



Update on GALILEO System Deployment Status and Recovery of Satellites in Non-Nominal Orbits

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10th Annual Meeting of the International Committee on GNSS, Boulder, Colorado
2nd November 2015



Navigation solutions powered by Europe

Major Milestones 2014/2015

FOC-M1 / GSAT0201/02
Launched 22nd August 2014



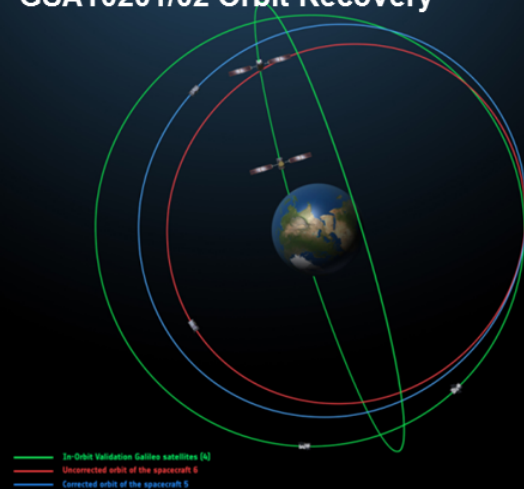
FOC-M2 / GSAT0203/04
Launched 27th March 2015



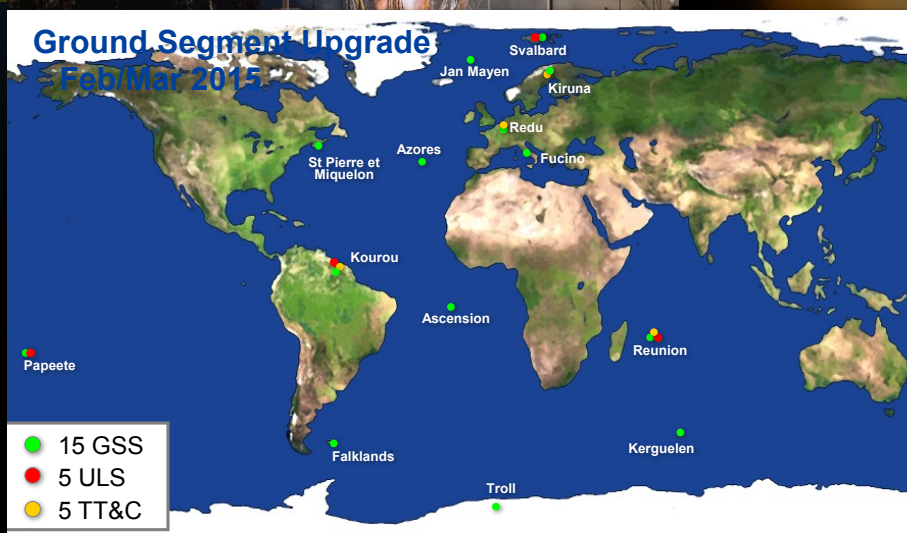
FOC-M3 / GSAT0205/06
Launched 11th September 2015



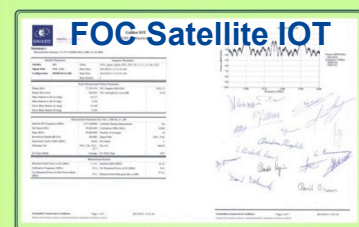
GSAT0201/02 Orbit Recovery



Ground Segment Upgrade
Feb/Mar 2015



FOC-Satellite IOT

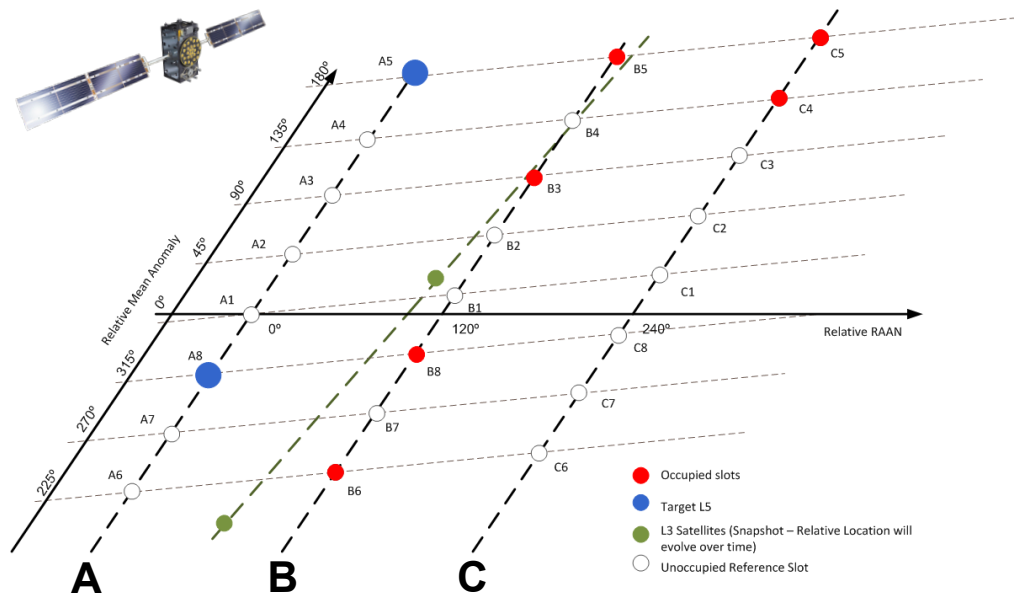


First Galileo GSAT0204 Signals Reception from IOT Station
ESA REDU, 21st May 2015, 11:31:16 GST

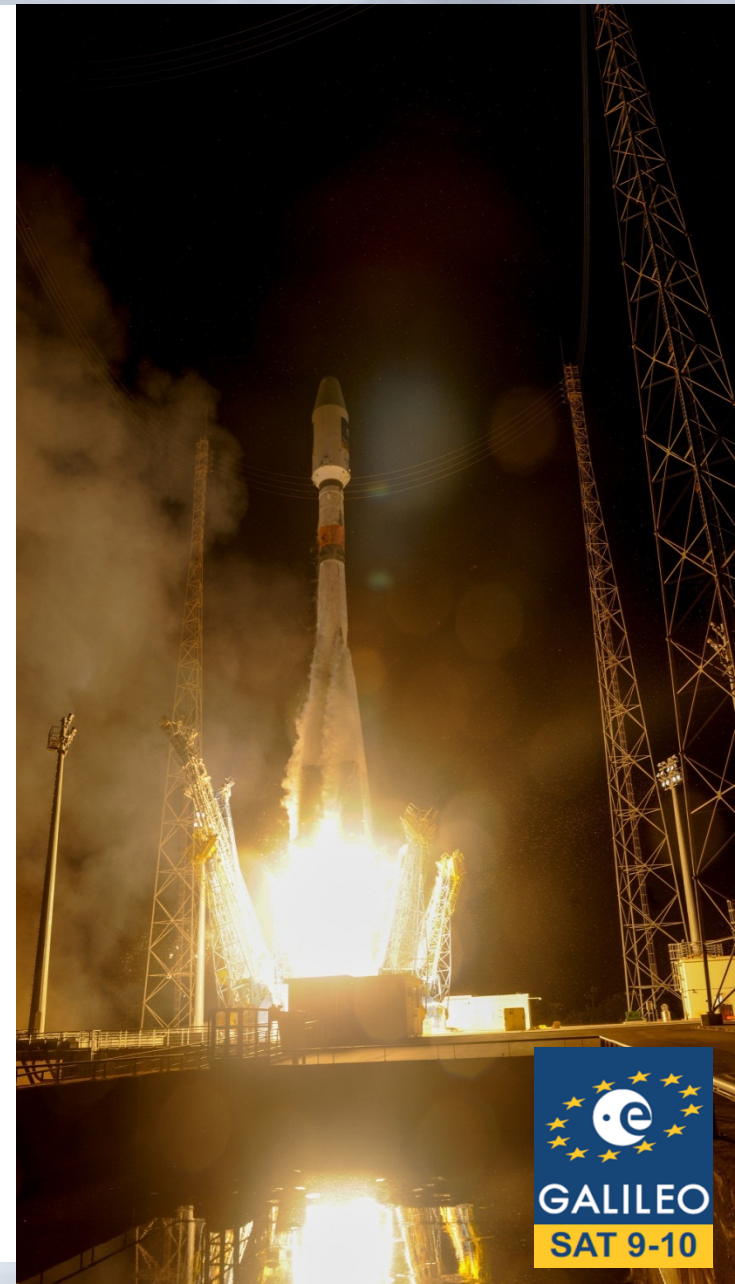


FOC-M3/SAT 9-10 Launched 11th September 2015

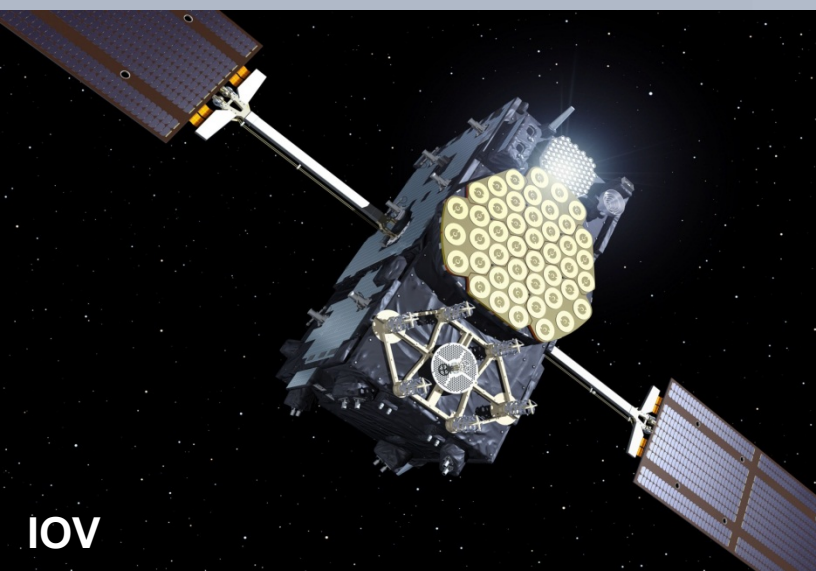
Galileo Constellation:
Semi-major axis: Walker 24/3/1
Inclination: 56 deg
Orbit Period: 14h 4m 42s
Ground track repeat cycle: 10 days / 17 orbits



**All 3 planes of Galileo Walker 24/3/1
populated with satellites
10 Galileo Satellites in Orbit**



Constellation Status

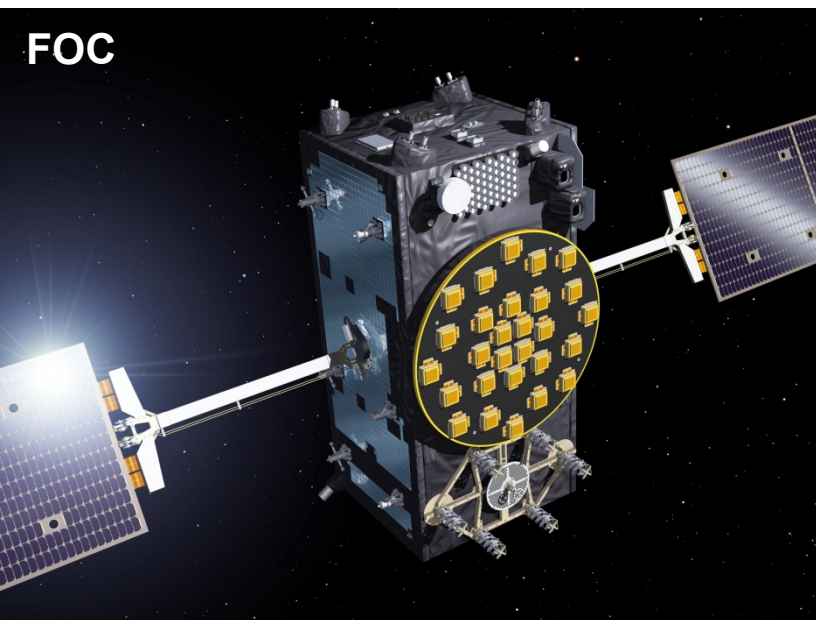


IOV

**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



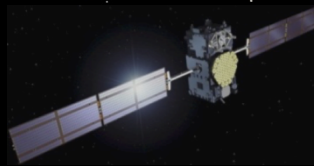
FOC

**S/C Prime Contractor OHB Systems GmbH
P/L Prime Contractor SSTL Ltd**

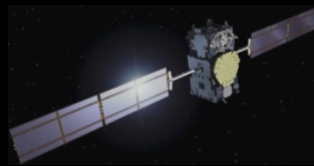
22 satellites – 6 In-Orbit

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

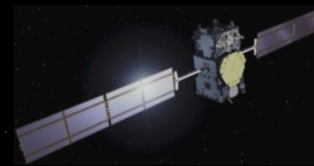
IOV Constellation Status (23 October 2015)



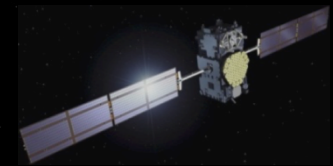
GSAT0101



GSAT0102



GSAT0103



GSAT0104

Launch Date

21 Oct. 2011

21 Oct. 2011

12 Oct. 2012

12 Oct. 2012

SV ID

11

12

19

20

Orbital Slot

B05

B06

C04

C05

Clock

PHM

RAFS

PHM

RAFS

Technical Status

Healthy

Healthy

Healthy

Unavailable from
2014-05-27
(NAGU 2014014)

EIRP

All bands aligned to
Public OS SIS ICD

All bands aligned to
Public OS SIS ICD

All bands in
temporary back-off

E1 only
E5+E6 permanently
not available

SAR

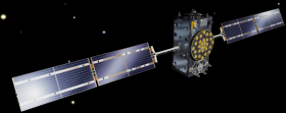
N/A

N/A

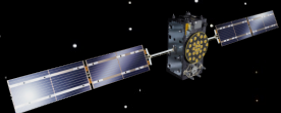
Transponder ON

Transponder ON

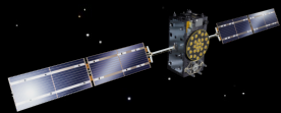
FOC Constellation Status (23 October 2015)



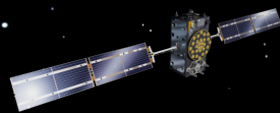
GSAT0201



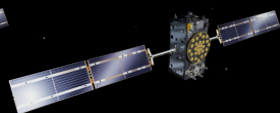
GSAT0202



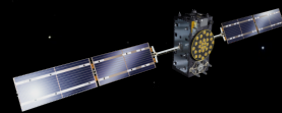
GSAT0203



GSAT0204



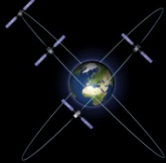

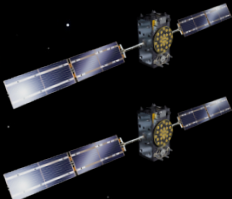
GSAT0205



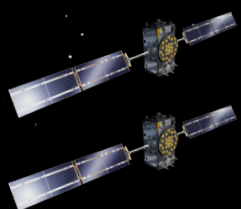

GSAT0206

Launch Date	22 Aug. 2014	22 Aug. 2014	27 Mar. 2015	27 Mar. 2015	11 Sep. 2015	11 Sep. 2015
SV ID	18	14	26	22	24	30
Orbital Slot	N/A (eccentric orbit)	N/A (eccentric orbit)	B08	B03	A08	A05
Clock	PHM	PHM	PHM	PHM	OFF	OFF
Technical Status	In Orbit Testing: Transmission of dummy Nav Msg	In Orbit Testing: Transmission of dummy Nav Msg	In Orbit Testing: Transmission of valid Nav Msg	In Orbit Testing: Transmission of dummy Nav Msg	In Orbit Testing: Payload Keep Alive	In Orbit Testing: Payload Keep Alive
EIRP	All bands aligned to Public OS SIS ICD	All bands aligned to Public OS SIS ICD	All bands aligned to Public OS SIS ICD	All bands aligned to Public OS SIS ICD	Signal OFF	Signal OFF
SAR	Transponder ON	Transponder OFF	Transponder OFF	Transponder OFF	Transponder OFF	Transponder OFF

Active NAGUs (20th October 2015)

NAGU NUMBER	GSAT	NAGU TYPE	EVENT START (UTC)	EVENT DESCRIPTION
2013022	ALL 	GENERAL	2013-12-02 00:00	DUE TO ON-GOING TESTS ON THE SYSTEM INFRASTRUCTURE, CHANGES ON FLAGS STATUS CAN BE OBSERVED. USERS ARE ADVISED TO DISREGARD THESE FLAGS TILL FURTHER NOTICE.
2014014	GSAT0104 	UNP_UNUFN	2014-05-27 12:30	GALILEO SATELLITE GSAT0104 (ALL SIGNALS) IS UNAVAILABLE SINCE 2014-05-27 BEGINNING 12:30 UTC UNTIL FURTHER NOTICE.
2015009	GSAT0203 GSAT0204 	GENERAL	2015-03-27 21:46	GALILEO SATELLITES GSAT0203 (SV_ID 26) AND GSAT0204 (SV_ID 22) WERE LAUNCHED ON 2015-03-27 AT 21:46:18 UTC. GSAT0203 AND GSAT0204 ARE PLANNED TO BE POSITIONED IN SLOTS B08 AND B03 OF THE CONSTELLATION. USERS WILL BE ADVISED OF AVAILABILITY OF SIGNALS FOLLOWING COMPLETION OF COMMISSIONING ACTIVITIES.

Active NAGUs (20th October 2015)

NAGU NUMBER	GSAT	NAGU TYPE	EVENT START (UTC)	EVENT DESCRIPTION
2015011	GSAT0205 GSAT0206 	GENERAL	2015-09-11 02:08	GALILEO SATELLITES GSAT0205 (SV_ID 24) AND GSAT0206 (SV_ID 30) WERE LAUNCHED ON 2015-09-11 AT 02:08 UTC. GSAT0205 AND GSAT0206 ARE PLANNED TO BE POSITIONED IN SLOTS A08 AND A05 OF THE CONSTELLATION. USERS WILL BE ADVISED OF AVAILABILITY OF SIGNALS FOLLOWING COMPLETION OF COMMISSIONING ACTIVITIES.
2015013	GSAT0103 	AVAILABLE	2015-10-08 22:11	GALILEO SATELLITE GSAT0103 (ALL SIGNALS) IS AVAILABLE SINCE/AS OF 2015-10-08 BEGINNING 22:11 UTC. PAYLOAD ON PHM CLOCK. GALILEO SATELLITE GSAT0103 (ALL SIGNALS) WAS UNAVAILABLE FROM 2015-10-07 BEGINNING 04:51 UTC.

NAGUs are published on the European GNSS Service Centre website
(<http://www.gsc-europa.eu>)

FOC Satellites Production & Qualification

OHB Bremen, D



ESTEC Noordwijk, NL

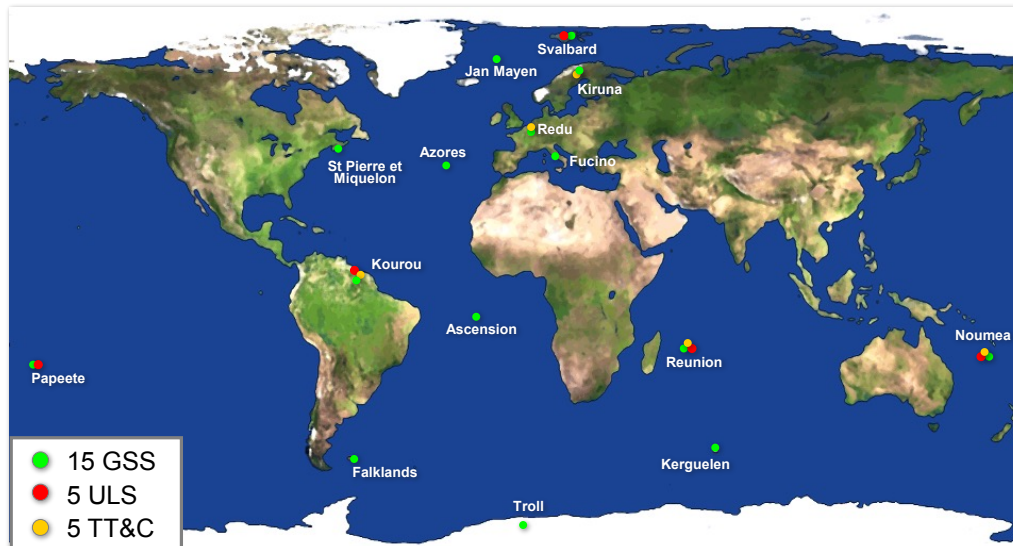
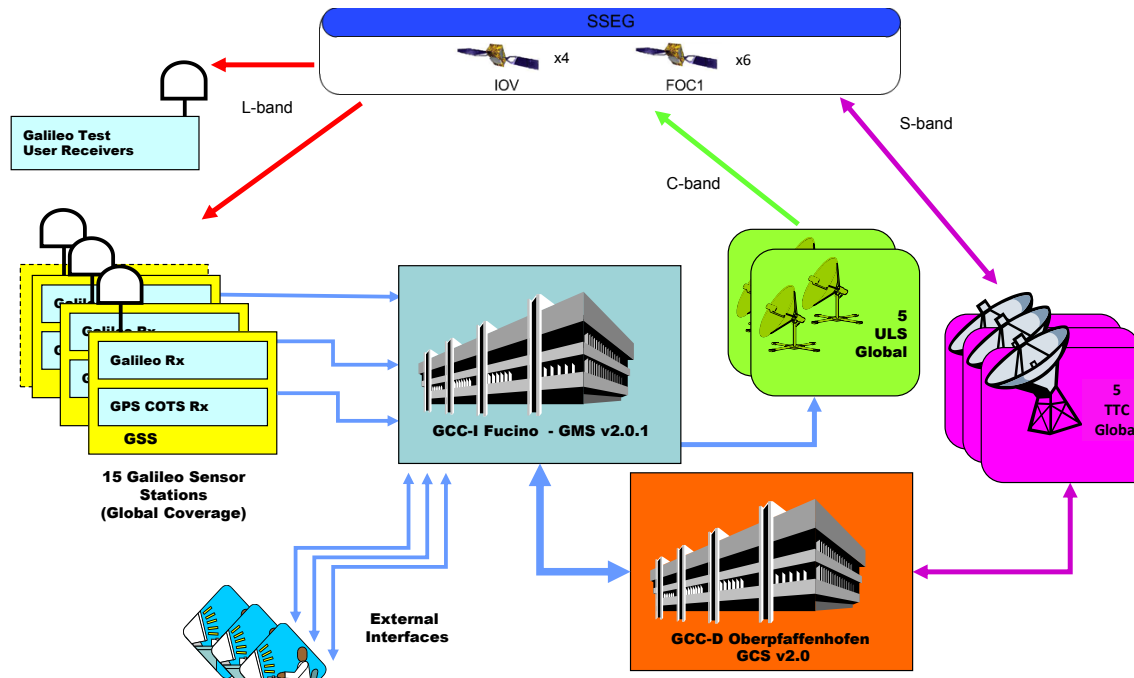


FOC Satellites Production



- **FOC-M4 (Launch planned on 17/12/15 with Soyuz to orbital slots C02 & C07)**
 - **GSAT0208** waiting for delivery to CSG
 - **GSAT0209** waiting for delivery to CSG
- **FOC-M5 (Launch planned in Fall 2016 with Ariane-5)**
 - **GSAT0210** TVAC completed, under final Functional Testing
 - **GSAT0211** TVAC completed, under final Functional Testing
 - **GSAT0212** at IABG Munich, completing A5 Delta Qualification activities
 - **GSAT0207** at OHB Bremen, TVAC planned in Dec. 2015
- **FOC-M6 (Launch planned in Spring 2017 with Soyuz)**
 - **GSAT0213-14** at OHB Bremen, under integration
- **FOC-M7 (Launch planned in Fall 2017 with Ariane-5)**
 - **GSAT0215-18** at OHB Bremen, under integration
- **FOC-M8 (Launch planned in Spring 2018 with Ariane-5)**
 - **GSAT0219-22** at OHB Bremen, under integration

2015: Major Upgrade of Ground Infrastructure and Completion Global Network of FOC Sites



Expansion of the Galileo Ground Segment Capability

Main upgrades of latest version of GMS compared with previous IOV system configurations include:

- ✓ From one to **two fully operational Galileo Control Centers**: GCC-I Fucino (GMS) and GCC-D Oberpfaffenhofen (GCS)
- ✓ **Four new Galileo Sensor Stations (GSS)** located in St Pierre et Michelon, Kiruna, Ascension, and Azores were added to the operations chain, leading to a **total of 15 operational GSSs**.
- ✓ **A total of 5 Mission Uplink Stations (ULS)** with the inclusion of the Svalbard and Papeete uplink stations. 2 antenna at each ULS
- ✓ **A total of 5 TTC stations**, with the inclusion of Noumea and Reunion.

Improved navigation performance and robustness for all services

FOC New Operational Sites

**Galileo Control Centre
Fucino
GCC-I** 



**Galileo Control Centre
Oberpfaffenhofen
GCC-D** 



**Launch & Early
Ops Centre,
ESOC D'stadt, D &
CNES TLS, F**



IOT and TTC Station Redu, B



**TTC Station
Kiruna, S**



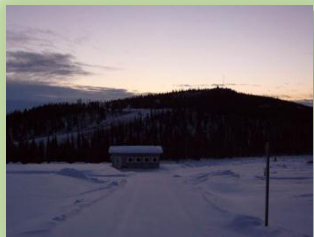
**Uplink Station
Svalbard, N**



**TTC & Uplink
Station Noumea, F**



**TTC & Uplink
Station Kourou, F**



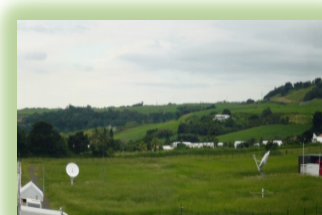
GSS Kiruna, S



GSS Ascension, UK



GSS Azores, P



**TTC & Uplink
Station Reunion, F**

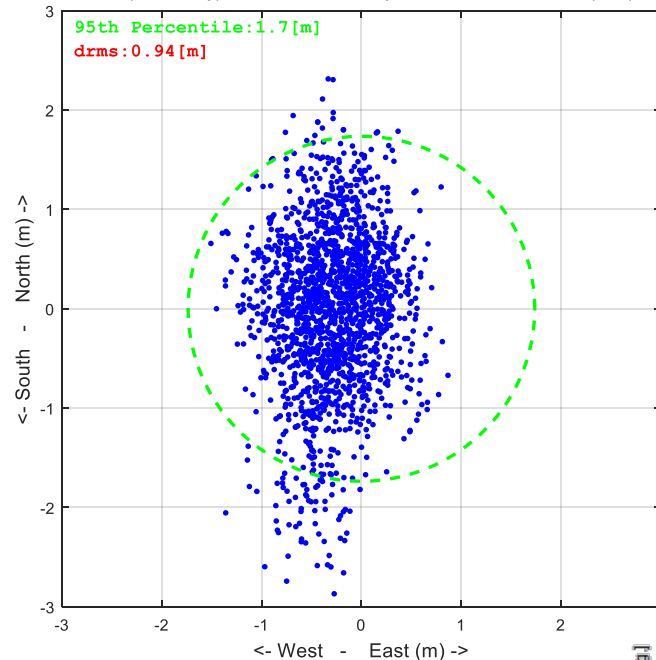


**Uplink Station
Papeete, F**

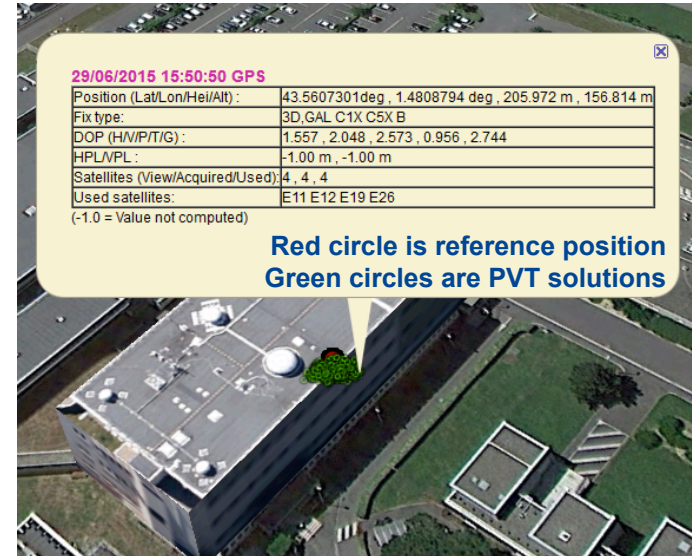
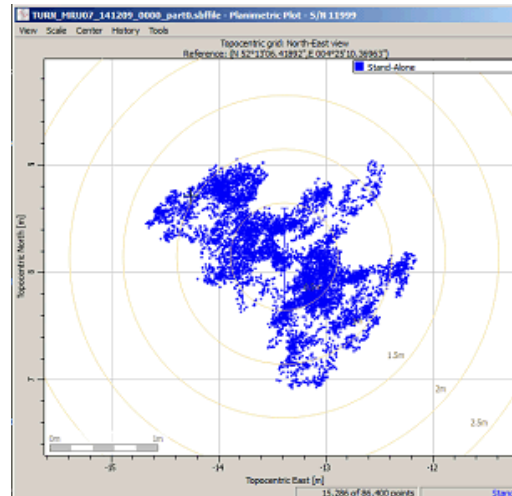
PVT Field Tests with FOC Satellites

- ★ FOC Position Fix performed by both ESA and CNES based on broadcast of experimental Navigation Message
- ★ Achieved good performance with FOC satellites

GIEN (Turin, Italy) - Horizontal Accuracy 2015-07-19 14:00 - 15:00 (UTC)

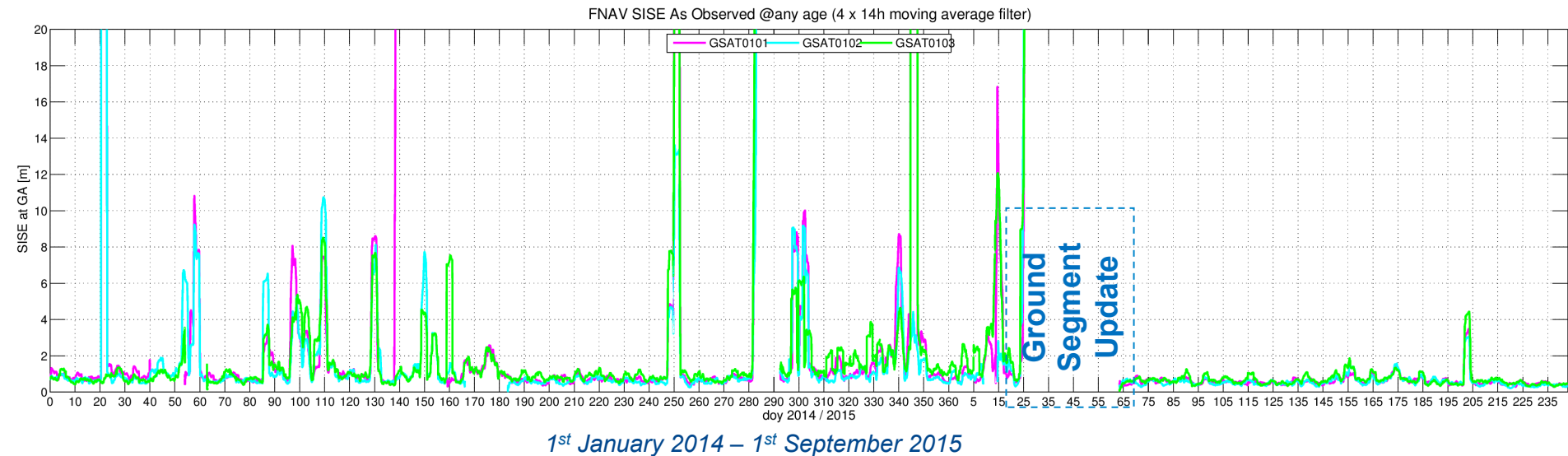


PVT at GIEN station (Turin, I)
3 IOV + 1 FOC
19/07/2015, PDOP < 2.6
Horizontal Accuracy: **1.7m (95%)**
Vertical Accuracy: **2.5m (95%)**



PVT at CNES Toulouse, F
3 IOV + 1 FOC
29/06/2015
Horizontal Accuracy: **3.2m (95%)**
Vertical Accuracy: **2.8 m (95%)**

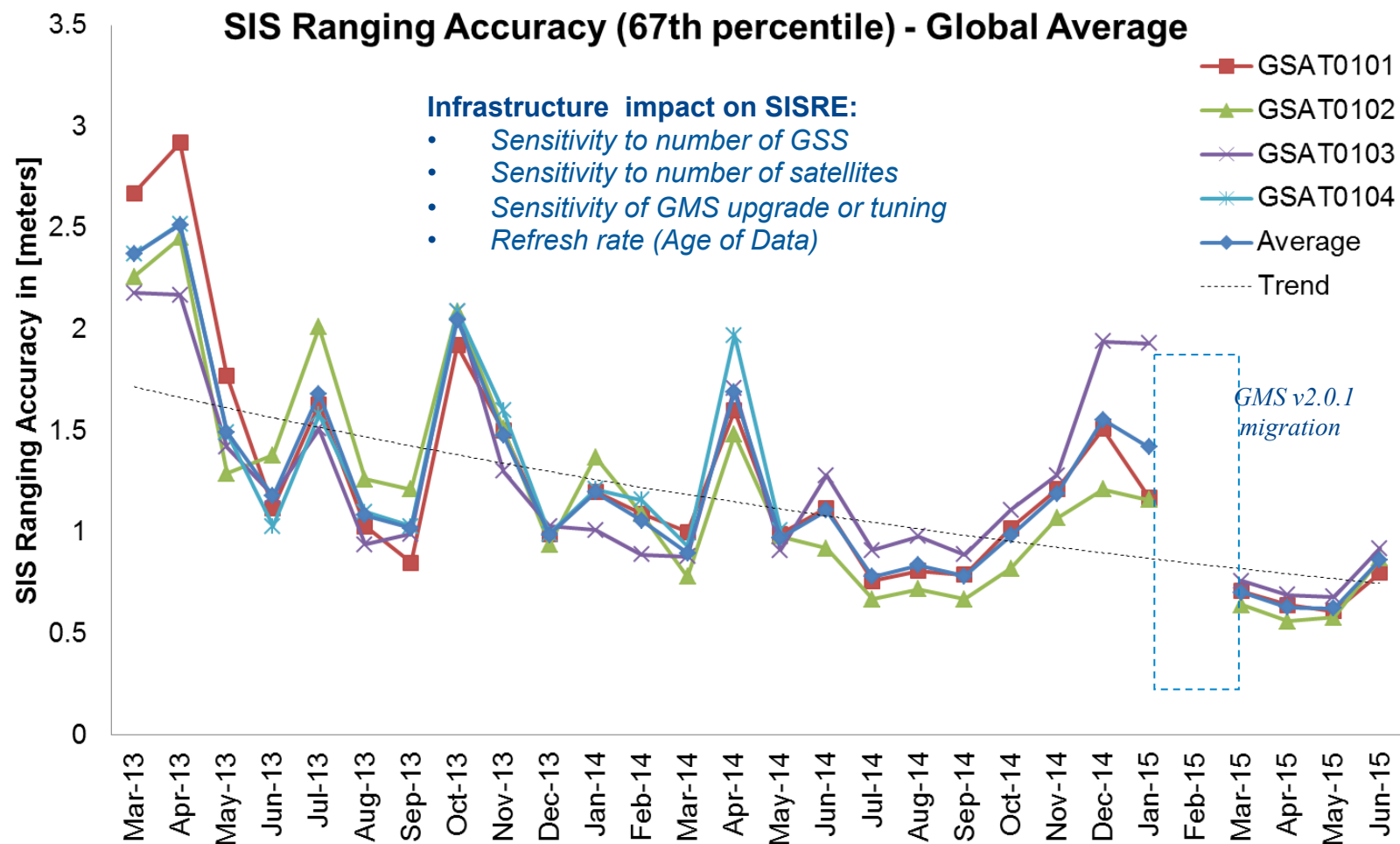
Signal In Space Ranging Accuracy (SISRE): Detailed Time Series



Satellite	Ranging Accuracy 2014/15 67 th percentile
GSAT0101	0.98 m
GSAT0102	0.87 m
GSAT0103	1.07 m
GSAT0104	1.20 m

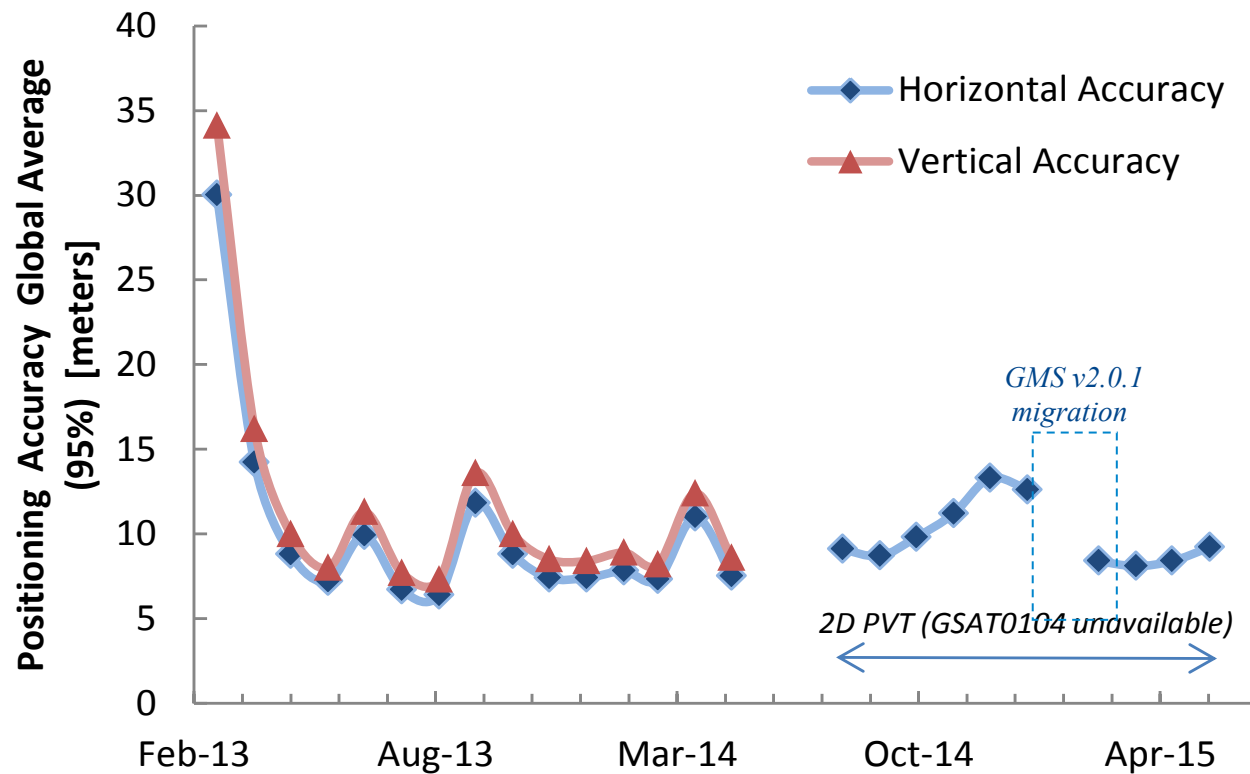
- ❑ Ranging Performance **improved by 30%** since Ground Segment Upgrade
- ❑ Ranging Accuracy: ~1m -> **0.69m (67%)** after upgrade
- ❑ **Age of Data ~100minutes (90%)** in July 2015
- ❑ **Refresh rate of ephemeris as low as 10 minutes** thanks to 5 ULS in operations.

Signal In Space Ranging Accuracy (SISRE): Monthly Statistics



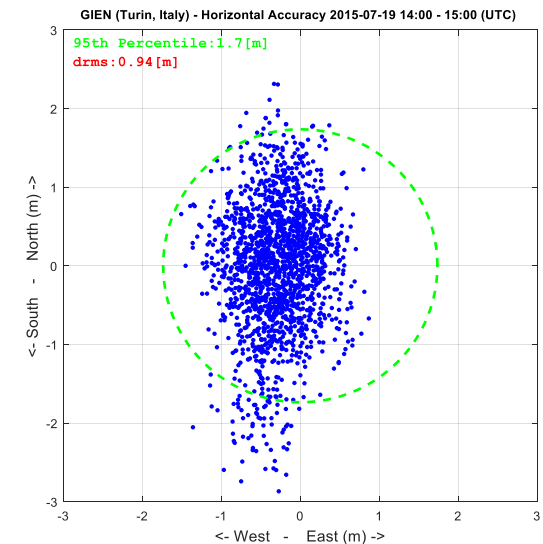
The long term analysis of SISRE show a decreasing trend over time since the IOV phase, even with a limited set of satellites in the ODTS processing. The performance will further improve as the FOC satellites will declared operational and inserted in the GMS processing.

Galileo Positioning Performance



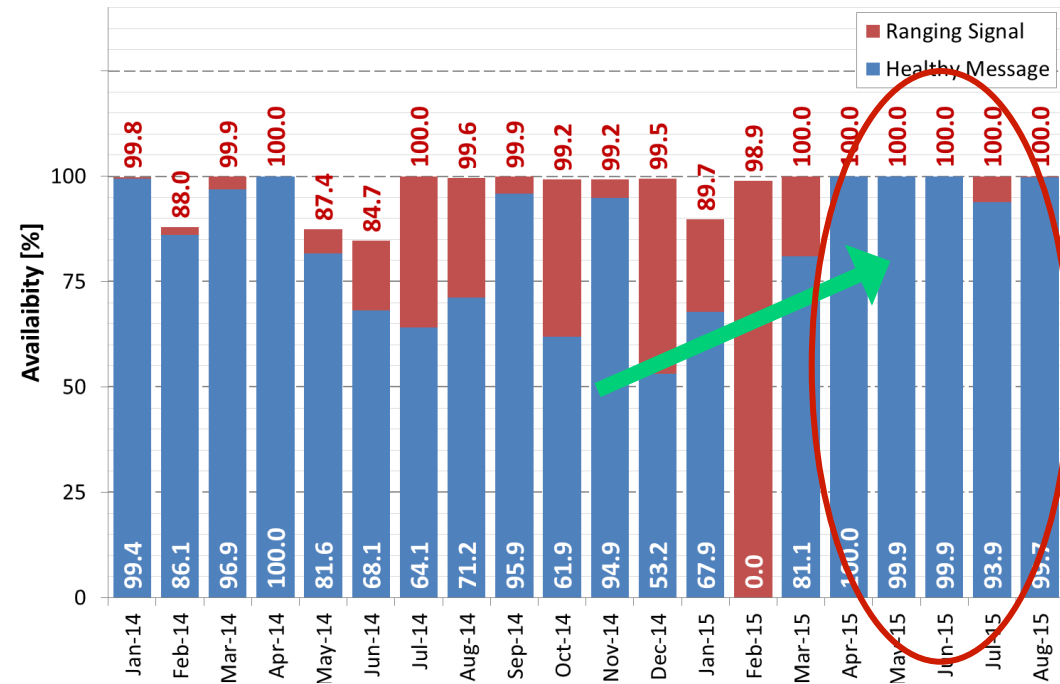
Monthly DF Open Service horizontal and vertical accuracy – extrapolated global averages (PDOP≤6) obtained projecting the computed IOV satellites SISRE values onto a dense worldwide user grid. Since June 2015, due to GSAT0104 unavailability, only 3 healthy IOV satellites have been available. Assuming a zero elevation above Earth a 2D PVT (horizontal accuracy) was computed.

Example of real Galileo PVT with 3 IOV + 1 FOC satellites



GIEN station (Turin, Italy)
2015-07-19 14:00-15:00h
UTC, PDOP < 2.6
H: 1.7m (95%)
V: 2.5m (95%)

Signal and Message Availability



Satellite	Availability 2014/15	
	Signal	Message
GSAT0101	96.0%	65.6%
GSAT0102	96.3%	80.0%
GSAT0103	99.0%	85.7%
GSAT0104*	28.5%	28.4%

★ Availability significantly improved by Ground Segment Upgrade

★ Availability since Ground Segment upgrade (since April 2015):

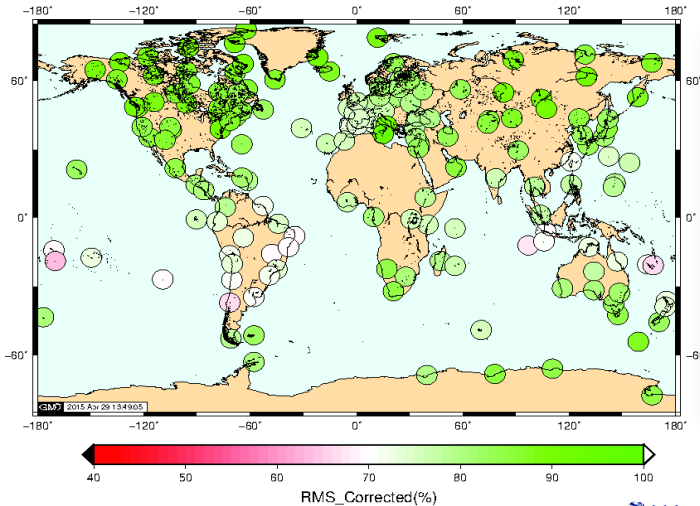
Availability of Signal broadcast: **100%**

Availability of Healthy Messages: **98.5%**

Galileo Nequick-G Ionospheric Correction Performance

Galileo broadcast (NeQuick G)

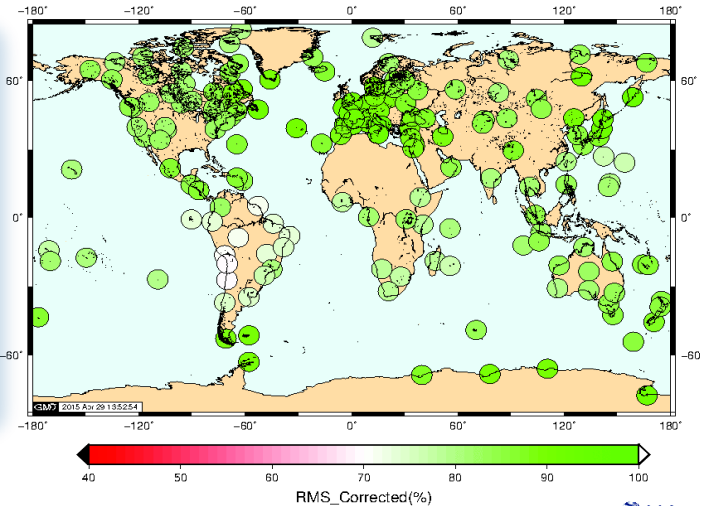
Doy 2015_76, Mean_Correction 79.4%



Good performance of Nequick-G model to correct Iono errors for Single Freq users.

White to green >= 70% correction level >100 stations, reference ionosphere based on dual-freq IONEX-levelled:

Doy 2015_80, Mean_Correction 82.9%

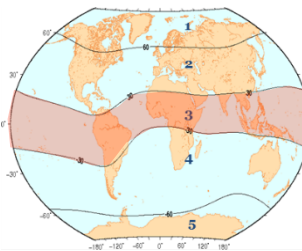
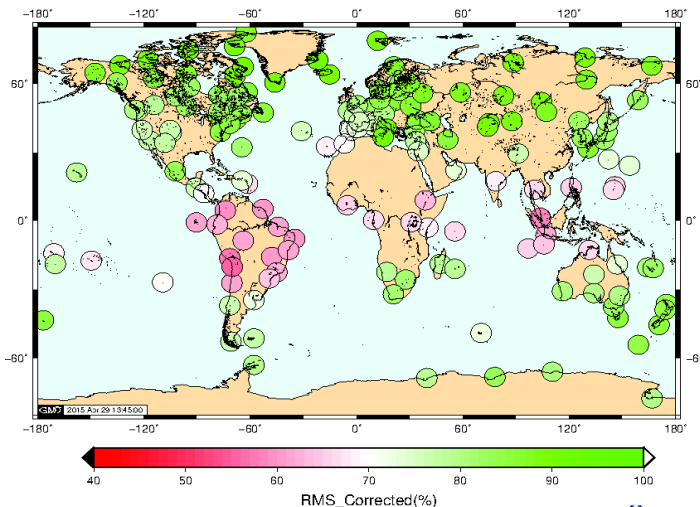


17th March 2015 St. Patrick's Day Solar Storm

21st March 2015

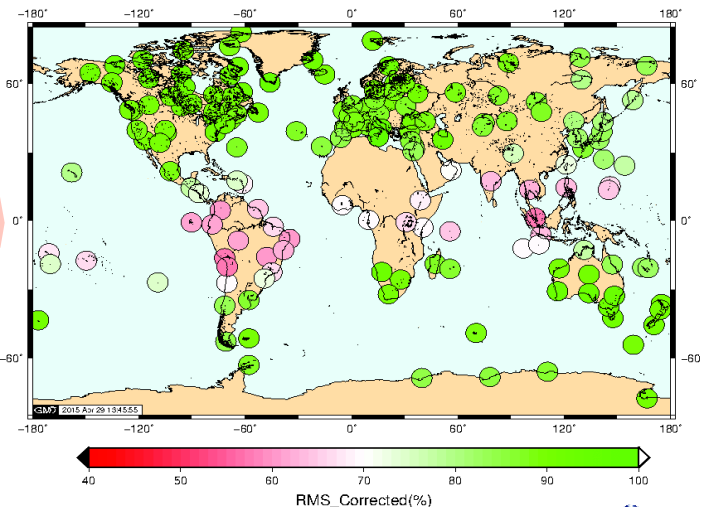
GPS broadcast (Klobuchar)

Doy 2015_76, Mean_Correction 76.2%

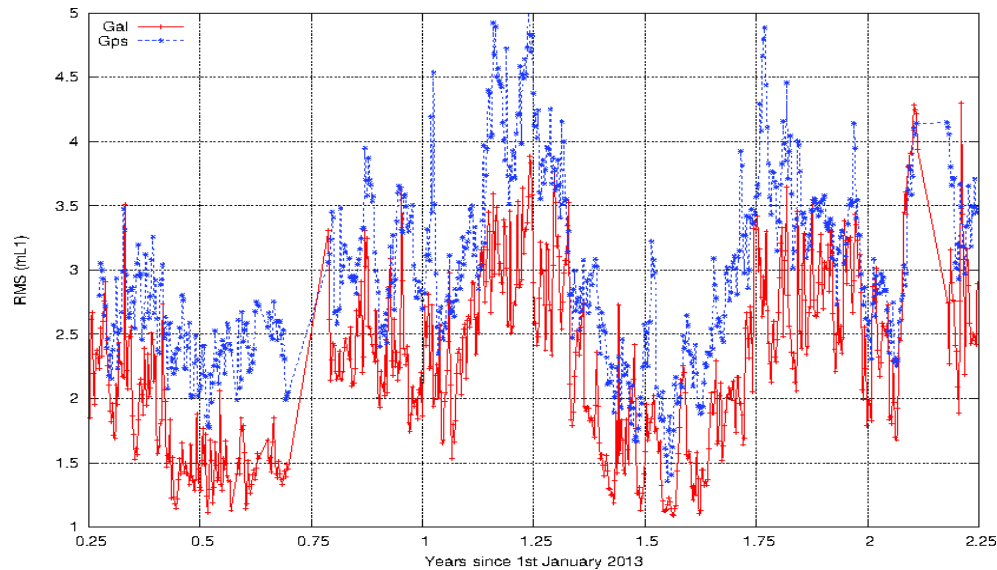


Higher ionospheric activity in Equatorial band MODIP=3

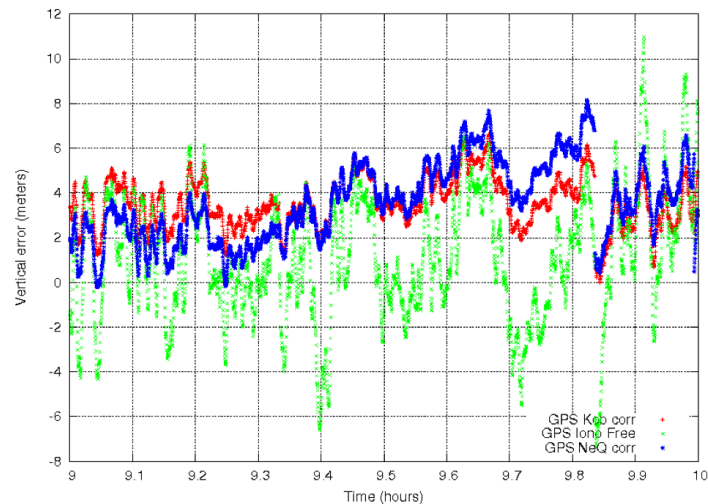
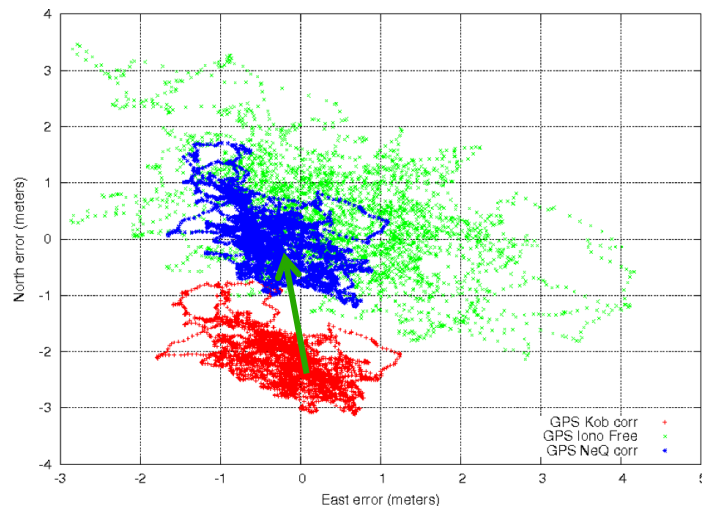
Doy 2015_80, Mean_Correction 80.3%



Residual IONO RMS error (meters_{L1}): Daily Evolution 2013-2015

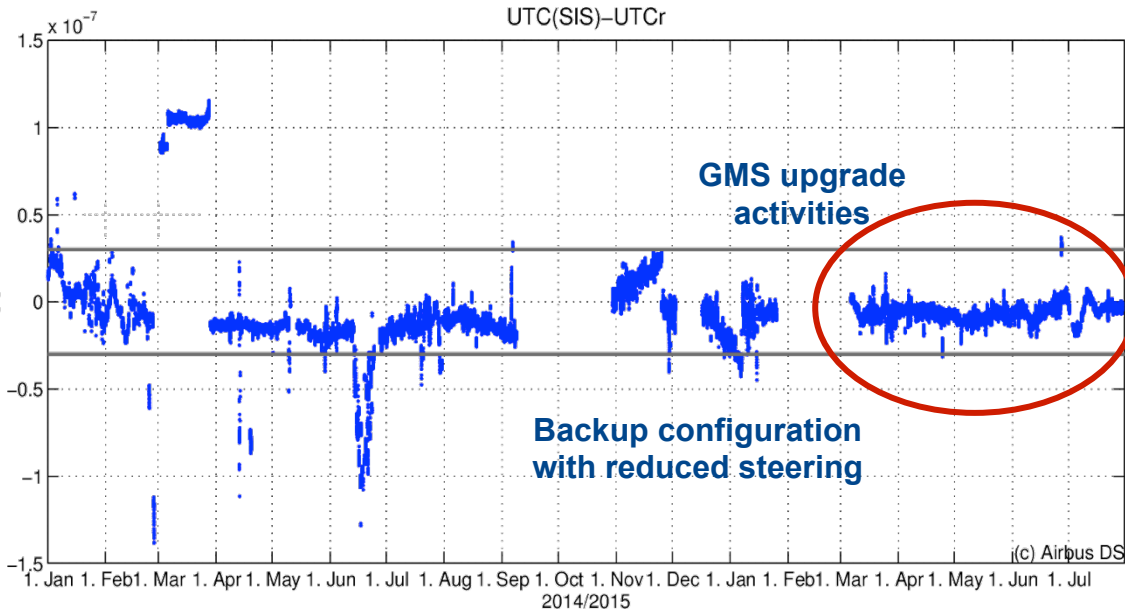


Broadcast NeQuick G performance **very good** despite the low (3-4) number of satellites used to drive the model.
On average **~1m error reduction** with NeQuick compared to Klobuchar.

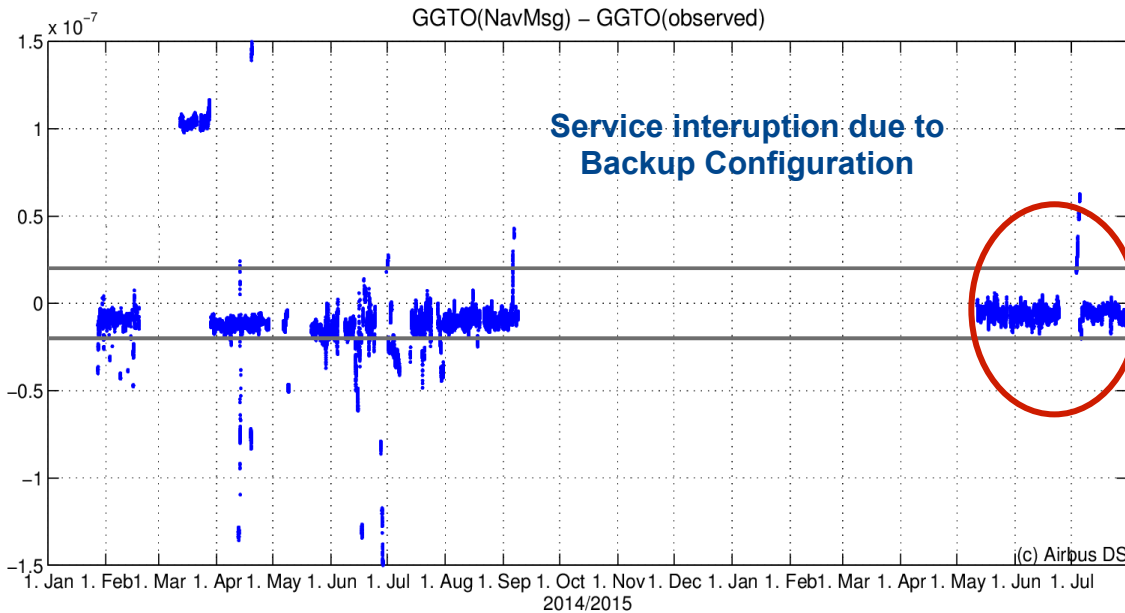


Horiz. (left) and Vert. (right) GPS positioning error on L1 and single-frequency NeQuick G correction (blue), L1 and GPS ICA (red) and dual-frequency ionospheric-free (green) for low-latitude station Malindi (doy 172, 2013)

UTC Dissemination & GGTO Performance



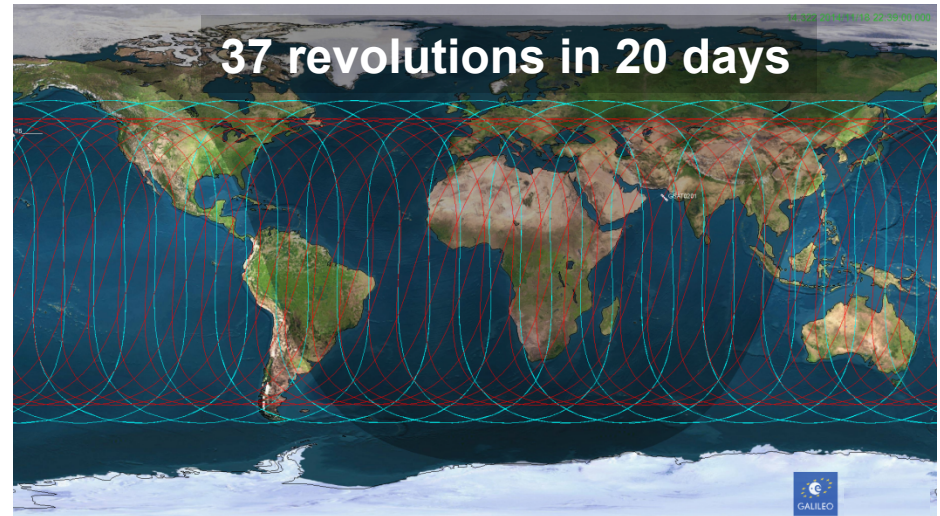
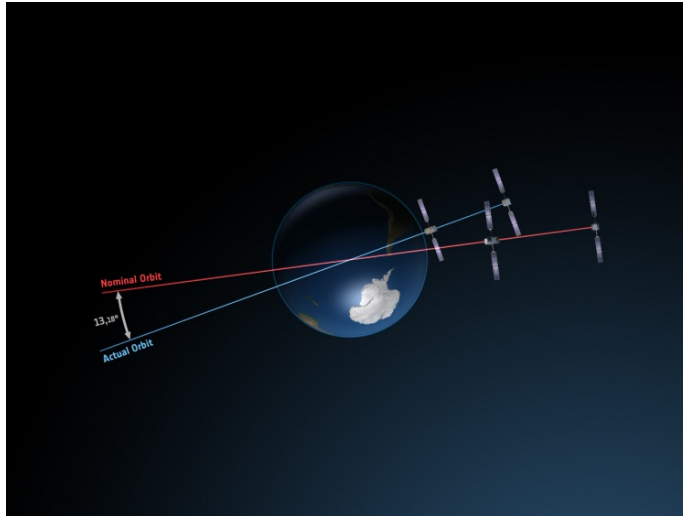
- ★ Measured UTC Dissemination Performance: **< 10ns (95%)** since Ground Segment Upgrade



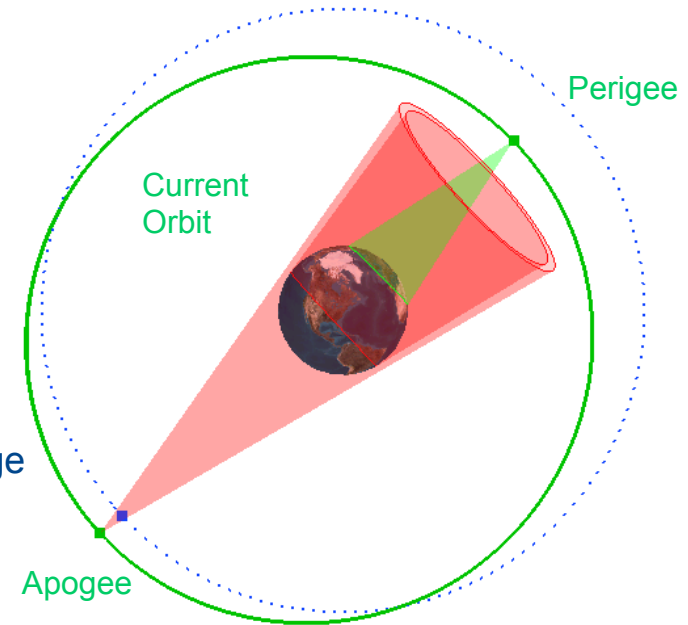
- ★ Measured GGTO Performance: **< 9.6 ns (95%)** since Ground Segment Upgrade; GGTO dissemination resumed on 11/05/2015

GSAT0201/0202 Orbit Recovery

- ★ VS09 Orbit injection anomaly left GSAT0201/0202 in eccentric orbits



- ★ Both spacecraft safely raised to higher orbit
- ★ Satellites currently transmitting Dummy Navigation Message
 - ✓ Perigee raised from **13700** to **17200** km
 - ✓ Eccentricity reduced from **0.23** to **0.15**
 - ✓ Above Van Allen belts & Earth Sensors in operational range

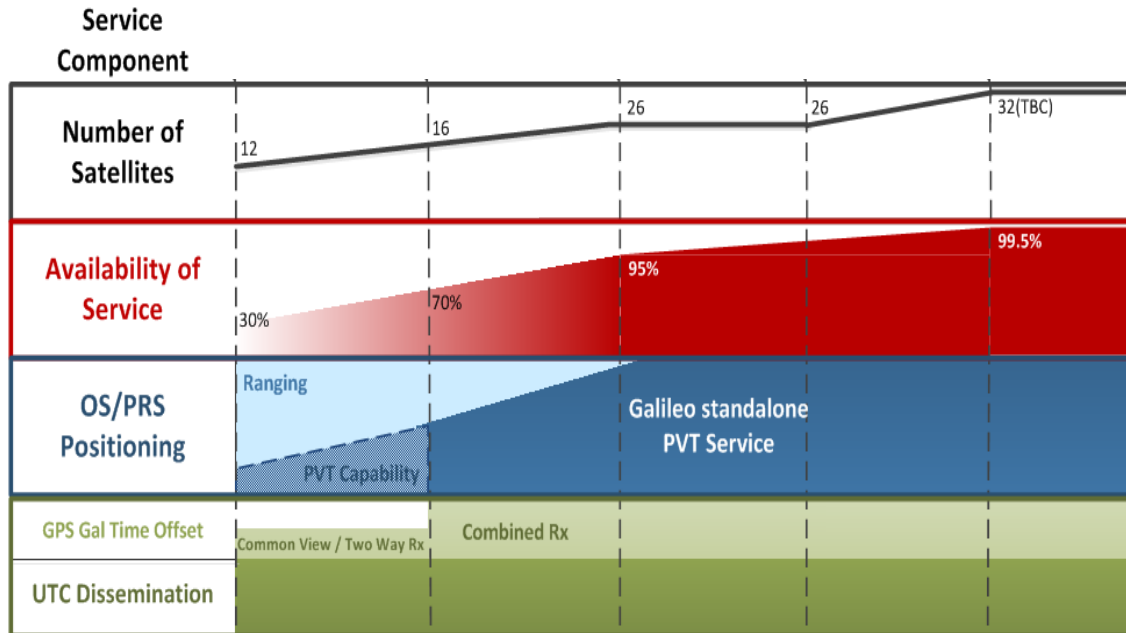


GSAT0201/0202 Recovery

Recovery of GSAT0201/0202 is achieved through following steps:

- ★ Orbit Raising to allow for nominal operation of satellites ☒
- ★ Receiver tracking demonstrated during field test campaigns ☒
- ★ Planned update of the Ground Segment to broadcast Navigation Message and Dummy Almanac ☐
 - ★ Short term: Update of Orbit and Clock processing to generate Navigation information and uplink **once per orbit**
 - ★ Medium term: Update of dissemination infrastructure to allow for **nominal dissemination** of the Navigation information
 - ★ Validation campaign confirming the quality of the Navigation products before full introduction in processing Q4/2016
- ★ Planned Usage for SAR Forward Link Service ☐
 - ★ Orbit Information generated **by Time and Geodesy Validation Facility** for GSAT0201/0202 and 0104
 - ★ Made available to SAR users **by European GNSS Service Centre**

Future System Upgrades & Deployment



Continuous improvement of System Performance with the on-going deployment of the Space and Ground infrastructure

System Upgrades will improve performance and robustness for all services up to FOC Targets.

- ✓ Completion of the Satellite Constellation
- ✓ Ground Segment upgrade roll out with minimum impact on broadcast SIS availability
- ✓ Further improve the robustness and operability of the system
- ✓ Expand the capabilities of the ground segment to the full extent for FOC
- ✓ Gradually introduce system flags
- ✓ Introduce GSAT0201/0202 navigation processing upon successful testing

Conclusions

- ★ **VS12 successfully deployed GSAT0205/0206 on 11 Sep. 2015**
- ★ VS11 successfully deployed GSAT0203/0204 on 27 Mar. 2015
- ★ Orbit Recovery achieved for GSAT0201/0202
- ★ **10 Galileo Satellites in Orbit** – one third of the constellation
- ★ **Successful Upgrade of Ground Segment** with major improvements on product quality and availability. Expansion of global network of stations.
- ★ System Deployment will continue to improve navigation message performance, availability and robustness.
- ★ **OBJECTIVE to reach stable and continuous availability of Galileo Signal-in-Space to users**