Ingegneria delle Telecomunicazioni
Satellite Communications

22. Isn’t it Enough? Augmentation and Integrity

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• **AUGMENTING** a GNSS means enhancing its performance by means of additional information to:
  – Improve ACCURACY via differential corrections
  – Improve INTEGRITY via real-time monitoring
  – Improve CONTINUITY, therefore
  – Improve AVAILABILITY

• **Satellite Based Augmentation Systems (SBAS)**
  – E.g., WAAS, EGNOS, MSAS

• **Ground Based Augmentation Systems (GBAS)**
  – E.g., LAAS

• **Aircraft Based Augmentation (ABAS)**
  – E.g., RAIM, Inertials, Baro Altimeter
What does it mean?

- **Accuracy:**
  - Given, required values of rms positioning (or PVT altogether) errors

- **Integrity:**
  - Capability of a GNSS to provide timely warnings to users or to shut itself down when it should not be used for navigation

- **Continuity:**
  - Capability of a GNSS to perform its function without (unpredicted) interruptions during intended operation.

- **Availability:**
  - Capability of a GNSS to perform its function as expected - system availability is the percentage of time in which accuracy, integrity and continuity requirements are met
• **GPS/GLONASS Satellites:**
  - Time to alarm is from minutes to hours
  - No indication of quality of service

• **Health Messages:**
  - GPS up to 2 hours late
  - GLONASS up to 16 hours late

• **Continuity:**
  - Less than $10^{-5}$ Chance of Aborting a Procedure Once it is Initiated.

• **Availability:**
  - >99% for every phase of flight (ICAO SARPS).
<table>
<thead>
<tr>
<th>Maritime</th>
<th>Accuracy (H) 95%</th>
<th>Alert Limit (H)</th>
<th>Time to alert</th>
<th>Integrity risk (per 3 hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ocean</td>
<td>10m</td>
<td>25m</td>
<td>10sec</td>
<td>$10^{-5}$</td>
</tr>
<tr>
<td>Costal</td>
<td>10m</td>
<td>25m</td>
<td>10s</td>
<td>$10^{-5}$</td>
</tr>
<tr>
<td>Port approach and restricted waters</td>
<td>10m</td>
<td>25m</td>
<td>10s</td>
<td>$10^{-5}$</td>
</tr>
<tr>
<td>Port</td>
<td>1m</td>
<td>2.5m</td>
<td>10s</td>
<td>$10^{-5}$</td>
</tr>
<tr>
<td>Inland waterways</td>
<td>10m</td>
<td>25m</td>
<td>10s</td>
<td>$10^{-5}$</td>
</tr>
</tbody>
</table>
Most of the errors affecting pseud-range measurements are *common* to all satellites: clock, ephemeris (sat orbits), ionosphere and troposphere and can be canceled by suited *differencing* of observations.

A common correction valid for any receiver within the Local Area of Differential GPS (LADGPS) area is generated and *broadcast*.

The accuracy is limited by the spatial (de)correlation of those error sources (1 m at 100Km).
• Most of the errors affecting pseud-range measurements are *common* to all satellites: clock, ephemeris (sat orbits), ionosphere and troposphere and can be canceled by suited *differencing* of observations.

• A common correction valid for any receiver within the Local Area of Differential GPS (LADGPS) area is generated and broadcast.

• The accuracy is limited by the spatial (de)correlation of those error sources (1 m at 100Km).
- The receiver in a reference station can calculate these errors knowing its exact location (corrections “PRC” calculated by the GBAS ground station):

\[ \text{PRC} = \text{PR}_{\text{ref}} - \rho_{\text{ref}} \]

- The user receiver will use these corrections to correct its own measurements and increase the accuracy of these measurements:

\[ \text{PR}_{\text{user}} - \text{PRC} \]
Error Budget

Measured Pseudorange

- Geometric Range
- User receiver
- Rec Clock
- Sat. Clock
- Eph
- Iono
- Tropo
- Noise

Correlated Errors

Uncorrelated

PRC: Pseudo-Correction broadcasted

Residual

Corrected Pseudorange

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## Error Budget

<table>
<thead>
<tr>
<th>Error Source</th>
<th>Approx. $1\sigma$ Error for Standalone GPS Users</th>
<th>Approx. $1\sigma$ Error for LADGPS Users $(a = 50 \text{ km})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SV Clock</td>
<td>$1 - 2 \text{ m}$</td>
<td>$2 - 3 \text{ cm}$</td>
</tr>
<tr>
<td>SV Ephemeris</td>
<td>$1 - 3 \text{ m}$</td>
<td>$1 - 5 \text{ cm}$</td>
</tr>
<tr>
<td>Troposphere</td>
<td>$2 - 3 \text{ m (uncorrected)}$</td>
<td>$1 - 5 \text{ cm}$</td>
</tr>
<tr>
<td></td>
<td>$0.1 - 0.5 \text{ m (corrected by atmospheric model)}$</td>
<td></td>
</tr>
<tr>
<td>Ionosphere</td>
<td>$1 - 7 \text{ m (corrected by Klobuchar model)}$</td>
<td>$10 - 30 \text{ cm}$</td>
</tr>
<tr>
<td>Multipath (ref. and user receivers)</td>
<td>$\text{PR: } 0.5 - 2 \text{ m}^{(r)}$</td>
<td>$\text{PR: } 0.5 - 2 \text{ m}^{(r)}$</td>
</tr>
<tr>
<td></td>
<td>$1\sigma: 0.5 - 1.5 \text{ cm}$</td>
<td>$1\sigma: 0.5 - 1.5 \text{ cm}$</td>
</tr>
<tr>
<td>Receiver noise (ref. and user receivers)</td>
<td>$\text{PR: } 0.2 - 0.35 \text{ m}^{(i)}$</td>
<td>$\text{PR: } 0.2 - 0.35 \text{ m}^{(i)}$</td>
</tr>
<tr>
<td></td>
<td>$1\sigma: 0.2 - 0.5 \text{ cm}$</td>
<td>$1\sigma: 0.2 - 0.5 \text{ cm}$</td>
</tr>
<tr>
<td>Antenna survey error/motion</td>
<td>N/A</td>
<td>$0.2 - 1 \text{ cm}$</td>
</tr>
</tbody>
</table>
• Tracking the code, we can attain an accuracy of, say, 1/100 of a chip=3 m (typical of code-based GNSS)
• Tracking the carrier, we can attain an accuracy of 1/100 of a cycle=0.2 mm
• The issue is: carrier is ambiguous (no starting point) and very sensitive to unknown offsets and noise terms
• It is best implemented for static or slowly-moving receivers
• Differential receivers using carrier navigation are called Real-Time Kinematics (RTK) receivers and need a reference station to implement phase-level differential corrections
Surveying RTK Receiver(s)

So-called “Rover”

Fixed Base Station
Super-Accurate DGPS: Real-Time Kinematics (RTK)
Single- and Double-Phase Differencing

\[ \theta_B = \theta_S + \theta_{atm} - 2\pi f_c r_B / c - \theta_{0B} \]

\[ \theta_R = \theta_S + \theta_{atm} - 2\pi f_c r_2 / c - \theta_{0R} \]

\[ \Delta \theta = \theta_R - \theta_B = -2\pi f_c (r_R - r_B) / c - (\theta_{0R} - \theta_{0B}) \]

\[ \Delta^{(2)} \theta = \Delta \theta_1 - \Delta \theta_2 = -2\pi f_c \left[ (r_{R1} - r_{B1}) - (r_{R2} - r_{B2}) \right] (r_{R1} - r_{B1}) / c \]
Satellite-Based Augmentation Systems (SBAS)

- Correction terms (mainly ionosphere) are sent down to GNSS receivers from dedicated GEO satellites equipped with GNSS-like data signals.
Operational SBASs

- WAAS
- EGNOS
- SDCM
- BDSBAS
- MSAS, QZSS-SBAS
- GAGAN

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EGNOS (European Geostationary Navigation Overlay Service)

- **GEO**
- **GPS**

**Space Segment**

**Ground Segment**

- **NLES**
  - Navigation
  - Land Earth Stations

- **MCC**
  - Mission Control Centres

**User Segments**

- **RIMS**
  - Ranging & Integrity Monitoring Stations

**EWAN (EGNOS Wide Area Network)**

- **PACF**
  - Performance Assessment and Check-out Facility

- **ASQF**
  - Application Specific Qualification Facility

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**EGNOS Satellites & Coverage**

- **Astra Ses-5** | PRN Number 136 | Orbital Slot 5 E
- **Astra-5B** | PRN Number 123 | Orbital Slot 31.5 E
- **Inmarsat 4F2 Emea** | PRN Number 126 | Orbital Slot 64 E (experimental)
EGNOS Signals Structure

- EGNOS uses the same frequency (L1 1575.42 MHz) and ranging codes as GPS, but has a different data message format. Sixteen different message types have so far been defined to broadcast integrity data and Wide Area Differential (WAD) corrections.

- Integrity is provided at two levels:
  - use/don’t use flags for satellites and for ionospheric grid points;
  - two statistical estimates of the satellite and ionospheric errors, respectively, remaining after applying the WAD corrections - UDRE and GIVE. These are used to compute a certified error bound for the position solution in an integrity assessment.

- EGNOS signals are compatible with the other SBAS’s
  - An EGNOS-equipped receiver conforming to GPS/WAAS MOPS (DO-229C) is also capable of receiving other WAAS in the relevant coverage zones
### Example of EGNOS Messages

<table>
<thead>
<tr>
<th>Type</th>
<th>Contents (Satellite-Related Information)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>PRN mask assignments, set up to 51 of 210 possible</td>
</tr>
<tr>
<td>2-5</td>
<td>Fast corrections</td>
</tr>
<tr>
<td>6</td>
<td>Integrity information</td>
</tr>
<tr>
<td>7</td>
<td>Fast correction degradation factor</td>
</tr>
<tr>
<td>9</td>
<td>Geo Navigation message (X,Y,Z, time, etc.)</td>
</tr>
<tr>
<td>17</td>
<td>Geo satellite almanacs</td>
</tr>
<tr>
<td>24</td>
<td>Mixed fast corrections/long term satellite error corrections</td>
</tr>
<tr>
<td>25</td>
<td>Long term satellite error corrections</td>
</tr>
<tr>
<td>28</td>
<td>Clock Ephemeris Covariance Matrix message</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Type</th>
<th>Contents (Ionospheric Corrections)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>Ionospheric grid points masks</td>
</tr>
<tr>
<td>26</td>
<td>Ionospheric delay corrections</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Type</th>
<th>Contents (System)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Don’t use for safety applications</td>
</tr>
<tr>
<td>10</td>
<td>Degradation parameters</td>
</tr>
<tr>
<td>12</td>
<td>SBAS Network time / UTC offset parameters</td>
</tr>
<tr>
<td>27</td>
<td>SBAS Service message</td>
</tr>
<tr>
<td>62</td>
<td>Internal test message</td>
</tr>
<tr>
<td>63</td>
<td>Null message</td>
</tr>
</tbody>
</table>
EGNOS Ionosphere Gridpoints
Faster Fix: Assisted GPS (A-GPS)

- **TTFF**: Time To First Fix, the time it takes to get a PVT (or positioning) solution after receiver switch-on (aka cold start)
  - Must receive all the satellite ephemeris and then lock onto the diverse signals of the satellites in view – half a minute at least

- **If the user receiver is part of a communications network** it can be assisted to provide a faster fix
  - The satellite almanac is derived by a local A-GPS server belonging to a cellular network and can be sent to the receiver
  - OR the receiver obtains the same data via any Internet connection to a SUPL (Secure User Plane Location) server

- The TFFF is reduced to a few seconds, just the time to lock onto signals (the receiver is warmed-up by the network)