E1)																		
Orbit RMS error @WUL [m]	0.33	0.42	0.35	0.36	0.56	0.34	0.35	0.38	0.36	0.36	2.99	3.12	0.27	0.34	0.39	0.39	0.32	1.10
Clock RMS error [m]	0.19	0.22	0.23	0.22	0.21	0.16	0.21	0.26	0.22	0.24	0.21	0.21	0.26	0.28	0.17	0.27	0.22	0.23
Ranging 95%-ile error @WUL [m]	0.63	0.92	0.80	0.82	1.02	0.73	0.76	0.91	0.67	0.71	1.25	2.49	0.67	0.96	0.75	0.86	0.70	0.85
Ranging 95%-ile error @AUL [m]	0.46	0.58	0.54	0.53	0.70	0.49	0.55	0.64	0.43	0.52	0.82	1.58	0.51	0.67	0.46	0.67	0.49	0.61

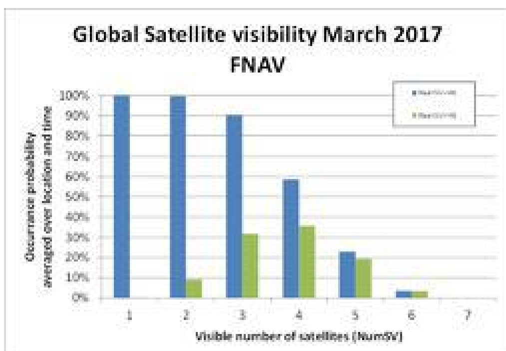
Positioning Performance & Availability

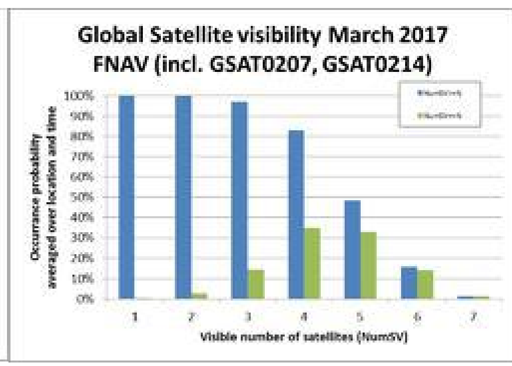
Horizontal accuracy of global stations on a sample day:

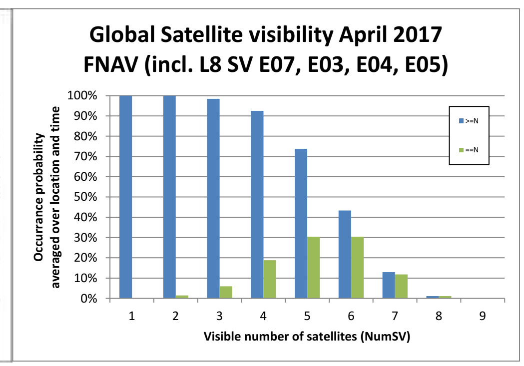


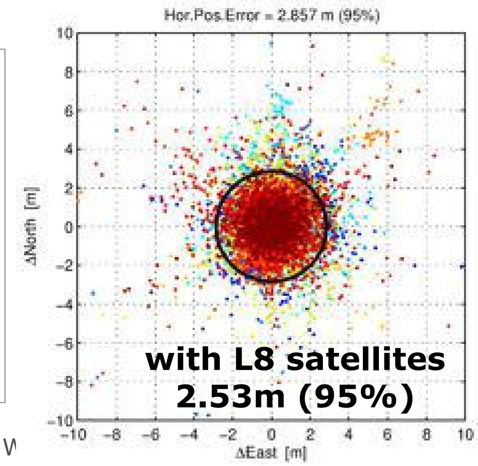
- ★ 4 more satellites operational: in May/June 2017

★ Satellites in operational constellation	11	→ 13	→ 15
★ Availability of H Accuracy <10 m	89%	→ 96%	→ 98%
★ Global PDOP <=6 availability	41%	→ 60%	→ 78%



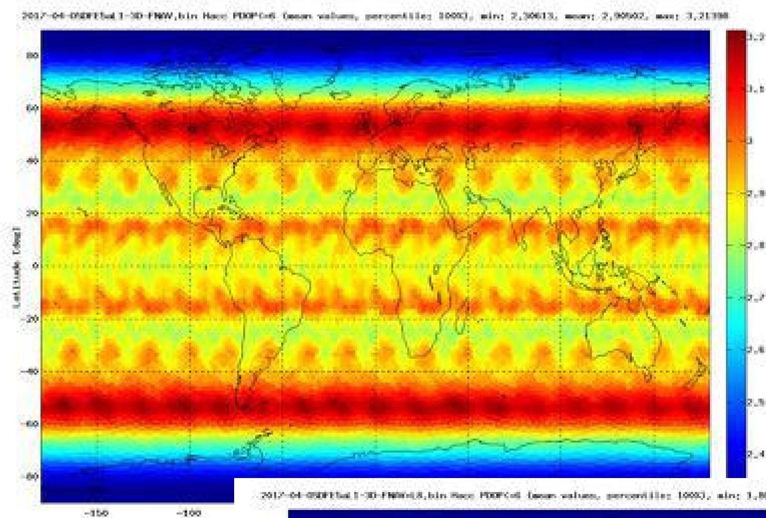






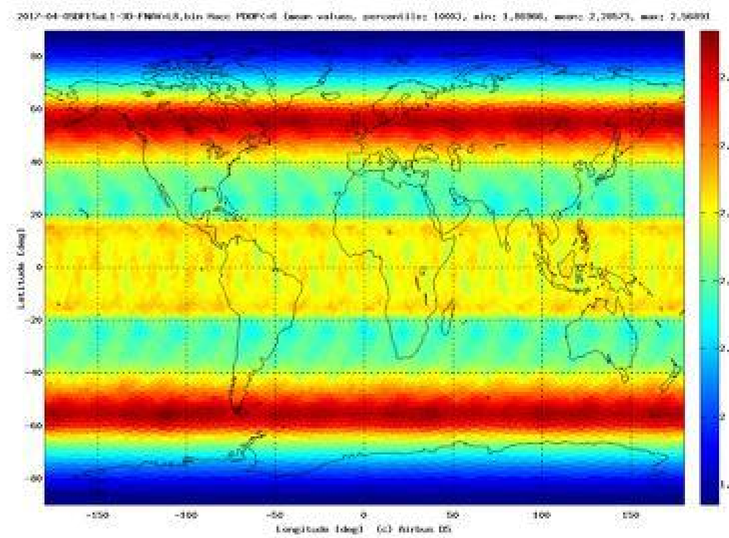
Positioning Performance

- Comparison:
  → w/o L8 s/c
  → with L8 step1 (GSAT0207, GSAT0214)
  → with L8 step2 (GSAT0212, GSAT0213)



w/o L8 SV

- Constraint: PDOP <=6
- 3-D Positioning FNAV dual frequency
  - H Acc Mean: 2.96 m → 2.62 m → **2.29 m**
- 3-D Positioning FNAV single frequency
  - H Acc Mean: 16.80 m → **15.06 m** → **13.39 m**



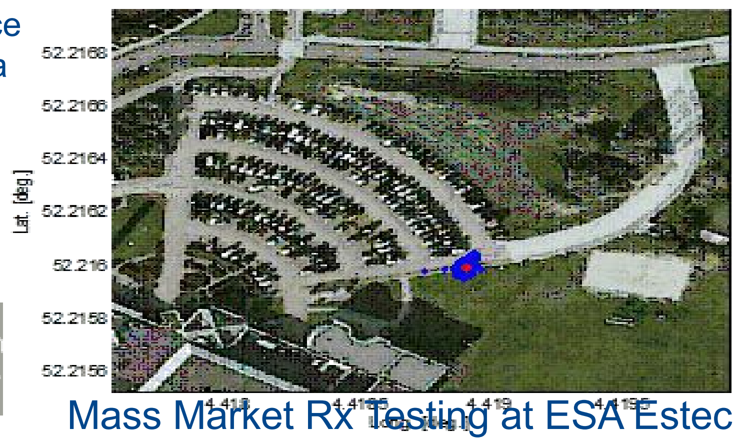
with L8 SV

PVT Field Testing

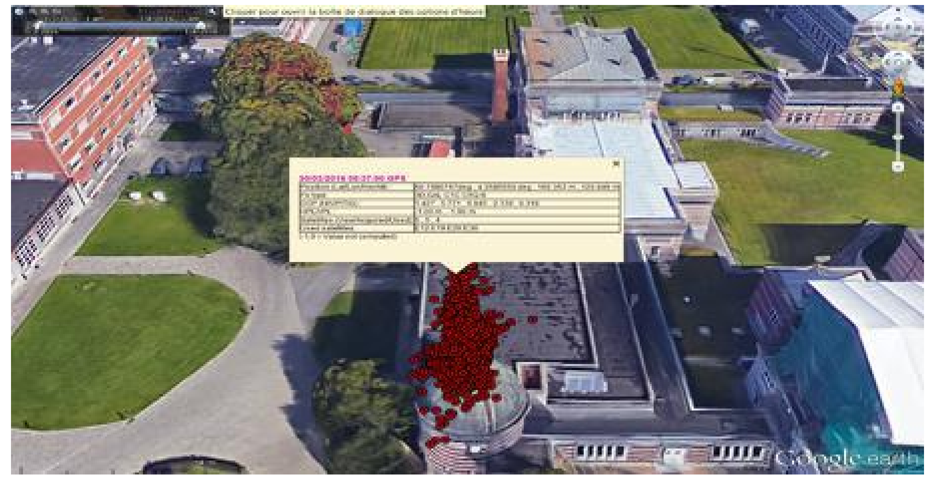
1hr flight PVT in Toulouse, France
GALILEO only FNAV E1BC/E5a
3 IOV + 2 FOC, 28 April '16
H Accuracy 2.2m (95%)
V Accuracy 3.5m at (95%)

cnes

European Global Navigation Satellite Systems Agency



Mass Market Rx Testing at ESA Estec
Galileo only position accuracy < 2 m (95%)

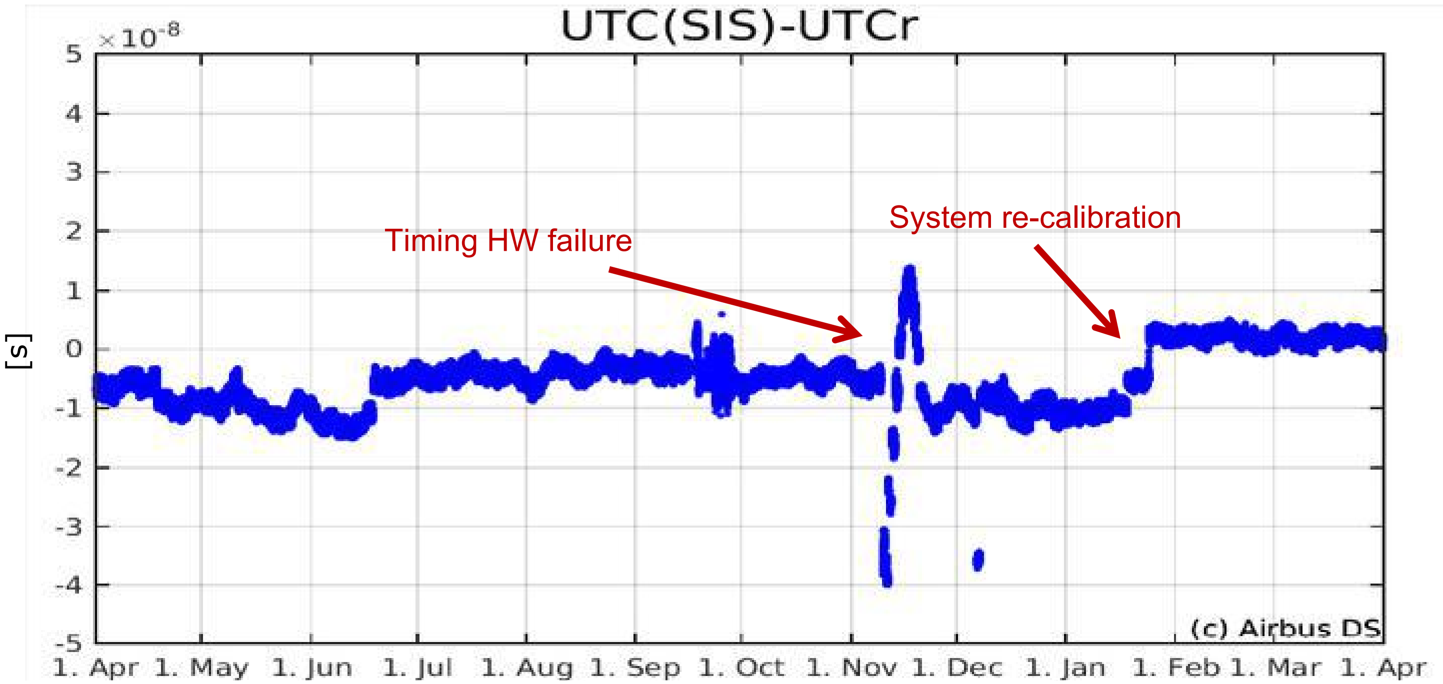


PVT at ORB Brussels in ORB, Belgium
GALILEO only FNAV E1BC/E5a PDOP<6
3 IOV + 4 FOC, whole March '16
H Accuracy 2.5m (95%)
V Accuracy 2.8m at (95%)

cnes

esa
European Space Agency

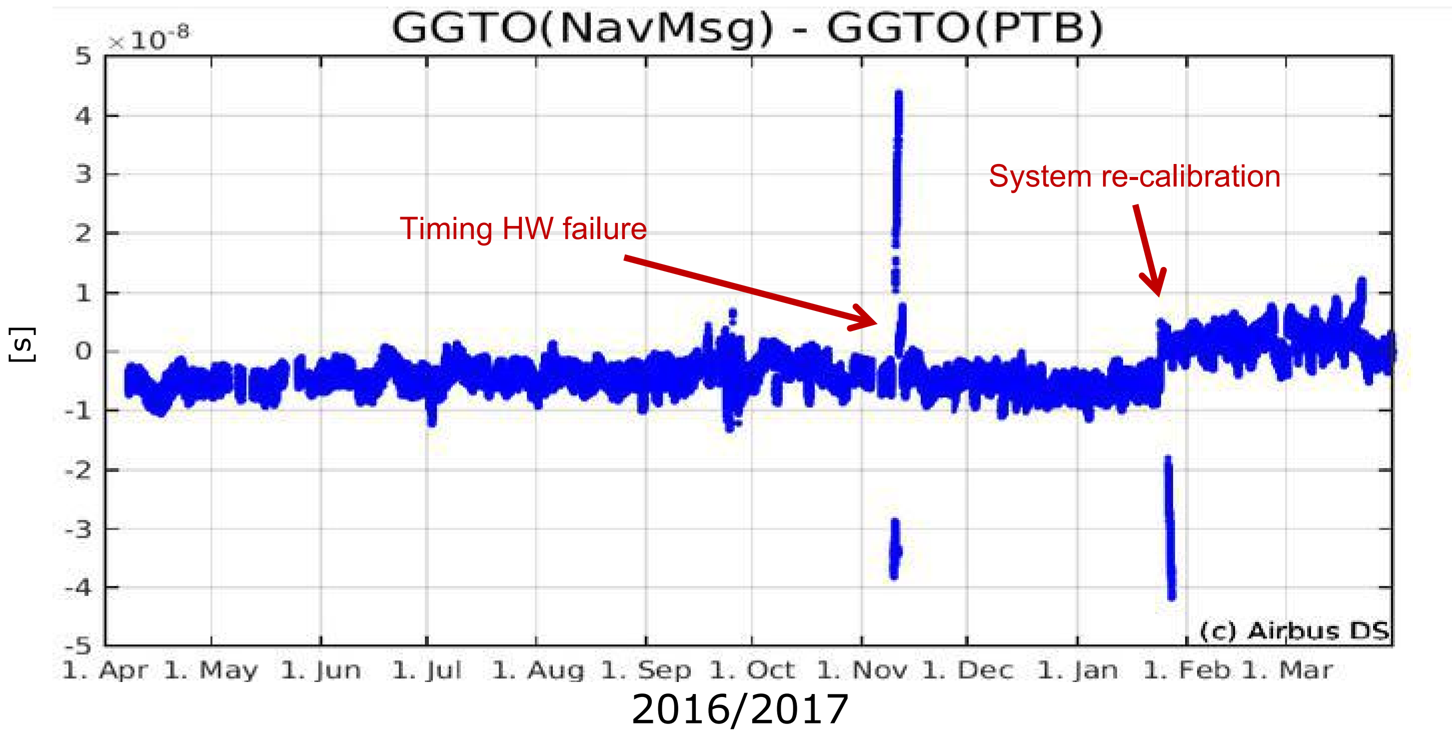
UTC Dissemination



2016/2017

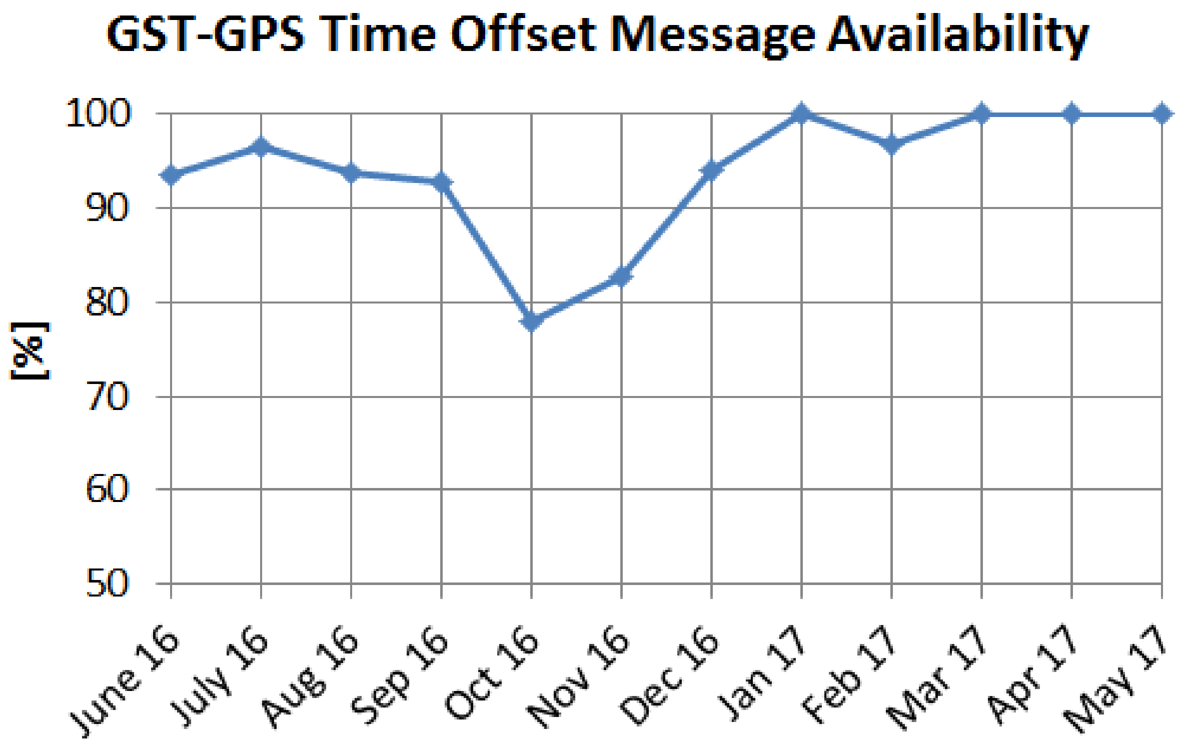
- Overall good performance of 11 ns (95%)
- Initial Services target: 30 ns (95%)

Galileo-GPS Time Offset



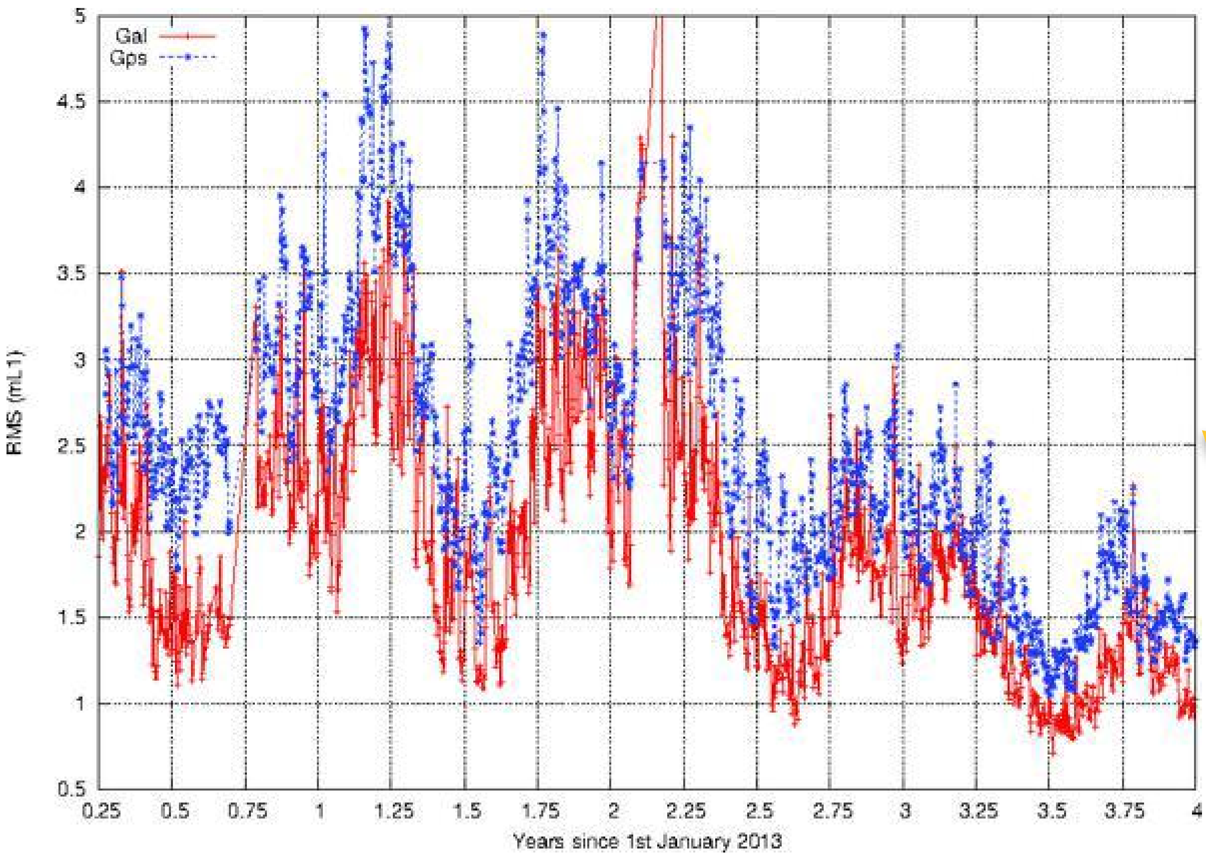
- GGTO long term accuracy ~8 ns (95%), March: 5.5ns
- Initial Services target: 20 ns (95%)

Galileo-GPS Time Offset



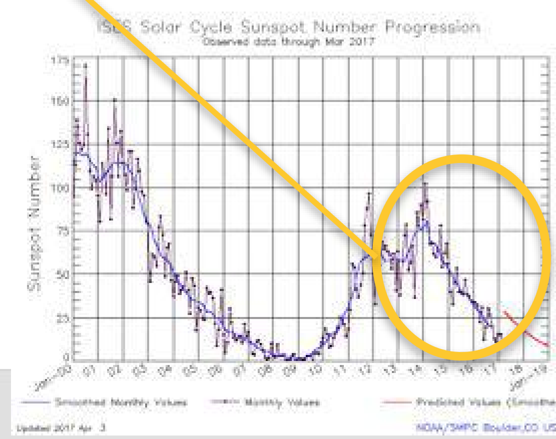
- GGTO availability improved over the last year

NeQuick G performance



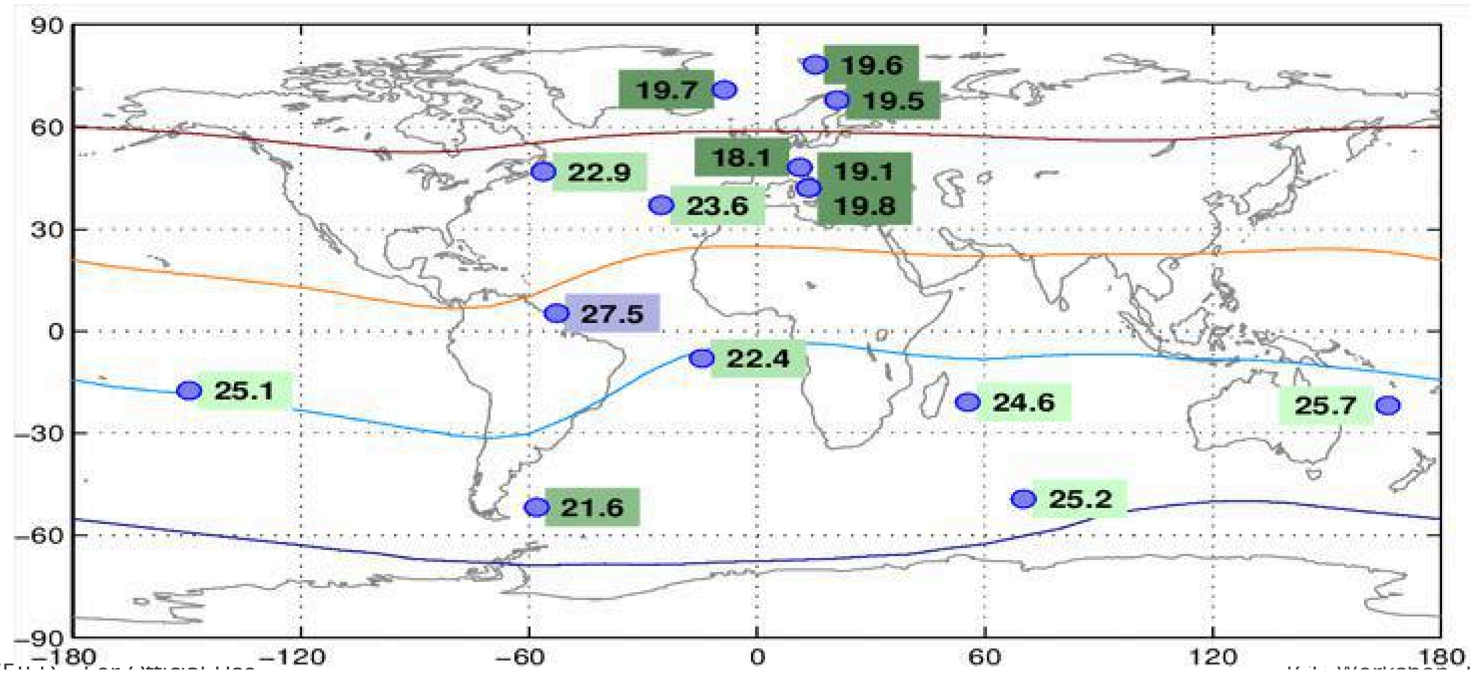
- NeQuick G exhibits consistently better global performance during the last Solar Maximum (Cycle 24) **the Average difference in RMS is around 50 cmL1 in STEC.**

- The NeQuick G meets the perfomance target specification globally for the entire period (March 2013 to December 2016)



NeQuick Correction Performance

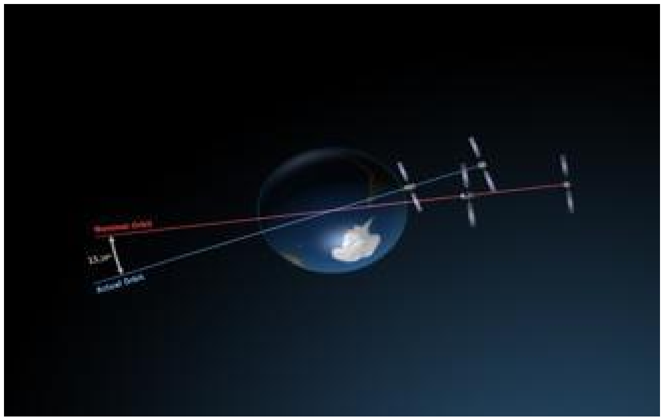
- Correction performance defined as the remaining ionospheric delay after correction with the Nequick model (Jan - Jun 2016 1Hz data)
- 75 to 80% average ionospheric model correction capability (very good behavior in equatorial zones)



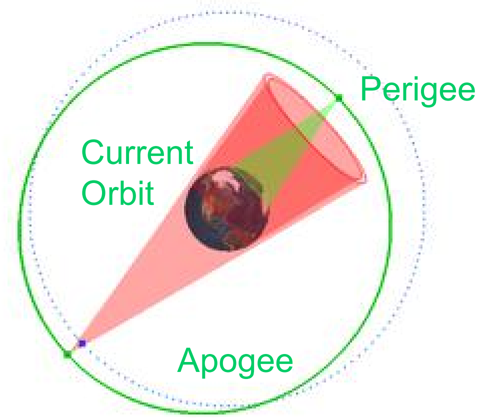
Remaining error after correction in % of E1 iono delays exceeding 3 meters

GSAT0201/0202 Orbit

VS09 Orbit injection anomaly left GSAT0201/0202 in highly eccentric orbits

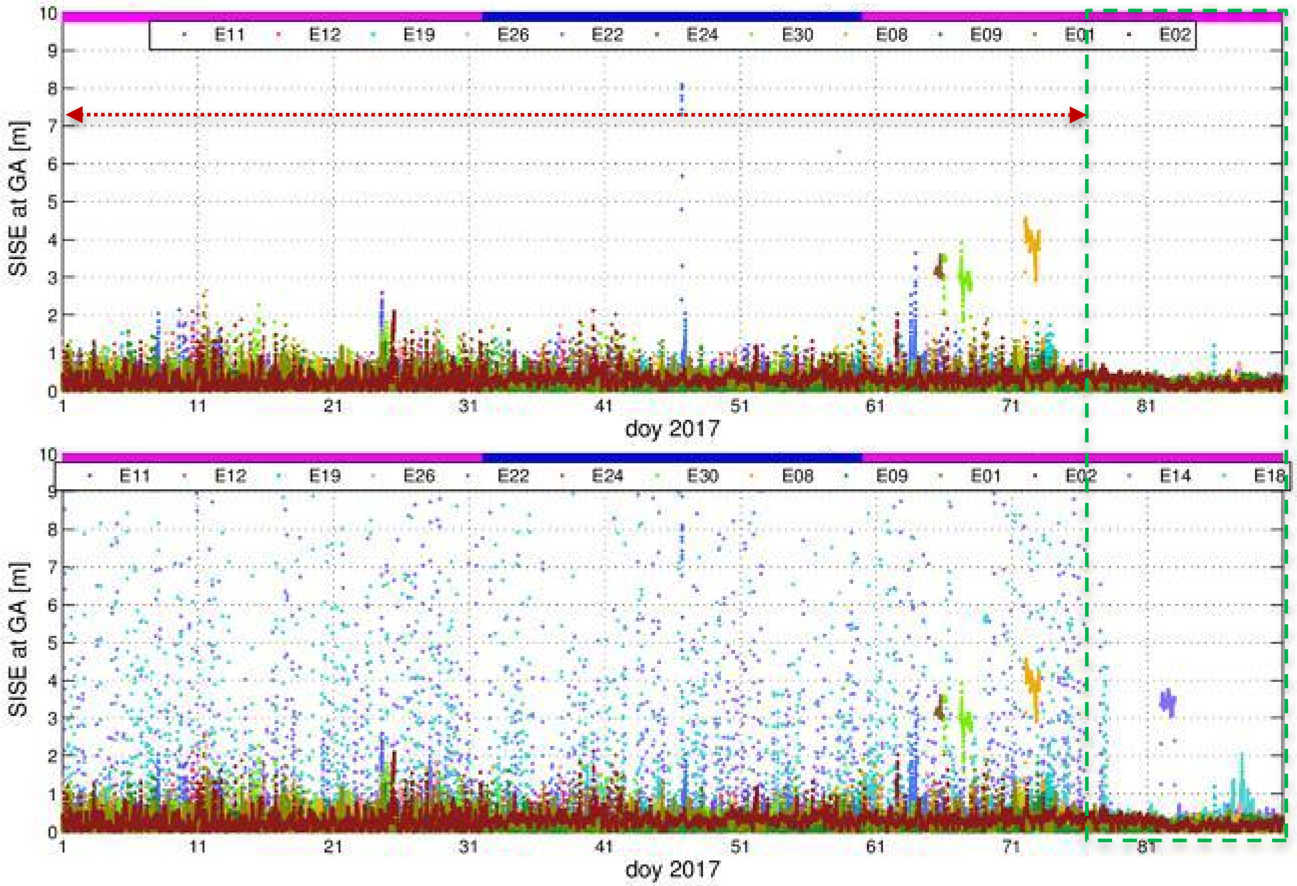


- Both spacecraft safely raised to higher orbit
  - ✓ Perigee raised from **13700** to **17200** km
  - ✓ Eccentricity reduced from **0.23** to **0.15**
  - ✓ Above Van Allen belts & Earth Sensors operational range
- Broadcasting of Dummy Messages since 2015 to support scientific experimentation
- Broadcasting navigation message since August 2016 for testing



L3 Ranging Performance Improvement Test

GSAT0201 FNAV Dual Frequency SISE Global Average **(January - March 2017)**

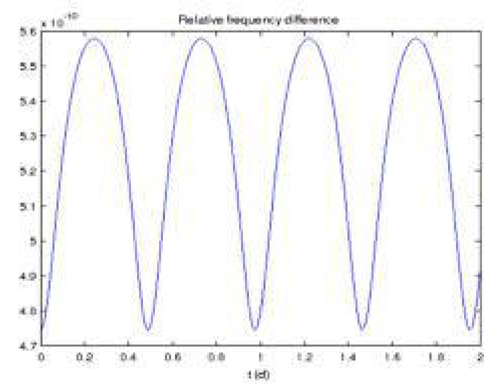


F/NAV Ranging Performance 95th percentile	Worst Nominal S/C	Worst L3 S/C
Before optimisation	0.90 m	3.59 m
After optimisation	0.64 m	0.67 m

GSAT0201/0202 GREAT Experiment

- Opportunity for Scientific Community
  - ★ use the satellites to test the laws of General Relativity and fundamental physics
  - ★ based on the excellent stability of the PHM clocks in a varying gravitational environment

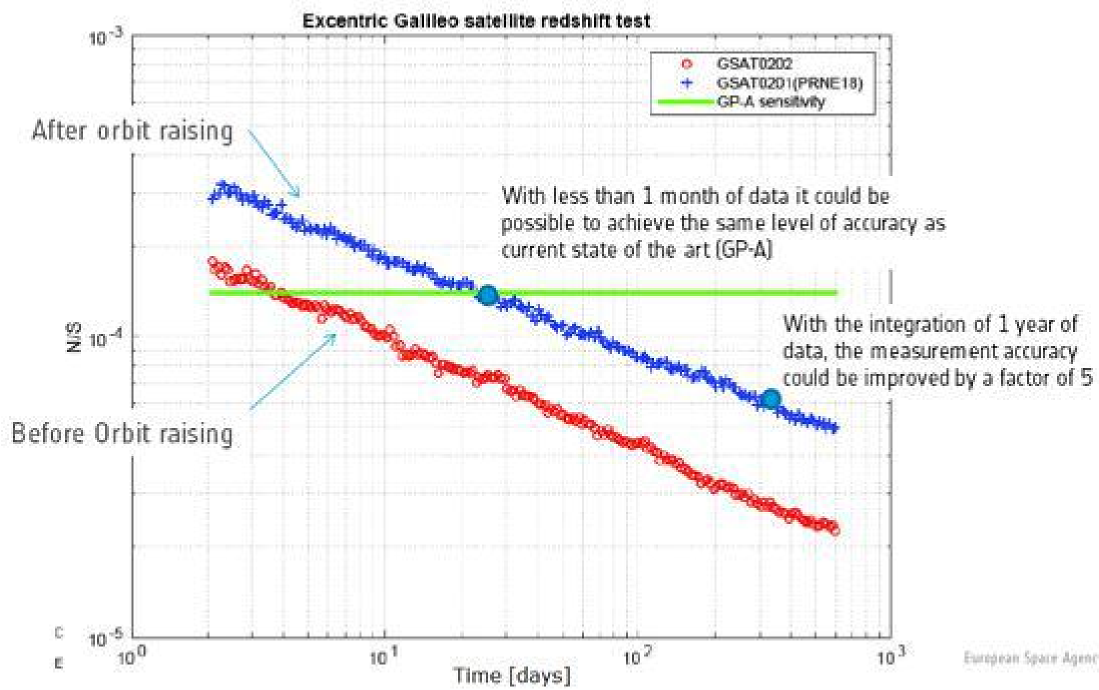
- Features supporting GREAT (Galileo gravitational Redshift Experiment with eccentric sATellites)
  - ★ High eccentricity of the final orbits of 2 satellites of approx. 0.156
  - ★ Highly stable on-board time reference via Passive Hydrogen Maser (PHM) space clocks
  - ★ Design lifetime allows for long-term observations
  - ★ Equipped with laser retro-reflector to support satellite laser ranging
  - ★ Satellites permanently monitored by IGS



- Objective of the Experiment
  - ★ Orbit eccentricity induces periodic modulation of gravitational redshift at orbital frequency
  - ★ Highly stable clocks allow to monitor this effect by observing periodic change of clock rate
  - ★ Change of clock rate is related to the periodic variation of the gravitational potential.
  - ★ Averaging these measurement over many orbits (≥1 year) will increase measurement accuracy and allow to push the current state of art by about 1 order of magnitude.
  - ★ Today State of the Art:
    Gravity Probe-A - gravitational redshift verified with an accuracy of 1.4 x10-4 in 1976

GSAT0201/0202 GREAT Experiment

- Achievable Accuracy



- Who is Involved
  - ★ Two parallel contracts launched (Oct 2015) by ESA with SYRTE/Observatoire de Paris and ZARM/University of Bremen to perform these tests
  - ★ The tests are encouraging and consolidated results are expected by Oct 17.

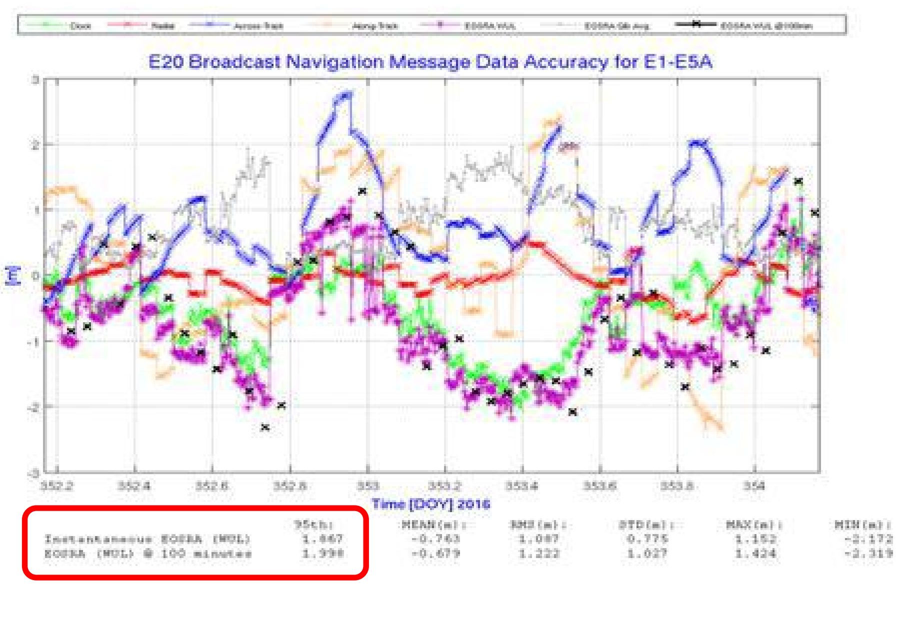
GSAT0104 (E20) IOV Satellite Usage

- Since May 2014 **GSAT0104 (E20) only transmitting E1 signal** with reduced power
- Galileo is a dual-frequency system but a high proportion of civil users will foreseeably use single frequency receivers, therefore a recovery action has been undertaken to allow use of GSAT0104 for user positioning as well as SAR applications
- **First Step - Prototyping:** to define and prototype (in TGVF) a ground processing method to achieve this, using the code&phase GRAPHIC observables in place of dual frequency IONO-free combinations
  - The navigation message generated is consistent with the message broadcast by the nominal constellation (e.g. Clocks and Broadcast Group Delays) allowing seamless combination at receiver level PVT processing
- **Second Step - Galileo System Ground Mission Segment:**
  - **Definition of implementation currently under finalisation for inclusion in operations**

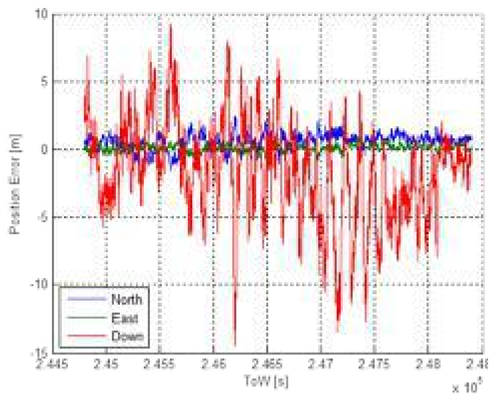
GSAT0104 (E20) Performance

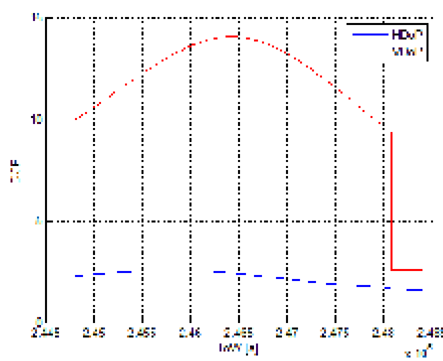
- Prototyped performance in realistic conditions comfortably **meets the Initial Services per satellite SF ranging accuracy SDD MPL ≤ 7m (95%)**

- PVTs using GSAT0104 prototyped message have also been demonstrated

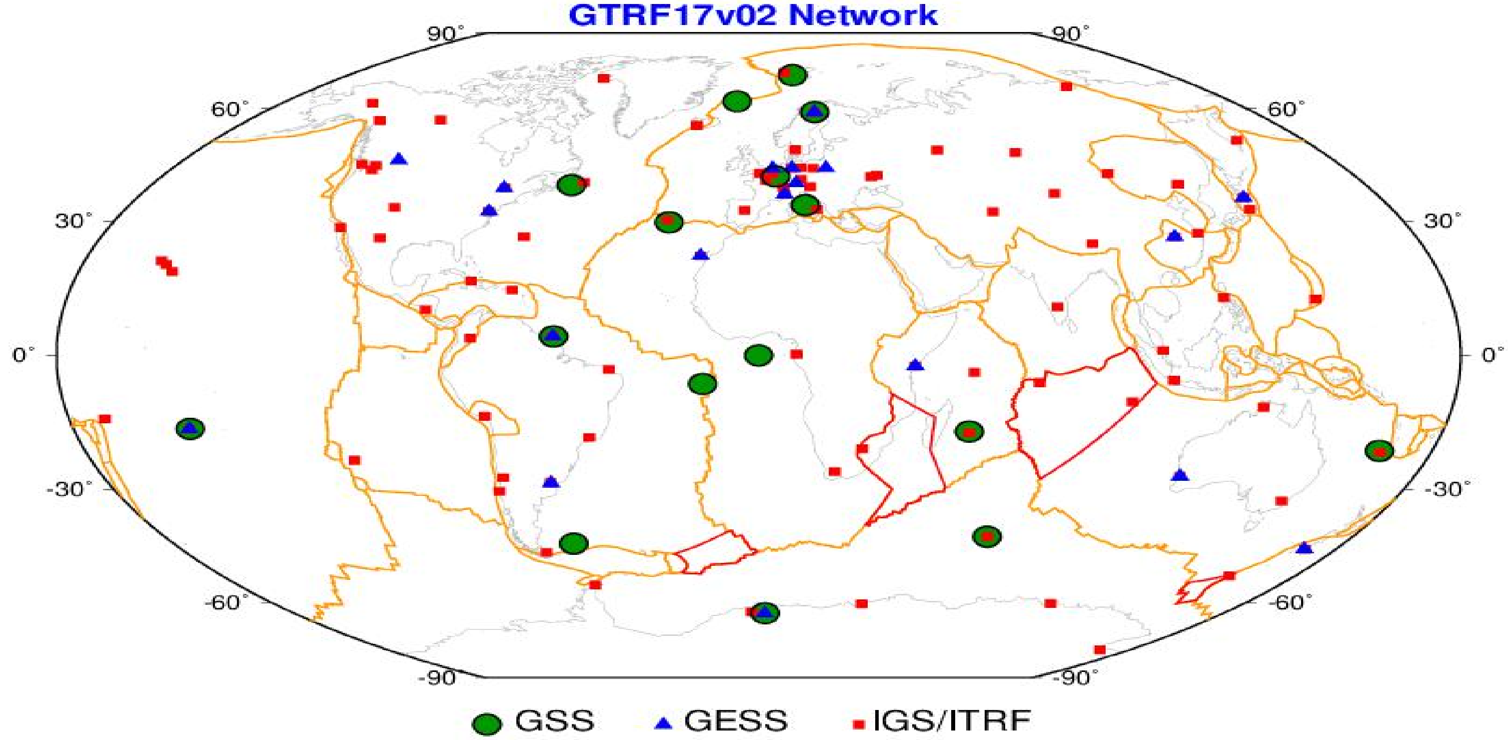


E1 Single Frequency PVT using real data from GNNO GESS station (DOY187 2016, 20:00 - 21:00 UTC) with 4 Galileo satellites in view (including E20)





GTRF17v02 tracking network



GTRF17 version 02 available from 31/03/2017

GSS = Galileo Sensor Station

GESS = TGVF - Galileo Experimental Sensor Stations

GTRF17v02 comparison of to ITRF2014

Transformation parameters from GTRF17v02 to IGS14 (ITRF2014) indicate a few millimeter (and mm/yr) level agreement between the two frames.

	T1 mm	T2 mm	T3 mm	D 10-9	R1 mas	R2 mas	R3 mas	Epoch y
	0.0	0.0	0.0	0.00	0.000	0.000	0.000	17:001
+/-	0.2	0.2	0.2	0.03	0.007	0.008	0.008	
Rates	0.0	0.0	0.0	0.00	0.000	0.000	0.000	
+/-	0.2	0.2	0.2	0.03	0.007	0.008	0.008	

Station #	RMS-Pos. E (mm)	RMS-Pos. N (mm)	RMS-Pos. U (mm)	Epoch y	RMS-Vel. E (mm/y)	RMS-Vel. N (mm/y)	RMS-Vel. U (mm/y)
127	2.5	2.0	4.0	17:001	0.4	0.3	0.6

Metadata publication request

Requested by Scientific community

- Galileo scientific advisory committee (GSAC)
- International GNSS Service (IGS)

International GNSS Service

Formerly the International GPS Service

20. August 2012

Mr. Paul Flament
Galileo Programme Manager
European Commission
Enterprise and Industry Directorate
Rue de Mot, 28
B-1049 Brussels

cc: Gerhard Beutler, Bertram Arbesser-Rastburg

Dear Mr. Flament,

Prof. Gerhard Beutler, Chair of ESA's Galileo Science Advisory Committee (GSAC), requested in his letter of October 13, 2011 access to meta data related to the Galileo satellites and sensor stations for the scientific community. On behalf of the International GNSS Service (IGS) I strongly support this request and would like to add a few remarks from the IGS perspective.

The information and data requested by Prof. Beutler are essential for the precise modeling of observations and orbits of the Galileo satellites, for the consistent and interoperable integration of Galileo products into the highest quality products of the IGS, and for a consistent alignment of terrestrial reference frames. Our products serve Earth system research, hazards detection, and many more applications relevant to society as a whole.

The list provided by Prof. Beutler represents in essence a complete list of the required information. From the IGS perspective the following subset of information is needed urgently in the nearest future. This information is crucial for a correct high precision modeling of the Galileo observables, in particular for the consistent determination of satellite clock corrections:

- *navigation antenna phase center offsets* in the body-fixed reference frames w. r. t. the satellites' centers of mass for each carrier frequency and for all Galileo satellites (together with the definition of the body-fixed reference frames).
- *attitude models* for the Galileo satellites (which are of particular importance, if the antenna phase center is not located on the axis connecting the satellite's center of mass with the center of mass of the Earth).

The IGS would be most obliged, if the above information could be made available to the scientific community with highest priority.

Sincerely yours

Prof. Urs Hugentobler
Chairman
IGS Governing Board

Metadata content

Requested by

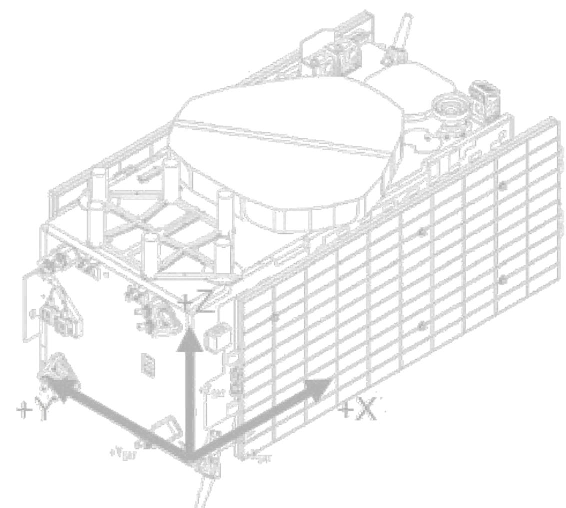
- Galileo scientific advisory committee (GSAC)
- International GNSS Service (IGS)

Status

- Galileo IOV Satellite Metadata released during Initial Service Declaration.
- Galileo FOC metadata to be released.

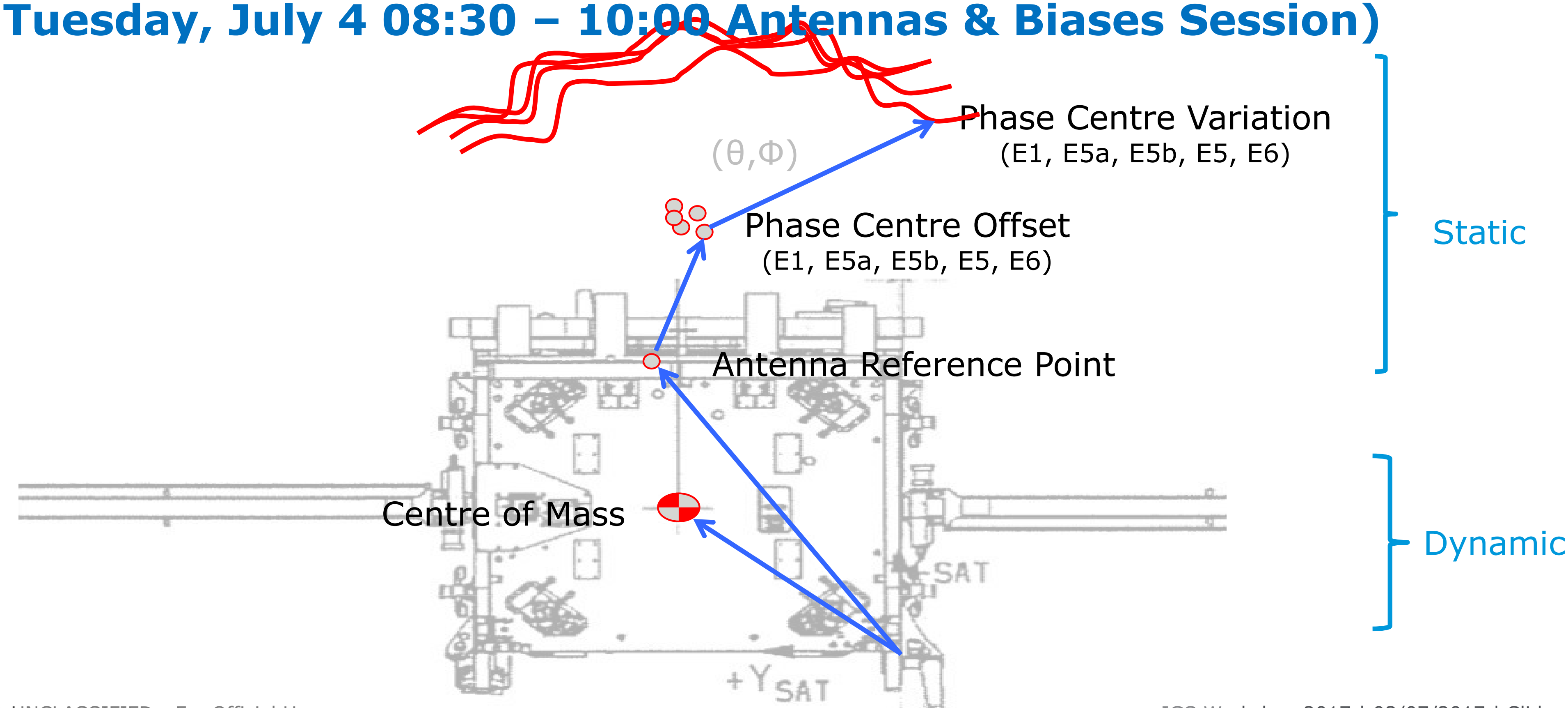
Content

- Attitude Law
- Mass and Centre Of Mass evolution
- Navigation Antenna Phase Centre Corrections
- Geometry and optical properties
- Laser Retro Reflector Location
- Satellite Group Delay



Galileo Satellite Navigation Antenna Phase Centre Calibration Paper

(Tuesday, July 4 08:30 – 10:00 Antennas & Biases Session)



Metadata location

https://www.gsc-europa.eu/support-to-developers/galileo-iov-satellite-metadata#2

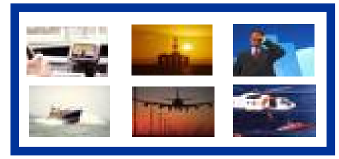
https://ilrs.cddis.eosdis.nasa.gov/missions/satellite_missions/current_missions/ga01_com.html

Deployment / Exploitation Plan

FOC2
Full Services

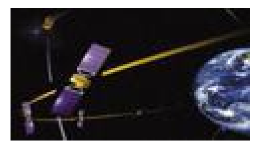
2020

Exploitation Phase



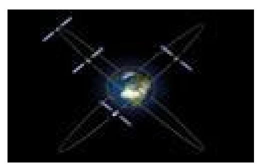
2017-2019

FOC1
Initial Services



2014-2016

In-Orbit Validation



2011-2013

Development
GIOVE A & B

2005 & 2008

Ground Segment Upgrades

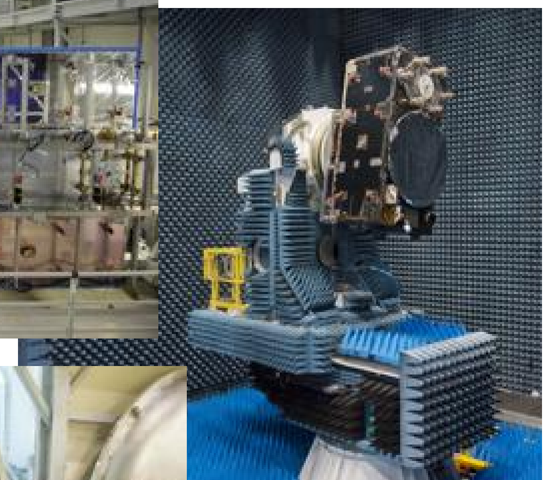
- Ground Control Segment 2.1.2
  - Deployed at GCC-D and GCC-I
  - Spacecraft control automation
  - 26 satellite capability
  - Business Continuity
  - Additional TTCF-6 in Papeete

- Ground Mission Segment 2.2
  - Deployed at GCC-D and GCC-I
  - GSAT201/202 support
  - Seamless PTF switch capability
  - Business Continuity
  - Additional GSS and ULS redundancy

FOC Satellites Production Status

- FOC-M7 (L9 Ariane-5 end 2017)
  - **FM15** in OHB Bremen
  - **FM16** in OHB Bremen
  - **FM17** in OHB Bremen
  - **FM18** in OHB Bremen

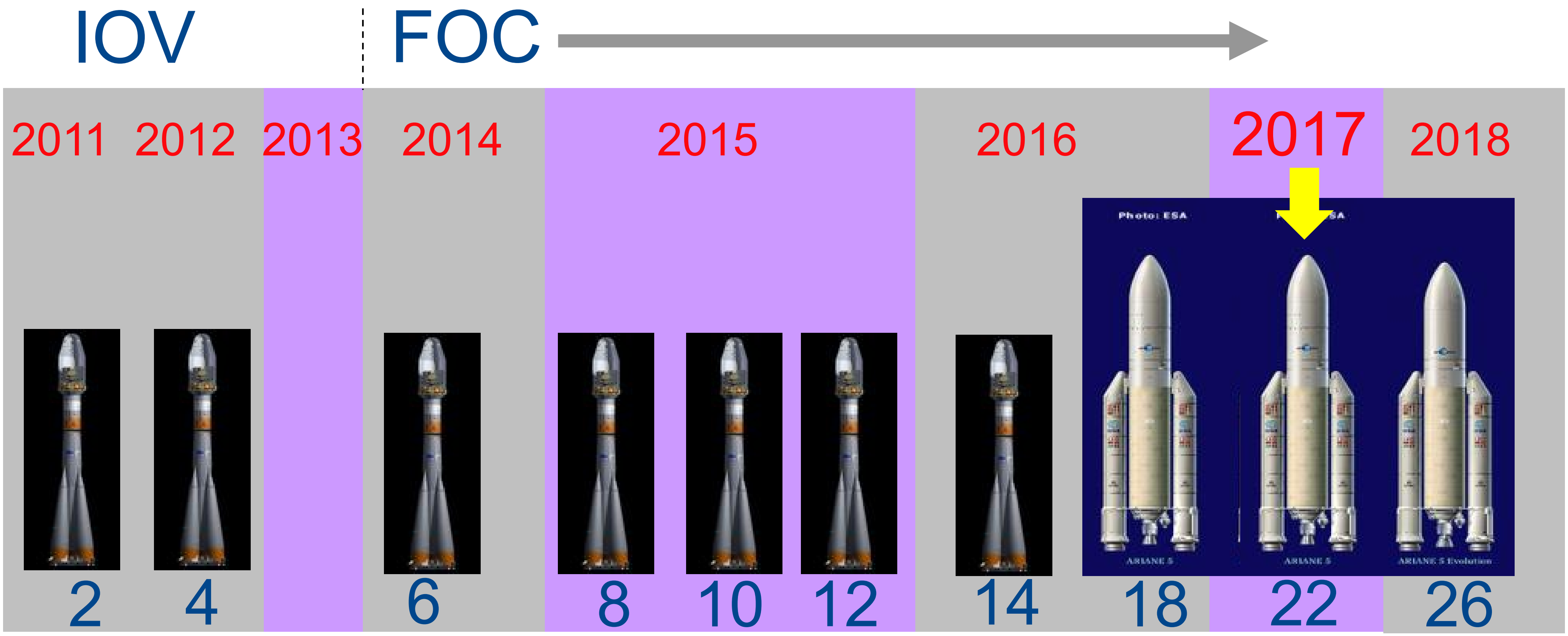
- FOC-M8 (L10 Ariane-5 mid 2018)
  - **FM19** in OHB Bremen
  - **FM20** in OHB Bremen
  - **FM21** in ESA ESTEC, under testing
  - **FM22** in OHB Bremen, under testing



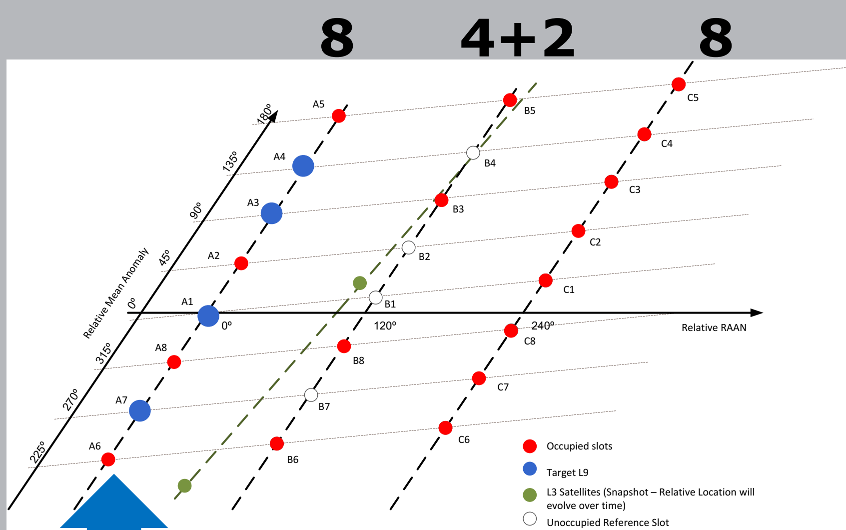
BATCH3 Satellites Procurement

- ‘Batch 3’ satellites Contract to build and test another 8 satellites signed at the Paris Air and Space Show on 22 June 2017
- Awarded to a consortium led by prime contractor OHB with Surrey Satellite Technology Ltd as payload manufacturer

Launch Plan


IOV
FOC
2011
2012
2013
2014
2015
2016
2017
2018
2
4
6
8
10
12
14
18
22
26

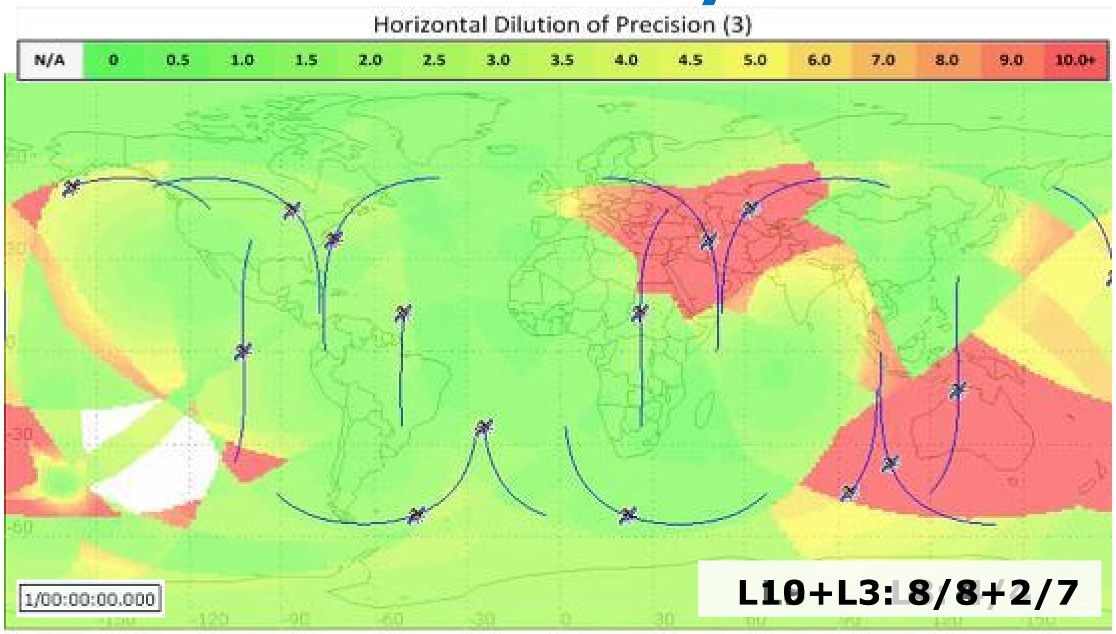
Launch #9 (Ariane 5) – December 2017

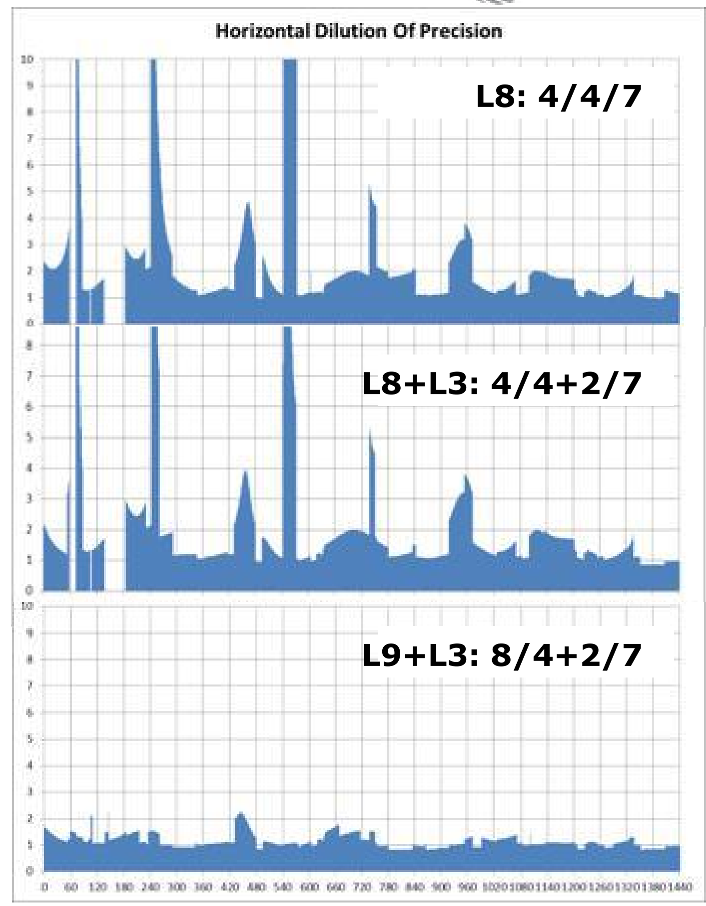


GSAT0215 - GSAT0216
GSAT0217 - GSAT0218
SAT 19-20-21-22
Plane A slots 1,3,4,7

GALILEO
19-20-21-22

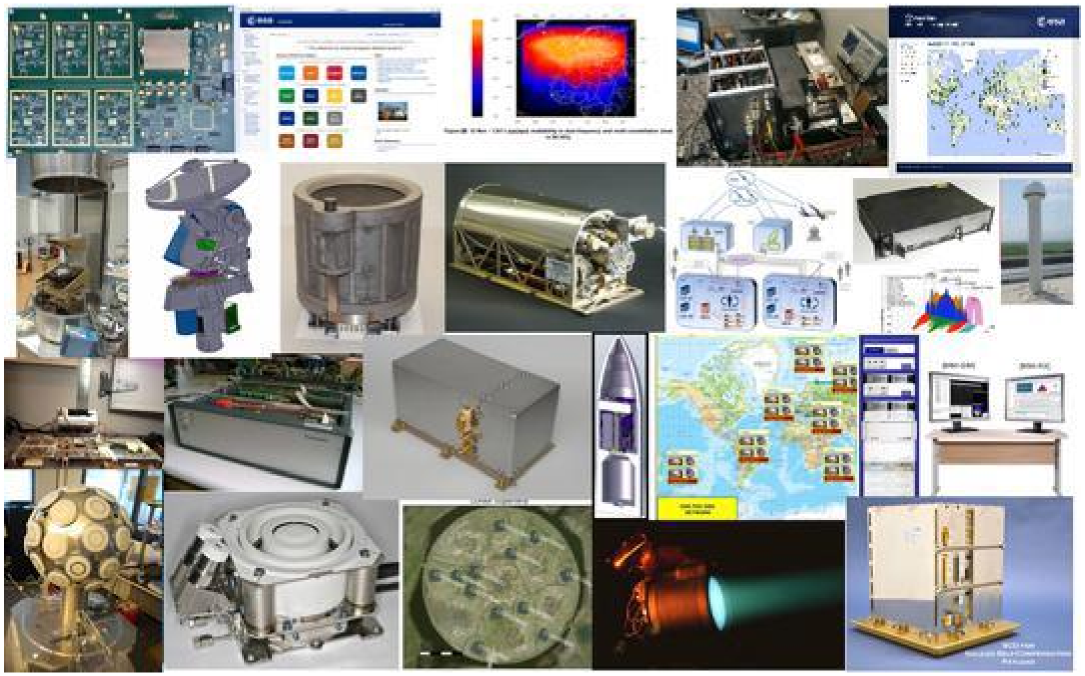
Increased Availability of Positioning





Central European User (@ 5deg masking)			
Launch	**Constellation configuration**	**Availability of PDOP < 5**	**PVT Opportunities over 10 days/ average duration**
L8	4/4/7	79.6%	74 / 2.58 hrs
L8 + L3	4/4/7+2	86.0%	62 / 3.33 hrs
L9	8/4/7+2	99.8%	4 / 59.89 hrs (~8 min average time with insufficient geometry)

GNSS Evolutions activities



- European GNSS Evolution Programme started in 2008 – Phasing out in 2018
- Continuity of R&D ensured through H2020 already since 2016
- EGEP invested 170 M€ (70+ contracts) in GNSS R&D:
    - EGNOS V3 and Galileo G2 Definition Phase.
    - Galileo Evolutions Technology pre-developments
    - Science and GNSS Transversal R&D.

Main Drivers:

- Lessons learned
- User Needs
- New Technologies

↓

- Increased System Robustness
- Flexibility for Improved Re-configurability
- Improved Services

Galileo Evolution Scenarios

Mission Evolution Scenario ES-1 ("Basic")

Galileo FOC optimisation scenario in terms of performance and operability:

- similar spacecraft platform envelope with the same Signal In Space
- improved performance
- limited set of new services
- technology obsolescence

Mission Evolution Scenario ES-2 ("Medium")

a first step in the alignment of Galileo with other GNSS Systems competitiveness.

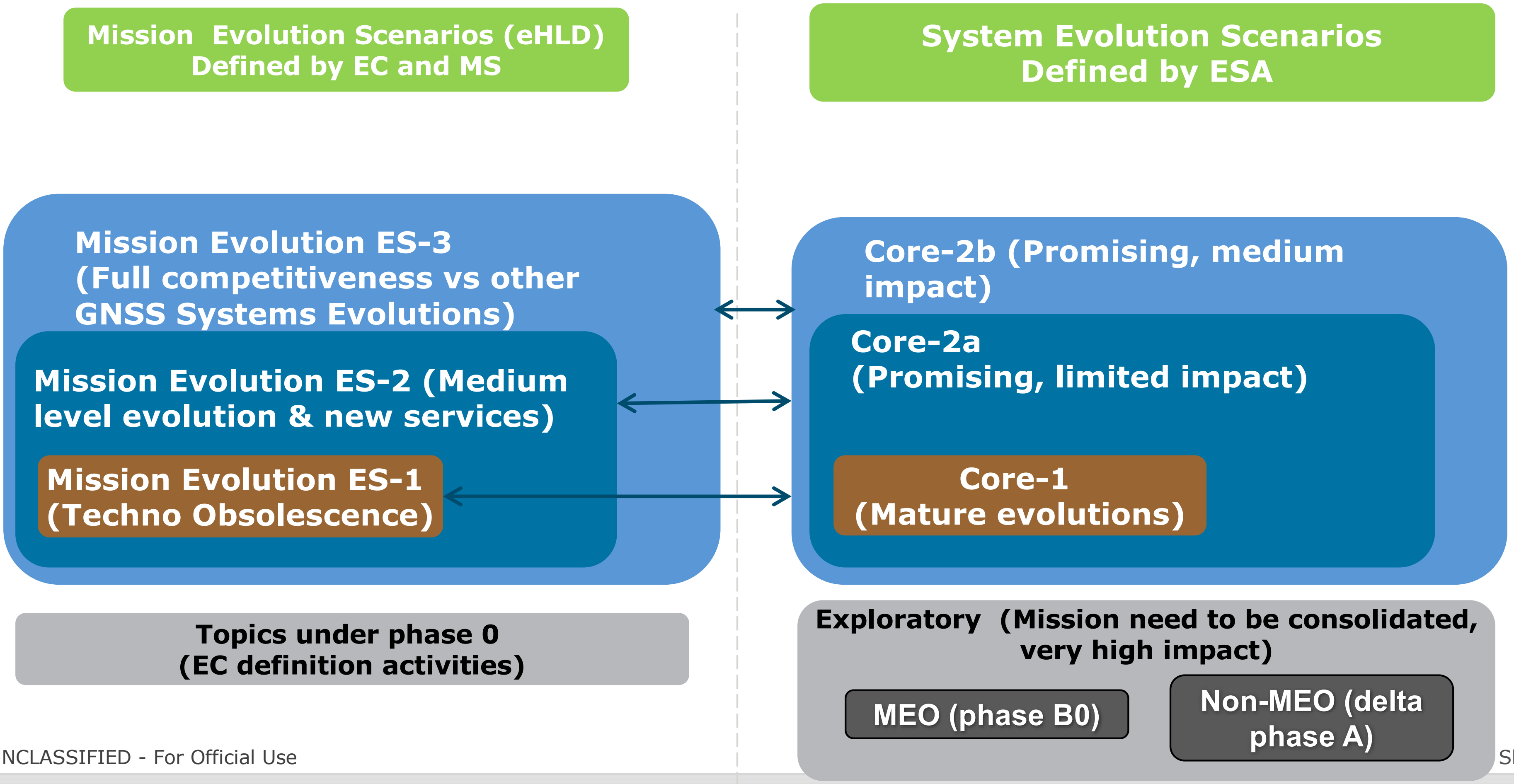
- medium sized platform
- new signals/services
- increased robustness & capabilities
- enhanced performance

Mission Evolution Scenario ES-3 ("Ambitious")

the state of the art

- medium/large size platform
- advanced features
- flexibility of service provision
- high performance and robustness

Galileo Evolutions Scenarios



Conclusions

- **Initial Services Declaration on 15th December 2016**
- **18 satellites in orbit** and production of remaining 8 planned to be completed in 2017
- Constellation deployment "boosted" by Ariane-5 launch capability fully qualified: next Launch#9 in December '17
- Procurement of additional **3rd Batch of 8 satellites** initiated
- Galileo Core Infrastructure handed over to EC-GSA to start Exploitation Phase (**Galileo Service Operator**)
- Ground Segment deployment continues to support **stable and continuous availability of Galileo Signal-in-Space to users**
- **GNSS Evolution R&D** well under way