Completing the landing – Evaluating continuity in GBAS

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WHAT WE DO

- Instrument landing systems
- Surface movement guidance and control
- Satellite landing systems
- Approach control
- ATC voice communications
- Electronic flight strips
- DME/DVOR
- Instrument landing systems

Communication
Navigation
Surveillance
The current system: ILS (Instrument Landing System)

NORMARC 3525 24-element Localizer
Ezeiza, Argentina
The future system: GBAS (Ground Based Augmentation System)

- Differential GNSS system
- Ground subsystem provides pseudorange corrections
- Integrity monitors in ground and airborne subsystems provide integrity to position solutions
- Ground system transmits coordinates for approach path (FAS blocks) and other GBAS data
Why GBAS?

- One GBAS ground station can cover all runways on an airport
- A GBAS ground station (GS) can reduce time between approaches
- A GBAS GS can optimize curved approaches
- Several thresholds, several glide path angles
- Curved approaches and reduced time between approaches may reduce fuel consumption in the landing phase
- A GBAS GS is less dependent on civil works in front of the runways and on topography in general, but will also to some extent be dependent on topography and buildings as reception of the GNSS signals depends on Line Of Sight (LOS)

GBAS is a more efficient solution; less equipment, less maintenance, hence lower cost
What performance is needed to land and aircraft in low or zero visibility?

- **Accuracy** of differentially corrected position solution
  - Limit multipath on ground subsystem by
    - Code carrier smoothing (Hatch filter)
    - Multipath Limiting Antennas (MLA)
    - Siting rules and no-movement zones

- **Integrity**

- **Continuity**

- **Availability**
Integrity

A measure of trust that can be placed in the correctness of the information supplied by the total system. Integrity includes the ability of the system to provide timely warnings to the user (alerts) when the system should not be used for the intended operation.

- The ground subsystem transmits standard deviations (sigmas), which overbound the statistical error in the transmitted corrections

- Airborne user calculates vertical and horizontal error bounds or protection levels (HPL /VPL)
  - If xPL > alarm limit -> interrupt operation

- Ground integrity monitors
  - Satellite clock fault
  - Signal deformation
  - Code carrier divergence
  - Ephemeris errors
  - Ionosphere gradients (split responsibility with air)
Continuity

The ability of the total system to perform its function without interruption during the intended operation. More specifically, continuity is the probability that the specified system performance will be maintained for the duration of a phase of operation, presuming that the system was available at the beginning of that phase of operation.

- Short definition: interrupted landing
- Aircraft needs to do a go-around
- Increased workload for air traffic control
- Multiple go-arounds classified as a safety issue*
- Continuity risk allocated to ground integrity monitors: $2 \times 10^{-7}$ over 15s for a single satellite

* Source: GBAS concept paper
Continuity – effect on individual integrity monitors

- Continuity allocation to ground integrity monitor is used to set false alarm rates of individual monitors

- False alarm rate $P_{FA} \approx 10^{-9}$

- Noise floor may vary
  - Elevation
  - Satellite dependent changes
  - Seasonal variations

- Standard approach: assume worst case condition when setting threshold
  - Worst case elevation, satellite etc
Specific vs average risk

- GBAS concept paper: specific risk must be applied to continuity for GAST D (zero visibility below 200 ft)

- Pullen and Enge, 2011:

  **Specific risk** is the probability of unsafe conditions subject to the assumption that all credible unknown events that could be known occur with a probability of one (on an individual basis).

  **Average risk** is the probability of unsafe conditions based upon the convolved (“averaged”) estimated probabilities of all unknown events.

- Critical satellite: satellite that if lost, cause loss of continuity
  - Present with probability 1?
Phase scintillations

- Electrons flow from the dayside towards the nightside along the Auroral oval
  - Normal location of Auroral oval is ~70 deg latitude
  - Expands and moves south during iono storm conditions

- Cause of Auroral lights, but also phase scintillations
  - Small scale anomalies

- Effect on GNSS
  - Increased noise carrier phase measurements
  - Loss off lock on individual satellites
  - Cycle slips

- Effect on GBAS
  - Loss of satellites
  - Increased noise on integrity monitors

Image courtesy: www.northernlightscentre.ca
Amplitude scintillations

- Occur at low magnetic latitudes (equatorial region) after sunset
- Local depletions of electrons in the ionosphere (plasma bubbles)
  - Large scale anomalies
- Signal fading/ amplitude scintillations
  - Fluctuations in carrier to noise ratio
  - ‘Deep fades’ with loss of lock
Scintillations and continuity

- Traditional approach of setting thresholds based on ‘worst case conditions’ breaks down
  - Worst case condition = loss of lock

- Propose to clarify that specific risk considerations do not apply on a signal level

- Propose to use average risk approach to assess risk of losing satellites due to scintillations

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Loss of continuity
    └── Loss of single satellite
        └── Monitor triggering
            └── Loss of lock
                └── Scintillation state
```

Specific risk to be applied here (if at all)
**TOTAL PROBABILITY THEOREM**

- **Total probability theorem**: The probability of an event $A$ given a set of mutually exclusive events $B_i$, is given by

$$ P(A) = \sum_i P(A|B_i)P(B_i) $$

- Want to apply the theorem to calculate the false alarm rate on a single monitor

$$ P(FA) = P(FA|NO\ SCINT)P(NO\ SCINT) $$

$$ + P(FA|SCINT\ at\ level\ 1)P(SCINT\ at\ level\ 1) $$

$$ + P(FA|SCINT\ at\ level\ 2)P(SCINT\ at\ level\ 2) $$

$$ + P(FA|SCINT\ at\ level\ 3)P(SCINT\ at\ level\ 3) \ldots $$
Main building blocks in proposed framework

Data collection

Classification of threat space

Classes/ events

Caracterization of influence on monitor

Prior probabilities

Probability of false alarm for event

Total probability of false alarm
Example: use Rate of Tec Index (ROTI) as classifier *

\[ ROTI = \frac{1}{T} \sqrt{\text{variance}(\Delta \text{TEC})} \]

- Data from 10 individual receivers, from all of 2012
- Cut-off elevation at 15 degrees, to eliminate elevation effects in ROTI on low satellites

Nighttime vs daytime risk

- Night: 21-03 UTC
- Day 09-15 UTC
Results single case study

- Inflation needed to maintain the average false alarm rate
- Conclusion: Excessive acceleration (satellite clock errors) can meet continuity and integrity requirements under phase scintillations, under an average risk assumption

Empirical relationship between ROTI and monitor noise, measured during high activity at 70 deg latitude

Inflation of monitor standard deviation needed to meet continuity requirement

<table>
<thead>
<tr>
<th>Latitude</th>
<th>$\sigma$ ($24H$) (mm)</th>
<th>$\sigma$ ($night$) (mm)</th>
<th>$\sigma$ ($day$) (mm)</th>
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<td>4.1</td>
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<td>5.0</td>
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</tr>
</tbody>
</table>
Empirical risk model, scintillation magnitude

Equatorial region

- Divide the threat space into N evenly spaced intervals \( S_{4,i} \), spanning from 0 to \( S_{4_{max}} \)

  NOTE: Someone need to invent a better index than S4.

- Define the events \( I_i: S_{4,i-1} \leq S_4 < S_{4,i} \)

- Based on historical data, derive the empirical risk for a given IPP position (IPP=ionospheric pierce point)

\[
P(I_i; IPP_{long}, IPP_{lat}, t)
\]

Auroral region:

- Use classifier \( \sigma_\Phi \)

- Base model on emerging networks of high bandwidth scintillation monitors
Joint empirical statistics over multiple satellites

- Want to derive the likelihood that multiple satellites are affected simultaneously
- Example*: Risk derived using ROTI

* Courtesy Jacobsen and Dähm, ROTI Statistics and correlation with PPP error, 2014
Other useful characteristics

- Size and shape characteristics for disturbed regions

- Correlation over space – what is the risk that both user at a distance $X$ from the ground station and the ground station are affected simultaneously
Conclusions

- Recommend to allow using an average risk approach when estimating the risk of losing satellites due to scintillations

- Propose several empirical risk models that can be used to assess system continuity (and availability) in the presence of scintillations

- Multi-constellation GBAS is expected to reduce the continuity risk due to scintillations
  - Empirical risk models can be used to estimate the gain
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