Extension of RTKLIB for the calculation and validation of protection levels

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Content

- Why?
  Plans to introduce GPS based flight procedures in Hungary

- Compare RTKLIB to proprietary programs

- Application: flight validation at Debrecen airport
Rationale
EGNOS improves GPS over Europe
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1. GALILEO, GPS and GLONASS satellite constellation

2. Ranging and Integrity Monitoring Stations (RIMS): receive GPS data and send it to MCC

3. Mission Control Centres (MCC): process GPS data to determine errors


5. 3 geostationary EGNOS satellites: relay error corrections to users
Accuracy

Standalone GPS

GPS with EGNOS corrections

Aircraft moving in 3D?

EGNOS monitor station at BME
www.agt.bme.hu/egnos
Integrity protection cylinder

Vertical and Horizontal Alert Limit cylinder are defined by the phase of flight

The aircraft's calculated position based on the EGNOS corrections is the center of cylinder

The aircraft's true position: not known

Protection level cylinder: VPL and HPL

Protection level (PL) calculation

\[ \sigma_i^2 = \sigma_{i,flt}^2 + \sigma_{i,iono}^2 + \sigma_{i,air}^2 + \sigma_{i,tropo}^2 \]

variance of \(i^{th}\) satellite has 4 components

\[ W^{-1} = \begin{bmatrix}
\sigma_1^2 & 0 & \ldots & 0 \\
0 & \sigma_2^2 & \ldots & 0 \\
\vdots & \vdots & \ddots & \vdots \\
0 & 0 & \ldots & \sigma_n^2
\end{bmatrix} \quad G_i^T = \begin{bmatrix}
\cos(El_i) \cdot \cos(Az_i) \\
\cos(El_i) \cdot \sin(Az_i) \\
\sin(El_i) \\
1
\end{bmatrix} \quad D = \begin{bmatrix}
d_{east}^2 & d_{EN} & d_{EU} & d_{ET} \\
d_{EN} & d_{north}^2 & d_{NU} & d_{NT} \\
d_{EU} & d_{NU} & d_{U} & d_{UT} \\
d_{ET} & d_{NT} & d_{UT} & d_t^2
\end{bmatrix} = (G^TWG)^{-1}

Inverse of the weight matrix
Geometry matrix
Variance/covariance matrix

\[ d_{\text{major}} = \sqrt{\frac{d_{\text{east}}^2 + d_{\text{north}}^2}{2}} + \sqrt{\frac{d_{\text{east}}^2 - d_{\text{north}}^2}{2}} + d_{EN} \]

\[ K_H = 6.00 \quad \text{Factor bounding users horizontal / vertical position} \]
\[ K_V = 5.33 \quad \text{with a probability of } 10^{-9} / 0.5 \times 10^{-7} \]

\[ \text{HPL} = K_H \cdot d_{\text{major}} \quad \text{Horizontal and vertical protection level} \]
\[ \text{VPL} = K_V \cdot d_U \]

Source: RTCA MOPS DO-229-C “Minimum Operational Performance Standards for Global Positioning System/Wide Area Augmentation System airborne equipment”
Variance includes

$$\sigma_i^2 = \sigma_{i,flt}^2 + \sigma_{i,iono}^2 + \sigma_{i,air}^2 + \sigma_{i,tropo}^2$$
Variance includes

\[ \sigma_i^2 = \sigma_{i,flt}^2 + \sigma_{i,iono}^2 + \sigma_{i,air}^2 + \sigma_{i,tropo}^2 \]

- Fast and long term correction
- Ionospheric delay
- Tropospheric delay
- Airborne error
Software to calculate PL

• Eurocontrol: Pegasus

• GMV: magicGemini
Open source solution: RTKLIB

- RTKLIB
  - SBAS positioning mode
  - no PL calculation
- Houghton Assoc Inc. fork of RTKLIB
  - PL calculation available
- Our enhanced version
  - https://github.com/zsiki/RTKLIB/tree/rtklib_2.4.3
PL calculated by different programs

<table>
<thead>
<tr>
<th></th>
<th>RTKLIB-mGemini</th>
<th>RTKLIB-pegasus</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta HPL$ [m]</td>
<td>-0.86</td>
<td>-1.18</td>
</tr>
<tr>
<td>$\Delta VPL$ [m]</td>
<td>-1.65</td>
<td>-1.85</td>
</tr>
<tr>
<td>$\Delta HPL$ [m]</td>
<td>+1.68</td>
<td>+1.57</td>
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<tr>
<td>$\Delta VPL$ [m]</td>
<td>+1.66</td>
<td>+1.40</td>
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<tr>
<td>mean</td>
<td>-0.08</td>
<td>-0.32</td>
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<tr>
<td>std. dev.</td>
<td>±0.18</td>
<td>±0.21</td>
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</tbody>
</table>

![Graph showing protection levels calculated by different programs](image)
What is Cat. I – II – III?
PL calculated by different programs

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</tr>
<tr>
<td>ΔVPL [m]</td>
<td>-1.65</td>
<td>-1.85</td>
</tr>
<tr>
<td>min</td>
<td>+1.68</td>
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<tr>
<td>max</td>
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<tr>
<td>mean</td>
<td>+1.66</td>
<td>-0.14</td>
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<tr>
<td>std. dev.</td>
<td>±0.18</td>
<td>±0.28</td>
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</tbody>
</table>

Different results
Data processing scheme

GPS+SBAS raw data

- magicGemini
  - output messages
- PEGASUS
  - pos and range output files
- rnx2rtkp (RTKLIB)
  - trace output

- gawk scripts
- CSV files

- GNUplot
- QGIS
  - text files
  - sql scripts in psql
1st reason: Some of the measurements are filtered out
2nd reason: Differences of variances

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<th>magicGemini vs. RTKLIB</th>
<th>Pegasus vs. RTKLIB</th>
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<tr>
<td>differences of fast and long term correction variance [m]</td>
<td></td>
<td></td>
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<tr>
<td>minimum</td>
<td>-2.14</td>
<td>+0.04</td>
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<tr>
<td>maximum</td>
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<td>mean</td>
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<td>±0.04</td>
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<td>differences of airborne variance [m]</td>
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<tr>
<td>minimum</td>
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<td>0.00</td>
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<td>maximum</td>
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<td>0.00</td>
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<td>differences of ionospheric delay variance [m]</td>
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<td>-26.23</td>
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<td>maximum</td>
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<td>mean</td>
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<tr>
<td>std. dev.</td>
<td>±0.41</td>
<td>±0.38</td>
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</table>
Airborne variance
Largest component: Ionosphere
Ionosphere grid models

EGNOS ionosphere map at 21/02/2017 13:59:59

EGNOS ionosphere GIVEi map at 21/02/2017 13:59:59

FOSS4G Europe 2017
IPP positions
all measurements during a 24 hour session at Budapest
IPP positions

Large ionosphere variance differences!
(RTKLIB vs. mGemini)
Range and Integrity Monitor Stations (RIMS)
Flight validation at Debrecen airport

12/13th July 2016
PL during flight validation

On a permanent station close to the airport

On the aircraft
To sum it up

- Open source SW compared to proprietary
  https://github.com/zsiki/RTKLIB/tree/rtklib_2.4.3
- Protection levels
- Reason behind the differences