LOOKING INTO NAVIGATION INTEGRITY FOR UAVs FROM A GEODETIC PERSPECTIVE

P. Molina, I. Colomina

Institute of Geomatics
Generalitat de Catalunya & Universitat Politècnica de Catalunya

European Calibration and Orientation Workshop (Castelldefels) – 2012-02-09

AGENDA

- UAV platforms and missions:

…What is the nature of UAV missions?

- Navigation Integrity:
  - Definitions and measures
  - From civil aviation to UAVs…

…Are the actual safety mechanisms and requirements protecting UAVs?

- Geodetic reliability:
  - Analogies with integrity
  - Derivation of the reliability frame for UAVs

…Are precision-based tolerances enough?

- Results and summary

AGENDA

- UAV platforms and missions:

…What is the nature of UAV missions?

- Navigation Integrity:
    - Definitions and measures
    - From civil aviation to UAVs…

…Are the actual safety mechanisms and requirements protecting UAVs?

- Geodetic reliability:
    - Analogies with integrity
    - Derivation of the reliability frame for UAVs

…Are precision-based tolerances enough?

- Results and summary

UAV PLATFORMS AND MISSIONS

UAV platforms are a very convenient way to produce Earth observation (geomatic products, in general) due to its low-cost, easy deployment and fast product delivery. They fill the gap between satellite or airborne-observation and ground-observation with [increasing] quality imagery.

Although high-altitude UAVs are present, most of the platforms fly close to the ground.

Swiss UAV – NEO-S-300

… but major restrictions are present on [freely] using UAVs

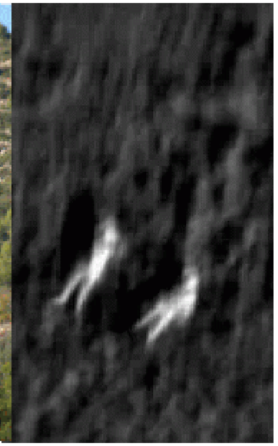
… they are not ‘socially welcome’

UAV-RELATED PROJECTS AT THE INSTITUTE


In **uVISION (2006-2008)** a UA-helicopter prototype was developed for Earth Observation and geoinformation acquisition, contributing with BA/INS/GNSS navigation system and the calibration of imaging sensors.

In **ITUMA (2008-2009)**, the consortium is developing a prototype system for a mini UA-plane with a thermal camera payload. The Institute was in charge of the position/attitude determination and calibration of the thermal camera payload.

In **CLOSE-SEARCH (2010)** an integration of a UA-helicopter, a thermal and optical camera together with a BA/RINS/EGNOS-GNSS navigation system for real-time control is targeted for a particular application: search-and-rescue missions.

SAFETY IN UAVs MISSIONS

- **UAVs are still unregulated**
  - Few, country-dependent rules are barely know by UAV operators
    - New initiatives: JARUS → rules for Line-of-Sight (LOS), flying altitude…
  - Integration into non-segregated airspace is complex (detect-&-avoid)

- **Actual navigation requirements are not suitable**
  - EASA (European Aviation Safety Agency): "*Certification specs are written for manned aircraft, and need to be customized*" (foreseen end 2016)
  - Integrity/safety requirements are written in compliance with civil aviation
    - A larger community (trains, cars, UAVs, pedestrians…) want to benefit from safety mechanisms for navigation

New integrity/safety requirements have been stated adapted to VTOL, low-altitude UAV missions (*)

(*) Molina et al., "*INTEGRITY ASPECTS OF HYBRID EGNOS-BASED NAVIGATION ON SUPPORT OF SEARCH-AND-RESCUE MISSIONS WITH UAVs*", ION GNSS 2011, 2011-09-21/23, Portland, OR.

AGENDA

- UAV platforms and missions:

…What is the nature of UAV missions?

- Navigation Integrity:
  - Definitions and measures
  - From civil aviation to UAVs…

…Are the actual safety mechanisms and requirements protecting UAVs?

- Geodetic reliability:
  - Analogies with integrity
  - Derivation of the reliability frame for UAVs

…Are precision-based tolerances enough?

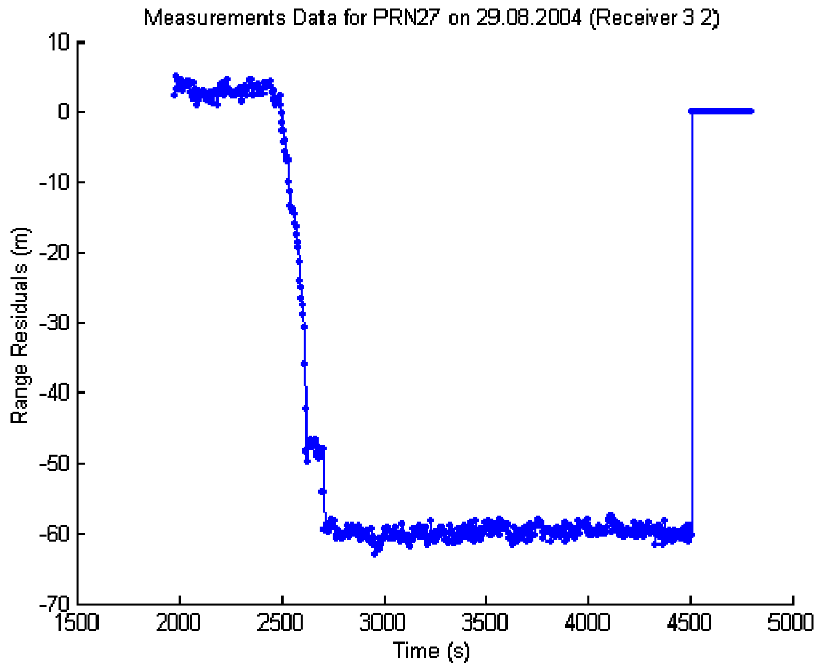
- Results and summary

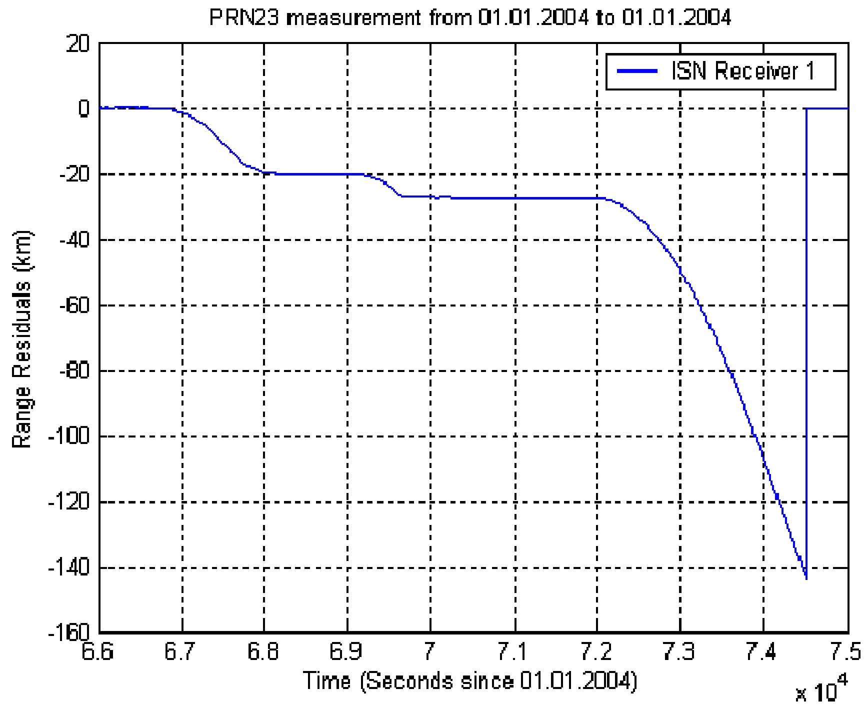
INTEGRITY: THE THING TO LOOK AT…

Something goes wrong

on-board electronics | on-board mechanics | comm | … | navigation | … | human operator

(CNES report, 2009)





Figures @ W. Ochieng, "*Integrity Monitoring for Detection of Interference*", GPS World

FRAME FOR AND MEASURE OF INTEGRITY

Performance Of Navigation Systems

- Accuracy
- **Integrity**
- Continuity
- Availability

Ability of a system to provide timely warnings in presence of a system failure causing a misleading user position

GPS stand-alone
→ limited # of ground stations
→ undetected faults up to 6h!

GNSS Integrity is provided by **Augmentation Systems**

Satellite-based (**SBAS**) → EGNOS, WAAS…
Ground-based (**GBAS**) → airport environments
Aircraft-based (**ABAS**) → RAIM

Integrity frame:
- Alert Limits (ALs)
- Integrity Risk (IR)
- Time-to-Alarm (TTA)

"If an error exceeds the AL, the probability of not warning the user within specified TTA shall be lower than the IR"

Integrity measure:
Protection Levels (PLs) are precision-based tolerances

PL < AL → system available
PL > AL → system unavailable

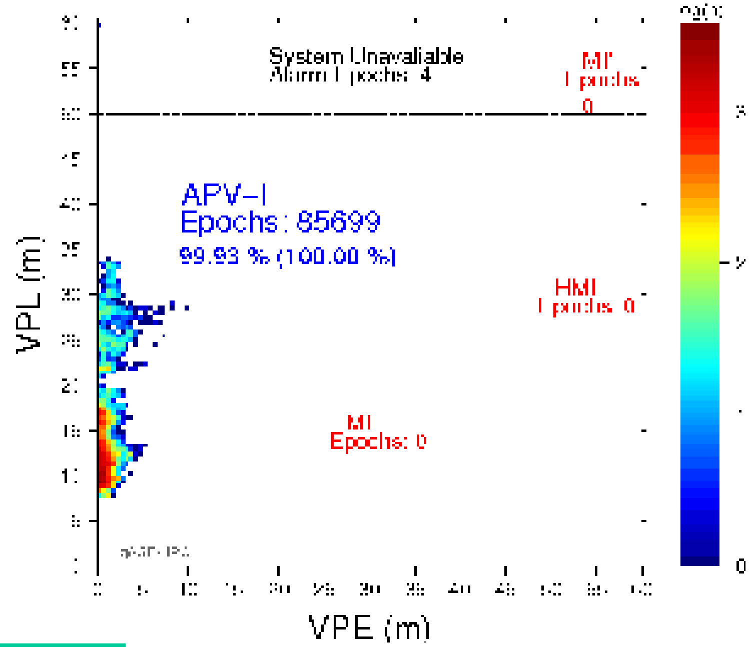
EGNOS: FROM CIVIL AVIATION TO UAV MISSIONS…

Approach	HAL, VAL (m)	TTA (s)	IR (-/s)
APVI	40, 50	10	$1 \cdot 10^{-7}$ /150
CATI	40, 10-15	6	$1 \cdot 10^{-7}$ /150

EGNOS certification

Our thoughts

- large Alert Limits (ALs)
- low Integrity Risk (IR)
- long Time-To-Alarm (TTA)



Approach	HAL,VAL (m)	TTA (s)	IR (-/s)
W2W	4, 7.5	<<10	$1 \cdot 10^{-6}$ /150
GA/S	2.5, 4	<<10	$1 \cdot 10^{-6}$ /150

Molina et al., "*INTEGRITY ASPECTS OF HYBRID EGNOS-BASED NAVIGATION ON SUPPORT OF SEARCH-AND-RESCUE MISSIONS WITH UAVs*", ION GNSS 2011, 2011-09-21/23, Portland, OR.

BUT WHAT IF…?

- no SBAS visibility
  - some environments are of reduced visibility (low GEO satellites elevations)

- Local effects
  - **Multipath**, ionospheric scintillation, troposhperic effects…
  - Jamming → receiver front-end saturated by unwanted strong signals

San Diego, CA – 2007-01-22
During US Navy comm jamming tests, Navy GPS receivers stopped working and affected all GPS users within a range 15 kms

  - **Disturbance** → wanted signals distorted by unwanted signals
  - **Spoofing** → receiver acquires & tracks fake GPS signals
  - ……..

WE NEED TO DEAL WITH FAULTS (OUTLIERS) ALSO AT THE LOCAL LEVEL

Conclusions of GNSS Evolutionary Architecture Study (GEAS), Phase I (Feb 2008):

"…the allocation of the burden for providing integrity should be balanced more and more towards the user receiver…"

AGENDA

- UAV platforms and missions:

…What is the nature of UAV missions?

- Navigation Integrity:
  - Definitions and measures
  - From civil aviation to UAVs…

…Are the actual safety mechanisms and requirements protecting UAVs?

- Geodetic reliability:
  - Analogies with integrity
  - Derivation of the reliability frame for UAVs

…Are precision-based tolerances enough?

- Results and summary

GEODETIC RELIABILITY FOR NAVIGATION INTEGRITY

Baarda (60's, 70's) provided a consistent, rigorous and systematic framework to the quality of geodetic networks through its the analysis of least-squares adjustments... and navigation is about least-squares.

	… faults, outliers, gross errors…
The Intergrity Risk (IR) is the probability of not detecting a fault, …	Probability of missed detection / false alarm $1-\beta_0$ α_0
… and this fault having an impact beyond tolerances (AL)	Impact of non-detected outliers (*external reliability*)

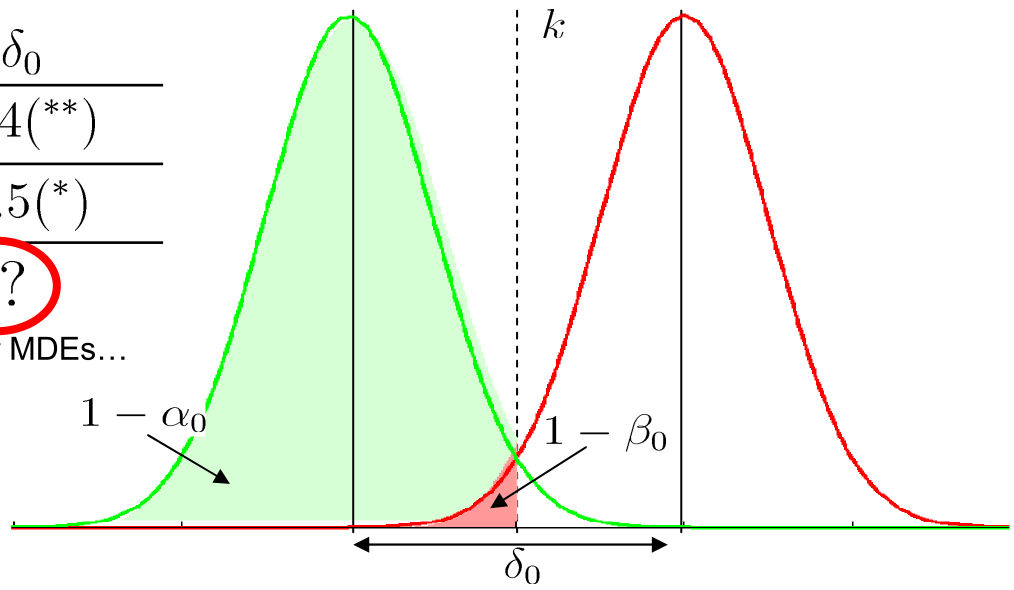
We want to find the Marginally Detectable Error –MDE- *(internal reliability)* yielding a maximum impact on parameters *(external reliability)* lower than the Safety Specification *(navigation integrity)*

ABOUT DETECTING FAULTS WITH CERTAIN PROBABILITIES

- Identify a convenient statistic: $w = \dfrac{\hat{v}}{\sigma_{\hat{v}}}$ ~ $N(0,1)$ (…unless you take care of $\hat{\sigma_0}$)
- Null hypothesis: "*no outlier*" – Alternate hypothesis: "*outlier of size* δ_0"
  - $|w| < k$ is a test statistic for the null hypothesis
- Compute k, δ_0, given $\alpha_0, 1-\beta_0$

α_0	$1-\beta_0$	k	δ_0
10^{-3}	0.24	3.29	$4(^{**})$
10^{-6}	$4.5 \cdot 10^{-6}$	4.75	$9.5(^{*})$
??	??	??	??

…for fault detection for MDEs…



(*) W. Ochieng, "*An Assessment of the RAIM Performance of a Combined Galileo/GPS Navigation System using the Marginally Detectable Errors (MDE) Algorithm*", GPS solutions, 2002

(**) W. Förstner, "*The reliability of block triangulation*", Photogrametric Eng.& Remote Sensing, Vat. 51, No.6 August 1985, pp 1137-1149

ABOUT BOUNDING THE IMPACT OF NON-DETECTED FAULTS

Directly from the least-squares [linear] formulation,

$$l + v = A \cdot x \qquad\qquad \hat{x} = (A^t C_{ll}^{-1} A)^{-1} A^t C_{ll}^{-1} l$$

The following holds for outliers $\nabla_0 l_i$,

$$\nabla_{0,i} x = C_{\hat{x}\hat{x}} A^T C_{ee}^{-1} \cdot \nabla_0 l_i \doteq U \cdot \nabla_0 l_i$$

Therefore, given the maximum tolerable errors (ALs), we can bound for any $\nabla_0 l_i$,

$$HAL < max_i \left\{ U_{\mathrm{H}} \cdot \nabla_0 l_i \right\} \qquad\qquad VAL < max_i \left\{ U_{\mathrm{V}} \cdot \nabla_0 l_i \right\}$$

Supposing that:

- we are able to remove all outliers above the MDE, and
- we consider the ALs derived for UAV missions,

Then:

$$4 < \left| max_i \left\{ U \cdot MDE_i \right\} \right|^*$$

(*) note that we bound the modulus of the *impact vector*

THE INTEGRITY BREAKDOWN

Integrity Frame
(mission specification, platform dependant)

Alert Limits

Integrity Risk

$$|AL| < U \cdot \nabla_0 l_i$$

$$\nabla_0 l_i = \delta_0 \frac{\sigma_l}{\sqrt{r_i}}$$

δ_0 → *controllability* factor

scaled by the "a-priori" probability of a sensor to fail

$$IR = (1 - \beta_0) \cdot P_{sensor}$$

δ_0 — $1 - \beta_0$

α_0, k

For each navigation system configuration, for each platform and for each mission, these values shall be determined (AL = $4m$ and IR = $1 \cdot 10^{-6}$)

AGENDA

- UAV platforms and missions:

…What is the nature of UAV missions?

- Navigation Integrity:
    - Definitions and measures
    - From civil aviation to UAVs…

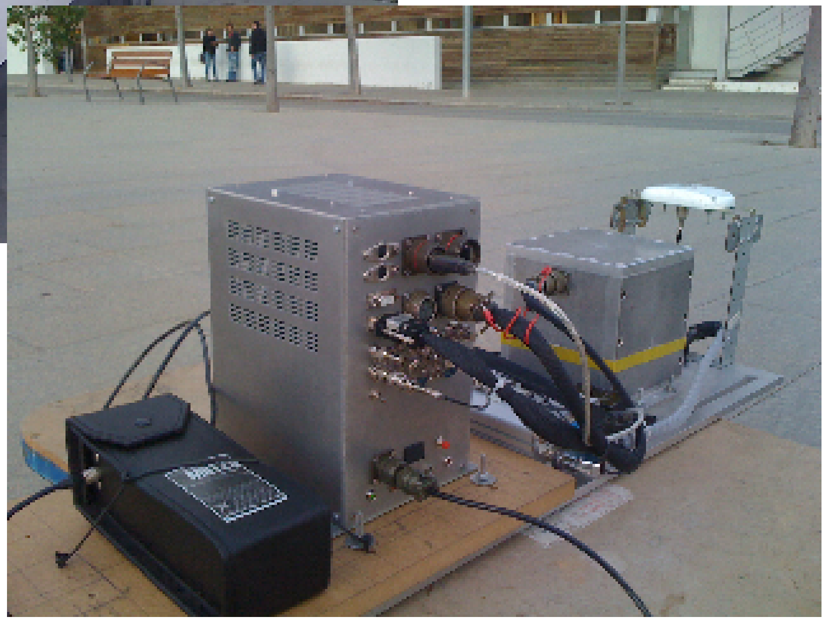
…Are the actual safety mechanisms and requirements protecting UAVs?

- Geodetic reliability:
    - Analogies with integrity
    - Derivation of the reliability frame for UAVs

…Are precision-based tolerances enough?

- Results and summary

TEST CAMPAIGN: LET'S GO FOR A RIDE

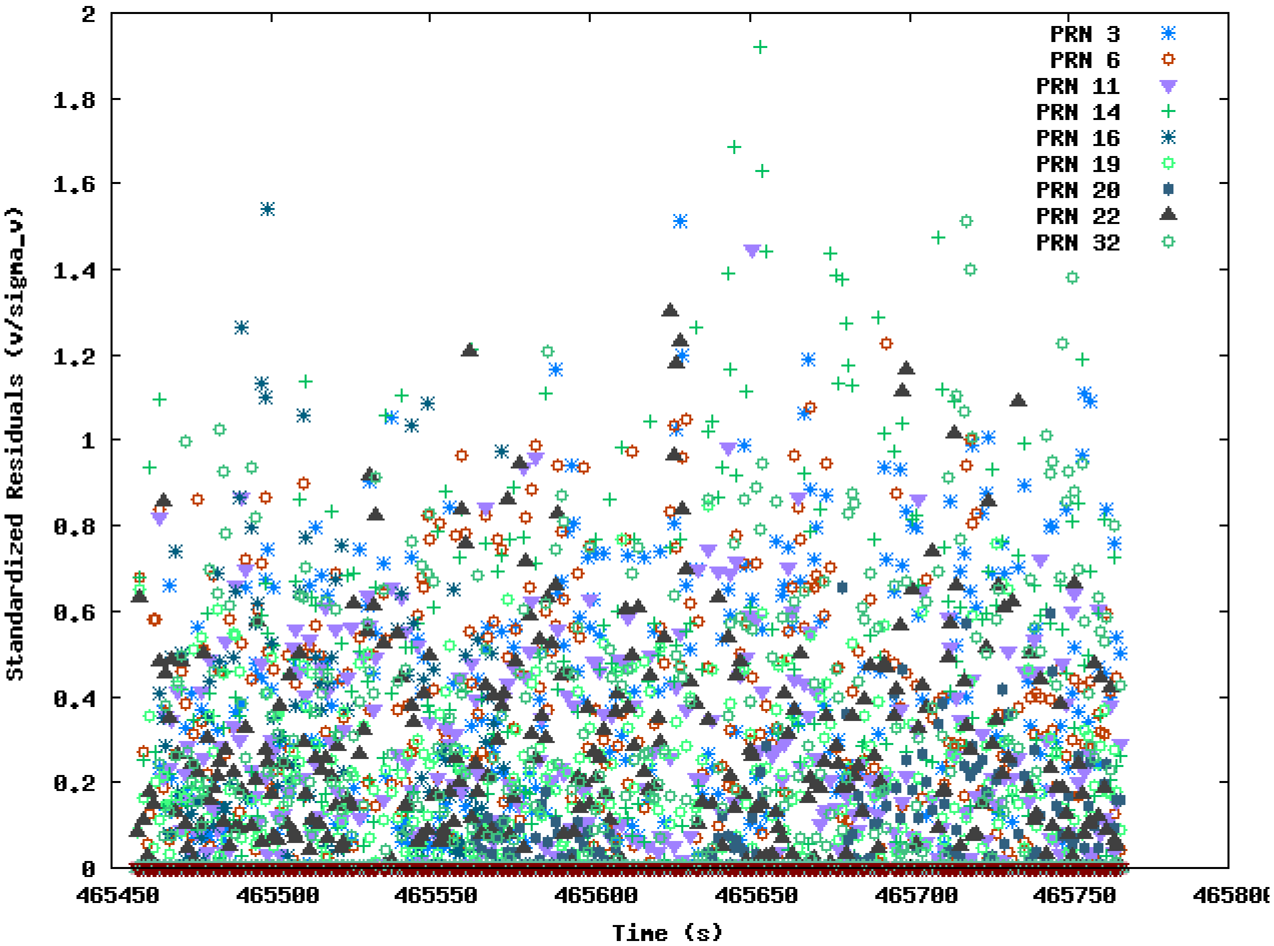


To be on-board of a UAV…

CLOSE-SEARCH project (March, 2012)

TEST CAMPAIGN: LET'S GO FOR A RIDE

HOW STANDARDIZED RANGE RESIDUALS LOOK LIKE



Sats ~ 8 # IMUs = 1

- EGNOS corrections
- Close-coupling

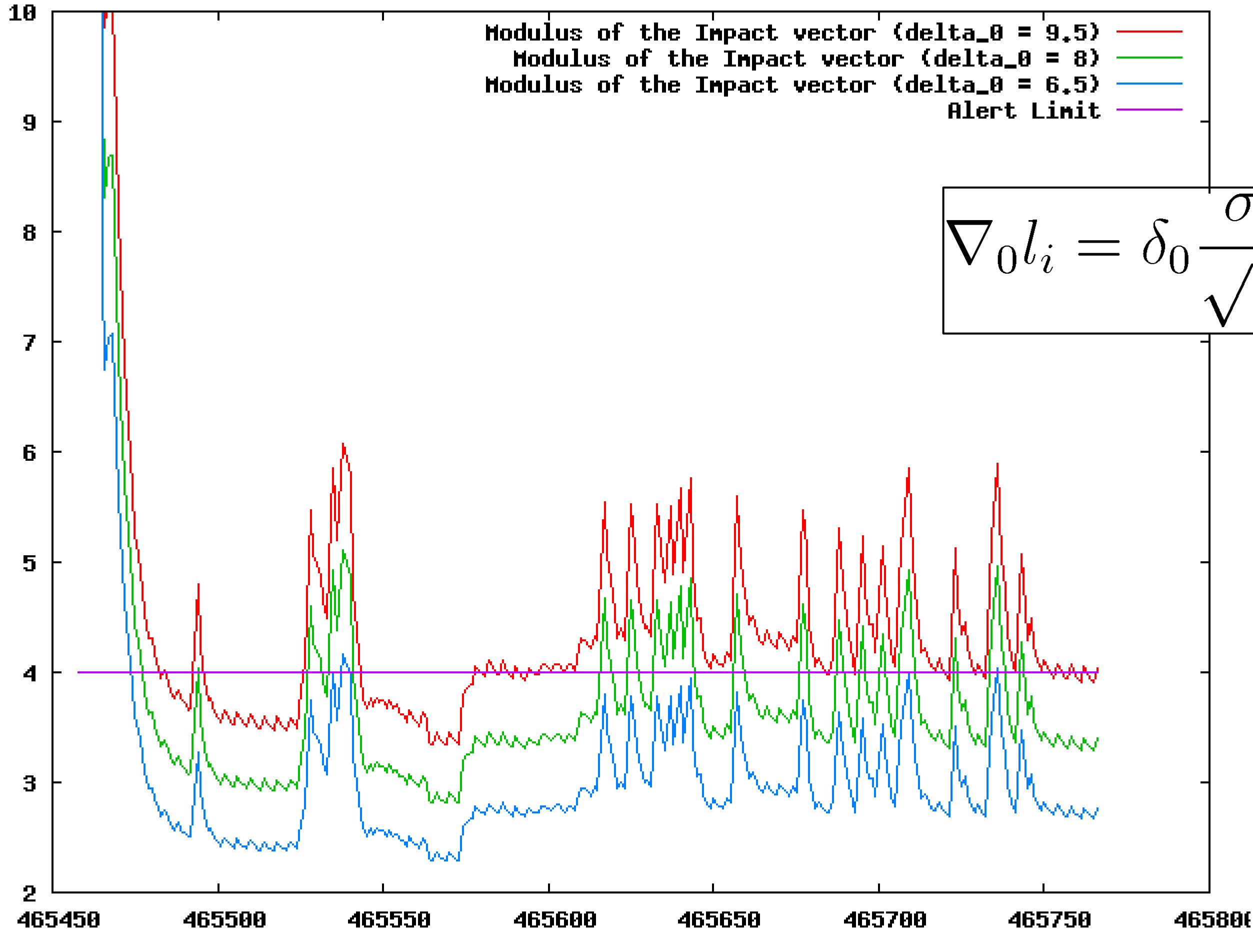
Total redundancy = #Sats

<u>Pseudorange observation group</u>

r_i → ~ 0.88

→ Most of the error is projected on the pseudorange residual

RESULTS: BOUNDING THE IMPACT OF NON-DETECTED FAULTS



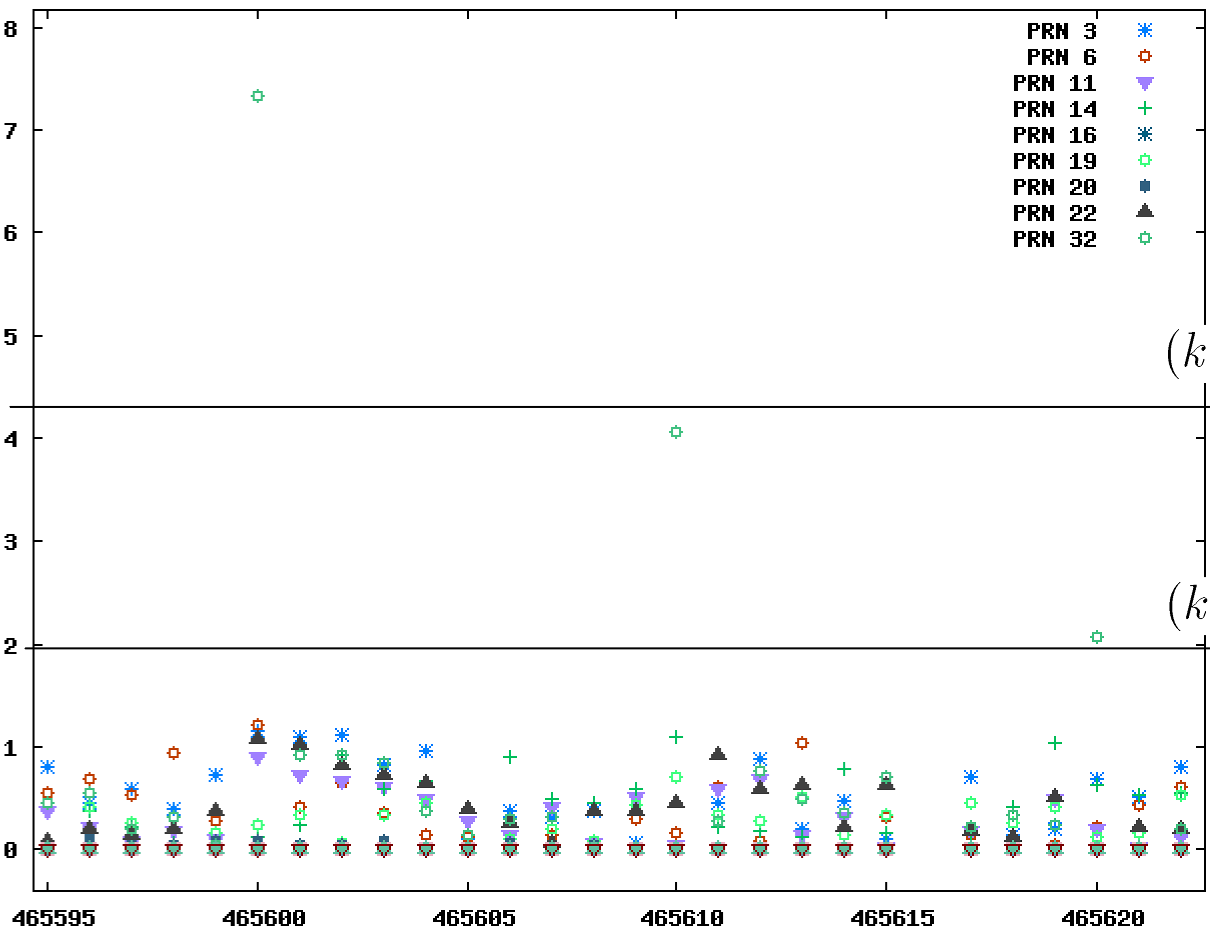
$$\nabla_0 l_i = \delta_0 \frac{\sigma_l}{\sqrt{r_i}}$$

$$\delta_0 = 6.5 \Rightarrow \begin{cases} (k, \alpha_0, 1-\beta_0) = (4.25, 10^{-5}, 0.012) \\ (k, \alpha_0, 1-\beta_0) = (2, 0.03, 3.5 \cdot 10^{-6}) \end{cases}$$

Necessary trade-off between false alarms and missed detections

EXAMPLES OF EVENTUAL OUTLIERS

Simulated single biases in PRN32 of 10m, 5m and 2.5m



$$(k, \alpha_0, 1-\beta_0) = (4.25, 10^{-5}, 0.012)$$

Two missed detections!

$$(k, \alpha_0, 1-\beta_0) = (2, 0.03, 3.5 \cdot 10^{-6})$$

The 3 values discarded…
…but there are chances to discard 'good' values (3%)

SUMMARY

- A review of the existing safety concepts and measures has been provided

- The integrity parameters (Integrity Risk and Alert Limits) have been adapted to smaller, VTOL platforms.

- Links have been built from Navigation Integrity to Geodetic Reliability

  - AL has been used to find the suitable Marginally Detectable Error (MDE)
  - The statistical test parameters $\alpha_0, \beta_0, k \text{ and } \delta_0$ have been derived from the IR and the MDE.

- Real data has been collected and processed. Results show that, for the particular elections of navigation sensors, the integrity frame is:

$$\begin{cases} (k, \alpha_0, 1-\beta_0) = (4.25, 10^{-5}, 0.012) \\ (k, \alpha_0, 1-\beta_0) = (2, 0.03, 3.5 \cdot 10^{-6}) \end{cases}$$ and $$AL, IR = 4m, 10^{-6}$$

QUESTIONS?