SESAR JOINT UNDERTAKING

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SESAR Innovation Days
12 – 15 November 2024

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SATERA Baseline: Identifying the Challenges of Space-Based Multilateration Systems

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12 – 15 November 2024

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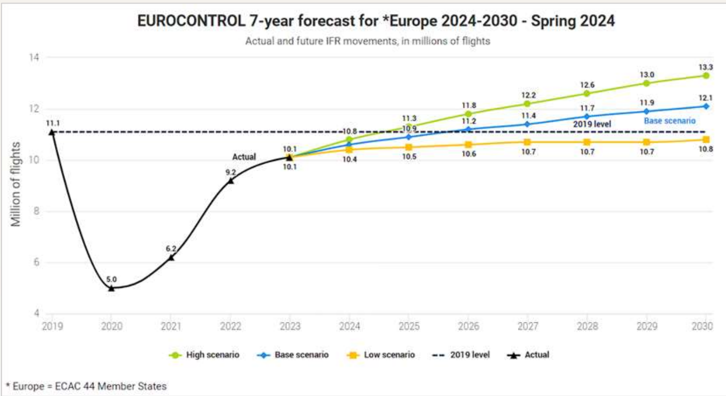
1. Introduction

Air traffic growth and congestion challenges

Need for safe and efficient management of aircraft in increasingly dense airspaces



Ref: Eurocontrol

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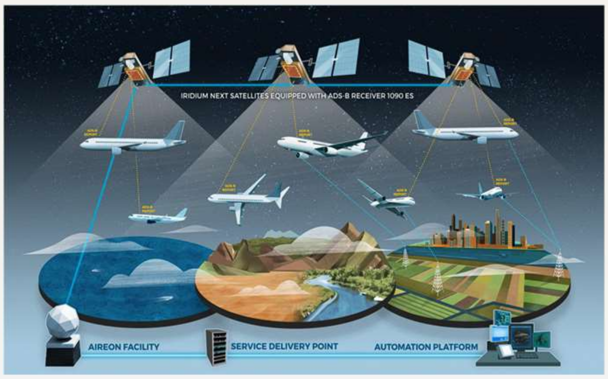
1. Introduction

SSR and ADS-B as main surveillance technologies

- Air surveillance primarily relies on SSR and ADS-B.
- ADS-B has improved ground-based surveillance, but there are **limitations remain in remote areas** without supporting infrastructure
- Remote areas still have limitations for surveillance, **restricting route optimization** and **increasing separation between aircraft**.

1. Introduction

Limitations in remote areas, solution: SB ADS-B



Ref: Aireon

- Monitoring aircraft through a network of **low earth orbit satellites**.
- **High update rates** on flight progress.
- Planning more **efficient and safer** routes, optimizing fuel use.

1. Introduction

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Challenges and risks of SB ADS-B

- **The dependence on GNSS makes SB ADS-B vulnerable to interference**, such as jamming or spoofing, affecting data quality. In addition, ADS-B itself is vulnerable to spoofing and jamming too.
- An **independent secondary system** is necessary to improve robustness.
- The combined use of **ADS-B and MLAT** systems, known as composite surveillance, offers an alternative to using ADS-B and SSR Mode S alone.

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1. Introduction

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Objective of the SATERA project

- Develop and validate, through simulations, a **space-based ADS-B + MLAT** composite system using **small satellites** in low Earth orbit (**LEO**).
- This paper aims to contribute to setting the baseline for the project and identify specific challenges.
- It presents the outcomes of the initial steps:
  - Adapting MLAT localization algorithms for the space environment.
  - Implementing regularization techniques to mitigate potential ill-conditioning issues.
  - Employing advanced tracking algorithms based on the Kalman filter and the Interacting Multiple Model (IMM) filter.

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Methodology

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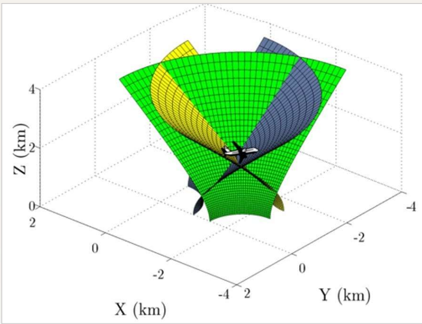
2. Methodology

Multilateration (MLAT)

- Cooperative and independent method for determining the position of a target.
- The system uses signals emitted by aircraft transponders to determine its position by measuring the Time Of Arrival (TOA) and calculates TDOA.



$$\widehat{TDOA}_{i,1} = \frac{1}{c}\|\theta - \vartheta_1\| - \frac{1}{c}\|\theta - \vartheta_i\| + n_{i,1} \quad ,i = 2, \dots, N_s$$

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2. Methodology

Localization algorithms

- Solving the inverse problem. $\mathbf{G}\boldsymbol{\theta} = \widehat{\mathbf{m}}$
- Taylor series expansion method is used. Based on **Least Squares (LS).**
- The problem is approached iteratively to refine the position estimate. Starting point given by **Bancroft's** algorithm.

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2. Methodology

Regularization

- When solving an inverse problem, the system can be either **well-conditioned or ill-conditioned**, depending on factors like system geometry, measurement noise, and initial estimation quality.
  - Ill-conditioning can lead to incorrect or divergent solutions, resulting in significant errors.
- To mitigate errors caused by ill-conditioning, **Tikhonov regularization** is applied to the iterative Taylor series method:
  - This helps reduce sensitivity to measurement errors and provides more stable, reliable results.

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2. Methodology

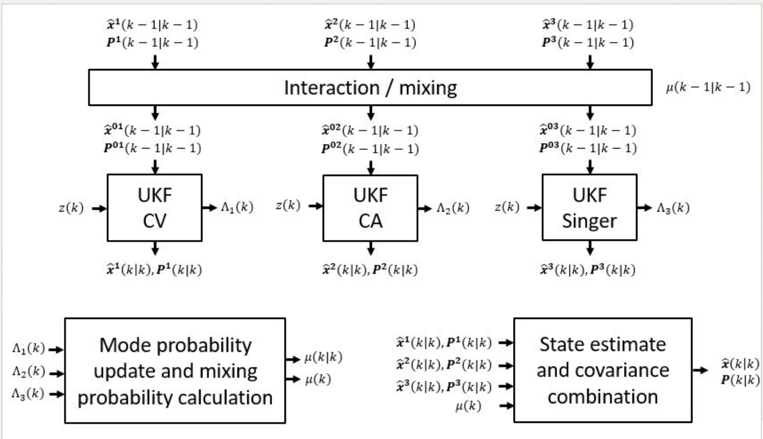
Tracking filter

- To overcome ill-conditioning issues, an **aircraft tracking filter** has been implemented.
- The advanced filter combines the **Unscented Kalman Filter (UKF)** with the **Interacting Multiple Model (IMM)** approach.
  - This approach allows us to adapt to different flight conditions by utilizing multiple maneuver models, ensuring robust tracking in dynamic environments.

2. Methodology

Tracking filter

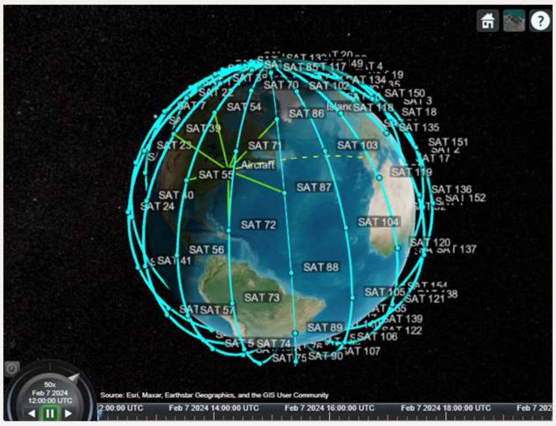
- Three UKF in parallel
- Maneuver models:
  - Constant Velocity (CV)
  - Constant Acceleration (CA)
  - Singer
- Get a joint estimate



2. Methodology

Simulations

- MATLAB environment
- Designed a constellation with 160 satellites spread across 10 orbital planes.
- Inclination: 86,4° (near polar)
- Height: 780 km



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2. Methodology

Simulations

- Trajectory in the North Atlantic region.
- A total of 100 waypoints.
- Evaluate the impact of:
  - TOA measurement error,
  - Satellite position errors
- To assess system performance:
  - Analysis of 2D RMS error and bias.
  - Computed through 100 Monte Carlo trials.
  - Compared with the Cramér-Rao Lower Bound (CRLB).

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Results

3. Results

Comparison of the CRLB, the Taylor series method, its Tikhonov-regularized version, and the IMM+UKF.

Scenario 1

$\sigma_{TOA} = 10\ ns$

$\sigma_{SAT} = 10$ m

Scenario 2

$\sigma_{TOA} = 1\ \mu s$

$\sigma_{SAT} = 10$ m

Scenario 3

$\sigma_{TOA} = 10\ ns$

$\sigma_{SAT} = 240$ m

Main conclusions

IMM+UKF demonstrates significantly greater accuracy and lower bias, with RMS error levels below 300 meters in all scenarios, aligning closely with regulatory standards.

Taylor Method and Tikhonov Regularization produce similar error and bias results across all scenarios. However, in Scenarios 1 and 3, Tikhonov achieves lower RMS error values at specific points along the trajectory, suggesting the presence of some ill-conditioning.

Both RMS error and bias levels are higher in the Scenario 2, indicating greater sensitivity to random time measurement errors.

Conclusion

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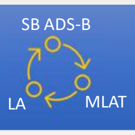
4. Conclusion



Analysis of various localization methods in the context of a space-based MLAT system for aircraft position estimation.

Superior performance of the IMM+UKF filter, approaching the standards governed by regulations.

Future work

- Analyze synchronization errors in satellites,
- Used hybrid methods (AOA,FDOA,…),
- Analyzing the communication network, …

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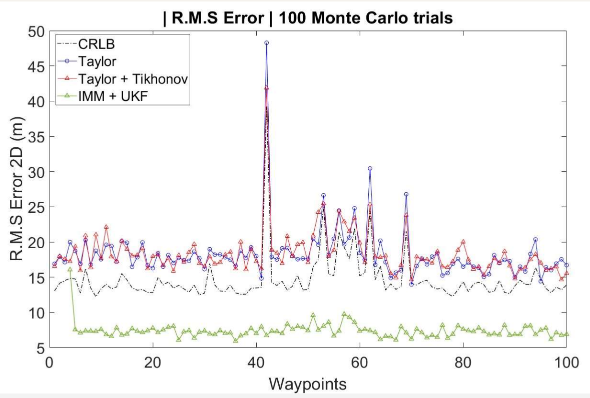
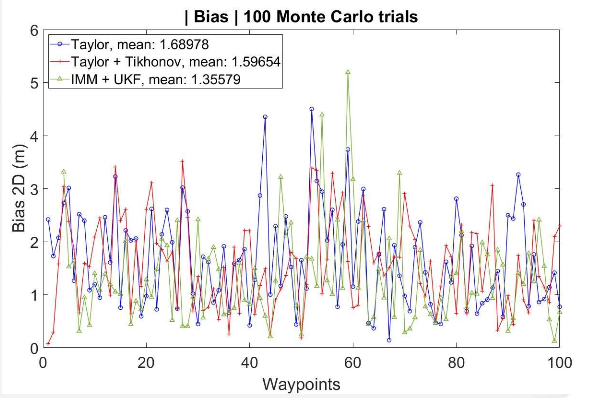
3. Results

Comparison of the CRLB, the Taylor series method, its Tikhonov-regularized version, and the IMM+UKF filter with a $\boldsymbol{\sigma_{TOA} = 10^{-8}\ s}$, $\boldsymbol{\sigma_{SAT} = 10}$ **m** and a take-off time of **12:00h**.





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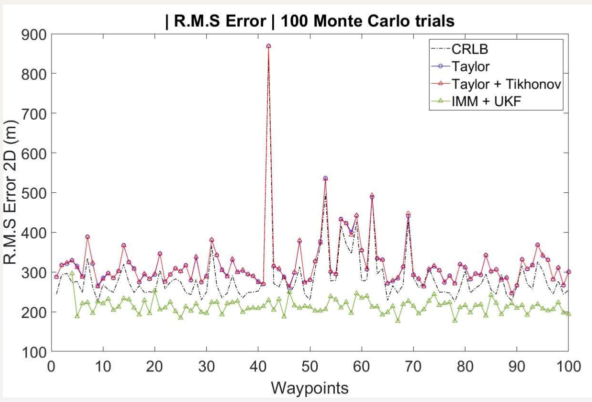
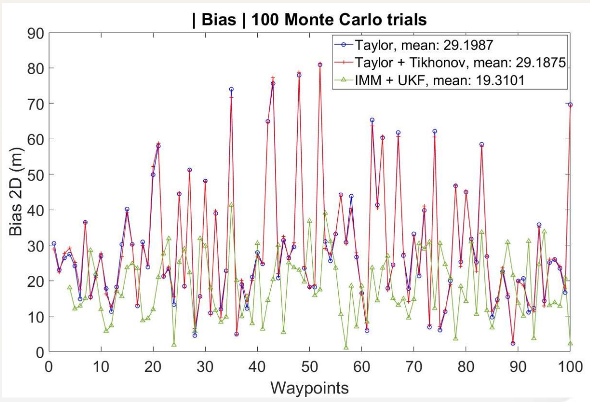
3. Results

Comparison of the CRLB, the Taylor series method, its Tikhonov-regularized version, and the IMM+UKF filter with a $\boldsymbol{\sigma_{TOA} = 10^{-6}\ s}$, $\sigma_{SAT} = 10$ m and a take-off time of 12:00h.





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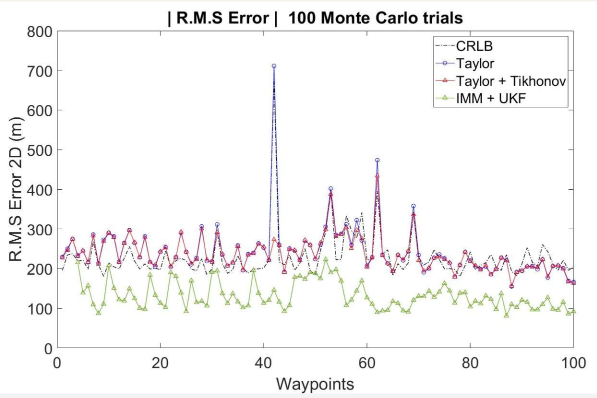
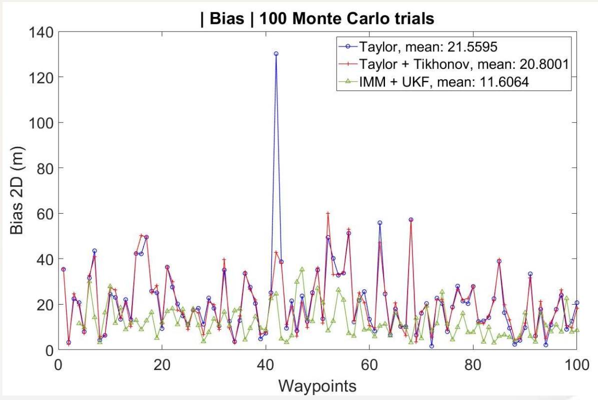
3. Results

Comparison of the CRLB, the Taylor series method, its Tikhonov-regularized version, and the IMM+UKF filter with a $\sigma_{TOA} = 10^{-8}\ s$, $\boldsymbol{\sigma_{SAT}} = \mathbf{240\ m}$ and a take-off time of 12:00h.





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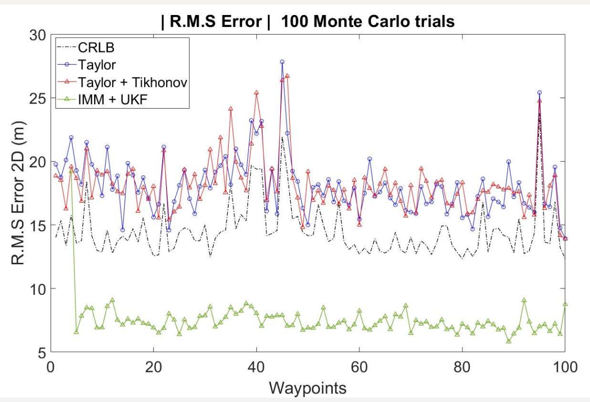
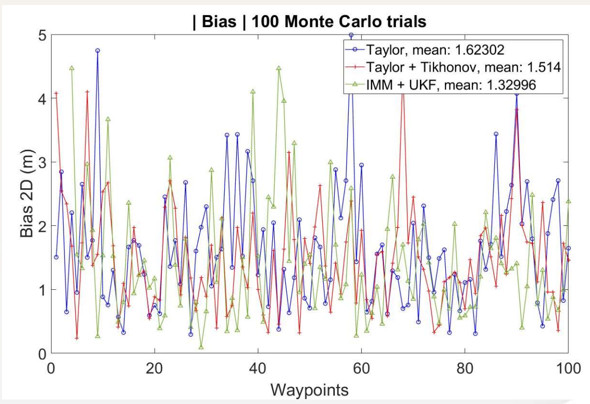
3. Results

Comparison of the CRLB, the Taylor series method, its Tikhonov-regularized version, and the IMM+UKF filter with a $\sigma_{TOA} = 10^{-8}\ s$, $\sigma_{SAT} = 10$ m and a take-off time of **14:00h**.





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3. Results

Comparison of the CRLB, the Taylor series method, its Tikhonov-regularized version, and the IMM+UKF.

Scenario 1 - $\sigma_{TOA} = 10\ ns, \sigma_{SAT} = 10$ m

- Taylor method and Tikhonov regularization produce similar error and bias results (RMS error around 15-20 m and bias around 1.5 m).
- Tikhonov achieves lower RMS error values at specific points along the trajectory, suggesting some ill-conditioning.
- Both positioned slightly above the Cramer-Rao bound by a few meters.
- IMM+UKF filter, however, consistently performs better, with lower RMS error and bias (around 7 m and 1.3 m, respectively).

3. Results

Scenario 2 - $\sigma_{TOA} = 1\ \mu s, \sigma_{SAT} = 10$ m

- RMS error and bias increased significantly across all evaluated methods, highlighting their sensitivity to noise in the time measurements.
- Taylor and Tikhonov methods yield very similar results (error around 300 m and bias of 29 m).
- IMM+UKF filter continues demonstrating a stable performance (error around 200m and bias of 19 m).

Scenario 3 - $\sigma_{TOA} = 10\ ns, \sigma_{SAT} = 240$ m