Introduction to Global Navigation Satellite System (GNSS)
Module: 1

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Module 1: Course Contents

- Introduction
- How GPS Works?
- GPS Signal Structure
- GNSS Systems
  - GPS
  - GLONASS
  - GALILEO
  - BEIDOU
  - QZSS
  - IRNSS
- SBAS
- Multi-GNSS
Fundamental Problem

• How to know my location precisely?
  • In any condition
  • At any time
  • Everywhere on earth (at least outdoors!)

• How to navigate to the destination?
  • Guidance or Navigation
Navigation Types

- **Landmark-based Navigation**
  - Stones, Trees, Monuments
    - Limited Local use

- **Celestial-based Navigation**
  - Stars, Moon
    - Complicated, Works only at Clear Night

- **Sensors-based Navigation**
  - Dead Reckoning
    - Gyroscope, Accelerometer, Compass, Odometer
    - Complicated, Errors accumulate quickly

- **Radio-based Navigation**
  - LORAN, OMEGA
    - Subject to Radio Interference, Jamming, Limited Coverage

- **Satellite-based Navigation or GNSS**
  - TRANSIT, GPS, GLONASS, GALILEO, QZSS, BEIDOU (COMPASS), IRNSS
    - Global, Difficult to Interfere or Jam, High Accuracy & Reliability
What is GNSS?

Global Navigation Satellite System (GNSS) is the standard generic term for all navigation satellites systems like GPS, GLONASS, GALILEO, BeiDou, QZSS, NAVIC.

- **Global Constellation**
  - GPS USA
  - GLONASS, Russia
  - Galileo, Europe
  - BeiDou (COMPASS), China

- **Regional Constellation**
  - QZSS, Japan
  - NAVIC (IRNSS), India
Satellite Based Augmentation System (SBAS)

• Satellite Based Augmentation System (SBAS) are used to augment GNSS Data
  • Provide Higher Accuracy, Integrity, Continuity and Availability
  • Some correction data like satellite orbit, satellite clock and atmospheric data are broadcasted from communication satellites
  • Used by ICAO for Aviation

• SBAS Service Providers
  • WAAS, USA
  • MSAS, Japan
  • EGNOS, Europe
  • GAGAN, India
  • SDCM, Russia
  • Korea
  • Australia
Determine the Distance using Radio Wave

Satellite with a known position transmit a regular time signal.

Speed of Light 300,000 km/s

Distance = (Transmission time – Reception time) × Speed of light

Satellite Transmits Signal at 0ms.

Receiver Receives the Same Signal after 67ms.

Distance = (0ms – 67ms) × 300,000 km/s

Distance = 20,200 km
GNSS Requirements

• GNSS needs a common time system.
  • Each GNSS satellite has atomic clocks.
  • How about user receivers?

• The signal transmission time has to be measurable.
  • Each GNSS satellite transmits a unique digital signature, which consists an apparent random sequence, PRN Code
  • A Time Reference is transmitted using the Navigation Message

• Each signal source has to be distinguishable.
  • GNSS utilizes code division multiple access (CDMA) or frequency division multiple access (FDMA).

• The position of each signal source must be known.
  • Each satellite sends its orbit data using the Navigation Message
  • Orbit Data: Almanac and Ephemeris
Characteristics of GNSS Signals

• GNSS Signals have basically three types of signals
  • Carrier Signal
  • PRN Code (C/A Code)
  • Navigation Data

• All GNSS Signals except GLONASS are based on CDMA
  • Only GLONASS use FDMA
  • Future Signals of GLONASS will also use CDMA

• The modulation scheme of GNSS signals
  • BPSK
  • Various versions of BOC

CDMA: Code Division Multiple Access
FDMA: Frequency Division Multiple Access
BPSK: Binary Phase Shift Keying
BOC: Binary Offset Carrier
GPS Signal Structure

- **L1 Carrier, 1575.42Mhz**
- **C/A Code, 1.023Mhz**
- **Navigation Data, 50Hz**
- **P Code, 10.23Mhz**
Characteristics of PRN Code

- PRN codes are very uniquely designed.
- GPS and other GNSS use CDMA
  - One PRN code is assigned to one satellite.
  - In case of GPS, PRN code is 1023 bits long.
  - GLONASS is different. It uses FDMA. The same code for all satellites but different frequencies.
  - Some new signals of GLONASS also uses CDMA signals

- Maximum Cross-correlation Value is -23dB.
- If any signal above this power enters a GPS receiver, it will totally block all GPS signals.
- If longer PRN code is used, receiver becomes more resistive to jamming signal
  - But, signal processing is more complex

Auto-correlation: Only four values:
1023, 1, 63 or 65 (Ideal case)

Cross-correlation: Only three values:
1, 63 or 65 (Ideal Case)
GPS Signal Power: How Strong or How Weak?

- GPS satellites are about 22,000km away
- Transmit power is about 30W
- This power when received at the receiver is reduced by $10^{16}$ times.
  - The power reduces by $1/\text{distance}^2$
  - This is similar to seeing a 30W bulb 22,000Km far
- GPS signals in the receiver is about $10^{-16}$ Watt, which is below the thermal noise
GPS Signal Power: How Strong or How Weak?

• GPS Signal Power at Receiver
  • -130dBm or -160dBW

• Thermal Noise Power
  • Defined by $kT_{\text{eff}}B$, where
    • $K = 1.380658e^{-23} \text{JK}^{-1}$, Boltzman Constant
    • $T_{\text{eff}} = 362.95$, for Room temperature in Kelvin at 290
      • $T_{\text{eff}}$ is effective Temperature based on Frii’s formula
    • $B = 2.046\text{MHz}$, Signal bandwidth
  • Thermal Noise Power = -110dBm for 2MHz bandwidth
  • If Bandwidth is narrow, 50Hz
    • Noise Power = -156dBm
GPS Signal Power

Any Signal below this noise level can’t be measured in a Spectrum Analyzer.

GPS Signal Power at Antenna, -130dBm

Mobile phone, WiFi, BT etc have power level above -110dBm, much higher than GPS Signal Power.
### Power of GPS Signal vs. Other Signals

<table>
<thead>
<tr>
<th>Signal Type</th>
<th>Power (based on calculations, not measured)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Watt</td>
</tr>
<tr>
<td>Mobile Phone Handset TX Power *</td>
<td>1W</td>
</tr>
<tr>
<td>RX Power at Mobile Phone Handset*</td>
<td>100e-6W</td>
</tr>
<tr>
<td>ZigBee</td>
<td>316e-16W</td>
</tr>
<tr>
<td>VHF</td>
<td>200e-16W</td>
</tr>
<tr>
<td>Thermal Noise</td>
<td>79e-16W</td>
</tr>
<tr>
<td>GPS**</td>
<td>1e-16W</td>
</tr>
</tbody>
</table>

- * Actual power values will differ. These are just for comparison purpose
- ** GPS Signals are hidden under the noise. Thus, it can’t be measured directly e.g. using a Spectrum Analyzer
Method of GPS L1C/A Signal Generation

\[ s_i(t) = \sqrt{2P_i(t) \cdot CA(t - \tau_i(t)) \cdot D(t - \tau_i(t)) \cdot \cos(2\pi(f_L + \delta f_{L\delta}(t))t + \phi_i(t)) + n_i(t)} \]
GPS signal structure

\[ \sqrt{2P} \sin(2\pi ft) \]

Carrier Wave

\[ \sqrt{2Px(t)D(t)} \sin(2\pi ft) \]

GPS Signal

PRN

\[ x(t) \]

+1
-1

1.023Mbps

Navigation Message

\[ D(t) \]

+1
-1

50bps
GPS L1C/A PRN Code Generator

G1 Polynomial: [3,10]

G2 Polynomial: [2,3,6,8,9,10]
# CDMA vs. FDMA

<table>
<thead>
<tr>
<th></th>
<th>CDMA</th>
<th>FDMA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[GPS, QZSS, Galileo, BeiDou, IRNSS, Future GLONASS Satellites]</td>
<td>[GLONASS]</td>
</tr>
<tr>
<td>PRN Code</td>
<td>Different PRN Code for each satellite</td>
<td>One PRN Code for all satellites</td>
</tr>
<tr>
<td></td>
<td>Satellites are identified by PRN Code</td>
<td>Satellites are identified by center</td>
</tr>
<tr>
<td></td>
<td></td>
<td>frequency</td>
</tr>
<tr>
<td>Frequency</td>
<td>One Frequency for all satellites</td>
<td>Different frequency for each satellite</td>
</tr>
<tr>
<td>Merits &amp;</td>
<td>Receiver design is simpler</td>
<td>Receiver design is complex</td>
</tr>
<tr>
<td>Demerits</td>
<td>No Inter-Channel Bias</td>
<td>Inter-channel bias problem</td>
</tr>
<tr>
<td></td>
<td>More susceptible to Jamming</td>
<td>Less susceptible to Jamming</td>
</tr>
</tbody>
</table>

Frequency One Frequency for all satellites

Different frequency for each satellite

Merits & Demerits Receiver design is simpler

No Inter-Channel Bias

More susceptible to Jamming

Receiver design is complex

Inter-channel bias problem

Less susceptible to Jamming
PRN (Pseudo Random Noise) Code

- PRN Code is a sequence of randomly distributed zeros and ones that is one millisecond long.
  - This random distribution follows a specific code generation pattern called Gold Code.
  - There are 1023 zeros or ones in one millisecond.
- Each GPS satellite transmits a unique PRN Code.
  - GPS receiver identifies satellites by its unique PRN code or ID.
- It is continually repeated every millisecond and serves for signal transit time measurement.
  - The receiver can measure where the PRN code terminated or repeated.
Modulation

Modulation is the process of conveying a message signal, for example a digital bit stream, into a radio frequency signal that can be physically transmitted.

1 1 0 0 1 0 1 1

You want to transmit this binary code

Amplitude Shift Keying

Frequency Shift Keying
BPSK (Binary Phase Shift Keying)

Phase shift keying is a digital modulation scheme that conveys data by changing, or modulating, the phase of the carrier wave. BPSK uses two phases which are separated by a half cycle.
Navigation Data

- Navigation Data or Message is a continuous stream of digital data transmitted at 50 bit per second. Each satellite broadcasts the following information to users:
  - Its own highly accurate orbit and clock correction (*ephemeris*)
  - Approximate orbital correction for all other satellites (*almanac*)
  - System health, etc.
GPS L1C/A Signal NAV MSG
Principle of Satellite-based Navigation

\[ \rho^k = \sqrt{(x^k - x)^2 + (y^k - y)^2 + (z^k - z)^2} - b \]

If \( k \geq 4 \), solve for \( x, y, z \) and clock bias, \( b \)
Pseudorange (1/2)

A GPS receiver measures the signal transmission time from the code phase at signal reception time.

\[
Pseudorange = (\text{Transmission time} - \text{Reception time}) \times \text{Speed of light}
\]
Pseudorange (2/2)

• Essential GNSS observable
• **Full** distance between the satellite and the receiver
• Provides a position accuracy of approximately a few meters
Carrier phase (1/2)

• PRN repeats every 1ms, which corresponds 300 km in distance at the speed of light, but pseudorange accuracy is about 1 m.

• Carrier phase provides millimeter range accuracy, but repeats every cycle, which correspond 19 cm in distance at a GPS signal carrier frequency of 1575.42 MHz.
Carrier phase (2/2)

- **Fractional** carrier phase of the received signal
- Therefore there is an unknown integer number of full carrier cycles between the satellite and the receiver
- Provide “survey-grade” accuracy of 1-2 cm once the unknown number of full carrier cycles are resolved

19 cm

1 cm
GPS
(Global Positioning System)
USA
History of GPS (1/2)

• Originally designed for military applications at the height of the Cold War in the 1960s, with inspiration coming from the launch of the Soviet spacecraft Sputnik in 1957.

• Transit was the first satellite system launched by the United States and tested by the US Navy in 1960.
  • Just five satellites orbiting the earth allowed ships to fix their position on the seas once every hour.

• GPS developed quickly for military purposes thereafter with a total of 11 “Block” satellites being launched between 1978 and 1985.

• The Reagan Administration in the US had the incentive to open up GPS for civilian applications in 1983.

How to Drop Five Bombs from Different Aircrafts into the Same Hole? (with an accuracy of 10m)
History of GPS (2/2)

• Upgrading the GPS was delayed by NASA space shuttle Challenger disaster in 1989 and it was not until 1989 that the first Block II satellites were launched.

• By the summer of 1993, the US launched the 24th GPS satellite into orbit, which complete the modern GPS constellation of satellites.

• In 1995, it was declared fully operational.

• Today’s GPS constellation has 31 active satellites.

• GPS is used for applications that require position and time data.
GPS Segments

Space Segment

Control Segment

User Segment

Marine / AIS

Aviation / WAAS

Railway

ITS / ADAS

GPS Segments

- Space Segment
- Control Segment
- User Segment

Marine / AIS

Aviation / WAAS

Railway

ITS / ADAS
## GPS Space Segment: Current & Future Constellation

<table>
<thead>
<tr>
<th>Legacy Satellites</th>
<th>Modernized Satellites</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Block IIA</strong></td>
<td><strong>Block IIR</strong></td>
</tr>
<tr>
<td>0 operational</td>
<td>12 operational</td>
</tr>
<tr>
<td>• L1C/A, L1P(Y)</td>
<td>• L1C/A, L1P(Y)</td>
</tr>
<tr>
<td>• L2P(Y)</td>
<td>• L2P(Y)</td>
</tr>
<tr>
<td>• Last one decommissioned in 2016</td>
<td>• L2C, L2M</td>
</tr>
</tbody>
</table>

http://www.gps.gov/systems/gps/space/#IIF
# GPS Signals

<table>
<thead>
<tr>
<th>Band</th>
<th>Frequency, MHz</th>
<th>Signal Type</th>
<th>Code Length, msec</th>
<th>Chip Rate, MHz</th>
<th>Modulation Type</th>
<th>Data / Symbol Rate, bps/sps</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>1575.42</td>
<td>C/A</td>
<td>1</td>
<td>1.023</td>
<td>BPSK</td>
<td>50</td>
<td>Legacy Signal</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C_{Data}</td>
<td>10</td>
<td>1.023</td>
<td>BOC(1,1)</td>
<td>50 / 100</td>
<td>From 2014</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C_{Pilot}</td>
<td>10</td>
<td>1.023</td>
<td>TMBOC</td>
<td>No Data</td>
<td>BOC(1,1) &amp; BOC(6,1)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>P(Y)</td>
<td>7 days</td>
<td>10.23</td>
<td>BPSK</td>
<td></td>
<td>Restricted</td>
</tr>
<tr>
<td>L2</td>
<td>1227.60</td>
<td>CM</td>
<td>20</td>
<td>0.5115</td>
<td>BPSK</td>
<td>25 / 50</td>
<td>Modulated by TDM of (L2CM xor Data) and L2CL</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CL</td>
<td>1500</td>
<td>0.5115</td>
<td>BPSK</td>
<td>No Data</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>P(Y)</td>
<td>7 days</td>
<td>10.23</td>
<td>BPSK</td>
<td></td>
<td></td>
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<tr>
<td>L5</td>
<td>1176.45</td>
<td>I</td>
<td>1</td>
<td>10.23</td>
<td>BPSK</td>
<td>50 / 100</td>
<td>Provides Higher Accuracy</td>
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<tr>
<td></td>
<td></td>
<td>Q</td>
<td>1</td>
<td>10.23</td>
<td>BPSK</td>
<td>No Data</td>
<td></td>
</tr>
</tbody>
</table>
GPS Receiver Outputs (1/3)

Sky Plot: Visibility of Satellites at Receiver Antenna

Computed Position from GPS displayed over Google Map
### GPS Receiver Outputs (2/3)

**GNSS Signals Received by the Receiver**

<table>
<thead>
<tr>
<th>SV</th>
<th>Type</th>
<th>GLONASS</th>
<th>Galileo</th>
<th>QZSS</th>
<th>SBAS</th>
<th>OMNI</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Elev. [Deg]</td>
<td>Azim. [Deg]</td>
<td>L1-C/No [dBHz]</td>
<td>L2-C/No [dBHz]</td>
<td>L1-C/No [dBHz]</td>
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<tr>
<td>1</td>
<td>GPS</td>
<td>57.51</td>
<td>31.89</td>
<td>42.7</td>
<td>CA</td>
<td>26.44</td>
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<tr>
<td>3</td>
<td>GPS</td>
<td>61.11</td>
<td>148.93</td>
<td>43.4</td>
<td>CA</td>
<td>27.43</td>
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<td>8</td>
<td>GPS</td>
<td>26.97</td>
<td>103.42</td>
<td>37.3</td>
<td>CA</td>
<td>16.9</td>
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<tr>
<td>11</td>
<td>GPS</td>
<td>48.36</td>
<td>57.30</td>
<td>41.4</td>
<td>CA</td>
<td>23.3</td>
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<td>GPS</td>
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<td>307.48</td>
<td>37.9</td>
<td>CA</td>
<td>19.3</td>
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<tr>
<td>22</td>
<td>GPS</td>
<td>61.99</td>
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<td>43.9</td>
<td>CA</td>
<td>26.8</td>
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<tr>
<td>28</td>
<td>GPS</td>
<td>60.44</td>
<td>288.95</td>
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<td>25.0</td>
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<tr>
<td>11</td>
<td>Galileo</td>
<td>20.59</td>
<td>285.13</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
<td>12</td>
<td>Galileo</td>
<td>59.51</td>
<td>325.63</td>
<td>41.5</td>
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<td>-</td>
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<tr>
<td>19</td>
<td>Galileo</td>
<td>38.81</td>
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<td>-</td>
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<td>20</td>
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<td>CB/OC</td>
<td>-</td>
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<td>24</td>
<td>Galileo</td>
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<td>CB/OC</td>
<td>-</td>
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<tr>
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<td>GLONASS</td>
<td>15.60</td>
<td>30.81</td>
<td>33.7</td>
<td>32.3</td>
<td>CA</td>
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<td>4</td>
<td>GLONASS</td>
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<td>5</td>
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<td>9</td>
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<td>37.1</td>
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<td>CA</td>
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<td>20</td>
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<td>318.99</td>
<td>33.0</td>
<td>30.7</td>
<td>CA</td>
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<tr>
<td>193</td>
<td>QZSS</td>
<td>59.95</td>
<td>172.86</td>
<td>40.9</td>
<td>40.2</td>
<td>40.7</td>
</tr>
<tr>
<td>128</td>
<td>SBAS</td>
<td>18.24</td>
<td>249.03</td>
<td>32.4</td>
<td>CA</td>
<td>-</td>
</tr>
<tr>
<td>129</td>
<td>SBAS</td>
<td>48.27</td>
<td>170.87</td>
<td>34.3</td>
<td>CA</td>
<td>-</td>
</tr>
<tr>
<td>137</td>
<td>SBAS</td>
<td>48.27</td>
<td>170.87</td>
<td>34.1</td>
<td>CA</td>
<td>-</td>
</tr>
<tr>
<td>140</td>
<td>SBAS</td>
<td>-50.00</td>
<td>0.00</td>
<td>35.5</td>
<td>CA</td>
<td>-</td>
</tr>
<tr>
<td>141</td>
<td>SBAS</td>
<td>-45.00</td>
<td>0.00</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

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**Training on GNSS – Course (T151-30), Organized by: GIC/AIT, CSIS/UT and ICG, held at: GIC/AIT, Thailand from 14 – 18 JAN 2019**

Dinesh Manandhar, CSIS, The University of Tokyo, dinesh@iis.u-tokyo.ac.jp
GPS Receiver Outputs (3/3)

Position, Velocity, Time (PVT) and Other Observation Related Outputs

**Position:**
- Lat: 35° 39' 40.85496" N
- Lon: 139° 40' 41.32632" E
- Hgt: 118.521 [m]
- Type: Autonomous
- Datum: WGS-84

**Velocity:**
- East: 0.01 [m/s]
- North: -0.01 [m/s]
- Up: -0.02 [m/s]

**Position Solution Detail:**
- Position Dimension: 3D
- Augmentation: GPS+GLN+GAL+QZSS
- Height Mode: Normal
- Correction Controls: Off

**Satellites Used:**
- GPS(7): 1, 3, 8, 11, 17, 22, 28
- GLONASS(8): 3, 4, 5, 9, 10, 11, 19, 20
- Galileo(3): 12, 19, 24
- QZSS(1): 193

**Satellites Tracked:**
- GPS (7): 1, 3, 8, 11, 17, 22, 28
- GLONASS (8): 3, 4, 5, 9, 10, 11, 19, 20
- Galileo (4): 12, 19, 20, 24
- SBAS (3): 128, 137, 140
- QZSS (1): 193

**Receiver Clock:**
- GPS Week: 1910
- GPS Seconds: 447816
- Offset: 0.00001 [msec]
- Drift: 0.00007 [ppm]

**Multi-System Clock Offsets:**
- Master Clock System: GPS
- GLONASS Offset: 97.2 [ns]
- Galileo Offset: 0.5 [ns]
- GLONASS Drift: -0.044 [ns/s]
- Galileo Drift: 0.003 [ns/s]

**Dilutions of Precision:**
- PDOP: 1.5
- HDOP: 0.7
- VDOP: 1.3
- TDOP: 1.1

**Error Estimates(1α):**
- East: 0.878 [m]
- North: 1.123 [m]
- Up: 2.691 [m]
- Semi Major Axis: 1.155 [m]
- Semi Minor Axis: 0.834 [m]
- Orientation: 19.9°
GLONASS
(Global Navigation Satellite System)
Russia
## GLONASS Current & Future Constellation

<table>
<thead>
<tr>
<th>1982 First Launch</th>
<th>2003</th>
<th>2011</th>
<th>Planned Launch</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="GLONASS Satellite" /></td>
<td><img src="image2.png" alt="GLONASS-M Satellite" /></td>
<td><img src="image3.png" alt="GLONASS-K1 Satellite" /></td>
<td><img src="image4.png" alt="GLONASS-K2 Satellite" /></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>GLONASS</th>
<th>GLONASS-M</th>
<th>GLONASS-K1</th>
<th>GLONASS-K2</th>
</tr>
</thead>
<tbody>
<tr>
<td>DECOMMISSIONED</td>
<td>Under Normal Operation</td>
<td>Under Production / Operation</td>
<td>Under Development</td>
</tr>
<tr>
<td>87 Launched 0 Operational 81 Retired 6 Lost</td>
<td>45 Launched 27 Operational 12 Retired 6 Lost</td>
<td>2 Launched 2 Operational First launch Dec 2014</td>
<td>3 On Order First Launch Expected 2018</td>
</tr>
</tbody>
</table>

- **GLONASS**
  - L1OF, L1SF
  - L2SF

- **GLONASS-M**
  - L1OF, L1SF
  - L2OF, L2SF
  - L3OC

- **GLONASS-K1**
  - L1OF, L1SF
  - L2OF, L2SF
  - L3OC

- **GLONASS-K2**
  - L1OF, L1SF
  - L2OF, L2SF
  - L1OC, L1SC
  - L2OC, L2SC
  - L3OC

---

GLONASS FDMA Signals

• L1 Band 1598.0625 - 1604.40 MHz
  • 1602 MHz + \( n \times 0.5625 \) MHz
    • where \( n \) is a satellite's frequency channel number (\( n=-7,-6,-5,\ldots,7 \)).

• L2 Band 1242.9375 - 1248.63 MHz
  • 1246 MHz + \( n\times0.4375 \) MHz
Galileo, Europe
Galileo Space Segment

Galileo is implemented in a step-wise approach

By 2020 Galileo will be:
- fully deployed and recognised
- adopted by the widest user communities
- a civilian infrastructure delivering robust positioning and timing services with high degree of performances

Full Operational Capability
Full services, 30 satellites
2020

Initial Services Provision
Initial services for OS, SAR, PRS, and demonstrator for CS
2016

In-Orbit Validation
4 operational satellites and ground segment
2013

GIOVE A/B
2 test satellites
2005/2008

Galileo System Testbed v1
Validation of critical algorithms
2003

Training on GNSS – Course (T151-30), Organized by: GIC/AIT, CSIS/UT and ICG, held at: GIC/AIT, Thailand from 14 – 18 JAN 2019

Dinesh Manandhar, CSIS, The University of Tokyo, dinesh@iis.u-tokyo.ac.jp
## Galileo Signals

<table>
<thead>
<tr>
<th>Band</th>
<th>Frequency, MHz</th>
<th>Signal Type</th>
<th>Code Length, msec</th>
<th>Chip Rate, MHz</th>
<th>Modulation Type</th>
<th>Data / Symbol Rate, bps/sps</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>1575.42</td>
<td>A</td>
<td>10</td>
<td>10.23</td>
<td>BOC(15,2.5)</td>
<td>??</td>
<td>Restricted</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B_{Data}</td>
<td>4</td>
<td>1.023</td>
<td>CBOC, Weighted combination of BOC(1,1) &amp; BOC(6,1)</td>
<td>125 / 250</td>
<td>Data</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C_{Pilot}</td>
<td>100</td>
<td>1.023</td>
<td></td>
<td>No Data</td>
<td>Pilot</td>
</tr>
<tr>
<td>E6</td>
<td>1278.75</td>
<td>A</td>
<td>10</td>
<td>5.115</td>
<td>BOC(15,5)</td>
<td>??</td>
<td>PRS</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B</td>
<td>1</td>
<td>5.115</td>
<td>BPSK(5)</td>
<td>500 / 1000</td>
<td>Data</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C</td>
<td>100</td>
<td>5.115</td>
<td></td>
<td>No Data</td>
<td>Pilot</td>
</tr>
<tr>
<td>E5</td>
<td>1176.45</td>
<td>A-I</td>
<td>20</td>
<td>10.23</td>
<td>AltBOC(15,10)</td>
<td>25 / 50</td>
<td>Data</td>
</tr>
<tr>
<td></td>
<td>1191.795 MHz</td>
<td>A-Q</td>
<td>100</td>
<td>10.23</td>
<td></td>
<td>No Data</td>
<td>Pilot</td>
</tr>
<tr>
<td></td>
<td>1207.14</td>
<td>B-I</td>
<td>4</td>
<td>10.23</td>
<td></td>
<td>125 / 250</td>
<td>Data</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B-Q</td>
<td>100</td>
<td>10.23</td>
<td></td>
<td>No Data</td>
<td>Pilot</td>
</tr>
</tbody>
</table>
Galileo Signals

1176.45 MHz ~ 1207.14 MHz
AltBOC(15,10)

1278.75 MHz ~ 1545 MHz

1575.42 MHz

E5a-I
E5b-I

E5a-Q
E5b-Q

E6_B, E6_C
BPSK(5)

E6_B, E6_C
BOC_c(10,5)

E1_B, E1_C
CBOC(6,1,1/11)

E1_A
BOC_c(15,2,5)

E5 Band
E6 Band
E1 Band

Dinesh Manandhar, CSIS, The University of Tokyo, dinesh@iis.u-tokyo.ac.jp
**Galileo Services**

<table>
<thead>
<tr>
<th>Service Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Open Service (OS)</strong></td>
<td>Freely accessible service for positioning, navigation and timing for mass market</td>
</tr>
<tr>
<td><strong>Commercial Service (CS)</strong></td>
<td>Delivers authentication, high accuracy and guaranteed services for commercial applications</td>
</tr>
<tr>
<td><strong>Public Regulated Service (PRS)</strong></td>
<td>Encrypted service designed for greater robustness in challenging environments</td>
</tr>
<tr>
<td><strong>Search And Rescue Service (SAR)</strong></td>
<td>Locates distress beacons and confirms that message is received</td>
</tr>
<tr>
<td><strong>Safety of Life Service (SoL)</strong></td>
<td>The former Safety of Life service is being re-profiled</td>
</tr>
</tbody>
</table>

Dinesh Manandhar, CSIS, The University of Tokyo, dinesh@iis.u-tokyo.ac.jp
BeiDou, China
BeiDou Space Segment

**Space Segment**
- 5 GEO satellites
- 3 IGSO satellites
- 27 MEO satellites

**Ground Segment**
- Master Control Stations (MCS)
- Uplink Stations (US)
- Monitoring Stations (MS)

**User Segment**
- BeiDou terminals
- Terminals compatible with other navigation satellite systems

Four types of services:
- open, authorized,
- differential augmentation,
- and short message services.

The nominal positioning accuracy is better than 10 m, timing and velocity accuracy is better than 20 ns and 0.2 m/s respectively.

Source: Update on BeiDou Navigation Satellite System, Chengqi Ran, China Satellite Navigation Office
Tenth Meeting of ICG, NOV 2015
COMPASS / BEIDOU Signals: Already Transmitted

<table>
<thead>
<tr>
<th>Band</th>
<th>Frequency MHz</th>
<th>Signal Type</th>
<th>Chip Rate (MHz)</th>
<th>Modulation Type</th>
<th>Data / Symbol rate</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>1561.098</td>
<td>B1(I)</td>
<td>2.046</td>
<td>QPSK</td>
<td>50 / 100</td>
<td>Open</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B1(Q)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1589.742</td>
<td>B1-2(I)</td>
<td>2.046</td>
<td>QPSK</td>
<td>50 / 100</td>
<td>Open</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B1-2(Q)</td>
<td></td>
<td></td>
<td>25 / 50</td>
<td>Authorized</td>
</tr>
<tr>
<td>B2</td>
<td>1207.14</td>
<td>B2(I)</td>
<td>2.046</td>
<td>QPSK</td>
<td>None</td>
<td>Open</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B2(Q)</td>
<td>10.23</td>
<td>QPSK</td>
<td>50 / 100</td>
<td>Authorized</td>
</tr>
<tr>
<td>B3</td>
<td>1268.52</td>
<td>B3</td>
<td>10.23</td>
<td>QPSK</td>
<td>500</td>
<td>Authorized</td>
</tr>
</tbody>
</table>
Development of BDS

• 5\textsuperscript{th} NOV 2017
  • The first Two BDS – 3 MEO satellites were successfully launched.

• The BDS-3 satellites are equipped with two new civil signals, B1C and B2a, with optimized performance.

• The Interface Control Document for B1C and B2a (Beta version) has been released, and the official version will be released in 2018.
BDS-3 Constellation

- Since 5th NOV 2017, 8 pairs of BDS-3 MEO satellites and 1 BDS GEO satellite have been successfully launched.

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Launch Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>First pair</td>
<td>2017.11.05</td>
</tr>
<tr>
<td>Second pair</td>
<td>2018.01.12</td>
</tr>
<tr>
<td>Third pair</td>
<td>2018.02.11</td>
</tr>
<tr>
<td>Fourth pair</td>
<td>2018.03.30</td>
</tr>
<tr>
<td>Fifth pair</td>
<td>2018.07.29</td>
</tr>
<tr>
<td>Sixth pair</td>
<td>2018.08.25</td>
</tr>
<tr>
<td>Seventh pair</td>
<td>2018.09.19</td>
</tr>
<tr>
<td>Eighth pair</td>
<td>2018.10.15</td>
</tr>
<tr>
<td>First GEO</td>
<td>2018.11.01</td>
</tr>
</tbody>
</table>

Source: Plenary Session of ICG 2018
# BDS-3 Services

<table>
<thead>
<tr>
<th>Service Type</th>
<th>Satellites</th>
</tr>
</thead>
<tbody>
<tr>
<td>RNSS</td>
<td>3 GEO + 3 IGSO + 24 MEO</td>
</tr>
<tr>
<td>SBAS</td>
<td>3 GEO</td>
</tr>
<tr>
<td>Regional SMS</td>
<td>3 GEO</td>
</tr>
<tr>
<td>Global SMS</td>
<td>14 MEO</td>
</tr>
<tr>
<td>International SAR</td>
<td>6 MEO</td>
</tr>
<tr>
<td>PPP (Precise Point Positioning)</td>
<td>3 GEO</td>
</tr>
</tbody>
</table>

Source: Plenary Session of ICG 2018
QZSS
(Quasi-Zenith Satellite System)
Japan
Merits of QZSS

- QZSS signal is designed in such a way that it is interoperable with GPS.
- QZSS is visible near zenith; improves visibility & DOP in dense urban area.
- Provides Orbit Data of other GNSS signals.
- Provides Augmentation Data for Sub-meter and Centimeter level position accuracy.
- Provides Messaging System during Disasters.

http://qzss.go.jp/en/overview/services/sv04_pnt.html
QZSS Development Plan

1\textsuperscript{st} Satellite launched on 11\textsuperscript{th} September 2010 : QZ Orbit
2\textsuperscript{nd} Satellite launched on 1\textsuperscript{st} June 2017 : QZ Orbit
3\textsuperscript{rd} Satellite launched on 19\textsuperscript{th} August 2017 : Geostationary Orbit
QZSS Constellation Status

• Current Status
  • One Satellite launched on 11th SEP 2010

• Total constellation of Seven Satellites
  • Three more satellites were launched by the end of 2017
QZSS Satellite Visibility

Source: SPAC Animation Video
### QZSS Satellites & Signal Types

<table>
<thead>
<tr>
<th>Signal Name</th>
<th>QZS-1 Block I/Q</th>
<th>QZS-2 to QZS-4 Block I/Q</th>
<th>Block II</th>
<th>Transmission service</th>
<th>Center Frequency MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1C/A</td>
<td>◎</td>
<td>◎</td>
<td>◎</td>
<td>Satellite positioning service</td>
<td></td>
</tr>
<tr>
<td>L1C</td>
<td>◎</td>
<td>◎</td>
<td>◎</td>
<td>Satellite positioning service</td>
<td></td>
</tr>
<tr>
<td>L1SAIF</td>
<td>◎</td>
<td></td>
<td></td>
<td>Sub-meter Level Augmentation Service (SLAS) / Disaster and Crisis Management</td>
<td>1575.42</td>
</tr>
<tr>
<td>L1S</td>
<td>◎</td>
<td>◎</td>
<td>◎</td>
<td>Satellite positioning service</td>
<td></td>
</tr>
<tr>
<td>L1Sb</td>
<td>-</td>
<td>-</td>
<td>◎</td>
<td>SBAS Transmission Service from around 2020</td>
<td></td>
</tr>
<tr>
<td>L2C</td>
<td>◎</td>
<td>◎</td>
<td>◎</td>
<td>Satellite positioning service</td>
<td>1227.60</td>
</tr>
<tr>
<td>L5</td>
<td>◎</td>
<td>◎</td>
<td>◎</td>
<td>Satellite positioning service</td>
<td>1176.45</td>
</tr>
<tr>
<td>L5S</td>
<td>-</td>
<td>◎</td>
<td>◎</td>
<td>Positioning Technology Verification Service</td>
<td></td>
</tr>
<tr>
<td>LEX</td>
<td>◎</td>
<td></td>
<td></td>
<td>MADOCA</td>
<td>1278.75</td>
</tr>
<tr>
<td>L6</td>
<td>◎</td>
<td>◎</td>
<td>◎</td>
<td>Centimeter Level Augmentation Service (CLAS)</td>
<td></td>
</tr>
<tr>
<td>S-band</td>
<td>-</td>
<td>-</td>
<td>◎</td>
<td>QZSS Safety Service / SAR</td>
<td>2GHz</td>
</tr>
</tbody>
</table>
QZSS New Applications
QZSS New Applications

• Short Message Broadcast during Emergencies and Disasters
  • L1SAIF / L1S Signals

• Sub-meter Level Augmentation Service (SLAS)
  • L1SAIF / L1S / L1Sb Signals

• Centimeter Level Augmentation Service (CLAS)
  • L6 Signal
    • PPP-RTK
  • LEX Signal: MADOCA Service
    • PPP
Short Message Broadcast during Disaster
Sub-meter Level Augmentation Service (SLAS)

SLAS : Sub-meter Level Augmentation Service
Signal Used: L1SAIF / L1S
Centimeter Level Augmentation Service (CLAS)

CLAS: Centimeter Level Augmentation Service
Signal Used: LEX: MADOCA & L6
NavIC / IRNSS

Navigation with Indian Constellation
Indian Regional Navigation Satellite System
### NavIC Signal Types

<table>
<thead>
<tr>
<th>Signal</th>
<th>Carrier Frequency</th>
<th>Bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>L5</td>
<td>1176.45MHz</td>
<td>24MHz</td>
</tr>
<tr>
<td>S</td>
<td>2492.028MHz</td>
<td>16.5MHz</td>
</tr>
</tbody>
</table>
NavIC (Navigation with Indian Constellation)

• Consists of 7 Satellites
• 4 Geo Synchronous Orbit (GSO) satellites
  • at 55ºE and 111.75ºE at an inclination of 27º
• 3 Geo Stationary Satellites (GEO)
  • at 32.5ºE, 83ºE and 129.5º E at an inclination of 5º
• Transmits signals in L5 band (1176.45MHz) and S band (2492.028MHz)
NavIC Space Segment

- All Seven Satellites are successfully realized in orbit.
- IRNSS-1A (1 July 2013) IRNSS-1B (4 Apr 2014)
- IRNSS-1C (10 Nov 2014) IRNSS-1D (28 Mar 2015)
- IRNSS-1E (20 Jan 2016) IRNSS-1F (10 Mar 2016)
- IRNSS-1G (28 Apr 2016) IRNSS-1I (12 Apr 2018)
Multi GNSS Issues

• In the past we had only GPS & GLONASS, now we have Galileo, BeiDou, QZSS, IRNSS

• Compatibility
  • Lets not hurt each other
  • Interference issues

• Interoperable
  • I’ll use yours, you can use mine
  • Use of the same receiver and antenna to receive different signals

• Interchangeable
  • Any four will do
  • Can ONE GPS, ONE GLONASS, ONE Galileo and ONE COMPASS provide 3D Position?
Multi-GNSS Signals

- **GPS**
  - L5 / E5
  - L2
  - L6 / E6
  - L1 / E1
- **QZSS**
  - L5
  - L2C
  - L6 (LEX)
- **GLONASS**
  - L3
  - G2C/A
- **BeiDou**
  - L5
  - B2
- **Galileo**
  - E5a
  - E5b
  - E6
- **IRNSS**
  - L5
  - S

Training on GNSS – Course (T151-30), Organized by: GIC/AIT, CSIS/UT and ICG, held at: GIC/AIT, Thailand from 14 – 18 JAN 2019

Dinesh Manandhar, CSIS, The University of Tokyo, dinesh@iis.u-tokyo.ac.jp
Multi GNSS Signals: Benefits to Users

- GPS+GLONASS+Galileo+COMPASS+IRNSS+QZSS
- Asia-Oceanic region will see the maximum number of satellites
Multi GNSS Signals: Benefits to Users

• Increase in usable SVs, signals and frequencies
  • Increase in availability and coverage
  • More robust and reliable services
  • Higher accuracy in bad conditions
  • Less expensive high-end services
  • Better atmospheric correction

• Emerging new and expanding existing applications are to be expected
  • Atmosphere related applications
  • Short Message Broadcasting
  • SAR (Search And Rescue Applications)
  • Bi-static Remote Sensing
    • Compute Soil Moisture, Wind Velocity, Sea Wave Height etc…