Keynote Lecture: Galileo

Marco FALCONE – European Space Agency

IGS Workshop 2017, Paris – July 3-7 2017
Development
GIOVE A & B
2005 & 2008

In-Orbit Validation
2011-2013

FOC1
Initial Services
2014-2016

Exploitation Phase
2017-2019

FOC2
Full Services
2020

Deployment / Exploitation Plan
Constellation Satellites

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

4 satellites – 4 In-Orbit

<table>
<thead>
<tr>
<th>Mass at Launch</th>
<th>700kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Consumption</td>
<td>1420W</td>
</tr>
<tr>
<td>Dimensions</td>
<td>2.7 x 1.6 x 14.5 m</td>
</tr>
<tr>
<td>Orbit Injection</td>
<td>Direct into MEO orbit</td>
</tr>
<tr>
<td>Attitude Profile</td>
<td>Yaw Steered</td>
</tr>
</tbody>
</table>

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

22 satellites – 14 In-Orbit

<table>
<thead>
<tr>
<th>Mass at Launch</th>
<th>733kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Consumption</td>
<td>1900 W</td>
</tr>
<tr>
<td>Dimensions</td>
<td>2.5 x 1.1 x 14.7 m</td>
</tr>
<tr>
<td>Orbit Injection</td>
<td>Direct into MEO orbit</td>
</tr>
<tr>
<td>Attitude Profile</td>
<td>Yaw Steered</td>
</tr>
</tbody>
</table>
Current FOC1 constellation: 18 spacecraft
## Constellation Status (30 June 2017)

<table>
<thead>
<tr>
<th>Satellite ID</th>
<th>Launch Date</th>
<th>SV ID</th>
<th>Orbital Slot</th>
<th>Clock</th>
<th>Technical Status</th>
<th>EIRP (wrt Public OS SIS ICD)</th>
<th>SAR Transponder</th>
</tr>
</thead>
<tbody>
<tr>
<td>GSAT0101</td>
<td>21 Oct. 2011</td>
<td>11</td>
<td>B05</td>
<td>RAFS</td>
<td>Nominal</td>
<td>All bands aligned</td>
<td>N/A</td>
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<tr>
<td>GSAT0102</td>
<td>21 Oct. 2011</td>
<td>12</td>
<td>B06</td>
<td>PHM</td>
<td>Nominal</td>
<td>All bands aligned</td>
<td>N/A</td>
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<tr>
<td>GSAT0103</td>
<td>12 Oct. 2012</td>
<td>19</td>
<td>C04</td>
<td>PHM</td>
<td>Nominal</td>
<td>All bands in temporary back-off</td>
<td>Nominal</td>
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<tr>
<td>GSAT0104</td>
<td>12 Oct. 2012</td>
<td>20</td>
<td>C05</td>
<td>RAFS</td>
<td>Unavailable (NAGU 2014014)</td>
<td>E1 only E5 + E6 permanently unavailable</td>
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<tr>
<td>GSAT0201</td>
<td>22 Aug. 2014</td>
<td>18</td>
<td>Ext01</td>
<td>PHM</td>
<td>Testing (NAGU 2016029)</td>
<td>All bands aligned</td>
<td>Nominal</td>
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<tr>
<td>GSAT0202</td>
<td>22 Aug. 2014</td>
<td>14</td>
<td>Ext02</td>
<td>PHM</td>
<td>Testing (NAGU 2016030)</td>
<td>All bands aligned</td>
<td>Nominal</td>
</tr>
</tbody>
</table>
## Constellation Status (30 June 2017)

<table>
<thead>
<tr>
<th>Satellite ID</th>
<th>Launch Date</th>
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<th>Orbital Slot</th>
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<th>EIRP (wrt Public OS SIS ICD)</th>
<th>SAR Transponder</th>
</tr>
</thead>
<tbody>
<tr>
<td>GSAT0203</td>
<td>27 Mar. 2015</td>
<td>26</td>
<td>B08</td>
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<tr>
<td>GSAT0204</td>
<td>27 Mar. 2015</td>
<td>22</td>
<td>B03</td>
<td>RAFS</td>
<td>Nominal</td>
<td></td>
<td>Nominal</td>
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<tr>
<td>GSAT0205</td>
<td>11 Sep. 2015</td>
<td>24</td>
<td>A08</td>
<td>PHM</td>
<td>Nominal</td>
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<tr>
<td>GSAT0206</td>
<td>11 Sep. 2015</td>
<td>30</td>
<td>A05</td>
<td>PHM</td>
<td>Nominal</td>
<td></td>
<td>Nominal</td>
</tr>
<tr>
<td>GSAT0208</td>
<td>17 Dec. 2015</td>
<td>08</td>
<td>C07</td>
<td>PHM</td>
<td>Nominal</td>
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<tr>
<td>GSAT0209</td>
<td>17 Dec. 2015</td>
<td>09</td>
<td>C02</td>
<td>PHM</td>
<td>Nominal</td>
<td></td>
<td>Nominal</td>
</tr>
</tbody>
</table>
### Constellation Status (30 June 2017)

<table>
<thead>
<tr>
<th>Satellite ID</th>
<th>Launch Date</th>
<th>SV ID</th>
<th>Orbital Slot</th>
<th>Clock</th>
<th>Technical Status</th>
<th>EIRP (wrt Public OS SIS ICD)</th>
<th>SAR Transponder</th>
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</thead>
<tbody>
<tr>
<td>GSAT0210</td>
<td>24 May 2016</td>
<td>01</td>
<td>A02</td>
<td>PHM</td>
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<td>Nominal</td>
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<tr>
<td>GSAT0211</td>
<td>24 May 2016</td>
<td>02</td>
<td>A06</td>
<td>PHM</td>
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<td>All bands aligned</td>
<td>Nominal</td>
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<td>GSAT0207</td>
<td>17 Nov. 2016</td>
<td>07</td>
<td>C06</td>
<td>PHM</td>
<td>Nominal</td>
<td>All bands aligned</td>
<td>Nominal</td>
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<tr>
<td>GSAT0212</td>
<td>17 Nov. 2016</td>
<td>03</td>
<td>C08</td>
<td>PHM</td>
<td>Nominal</td>
<td>All bands aligned</td>
<td>Nominal</td>
</tr>
<tr>
<td>GSAT0213</td>
<td>17 Nov. 2016</td>
<td>04</td>
<td>C03</td>
<td>PHM</td>
<td>Nominal</td>
<td>All bands aligned</td>
<td>Nominal</td>
</tr>
<tr>
<td>GSAT0214</td>
<td>17 Nov. 2016</td>
<td>05</td>
<td>C01</td>
<td>PHM</td>
<td>Nominal</td>
<td>All bands aligned</td>
<td>Nominal</td>
</tr>
</tbody>
</table>

**Under Commissioning (NAGU 2016050)**
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
High Signal Availability

Availabilities reported since first complete month in operation.

Availability reduced by

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

GSAT0207/0214 set healthy end of May
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

<table>
<thead>
<tr>
<th>DF 100 min prediction accuracy</th>
<th>GSAT</th>
<th>SVID</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0210</td>
<td>E01</td>
</tr>
<tr>
<td></td>
<td>0211</td>
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<td>E18</td>
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<td>E19</td>
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<td>0208</td>
<td>E24</td>
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<tr>
<td></td>
<td>0209</td>
<td>E26</td>
</tr>
<tr>
<td></td>
<td>0101</td>
<td>E30</td>
</tr>
<tr>
<td>Run 1 DF OS (E5a-E1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Orbit RMS error @WUL [m]</td>
<td>0.37</td>
<td>0.24</td>
</tr>
<tr>
<td>Clock RMS error [m]</td>
<td>0.38</td>
<td>0.26</td>
</tr>
<tr>
<td>Ranging 95%-ile error @WUL [m]</td>
<td>0.39</td>
<td>0.26</td>
</tr>
<tr>
<td>Ranging 95%-ile error @AUL [m]</td>
<td>0.75</td>
<td>0.87</td>
</tr>
<tr>
<td>Run 2 DF OS (E5b-E1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Orbit RMS error @WUL [m]</td>
<td>0.33</td>
<td>0.19</td>
</tr>
<tr>
<td>Clock RMS error [m]</td>
<td>0.42</td>
<td>0.22</td>
</tr>
<tr>
<td>Ranging 95%-ile error @WUL [m]</td>
<td>0.35</td>
<td>0.21</td>
</tr>
<tr>
<td>Ranging 95%-ile error @AUL [m]</td>
<td>0.63</td>
<td>0.55</td>
</tr>
</tbody>
</table>
Positioning Performance & Availability

- 4 more satellites operational: in May/June 2017
- Satellites in operational constellation: 11 \(\rightarrow\) 13 \(\rightarrow\) 15
- Availability of H Accuracy <10 m: 89\% \(\rightarrow\) 96\% \(\rightarrow\) 98\%
- Global PDOP <=6 availability: 41\% \(\rightarrow\) 60\% \(\rightarrow\) 78\%

Horizontal accuracy of global stations on a sample day:

- w/o L8 satellites: 3.46\,m (95\%)
- with L8 satellites: 2.53\,m (95\%)
Positioning Performance

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

- 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
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%)

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%)

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

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

UTC(SIS)-UTC\text{Cr}

2016/2017

Timing HW failure
System re-calibration
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 performance 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)

<table>
<thead>
<tr>
<th>F/NV Ranging Performance 95th percentile</th>
<th>Worst Nominal S/C</th>
<th>Worst L3 S/C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before optimisation</td>
<td>0.90 m</td>
<td>3.59 m</td>
</tr>
<tr>
<td>After optimisation</td>
<td>0.64 m</td>
<td>0.67 m</td>
</tr>
</tbody>
</table>
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

![Graph of Excentric Galileo satellite redshift test]

- 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.

<table>
<thead>
<tr>
<th></th>
<th>T1 mm</th>
<th>T2 mm</th>
<th>T3 mm</th>
<th>D 10-9</th>
<th>R1 mas</th>
<th>R2 mas</th>
<th>R3 mas</th>
<th>Epoch y</th>
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<tbody>
<tr>
<td>+/-</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.00</td>
<td>0.000</td>
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<td>0.03</td>
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Rates

<table>
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<th>T3 mm</th>
<th>D 10-9</th>
<th>R1 mas</th>
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<table>
<thead>
<tr>
<th>Station #</th>
<th>RMS-Pos.</th>
<th>Epoch</th>
<th>RMS-Vel.</th>
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<tbody>
<tr>
<td></td>
<td>E [mm]</td>
<td>N</td>
<td>U</td>
</tr>
<tr>
<td></td>
<td>127</td>
<td>2.5</td>
<td>2.0</td>
</tr>
</tbody>
</table>
Metadata publication request

Requested by Scientific community

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

Phase Centre Offset
(E1, E5a, E5b, E5, E6)

Phase Centre Variation
(E1, E5a, E5b, E5, E6)

Antenna Reference Point

Centre of Mass

Static

Dynamic
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
Development
GIOVE A & B

2005 & 2008

2011-2013

In-Orbit Validation

FOC1
Initial Services

2014-2016

Exploitation Phase

2017-2019

FOC2
Full Services

2020

Deployment / Exploitation Plan
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

2011 2012 2013

FOC

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
# Increased Availability of Positioning

## Central European User (@ 5deg masking)

<table>
<thead>
<tr>
<th>Launch</th>
<th>Constellation configuration</th>
<th>Availability of PDOP &lt; 5</th>
<th>PVT Opportunities over 10 days/average duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>L8</td>
<td>4/4/7</td>
<td>79.6%</td>
<td>74 / 2.58 hrs</td>
</tr>
<tr>
<td>L8 + L3</td>
<td>4/4/7+2</td>
<td>86.0%</td>
<td>62 / 3.33 hrs</td>
</tr>
<tr>
<td>L9</td>
<td>8/4/7+2</td>
<td>99.8%</td>
<td>4 / 59.89 hrs</td>
</tr>
</tbody>
</table>

(~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

System Evolution Scenarios Defined by ESA

Mission Evolution Scenarios (eHLD) Defined by EC and MS

Mission Evolution ES-1 (Techno Obsolescence)

Mission Evolution ES-2 (Medium level evolution & new services)

Mission Evolution ES-3 (Full competitiveness vs other GNSS Systems Evolutions)

Topics under phase 0 (EC definition activities)

Core-1 (Mature evolutions)

Core-2a (Promising, limited impact)

Core-2b (Promising, medium impact)

Exploratory (Mission need to be consolidated, very high impact)

MEO (phase B0)

Non-MEO (delta phase A)
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