Where Next for GNSS?

Professor Terry Moore

Professor of Satellite Navigation
Nottingham Geospatial Institute
The University of Nottingham
Where Next for GNSS
Back to the Future?

Professor Terry Moore
Professor of Satellite Navigation
Nottingham Geospatial Institute
The University of Nottingham
• Global Positioning System (GPS)
  - The best known operational system at the moment
  - Owned and funded by US Govt, operated by US Air Force

• GLONASS
  - Russian (originally military) system with global coverage

• Galileo
  - European civil controlled system, planned global coverage

• BeiDou
  - Chinese (originally military) system, planned global coverage
  - Developing very quickly

• Regional Systems
  - Japan: QZSS, India: IRNSS
GPS Modernisation

1995
- GPS IIA
  - Standard Service
    - Single frequency (L1)
    - Coarse acquisition code navigation
  - Precise Service
    - Y-Code (L1Y & L2Y)

2005 - 2017
- GPS II R / IIR-M
  - IIA/IIR capabilities plus
    - 2nd civil signal (L2C)
    - M-Code (L1M & L2M)

2009 - 2019
- GPS IIF
  - IIR-M capability plus
    - 3rd civil signal (L5)
    - 12 yr design life

2016 - 2021
- GPS III
  - Backward compatible
  - 4th civil signal (L1C)
  - Increased accuracy
  - Increased integrity
GLONASS Modernisation

GLONASS 1982-2008
Out of Service
Life-time 4.5 ys

GLONASS-M 2003 onwards
In Service
Life-time 7 years
2\textsuperscript{nd} civil signal

GLONASS-K 2011 onwards
Design & Development Phase
Life-time >10 yrs
3\textsuperscript{rd} civil signal (L3)
CDMA

GLONASS-KM
Research Phase
<table>
<thead>
<tr>
<th>Satellite series</th>
<th>Launch</th>
<th>Current status</th>
<th>1602 + n×0.5625 MHz (L1, FDMA)</th>
<th>1575.42 MHz (L1, CDMA)</th>
<th>1246 + n×0.4375 MHz (L2, FDMA)</th>
<th>1242 MHz (L2, CDMA)</th>
<th>1207.14 MHz (L3, CDMA)</th>
<th>1176.45 MHz (L5, CDMA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GLONASS</td>
<td>1982</td>
<td>Out of service</td>
<td>L1OF, L1SF</td>
<td></td>
<td>L2SF</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GLONASS-M</td>
<td>2003</td>
<td>In service</td>
<td>L1OF, L1SF</td>
<td></td>
<td>L2OF, L2SF</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GLONASS-K1</td>
<td>2011</td>
<td>In service</td>
<td>L1OF, L1SF</td>
<td></td>
<td>L2OF, L2SF</td>
<td></td>
<td>L3OC †</td>
<td></td>
</tr>
<tr>
<td>GLONASS-K2</td>
<td></td>
<td>Design phase</td>
<td>L1OF, L1SF</td>
<td>L1OC, L1SC</td>
<td>L2OF, L2SF</td>
<td>L2SC</td>
<td>L3OC</td>
<td></td>
</tr>
<tr>
<td>GLONASS-KM</td>
<td></td>
<td>Research phase</td>
<td>L1OF, L1SF, L1OC, L1SC</td>
<td>L2OF, L2SF</td>
<td>L2OC, L2SC</td>
<td>L3OC</td>
<td>L5OC</td>
<td></td>
</tr>
</tbody>
</table>

"O": open signal (standard precision), "S": obfuscated signal (high precision); "F": FDMA, "C": CDMA; n=-7,-6,-5,...,6

†Glonass-K1 series use 1202.025 MHz for the L3OC signal
**Galileo Implementation Steps**

- **Galileo System Testbed v1**
  - Validation of critical algorithms
  - 2003

- **Galileo System Testbed v2**
  - 2 initial test satellites
  - 2005/08

- **In-Orbit Validation**
  - 4 IOV satellites plus ground segment
  - 2012

- **Early Services for OS, SAR, PRS**
  - 18 satellites
  - 2016

- **Full Operational Capability**
  - Full services, 30 satellites
  - 2020

---

**Nottingham Geospatial Institute**

**The University of Nottingham**

UNITED KINGDOM • CHINA • MALAYSIA
• 20 Satellites launched
• BeiDou Phase 1. Operational 2012
  Regional, passive positioning
  12 SVs, 5 GEO, 3 IGSO, 4 MEO
  China & nearby areas
• BeiDou Phase 2. Operational 2020
  Global, passive positioning.
  24 MEO, 3 GEO, 3 IGSO (30 SVs)
• Four satellites launched (so far) in 2015
<table>
<thead>
<tr>
<th>Signal</th>
<th>Carrier frequency (MHz)</th>
<th>Bandwidth (MHz)</th>
<th>PRN code chip rate (Mcps)</th>
<th>Signal modulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>1561.098</td>
<td>4.092</td>
<td>2.046</td>
<td>QPSK</td>
</tr>
<tr>
<td>B1-2</td>
<td>1589.742</td>
<td>4.092</td>
<td>2.046</td>
<td>QPSK</td>
</tr>
<tr>
<td>B2</td>
<td>1207.14</td>
<td>24</td>
<td>10.23</td>
<td>QPSK</td>
</tr>
<tr>
<td>B3</td>
<td>1268.52</td>
<td>24</td>
<td>10.23</td>
<td>QPSK</td>
</tr>
<tr>
<td>B1-BOC</td>
<td>1575.42</td>
<td>16.368</td>
<td>1.023</td>
<td>MBOC (6, 1, 1/11)</td>
</tr>
<tr>
<td>B2-BOC</td>
<td>1207.14</td>
<td>30.69</td>
<td>5.115</td>
<td>BOC (10, 5)</td>
</tr>
<tr>
<td>B3-BOC</td>
<td>1268.52</td>
<td>35.805</td>
<td>2.5575</td>
<td>BOC (15, 2.5)</td>
</tr>
<tr>
<td>L5</td>
<td>1176.45</td>
<td>24</td>
<td>10.23</td>
<td>QPSK</td>
</tr>
</tbody>
</table>
2014
GPS, GLONASS, Galileo & BeiDou
Integrated processor

2011
GPS & GLONASS
Uses hosted processor
• All GNSS use independent realisations of the International Terrestrial Reference System (ITRS)
• GPS
  – WGS 84 (G1674) coincident with ITRF08 to cm level
• GLONASS
  – PZ-90.11 closely aligned to ITRF08 “to mm level”
• Galileo
  – Galileo Terrestrial Reference Frame - GTRF09v01
  – Aligned to ITRF05 to better than 3cm
• BeiDou
  – BeiDou Terrestrial Reference Frame (BTRF)
  – Based on the China Geodetic Coordinate System CGCS2000 - aligned to ITRF08
• All GNSS use independent realisations of atomic timescales ‘linked’ to UTC

• GPS
  – GPST started 6 Jan 1980, no leap seconds, <25ns
  – GPST now ahead of UTC by 17 seconds

• GLONASS
  – GLONASST = UTC + 3 hours, <15ns

• Galileo
  – GST started 22 Aug 1999, no leap seconds, <50ns
  – GST now ahead of UTC by 4 seconds

• BeiDou
  – BDT started 1 Jan 2006, no leap seconds, <100ns
  – BDT now ahead of UTC by 3 seconds

• Galileo GPS Time Offset GGTO, <5ns
• Increasing use of multi-constellation GNSS receivers
  – Improves integrity
  – Improves coverage

• GLONASS 1\textsuperscript{st} April 2014 Outage
  – Entire constellation disrupted by bad ephemerides uploads
  – Outage continued for more than 10 hours
  – Ephemerides were incorrect, but pseudo-ranges were correct

• Some RAIM algorithms ignored incorrect messages
  – Degraded GLONASS and GPS tracking
  – Some had complete tracking failures
  – Corruption of clock bias estimates
• ARAIM
  - Approved navigation system down to LPV-200
  - Multi-constellation GNSS (GPS-GLONASS-Galileo-Beidou)
  - Dual frequency
  - Multiple fault detection capability
Advanced RAIM

- Previous ARAIM performance analysis based on selected points on the Earth’s surface, with full view of the sky
  - No obstacles that can shadow satellites and no multipath
- ARAIM prediction considering the real trajectory of an aircraft:
  - Aircraft Attitude: Satellite shadowing
  - Terrain and objects: Satellite shadowing and multipath
  - ARAIM real-time prediction
Single constellation (GPS)

Number of Satellite in View

Horizontal Protection Level

Vertical Protection Level

Difference of Satellite ENU and Body and Terrain Shadowed satellites

Accuracy

Effective Monitoring Threshold new method
Tri constellation (GPS-GLONASS-Galileo)
Repeatability of two daily solutions over one year
Daily repeatability over 75 stations over 7 weeks
• Multi-Constellation GNSS
  - Geodesy
  - Time
  - System Independence
  - Advanced RAIM
  - Precise Point Positioning
  - Multi-Constellation and Multi-Frequency GNSS
  - Big Data

• Multi-System, Multi-Sensor Navigation
  - Hybridisation to address GNSS vulnerabilities
  - Provide required levels of accuracy and robustness
  - Autonomous or cooperative navigation
  - Integrated multi-sensor systems
  - Seamless transition
Professor Terry Moore
Director of the NGI
Nottingham Geospatial Building
The University of Nottingham
Triumph Road
Nottingham
NG7 2TU

Telephone: +44 (0) 115 951 3886
Fax: +44 (0) 115 951 3881
Email: terry.moore@nottingham.ac.uk
WWW: www.nottingham.ac.uk/angi