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# Solution Separation-Based Integrity Monitoring for Integer Ambiguity Resolution-Enabled GNSS Positioning

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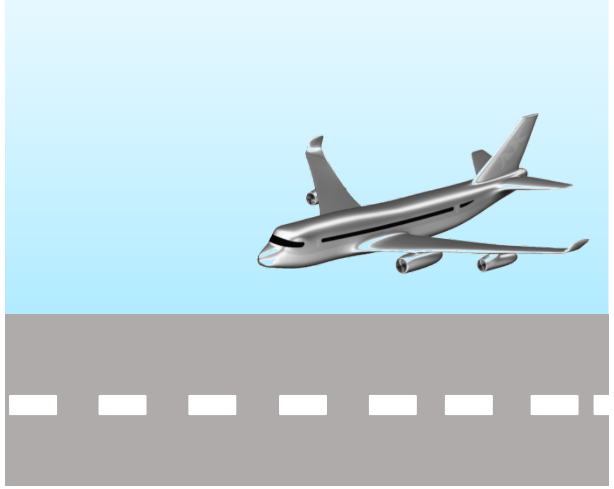
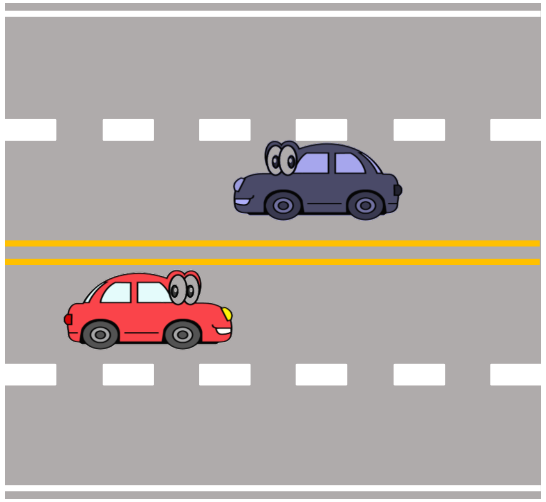
PPT Template Courtesy of IIT NavLab

Audio: by NaturalReader

# Background



Civil Aviation



Autonomous Vehicles

Urban Air Mobility (UAM)

*Pictures courtesy of Verdict*

**High-Integrity**

**High-Accuracy and High-Integrity** [1]

- **Accuracy** describes the uncertainty level of a navigation solution in nominal conditions.
- **Integrity** captures the upper bound of the error while considering the occurrence of faults.[2]

[1] Reid TGR, et al. Localization Requirements for Autonomous Vehicles. arXiv preprint, arXiv:1906.01061, 2019.
[2] International Civil Aviation Organization (ICAO). Annex 10, Aeronautical telecommunications, volume 1, amendment 84, Montreal, QC, Canada, 2009.

# Background

## Improving Accuracy

✓ **GNSS Precise Positioning**

- RTK[3] and PPP-RTK[4]
- ✓ Correction products-augmented
- ✓ Ambiguity Resolution (AR)-enabled
- ✓ Centimeter-level accuracy

## Ensuring Integrity

✓ **Integrity Monitoring**

- Fault Detection
- Fault Exclusion
- Evaluation of Protection Levels or Integrity Risk

× Integrity solution for GNSS precise positioning with ambiguity resolution?

✓ **Goal:** designing an integrity monitoring algorithm to protect GNSS precise positioning against **all sources of faults** and **incorrect ambiguity fixes**

[3] Odolinski, R., Odijk, D. and Teunissen, P.J.G., Combined GPS and BeiDou Instantaneous RTK Positioning. NAVIGATION, 2014, 61: 135-148.
[4] Zhang B, Chen Y, Yuan Y. PPP-RTK based on undifferenced and uncombined observations: theoretical and practical aspects. Journal of Geodesy, 2019, 93(7): 1011-1024.

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# Outline

1 Ambiguity Resolution (AR)-Enabled GNSS Positioning

2 Integrity Monitoring for AR-Enabled GNSS Positioning

- Modified MHSS:  Faults & Incorrect Ambiguity Fixes
- Closed-Form Protection Level Evaluation

3 Simulations and Results

# Outline

# Measurement Models

## ☐ GNSS Measurement Model [10]

**Pseudorange:**

$$\rho_{r,j}^{s,S} = \| \boldsymbol{X}^{s,S} - \boldsymbol{X}_r \| + dt_r - dt^{s,S} + isb_r^S + w_r^s \cdot T_r + \gamma_j^S \cdot I_{r,1}^{s,S} + (d_{r,j} - d_j^{s,S}) + \varepsilon_{r,j}^{s,S} + \xi_{r,j}^{s,S}$$

**Carrier Phase:**

$$l_{r,j}^{s,S} = \| \boldsymbol{X}^{s,S} - \boldsymbol{X}_r \| + dt_r - dt^{s,S} + isb_r^S + w_r^s \cdot T_r - \gamma_j^S \cdot I_{r,1}^{s,S} + \lambda_j^{s,S} \cdot (N_{r,j}^{s,S} + b_{r,j} - b_j^{s,S}) + \epsilon_{r,j}^{s,S} + \xi_{r,j}^{s,S}$$

$s, r, j, S$ represent satellite, receiver, frequency, and constellation;

| | | | |
|---|---|---|---|
| $dt$ | clock offset; | $isb$ | inter-system bias; |
| $T$ | zenith troposphere wet delay; | $I$ | slant ionosphere delay; |
| $d$ | code bias; | $b$ | phase bias; |
| $\lambda$ | signal wavelength; | $N$ | carrier-phase integer ambiguity; |
| $\varepsilon$, $\epsilon$ | white noises; | $\xi$ | errors that can be modelled, e.g., troposphere dry delay |

[10] Hauschild A., Springer Handbook of Global Navigation Satellite Systems, Chapter 19: Basic Observation Equations. Edited by Teunissen P.J.G. and Montenbruck O., Springer, 2017.

# Products and State Vector

## Precise Products for PPP-RTK

- **orbit, clock, troposphere, ionosphere, code bias, phase bias**

$$\rho_{r,j}^{s,S} = \| \boldsymbol{X}^{s,S} - \boldsymbol{X}_r \| + dt_r - dt^{s,S} + isb_r^S + w_r^s \cdot T_r + \gamma_j^S \cdot I_{r,1}^{s,S} + (d_{r,j} - d_j^{s,S}) + \varepsilon_{r,j}^{s,S} + \xi_{r,j}^{s,S}$$

$$l_{r,j}^{s,S} = \| \boldsymbol{X}^{s,S} - \boldsymbol{X}_r \| + dt_r - dt^{s,S} + isb_r^S + w_r^s \cdot T_r - \gamma_j^S \cdot I_{r,1}^{s,S} + \lambda_j^{s,S} \cdot (N_{r,j}^{s,S} + b_{r,j} - b_j^{s,S}) + \epsilon_{r,j}^{s,S} + \xi_{r,j}^{s,S}$$

## State Vector (Using GPS+BDS as an example)

- **position, clock, ISB, receiver bias, troposphere, ionosphere, ambiguity**

$$\boldsymbol{x} \triangleq [\underbrace{\boldsymbol{X}_r}_{\text{pos}} \quad \underbrace{dt^G}_{\text{clk}} \quad \underbrace{isb^C}_{\text{isb}} \quad \underbrace{dcb^G \ b_{r,1}^G \ b_{r,2}^G \ dcb^C \ b_{r,1}^C \ b_{r,2}^C}_{\text{rcv. bias}} \quad \underbrace{T_r \ \boldsymbol{I}_{r,1}^G \ \boldsymbol{I}_{r,1}^C}_{\text{trp \& ion}} \quad \underbrace{\boldsymbol{N}_{r,1}^G \ \boldsymbol{N}_{r,2}^G \ \boldsymbol{N}_{r,1}^C \ \boldsymbol{N}_{r,2}^C}_{\text{amb}}]^{\mathrm{T}}$$

# State Estimation

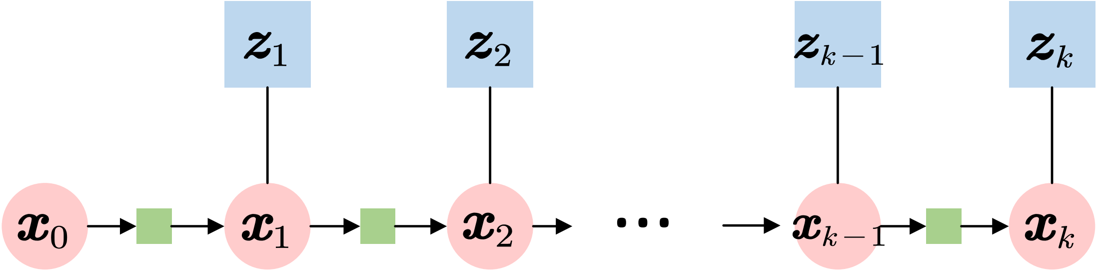
State Models $\boldsymbol{x}_k = \mathbf{F}_k \boldsymbol{x}_{k-1} + \boldsymbol{\omega}_k$ Measurement Models $\boldsymbol{z}_k = \mathbf{H}_k \boldsymbol{x}_{k-1} + \boldsymbol{\nu}_k$

## Error Models (Simplified) see Tables 1 ~ 3

- Process noise $\boldsymbol{\omega}_k$ ; measurement noise $\boldsymbol{\nu}_k$
- Assumptions: zero-mean white noises & uncorrelated

## Kalman Filter

- Recursive Estimation
- Equivalent to Batch Least Squares [11]




Ambiguity-Float Solution: State Estimate $\rightarrow \hat{\boldsymbol{x}}_k$ Error Covariance $\rightarrow \hat{\mathbf{P}}_k$

[11] Joerger M. and Pervan B. Kalman Filter-Based Integrity Monitoring Against Sensor Faults. JGCD, 2013, 36(2): 349-361

# Ambiguity Resolution

## ☐ Ambiguity Resolution: Exploiting the integer nature of the ambiguities [12]

$$\left(\hat{\boldsymbol{x}}_k,\ \hat{\mathbf{P}}_k\right) \longrightarrow \boldsymbol{x} \triangleq [\ \boldsymbol{x}_{pos}\quad others\quad \boldsymbol{x}_{amb}\ ]^{\mathrm{T}} \xrightarrow{\triangle} \boldsymbol{a} = \boldsymbol{x}_{amb},\ \boldsymbol{b} = \boldsymbol{x}_{pos}$$

### 1.Fix the ambiguities by Integer Bootstrapping [11]

$$\check{a}_1 = \lfloor \hat{a}_1 \rceil$$

$$\check{a}_2 = \lfloor \hat{a}_{2|1} \rceil = \lfloor \hat{a}_2 - \sigma_{2|1}\sigma_1^{-2}(\hat{a}_1 - \check{a}_1) \rceil$$

$$\vdots$$

$$\check{a}_n = \lfloor \hat{a}_{n|N} \rceil = \left\lfloor \hat{a}_n - \sum_{i=1}^{n-1} \sigma_{n,i|I}\sigma_{i|I}^{-2}(\hat{a}_{i|I} - \check{a}_i) \right\rceil$$

sequentially fixed!

$$\hat{\mathbf{P}}_{\boldsymbol{aa}} = \mathbf{L}^{\mathrm{T}}\mathbf{D}\mathbf{L}$$

### 2.Adjust the positions

$$\check{\boldsymbol{b}} = \hat{\boldsymbol{b}} - \hat{\mathbf{P}}_{\boldsymbol{ba}}\hat{\mathbf{P}}_{\boldsymbol{aa}}^{-1}(\hat{\boldsymbol{a}} - \check{\boldsymbol{a}})$$

$$\check{\mathbf{P}}_{\boldsymbol{bb}} = \hat{\mathbf{P}}_{\boldsymbol{bb}} - \hat{\mathbf{P}}_{\boldsymbol{ba}}\hat{\mathbf{P}}_{\boldsymbol{aa}}^{-1}\hat{\mathbf{P}}_{\boldsymbol{ba}}^{\mathrm{T}} \downarrow$$

Improved Accuracy!

✓ **IB offers a closed-form prior probability of the correct- or incorrect- fix event.** [12]

[12] Teunissen P.J.G., Success Probability of Integer GPS Ambiguity Rounding and Bootstrapping. Journal of Geodesy, 1998, 72(10): 606-612.

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# Outline

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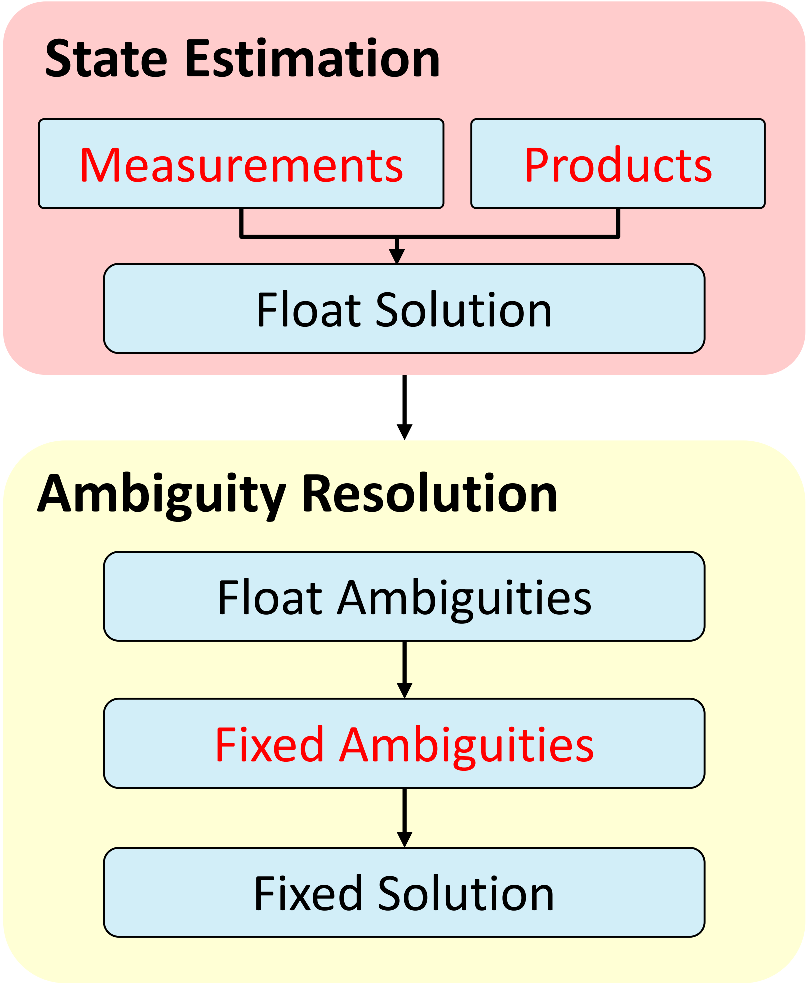
# Threats




× **Measurement Faults**
- Heavy multipath / NLOS
- Undetected Cycle Slips

× **Product Faults**
- Incorrect precise products

× **Incorrect Ambiguity Resolution**
- Incorrect-fix events

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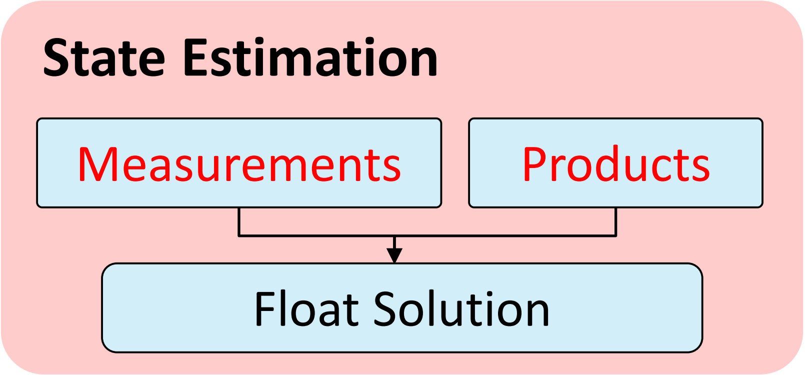
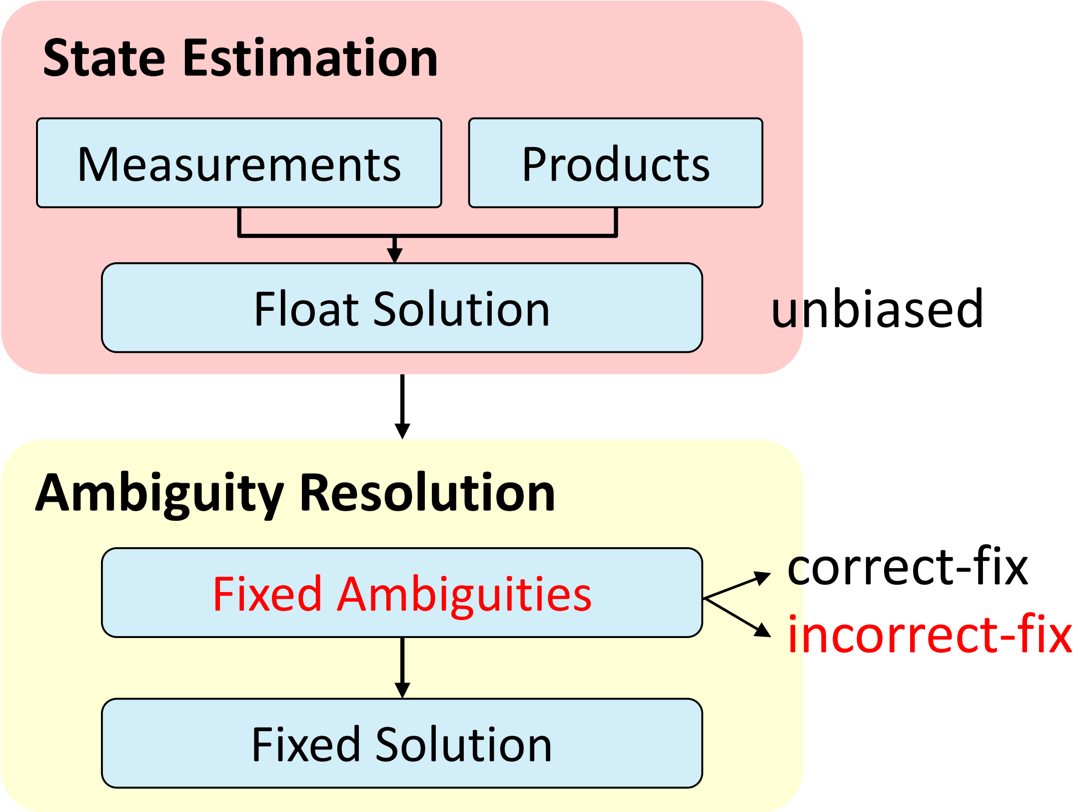
# Literature Review

## ☐ Prior Work on PPP/RTK/PPP-RTK Integrity Monitoring:

- evaluated the protection levels for the ***ambiguity-float*** solutions[5-7]




- quantified the integrity risk from ***incorrect-fix events*** in a ***fault-free*** condition[8-9]





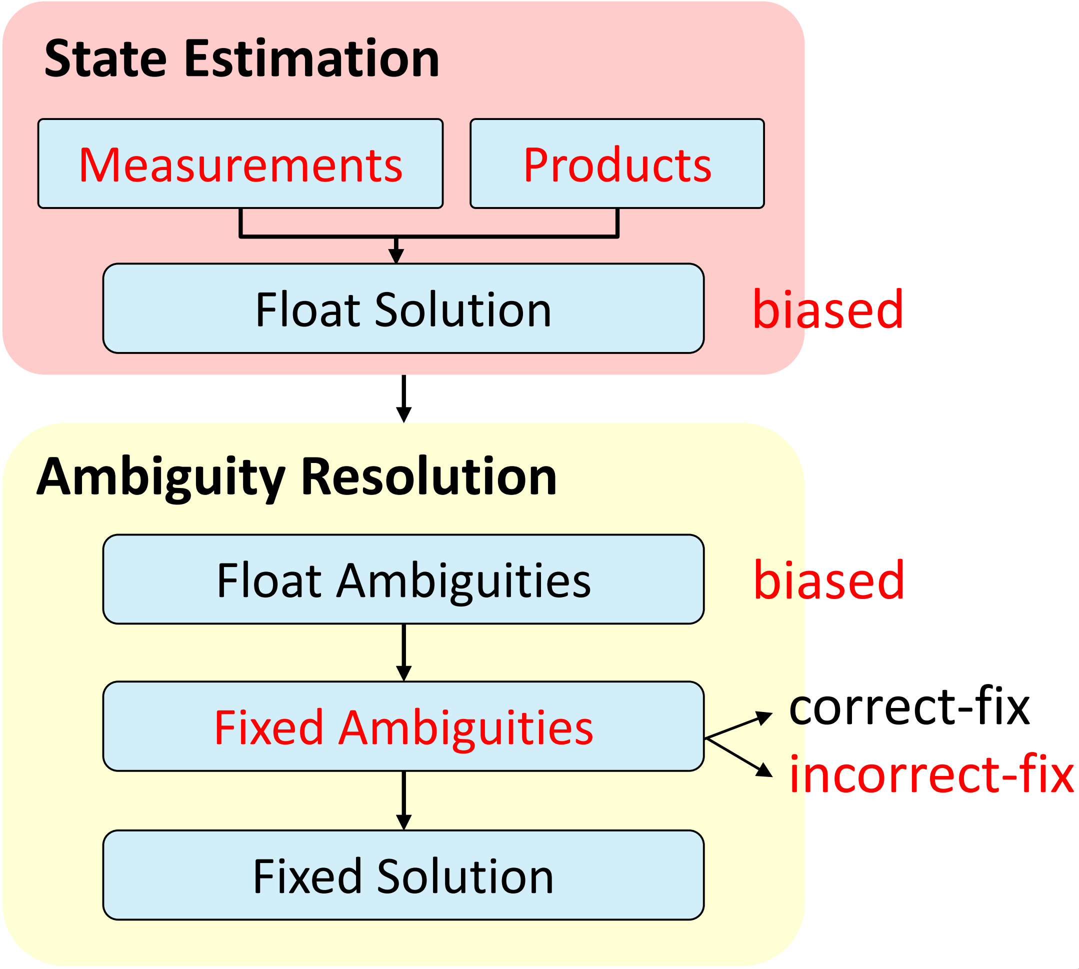
[5] Gunning K., et al. Design and Evaluation of Integrity Algorithms for PPP in Kinematic Applications. ION GNSS+ 2018.
[6] Gunning K. et al. Integrity for Tightly Coupled PPP and IMU. ION GNSS+ 2019.
[7] Blanch J. et al. Reducing Computational Load in Solution Separation for Kalman Filters and an Application to PPP Integrity. ION ITM 2019.
[8] Khanafseh S. and Pervan B. New Approach for Calculating Position Domain Integrity Risk for Cycle Resolution in Carrier Phase Navigation Systems. IEEE TAES, 2010, 46(1): 296-307.
[9] Green G. and Humphreys T. Position-Domain Integrity Analysis for Generalized Integer Aperture Bootstrapping. IEEE TAES, 2019, 55(2): 734-746.

# Literature Review

## ☐ What if measurement/product faults occur to AR-enabled positioning systems?

## ☐ Motivation:

- Monitoring measurement/product faults and incorrect-fix events simultaneously.
- The occurrence of measurement/product faults will influence the probability of incorrect-fix events.
- Therefore, *a simple combination of previous approaches doesn't work!*



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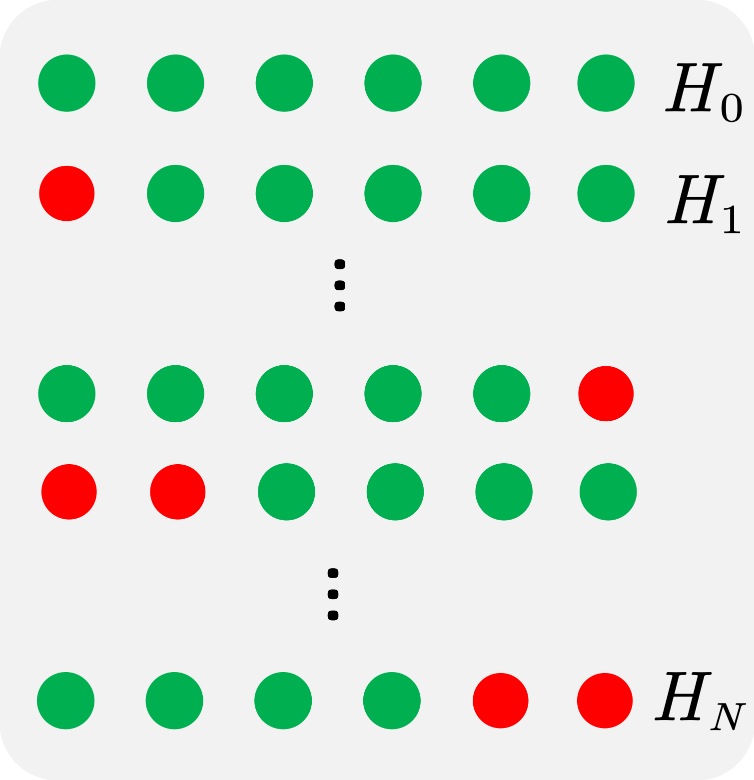
# Fault Modes

- **Approach: Multiple Hypothesis Solution Separation (MHSS)** [13][14]
- **Satellite (SV) Fault:**
  - The <u>measurement</u> or <u>product</u> of this SV is faulted
- **Fault Mode, $H_i$ :** [13][14]
  - An event combination of SV faults
- **Subset solution for a fault mode, $x^{(i)}$:**
  - Use the healthy SVs to estimate the states
  - The ambiguities of the faulted SVs are not included in $x^{(i)}$





[13] Blanch J., et al. Baseline Advanced RAIM User Algorithm and Possible Improvements. IEEE Transactions on Aerospace and Electronic Systems, 2015, 51(1): 713-732.
[14] Joerger M., Chan F.C., and Pervan B., Solution separation versus residual-based RAIM. NAVIGATION, 2014, 61(4): 273-291.

# Fault Detection

## Test Statistics [13][14]

For Subset $i$: $\Delta x_q^{(i)} = \check{x}_q^{(i)} - \check{x}_q^{(0)},\ i = 1, 2, \ldots, N_S,\ q = 1, 2, 3\ (\text{east, north, up})$

## Test Thresholds [13][14]

Threshold: $T_q^{(i)} = Q^{-1}\left(P_{FA,q} \big/ 2N_S\right) \cdot \sigma_{ss,q}^{(i)}$ Solution separation variance: $\sigma_{ss,q}^{(i)2} = \check{\mathbf{P}}_{q,q}^{(i)} - \check{\mathbf{P}}_{q,q}^{(0)}$ [5]

$P_{FA,q}$ : False alert budget $Q^{-1}(p)$ : the $(1-p)$ quantile of the normal distribution $N(0,1)$

## Fault Detection

No Fault Alert: $\textit{For all } i \textit{ and } q,\ \textit{we have the following: } |\Delta x_q^{(i)}| < T_q^{(i)}$

[5] Gunning K., et al. Design and Evaluation of Integrity Algorithms for PPP in Kinematic Applications. ION GNSS+ 2018.
[13] Blanch J., et al. Baseline Advanced RAIM User Algorithm and Possible Improvements. IEEE Transactions on Aerospace and Electronic Systems, 2015, 51(1): 713-732.
[14] Joerger M., Chan F.C., and Pervan B., Solution separation versus residual-based RAIM. NAVIGATION, 2014, 61(4): 273-291.

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# Integrity Risk Evaluation

- **According to Multiple Hypothesis Solution Separation,** [13]

$$P\left(|\check{x}_q^{(0)}-x_q|>PL_q,\ no\ alert\right)<\sum_{i=0}^{N_S}\underbrace{P(H_i)\times P\left(|\check{x}_q^{(0)}-x_q|>PL_q,\ no\ alert|H_i\right)}+P_{NM,q}$$

- **Under Fault Mode $\boldsymbol{i}$:**

$$IR^{(i)}<P(H_i)\times P\left(|\check{x}_q^{(0)}-x_q|>PL,no\ alert|H_i\right)$$

$$=P(H_i)\times\sum_{j=0}^{\infty}P\left(|\check{x}_q^{(0)}-x_q|>PL,no\ alert\middle|\ H_i\cap\left(\Delta^{(i)}=\Delta_j^{(i)}\right)\right)\times P\left(\Delta^{(i)}=\Delta_j^{(i)}|H_i\right)$$

Ambiguity Offset

Two-layer hypothesis

$\Delta^{(i)}=\check{\boldsymbol{a}}^{(i)}-\boldsymbol{a}^{(i)}$ ($\boldsymbol{a}^{(i)}$: truth for the ambiguity vector in $\boldsymbol{x}^{(i)}$)

$\Delta_0^{(i)}=0$ ***Correct-fix***

$\Delta_j^{(i)}\neq 0,\ j>0$ ***An incorrect-fix event***

[13] Blanch J., et al. Baseline Advanced RAIM User Algorithm and Possible Improvements. IEEE Transactions on Aerospace and Electronic Systems, 2015, 51(1): 713-732.

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# Integrity Risk Evaluation

## Integrity Risk Under Hypothesis $i$:

$$IR^{(i)} = P(H^{(i)}) \times \sum_{j=0}^{\infty} P(|\breve{x}_q^{(0)} - x_q| > PL_q, no\ alert | H_i \cap (\Delta^{(i)} = \Delta_j^{(i)})) \times P(\Delta^{(i)} = \Delta_j^{(i)} | H_i)$$

✓ **The first term:** **See the paper for the derivations!**

$$P(|\breve{x}_q^{(0)} - x_q| > PL, no\ alert | H_i \cap (\Delta^{(i)} = \Delta_j^{(i)})) < Q\left(\frac{PL_q}{\breve{\sigma}_q^{(0)}}\right) + Q\left(\frac{PL_q - T_q^{(i)} - \mathbf{A}_q^{(i)} \Delta_j^{(i)}}{\breve{\sigma}_q^{(i)}}\right) \quad (i > 0)$$

$$P(|\breve{x}_q^{(0)} - x_q| > PL, no\ alert | H_0 \cap (\Delta^{(0)} = \Delta_j^{(0)})) < 2 \times Q\left(\frac{PL_q - \mathbf{A}_q^{(0)} \Delta_j^{(0)}}{\breve{\sigma}_q^{(0)}}\right) \quad (i = 0)$$

$Q$: Tail probability of a zero-mean unit normal distribution

$\mathbf{A}_q^{(i)}$ : Mapping the ambiguity offset $\Delta^{(i)}$ to the position error $\mathbf{A}_q^{(i)} = \mathbf{e}_q \cdot \widehat{\mathbf{P}}_{\boldsymbol{ba}}^{(i)} \cdot \left(\widehat{\mathbf{P}}_{\boldsymbol{aa}}^{(i)}\right)^{-1}$

# Integrity Risk Evaluation

## Integrity Risk Under Hypothesis $i$:

$$IR^{(i)} = P(H_i) \times \sum_{j=0}^{\infty} P\left(|\breve{x}_q^{(0)} - x_q| > PL_q, no\ alert | H_i \cap (\Delta^{(i)} = \Delta_j^{(i)})\right) \times P(\Delta^{(i)} = \Delta_j^{(i)} | H_i)$$

✓ **The second term:** [8][12]

$$P_{A,j}^{(i)} \triangleq P(\Delta^{(i)} = \Delta_j^{(i)}) = \prod_{\mathbb{i}=1}^{m_i} \left( \Phi\left( \frac{1 - 2\boldsymbol{l}_{\mathbb{i}}^{(i)\mathrm{T}} \cdot \Delta_j^{(i)}}{2\sigma_{\mathbb{i}|\mathbb{I}}^{(i)}} \right) + \Phi\left( \frac{1 + 2\boldsymbol{l}_{\mathbb{i}}^{(i)\mathrm{T}} \cdot \Delta_j^{(i)}}{2\sigma_{\mathbb{i}|\mathbb{I}}^{(i)}} \right) - 1 \right)$$

$$\hat{\mathbf{P}}_{\boldsymbol{aa}} = \mathbf{L}^{\mathrm{T}} \mathbf{D} \mathbf{L}$$

✓ **Ambiguity resolution success rate (i.e., correct-fix):** [12]

$$P_S^{(i)} \triangleq P(\Delta^{(i)} = 0) = \prod_{\mathbb{i}=1}^{m_i} \left( 2 \times \Phi\left( \frac{1}{2\sigma_{\mathbb{i}|\mathbb{I}}^{(i)}} \right) - 1 \right)$$

[8] Khanafseh S. and Pervan B. New Approach for Calculating Position Domain Integrity Risk for Cycle Resolution in Carrier Phase Navigation Systems. IEEE TAES, 2010, 46(1): 296-307.
[12] Teunissen P.J.G., Success Probability of Integer GPS Ambiguity Rounding and Bootstrapping. Journal of Geodesy, 1998, 72(10): 606-612.

# Integrity Risk Evaluation

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- **Integrity Risk Under Hypothesis $i$:** **Cannot monitor all the incorrect-fix events**

$$IR^{(i)} = P(H_i) \times \sum_{j=0}^{\infty} P\left(|\check{x}_q^{(0)} - x_q| > PL_q, no\ alert \,|\, H_i \cap (\Delta^{(i)} = \Delta_j^{(i)})\right) \times P(\Delta^{(i)} = \Delta_j^{(i)} | H_i)$$

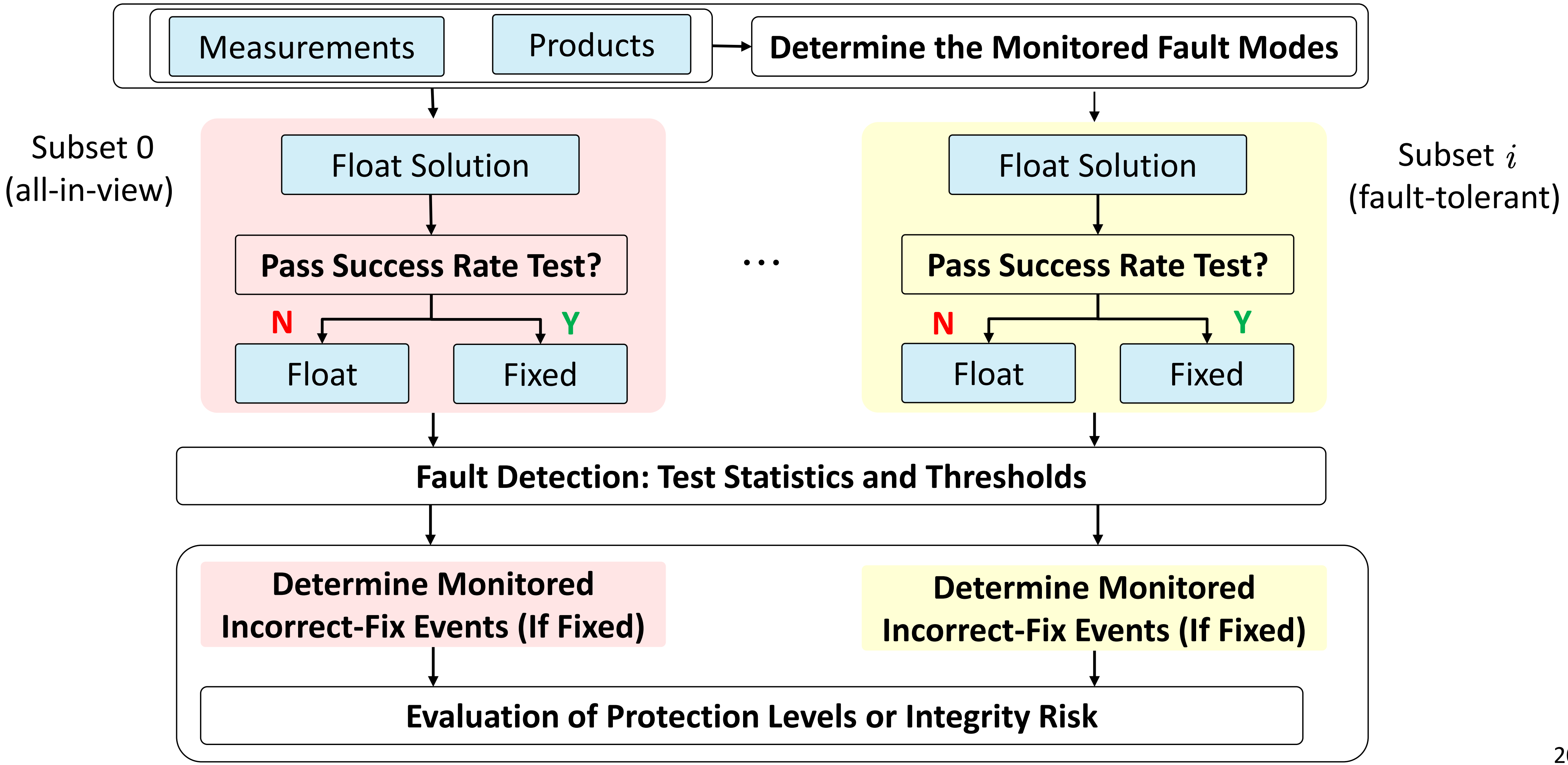
✓ **1. Determine the ambiguity candidates that need monitoring**

Monitor $\Delta^{(i)} = \{0, \Delta_1^{(i)}, -\Delta_1^{(i)}, \cdots, \Delta_{n_a^{(i)}}^{(i)}, -\Delta_{n_a^{(i)}}^{(i)}\}$ such that $1 - P_S^{(i)} - 2 \times \sum_{j=1}^{n_a^{(i)}} P_{A,j}^{(i)} < P_{A,NM,thr}^{(i)}$

✓ **2. Set the threshold for ambiguity resolution success rate**

- Subset $i$: $P_S^{(i)} > P_{S,thr}^{(i)}$ **To Fix** $P_S^{(i)} < P_{S,thr}^{(i)}$ **Not to Fix**
- If the all-in-view solution is not fixed, then all the subset solutions keep float.

# Summary


Measurements
Products
Determine the Monitored Fault Modes
Subset 0
(all-in-view)
Float Solution
Pass Success Rate Test?
N
Y
Float
Fixed
...
Subset $i$
(fault-tolerant)
Float Solution
Pass Success Rate Test?
N
Y
Float
Fixed
Fault Detection: Test Statistics and Thresholds
Determine Monitored Incorrect-Fix Events (If Fixed)
Determine Monitored Incorrect-Fix Events (If Fixed)
Evaluation of Protection Levels or Integrity Risk

# Outline

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# Simulation Set-up

| Category | Parameters | Values |
|---|---|---|
| **Constellations** | Constellations in use | GPS + BDS-3 |
| **Probabilities** | Satellite fault probabilities | $P_{sat} = 10^{-5}$ |
| **Performance Requirements** | Integrity risk allocations for east, north, and up positions | $P_{HMI,1} = P_{HMI,2} = 1 \times 10^{-9}$<br>$P_{HMI,3} = 9.8 \times 10^{-8}$ |
| | False alert budgets for east, north, and up positions | $P_{FA,1} = P_{FA,2} = 4.5 \times 10^{-8}$<br>$P_{FA,3} = 3.9 \times 10^{-6}$ |
| **Algorithm Settings** | Success rate thresholds for the all-in-view solution and fault-tolerant solutions | $P_{S,thr}^{(0)} = 0.9999$<br>$P_{S,thr}^{(i)} = 0.99$ |
| | Threshold for the integrity risk from unmonitored fault modes | $P_{THRES} = 6 \times 10^{-8}$ |
| | Thresholds for the integrity risk from unmonitored ambiguity candidates | $P_{A,NM,thr}^{(0)} = 1 \times 10^{-9}$<br>$P_{A,NM,thr}^{(i)} = 1 \times 10^{-5}$ |

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# Simulation Results

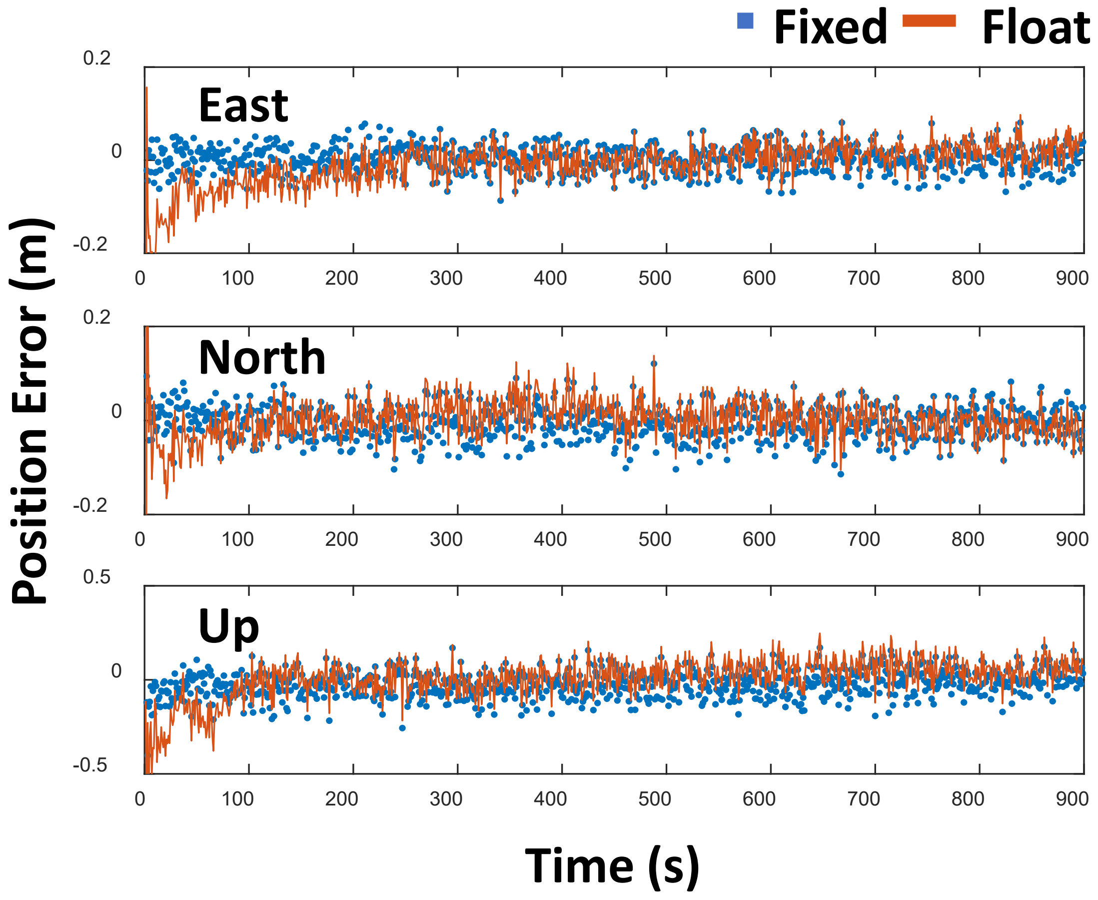


**Fig. 1**. Position error comparison between fixed and float solutions

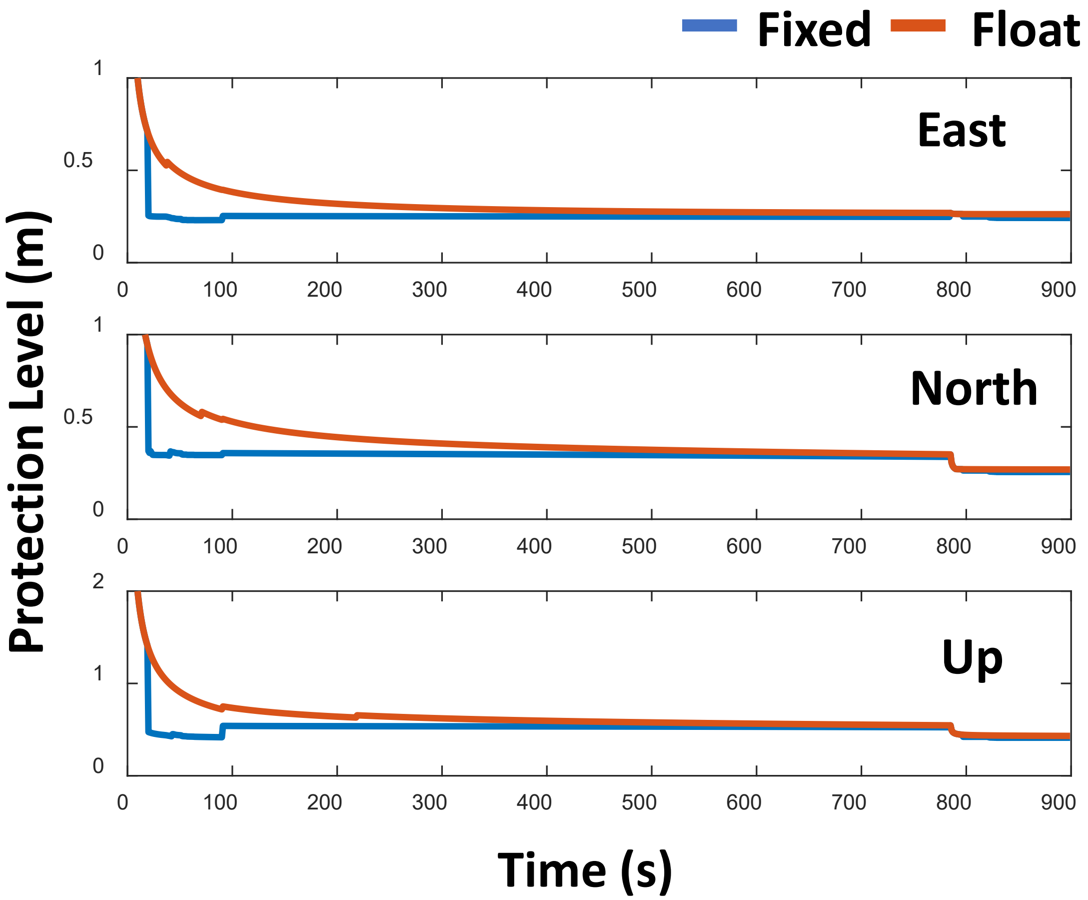


**Fig. 2**. Protection level comparison between fixed and float solutions

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# Simulation Results

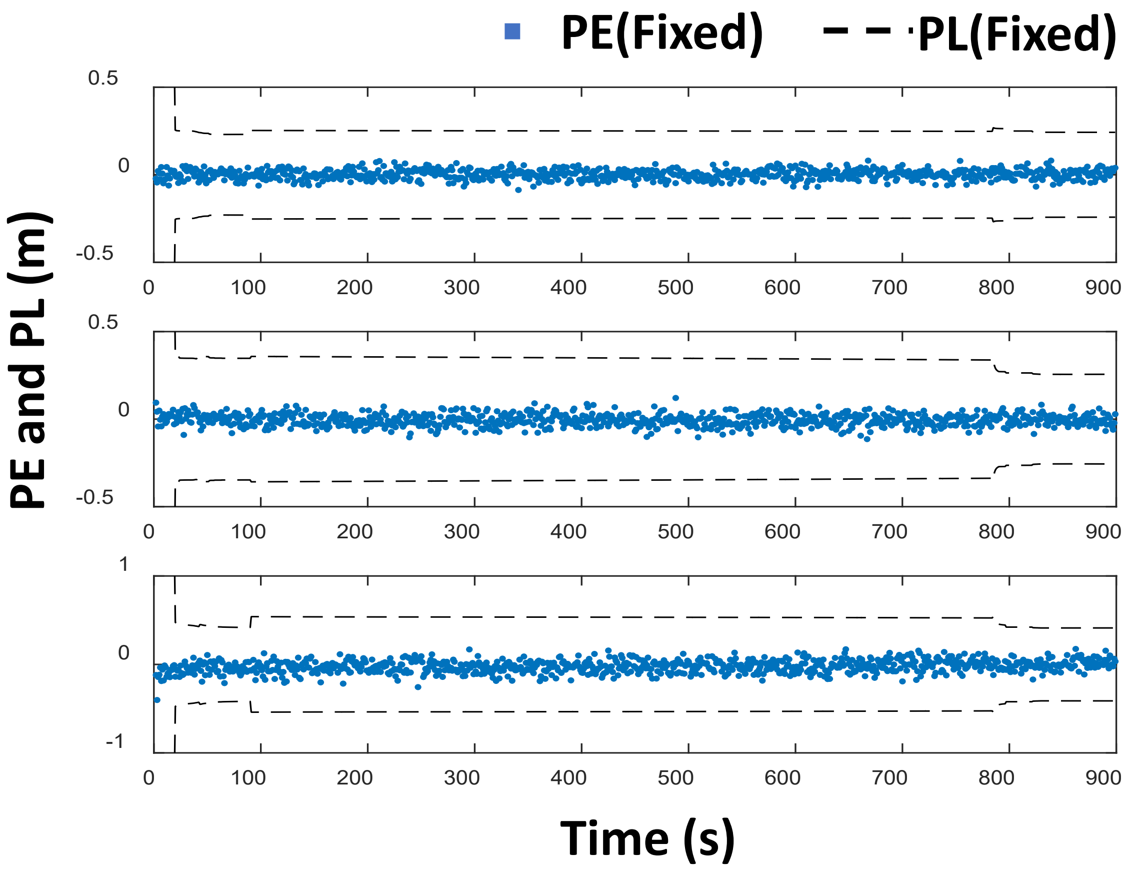


**Fig. 3**. Protection levels (PL) and position errors (PE) in a fault-free condition

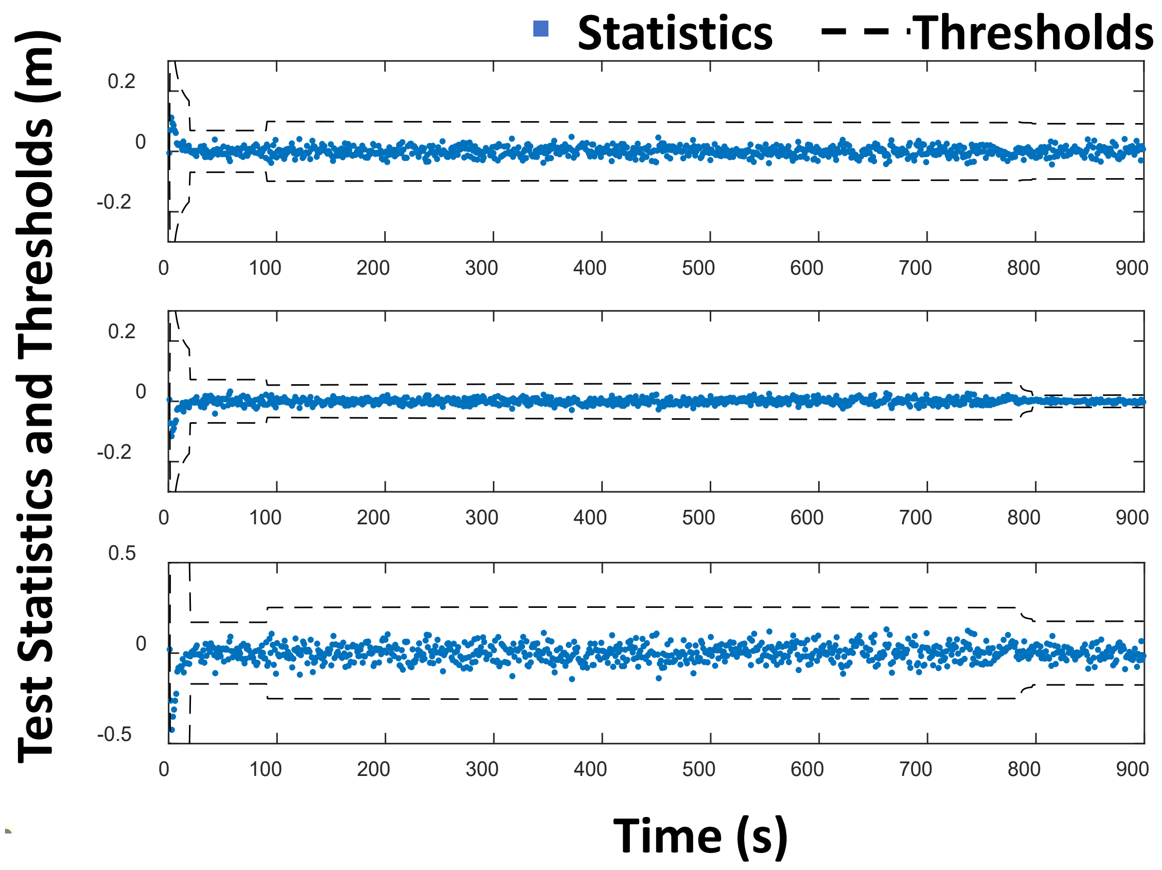


**Fig. 4**. Test statistics and thresholds (for subset 1) in a fault-free condition

# Simulation Results

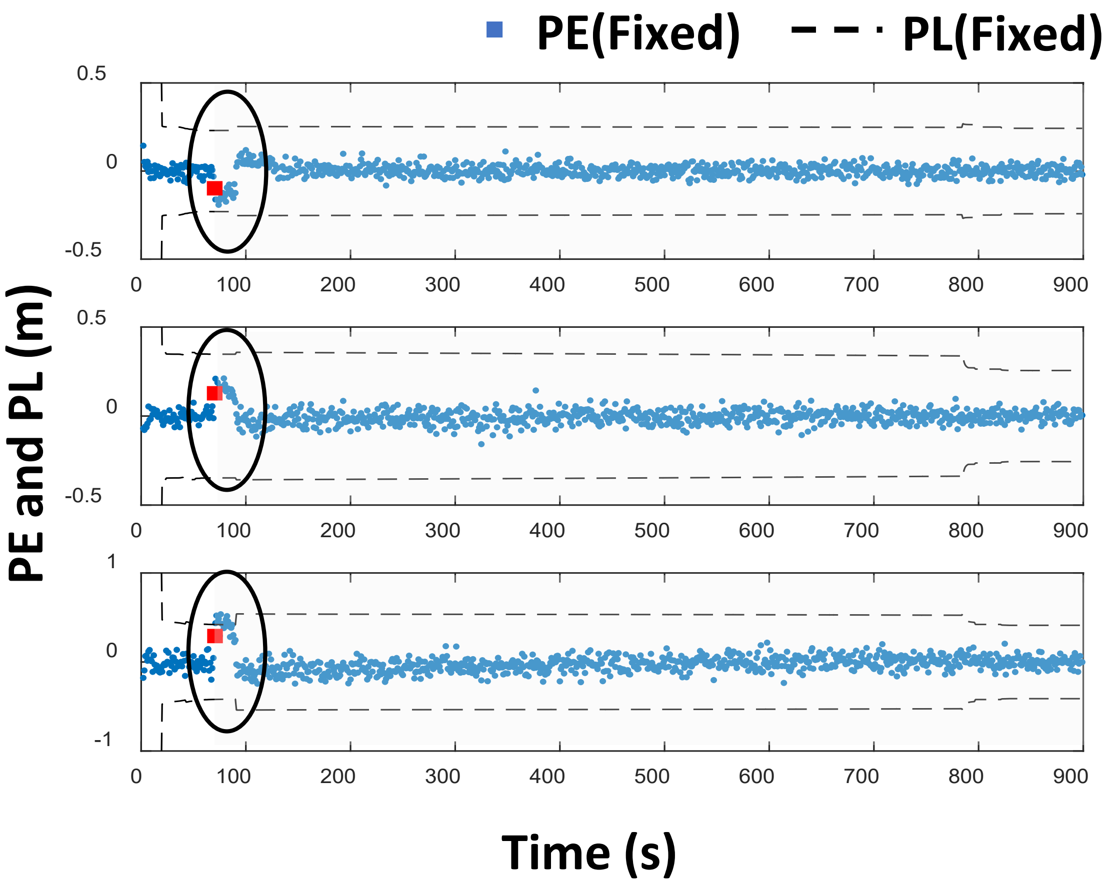


**Fig. 5**. Protection levels and position errors in the presence of an undetected cycle slip

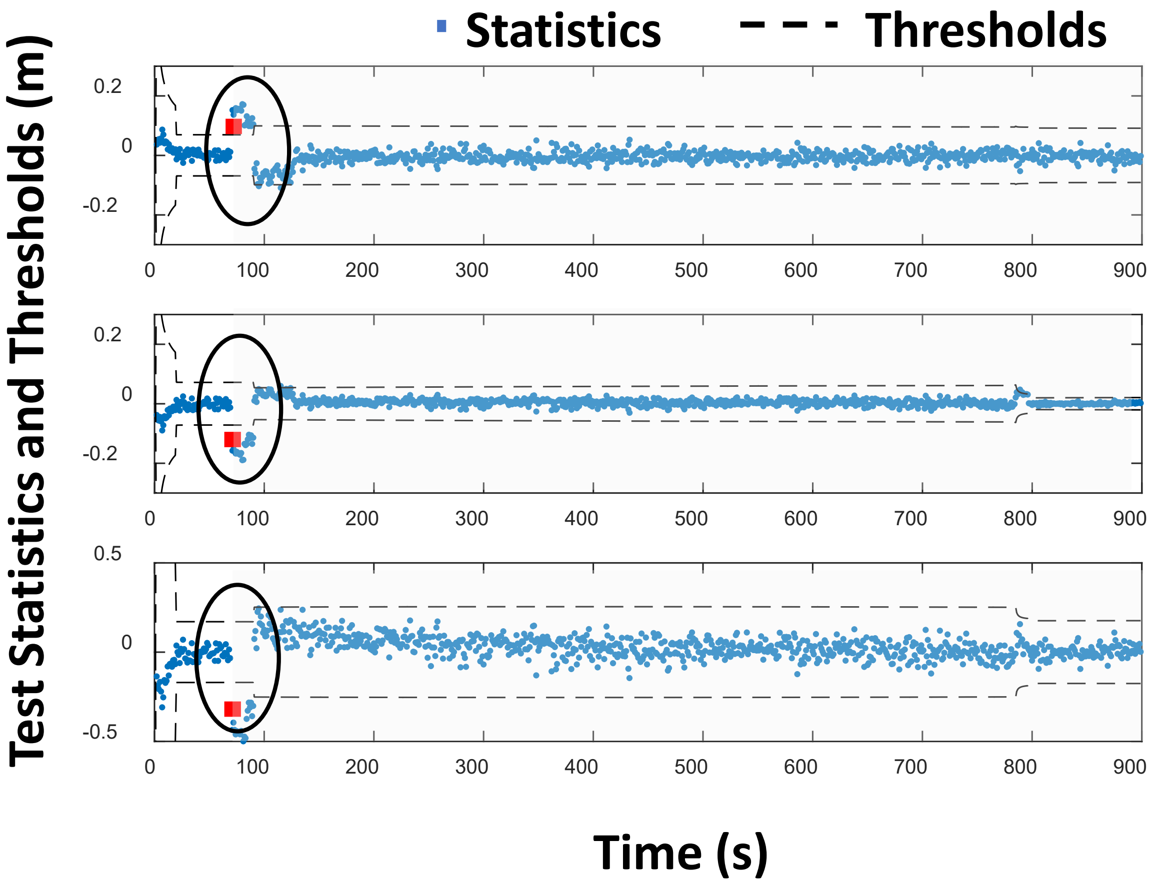


**Fig. 6**. Test statistics and thresholds for subset 1 in the presence of an undetected cycle slip

# Simulation Results

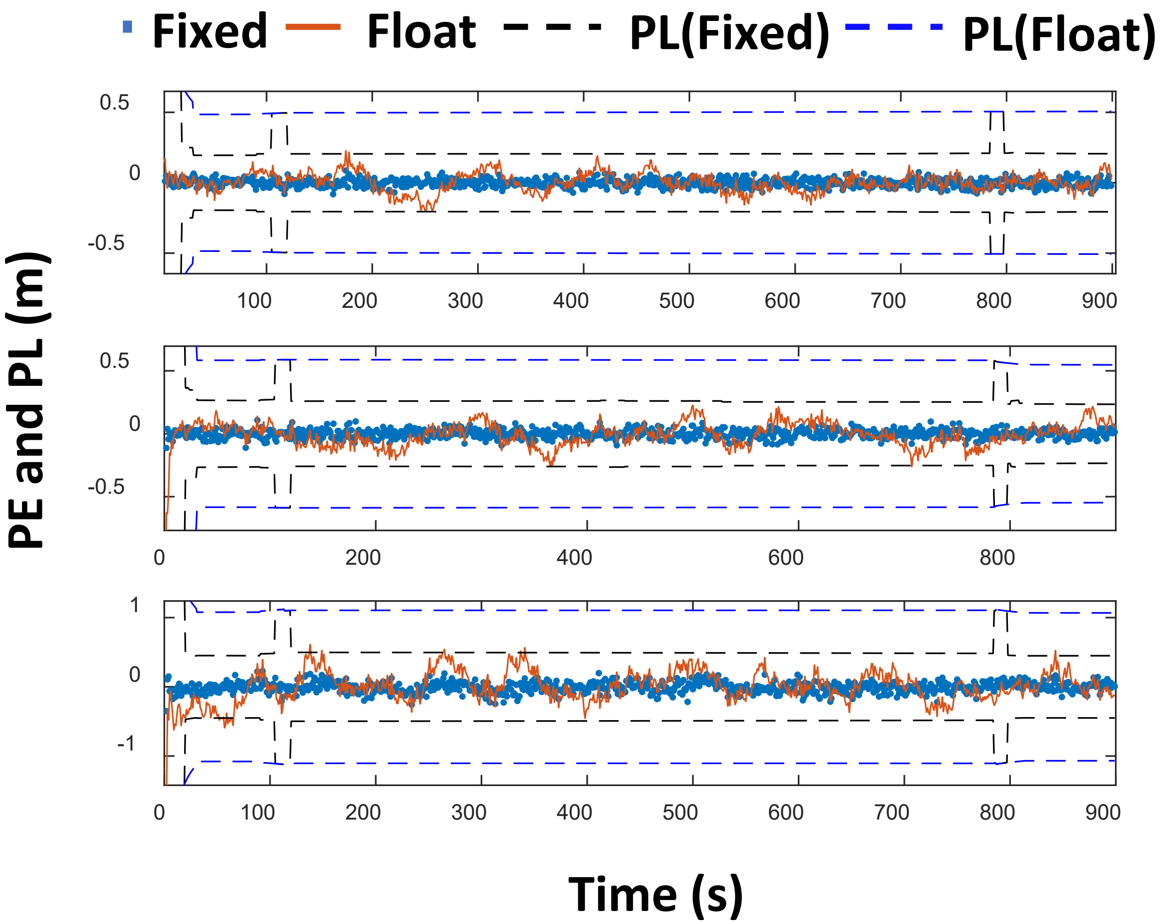


**Fig. 7**. Protection levels and position errors with a sliding-window least-squares estimator

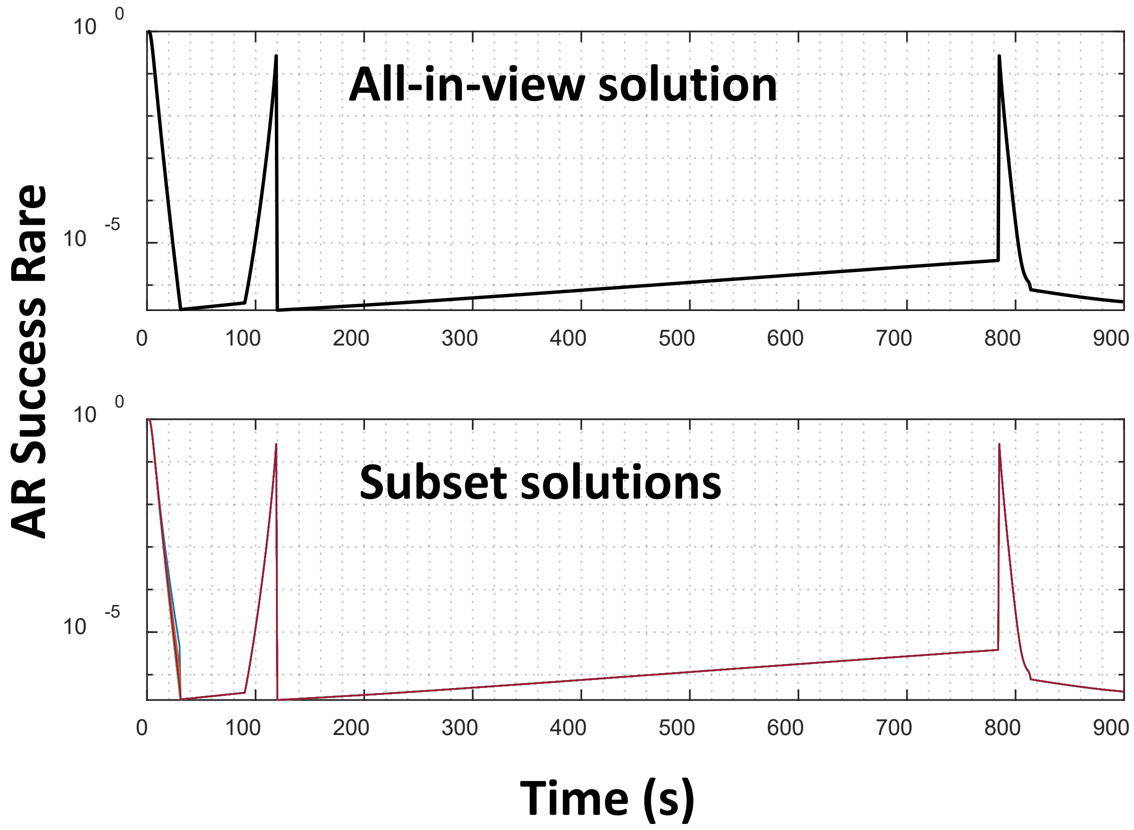


**Fig. 8**. Ambiguity resolution success rate with a sliding-window least-squares estimator

# Conclusions

- **We develop an integrity monitoring algorithm for GNSS positioning with ambiguity resolution, based on a modified MHSS architecture:**
  - We derive the closed-form protection level evaluation equation
  - Monitor measurement/product faults and incorrect ambiguity resolution simultaneously.
  - Simulation results suggest the effectiveness of this algorithm and imply that enabling ambiguity resolution can benefit navigation accuracy and integrity.

- **Our future work will focus on:**
  - (a) Fault exclusion; (b) support other AR methods; (c) time correlation

# Thank you for your attention!

## Questions? More Information?

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Full-text