Workshop on INTEGRITY MONITORING FOR TERRESTRIAL USERS
IBPL AND KIPL ALGORITHMS DEVELOPED BY GMV. REMAINING ISSUES
VILLENEUVE D’ASCQ, DECEMBER 15th 2015
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**DO TERRESTRIAL USERS REQUIRE INTEGRITY?**

**Position integrity** concept mainly linked to safety critical applications and, in particular aviation.

As a matter of fact GNSS integrity has been formalized and progressed thanks to the Civil Aviation domain.

Is the concept applicable for terrestrial users?

- By analogy it should be applicable for safety critical terrestrial applications (Autonomous Driving, Automatic Driver Assistance Systems –ADAS- in vehicles...)
- It is believed to be also of application for the so called “liability critical” applications (other authors call it “financial grade” applications).

Note that this question seems to have an obvious answer today but this has not been the case in the last 10 years. Change has been provided thanks to different initiatives where IFSTTAR, and very in particular Mr. Peyret, has had a key role.
AUTONOMOUS DRIVING: THE MOST DEMANDING INTEGRITY APPLICATION

**GNSS Challenges**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>GNSS Market</th>
<th>Challenges</th>
</tr>
</thead>
<tbody>
<tr>
<td>absolute position accuracy</td>
<td>~2 m (no correction) ~ 20 cm (PPP*) &lt; 10 cm (RTK**)</td>
<td>Availability at blockage, worldwide correction service availability</td>
</tr>
<tr>
<td>velocity accuracy</td>
<td>&gt; 0.1 m/s</td>
<td></td>
</tr>
<tr>
<td>time to first fix (full accuracy)</td>
<td>&gt; 20 min (PPP**) &gt; 30 s (RTK**)</td>
<td>Fast availability for automotive applications crucial</td>
</tr>
<tr>
<td>Life time, temperature, durability</td>
<td>Several applications driven from short lifetime with non safety of life functionality</td>
<td>Approved lifetime, durability and temperature ranges for automotive safety applications</td>
</tr>
<tr>
<td>functional safety,</td>
<td>no Application of ISO26262 Integrity concepts for Airplanes</td>
<td>Fulfilling automotive standards and high integrity important</td>
</tr>
<tr>
<td>Guarantee of service...</td>
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Today not only GNSS industry but also automotive stakeholders such as Renault or Bosch believe that integrity is key for autonomous driving.
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RECALL ON INTEGRITY

Integrity basically means bounding different errors sources with a very high probability (or eliminating those errors that can be above a giving bound –threshold-).

Protection levels are, as a matter of fact, “no more” than a bounding of position errors with that high probability.

If we want to provide position integrity we have to bound the different error sources.
IDENTIFICATION OF GNSS ERRORS

GNSS errors can be classified in:

- **System Errors. E.g.:**
  - Orbits
  - Time synchronization
- **Propagation errors. E.g.:**
  - Iono
  - Tropo
- **Local Errors. E.g.:**
  - Jamming / Interferences
  - Multipath
- **Receiver Errors. E.g.:**
  - Tracking errors
  - Thermal noise
### HOW THEY ARE BOUNDED BY SBAS/GBAS

<table>
<thead>
<tr>
<th></th>
<th>SBAS</th>
<th>GBAS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>System Errors:</strong></td>
<td>Orbits</td>
<td>Estimated Separately: (UDRE+ GIVE)</td>
</tr>
<tr>
<td></td>
<td>Estimated Separately: (UDRE+ GIVE)</td>
<td>Estimated Globally</td>
</tr>
<tr>
<td><strong>Time synchronization</strong></td>
<td>Bounded by a-priori values</td>
<td>Bounded by a-priori values</td>
</tr>
<tr>
<td><strong>Propagation errors:</strong></td>
<td>Iono</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Estimated Separately: (UDRE+ GIVE)</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>Estimated Separately: (UDRE+ GIVE)</td>
<td></td>
</tr>
<tr>
<td><strong>Local Errors:</strong></td>
<td>Tropo</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Estimated Separately: (UDRE+ GIVE)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Estimated Separately: (UDRE+ GIVE)</td>
<td></td>
</tr>
<tr>
<td><strong>Interferences neglected</strong></td>
<td>Multipath (LoS and NLoS)</td>
<td></td>
</tr>
<tr>
<td><strong>Receiver Errors</strong></td>
<td>Estimated Separately: (UDRE+ GIVE)</td>
<td></td>
</tr>
</tbody>
</table>
APPLICATION TO TERRESTRIAL USERS

Are those boundings for local errors assumed for civil aviation valid for terrestrial users?

- No: those boundings are too optimistic for terrestrial users.

Are there other valid bounds?

- No that serve in a practical manner for the process:
  - Too large for some errors to provide valid values ...
  - and what is more critical other (larger) errors in particular NLoS Multipath cannot be reasonably bounded (errors of hundreds of meters are probable)

GBAS and SBAS cannot provide integrity for terrestrial users. Classical RAIM either.

For Civil Aviation the main threats for integrity are system and propagation errors. For terrestrial users the local errors are the most important threat
NEED OF DIFFERENT APPROACHES FOR INTEGRITY

As seen SBAS and GBAS: not valid.

Classical RAIM (single/dual failure assumption) implementation neither

Need to develop specific algorithms.

Approach to implement RAIM-like (autonomous) type algorithms

Help of GNSS augmentations to provide integrity not useful: Augmentations “are not aware” of the local errors suffered by the user

However, use of SBAS or GBAS as a source to improve accuracy may help to improve performances of autonomous integrity algorithms
CHALLENGES

Nature of errors: Multiple “faults” (large errors due to multipath) is very probable.

Complexity of FDE: being those “faults” very frequent the balance between miss-detection and false detection is specially complex.

Validity for all environments from open sky to deep urban: not possible to make assumptions on the type of environment.

Need to minimize PLs sizes in a context of large measurement errors.

Lack of continuous signals due to obstacles.

Phase measurement availability substantially reduced (quite less than pseudoranges).

Large DOPs due to limited sky visibility.
DIFFERENT APPROACHES FOR INTEGRITY (I)

Two different approaches:

- **Measurement Rejection Approach (MRA):**
  “Faulty” measurements must be identified and rejected; “faulty” meaning “with significant errors”, not necessarily due to satellite failures (e.g. large NLoSM). Classical RAIM not working as multiple “faulty” measurements appear.

- **Error Characterization Approach (ECA):**
  Measurement errors must be characterized, but measurements are not divided in groups of “good” and “bad”. Protection levels must account for measurement errors (even large ones) and their effect in position errors.
DIFFERENT APPROACHES FOR INTEGRITY (II)

GMV has focused the R&D in the ECA approach.

Two steps:

1) Initial algorithm for snapshot solution: IBPL

2) Generalization to Kalman filtered solution also allowing simpler integration of other sensors: KIPL

In parallel, Civil Aviation is mainly focused today in A-RAIM techniques
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BASIC REQUIREMENTS

Horizontal Position Integrity Risk:
The Horizontal Position Integrity Risk is the probability that the horizontal position error exceeds the horizontal position Protection Level.

- Reference values $10^{-4}$ or $10^{-6}$ for liability critical and $10^{-5}$ or $10^{-7}$ for safety critical.

Horizontal Position Protection Level Performance:
Horizontal position Protection level performance for a given Target integrity is defined as the set of three statistical values given by the 50th, 75th and 95th percentiles of the cumulative distribution of horizontal position Protection levels computed for that Target integrity risk.

- No clear reference values established.

Diagram:
- 95%: ~ 47m
- 75%: ~ 37m
- 50%: ~ 30m
HOW GOOD INTEGRITY ALGORITHM IS?

Algorithm is valid as far as it fulfills the requirements:
- IR < TIR: a must
- Small PL sizes

But no magic: PLs according to accuracy. Small PLs cannot be achieved without high accuracy

Efficiency of PLs computation (not directly PL sizes) is a better assessment of the goodness of the algorithm

Small PLs are then achieved with:
- “Efficient” PLs
- Highly accurate measurements/positioning (not depending on the algorithms but on the quality/capabilities of sensors)

Balance of safety (IR<TIR) and efficiency is the challenge

Safety Index: Error/Protection Level. The smaller safety the highest safety margin
ALGORITHMS EFFICIENCY: SAFETY INDEX PERSPECTIVE

IBPL less conservative than EGNOS while fulfilling that IR<TIR!
ALGORITHMS EFFICIENCY: STANFORD DIAGRAM PERSPECTIVE

The "magic" PL

Reasonable Reference. Slope according to TIR

Conservative PL

GNSS+IMU 1E-4 - Urban Canyon

log_{10} of the number of points per dot

0 20 40 60 80 100

0 10 20 30 40 50 60 70 80 90 100

Kalman-based HPL (meters)

Horizontal Position Error (meters)
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ISOTROPY-BASED PROTECTION LEVEL (I)

Isotropy assumption: the vector of measurement errors ($\varepsilon$) can point in any direction of the N-dimensional measurement space with the same probability (spherical distribution).

$\varepsilon$ can be projected in a 4-dimensional “plane” (vector $\delta$) linked through the observation matrix $H$ to the 4 dimensions space-time “plane” and the residuals (vector $\rho$) in the N-4 dimension.

Because of the isotropy assumption the probability that the vector points in a given surface is equal to the size of this area in relation to the sphere surface.

If we select the size of the two polar caps as 1-$\alpha$ ($\alpha$ being the integrity risk), the probability that the vector points outside de caps is $\alpha$. 
ISOTROPY-BASED PROTECTION LEVEL (II)

Thus, given a residual $\rho$, the probability that $\delta$ is larger than $B$ (i.e. $\epsilon$ pointing out of the caps) is bounded by this probability $\alpha$.

If we transform now to the space dimension (through the H matrix) we can ensure that $\Delta$ (position error) is within PR with the same probability $\alpha$. 
In practice, we compute the limit ratio $K$ as a function of $\alpha$ and $N$, then scale it with the size of the residual vector $\rho$. Finally, the pull-back through $H$ is represented by the DOP factor.

$$PL = K(N, \alpha) \times \|\rho\| \times \text{DOP}$$
**ISOTROPY-BASED PROTECTION LEVEL (IV)**

The Isotropy-Based Protection Level:

- Only relies on the isotropy assumption (that has been largely demonstrated with experimental data); no assumptions are required on:
  - a) individual measurement errors’ distribution
  - b) probability of multiple failures
- Is adaptive to different environments: zones with small or null NLoS multipath has associated small residuals and, hence, small Protection Levels:
- It can be computed for any required TIR (specially relevant to adapt to different integrity requirements)
- Easy and powerful exploitation of multiple constellations (e.g. GPS + Galileo). Because K largely decreases with the number of measurements, important PL size reduction is achieved in multi-constellation scenarios
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KIPL ALGORITHM (I)

IBPL method for integrity of least-squares navigation
- Based on simple statistical assumption: isotropy of measurement errors
- Highly reliable in all kind of environments

But Kalman filter preferred because:
- Higher accuracy
- Simpler integration of other sensors

Target: **Improved Accuracy + Decrease size of Protection Levels** (for any given TIR) w.r.t. the IBPL

New integrity method extends ideas from **IBPL to the Kalman-filtered navigation solutions (KIPL)**

Implemented solution based on multiconstellation receiver and low cost IMUs (but KIPL can cope with other different technologies)
KIPL ALGORITHM(II)

Statistical characterization of input errors based on IBPL

Statistical characterization of output errors

\[ S_k = K_k X_k + U_k S_{k-1} \]
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KIPL RESULTING PERFORMANCES (I)

Based on metrics defined by prEN16.803. Urban Canyon Scenario

**ACCURACY**

95%: ~12m  
75%: ~ 7m  
50%: ~ 4m

**INTEGRITY: HPL SIZE**

95%: ~ 32m  
75%: ~ 25m  
50%: ~ 20m
INTEGRITY: Measured IR < TIR

Target Integrity Risk | IR of GNSS-only [m] | IR of GNSS+IMU [m]
--- | --- | ---
1E-2 | 1.8E-3 | 1.5E-3
1E-3 | 3.4E-4 | 1.5E-4
**1E-4** | **6.1E-5** | 0
1E-5 | 6.1E-6 | 0
1E-6 | 0 | 0

0.345% of 99634 epochs out of plot limits

Measured IR always < TIR
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REMAINING ISSUES (I)

IBPL and KIPL are considered a solid basis for providing position integrity for road applications both for liability critical and safety critical applications.

Performances of KIPL has been demonstrated to be according to the needs of many liability critical applications.

Requirements for safety critical applications in particular for Autonomous Driving are still not mature. It is important to understand that different levels of autonomous driving may have very different requirements.
REMAINING ISSUES(II)

Major effort in KIPL to provide improved performances according to those needs

TIR should not be a major concern because IBPL/KIPL can be adapted to different TIRs (input parameter)

However testing of TIR $< 10^{-6}$ is a challenge

Major challenge is the provision of small PLs. Key is the use of technologies with high accuracy. Three main lines of investigation:

- Highly accurate GNSS-only solutions: RTK and PPP.
- Improvements in vehicle sensors performances (IMUs + odometers) allowing improvements on hybridized solutions
- Integration with other sensors and maps
REMAINING ISSUES (III)

Continuity requirements (not separated from availability in liability critical application) may be needed for safety critical applications and, therefore, this performance needs to be investigated for IBPL and KIPL algorithms.

Safety critical applications require not only absolute position but also relative position among vehicles. Integrity of relative position will be a new requirement.

Analysis of KIPL use for relative position and its resulting performance is another line of investigation for the future.
CONCLUSIONS

Position integrity for road applications (liability and safety critical applications) is today assumed as a key performance. It was not the case only one or two years ago!

Autonomous integrity is needed to cope with local errors

Two algorithms have been developed and largely tested by GMV: IBPL and KIPL

They are operational and able to cope with different application requirements and different technologies. TIR is an input parameter

Still challenges to provide integrity for safety critical applications where very small PLs are a must. Continuity requirements will be also needed

Remaining issues (as for many R&D initiatives) is almost unbounded!
Thank you!

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