NAVISP-EL1-016

GNSS/non-GNSS Sensor Fusion for Resilience in High Integrity Aviation Applications

Final Presentation

DEFENCE AND SPACE

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Agenda

1. **Study overview: scope, study logic, team**
2. **Performed activities**
    i. **WP1000**
    ii. **WP2000**
    iii. **WP3000**
    iv. **WP4000**
    v. **WP5000**
3. **Conclusions**

Scope of the project

Current state of the art

- GPS + SBAS (SFSC) used for approaches up to LPV-200
- CAT I is an applicable service for EV3
- ARAIM under development for LPV-200 using dual-frequency multi-constellation (DFMC) receivers
- Further performance improvements w.r.t. PL, TTA very challenging considering GNSS aspects only

Overall goals of the study

- Combine GNSS with avionic sensors to improve resilience and integrity of PNT for aviation applications
- Assess the suitability of multisensory navigation for operations more demanding than LPV-200 or CAT I

Team

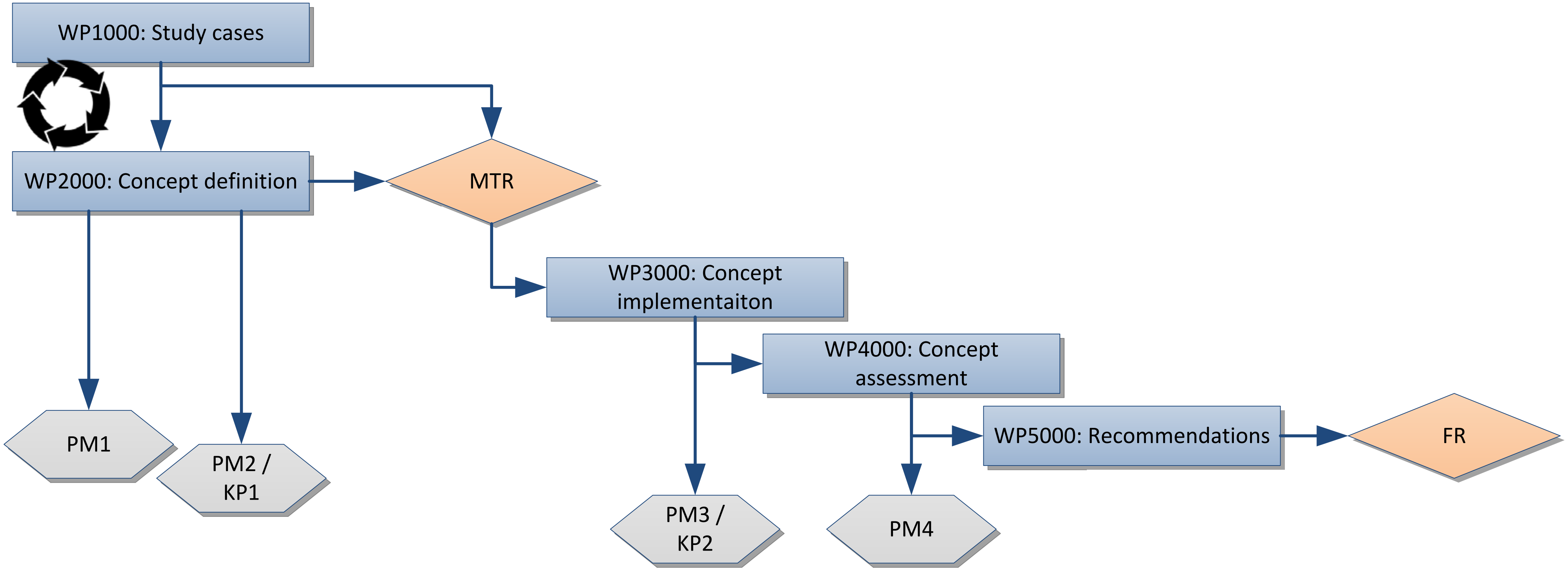
Airbus Defence and Space (ADS) GmbH

- Gabriele Ligorio (PM)
- Jan Wendel
- Santiago Perea

NLR

- Merle Snijders (PM)
- Hein Zelle
- Marijn Hoogendoorn
- Tim Dufourmont
- Heiko Engwerda

Study Logic

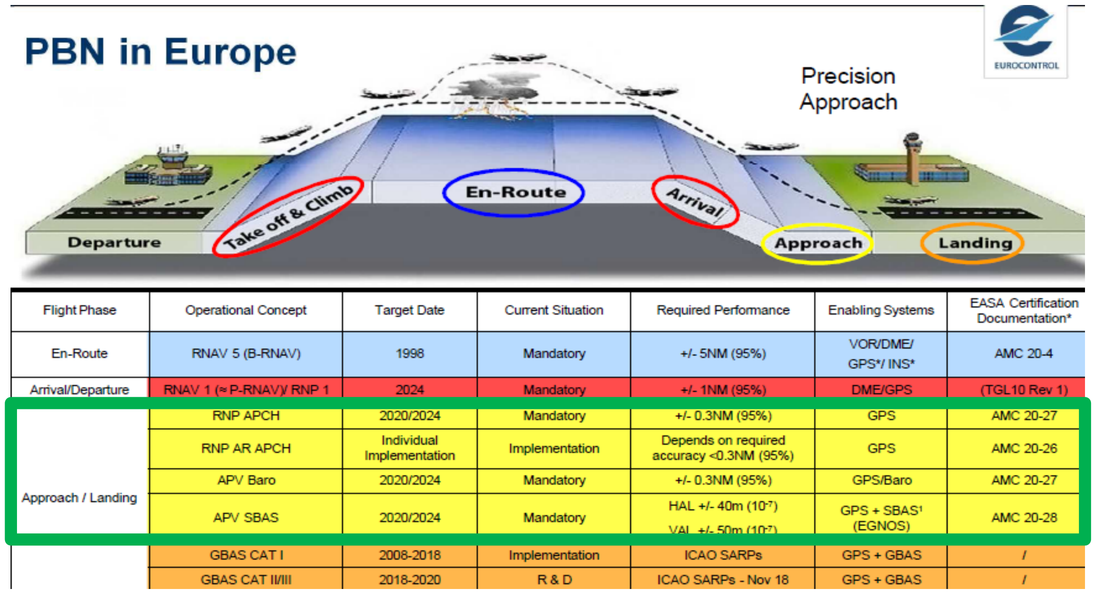

WP1000: Study cases
WP2000: Concept definition
MTR
WP3000: Concept implementaiton
WP4000: Concept assessment
WP5000: Recommendations
FR
PM1
PM2 / KP1
PM3 / KP2
PM4

WP 1000

WP1100: Study cases, sensors and bibliography (NLR Lead)

WP1200: Assessment of added value by aviation sensors (ADS Lead)

WP1100: Study case



Flight Phase	Operational Concept	Target Date	Current Situation	Required Performance	Enabling Systems	EASA Certification Documentation*
En-Route	RNAV 5 (B-RNAV)	1998	Mandatory	+/- 5NM (95%)	VOR/DME/ GPS*/ INS*	AMC 20-4
Arrival/Departure	RNAV 1 (≈ P-RNAV)/ RNP 1	2024	Mandatory	+/- 1NM (95%)	DME/GPS	(TGL10 Rev 1)
Approach / Landing	RNP APCH	2020/2024	Mandatory	+/- 0.3NM (95%)	GPS	AMC 20-27
	RNP AR APCH	Individual Implementation	Implementation	Depends on required accuracy <0.3NM (95%)	GPS	AMC 20-26
	APV Baro	2020/2024	Mandatory	+/- 0.3NM (95%)	GPS/Baro	AMC 20-27
	APV SBAS	2020/2024	Mandatory	HAL +/- 40m (10^{-7}) VAL +/- 50m (10^{-7})	GPS + SBAS[1] (EGNOS)	AMC 20-28
	GBAS CAT I	2008-2018	Implementation	ICAO SARPs	GPS + GBAS	/
	GBAS CAT II/III	2018-2020	R & D	ICAO SARPs - Nov 18	GPS + GBAS	/

Most critical phase of flight will be assessed, for an approach purely based on space based navigation aids.

WP1100: Aircraft Sensor Characterization

Sensor	Output	External dependency	Maturity	Availability	Data Rate	Accuracy (main error)
Air Data System	Pressure altitude Vertical speed True airspeed	Baro-setting	Widely adopted	Always	Medium	Medium (Position error)
IMU	Attitude Velocity (Position)	Initialization point	Widely adopted	Always	High	High (Drift)
Radio Altimeter	AGL altitude	Terrain database	Widely adopted	Low altitudes	Medium	Medium (distortions)
Magnetic Compass	Magnetic Heading		Legacy	Limited attitudes Not on poles	High	Low (Magnetic dip)
Doppler Radar	Ground speed		Legacy	Medium range	Medium	Medium (Reflections)
VOR/DME	Horizontal Position	Ground equipment	Legacy	Beacon LoS	Medium	Medium (Vertical component)
LiDAR	Range/AGL altitude	Terrain database	In development	Long range, Visibility	High	High (Attenuation)
	Ground speed		In development	Visibility	Medium	High (Attenuation)
	Air speed		Demonstrated	Always	Medium	High (Insufficient return)
Vision-Based	Velocity Position	Terrain database	In development	Visibility	Medium	Depends on application

WP1100: State of the art GNSS/INS integrity monitoring

1) Batch processing [Joerger 2013]

Reformulate Kalman filtering as a WLS over a certain time horizon

Computational expense not manageable in a real world scenario

$$\begin{pmatrix}\tilde{\mathbf{y}}_k\\ \mathbf{0}\\ \tilde{\mathbf{y}}_{k-1}\\ \mathbf{0}\\ \tilde{\mathbf{y}}_{k-2}\end{pmatrix} = \begin{pmatrix}\mathbf{H}_k & \mathbf{0} & \mathbf{0}\\ \mathbf{I} & -\mathbf{\Phi}_{k,k-1} & \mathbf{0}\\ \mathbf{0} & \mathbf{H}_{k-1} & \mathbf{0}\\ \mathbf{0} & \mathbf{I} & -\mathbf{\Phi}_{k-1,k-2}\\ \mathbf{0} & \mathbf{0} & \mathbf{H}_{k-2}\end{pmatrix}\begin{pmatrix}\mathbf{x}_k\\ \mathbf{x}_{k-1}\\ \mathbf{x}_{k-2}\end{pmatrix} + \begin{pmatrix}\mathbf{v}_k\\ \mathbf{w}_k\\ \mathbf{v}_{k-1}\\ \mathbf{w}_{k-1}\\ \mathbf{v}_{k-2}\end{pmatrix}$$

2) Kalman Integrated Protection Level (KIPL) [Navarro 2015]

Estimation error modeled as the fusion of two t-distributions: a priory state and measurements.

No Fault Detection and Exclusion (FDE) proposed

$$\overset{\text{Current epoch error}}{\mathbf{E}_s^+} = \overset{\text{Measurement error}}{\mathbf{K}\mathbf{e}_s} + (\mathbf{I}-\mathbf{K}\mathbf{H})\mathbf{F}\overset{\text{Previous epoch error}}{\mathbf{E}_s^-}$$

$\mathbf{F},\mathbf{H},\mathbf{K}$ = Kalman filter matrices

3) Filter bank approach

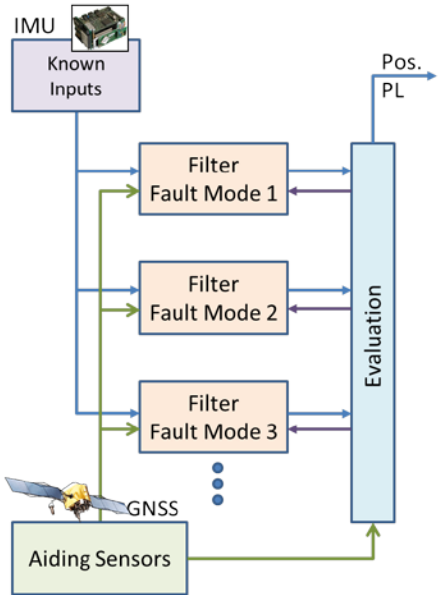
- Each subfilter assumes a different threat scenario
- A global solution is calculated from subfilter states
  and their probabilities

Robustification of subfilters

- Each subfilter assumes a different set of satellites to be faulty
- Measurements from satellites assumed faulty not processed in subfilter
- Constant state vector dimension

Most popular solutions

- Markov Jump Linear Systems (MJLS)
- Interacting Multiple Models (IMM)
- Generalized Pseudo-Bayesian 1 (GBP1)



WP1200: Potential added value by aviation sensors

IMU augmentation

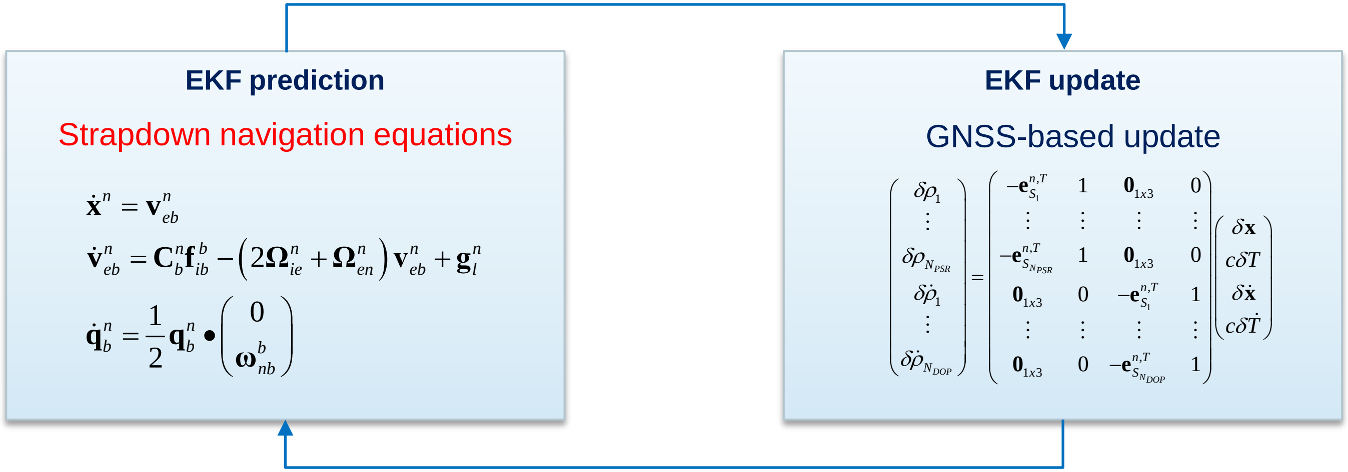
Advantages

- **GNSS-only + IMU**
  - Increase in continuity (GNSS outages)
  - Mahalanobis distance-based GNSS data validation;

- **SBAS-augmented GNSS + IMU**
  - Relocation of the TTA between SBAS and user algorithm;
  - Increase in continuity (SBAS outages);

Challenges

- Time-correlation is introduced in the navigation output;
- Additional feared events to be considered;



EKF prediction

Strapdown navigation equations

$$\dot{\mathbf{x}}^n = \mathbf{v}^n_{eb}$$

$$\dot{\mathbf{v}}^n_{eb} = \mathbf{C}^n_b \mathbf{f}^b_{ib} - \left(2\boldsymbol{\Omega}^n_{ie} + \boldsymbol{\Omega}^n_{en}\right)\mathbf{v}^n_{eb} + \mathbf{g}^n_l$$

$$\dot{\mathbf{q}}^n_b = \frac{1}{2}\mathbf{q}^n_b \bullet \begin{pmatrix} 0 \\ \boldsymbol{\omega}^b_{nb} \end{pmatrix}$$

EKF update

GNSS-based update

$$\begin{pmatrix} \delta\rho_1 \\ \vdots \\ \delta\rho_{N_{PSR}} \\ \delta\dot{\rho}_1 \\ \vdots \\ \delta\dot{\rho}_{N_{DOP}} \end{pmatrix} = \begin{pmatrix} -\mathbf{e}^{n,T}_{S_1} & 1 & \mathbf{0}_{1x3} & 0 \\ \vdots & \vdots & \vdots & \vdots \\ -\mathbf{e}^{n,T}_{S_{N_{PSR}}} & 1 & \mathbf{0}_{1x3} & 0 \\ \mathbf{0}_{1x3} & 0 & -\mathbf{e}^{n,T}_{S_1} & 1 \\ \vdots & \vdots & \vdots & \vdots \\ \mathbf{0}_{1x3} & 0 & -\mathbf{e}^{n,T}_{S_{N_{DOP}}} & 1 \end{pmatrix} \begin{pmatrix} \delta\mathbf{x} \\ c\delta T \\ \delta\dot{\mathbf{x}} \\ c\delta\dot{T} \end{pmatrix}$$

ADS, RA, Lidar measurement models

$$\tilde{y}_{ADS,h} = \mathbf{u}_3 \cdot \mathbf{x}^n_{BAR} + b_{BAR} + n_{BAR,h}$$

$$\tilde{y}_{ADS,\dot{h}} = \mathbf{u}_3 \cdot \dot{\mathbf{x}}^n_{BAR} + b_{BAR,\dot{h}} + n_{BAR,\dot{h}}$$

$$\tilde{y}_{ADS,TV} = \left|\mathbf{v}^n_{eb} + \mathbf{C}^n_b \boldsymbol{\Omega}^b_{ib} \mathbf{l}^b_{BAR} + \mathbf{b}^n_{AIR}\right| + n_{TV}$$

$$\tilde{y}_{RA} = \mathbf{u}_3 \cdot \mathbf{x}^n_{RA} + b_{RA} + n_{RA}$$

$$\tilde{\mathbf{y}}_{LID} = \dot{\mathbf{x}}^l_{LID} + \mathbf{C}^l_n \mathbf{b}^n_{AIR} + \mathbf{n}_{LID}$$

GNSS-based positioning

$$\begin{pmatrix} \delta\rho_1 \\ \vdots \\ \delta\rho_{N_{PSR}} \\ \delta\dot{\rho}_1 \\ \vdots \\ \delta\dot{\rho}_{N_{DOP}} \end{pmatrix} = \begin{pmatrix} -\mathbf{e}^{n,T}_{S_1} & 1 & \mathbf{0}_{1x3} & 0 \\ \vdots & \vdots & \vdots & \vdots \\ -\mathbf{e}^{n,T}_{S_{N_{PSR}}} & 1 & \mathbf{0}_{1x3} & 0 \\ \mathbf{0}_{1x3} & 0 & -\mathbf{e}^{n,T}_{S_1} & 1 \\ \vdots & \vdots & \vdots & \vdots \\ \mathbf{0}_{1x3} & 0 & -\mathbf{e}^{n,T}_{S_{N_{DOP}}} & 1 \end{pmatrix} \begin{pmatrix} \delta\mathbf{x} \\ c\delta T \\ \delta\dot{\mathbf{x}} \\ c\delta\dot{T} \end{pmatrix}$$

Sensor-based augmentation

Advantages

- Additional measurements increase the state vector observability, if unbiased
- Potentially, three number of pseudoranges become sufficient if one unbiased altimeter is available

Challenges

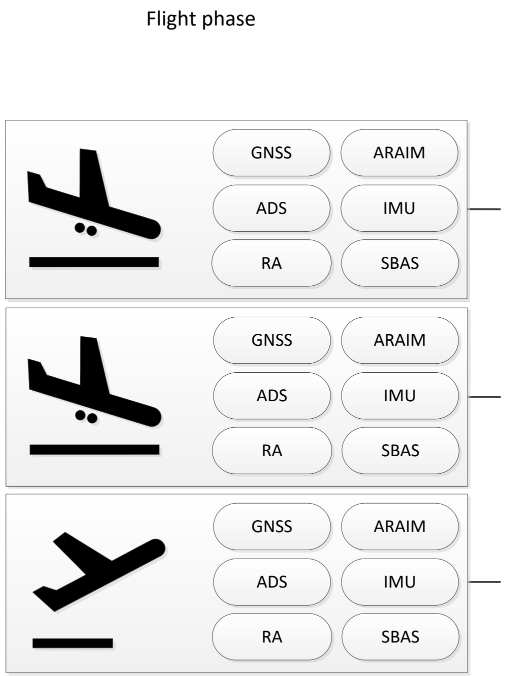
- Time-varying biases need to be compensated
- Lever arm compensation is only partially possible if attitude is not estimated

WP 2000

WP2100: Sensor reliability & verification preparation (NLR Lead)

WP 2200: Concept definition (ADS Lead)

WP2100 (2): Sensor reliability and verification preparation



Flight phase

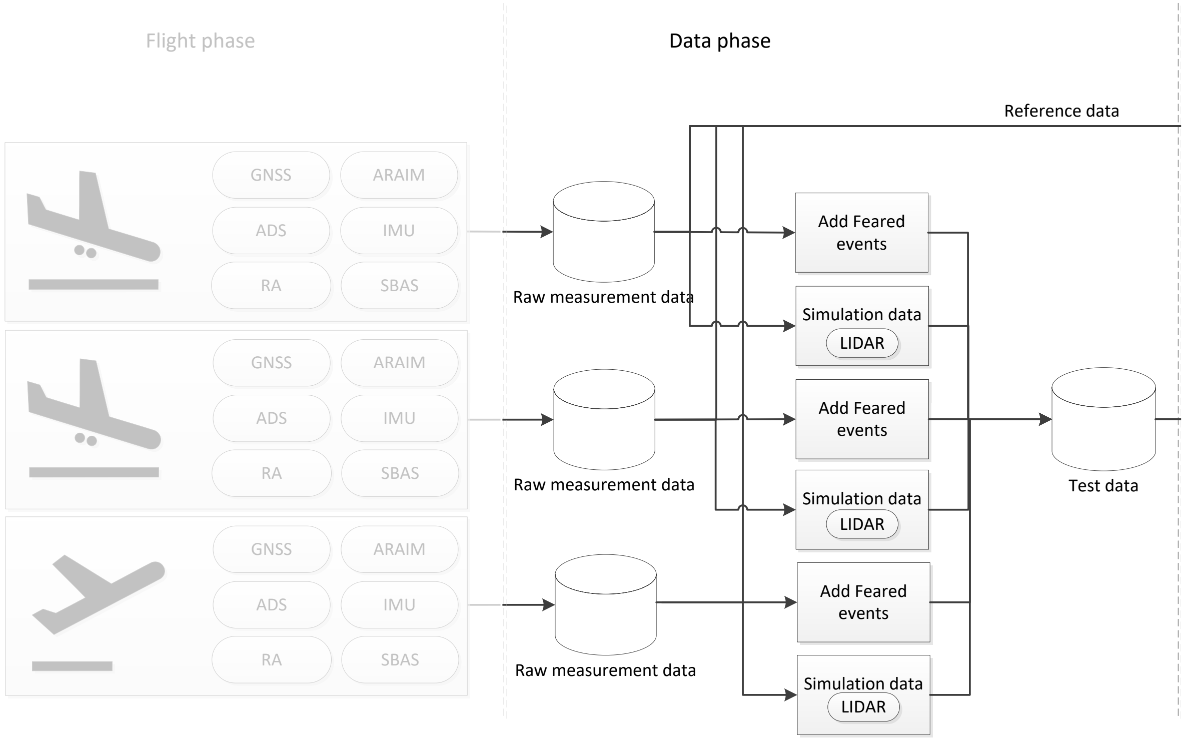
GNSS
ARAIM
ADS
IMU
RA
SBAS

GNSS
ARAIM
ADS
IMU
RA
SBAS

GNSS
ARAIM
ADS
IMU
RA
SBAS

1. straight-in RNP approach down to CAT I minima
2. more complex CAT I operations
3. departure

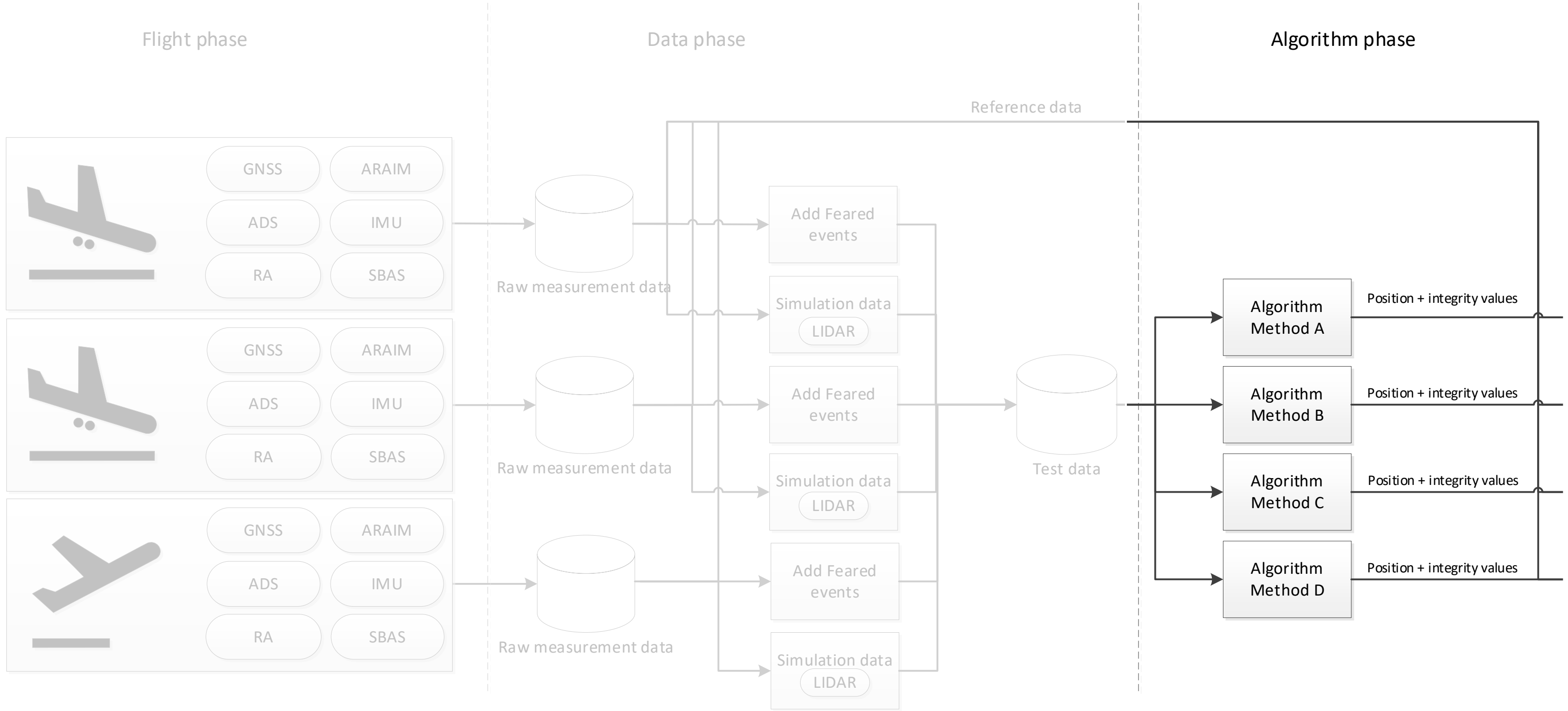
WP2100 (3): Sensor reliability and verification preparation



Sensor	Feared event	Result
IMU	Internal error	Data freeze or null output
Air Data System	Icing	Large bias increase
Radio Altimeter	Direct Coupling	Constant minimum output
GNSS	Imperfect ionosphere corrections	Bias in the GNSS pseudo-range

- Simulation data
- Simulation feared events

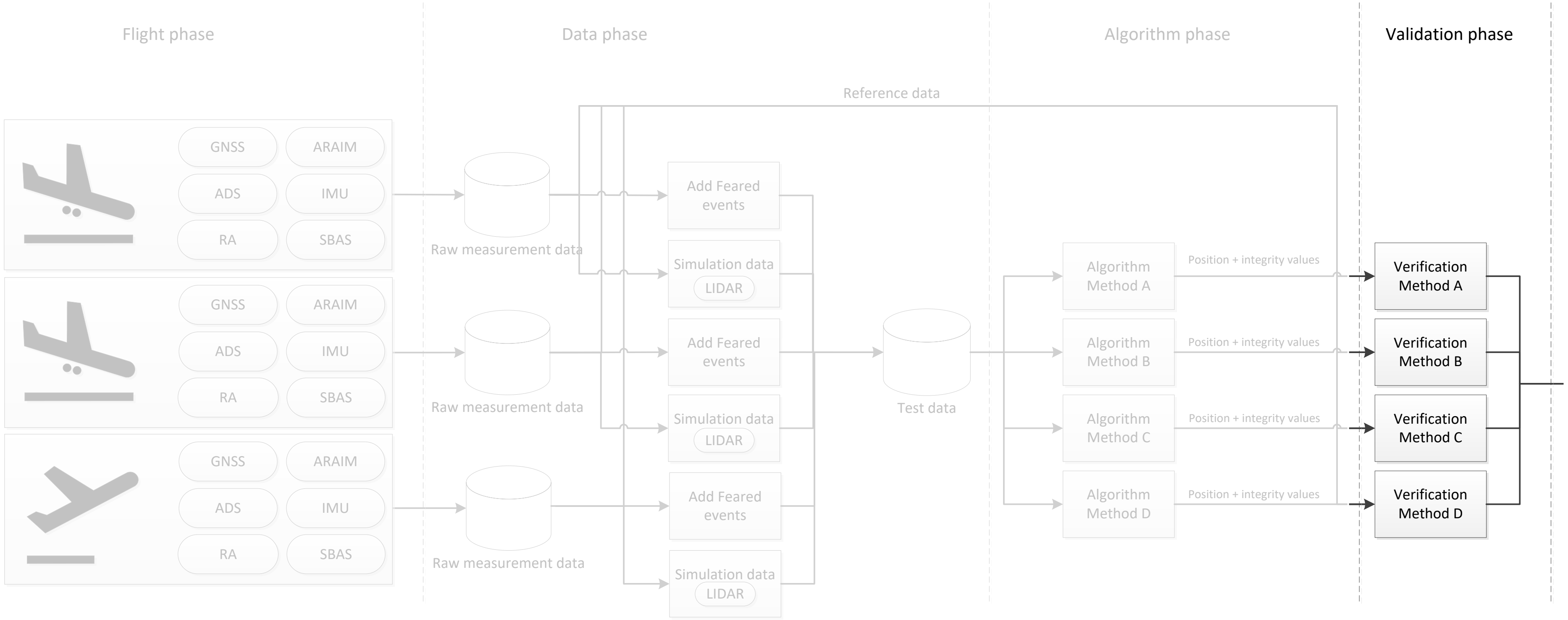
WP2100 (4): Sensor reliability and verification preparation



- Algorithm track
- Reference track

⇒ Test data into test cases

WP2100 (5): Sensor reliability and verification preparation



Flight phase

Data phase

Algorithm phase

Validation phase

Reference data

GNSS ARAIM
ADS IMU
RA SBAS

GNSS ARAIM
ADS IMU
RA SBAS

GNSS ARAIM
ADS IMU
RA SBAS

Raw measurement data

Raw measurement data

Raw measurement data

Add Feared events

Simulation data LIDAR

Add Feared events

Simulation data LIDAR

Add Feared events

Simulation data LIDAR

Test data

Algorithm Method A

Algorithm Method B

Algorithm Method C

Algorithm Method D

Position + integrity values

Position + integrity values

Position + integrity values

Position + integrity values

Verification Method A

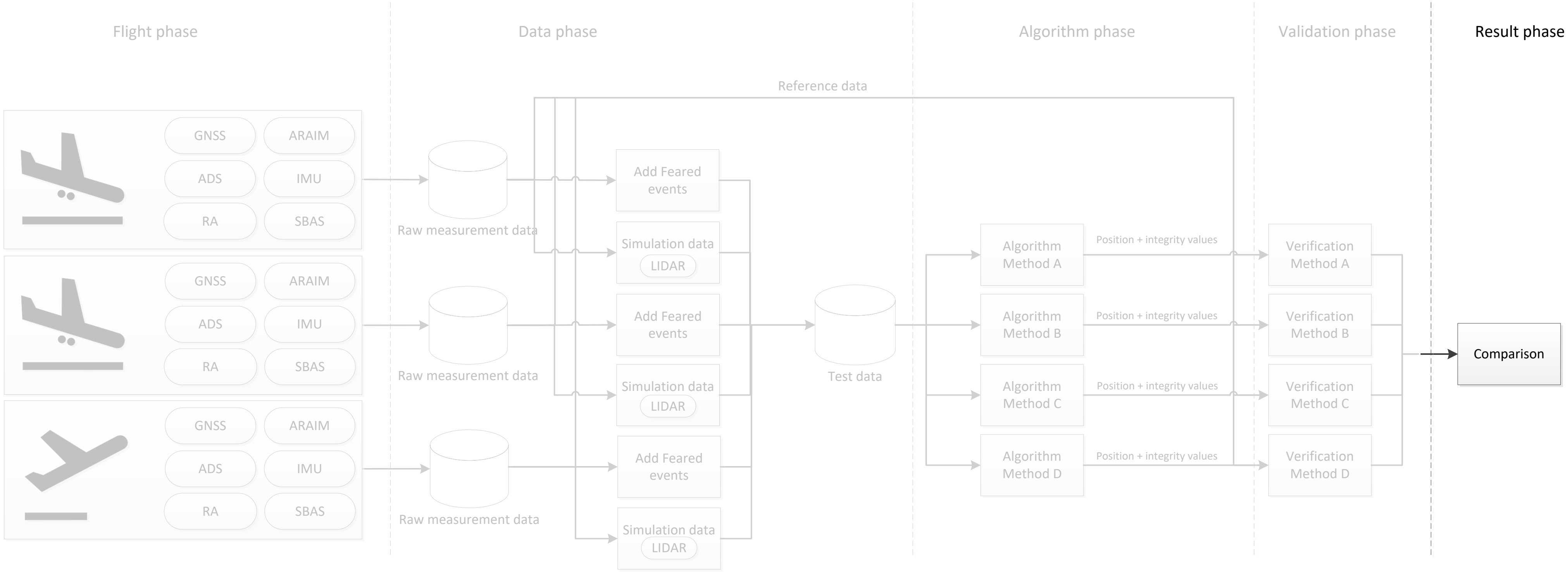
Verification Method B

Verification Method C

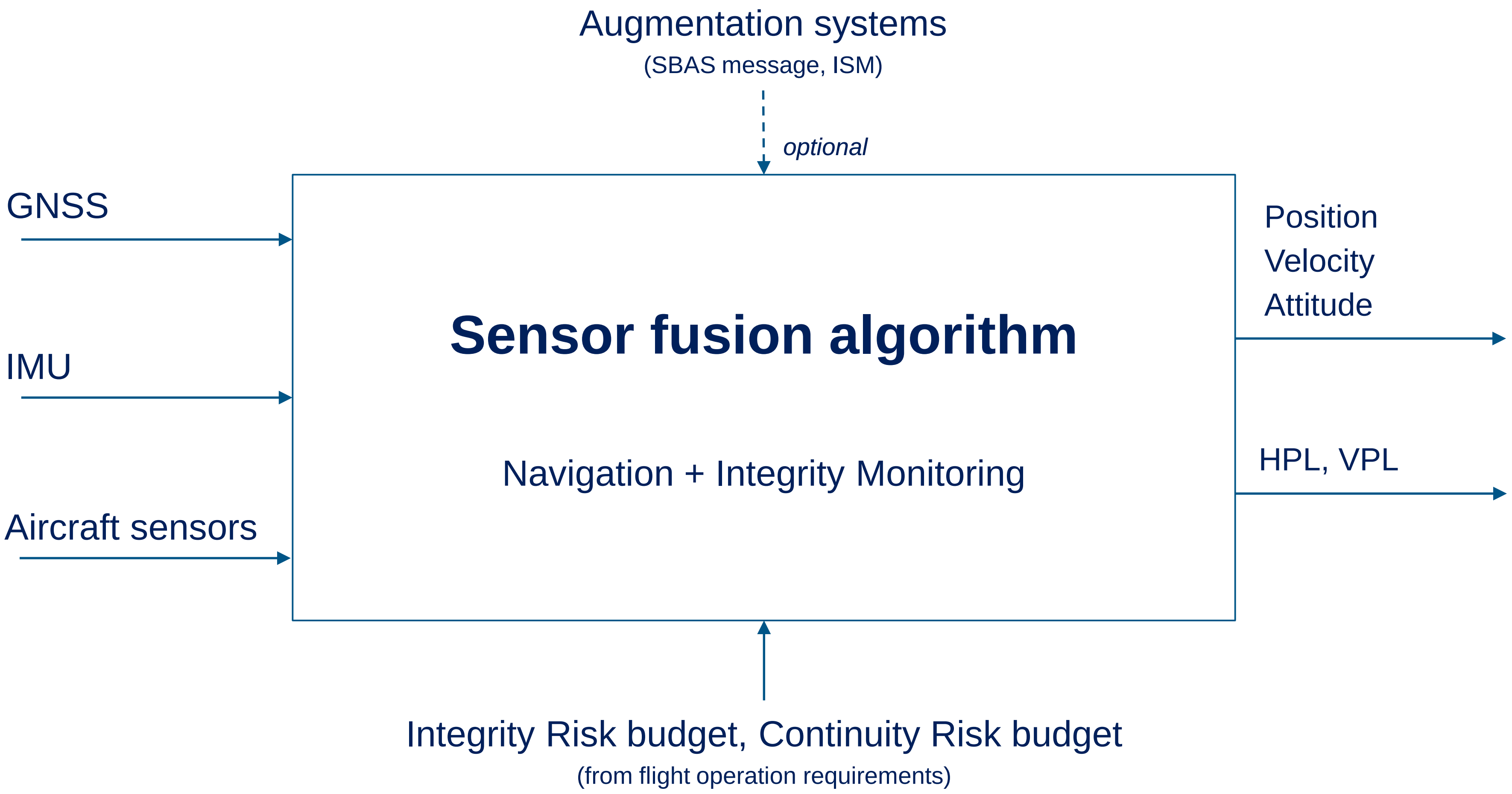
Verification Method D

- Accuracy
- Continuity
- Availability
- Integrity

WP2100 (6): Sensor reliability and verification preparation



WP2200 (1): High-level design



Augmentation systems

(SBAS message, ISM)

optional

GNSS

IMU

Aircraft sensors

Sensor fusion algorithm

Navigation + Integrity Monitoring

Position

Velocity

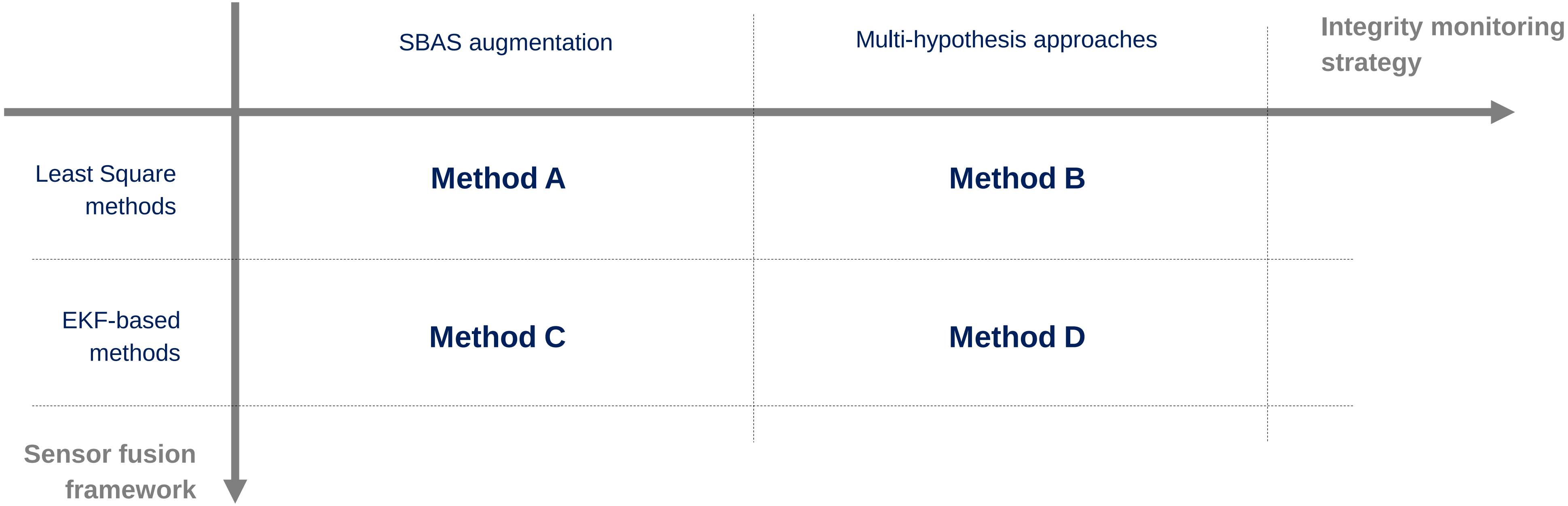
Attitude

HPL, VPL

Integrity Risk budget, Continuity Risk budget

(from flight operation requirements)

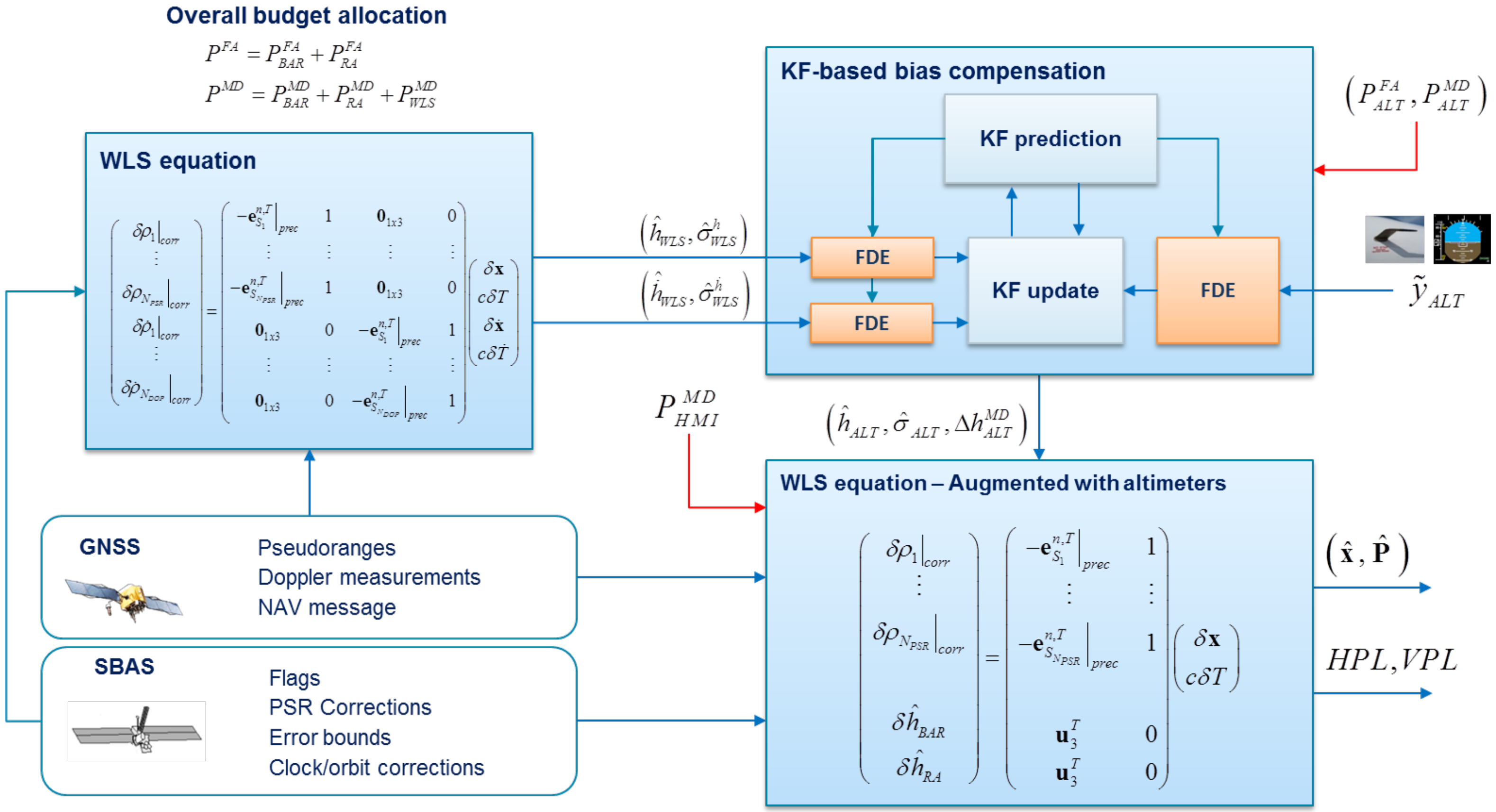
WP2200 (2): Identified solutions for extended GNSS-augmentations



	SBAS augmentation	Multi-hypothesis approaches	Integrity monitoring strategy
Least Square methods	**Method A**	**Method B**	
EKF-based methods	**Method C**	**Method D**	
Sensor fusion framework			

GNSS AUGMENTATION	SBAS message	ARAIM message	EKF-based PVT	IMU	Ranging sensors	Velocity sensors
Method A	✓	✗	✗	✗	✓	✗
Method B	✗	✓	✗	✗	✓	✗
Method C	✓	✗	✓	✓	✓	✓
Method D	✗	✗	✓	✓	✓	✓

Method A: WLS augmented with SBAS and altimeter measurements



Overall budget allocation

$$P^{FA} = P^{FA}_{BAR} + P^{FA}_{RA}$$

$$P^{MD} = P^{MD}_{BAR} + P^{MD}_{RA} + P^{MD}_{WLS}$$

WLS equation

$$\begin{pmatrix} \delta\rho_1|_{corr} \\ \vdots \\ \delta\rho_{N_{PSR}}|_{corr} \\ \delta\dot{\rho}_1|_{corr} \\ \vdots \\ \delta\dot{\rho}_{N_{DOP}}|_{corr} \end{pmatrix} = \begin{pmatrix} -\mathbf{e}^{n,T}_{S_1}|_{prec} & 1 & \mathbf{0}_{1x3} & 0 \\ \vdots & \vdots & \vdots & \vdots \\ -\mathbf{e}^{n,T}_{S_{N_{PSR}}}|_{prec} & 1 & \mathbf{0}_{1x3} & 0 \\ \mathbf{0}_{1x3} & 0 & -\mathbf{e}^{n,T}_{S_1}|_{prec} & 1 \\ \vdots & \vdots & \vdots & \vdots \\ \mathbf{0}_{1x3} & 0 & -\mathbf{e}^{n,T}_{S_{N_{DOP}}}|_{prec} & 1 \end{pmatrix} \begin{pmatrix} \delta\mathbf{x} \\ c\delta T \\ \delta\dot{\mathbf{x}} \\ c\delta\dot{T} \end{pmatrix}$$

GNSS

Pseudoranges
Doppler measurements
NAV message

SBAS

Flags
PSR Corrections
Error bounds
Clock/orbit corrections

$\left(\hat{h}_{WLS}, \hat{\sigma}^{h}_{WLS}\right)$

$\left(\hat{\dot{h}}_{WLS}, \hat{\sigma}^{\dot{h}}_{WLS}\right)$

KF-based bias compensation

$\left(P^{FA}_{ALT}, P^{MD}_{ALT}\right)$

$\tilde{y}_{ALT}$

P^{MD}_{HMI}

$\left(\hat{h}_{ALT}, \hat{\sigma}_{ALT}, \Delta h^{MD}_{ALT}\right)$

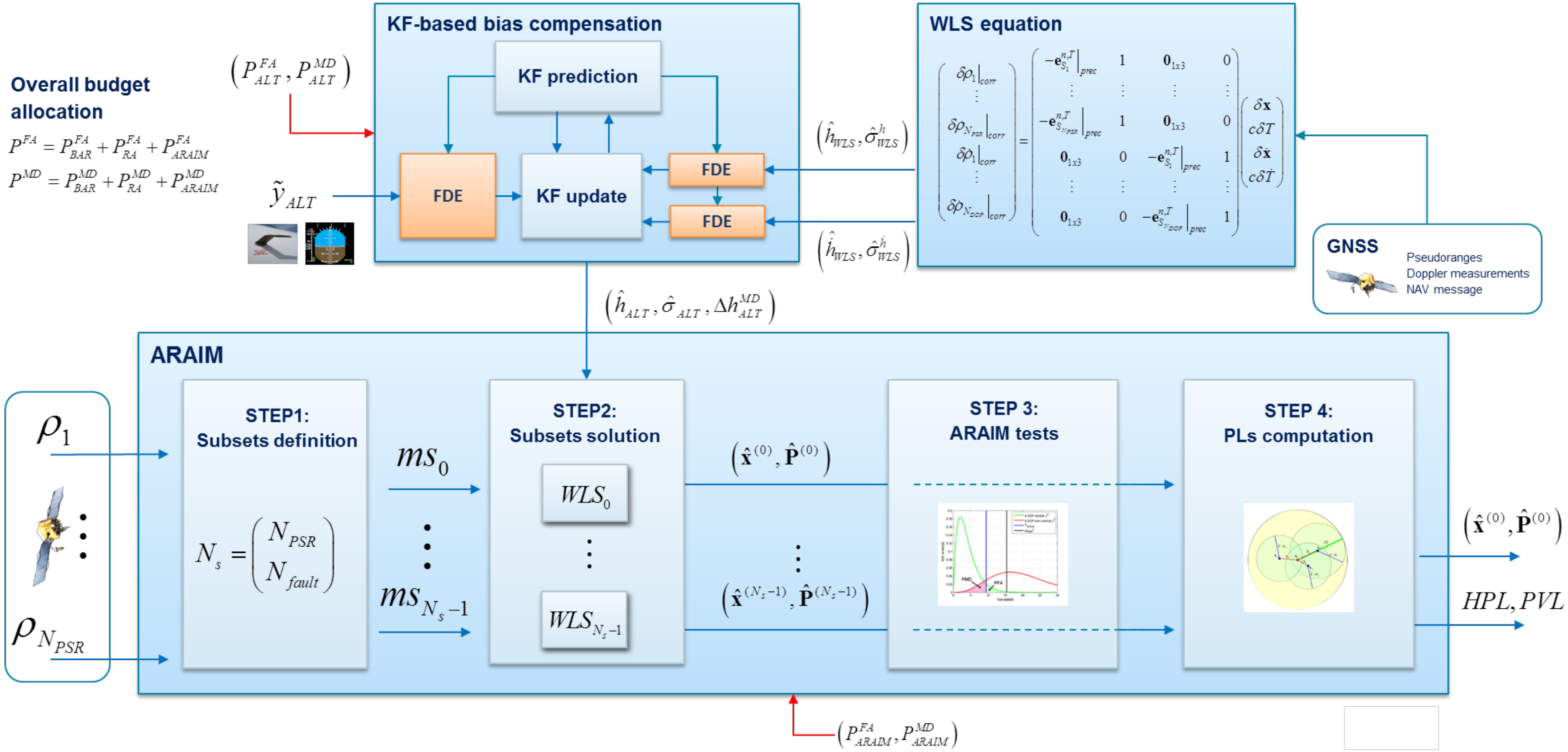
WLS equation – Augmented with altimeters

$$\begin{pmatrix} \delta\rho_1|_{corr} \\ \vdots \\ \delta\rho_{N_{PSR}}|_{corr} \\ \delta\hat{h}_{BAR} \\ \delta\hat{h}_{RA} \end{pmatrix} = \begin{pmatrix} -\mathbf{e}^{n,T}_{S_1}|_{prec} & 1 \\ \vdots & \vdots \\ -\mathbf{e}^{n,T}_{S_{N_{PSR}}}|_{prec} & 1 \\ \mathbf{u}^T_3 & 0 \\ \mathbf{u}^T_3 & 0 \end{pmatrix} \begin{pmatrix} \delta\mathbf{x} \\ c\delta T \end{pmatrix}$$

$\left(\hat{\mathbf{x}}, \hat{\mathbf{P}}\right)$

HPL, VPL

Method B: ARAIM augmented with altimeter measurements



Overall budget allocation

$$P^{FA} = P^{FA}_{BAR} + P^{FA}_{RA} + P^{FA}_{ARAIM}$$

$$P^{MD} = P^{MD}_{BAR} + P^{MD}_{RA} + P^{MD}_{ARAIM}$$

$\left(P^{FA}_{ALT}, P^{MD}_{ALT}\right)$

$\tilde{y}_{ALT}$

KF-based bias compensation

KF prediction

FDE

KF update

FDE

FDE

$\left(\hat{h}_{WLS}, \hat{\sigma}^{h}_{WLS}\right)$

$\left(\hat{\dot{h}}_{WLS}, \hat{\sigma}^{\dot{h}}_{WLS}\right)$

WLS equation

$$\begin{pmatrix} \delta\rho_1|_{corr} \\ \vdots \\ \delta\rho_{N_{PSR}}|_{corr} \\ \delta\dot{\rho}_1|_{corr} \\ \vdots \\ \delta\dot{\rho}_{N_{DOP}}|_{corr} \end{pmatrix} = \begin{pmatrix} -\mathbf{e}^{n,T}_{S_1}|_{prec} & 1 & \mathbf{0}_{1x3} & 0 \\ \vdots & \vdots & \vdots & \vdots \\ -\mathbf{e}^{n,T}_{S_{N_{PSR}}}|_{prec} & 1 & \mathbf{0}_{1x3} & 0 \\ \mathbf{0}_{1x3} & 0 & -\mathbf{e}^{n,T}_{S_1}|_{prec} & 1 \\ \vdots & \vdots & \vdots & \vdots \\ \mathbf{0}_{1x3} & 0 & -\mathbf{e}^{n,T}_{S_{N_{DOP}}}|_{prec} & 1 \end{pmatrix} \begin{pmatrix} \delta\mathbf{x} \\ c\delta T \\ \delta\dot{\mathbf{x}} \\ c\delta\dot{T} \end{pmatrix}$$

GNSS

Pseudoranges
Doppler measurements
NAV message

$\left(\hat{h}_{ALT}, \hat{\sigma}_{ALT}, \Delta h^{MD}_{ALT}\right)$

ARAIM

ρ_1

$\rho_{N_{PSR}}$

STEP1: Subsets definition

$$N_s = \begin{pmatrix} N_{PSR} \\ N_{fault} \end{pmatrix}$$

ms_0

ms_{N_s-1}

STEP2: Subsets solution

WLS_0

WLS_{N_s-1}

$\left(\hat{\mathbf{x}}^{(0)}, \hat{\mathbf{P}}^{(0)}\right)$

$\left(\hat{\mathbf{x}}^{(N_s-1)}, \hat{\mathbf{P}}^{(N_s-1)}\right)$

STEP 3: ARAIM tests

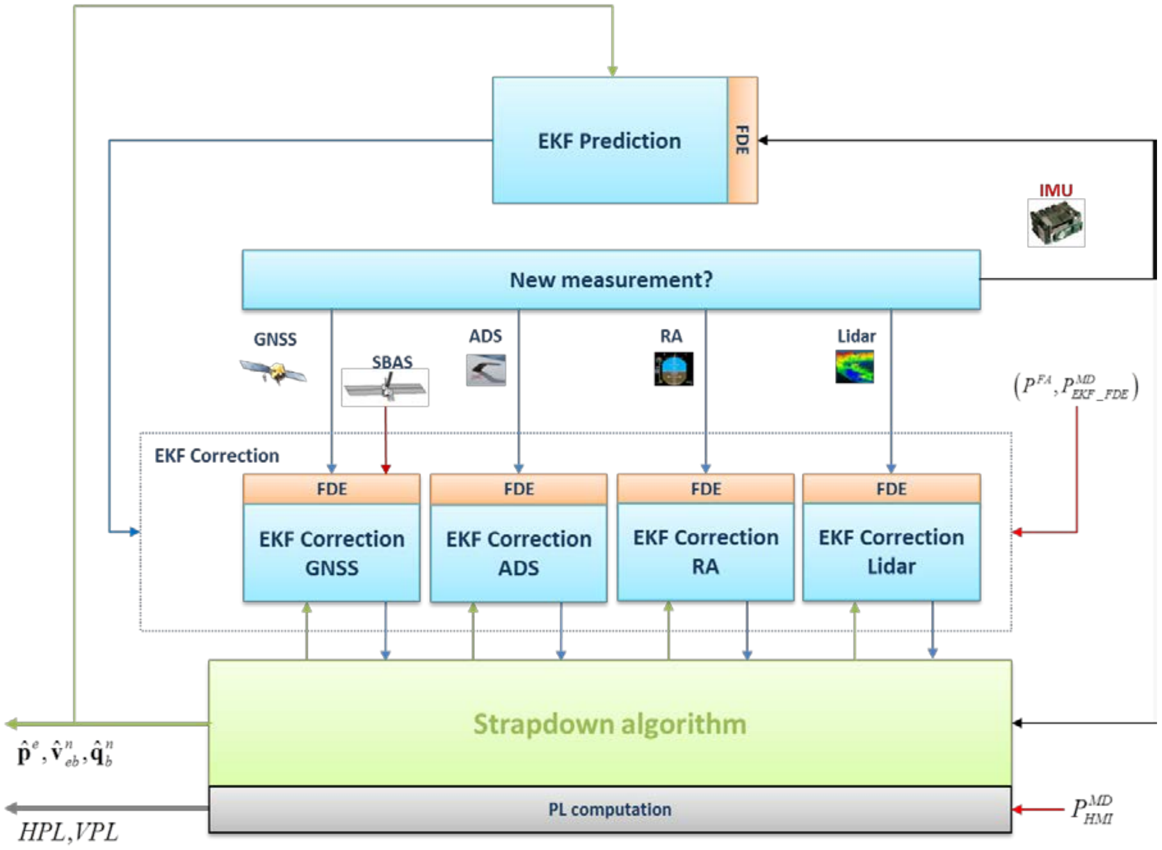
STEP 4: PLs computation

$\left(\hat{\mathbf{x}}^{(0)}, \hat{\mathbf{P}}^{(0)}\right)$

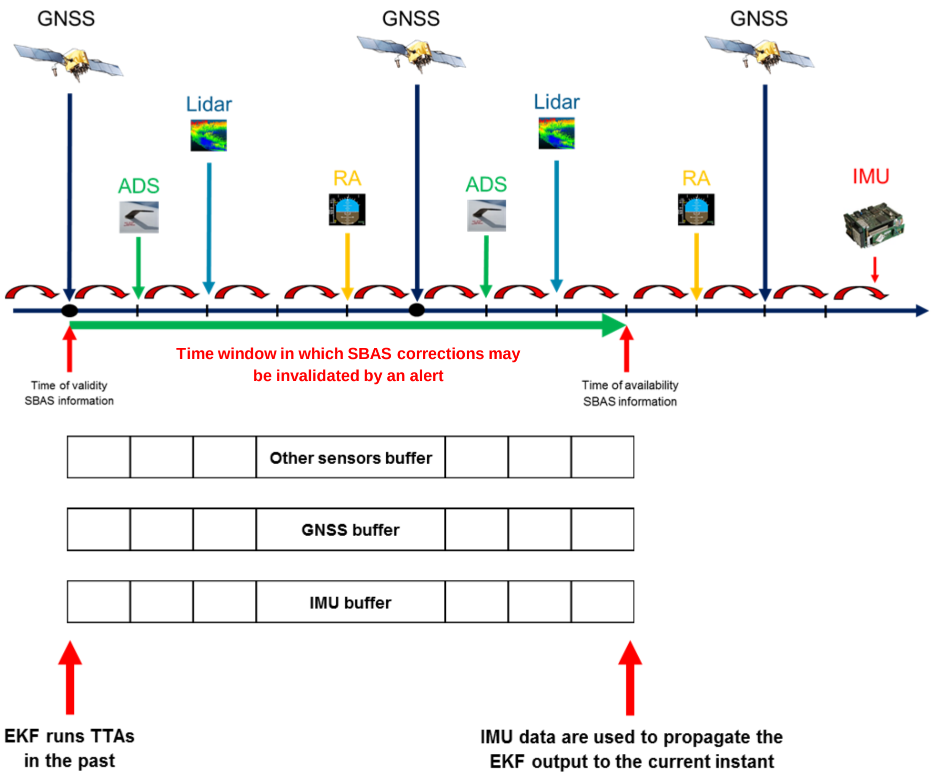
HPL, PVL

$\left(P^{FA}_{ARAIM}, P^{MD}_{ARAIM}\right)$

Method C: SBAS-augmented EKF



GNSS integrity: SBAS and delayed processing

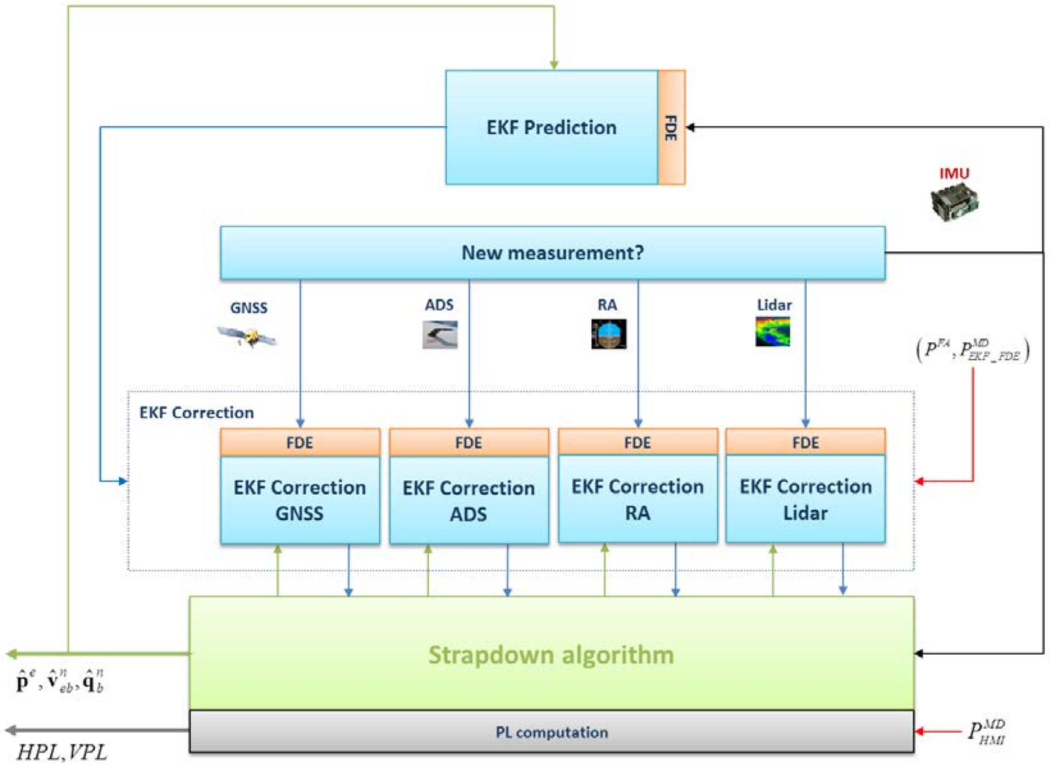


Time window in which SBAS corrections may be invalidated by an alert

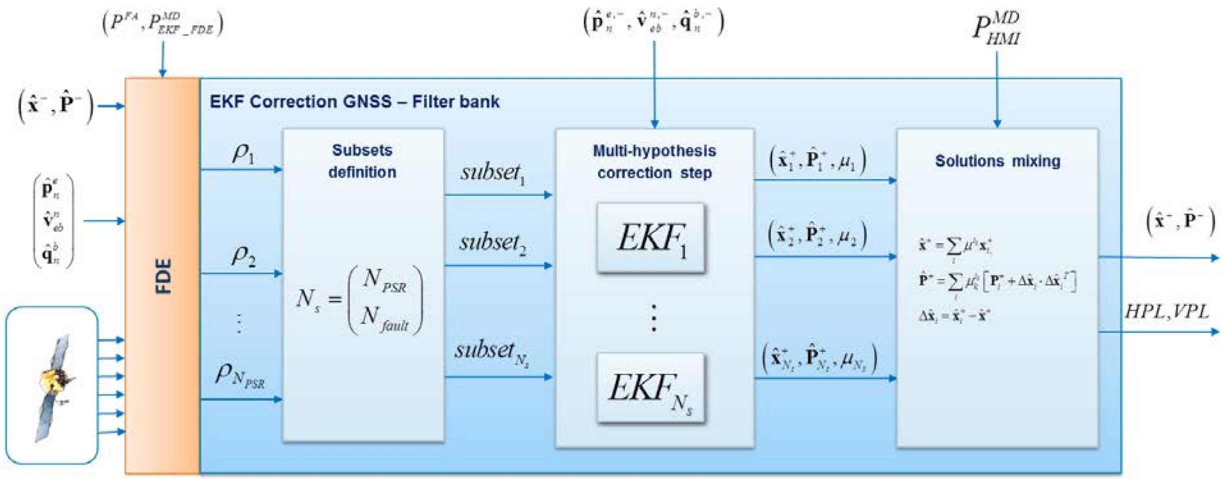
EKF runs TTAs in the past

IMU data are used to propagate the EKF output to the current instant

Method D: EKF-bank for fully autonomous integrity monitoring



GNSS integrity: Filter bank

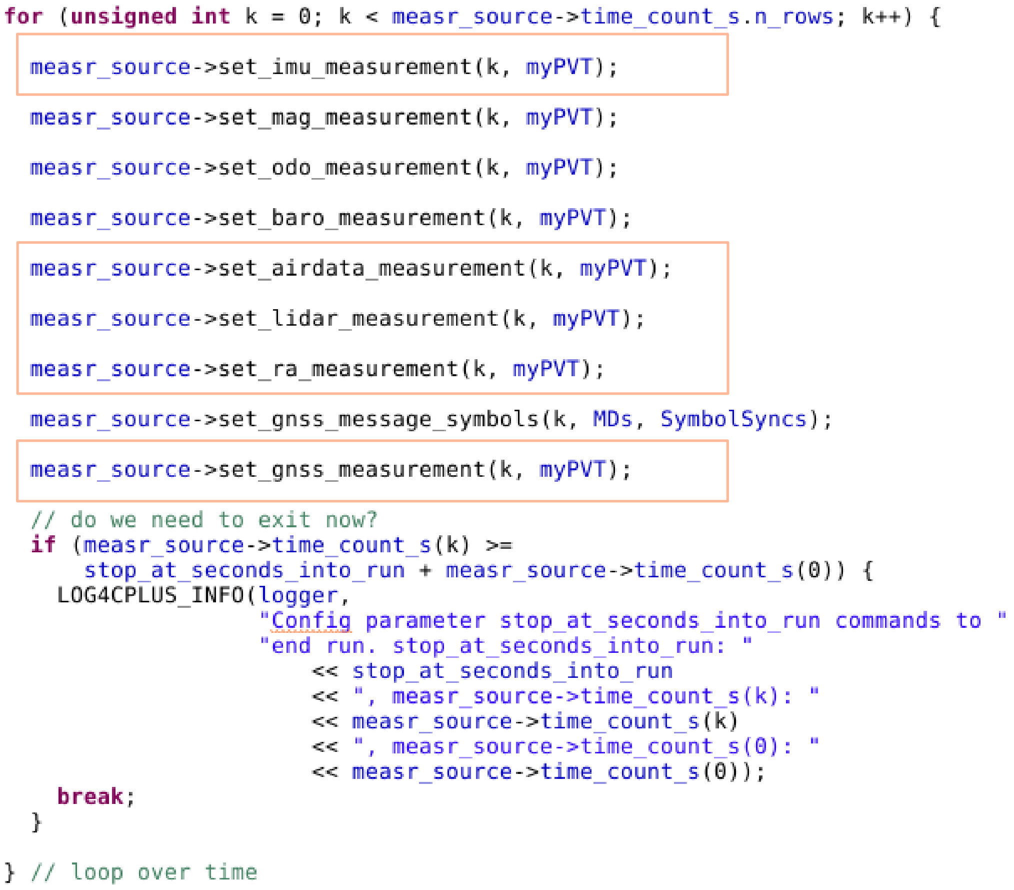


WP 3000

WP3100: Algorithm implementation (ADS Lead)

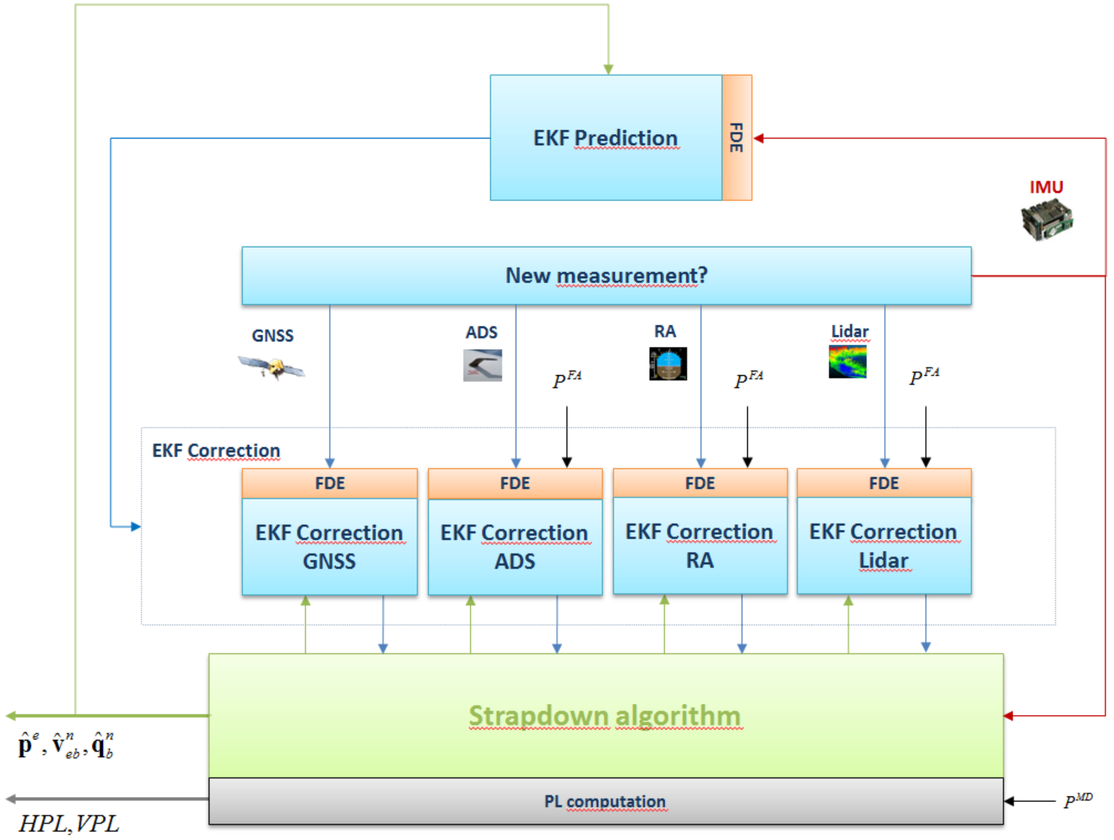
WP 3200: Verification cases (NLR Lead)

WP3100: PIPE PVT feeder - overview



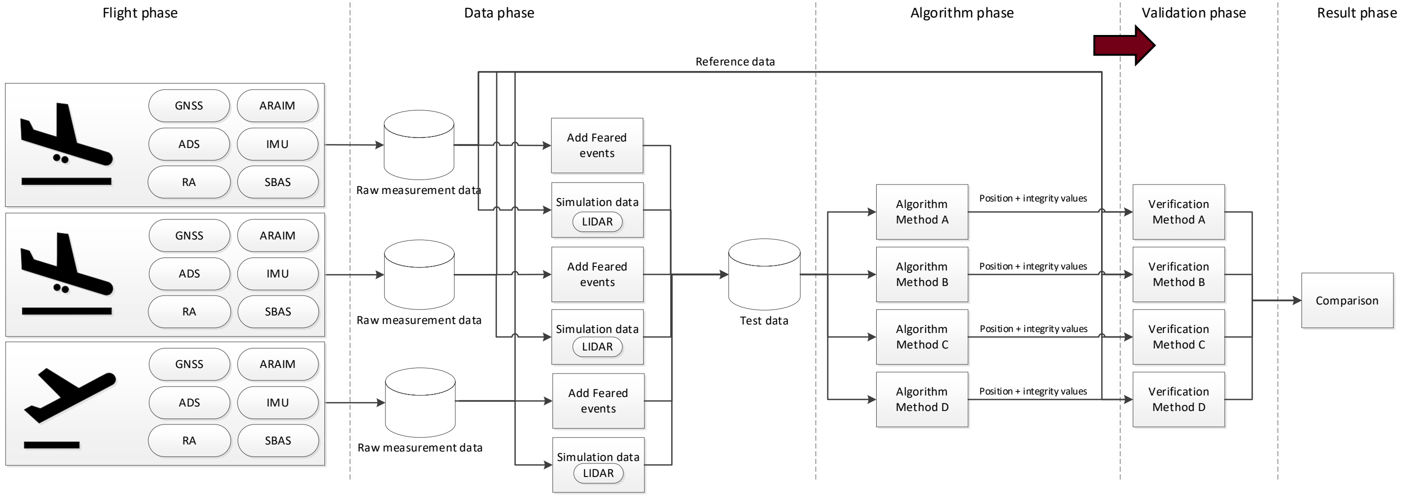
```
for (unsigned int k = 0; k < measr_source->time_count_s.n_rows; k++) {
  measr_source->set_imu_measurement(k, myPVT);
  measr_source->set_mag_measurement(k, myPVT);
  measr_source->set_odo_measurement(k, myPVT);
  measr_source->set_baro_measurement(k, myPVT);
  measr_source->set_airdata_measurement(k, myPVT);
  measr_source->set_lidar_measurement(k, myPVT);
  measr_source->set_ra_measurement(k, myPVT);
  measr_source->set_gnss_message_symbols(k, MDs, SymbolSyncs);
  measr_source->set_gnss_measurement(k, myPVT);
  // do we need to exit now?
  if (measr_source->time_count_s(k) >=
      stop_at_seconds_into_run + measr_source->time_count_s(0)) {
    LOG4CPLUS_INFO(logger,
                   "Config parameter stop_at_seconds_into_run commands to "
                   "end run. stop_at_seconds_into_run: "
                       << stop_at_seconds_into_run
                       << ", measr_source->time_count_s(k): "
                       << measr_source->time_count_s(k)
                       << ", measr_source->time_count_s(0): "
                       << measr_source->time_count_s(0));
    break;
  }

} // loop over time
```



- Each function will launch the routine corresponding to the current sensors sample - if that routine is implemented in myPVT.
- myPVT can be an instance of the classes PVTNavispA, PVTNavispB, PVTNavispC, PVTNavispD.

WP3200



➡ Flight data into Test Cases

Test ID	Configuration	Flight segments
TC_110	Straight Approach	Flight 2 – part 1+ Flight 3 – part 2+ Flight 4 - part 2+ Flight 5 - part 2
TC_120	Complex Approach	Flight 1 - part 1+ Flight 4 - part 4+ Flight 5 - part 4
TC_130	Departure	Flight 3 – part 1+ Flight 4 - part 1+ Flight 4 - part 3+ Flight 5 - part 1+ Flight 5 - part 3
TC_200	All Flight Data	Flight 1 + Flight 2 + Flight 3 + Flight 4 + Flight 5

Sensor	Simulated	Tested
IMU	Short duration 1-axis data freeze Flight 5	Check error output
Air Data System	Short duration Bias Flight 5	TC-200
Radio Altimeter	3 x Short duration Zero output Flight 5	All TC’s
GNSS	Full length Slight modification of the parameters of the Klobuchar Ionospheric model in the Rinex nav header. Flight 5	Method B and D

Verification

- Accuracy
- Integrity
- Continuity
- Availability

- Proposed method integrity:
- Calculate the safety index
- Calculate the safety index for EGNOS
- Compare the two

$$HSI = \frac{HPE}{HPL}$$

- Extra test cases to check ability GIMAT

Phase of Flight	Accuracy	Integrity			Continuity	Availability
	SIS (2σ)	Alert Limits	Integrity Risk	TTA [s]	Continuity Risk	Availability
LPV-200	16m (L) - 6m (V)	40m (L) 35 m (V)	2E-7/150s	6	8E-6/15s	0.99-0.99999
Precision Approach CAT I	16m (L) - 4m (V)	40m (L) 10 m (V)	2E-7/150s	6	8E-6/15s	0.99-0.99999
Precise Landing CAT II	6.1 m (L) 1.4 m (V)	17.9m (L) 4.4 m (V)	1E-9/150s	2	4E-6/15s	0.99-0.99999

WP 4000

WP4100: Algorithms verification (ADS)

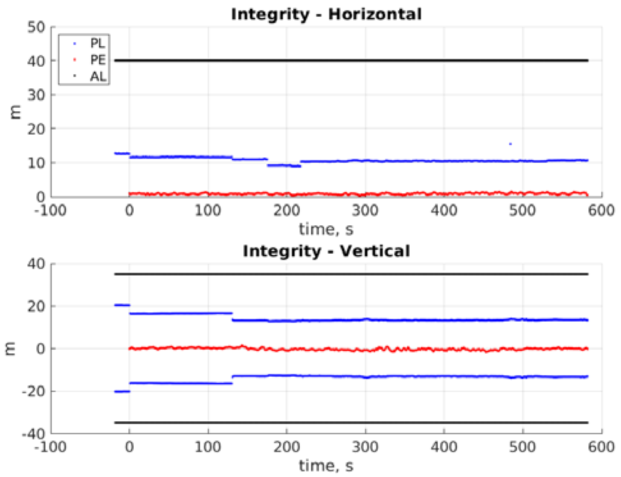
WP4200: Data processing and recommendations (ADS)

WP4300: Results and complexity assessment (NLR)

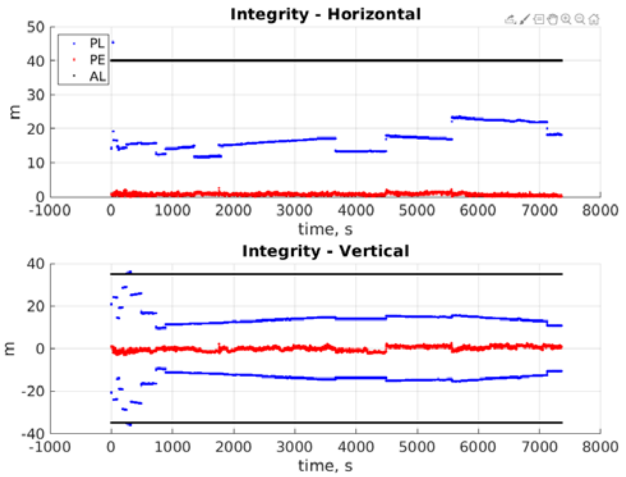
Experimental results – nominal case

Method A: PE vs PL – nominal case

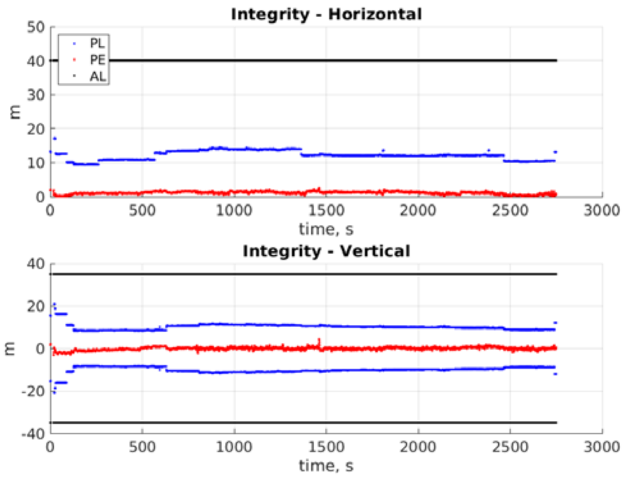
Flight 1



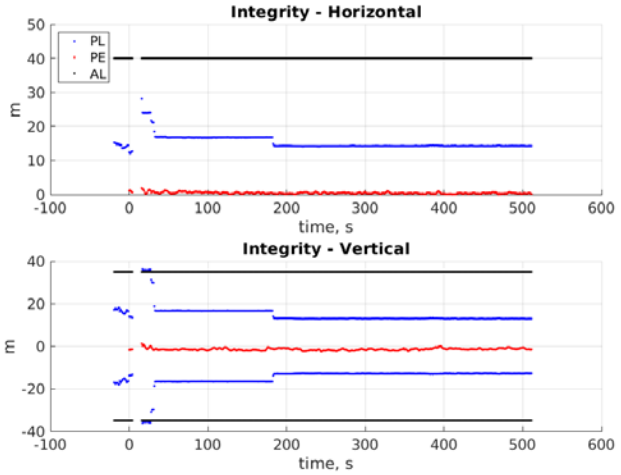
Flight 3



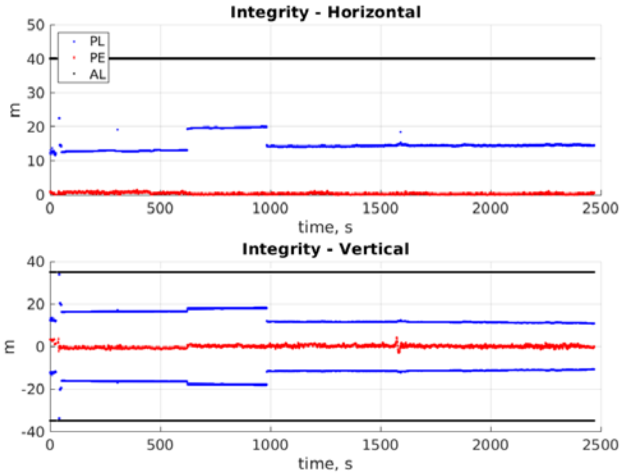
Flight 5



Flight 2

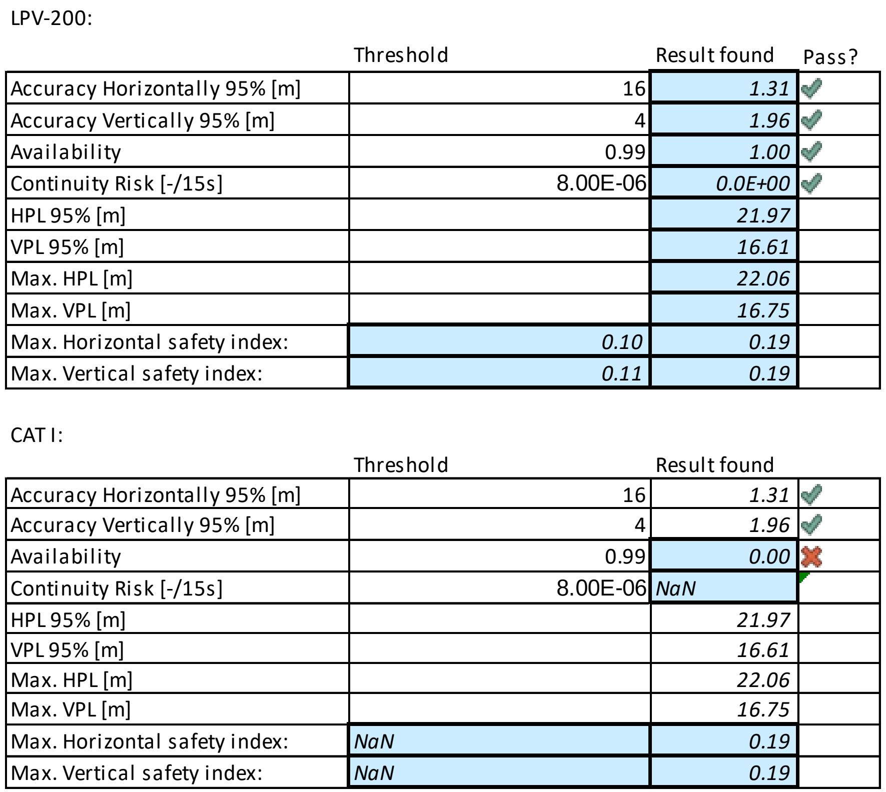


Flight 4



Method A: Performance metrics – nominal case

Straight approach TC_110



LPV-200:

	Threshold	Result found	Pass?
Accuracy Horizontally 95% [m]	16	*1.31*	✓
Accuracy Vertically 95% [m]	4	*1.96*	✓
Availability	0.99	*1.00*	✓
Continuity Risk [-/15s]	8.00E-06	*0.0E+00*	✓
HPL 95% [m]		*21.97*	
VPL 95% [m]		*16.61*	
Max. HPL [m]		*22.06*	
Max. VPL [m]		*16.75*	
Max. Horizontal safety index:	*0.10*	*0.19*	
Max. Vertical safety index:	*0.11*	*0.19*	

CAT I:

	Threshold	Result found	
Accuracy Horizontally 95% [m]	16	*1.31*	✓
Accuracy Vertically 95% [m]	4	*1.96*	✓
Availability	0.99	*0.00*	✗
Continuity Risk [-/15s]	8.00E-06	*NaN*	
HPL 95% [m]		*21.97*	
VPL 95% [m]		*16.61*	
Max. HPL [m]		*22.06*	
Max. VPL [m]		*16.75*	
Max. Horizontal safety index:	*NaN*	*0.19*	
Max. Vertical safety index:	*NaN*	*0.19*	

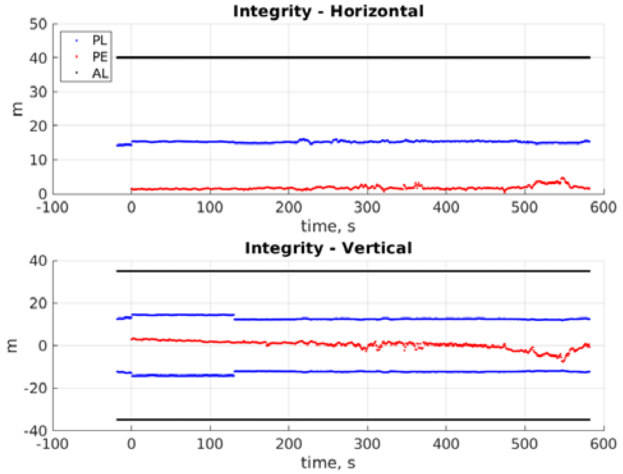
Discussion points

- LPV-200 (VAL = 35m) fulfilled;
- CAT-I (VAL = 10m) not achieved due to VPLs (> VAL);
- SI slightly higher than EGNOS due to covariance reduction from the altimeters;
- Altimeters contribution on vertical accuracy is limited.

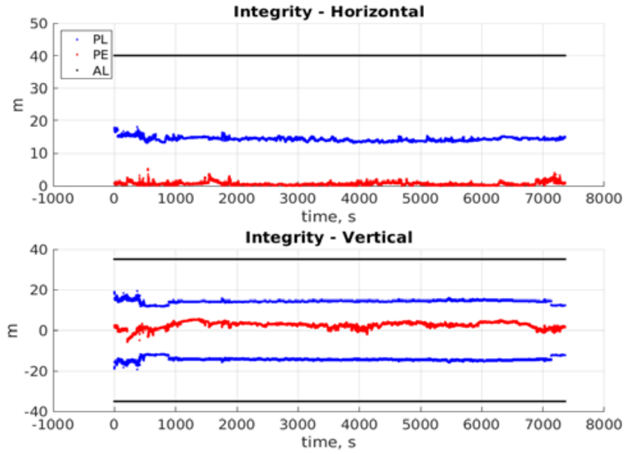
Similar performance observed for the other test cases, not reported for brevity

Method B: PE vs PL – nominal case

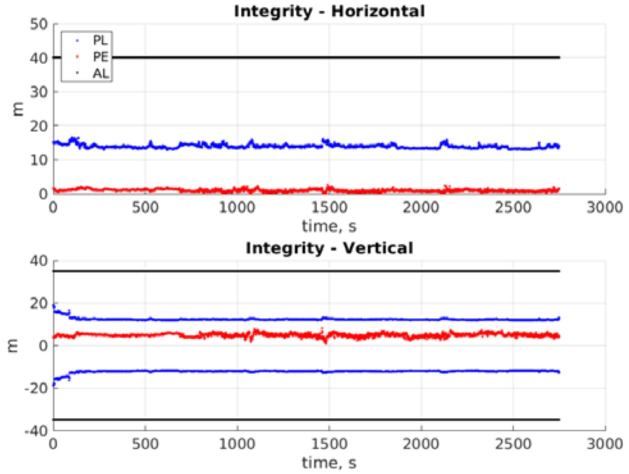
Flight 1



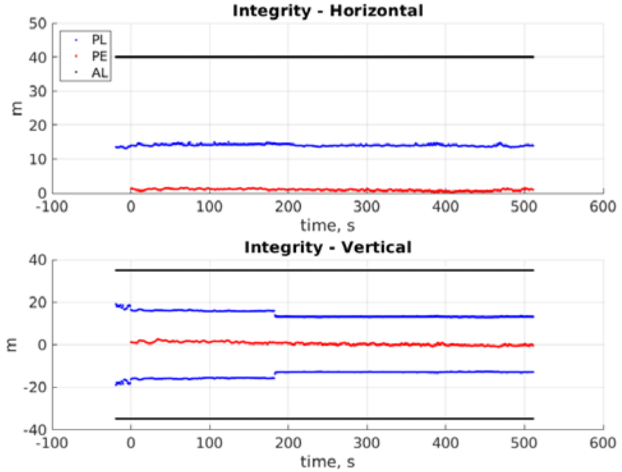
Flight 3



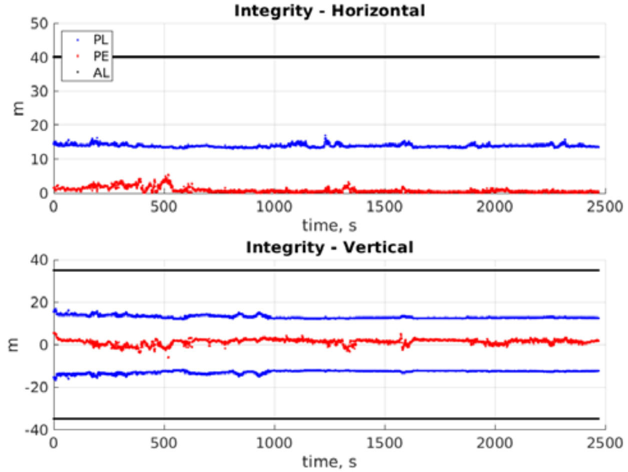
Flight 5



Flight 2

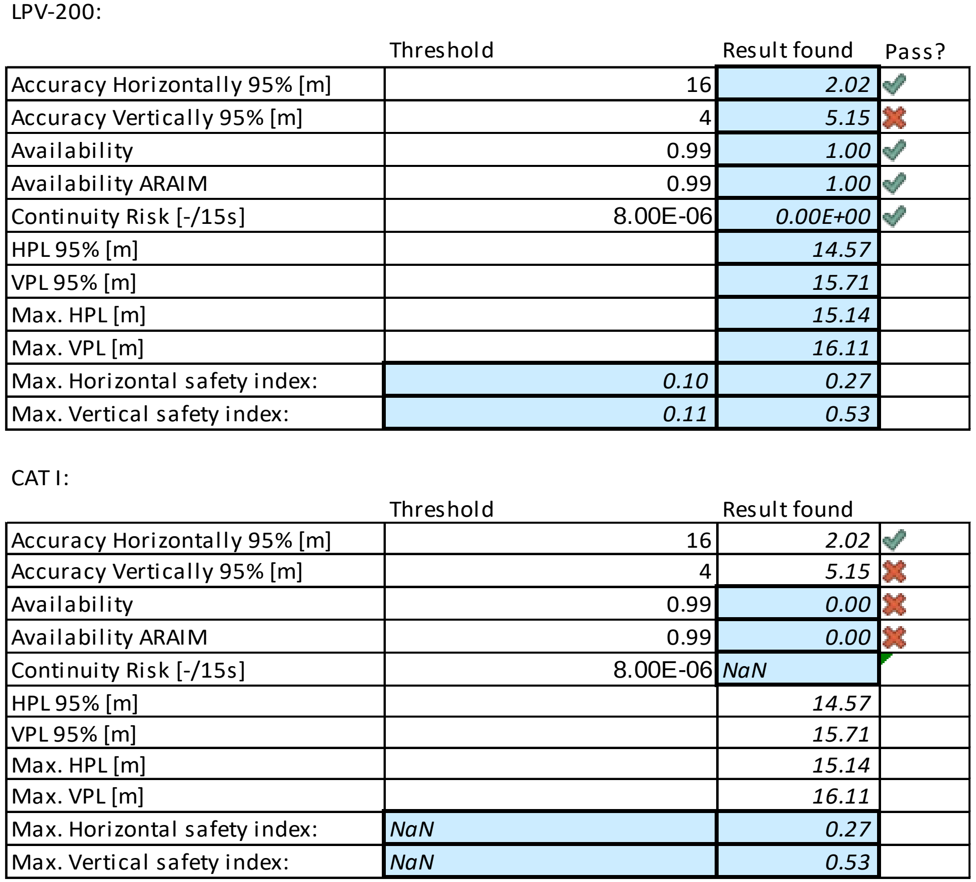


Flight 4



Method B: Performance metrics – nominal case

Straight approach TC_110



LPV-200:

	Threshold	Result found	Pass?
Accuracy Horizontally 95% [m]	16	*2.02*	✓
Accuracy Vertically 95% [m]	4	*5.15*	✗
Availability	0.99	*1.00*	✓
Availability ARAIM	0.99	*1.00*	✓
Continuity Risk [-/15s]	8.00E-06	*0.00E+00*	✓
HPL 95% [m]		*14.57*	
VPL 95% [m]		*15.71*	
Max. HPL [m]		*15.14*	
Max. VPL [m]		*16.11*	
Max. Horizontal safety index:	*0.10*	*0.27*	
Max. Vertical safety index:	*0.11*	*0.53*	

CAT I:

	Threshold	Result found	
Accuracy Horizontally 95% [m]	16	*2.02*	✓
Accuracy Vertically 95% [m]	4	*5.15*	✗
Availability	0.99	*0.00*	✗
Availability ARAIM	0.99	*0.00*	✗
Continuity Risk [-/15s]	8.00E-06	*NaN*	
HPL 95% [m]		*14.57*	
VPL 95% [m]		*15.71*	
Max. HPL [m]		*15.14*	
Max. VPL [m]		*16.11*	
Max. Horizontal safety index:	*NaN*	*0.27*	
Max. Vertical safety index:	*NaN*	*0.53*	

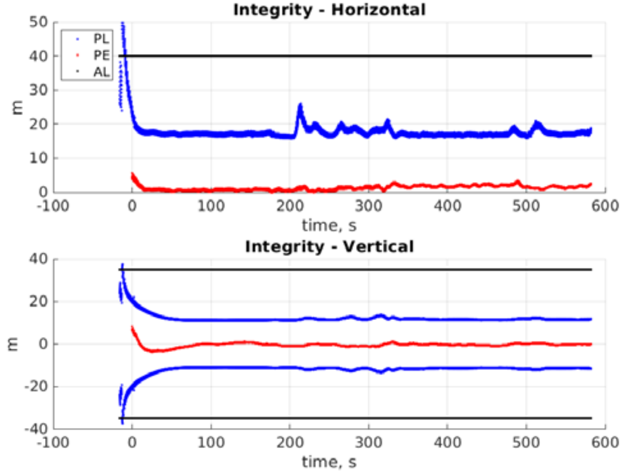
Discussion points

- LPV-200 (VAL = 35m) and CAT-I (VAL = 10m) not achieved due to vertical accuracy;
- Method B is based on ARAIM but dual constellation (GPS and GAL) and single frequency has been performed in this project;
- The altimeter data, being un-biased through the GNSS measurements, failed at removing the bias in the vertical direction;
- Availability was 100% in spite of the unsufficient accuracy measured on the vertical direction.
- *The estimated accuracy used in the „Availability ARAIM“ should take into account also bias error components.*

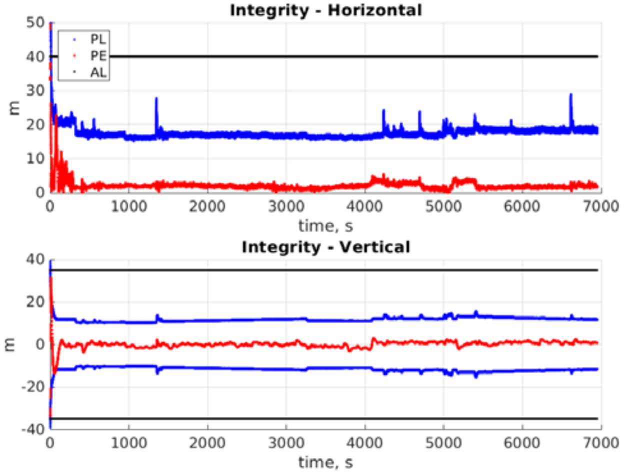
Similar performance observed for the other test cases, not reported for brevity

Method C: PE vs PL – nominal case

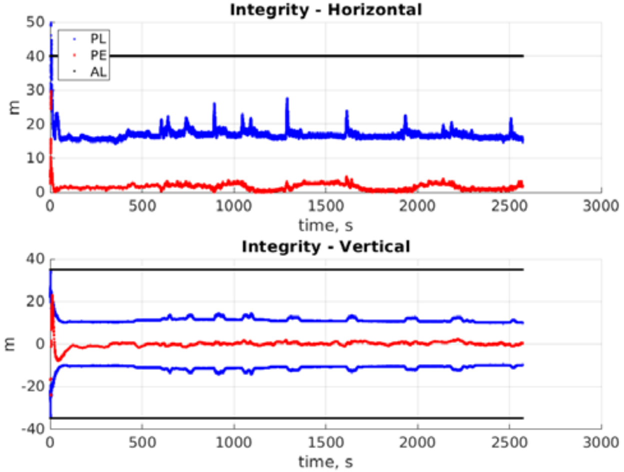
Flight 1



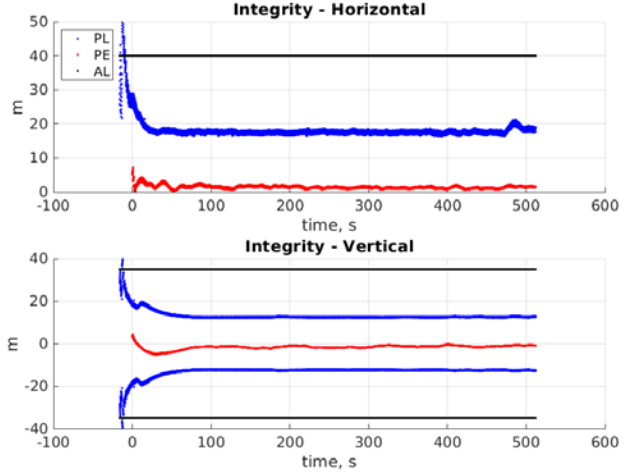
Flight 3



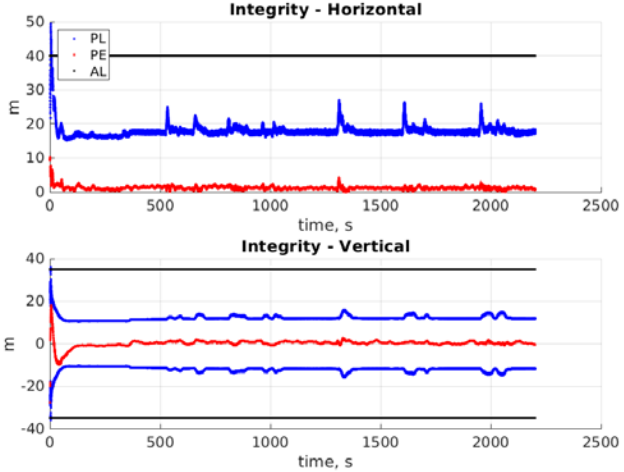
Flight 5



Flight 2

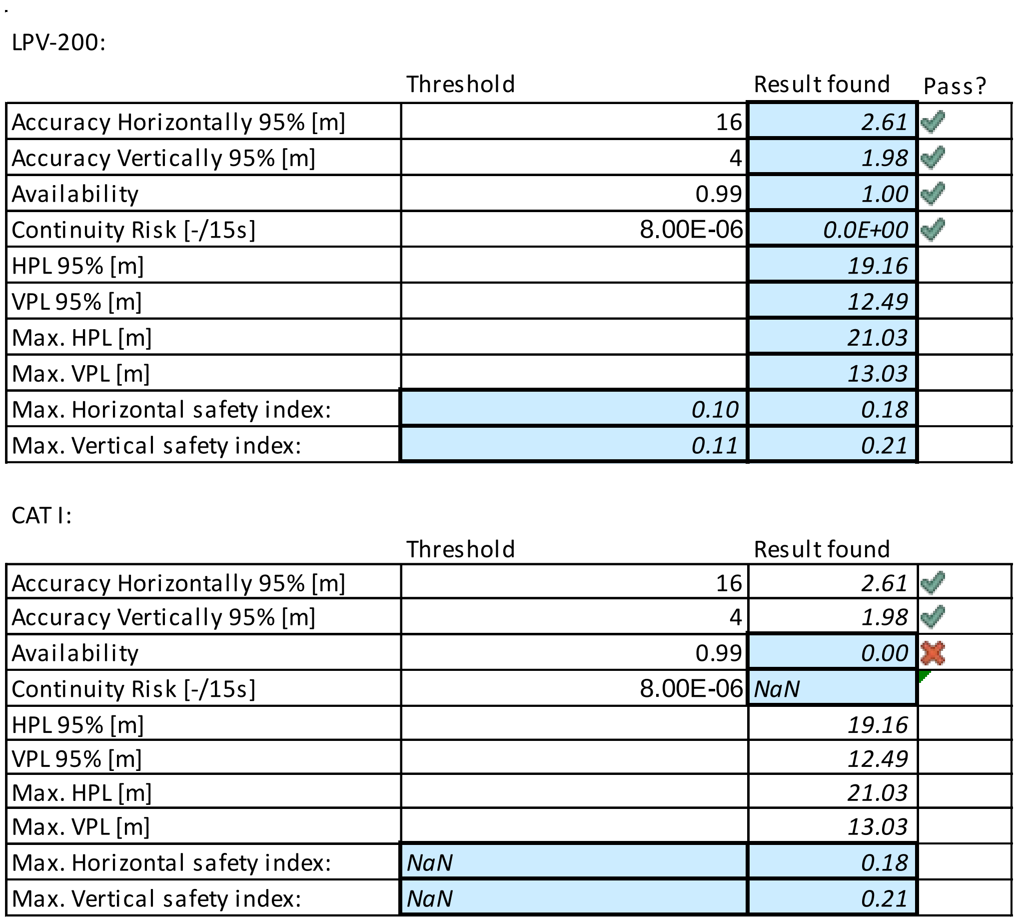


Flight 4



Method C: Performance metrics – nominal case

Straight approach TC_110



LPV-200:

	Threshold	Result found	Pass?
Accuracy Horizontally 95% [m]	16	*2.61*	✓
Accuracy Vertically 95% [m]	4	*1.98*	✓
Availability	0.99	*1.00*	✓
Continuity Risk [-/15s]	8.00E-06	*0.0E+00*	✓
HPL 95% [m]		*19.16*	
VPL 95% [m]		*12.49*	
Max. HPL [m]		*21.03*	
Max. VPL [m]		*13.03*	
Max. Horizontal safety index:	*0.10*	*0.18*	
Max. Vertical safety index:	*0.11*	*0.21*	

CAT I:

	Threshold	Result found	
Accuracy Horizontally 95% [m]	16	*2.61*	✓
Accuracy Vertically 95% [m]	4	*1.98*	✓
Availability	0.99	*0.00*	✗
Continuity Risk [-/15s]	8.00E-06	*NaN*	
HPL 95% [m]		*19.16*	
VPL 95% [m]		*12.49*	
Max. HPL [m]		*21.03*	
Max. VPL [m]		*13.03*	
Max. Horizontal safety index:	*NaN*	*0.18*	
Max. Vertical safety index:	*NaN*	*0.21*	

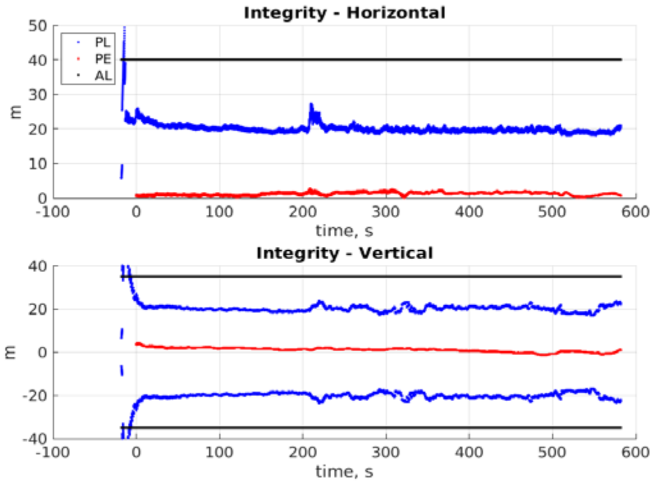
Discussion points

- LPV-200 (VAL = 35m) fulfilled;
- CAT-I (VAL = 10m) not achieved due to VPLs (> VAL);
- VPLs of Method C are the tightest observed in the project (max about 13 m)
- Overall TTA has been reduced to 4s;
- PLs include an inflation factor due to 2s IMU-based coasting
- Tighter PLs could be achieved:
  - Double constellation SBAS augmentation;
  - Lower EKF process noise (higher grade IMUs)
  - Shorter coasting;
- SI index close to 1 for departure and all configurations are only due to initializations in shaded area in Flight 3 (not relevant for the project).

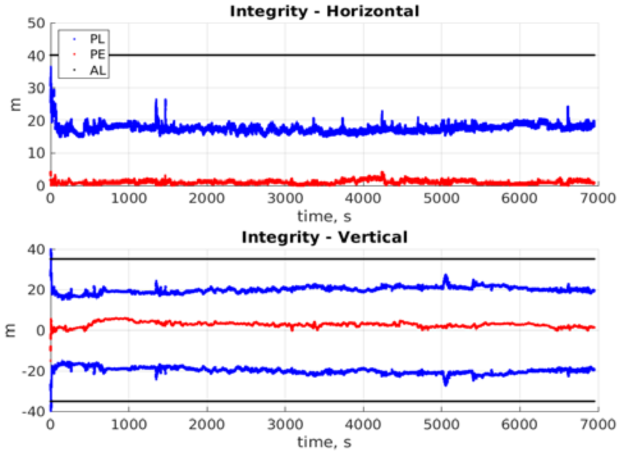
Similar performance observed for the other test cases, not reported for brevity

Method D: PE vs PL – nominal case

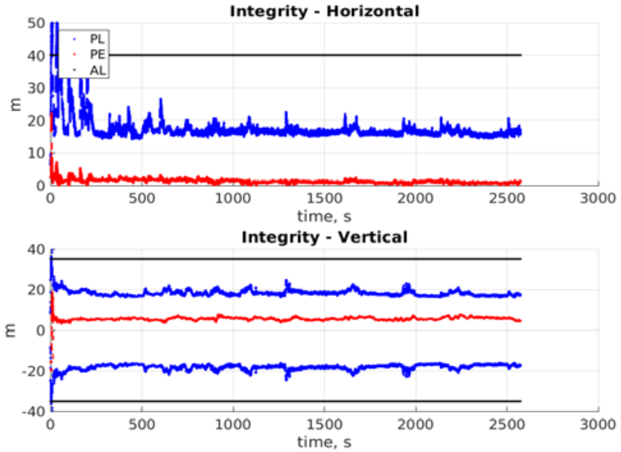
Flight 1



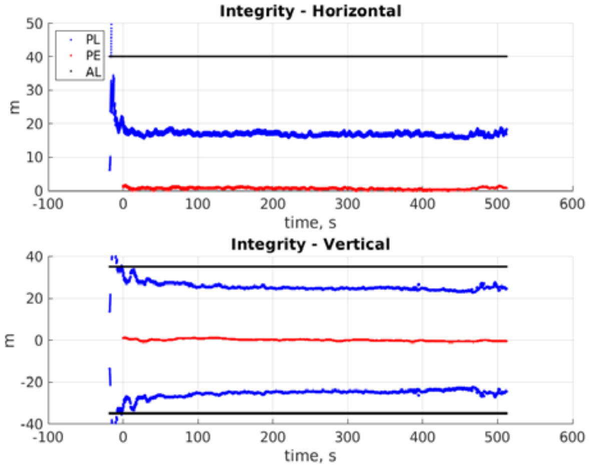
Flight 3



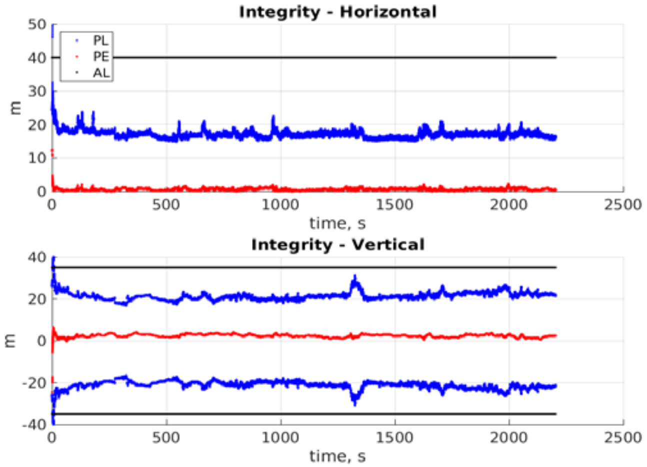
Flight 5



Flight 2

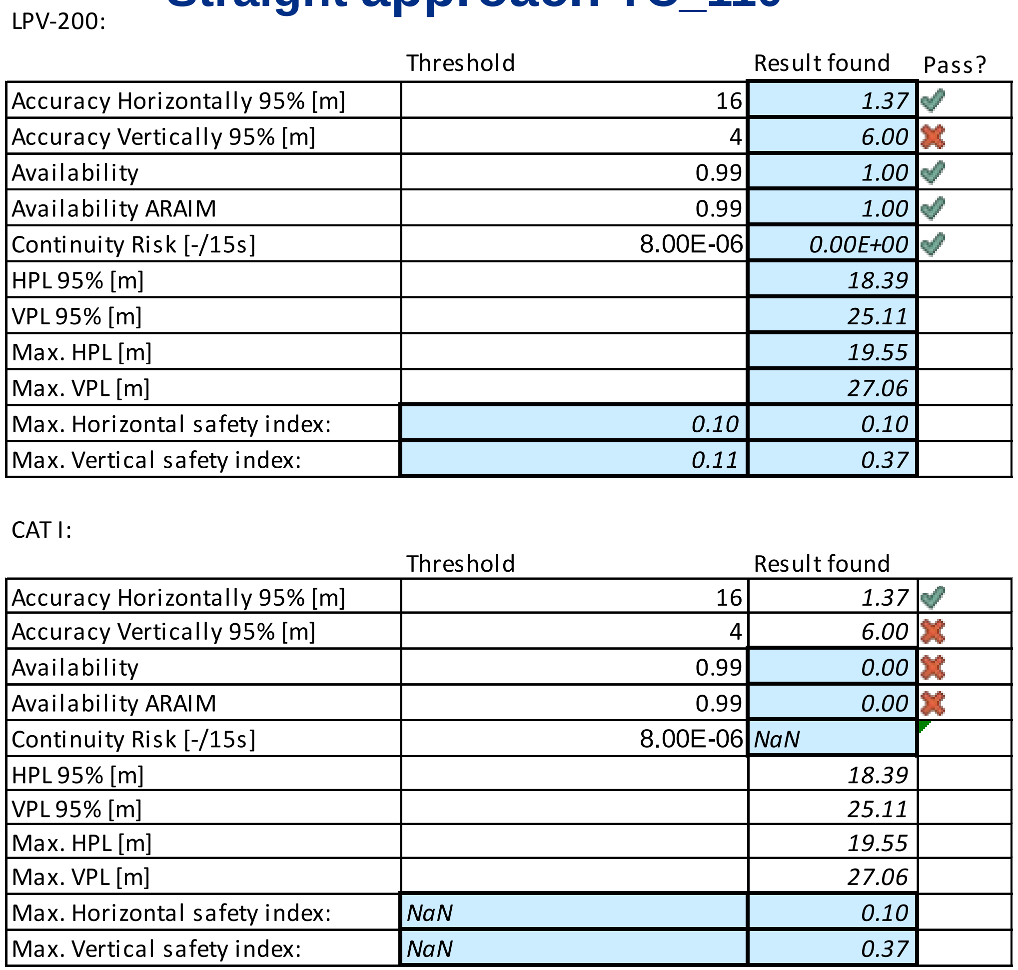


Flight 4



Method D: Performance metrics – nominal case

Straight approach TC_110



LPV-200:

	Threshold	Result found	Pass?
Accuracy Horizontally 95% [m]	16	*1.37*	✓
Accuracy Vertically 95% [m]	4	*6.00*	✗
Availability	0.99	*1.00*	✓
Availability ARAIM	0.99	*1.00*	✓
Continuity Risk [-/15s]	8.00E-06	*0.00E+00*	✓
HPL 95% [m]		*18.39*	
VPL 95% [m]		*25.11*	
Max. HPL [m]		*19.55*	
Max. VPL [m]		*27.06*	
Max. Horizontal safety index:	*0.10*	*0.10*	
Max. Vertical safety index:	*0.11*	*0.37*	

CAT I:

	Threshold	Result found	
Accuracy Horizontally 95% [m]	16	*1.37*	✓
Accuracy Vertically 95% [m]	4	*6.00*	✗
Availability	0.99	*0.00*	✗
Availability ARAIM	0.99	*0.00*	✗
Continuity Risk [-/15s]	8.00E-06	*NaN*	
HPL 95% [m]		*18.39*	
VPL 95% [m]		*25.11*	
Max. HPL [m]		*19.55*	
Max. VPL [m]		*27.06*	
Max. Horizontal safety index:	*NaN*	*0.10*	
Max. Vertical safety index:	*NaN*	*0.37*	

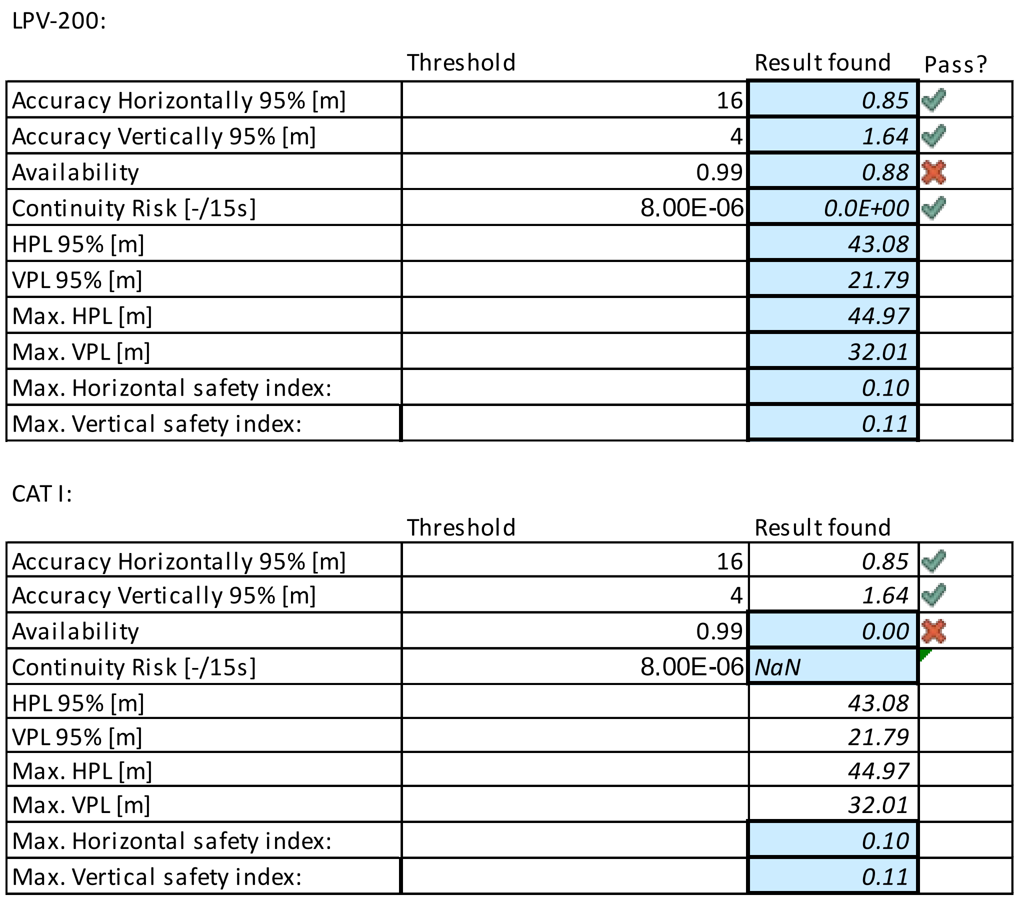
Discussion points

- LPV-200 (VAL = 35m) and CAT-I (VAL = 10m) not achieved due to vertical accuracy;
- As for Method B, the multi-hypothesis approach fails at rejecting vertical bias errors coming from common error modes.
- The altimeter data, being un-biased through the GNSS measurements, failed at removing the bias in the vertical direction;
- Availability was 100% in spite of the unsufficient accuracy measured on the vertical direction.
- *The estimated accuracy used in the „Availability ARAIM“ should take into account also bias error components.*

Similar performance observed for the other test cases, not reported for brevity

Comparison with SBAS

Straight approach TC_110



LPV-200:

	Threshold	Result found	Pass?
Accuracy Horizontally 95% [m]	16	*0.85*	✓
Accuracy Vertically 95% [m]	4	*1.64*	✓
Availability	0.99	*0.88*	✗
Continuity Risk [-/15s]	8.00E-06	*0.0E+00*	✓
HPL 95% [m]		*43.08*	
VPL 95% [m]		*21.79*	
Max. HPL [m]		*44.97*	
Max. VPL [m]		*32.01*	
Max. Horizontal safety index:		*0.10*	
Max. Vertical safety index:		*0.11*	

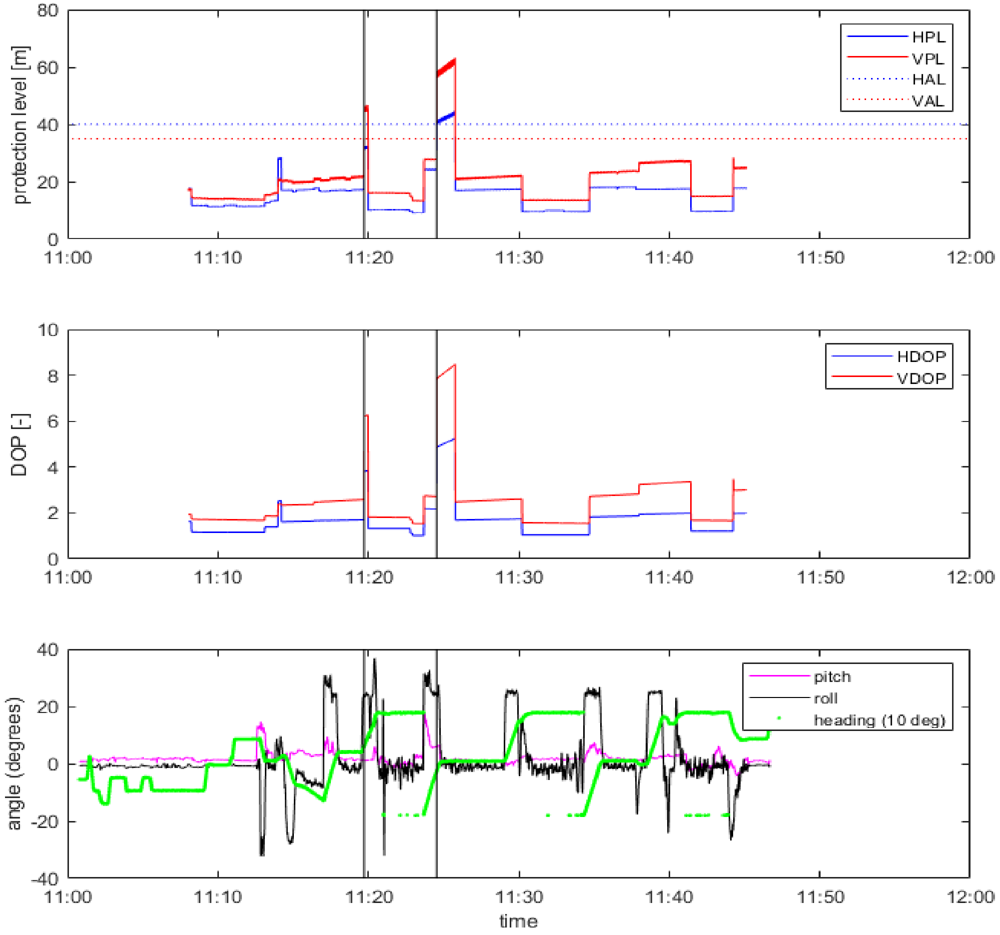
CAT I:

	Threshold	Result found	
Accuracy Horizontally 95% [m]	16	*0.85*	✓
Accuracy Vertically 95% [m]	4	*1.64*	✓
Availability	0.99	*0.00*	✗
Continuity Risk [-/15s]	8.00E-06	*NaN*	
HPL 95% [m]		*43.08*	
VPL 95% [m]		*21.79*	
Max. HPL [m]		*44.97*	
Max. VPL [m]		*32.01*	
Max. Horizontal safety index:		*0.10*	
Max. Vertical safety index:		*0.11*	

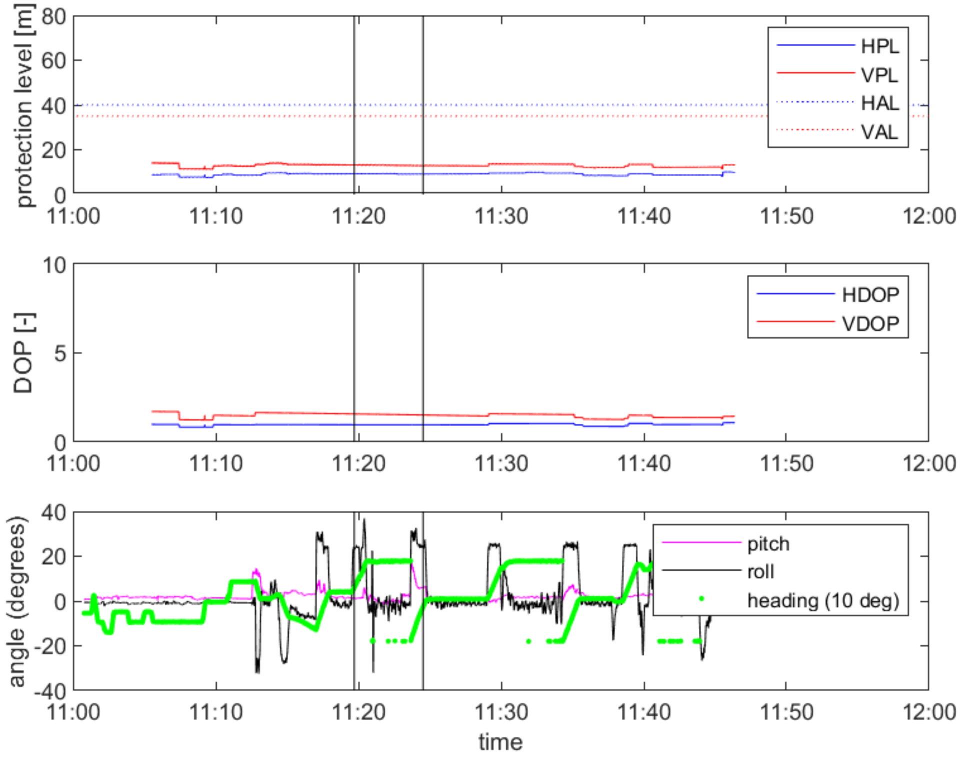
Discussion points

- Low availability SBAS
  - High PL

Comparison with SBAS – availability issue investigation



SNR 35



SNR 30

Experimental results – Feared events

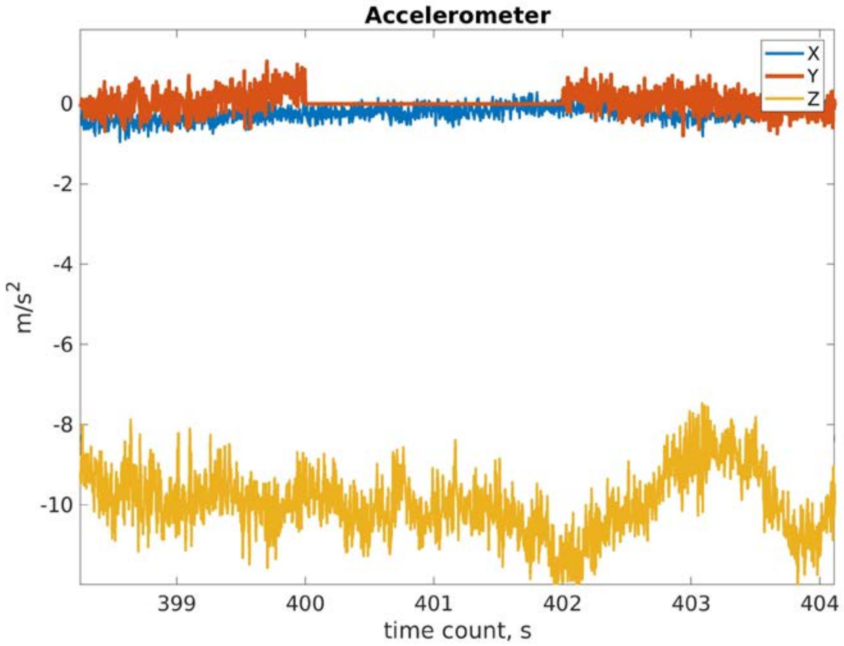
IMU feared event: example on Flight 1 - 20200318_FLT002_PHLA

IMU FEARED EVENT:

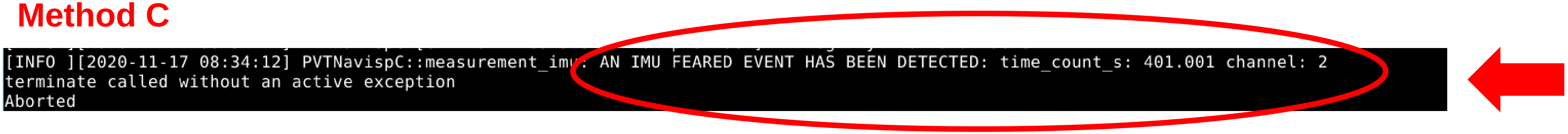
Data freeze applied from 400s to 402s to the Accelerometer Y axis

Buffer for FE detection in Method C and D (configurable parameter): **1.0 s**

Method C and D detect a feared event one second after and abort the estimation.

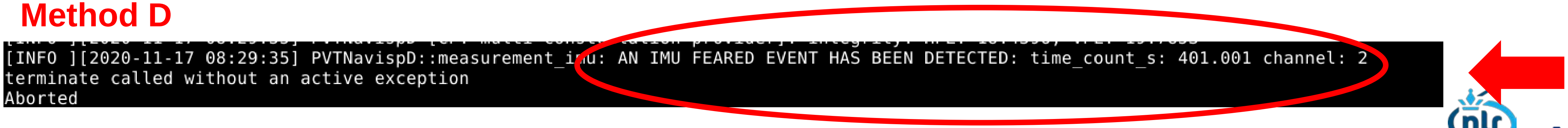


Method C



```
[INFO ][2020-11-17 08:34:12] PVTNavispC::measurement_imu: AN IMU FEARED EVENT HAS BEEN DETECTED: time_count_s: 401.001 channel: 2
terminate called without an active exception
Aborted
```

Method D



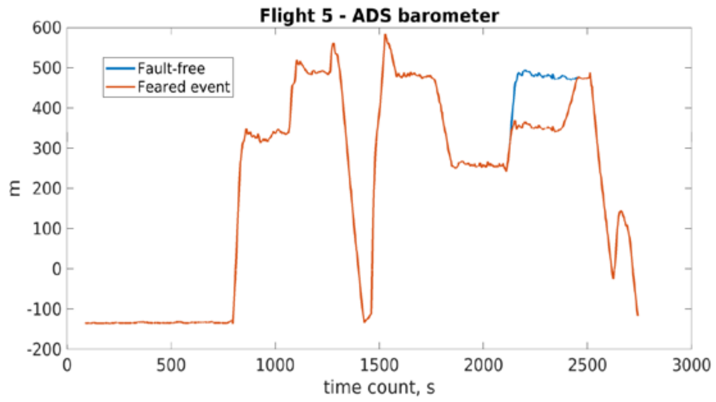
```
[INFO ][2020-11-17 08:29:35] PVTNavispD::measurement_imu: AN IMU FEARED EVENT HAS BEEN DETECTED: time_count_s: 401.001 channel: 2
terminate called without an active exception
Aborted
```

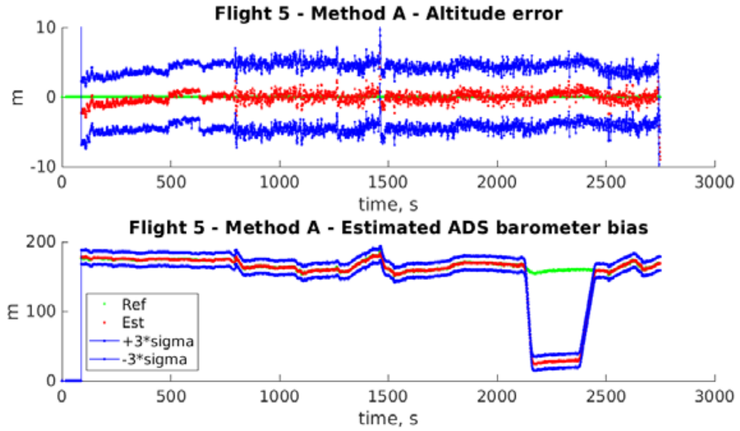
ADS feared event: Flight 5 - 20200318_FLT002_PHLA

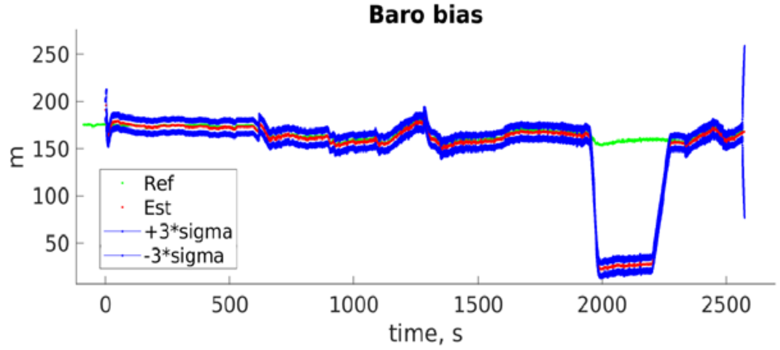
Feared event

Method A/B – KF bias compensation

Method C/D





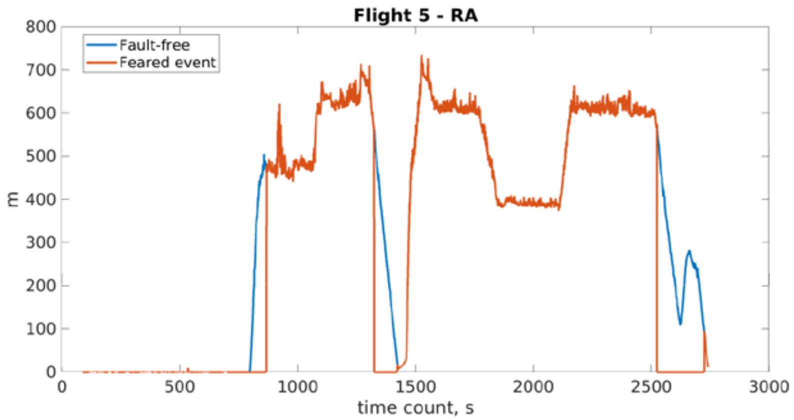


Feared events are absorbed in the bias state vector components

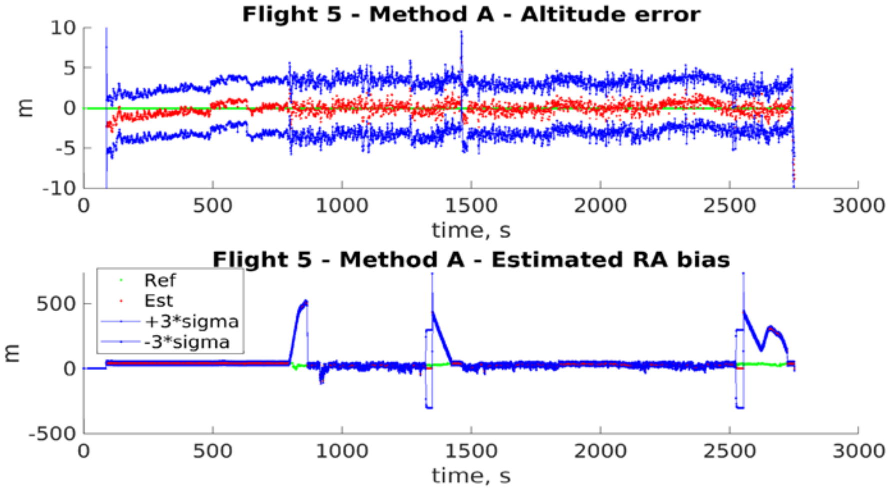
No variations in the performance metrics are observed in presence of the ADS FE

RA feared event: Flight 5 - 20200318_FLT002_PHLA

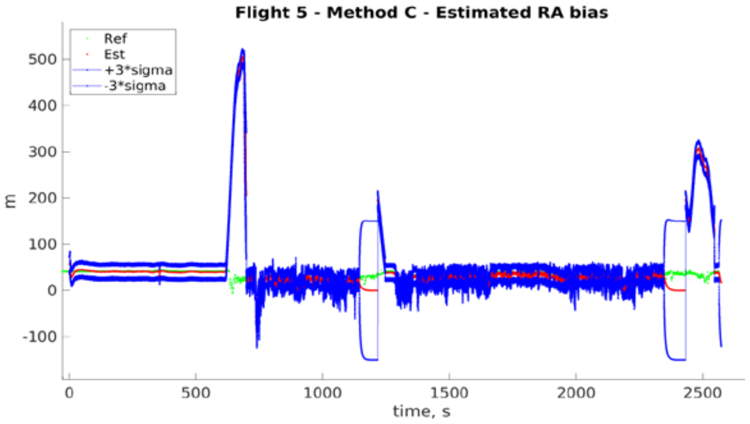
Feared event



Method A/B – KF bias compensation



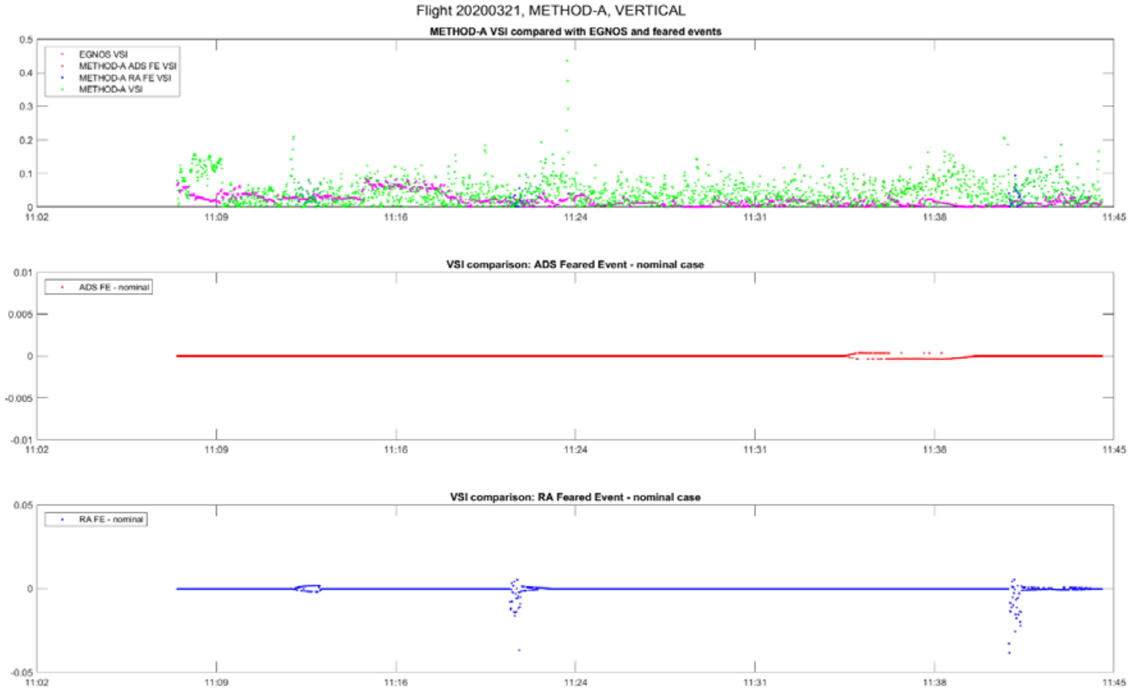
Method C/D

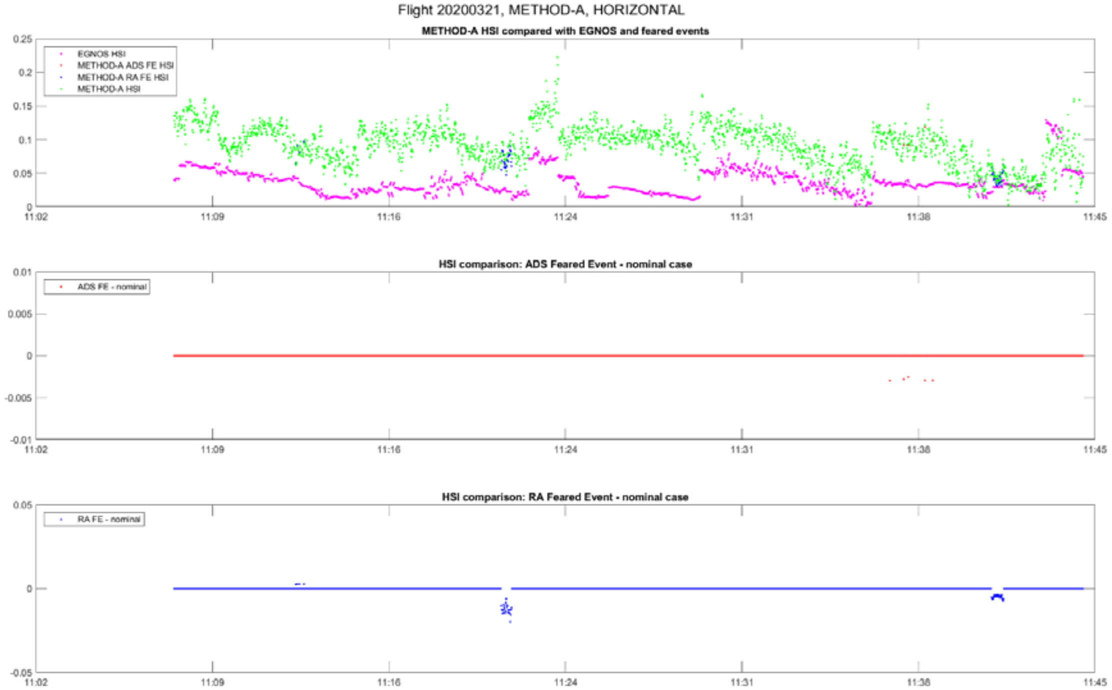


Feared events are absorbed in the bias state vector components or rejected;

No variations in the performance metrics are observed in presence of the ADS FE

ADS and RA FE: Safety Indices



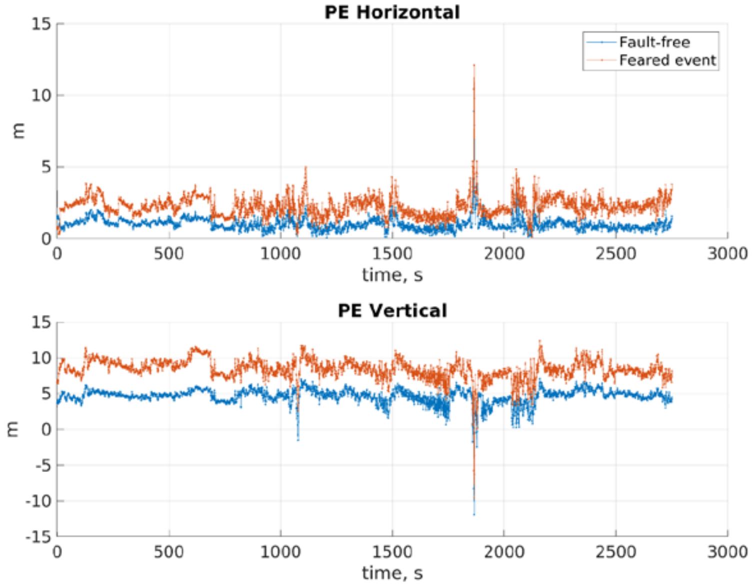


Feared events do not affect the behavior of the algorithms in terms of SI

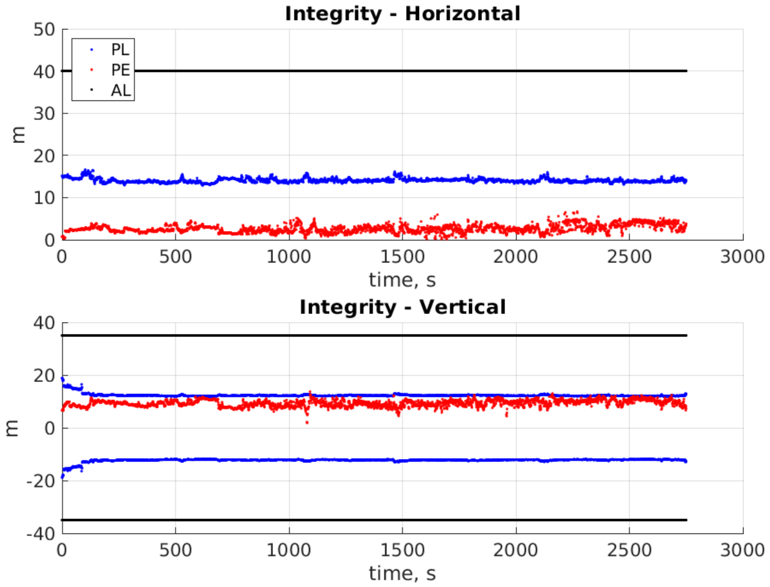
Similar plots are also reported in D5 for all the other methods

GNSS FE: Flight 5 - 20200318_FLT002_PHLA

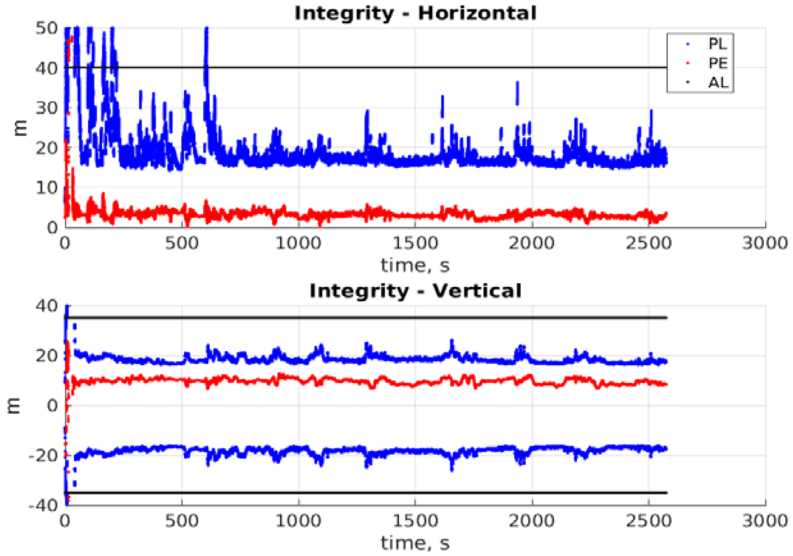
Feared event



Method B – KF bias compensation



Method D



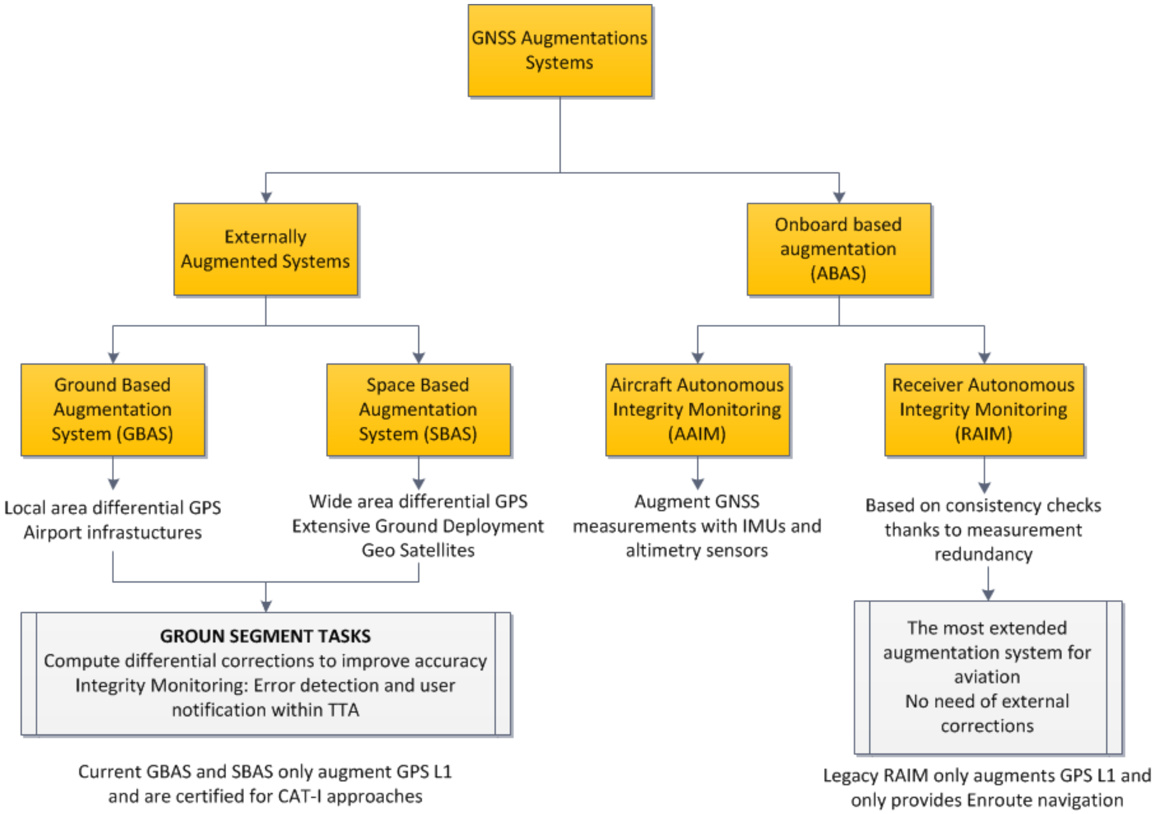
Method A and C are immune to the GNSS FE, due to the EGNOS augmentation;

Method B and D cannot properly deal with this feared event because the multi-hypothesis approach assumptions are violated;

WP 5000

WP5000: Impact to standardization (ADS Lead)

Current aviation standards for GNSS: GNSS Augmentation systems



GNSS Augmentations Systems

Externally Augmented Systems

Onboard based augmentation (ABAS)

Ground Based Augmentation System (GBAS)

Local area differential GPS
Airport infrastuctures

Space Based Augmentation System (SBAS)

Wide area differential GPS
Extensive Ground Deployment
Geo Satellites

GROUN SEGMENT TASKS
Compute differential corrections to improve accuracy
Integrity Monitoring: Error detection and user notification within TTA

Current GBAS and SBAS only augment GPS L1 and are certified for CAT-I approaches

Aircraft Autonomous Integrity Monitoring (AAIM)

Augment GNSS measurements with IMUs and altimetry sensors

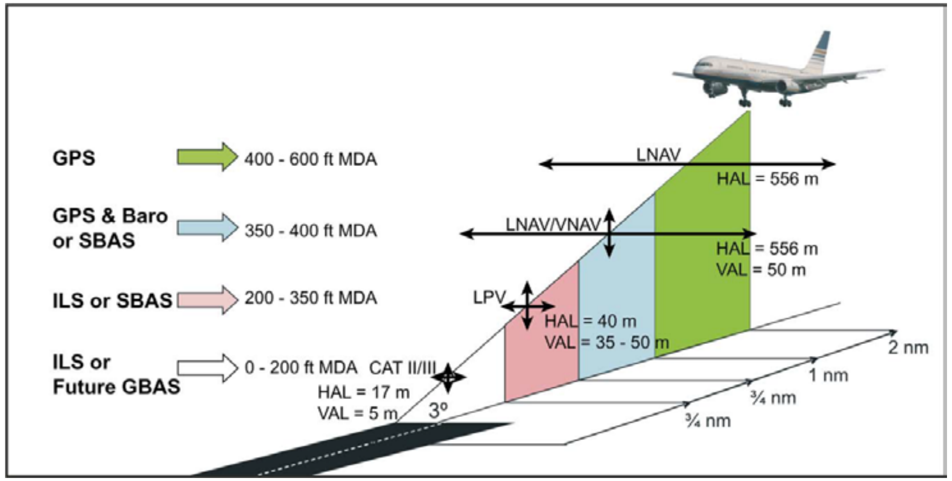
Receiver Autonomous Integrity Monitoring (RAIM)

Based on consistency checks thanks to measurement redundancy

The most extended augmentation system for aviation
No need of external corrections

Legacy RAIM only augments GPS L1 and only provides Enroute navigation

GNSS Augmentation systems classification



GNSS Augmentation for flight phases

Figure source: T. Walter et. al, “Worldwide Vertical Guidance of Aircraft Based on Modernized GPS and New Integrity Augmentations,"

Classification of the four methods as GNSS Augmentation systems

Integrity monitoring strategy

	SBAS augmentation	Multi-hypothesis approaches
Least Square methods	**Method A** **SBAS+AAIM**	**Method B** **ARAIM+AAIM**
EKF-based methods	**Method C** **SBAS+AAIM+EKF**	**Method D** **AAIM+EKF bank**

Sensor fusion framework

Impact on aviation for the four methods

	Certified	**Under certification/development**	**To be certified**
Method A	• GPS L1 augmented by EGNOS and WAAS • Current Avionics like barometric and radio altimeters, ADS	• GPS+GAL L1/L5-E1/E5a augmented by EGNOS and WAAS • Russian, Indian and Korean SBAS	• SBAS user algorithm with additional measurements • KF-based integrity concept
Method B	• Legacy RAIM for GPS L1 • Current Avionics like barometric and radio altimeters	• GPS+GAL L1/L5-E1/E5a ARAIM	• ARAIM user algorithm with additional measurements • KF-based integrity concept
Method C	• GPS L1 augmented by EGNOS and WAAS	• GPS+GAL L1/L5-E1/E5a augmented by EGNOS and WAAS	• SBAS user algorithm with additional measurements • IMU integrity concept (probability of failures)
Method D	• GPS L1 augmented by EGNOS and WAAS • Current Avionics like barometric and radio altimeters, ADS	• GPS+GAL L1/L5-E1/E5a ARAIM	• ARAIM user algorithm with additional measurements • IMU integrity concept (probability of failures)

Impact on aviation for the four methods: Critical aspects

Critical aspects for IMU-based method certification:

- Nominal error characterization: 1-sigma models to be incorporated within the position solution integrity
- A fault occurrence probability: Event probability to be incorporated within the onboard algorithms fault hypothesis

Certification processes similar to the ones implemented for GNSS (and settled for GPS-L1) need to be performed.

Proof of design assurance level up to DAL-B shall be provided by manufacturers.

Will the target market justify such an Investment?

Conclusions

Design of four sensor fusion and integrity monitoring algorithms

The designs driver of the methods was the extension of the SBAS and ARAIM approaches towards a multisensor scenario

Algorithms were developed in C++ and tested on real experimental data provided by NLR

The testing included the nominal case and the exposure to artificial feared events.

In a GNSS single frequency scenario, the algorithm proved to fulfill the LPV-200 requirements.

SBAS-based methods fulfill the CAT-I accuracy requirements, but PLs are not tight enough for this operation.

Method C representing an SBAS-augmented EKF provided the tightest protection level. It also enable interesting features like the TTA relocation between SBAS and user algorithm.

Main criticalities toward the standardization of the algorithms were highlighted

Lessons learned and further developments

Increasing the added value of the altimeters

Providing to the on-board algorithms (1) the barometric pressure at the lane (2) WGS84 altitude at the lane;
This would apply to all algorithms.

Dual Frequency

Switching to dual frequency would remove a common error mode among pseudoranges, i.e. errors in the corrections provided by Ionospheric models;
Common error modes are particularly detrimental for multi-hypothesis approaches;

Further potentialities of Method C

Method C has proved to be the most promising algorithm, due to:

- (1) Accuracy (EGNOS);
- (2) Thightest VPLs;
- (3) TTA can be reduced through the IMU data;
- (4) Continuity gain through the IMU data;

Further improvements towards tighter VPL to enter CAT-I operations would be:

- (1) Multi-constellation SBAS augmentation;
- (2) Different coasting strategies;
- (3) Addressing Doppler and multipath effects through filter banking;
- (4) Higher grade IMUs;

Increased dataset

Increasing the datase size would enable more meaningful integrity evaluation and comparison

Thank you