Simulation of GPS-based Launch Vehicle Trajectory Estimation using UNSW Kea GPS Receiver

UNSW AUSTRALIA

Never Stand Still | Faculty of Engineering | Australian Centre for Space Engineering Research (ACSER)

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SNAP Lab

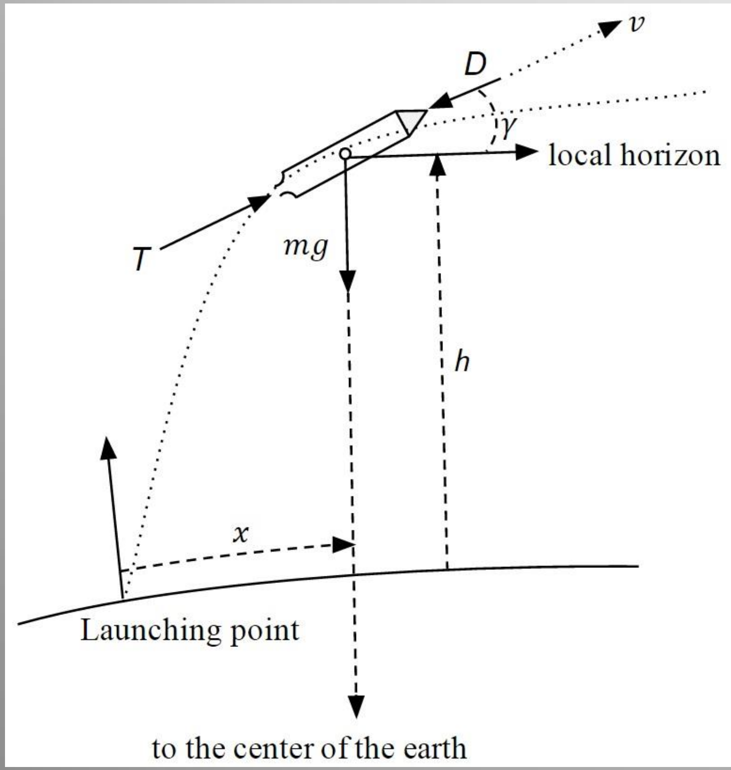
Outline

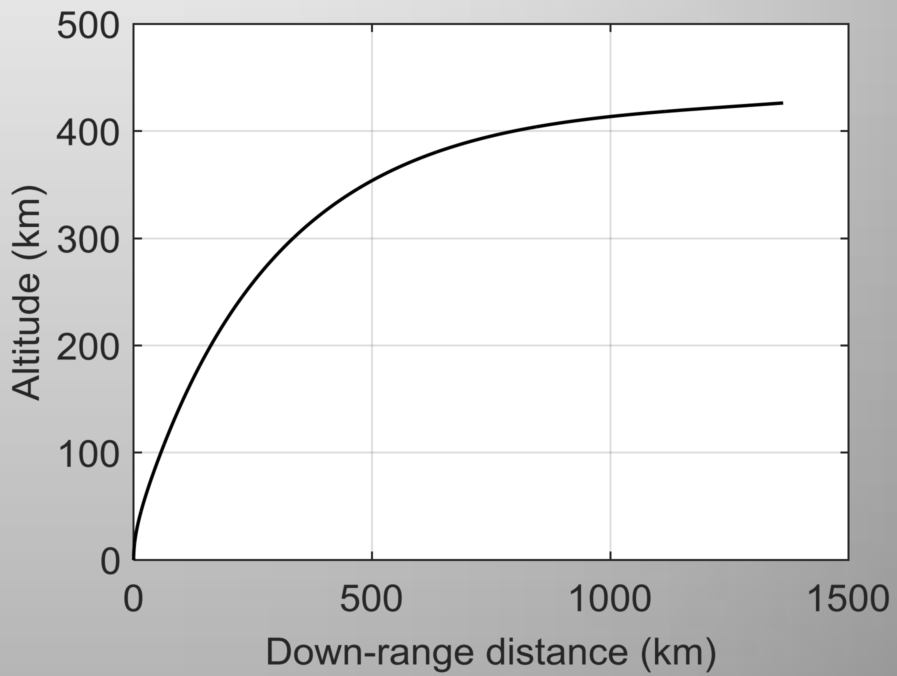
- Motivation
- Dynamic model of a launch vehicle
- Generation of GNSS signals/observations
- Simulation procedure
- Estimation algorithms
- Results
- Conclusion

Motivation

- For modern complex launch vehicle missions on-board navigation capability is required
- GPS-based navigation is the pre-eminent method for on-board navigation
- Extensive research is necessary in the following areas:
  - Advanced non-linear estimation
  - Optimization of the GPS receiver for high dynamics
- High fidelity simulations are crucial

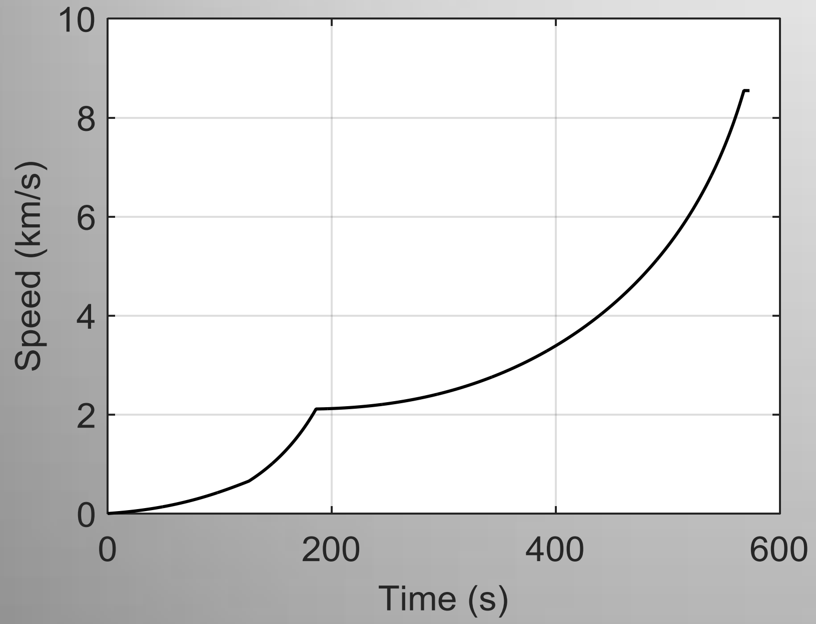
Dynamic model of a launch vehicle



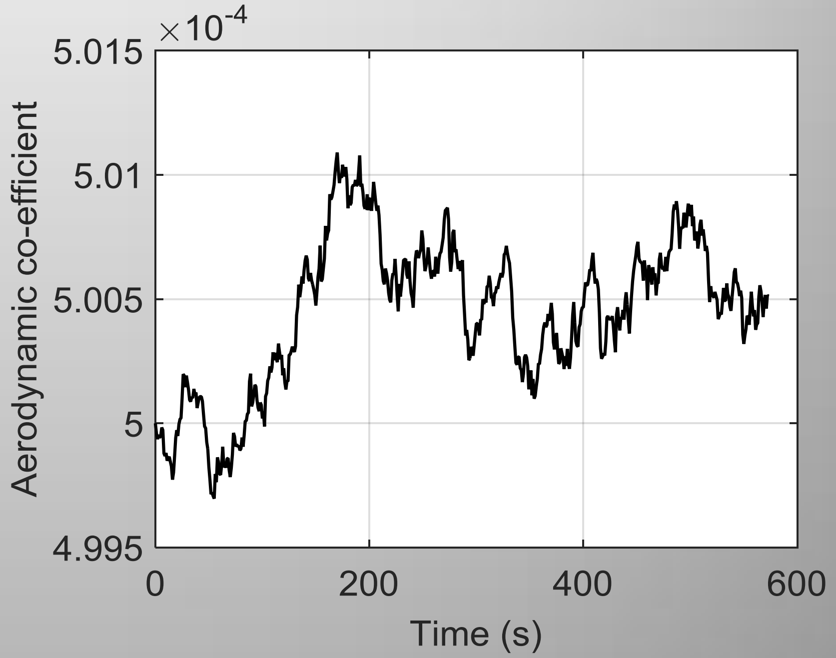


Reference launch vehicle trajectory

Dynamic model of a launch vehicle

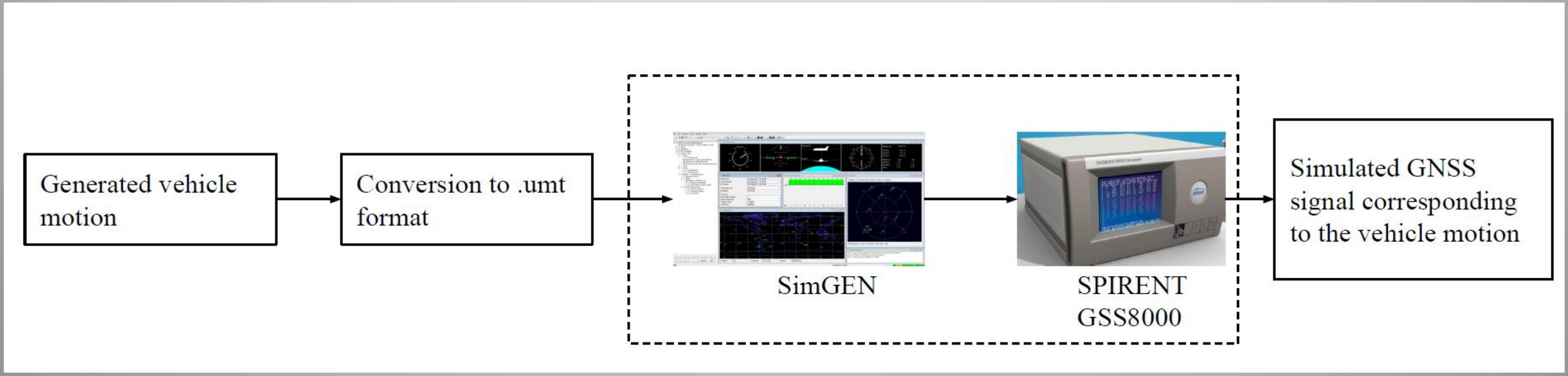


Velocity profile

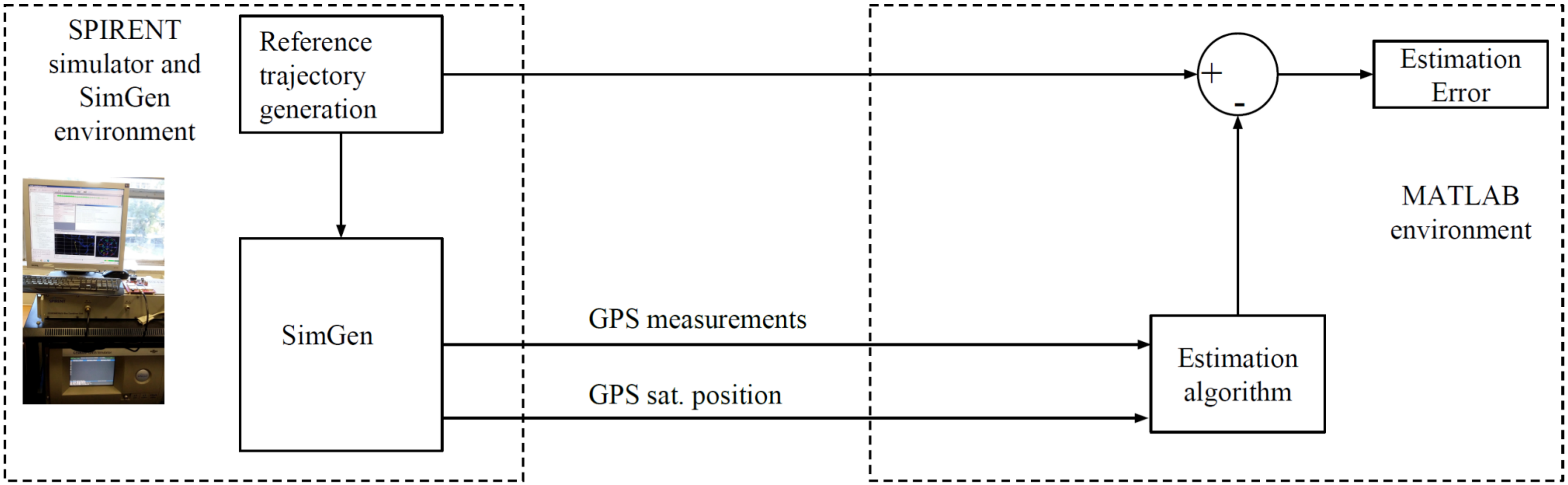


Aerodynamic co-efficient profile

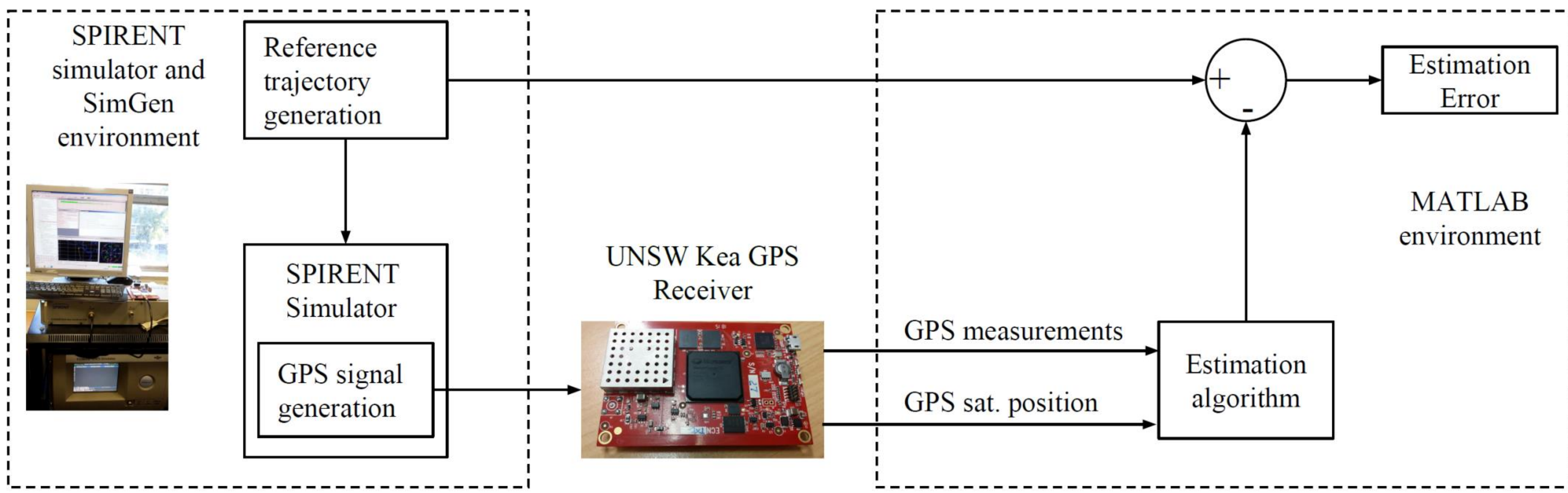
Simulation procedure



Simulation procedure



Simulation procedure

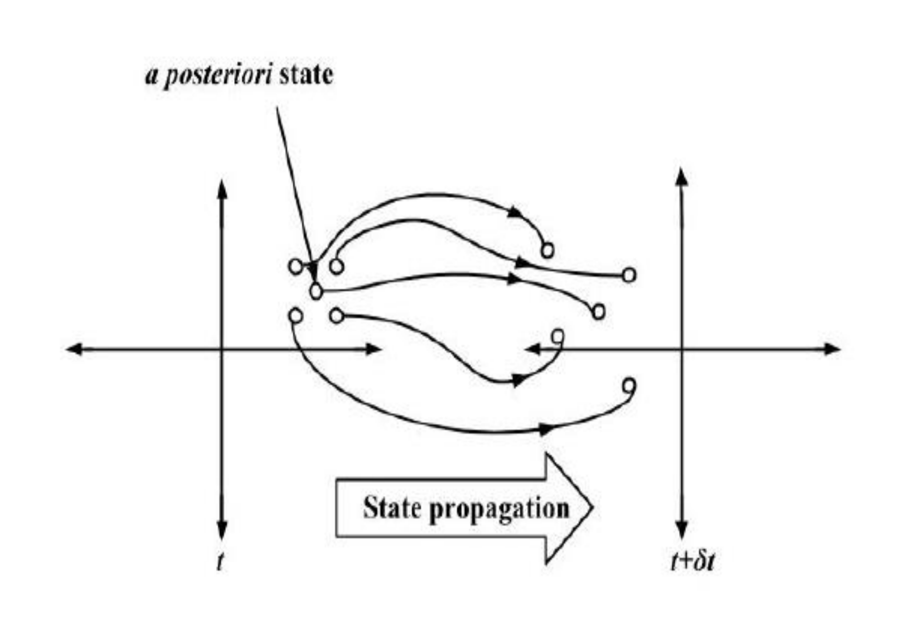


Unscented Kalman Filter (UKF)

- A generic estimation problem:

$$\dot{\boldsymbol{Y}}(t) = \boldsymbol{f}\big(t, \boldsymbol{Y}, \boldsymbol{\nu}(t)\big)$$
$$\boldsymbol{Z}(k) = \boldsymbol{h}\big(\boldsymbol{Y}(k)\big) + \boldsymbol{\omega}(t)$$

- The UKF uses deterministic sampling to predict the *a priori* mean and error covariance



Unscented Kalman Filter (UKF)

- 2n+1 sigma points has to be propagated separately using numerical integration for n dimensional state vector
- Computational time is higher than the EKF
- Cannot be used in a real-time application with limited computational resources
- SSUT and MUT were developed to reduce the computation time of UKF

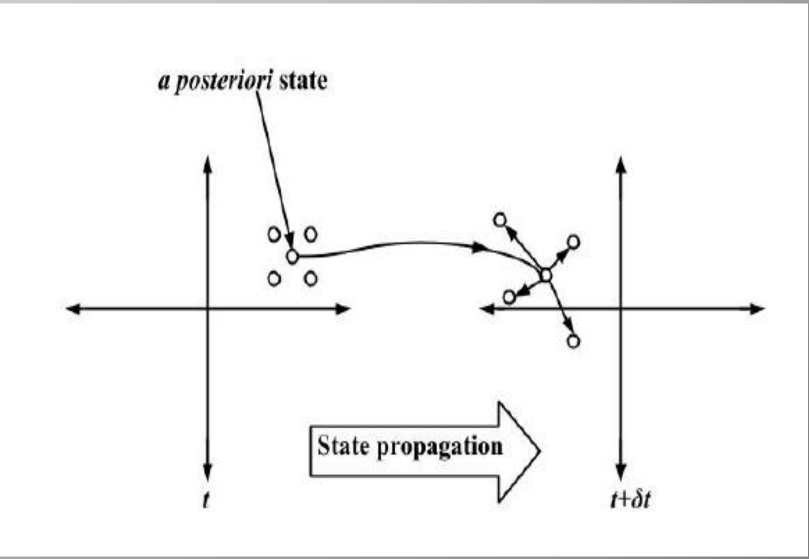
Single Propagation Unscented Kalman Filter (SPUKF)

- Only one sigma point is propagated to the next time step
- Other 2n sigma points are calculated from previous information

$$\boldsymbol{Y}_{\boldsymbol{i}}^{-}(t+\delta t) \approx \boldsymbol{F}\big(t, \boldsymbol{Y}^{+}(t), \boldsymbol{\nu}(t)\big) + \boldsymbol{D}_{\Delta \boldsymbol{Y}_{\boldsymbol{i}}}\boldsymbol{F}$$

$$\approx \boldsymbol{Y}_{\boldsymbol{0}}^{-}(t+\delta t) + \frac{\partial \boldsymbol{F}}{\partial \boldsymbol{Y}}\bigg|_{\boldsymbol{Y}^{+}} \boldsymbol{\Delta Y}_{\boldsymbol{i}}$$

$$\frac{\partial \boldsymbol{F}}{\partial \boldsymbol{Y}} = \boldsymbol{e}^{\boldsymbol{J}\delta t}$$



Extrapolated Single Propagation Unscented Kalman Filter (ESPUKF)

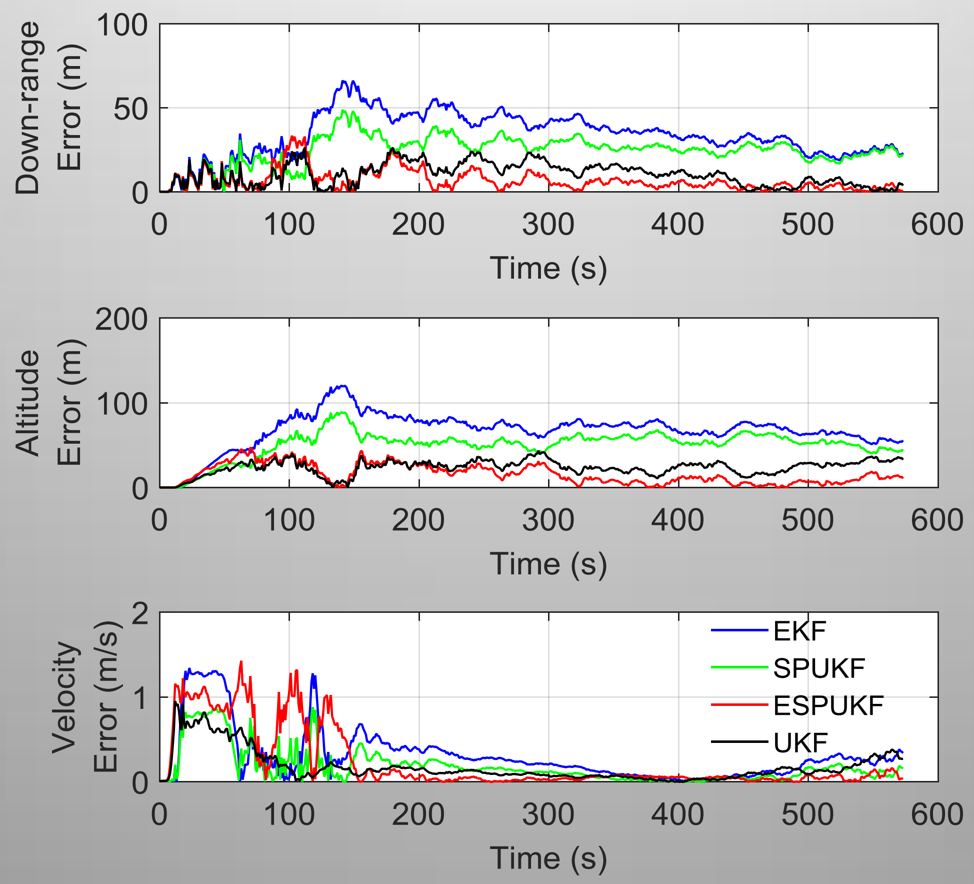
- Estimation error for the SPUKF is higher than the UKF and the SSUKF due to the 2nd order Taylor series terms
- ESPUKF reduces the error using Richardson Extrapolation

$$\boldsymbol{N_1}(\boldsymbol{\Delta Y_i}) = \boldsymbol{F}\left(t, \boldsymbol{Y}^+(t), \boldsymbol{\nu}(t)\right) + \boldsymbol{D}_{\boldsymbol{\Delta Y_i}}\boldsymbol{F}\Big|_{\boldsymbol{Y}^+}$$

$$\boldsymbol{N_2}\left(\frac{\boldsymbol{\Delta Y_i}}{2}\right) = \boldsymbol{F}(t, \boldsymbol{Y}^+, \boldsymbol{\nu}) + \boldsymbol{D}_{\frac{\boldsymbol{\Delta Y_i}}{2}}\boldsymbol{F}\Big|_{\boldsymbol{Y}^+} + \boldsymbol{D}_{\frac{\boldsymbol{\Delta Y_i}}{2}}\boldsymbol{F}\Big|_{\boldsymbol{Y}^+ + \frac{\boldsymbol{\Delta Y_i}}{2}}$$

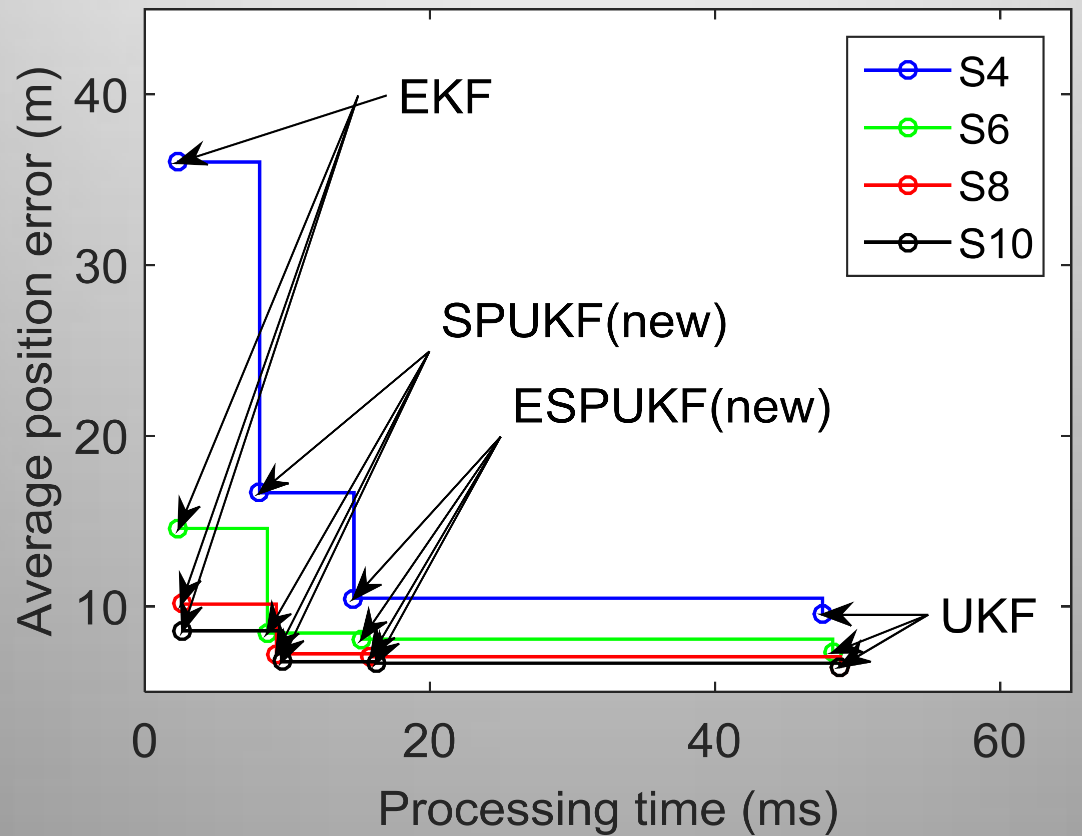
$$\boldsymbol{Y_i^-}(t+\delta t) = 2\boldsymbol{N_2}\left(\frac{\boldsymbol{\Delta Y_i}}{2}\right) - \boldsymbol{N_1}(\boldsymbol{\Delta Y_i}) - \left[\frac{1}{2}\frac{\boldsymbol{D}^3_{\boldsymbol{\Delta Y_i}}}{3!} + \frac{3}{4}\frac{\boldsymbol{D}^4_{\boldsymbol{\Delta Y_i}}}{4!} + \ \ldots\ldots\right]\boldsymbol{F}\Big|_{\boldsymbol{Y}^+}$$

Results

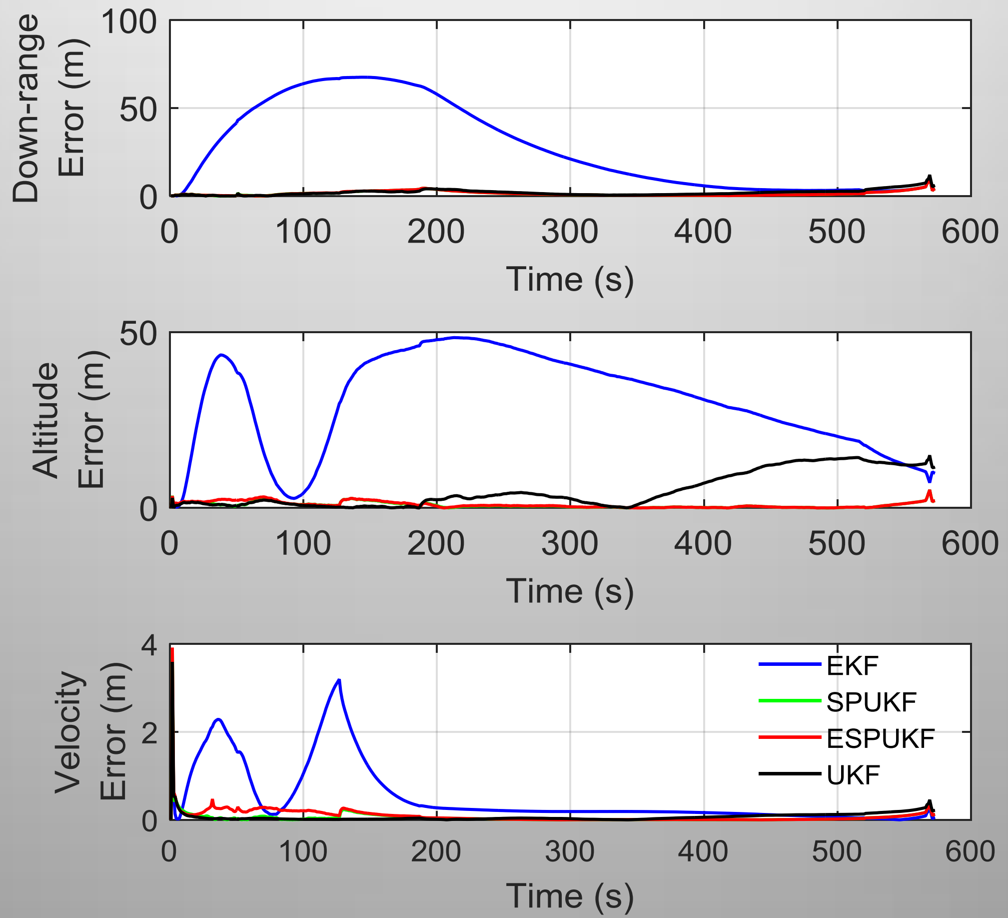


Down-range Error (m)
100
50
0
0 100 200 300 400 500 600
Time (s)
Altitude Error (m)
200
100
0
0 100 200 300 400 500 600
Time (s)
Velocity Error (m/s)
2
1
0
0 100 200 300 400 500 600
Time (s)
EKF
SPUKF
ESPUKF
UKF

Results

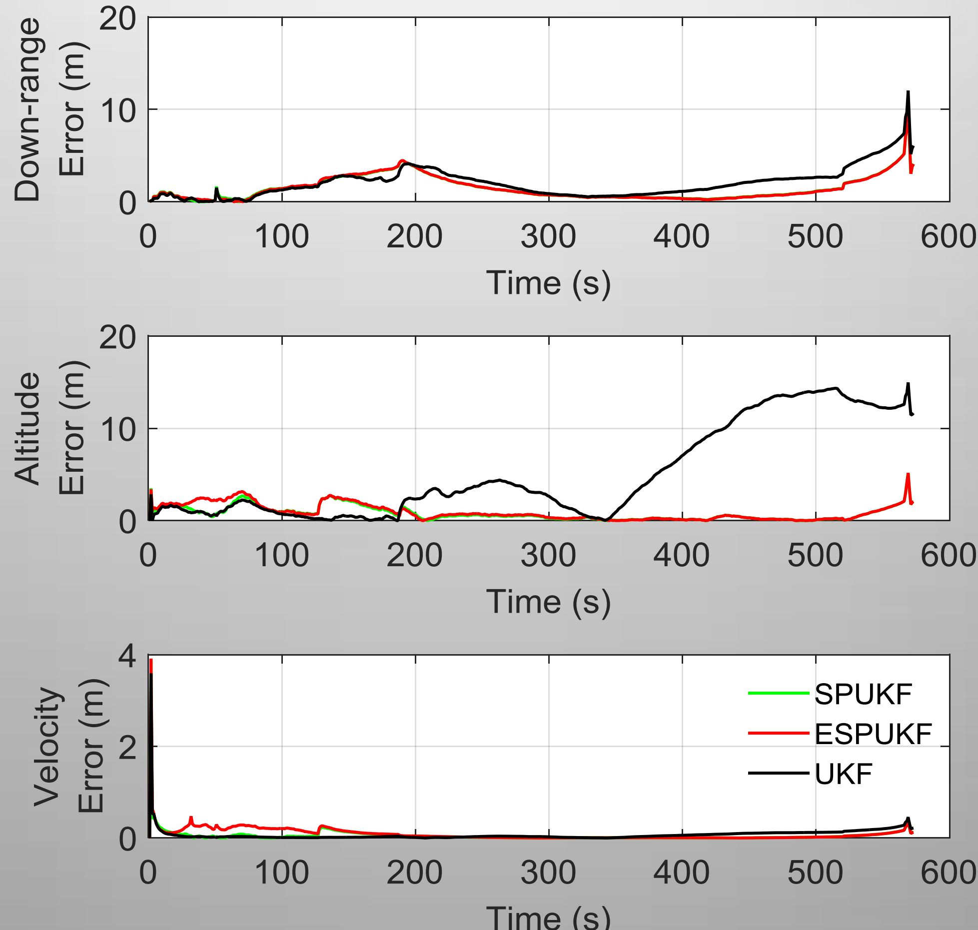

EKF
SPUKF(new)
ESPUKF(new)
UKF
S4
S6
S8
S10
40
30
20
10
0
20
40
60
Average position error (m)
Processing time (ms)

Results



Comparison of KFs

Results



Comparison of UKFs

Conclusion

- Simulation of a multi-stage launch vehicle trajectory is presented
- Procedure for generating corresponding GPS signals and measurements are shown
- Launch vehicle position estimation capability of KEA receiver is demonstrated
- Two new estimation algorithms are tested and compared with the existing estimation methods using the simulation method

Thank you

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