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

Rafael Lucas, European Space Agency
10th Annual Meeting of the International Committee on GNSS, Boulder, Colorado
2nd November 2015
FOC-M3/SAT 9-10 Launched 11th September 2015

Galileo Constellation: Walker 24/3/1
Semi-major axis: 29600.318 km
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

**S/C Prime Contractor**  Astrium GmbH
(now 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 – 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
<table>
<thead>
<tr>
<th></th>
<th>GSAT0101</th>
<th>GSAT0102</th>
<th>GSAT0103</th>
<th>GSAT0104</th>
</tr>
</thead>
<tbody>
<tr>
<td>SV ID</td>
<td>11</td>
<td>12</td>
<td>19</td>
<td>20</td>
</tr>
<tr>
<td>Orbital Slot</td>
<td>B05</td>
<td>B06</td>
<td>C04</td>
<td>C05</td>
</tr>
<tr>
<td>Clock</td>
<td>PHM</td>
<td>RAFS</td>
<td>PHM</td>
<td>RAFS</td>
</tr>
<tr>
<td>Technical Status</td>
<td>Healthy</td>
<td>Healthy</td>
<td>Healthy</td>
<td>Unavailable from 2014-05-27 (NAGU 2014014)</td>
</tr>
<tr>
<td>EIRP</td>
<td>All bands aligned to Public OS SIS ICD</td>
<td>All bands aligned to Public OS SIS ICD</td>
<td>All bands in temporary back-off</td>
<td>E1 only E5+E6 permanently not available</td>
</tr>
<tr>
<td>SAR</td>
<td>N/A</td>
<td>N/A</td>
<td>Transponder ON</td>
<td>Transponder ON</td>
</tr>
<tr>
<td>Satellite ID</td>
<td>Launch Date</td>
<td>SV ID</td>
<td>Orbital Slot</td>
<td>Clock</td>
</tr>
<tr>
<td>-------------</td>
<td>--------------</td>
<td>-------</td>
<td>--------------</td>
<td>-------</td>
</tr>
<tr>
<td>GSAT0201</td>
<td>22 Aug. 2014</td>
<td>18</td>
<td>N/A (eccentric orbit)</td>
<td>PHM</td>
</tr>
<tr>
<td>GSAT0202</td>
<td>22 Aug. 2014</td>
<td>14</td>
<td>N/A (eccentric orbit)</td>
<td>PHM</td>
</tr>
<tr>
<td>GSAT0203</td>
<td>27 Mar. 2015</td>
<td>26</td>
<td>B08</td>
<td>PHM</td>
</tr>
<tr>
<td>GSAT0204</td>
<td>27 Mar. 2015</td>
<td>22</td>
<td>B03</td>
<td>PHM</td>
</tr>
<tr>
<td>GSAT0205</td>
<td>11 Sep. 2015</td>
<td>24</td>
<td>A08</td>
<td>OFF</td>
</tr>
<tr>
<td>GSAT0206</td>
<td>11 Sep. 2015</td>
<td>30</td>
<td>A05</td>
<td>OFF</td>
</tr>
</tbody>
</table>

**FOC Constellation Status (23 October 2015)**

- **EIRP**: All bands aligned to Public OS SIS ICD
- **SAR**: Transponder ON
- **Launch Date**: 22 Aug. 2014
- **SV ID**: 18
- **Orbital Slot**: N/A (eccentric orbit)
- **Clock**: PHM
- **Technical Status**: In Orbit Testing: Transmission of dummy Nav Msg
- **EIRP**: All bands aligned to Public OS SIS ICD
- **SAR**: Transponder ON
### Active NAGUs (20th October 2015)

<table>
<thead>
<tr>
<th>NAGU NUMBER</th>
<th>GSAT</th>
<th>NAGU TYPE</th>
<th>EVENT START (UTC)</th>
<th>EVENT DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>2013022</td>
<td>ALL</td>
<td>GENERAL</td>
<td>2013-12-02 00:00</td>
<td>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.</td>
</tr>
<tr>
<td>2015009</td>
<td>GSAT0203 GSAT0204</td>
<td>GENERAL</td>
<td>2015-03-27 21:46</td>
<td>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.</td>
</tr>
</tbody>
</table>
### Active NAGUs (20th October 2015)

<table>
<thead>
<tr>
<th>NAGU NUMBER</th>
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<th>NAGU TYPE</th>
<th>EVENT START (UTC)</th>
<th>EVENT DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015011</td>
<td>GSAT0205</td>
<td>GENERAL</td>
<td>2015-09-11 02:08</td>
<td>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.</td>
</tr>
<tr>
<td>2015013</td>
<td>GSAT0103</td>
<td>AVAILABLE</td>
<td>2015-10-08 22:11</td>
<td>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.</td>
</tr>
</tbody>
</table>

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
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 Miquelon, 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

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

IOT and TTC Station Redu, B

GSS Kiruna, S
GSS Ascension, UK
GSS Azores, P

TTC Station
Kiruna, S

TTC & Uplink Station Noumea, F

Uplink Station
Svalbard, N

TTC & Uplink Station Kourou, F

GSS Reunion, F

Uplink Station
Papeete, F

Galileo Control Centre
Oberpfaffenhofen
GCC-D

GSS Girone, S
GSS Ascension, UK
GSS Azores, P
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

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: 2.8m (95%)
Signal In Space Ranging Accuracy (SISRE): Detailed Time Series

1\textsuperscript{st} January 2014 – 1\textsuperscript{st} September 2015

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

Infrastructure impact on SISRE:
- Sensitivity to number of GSS
- Sensitivity to number of satellites
- Sensitivity of GMS upgrade or tuning
- Refresh rate (Age of Data)
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.
Signal and Message Availability

- 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%**

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Availability 2014/15</th>
</tr>
</thead>
<tbody>
<tr>
<td>GSAT0101</td>
<td>96.0% 65.6%</td>
</tr>
<tr>
<td>GSAT0102</td>
<td>96.3% 80.0%</td>
</tr>
<tr>
<td>GSAT0103</td>
<td>99.0% 85.7%</td>
</tr>
<tr>
<td>GSAT0104*</td>
<td>28.5% 28.4%</td>
</tr>
</tbody>
</table>
Galileo Nequick-G Ionospheric Correction Performance

**Galileo broadcast (NeQuick G)**

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

- Doy 2015_76, Mean_Correction 79.4%
- Doy 2015_80, Mean_Correction 82.9%

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

White to green $\geq$ 70% correction level

- >100 stations, reference ionosphere based on dual-freq IONEX-levelled:

**GPS broadcast (Klobuchar)**

21st March 2015

- Doy 2015_76, Mean_Correction 76.2%
- Doy 2015_80, Mean_Correction 80.3%

Higher ionospheric activity in Equatorial band

- MODIP=3

In this context, the performances indicate the effectiveness of the NeQuick-G model in correcting ionospheric errors for single-frequency users, and the Klobuchar broadcast's accuracy in providing reliable corrections for dual-frequency users, with higher activity observed in the Equatorial band.
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: $<10\text{ns} \ (95\%)$ since Ground Segment Upgrade
- Measured GGTO Performance: $<9.6\text{ ns} \ (95\%)$ since Ground Segment Upgrade; GGTO dissemination resumed on 11/05/2015

![Graphs showing UTC(SIS)–UTCr and GGTO(NAVmsg) – GGTO(observed) with annotations for GMS upgrade activities and service interruption due to backup configuration.](c) Airbus DS
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
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

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

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