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

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Abstract

The simulation procedure for GNSS-based position estimation of a launch vehicle in a gravity turn trajectory is presented. A detailed mathematical model of the dynamics of a multi-stage launch vehicle is developed. In the mathematical model, the aerodynamic drag force and the jerk produced during the stage separation are considered, specifically for the SpaceX Falcon 9 V1.1 launch vehicle in the Commercial Resupply Service (CRS)-5 mission. The trajectory of the launch vehicle is simulated by using the vehicle and mission-specific parameters in the developed model. The SPIRENT GNSS simulator is used to generate the received GPS signals for the launch vehicle trajectory. The signals are acquired by the UNSW Kea GPS receiver which is optimized for acquiring GPS signals under high dynamics. The pseudo-range measurements received by the Kea receiver are used to test the performance of various estimation algorithms. This simulation procedure is convenient and efficient for testing new GNSS receivers and new navigation algorithms for launch vehicle applications.

1 Introduction

In recent years, innovative mission designs have enabled numerous possibilities of reducing the cost of accessing the space. For example, SpaceX has designed a reusable first

stage for the Falcon 9 V1.1 launch vehicle and it is capable of autonomous landing. This design concept require launch vehicles with complex maneuver capabilities. Therefore, a fast, robust and accurate on-board navigation solution is required to fulfill these demands. Traditionally the navigation of a launch vehicle is performed on ground using radar observations (Whiteman et al., 2005). However, the ground based radars have limited range and angular measurement accuracies. With the advent of the Global Navigation Satellite Systems (GNSS) as a simple and reliable mean of navigation, the GNSS observations are being used with the dead reckoning and radar observations (Farrell, 2001; Ailneni et al., 2013; Minor and Rowe, 1998). However, due to the high dynamics and non-linearity of the multi-stage launch vehicle, on-board navigation using the GNSS observation remains as a challenging problem.

To improve the on-board navigation capability of the launch vehicles, extensive research on advanced non-linear estimation and optimization of the GNSS receiver for high dynamics is necessary. To facilitate the research in this field, this paper presents a simulation procedure which will enable rapid performance evaluation of new position estimation algorithms and new GNSS receivers for launch vehicle mission scenarios. For demonstration, the SpaceX Falcon 9 V1.1 launch vehicle in Commercial Resupply Service (CRS)-5 mission is selected as the mission scenario. A UNSW Kea GPS receiver for high dynamic motion is used for acquiring GPS signals. Various Kalman Filter algorithms are used to estimate the trajectory information from the GPS observations and the estimation accuracies are compared.

The rest of the paper is organized as follows: detailed dynamic model of a launch vehicle is discussed in section 2. Procedures involving the reference trajectory generation is described in section 3. Method of generating GNSS observations corresponding to the reference trajectory is provided in section 4. Methodology for the launch vehicle trajectory estimation experiments are discussed in section 5. Section 6 discusses the results of the experiments. Section 7 concludes the paper outlining possible applications of this simulation procedure.

2 Launch vehicle dynamics

Primarily, a launch vehicle dynamics are similar to a projectile dynamics under the influence of the Earth's gravitation except the fact that the rocket motor of the launch vehicle provides a continuous thrust in the direction of the motion (Curtis, 2010). While in the atmosphere, the launch vehicle experiences an atmospheric drag in the opposite direction of the motion. Hence, in the force model, all the three forces must be accounted. For a multi-stage launch vehicle, the forward thrust goes to zero at the burnout of a lower stage and changes to a different value when the upper stage motor starts.

In a typical launch vehicle trajectory estimation problem, the state variables to be estimated are the down-range distance x, altitude h, speed v, the flight path angle of the launch vehicle γ, aerodynamic coefficient C and mass m. The trajectory of a launch vehicle is shown in figure 1.

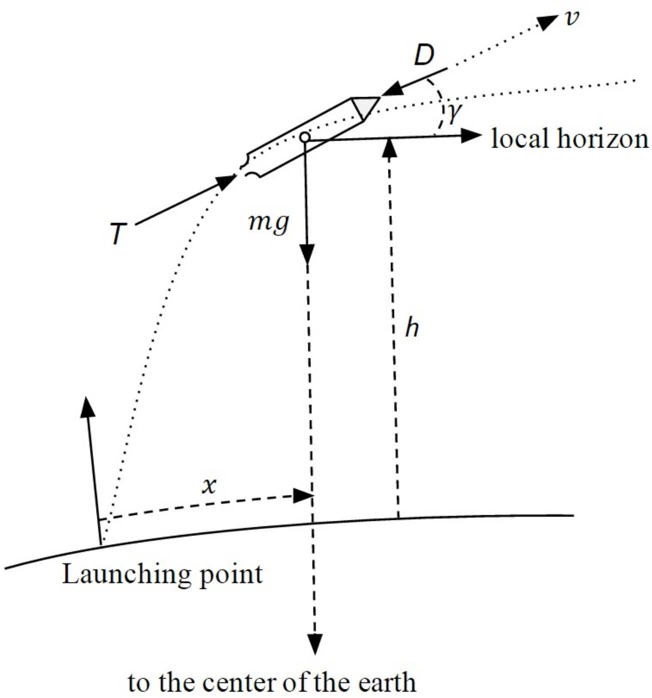


Figure 1: Launch vehicle trajectory

The system model can be expressed as (Turner, 2009; Wie, 1998)

$$\begin{bmatrix} \dot{x} \\ \dot{h} \\ \dot{v} \\ \dot{\gamma} \\ \dot{m} \\ \dot{C} \end{bmatrix} = \begin{bmatrix} \frac{R_E}{R_E+h} v \cos\gamma \\ v \sin\gamma \\ \frac{T}{m} - \frac{D}{m} - g \sin\gamma \\ -\frac{1}{v}\left(g - \frac{v^2}{R_E+h}\right)\cos\gamma \\ -\dot{m}_e \\ 0 \end{bmatrix} + \boldsymbol{\nu}(t) \tag{1}$$

where T is the engine thrust, D is the aerodynamic drag, g is the gravitational acceleration, R_E is the local radius of the Earth and $\dot{m}_e$ is the exhaust mass flow rate. $\boldsymbol{\nu}(t)$ is an 6×1 process noise vector. These parameters depend on the launch vehicle construction and the mission requirement. The drag force is modeled using exponential atmospheric density model (NOAA, 1976). The drag force equation is (Curtis, 2010)

$$D = \frac{1}{2} A C \rho_0 e^{-\frac{h}{H}} v^2 \tag{2}$$

where, A is the frontal area of the launch vehicle, ρ_0 is the atmospheric density at the sea level and $H = 7.1628$ km (NOAA, 1976) is the scale height.

Table 1: Mission and Launch Vehicle Specific Parameters

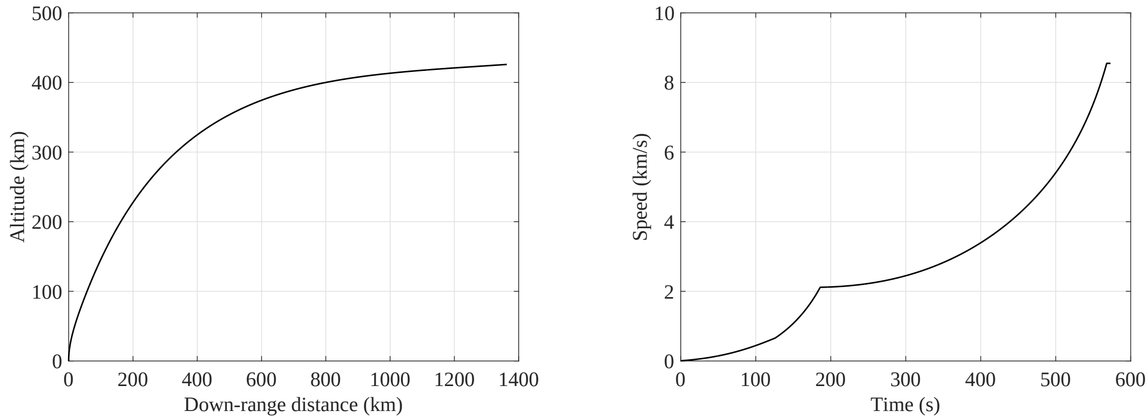
Mission parameters	
Payload	2317 kg
Dragon spacecraft mass	4200 kg
Orbit perigee	410 km
Orbit apogee	418 km
Stage 1	
Inert Mass	23,100 kg
Propellant Mass	395,700 kg
Engine	9× Merlin 1D
Thrust	5886 kN
Specific Impulse	282 s
Burnout Time	187 s
Stage 2	
Inert Mass	3,900 kg
Propellant Mass	92,670 kg
Engine	1× Merlin 1D Vac
Thrust	801 kN
Specific Impulse	340 s
Burnout Time	386 s

3 Reference trajectory generation

Commercial Resupply Service (CRS) -5 mission is selected for the launch vehicle simulation. In the CRS-5 mission a Falcon 9 V1.1 launch vehicle was used. The launch vehicle delivered a Dragon cargo spacecraft in space to resupply the International Space Station (ISS) . The launch site coordinate is $28.4889°N$, $80.5778°W$. The initial state vector is

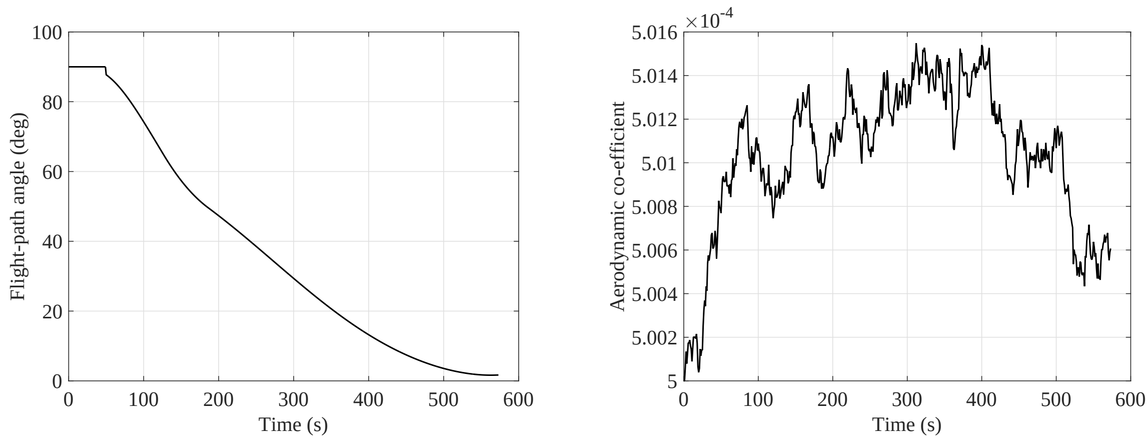
$$\boldsymbol{X}_0 = \begin{bmatrix} 0\ m & 0\ m & 5.6443\ m/s & 1.5708\ rad & 520876\ kg & 0.5 \end{bmatrix}^T \tag{3}$$

The mission and launch vehicle specific parameters for the scenario is provided in Table 1 (SpaceX, 2009; NASA, 2014). The initial conditions and the vehicle specific parameters are used in equation 1 and the reference trajectory is generated by propagating the differential equation using fourth order Runge-Kutta numerical integration method. The trajectory of the Falcon 9 V1.1 for the specified mission is shown in figure 2a. Figure 2b shows the velocity profile of the launch vehicle. At 187s a jerk can be observed in the velocity profile due to the first stage separation. The flight path angle is plotted in figure 3a. At 50s after launch, a small pitch over angle is provided to start gravity turn trajectory. A random walk variation can be observed in the aerodynamic coefficient evolution over time in figure 3b.



(a) Trajectory (b) Velocity profile

Figure 2: Falcon 9 V1.1 trajectory and velocity profile



(a) Flight path angle (b) Aerodynamic coefficient

Figure 3: Falcon 9 V1.1 flight path angle and aerodynamic coefficient

4 Simulation of GNSS observation

A SPIRENT GNSS simulator with the SimGEN software is used to perform estimation experiments using GNSS observations with the launch vehicle. Simulation experiments with and without GNSS receivers are performed. For the experiment with the GPS receiver a UNSW Kea GPS receiver is used.

4.1 SPIRENT GNSS Simulator and SimGEN

The SPIRENT GSS8000 GNSS simulator simulates GPS, GLONASS and Galileo signals. This simulator takes vehicle motion as input from SimGEN application software and generates GNSS satellites' positions from the GNSS constellation ephemeris and then simulates the signals to be received by the user GNSS-receiver from the visible GNSS

satellites. The SimGEN adds the tropospheric and ionospheric errors in GNSS measurements and also can incorporate receiver clock bias, if actual receiver is not available in the simulation.

4.2 UNSW Kea receiver

UNSW Kea GPS receiver in Figure 4 is the successor of the Namuru GNSS receiver family which are designed for LEO missions (Choudhury et al., 2013; Choudhury and Glennon, 2012). It is a credit card sized receiver equipped with 166MHz ARM Cortex M3 processor. The Kea receiver is specifically optimized for high dynamics motion (Glennon et al., 2015). The Kea receiver is chosen for the Launch vehicle trajectory estimation experiment because it is capable of maintaining a proper GPS signal lock during high acceleration of the launch vehicle.

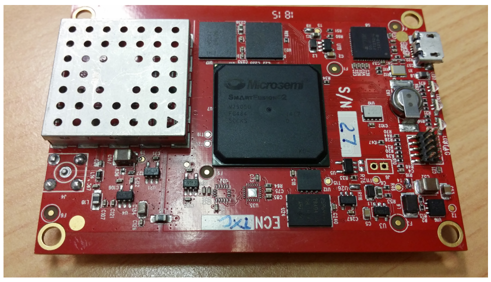


Figure 4: UNSW Kea GPS receiver

5 Methodology for the Launch Vehicle Navigation Simulation

The reference trajectory of the launch vehicle is generated externally using MATLAB because the complex multi-stage dynamics of a launch vehicle cannot be generated in SimGEN. The generated trajectory information is converted to SimGEN compatible user motion command file which is used as the launch vehicle motion input to the SimGEN

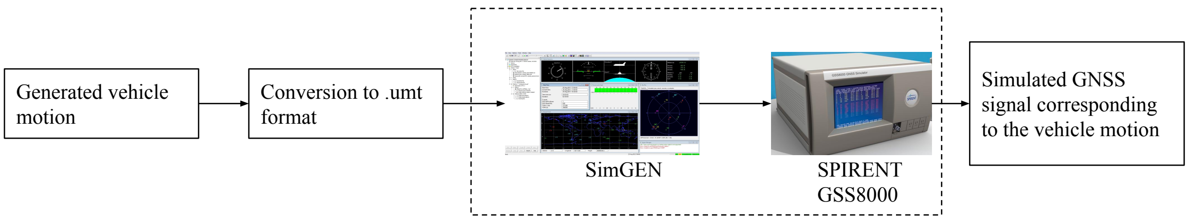


Figure 5: Using external trajectory data in SPIRENT simulator

application. The SimGEN provides input to the SPIRENT which generates the GNSS signals. The procedure is shown in figure 5.

Two types of experiments are designed for the launch vehicle trajectory estimation scenario. The first experiment is performed without any GPS receiver. In this case, the SimGEN generated the corresponding GPS pseudo-range and carrier-range observations with the atmospheric error and receiver clock bias. The observations are used in various estimation algorithms which are implemented in MATLAB. The estimated states for all the algorithms are compared with the reference trajectory for performance comparison of various estimation techniques. The block diagram of this experiement is shown in figure 6. For the second experiment the Kea GPS receiver is used to obtain the pseudo-

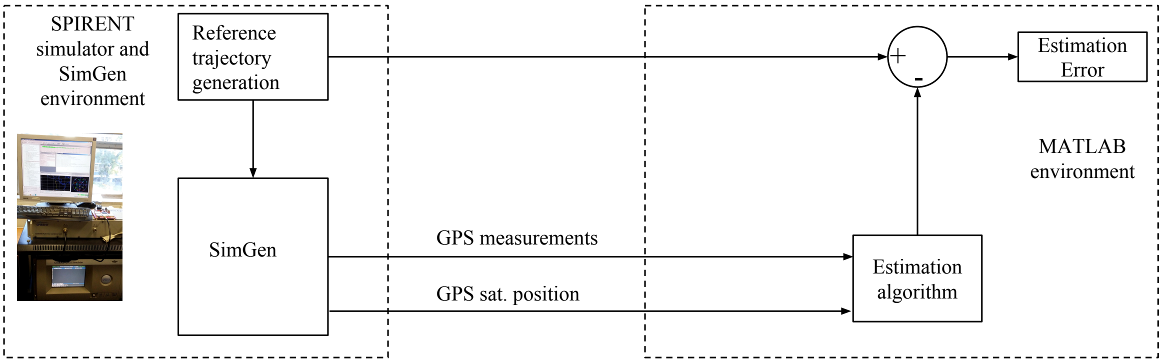


Figure 6: Simulation without GPS receiver

range and carrier-range observations. Similar to the previous experiment, the reference trajectory is provided in the SimGEN software and from this trajectory the SPIRENT GSS8000 generated the GPS signals to be received by the GPS receiver corresponding to the launch vehicle motion. The signal is acquired by the Kea GPS receiver and the range observations from the receiver is used in estimation algorithms for state estimation. The process is shown in figure 7.

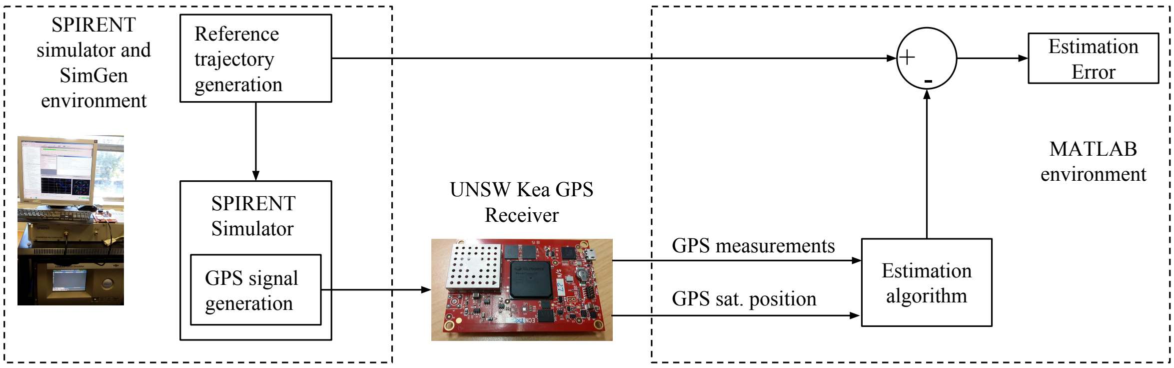


Figure 7: Simulation with GPS receiver

6 Results

Four estimation algorithms are tested with the procedure. The performance of the Extended Kalman Filter (EKF), Unscented Kalman Filter (UKF), newly developed Single Propagation Unscented Kalman Filter (SPUKF) and Extrapolated Single Propagation Unscented Kalman Filter (ESPUKF) (Biswas et al., 2016) in the launch vehicle trajectory estimation scenario using GPS observations are evaluated using the methodology described in section 5. Simulation experiments are performed with and without the Kea GPS receiver. The experiments are repeated by restricting the number of pseudo-range observations to 4, 6, 8 and 10. The estimation error and computation time are recorded. The state estimation errors in the down-range, altitude and velocity for different estimation algorithms using the generated pseudo-range data are shown in figure 8.

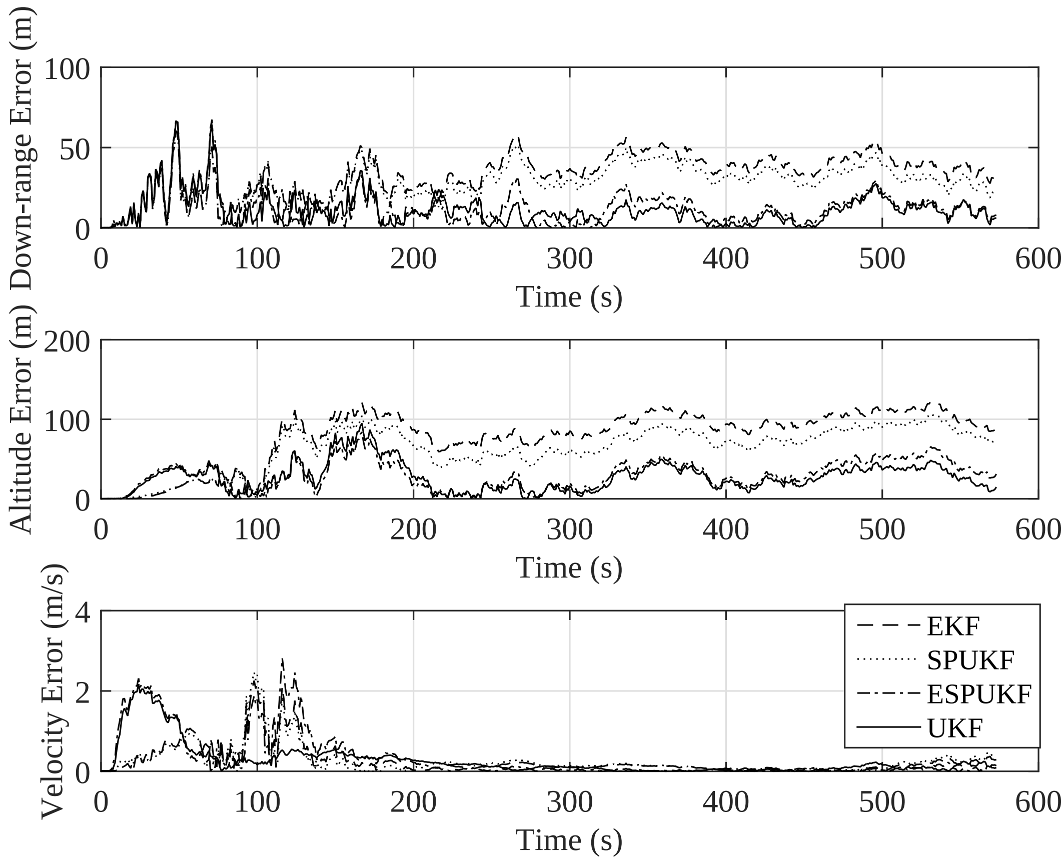


Figure 8: Estimation errors for different algorithms without GPS receiver

It is observed that the error using the EKF is higher than the UKF based algorithms. From figure 9 it is observed that the SPUKF and the ESPUKF have significantly lower processing time than the traditional UKF.

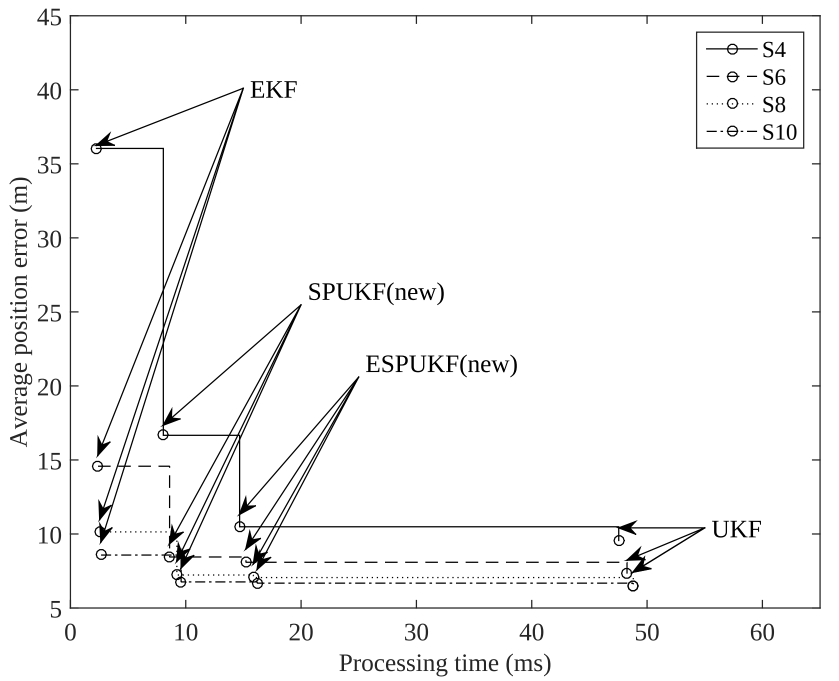


Figure 9: Processing time vs. estimation error

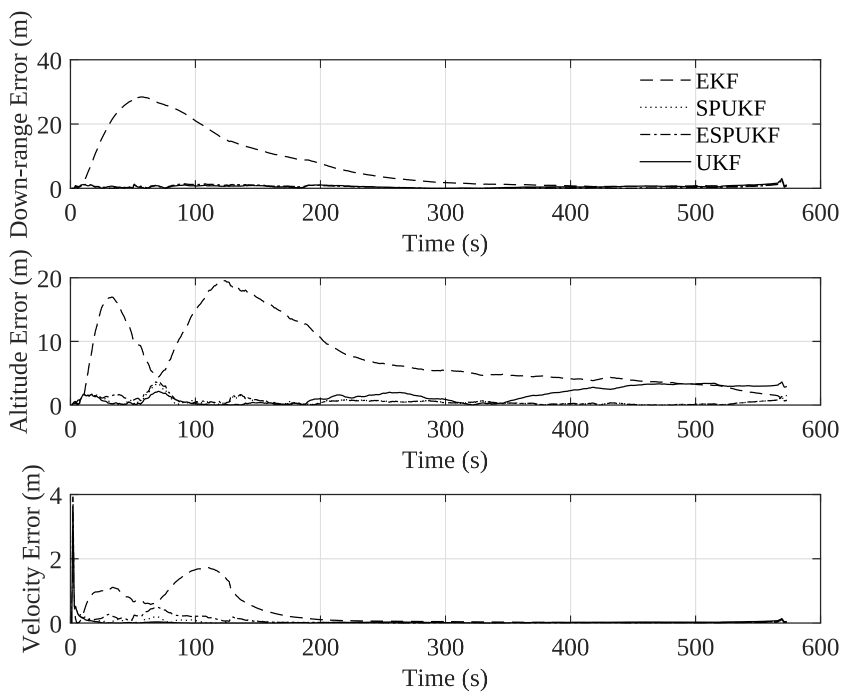


Figure 10: Estimation errors for different algorithms with Kea GPS receiver

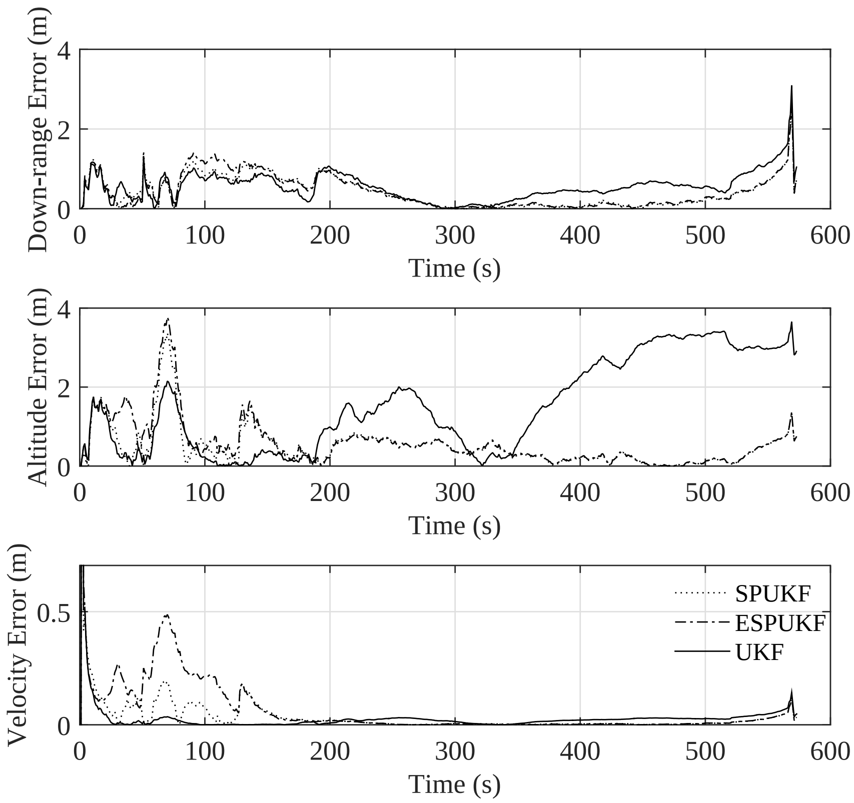


Figure 11: Estimation errors for different UKFs with Kea GPS receiver

The estimation errors for different Kalman Filters using the Kea GPS receiver is shown in figure 10. Similar to the previous set of experiments, the EKF accuracy is lower than the UKF based algorithms. The estimation errors of only UKF based algorithms are shown in figure 11. It is observed that the performance of the new filters are better than the original UKF.

7 Conclusion

A simulation procedure for launch vehicle trajectory estimation using GPS observations is presented. The designed simulation method is useful for rapid performance evaluation of new GNSS receivers and new estimation algorithms. A multi-stage launch vehicle in gravity-turn trajectory is simulated and the corresponding simulated pseudo-ranges are used in various estimation algorithms for performance evaluation. With simple modification, this procedure can be utilized to simulate GNSS based navigation of other high velocity ballistic vehicles. This methodology will be a convenient tool for research in estimation algorithm development for GNSS based navigation of high dynamic vehicles.

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