Optimizing LEO Orbital Monitoring: Multi-Static Radar for Improved Tracking During Low Thrust Maneuver

Poster ID-267

Bhaskar Ahuja[1,2], Luca Gentile[2], Marco Martorella[2,3]
[1]University of Trento , Trento (38123), Italy
[2]RaSS National Laboratory, National Inter-University Consortium for Telecommunications (CNIT), Pisa (56124), Italy
[3]University of Birmingham, Microwave Integrated Systems Laboratory (MISL), UK

1. Introduction

This study presents a cost-effective solution for real-time satellite tracking using combinations of radar and existing radio telescopes when spacecraft performs maneuver. By employing an Unscented Kalman Filter (UKF) to estimate state vectors, the integration of multi-static radar and tangential thrust improves spacecraft positioning and trajectory predictions. The system demonstrates significant accuracy enhancements, reducing errors in Keplerian parameters and improving Root Mean Square Error (RMSE) in position and velocity estimation.

Motivation

- Objects maneuvering with very low thrust
- LEO to GEO transfer mission
- Upcoming satellite missions with electric propulsion

2. Flow Chart

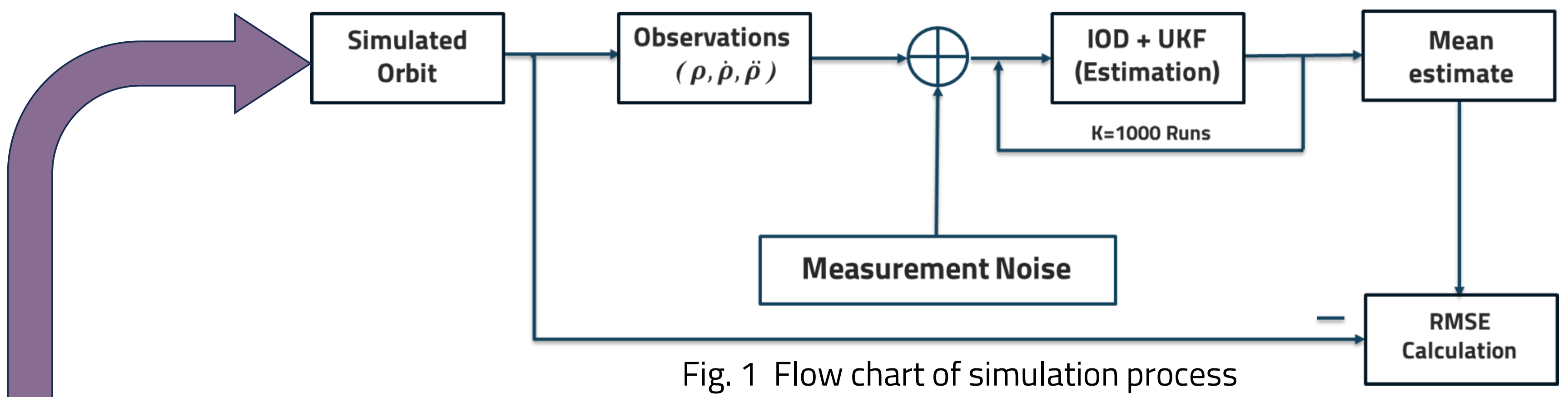
Simulated Orbit
Observations $(\rho, \dot{\rho}, \ddot{\rho})$
IOD + UKF (Estimation)
K=1000 Runs
Mean estimate
Measurement Noise
RMSE Calculation

Fig. 1 Flow chart of simulation process

Table 1- Initial Keplerian parameters of spacecraft

	Semi-Major axis (m)	Eccentricity	Inclination (°)	RAAN (°)	Arg periapsis (°)	True Anomaly (°)
Initial Parameters	8369506.747	0.0012	51.934	152.428	353.704	2.703

3. Orbit Propagation

$$\ddot{\vec{r}} = -\frac{\mu\vec{r}}{|r|^3} + \sum_{i=1}^{N} a_{perturb}$$, where μ=Standard Gravitational Parameter

Cowell's Formulation

$$X=\begin{Bmatrix} r_I \\ r_J \\ r_K \\ v_I \\ v_J \\ v_K \\ a_{th_I} \\ a_{th_J} \\ a_{th_K} \end{Bmatrix} \qquad \dot{X}=\begin{Bmatrix} v_I \\ v_J \\ v_K \\ -\frac{\mu r_I}{|r|^3}+a_{th_I} \\ -\frac{\mu r_J}{|r|^3}+a_{th_J} \\ -\frac{\mu r_K}{|r|^3}+a_{th_k} \\ 0 \\ 0 \\ 0 \end{Bmatrix}_{9\times1}$$

Allow us to Calculate maneuver directly

Solving differential Equation with Runge-kutta Method

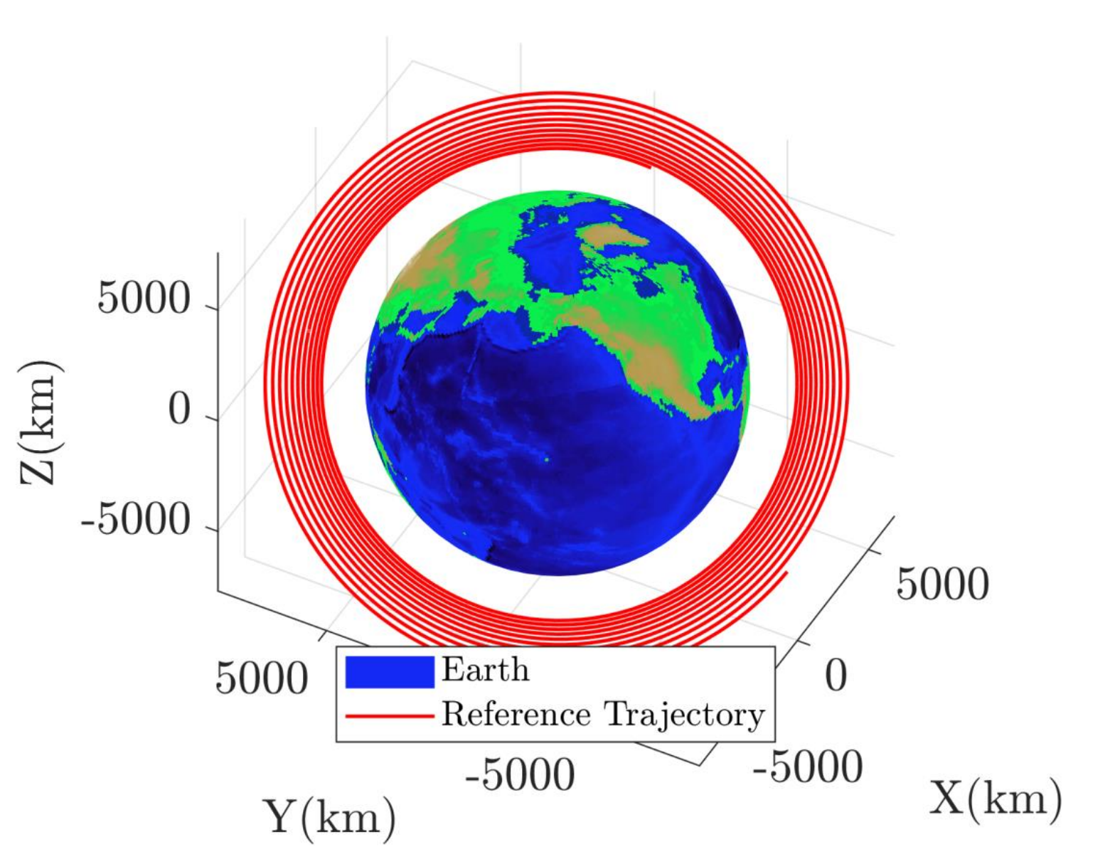

Fig. 2 Trajectory in ECI system with Propagation Time – 24 Hours, a_{thrust} ~ 9 mm/s²

4. Ground Track

Here we have considered combination of existing radars and radio telescopes from Italy.

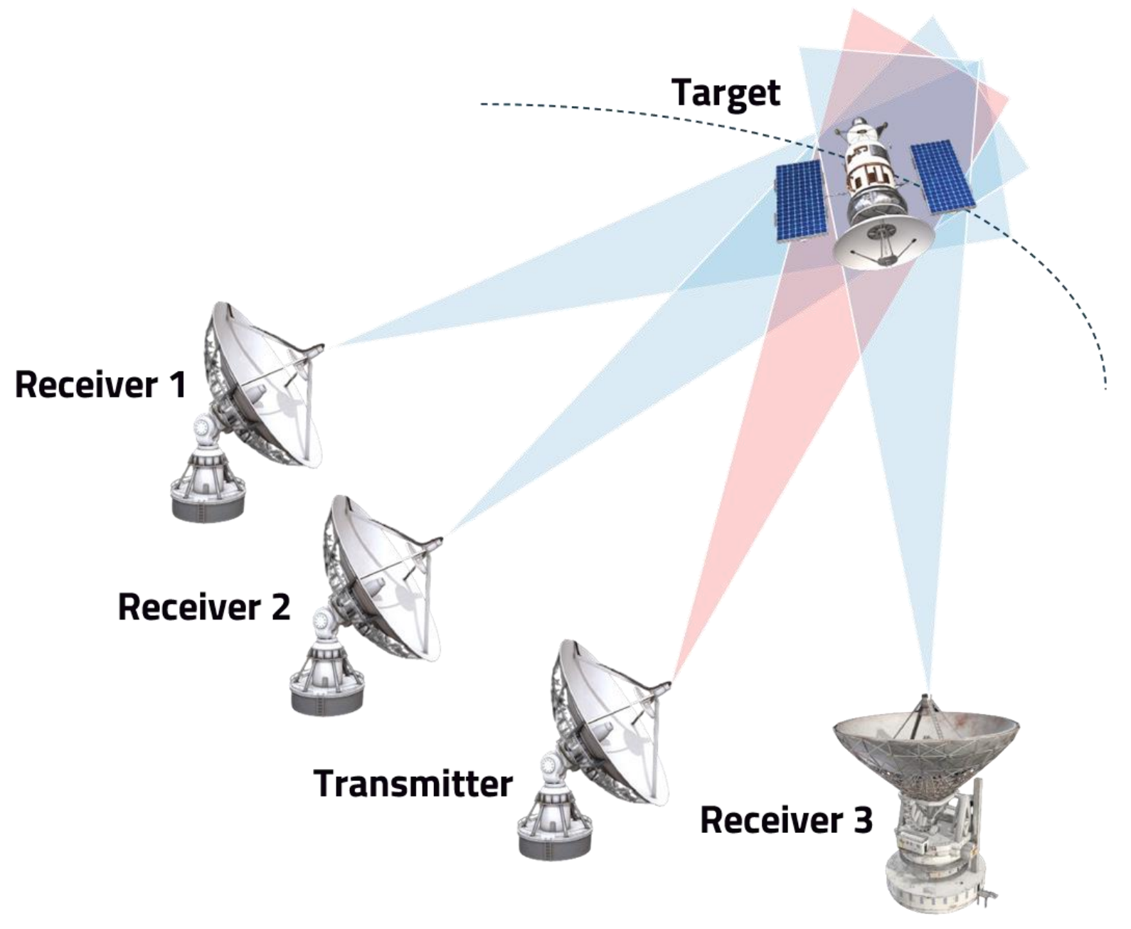

Fig. 3 Multi-static scenario utilizing one transmitter and three receivers

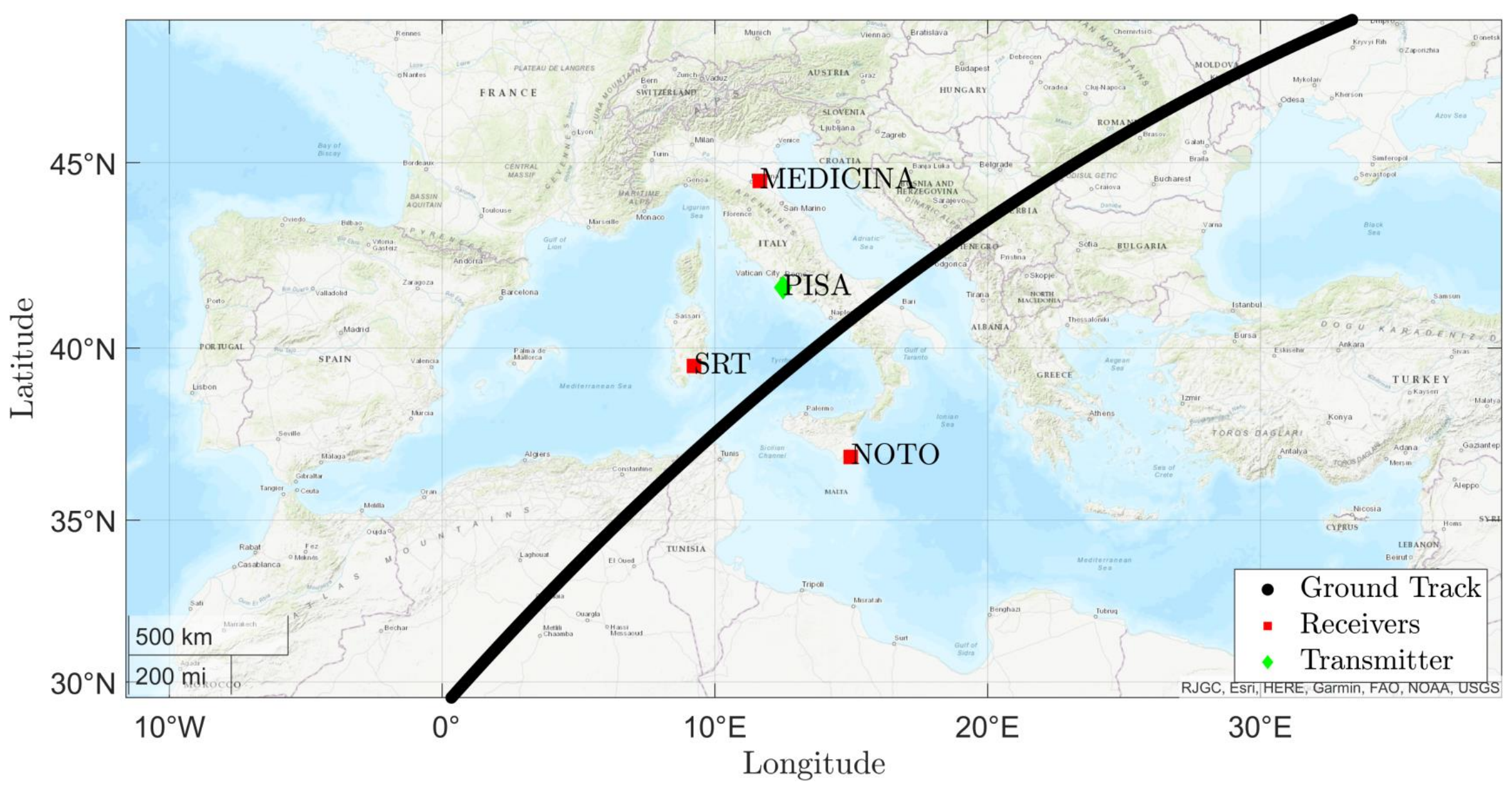

Fig. 4 Ground track of spacecraft when passing through considered sensors

5. Initial Orbit Determination

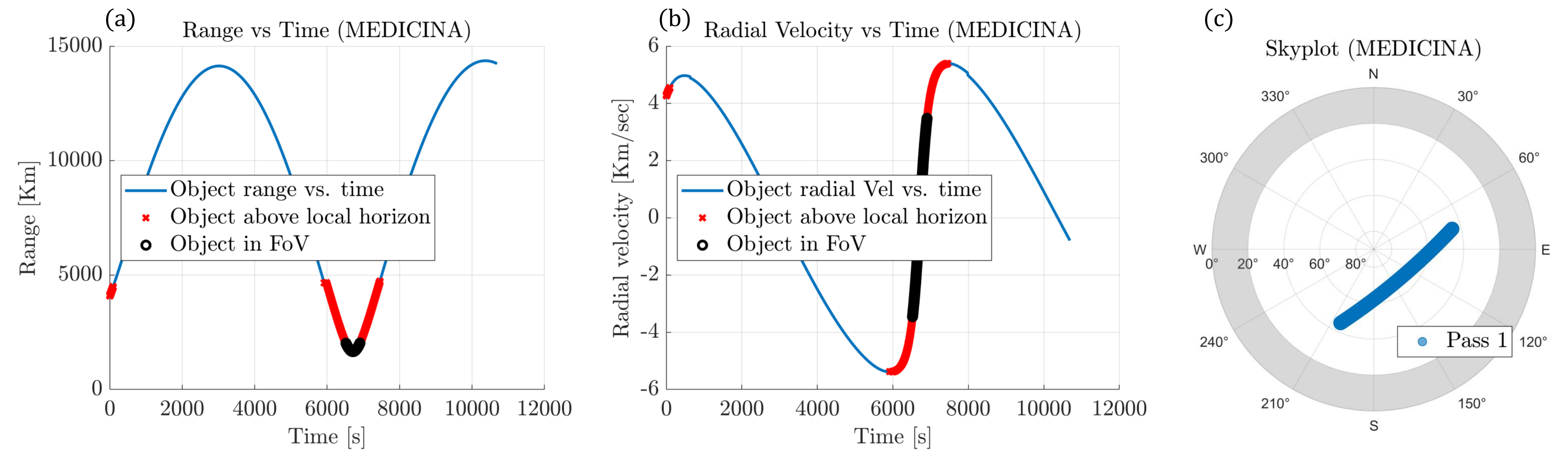

Fig. 5 Observations from the MEDICINA sensor (a) Range (b) Radial velocity (c) Skyplot (Azimuth and Elevation)

IOD with Mixed observations- Range and Range Rate

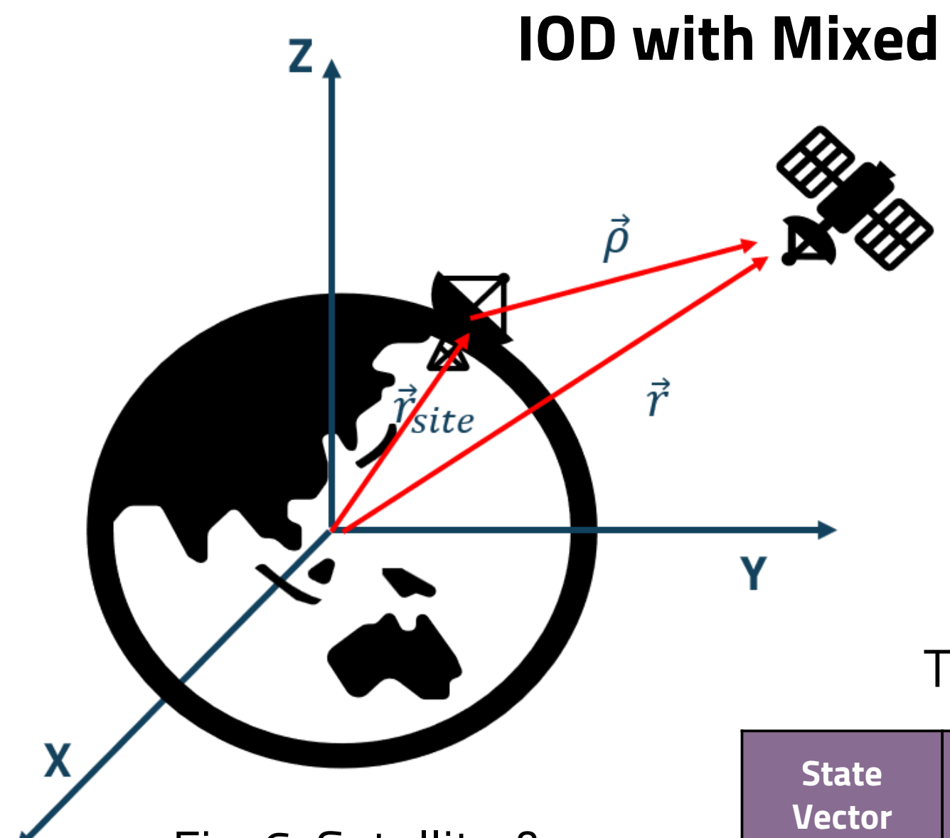

Fig. 6 Satellite & sensor position in ECI coordinate system

$$\vec{\rho_i} = \vec{r} - \vec{r}_{site_i} \qquad i = 1,2,3$$

$$\rho_i^2 = r^2 - 2\vec{r}\cdot\vec{r}_{site_i} + r_{site_i}^2$$

Table 2-RMSE In position and velocity for IOD

State Vector	r_I (m)	r_J (m)	r_K (m)	V_I (m/s)	V_J (m/s)	V_K (m/s)
RMSE Error	122.9	934.14	785.21	2.23	9.22	7.78

6. Tracking with UKF

- ❑ UKF is an advanced state estimation technique for non-linear systems
- ❑ Provides more accurate orbit determination by effectively managing non-linearities
- ❑ More reliable under high noise and uncertainty compared to traditional filters

Scan time – 0.1 s
Total Measurement time– 5 s
Total Observation – 50

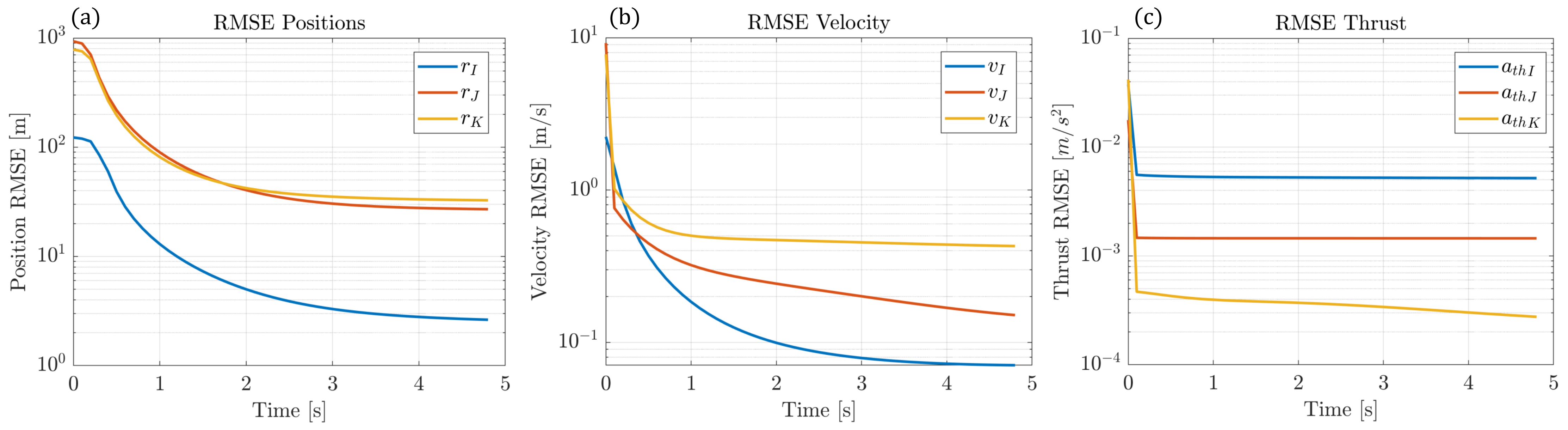

Fig. 7 Root Mean square in state vectors (a) Positions (b) Velocity (c) Acceleration due to thrust

7. Performance Analysis

Covariance Position Trace (3 σ)

- Shows error estimation and higher confidence in state estimate

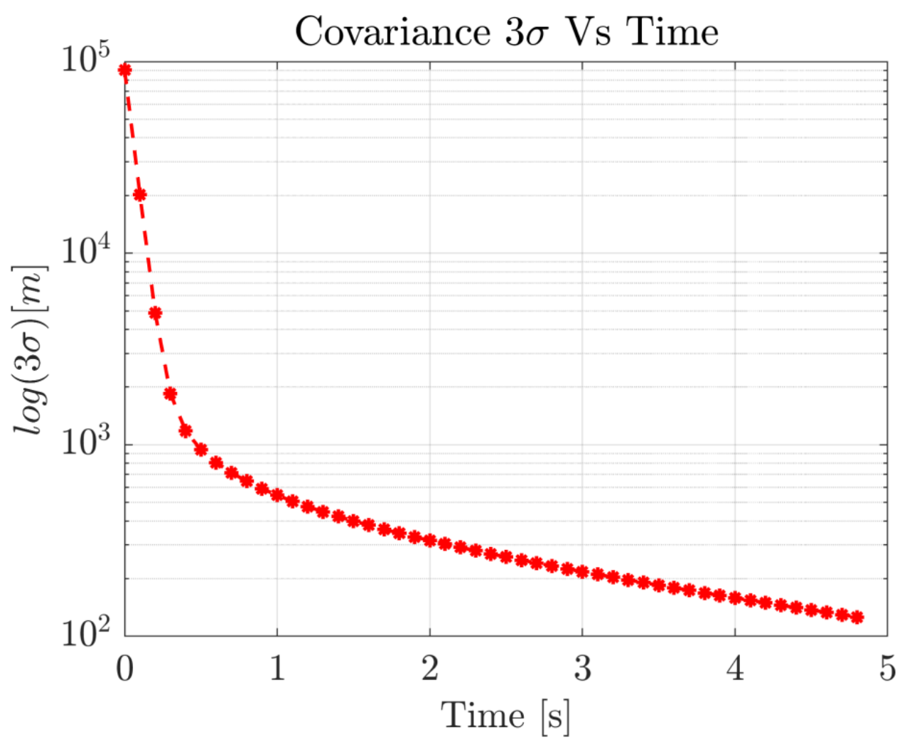

Fig. 8 Covariance Trace

Table 3- Absolute % error at the end of tracking filter

	Absolute Error(%)
Semi-Major axis (m)	0.0056
Eccentricity	5.1714
Inclination (°)	0.0012
RAAN (°)	0.0014
Arg periapsis (°)	0.2439
True Anomaly (°)	0.2425

8. Conclusion

By integrating maneuver detection capabilities into orbit determination routines, the system can adapt to changes in propulsion and provide more precise orbital calculations in real-time. This advancement will ultimately contribute to space missions' overall success and safety by ensuring that spacecrafts remain on their intended path.

Future Work

- More rigorous simulations, including perturbations
- Improvement in Initial orbit Determination with multiple radars
- Use of azimuth and elevation data from tracking radars
- Propagation of state vectors to the next sensor

References

1. D. A. Vallado "Fundamentals of astrodynamics and applications" Springer Science , 2001
2. T. Kelecy, et al, "Detection and orbit determination of a satellite executing low thrust maneuvers", Acta Astronautica 2010
3. G. M. Goff, "Orbit estimation of non-cooperative maneuvering spacecraft," 2015.
4. D. Catalado et al "Multi-Bistatic Radars for Space Surveillance and Tracking," IEEE AESS Magazine , 2020

Acknowledgements

This poster and related research have been conducted during and with the support of the Italian National inter-university PhD program in Space Science and Technology.

PhD SST
Space Science and Technology

Publication

B. Ahuja, L. Gentile, M. Martorella , "Improving satellite position and velocity calculation during low thrust maneuvers", 4th IAA conference on Space Situational Awareness , 2024 *(Won 3rd Best Paper Award)*

Contact Details

Bhaskar Ahuja (PhD Student 38th cycle)
University of Trento,
CNIT RaSS laboratory, Pisa
Email: bhaskar.ahuja@unitn.it

Scan me!