Global Navigation Satellite Systems – What’s Up?

Oliver Montenbruck

with support of
Peter Steigenberger and Steffen Thölert
## Constellation Status

<table>
<thead>
<tr>
<th>System</th>
<th>Blocks</th>
<th>Signals</th>
<th>Sats*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS</td>
<td>IIA, IIR IIR-M IIF III</td>
<td>L1 C/A, L1/L2 P(Y) +L2C +L5 +L1C</td>
<td>1,11</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>12</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(1)</td>
</tr>
<tr>
<td>GLONASS</td>
<td>M M+ K1</td>
<td>L1/L2 C/A+P L1/L2 C/A+P, L3 (CDMA)</td>
<td>21+(1)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>L1/L2 C/A+P, L3 (CDMA)</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1+(1)</td>
</tr>
<tr>
<td>BeiDou</td>
<td>BDS-2 MEO, IGSO, GEO</td>
<td>B1-2, B2b, B3 B1, B1-2, B2a/b/ab, B3</td>
<td>3, 7, 5</td>
</tr>
<tr>
<td></td>
<td>BDS-3S MEO, IGSO</td>
<td>B1, B1-2, B2a/b/ab, B3</td>
<td>(2), (2)</td>
</tr>
<tr>
<td></td>
<td>BDS-3 MEO, IGSO, GEO</td>
<td>B1, B1-2, B2a/b/ab, B3</td>
<td>18, (1), (1)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Galileo</td>
<td>IOV FOC</td>
<td>E1, E6, E5a/b/ab E1, E6, E5a/b/ab</td>
<td>3+(1)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>19+(3)</td>
</tr>
<tr>
<td>QZSS</td>
<td>Block I Block II IGSO, GEO</td>
<td>L1 C/A, L1C, L2C, L5, SAIF, E6 LEX L1 C/A, L1C, L2C, L5, L1S, E6, L5S</td>
<td>1 2 1</td>
</tr>
<tr>
<td>IRNSS</td>
<td>IGSO, GEO</td>
<td>L5, S</td>
<td>4+(1), 3</td>
</tr>
</tbody>
</table>

*) Status May 2019; brackets indicate satellites not declared healthy/operational
BeiDou-3

- Five experimental satellites (BDS-3S)
  - launched 2015-2016 (non-operational)
  - technology demonstration (ISL, H-Maser, platforms)
- Global Constellation (BDS-3)
  - 18 operational MEO satellites (launched 2017-2018)
  - 2 platforms (8 x SECM, 10 x CAST)
  - 1 IGSO and 1 GEO in testing
  - Early service declared Dec. 2018
- New Signals
  - B3I declared as open signal, available on BDS-2 and -3
  - New B1C and B2a signal on BDS-3
  - B2b and B2ab transmitted on BDS-3 but no ICD yet
  - New navigation CNAV1 on B1C and CNAV2 on B2a
    (resembling GPS CNAV2 on L1C and CNAV on L2C/L5)
  - Advanced modulation schemes (QMBOC, ACE-BOC)
  - PRN range extended to 63
BeiDou-2/3 MEO Constellation Chart
(Walker 24/3/1)
BeiDou Signal Spectrum

- B1I and B3I common to all satellites
- B2I phased out?
- New B1C/B2a signals (interoperable with GPS L1C/L5, Galileo E1/E5a)
BeiDou-3 Modulation Techniques

- Quadrature Multiplexed BOC modulation (QMBOC) for B1 signal
  - Independent realization of interoperable MBOC signal in L1 band (alternative to Galileo CBOC and GPS TMBOC)
  - Data signal uses BOC(1,1) on I-channel
  - Pilot signal uses superposition of BOC(1,1) (I-channel) and BOC(6,1) (Q-channel)
  - Flexible choice of relative signal powers for all components

- CEM via Intermodulation Construction (CEMIC)
  - Constant envelope modulation for “arbitrary” number of signals, power ratios, and phase relation / frequency (alternative to CASM and POCET)
  - Used to combine 5 (?) signal components plus intermodulation product in B1 band: B1I, B1C-data, B1C-pilot, B1A-data (TBC), B1A-pilot (TBC)

- Asymmetric Constant Envelope Binary Offset Carrier (ACE-BOC)
  - Dual-frequency constant envelope multiplexing technique
  - Similar to Galileo AltBOC, but allows different powers in the two sub-bands (here B2a, B2b)
BeiDou-3 B1 Spectrum and I/Q-Diagram

BeiDou-3 Intersatellite Links

- K-band dual one-way ranging
  - Earth oriented phased array antenna, steerable up to 60° off-nadir
  - Time-multiplexed operation using predefined link allocation table
  - One forward and backward ranging measurement per slot (1.5 s each)
  - ~5 cm precision

- Processing
  - Extrapolation of fwd/bkwd ranges to common epoch (coarse a priori orbit)
  - Arithmetic mean of fwd/bkwd one-way range yields geometric range plus delays, difference yields clock offsets plus delays

- Enables orbit determination with regional ground network
  - Measurements not publicly available
  - Published results limited to BDS-3S and partial BDS-3 MEO constellation
Galileo – “Accuracy Matters”

- Now 22 operational satellites
  - At least 5 sats above 5° elevation
  - PDOP mostly better than 3
- 2 additional sats in eccentric orbits
  - Not in almanac
  - Broadcast ephemerides (unhealthy)
- Exceptional SISRE:
  - ~20 cm RMS
  - ~40 cm 95%
  - Key to accurate point positioning

From https://www.glonass-iac.ru/
• Geodetic receiver and antenna (BRUX)
• E1+E5a code and carrier phase
• Kinematic positioning using with broadcast ephemerides
• Forward filter, hourly re-initialization
• 17cm RMS horizontal, 30 cm RMS vertical, 34 cm 3D RMS
Galileo – New Services in E6

• E6B and E6C codes released Jan 2019

• High Accuracy Service:
  • Free of charge
  • Tender released early April 2019: “an open access service based on the provision of precise corrections (orbit, clock, biases, ionosphere) transmitted in the Galileo E6 signal (E6-B, data component), at a maximum rate of 448 bps per Galileo satellite connected to an uplink station allowing the user to achieve improved positioning performance”.
  • Gradual introduction (service area, accuracy)

• Commercial Authentication Service:
  • “a controlled access service based on the encrypted spreading codes in the E6 signal (E6-C, pilot tone). Service access will be achieved by the distribution of the relevant key material (NAVSEC keys)”.
Galileo – Defining the Scale of the Geodetic Reference Frame

- GNSS contributes to International Terrestrial Reference Frame (ITRF) through coordinates of GNSS stations
- Estimated station height depends on phase center offset and variations of satellite and receiver antennas
- GPS, GLONASS:
  - Scale inherited from SLR and VLBI
  - Calibrated receiver antenna patterns
  - Estimated satellite antenna patterns
- Galileo:
  - Calibrated satellite antenna patterns
  - Calibrated receiver antenna patterns
  - Estimation of GNSS scale becomes feasible
GPS Flex Power

- Change of transmit power among signals for improved jamming resistance
- Exercised in various test campaigns and operations since 2017
- Available on IIR-M and IIF satellites

<table>
<thead>
<tr>
<th>#</th>
<th>Sats</th>
<th>f</th>
<th>Duration</th>
<th>Region</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>IIF</td>
<td>L1</td>
<td>since 2017/27</td>
<td>centered at 41°E, 37°N</td>
<td>C/A and P(Y) power increased by 2.5 dB</td>
</tr>
<tr>
<td>2</td>
<td>IIR-M IIF</td>
<td>L1 L2</td>
<td>2018/103-107</td>
<td>Global</td>
<td>6 dB/5 dB P(Y) power increase on L1/L2</td>
</tr>
<tr>
<td>3</td>
<td>IIR-M IIF</td>
<td>L1 L2</td>
<td>2018/117, 121, 124 2:00 – 13:00 UTC</td>
<td>centered at 115°W, 40°N</td>
<td>Sum of L1+L2 P(Y) power increased by 9 to 11 dB; IIR-M: L1 C/A power reduced by 2-3 dB</td>
</tr>
</tbody>
</table>
GPS Flex Power

- M-code deactivated
- Power from M-code and intermodulation product distributed to C/A (or L2C) and P(Y) signals
- Total transmit power reduced (#1) or retained (#2) or unknown (#3)

- IIF flex power transitions triggered by visibility in area of interest
• Differential code bias variations at 1 ns level  
  (subdaily; not covered by CNAV intersignal correction)
• $C/N_0$ changes for L1 C/A and semi-code less L1/L2 P(Y) tracking
• C/A-P(Y) phase relations unaffected (?)
• SPP users not affected; tolerable impact on precise point positioning
GPS III – A New Kid in Town

- GPS III-1 launched 23 Dec 2018
- Transmits as PRN 4 since 8 Jan. 2019
- Unhealthy, not in almanac
- Tracked and processed by International GNSS Service

- New platform (Lockheed Martin)
- First satellite transmitting L1C signal
GPS III – Signals

- New (mostly) digital signal generation
  - Very clean signals
  - Full coherency of L1, L2, L5 signals (unlike IIF)
- Five signals on L1
  - C/A-code
  - L1C data, L1C pilot, P(Y)-code
  - M-code
- Use of separate M-code transmit chain
- “Weighted voting” multiplexing scheme for L1C-(d,p) and P(Y)
  - Majority voting combination
  - Interlacing of raw L1C-p, P(Y)

(GPS World March 2019)
• Precise GNSS data processing relies on various spacecraft parameters
• GPS III Phase center offsets (PCO) released right after launch 😊
  • Individual PCOs for L1, L2, L5
  • Surprisingly good agreement (6 cm) with first L1/L2 PCO estimates of F. Dilssner (ESA)
  • Important for GPS contribution to reference frame scale!
• Estimated phase variations +/- 15 mm
• Only coarse mass and size available for non-gravitational force modeling
• Attitude control law for rapid noon/midnight turns so far unknown
## Public Availability of Metadata

<table>
<thead>
<tr>
<th></th>
<th>GPS</th>
<th>GLO</th>
<th>GAL</th>
<th>BDS-2</th>
<th>BDS-3S</th>
<th>BDS-3</th>
<th>QZSS</th>
<th>IRNSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>(L)</td>
<td>L</td>
<td>P</td>
<td>(L)</td>
<td>(L)</td>
<td>(L)</td>
<td>P</td>
<td>(L)</td>
</tr>
<tr>
<td>CoM</td>
<td>P</td>
<td>L</td>
<td>(L)</td>
<td>P</td>
<td>L</td>
<td>P</td>
<td>L</td>
<td></td>
</tr>
<tr>
<td>PCO/PCV</td>
<td>E,(P)/E</td>
<td>E</td>
<td>P</td>
<td>E,L/E</td>
<td>E,L/--</td>
<td>E,L/--</td>
<td>P</td>
<td>L/--</td>
</tr>
<tr>
<td>LRA offset</td>
<td>n/a</td>
<td>L</td>
<td>P</td>
<td>L</td>
<td>L</td>
<td>(L)</td>
<td>P</td>
<td>P?</td>
</tr>
<tr>
<td>Coarse geometry</td>
<td>(L)</td>
<td>(L)</td>
<td>P</td>
<td>L</td>
<td>(L)</td>
<td>(L)</td>
<td>P</td>
<td>L</td>
</tr>
<tr>
<td>Detailed geometry</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(P)</td>
</tr>
<tr>
<td>Optical properties</td>
<td>(L)</td>
<td></td>
<td>P</td>
<td>(E)</td>
<td></td>
<td></td>
<td>(P)</td>
<td></td>
</tr>
<tr>
<td>Transmit Power</td>
<td>(M)</td>
<td>M</td>
<td>M</td>
<td>(M)</td>
<td></td>
<td></td>
<td>P</td>
<td></td>
</tr>
<tr>
<td>Nominal Attitude</td>
<td>(L)</td>
<td>L</td>
<td>P</td>
<td>L</td>
<td>L</td>
<td>L</td>
<td>P</td>
<td>L</td>
</tr>
<tr>
<td>Detailed Attitude</td>
<td>(E)</td>
<td>(E)</td>
<td>(E)</td>
<td>(E)</td>
<td>(E)</td>
<td>(E)</td>
<td>(E)</td>
<td></td>
</tr>
<tr>
<td>Maneuvers</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(L)</td>
<td></td>
<td></td>
<td>P</td>
</tr>
</tbody>
</table>

P: Provider; L: Literature; E: Estimated; M: Measured; () incomplete
Summary and Conclusions

• Worldwide GNSSs are continuously evolving
  • Galileo and global BeiDou-3 system approaching full deployment

• Plethora of signals in various frequency bands
  • Open and regulated signals in all systems
  • Great diversity of advanced modulation schemes
  • Digital signal generation units offer improved signal quality (low biases!)

• What matters?
  • Trend to high accuracy services (QZSS, Galileo, …)
  • Cyber security, jamming and spoofing protection
    (GPS OCX, planned Galileo O/S and C/S authentication)

• GNSS for science and technology
  • Needs close interaction of science community, system providers and
    equipment manufacturers
  • Availability of proper satellite metadata is vital for high accuracy GNSS