Lunar S Band Pseudolite System Architecture & User Equipment

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Outline of the Presentation

- Hybrid Pseudolite & Satellite System for Lunar PNT
- Pseudolite & Satellite Hybrid Configuration
- EKF Design for Low Dynamic Lunar Rover
- Position Accuracy with Different Satellite & Pseudolite Combinations
- Doppler-based Positioning Receiver Proto-type Development
- Conclusion

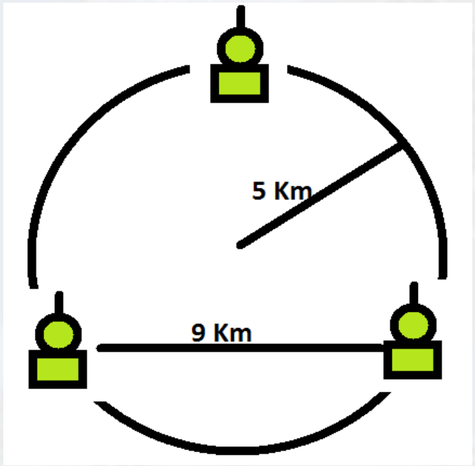
Introduction

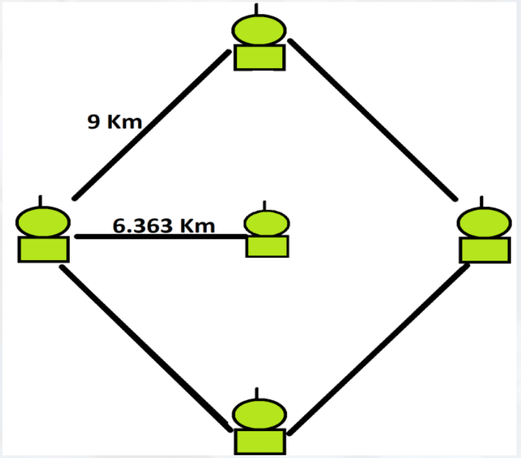
- Reliable and independent positioning, navigation, and timing capabilities are essential for sustained lunar surface operations.
- This work proposes architecture of a hybrid lunar navigation system which combines surface-based S-band pseudolites with an Elliptical Lunar Frozen Orbit (ELFO) satellite constellation.
- An EKF is designed & implemented to fuse satellite and pseudolite pseudorange measurements in order to provide dynamic state estimation and significantly reduce noise in low-dynamic lunar rover positioning.
- This is to ensure the continuous availability of signals and improved geometric diversity to achieve targeted 3D position accuracy.
- STK and MATLAB high-fidelity simulations evaluate coverage, navigation feasibility, and pseudolite augmentation benefits under various geometric configurations.
- Position accuracy is estimated with only Lunar navigation satellite data & with the combination of satellite & Pseudolite system.

Pseudolite System Architecture & Coverage

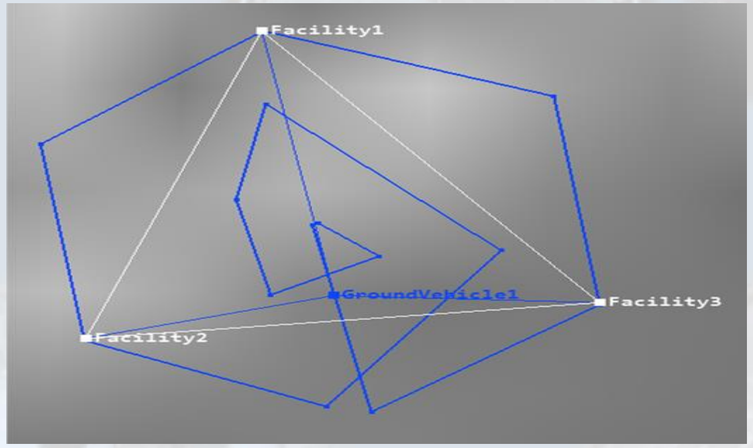
- Configuration with 3 and 5 pseudolite transceivers has been proposed.
- A circular area with different radii depending on the number of pseudolite transceivers has been worked out.

Number of Pseudolites	Maximum distance of rover from pseudolite (Km)	Service Area (km^2)
3	10	78.53
5	11.2	100.48

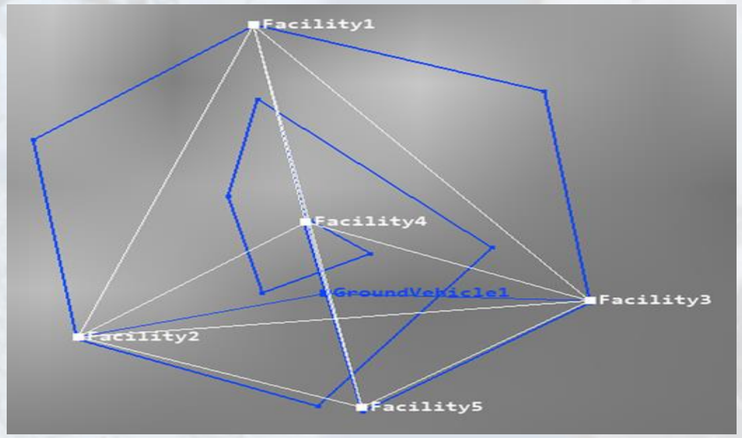




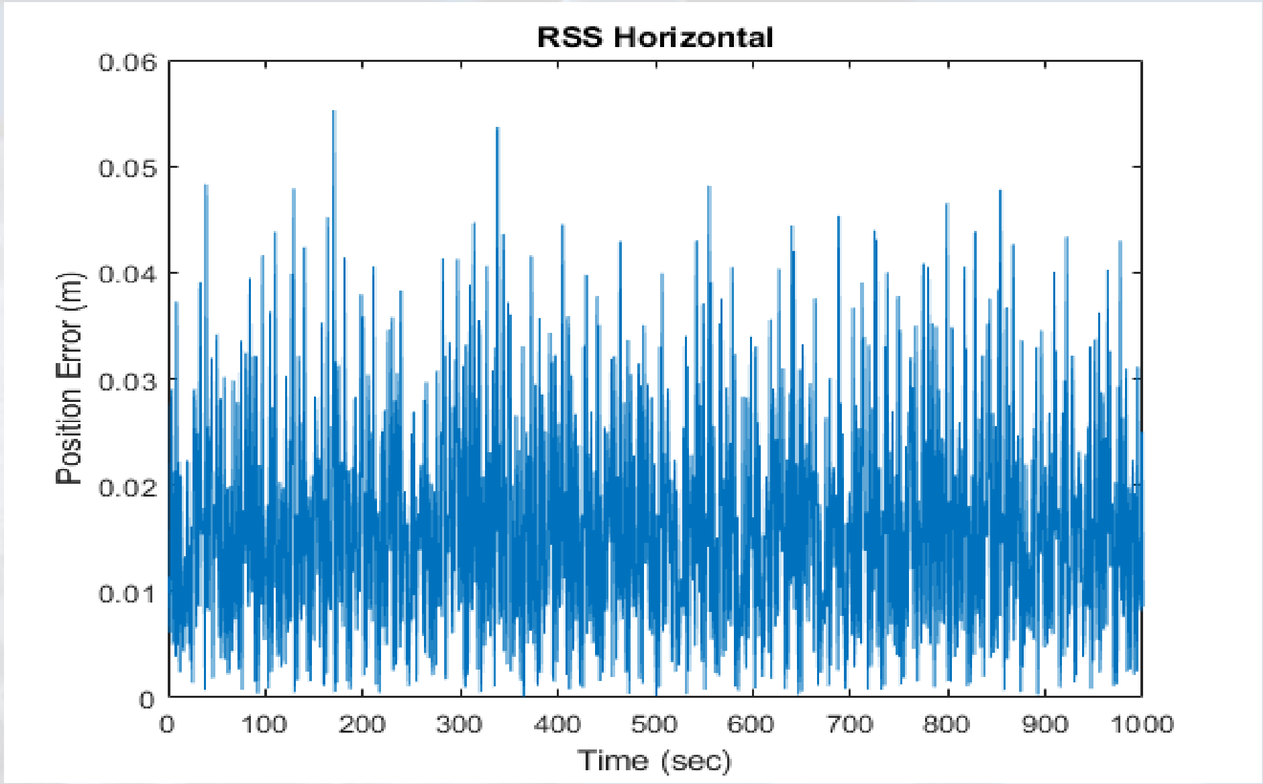
Pseudolite-based Rover Positioning



3-Pseudolite-Rover Geometry



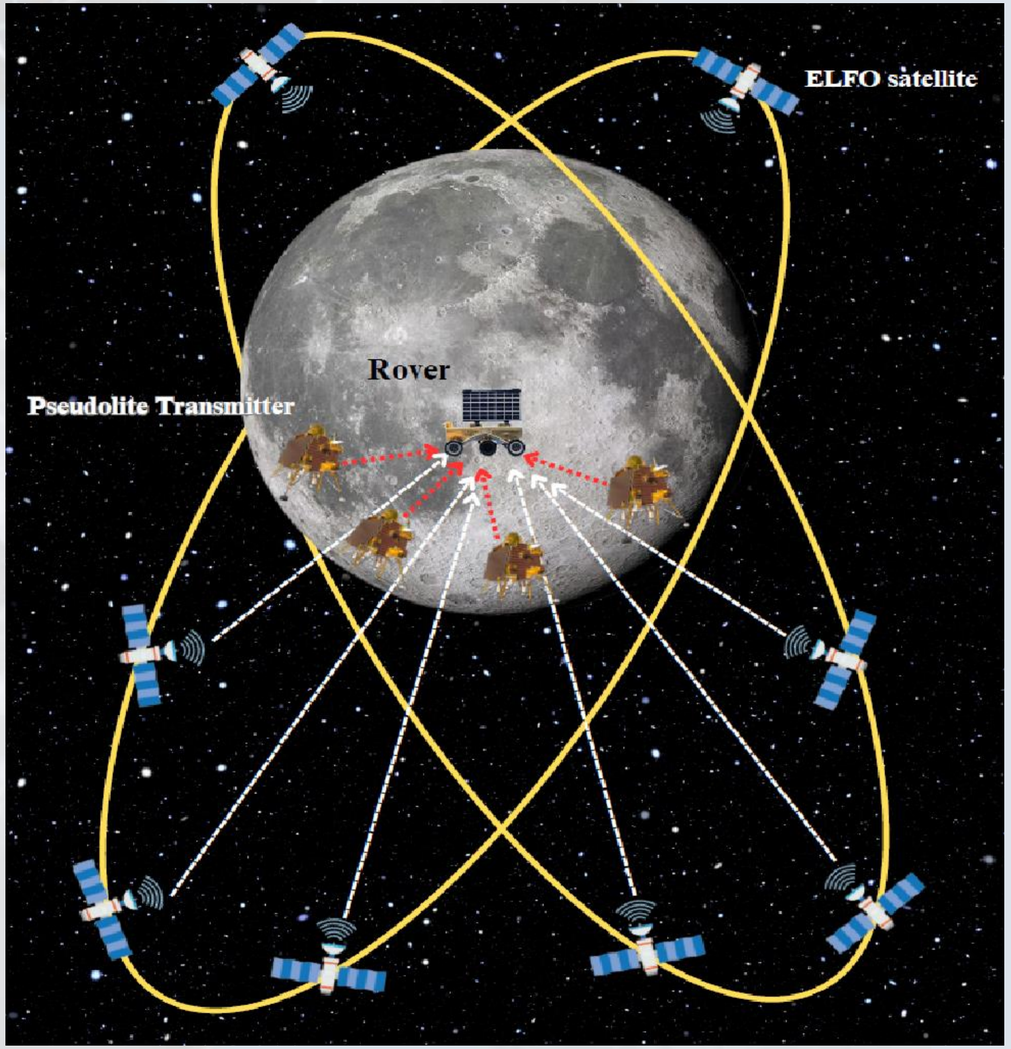
5-Pseudolite-Rover Geometry



Rover Position Accuracy

Architecture of Hybrid Pseudolite & Satellite Based Lunar PNT

- India is also proposing an hybrid Satellite & Pseudolite based lunar navigation system for future lunar missions.
- If the satellite based navigation systems are integrated with the Ground Based Navigation system, vertical & 3D position accuracy improves significantly.
- It may comprise of 8-10 satellite in ELFO orbit and a network of at-least 3 Pseudolite Transmitters on lunar surface.
- The hybrid system enhances spatial geometry, increases measurement redundancy, and improves the overall positioning precision for users located in complex polar regions.
- Furthermore, time synchronization can be done using very precise timing information from the lunar satellite constellation.



Lunar Pseudolite & Satellite Position Error Budget

Component	Value
Sat+ PL Orbit Error	2.5 m
Clock Error	2.0 m
Multipath Error	0.5 m
Rx Noise	0.3 m
UERE	3.25 m
PDOP	0.93
3D Position Accuracy	3.02 m

EKF Design for Low Dynamic Lunar Rover

- In order to refine the positioning accuracy obtained from the multilateration-based solution, an Extended Kalman Filter has been designed & implemented for lunar environment.
- In the proposed lunar navigation framework, the EKF fuses pseudorange observations from the ELFO satellites and surface pseudolite transmitters to estimate the user position.
- Proposed EKF has two steps:

✓ Prediction

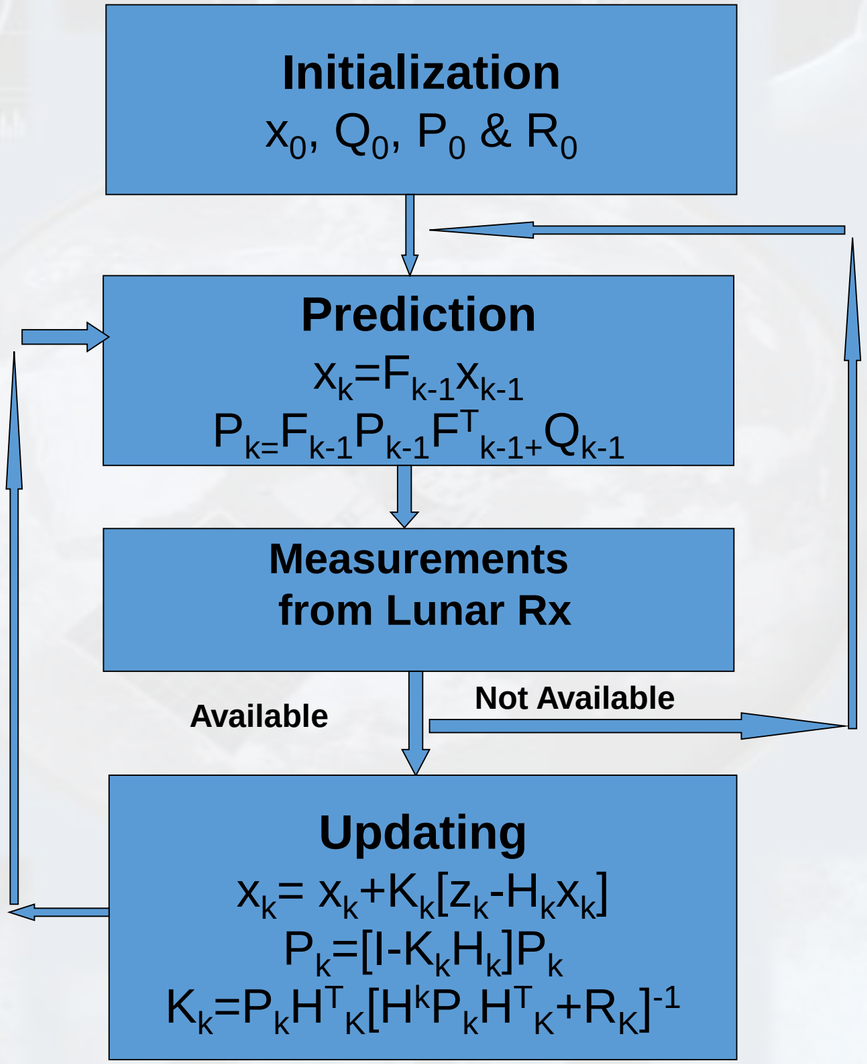
✓ Update

-The first step is the prediction step, which calculates the state of the receiver at epoch k as predicted from the previous epoch by using the dynamic motion model.

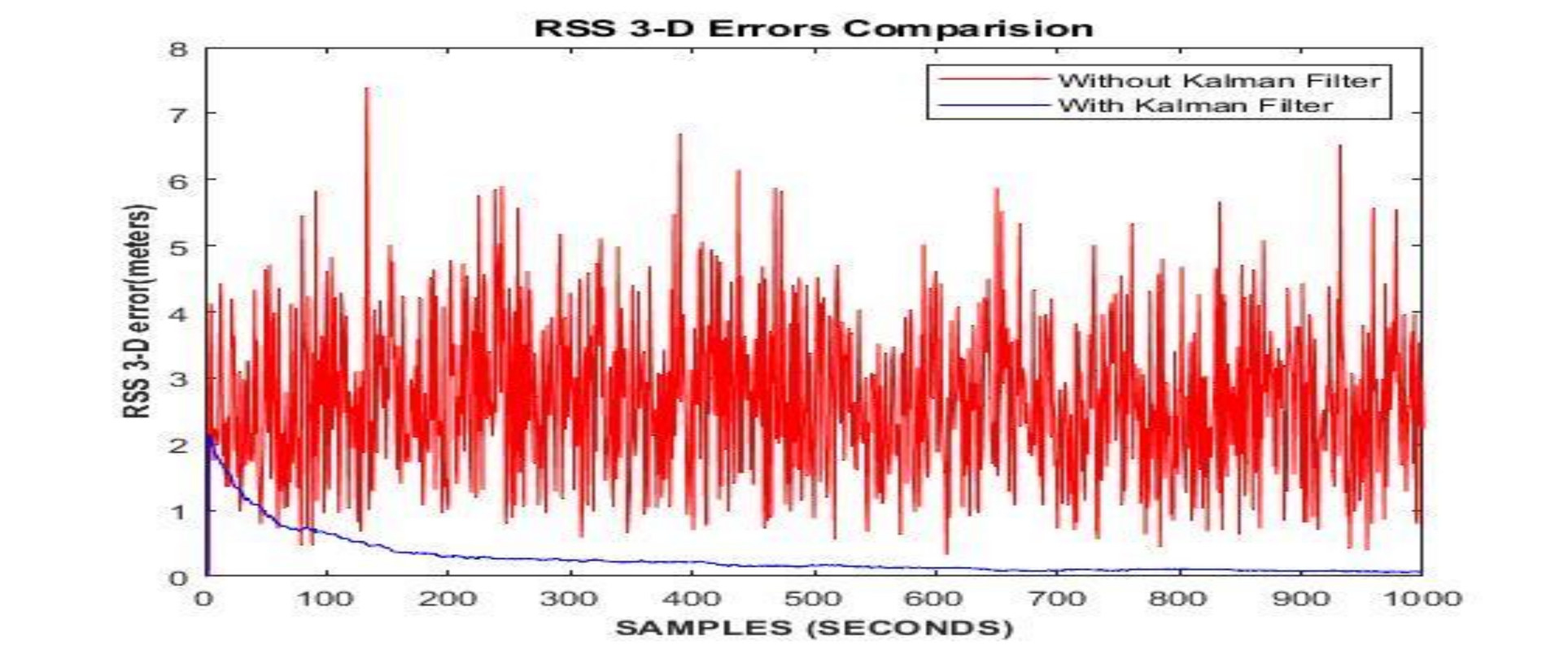
-In the update stage, new pseudorange measurements are added to correct the prediction of the state by making use of the measurement innovation.

- This recursive process will continuously correct navigation estimates, taking into consideration random noise and uncertainty of the model.

EKF Flow Chart



3D Position Accuracy of the Lunar Rover
(with 8 ELFO Lunar Navigation satellites & 4 Lunar Pseudolite Transmitters)



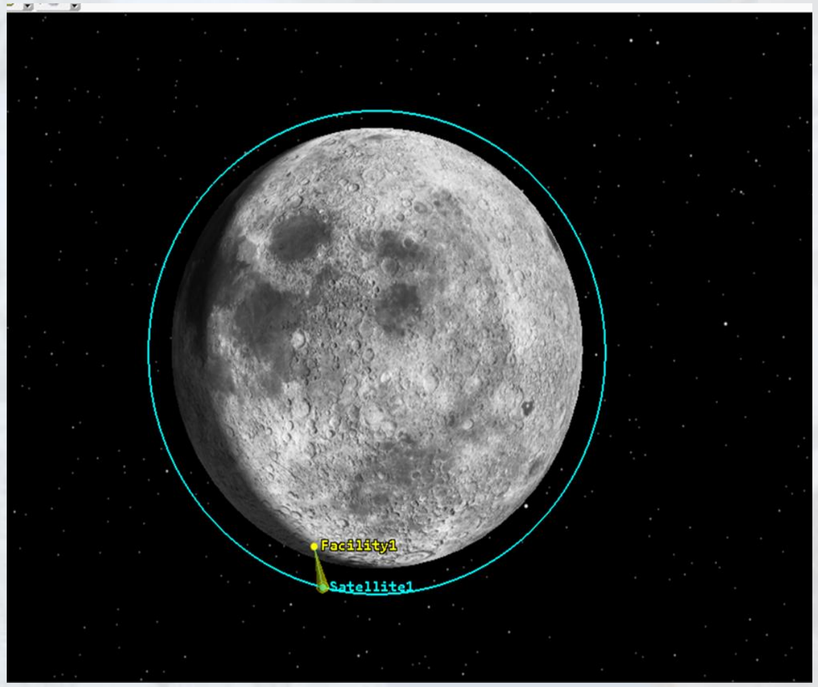
3D Position Accuracy of the Rover	
Without EKF	**With EKF**
3.46 m	0.67 m

Accuracy Analysis for Different Satellite & Pseudolite Combinations

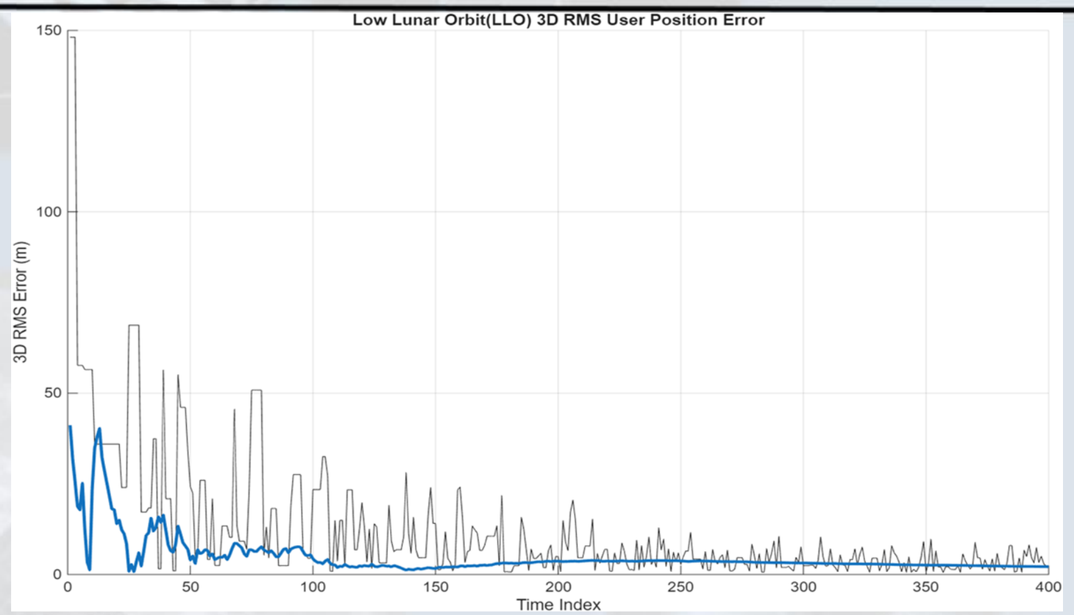
Configuration	3D Error	2D Error	Vertical Error	GDOP	HDOP	PDOP
Only with Lunar Navigation Satellite Constellation (ELFO)	13.08 m	3.46 m	12.61 m	4.48	1.16	4.32
Satellite+ Single Pseudolite	4.52 m	3.10 m	3.29 m	1.56	1.05	1.16
Satellite+ 2 Pseudolites	4.10 m	2.75 m	3.04 m	1.41	0.93	1.06
Satellite+ 3 Pseudolites	3.62 m	2.47 m	2.65 m	1.24	0.82	0.93
Satellite+ 4 Pseudolites	3.46	2.28	2.60	1.19	0.76	0.91

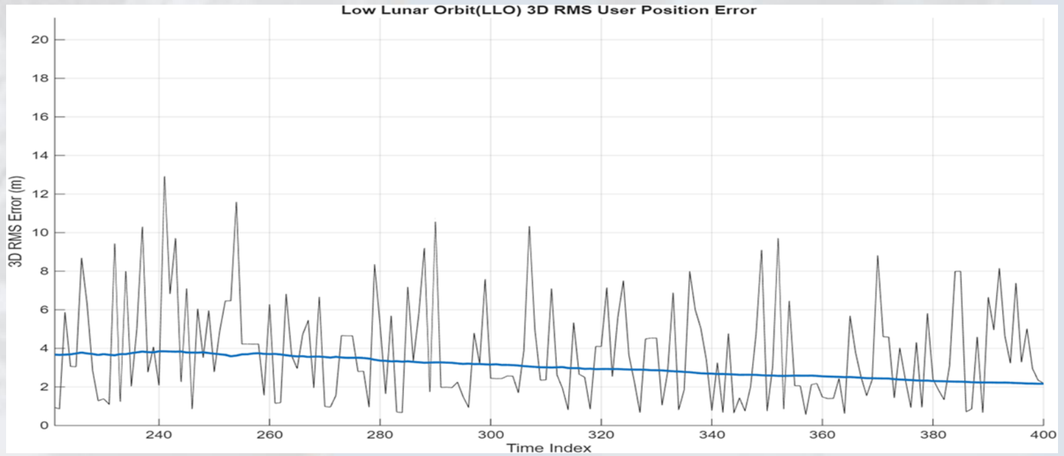
Doppler Positioning using Single LLO Satellite

- Low Lunar Orbit is simulated in STK with 200 km altitude & 90^0 inclination.
- Doppler, LLO satellite position & velocity data is generated at multiple time instances with user at Lunar South Pole.
- Doppler-based positioning is done with single satellite using EKF.
- Position accuracy is estimated w r to Shiv-Shakti Point using a single LLO satellite.



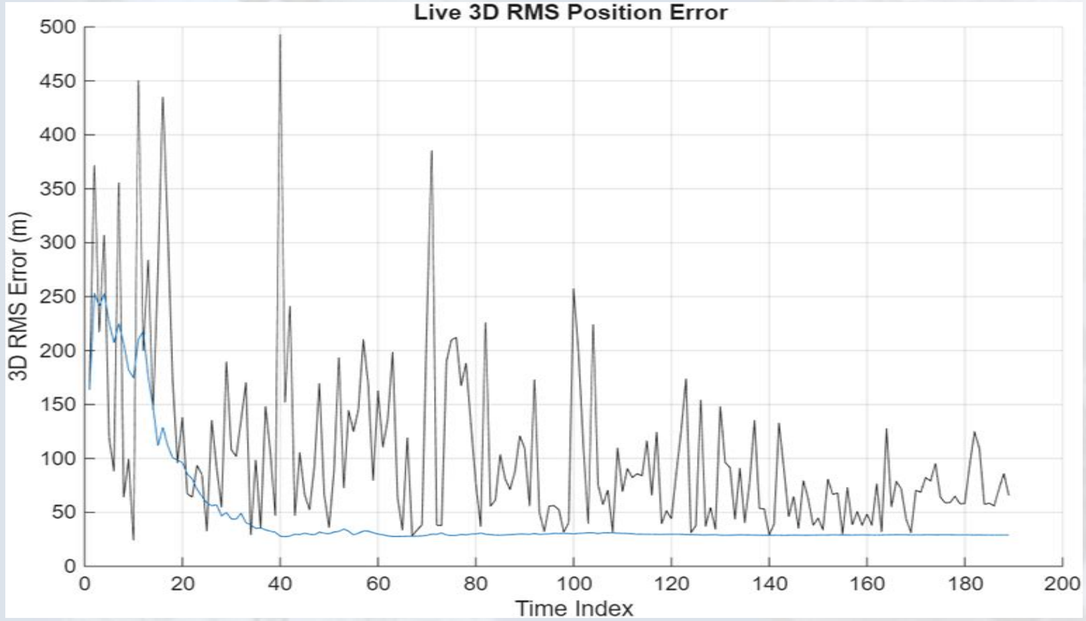
Low Lunar Orbit Signal Reception at Shiv-Shakti Point

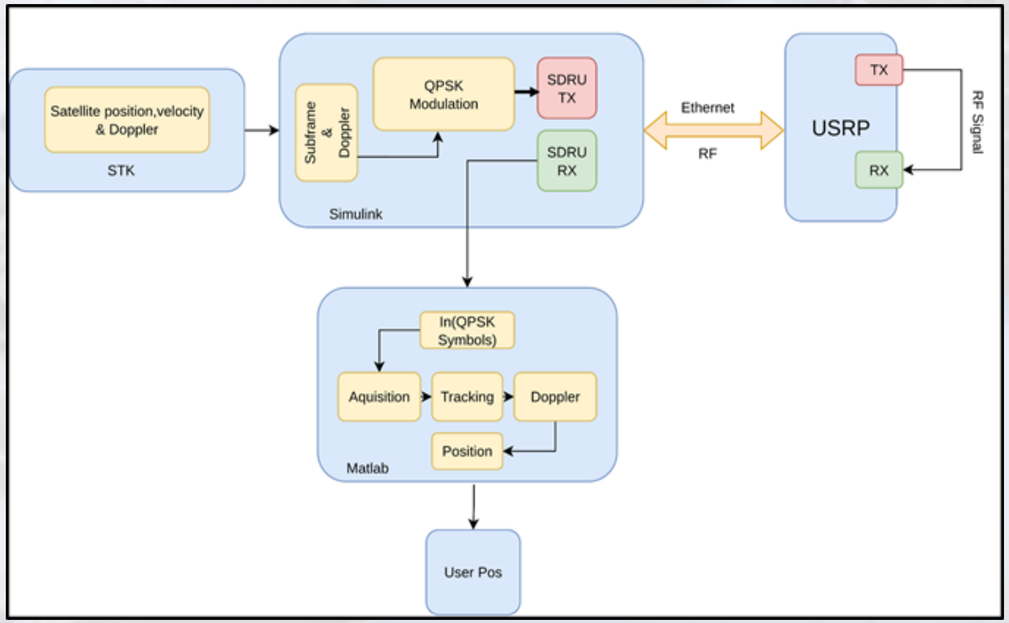




Lunar Receiver Proto-type Development

- LLO-Receiver proto-type is developed using USRP (NI 2954), Simulink & MATLAB with actual RF signal transmission at 2491.005 MHz frequency.
- RF signal was acquired, tracked & Doppler observable was measured by the receiver.
- Doppler-positioning with a single satellite in LLO orbit was performed using EKF.
- 3D Position accuracy of 28 m was achieved with actual RF signal transmission.





Conclusion

- Lunar navigation framework for Pseudolite & Hybrid Pseudolite & ELFO satellite constellation is presented.
- Extended Kalman Filter for low dynamic lunar rover at the lunar south pole is developed.
- Doppler-based positioning with EKF is attempted using a single LLO satellite.
- Simulations have been carried out in Systems Tool Kit (STK) software to generate the data and estimate the rover position accuracy.
- Lunar Receiver proto-type for Doppler positioning is developed & positioning is done with actual transmitted RF signals.

Thank You