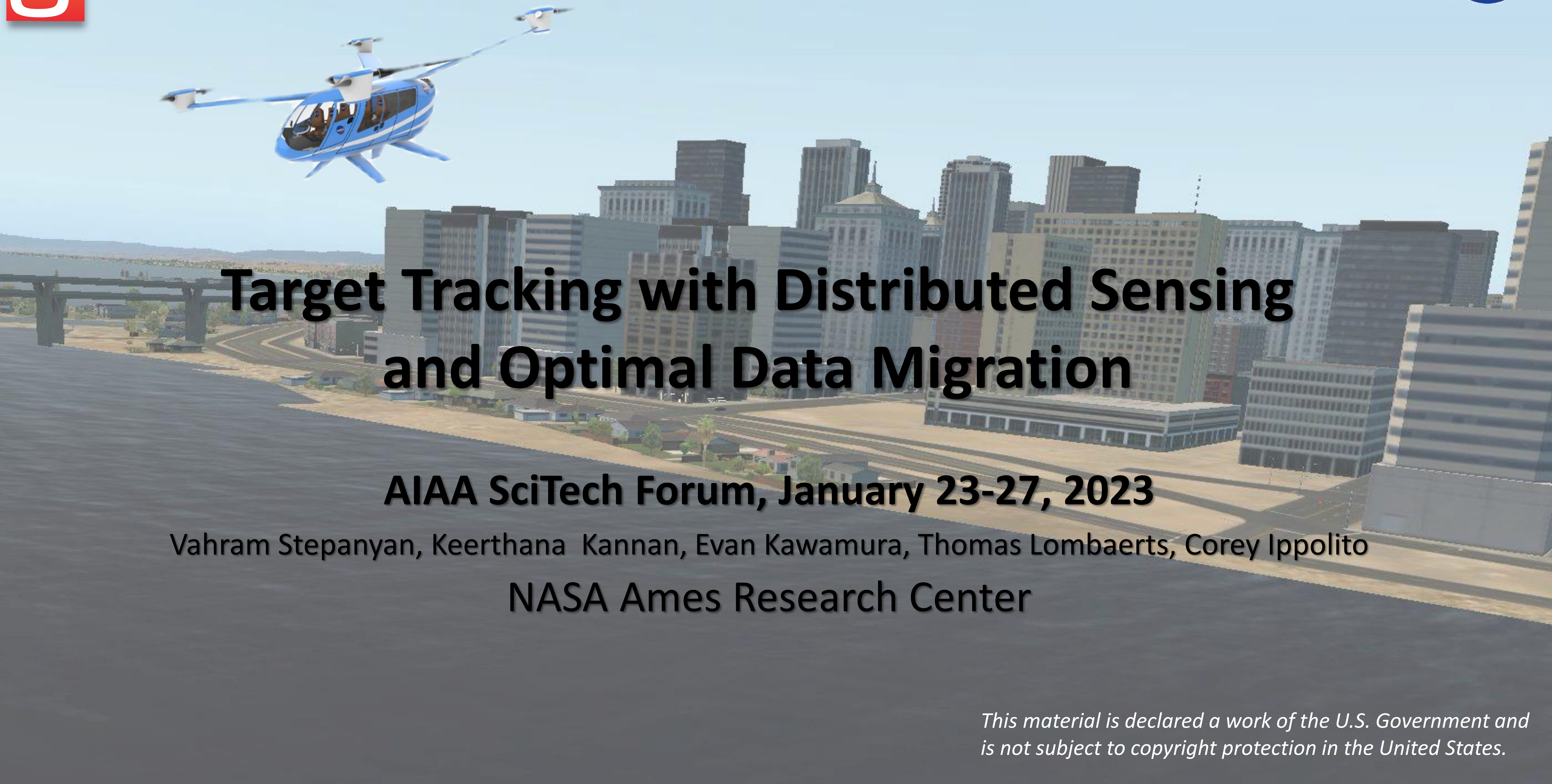

Target Tracking with Distributed Sensing and Optimal Data Migration

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Problem Formulation

Objective

- Develop Extended Kalman Filter based framework for airborne target tracking

Input

- Readings from ground based infrastructure of distributed multi-modal sensors

Assets

- Sensors (multi-modal, multi-rate)
- Warless/wired communication network
- Computing centers with diverse capabilities

Approaches

- Algorithm for optimal data relay between infrastructure and assets
- Algorithm for minimum latency data migration to computing centers
- Adaptive fusion algorithm to address variable rate of information arrival
- Implementation of Larsen's method to address the communication delays
- Extended Kalman Filter framework based adaptive tracking algorithm

Validation

- Desktop simulations using simulated target flight in Reflection simulation environment

Optimal Wireless Data Relay

$$\min\ f = \sum_{i=1}^{n}\sum_{j=1}^{n} x_{ij} d_{ij}$$

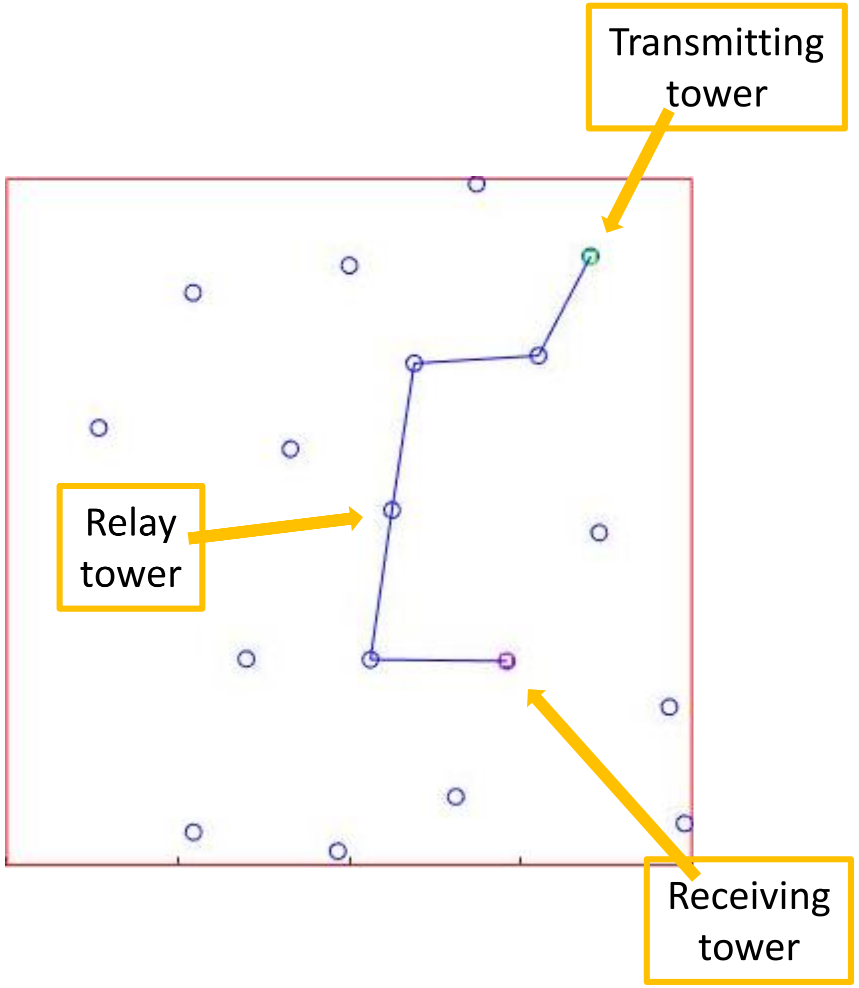
$$s.t.\quad \sum_{j=2}^{n} x_{1j} = 1,\ \sum_{i=1}^{n-1} x_{in} = 1$$

$$\sum_{j=2}^{n} x_{ij} = \sum_{j=1}^{n-1} x_{ji} <= 1,\ i = 2,\dots,n-1$$

$$\sum_{j=1}^{n} x_{ij} d_{ij} <= d_{\max},\ i = 1,\dots,n$$

$$2 \le u_i \le n,\ i = 2,\dots,n$$

$$u_i - u_j + 1 \le (n-1)(1 - x_{ij}),\ i = 2,\dots,n, j = 1,\dots,n-1$$



n - number of towers, first- transmitting tower, last- receiving tower

d_{ij} – pairwise distances

d_{max} - maximum allowable distance

x_{ij} – binary variables, 1 if a transmit to tower i is followed by a transmit to tower j

u_i – integer variables to prevent sub-tours

Optimal Data Migration

Migration as an optimization problem:

- Performance quality metrics:
  - End-to-end latency
- Constraints
  - Max acceptable latency may be imposed
  - Network and computing parameters

Assumptions

- Sensors are deployed at fixed locations
- Sensors communicate wirelessly or wired
- Computing centers communicate wirelessly or wired
- Towers communicate wirelessly or wired
- Resources already allocated
- Sensors and computing centers locations are know

Estimate for each location

- Elapsed time to receive data from all sources at i^th computing center τ_i

Optimization variables

- binary variables x_i

MILP problem

$$\min \; f = \sum_{i=1}^{n} x_i \tau_i$$

$$s.t. \quad 0 \leq x_i \leq 1, \; i = 1, \ldots, n, \; \sum_{i=1}^{n} x_i = 1, \; \sum_{i=1}^{n} x_i \tau_i \leq \tau_{\max}$$

Extended Kalman Filter Framework

- Continuous time coordinate-uncoupled white-noise acceleration model for a point-mass object

$$\hat{s}(k) = \Phi(k-1)\hat{s}(k-1) + \Gamma(k-1)w(k-1)$$

- Observation models are sensor specific and have variable sizes
  - Radar measurements

$$h_i = \left[r_i^m = r_i + b_i r_i + n_{ri},\quad \theta_i^m = \theta_i + n_{\theta i},\quad \phi_i^m = \phi_i + n_{\phi i}\right]$$
$$R_i = diag\left[\sigma_{ri}^2,\quad \sigma_{\theta i}^2,\quad \sigma_{\phi i}^2\right]$$

  - Camera measurements

$$h_i = \left[x_{pi}^m = x_{pi} + n_{pxi},\quad y_{pi}^m = y_{pi} + n_{pyi}\right]$$
$$R_i = diag\left(\left[\sigma_{pxi}^2,\quad \sigma_{pyi}^2\right]\right)$$

  - Nonlinear observations in i-th sensor's coordinate frame

$$h_i(x_i, y_i, z_i)$$

  - Compute Jacobean at predicted filter state

$$H_i = \frac{\partial h_i(x_i, y_i, z_i)}{\partial(x_i, y_i, z_i)} \frac{\partial(x_i, y_i, z_i)}{\partial \hat{s}(k|k-1)}$$

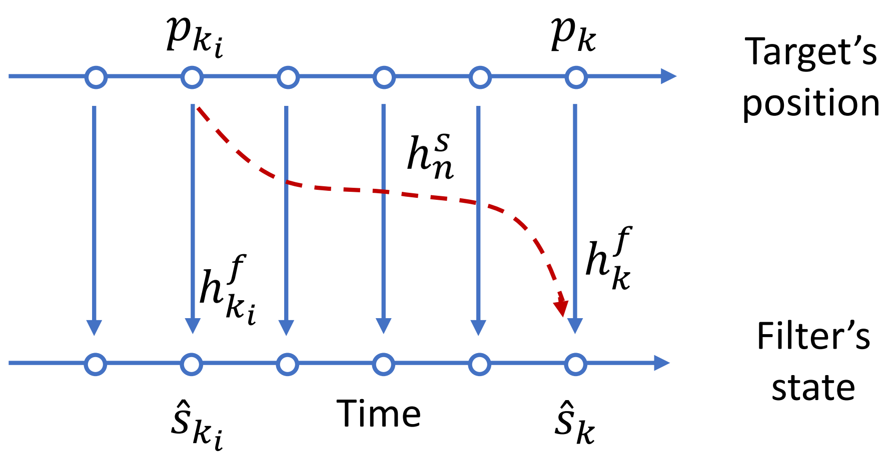
- Collect valid observations (dynamically changing the size based on the available information)

$$h_f(k) = [h_1, \cdots, h_n]$$
$$R_f(k) = diag([R_1, \cdots, R_n])$$
$$H_f(k) = [H_1^T \cdots H_n^T]^T$$

- Proceed with Kalman gain and innovation computation

$$K_f(k) = P(k|k-1)H_f^T(k)\left(H_f(k)P(k|k-1)H_f^T(k) + R_f(k)\right)^{-1}, \qquad e(k) = h_f(x,y,z) - H_f(k)\hat{s}(k|k-1)$$

Implementation of Larsen's Method



Run adaptive EKF up to time k

$$\begin{aligned} \hat{s}(k|k) &= \hat{s}(k|k-1) + K_f(k)e(k) \\ P(k|k) &= \left[\mathbb{I}_{n\times n} - K_f(k)H_f(k)\right] P(k|k-1) \end{aligned}$$

Make observation vector, nose covariance and Jacobean matrices

$$h_s(k, ki, x, y, z) = [h_1, \cdots, h_n]$$
$$R_s(k, ki, x, y, z) = diag([R_1, \cdots, R_n])$$
$$H_s(k) = [H_1^T \cdots H_n^T]^T$$

Compute modified Kalman gain for delayed measurements

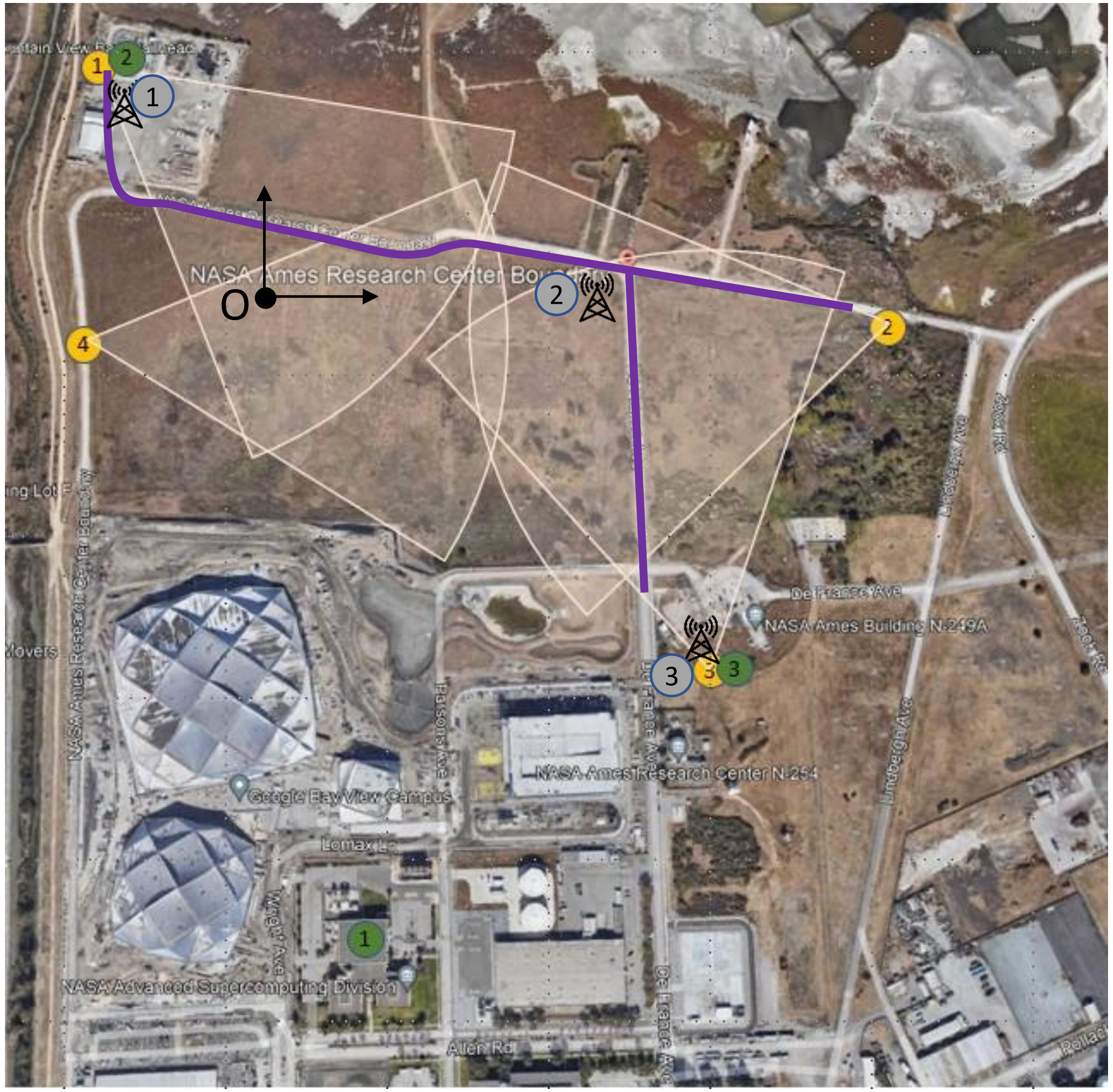
$$M_i^*(k) = \prod_{j=1}^{k_i^d} \left[\mathbb{I}_{n\times n} - K_f(k_i+j)H_f(k_j+j)\right] \Phi(k_i+j)$$

$$K_i^*(k) = M_i^*(k)P(k_i|k_i-1)H_i^{s\top}(k_i)\left[H_i^s(k_i)P(k_i|k_i-1)H_i^{s\top}(k_i) + R_i^s(k_i)\right]^{-1}$$

Run adaptive EKF at time k with modification for delays

$$\begin{aligned} \hat{s}(k|k) &= \hat{s}(k|k) + K_i^*(k)\left[h_i^e(k,x,y,z) - H_i^s(k)\hat{s}(k|k)\right] \\ P(k|k) &= P(k|k) - K_i^*(k)H_i^s(k)P(k_i|k_i-1)M_i^{*\top}(k)\,. \end{aligned}$$

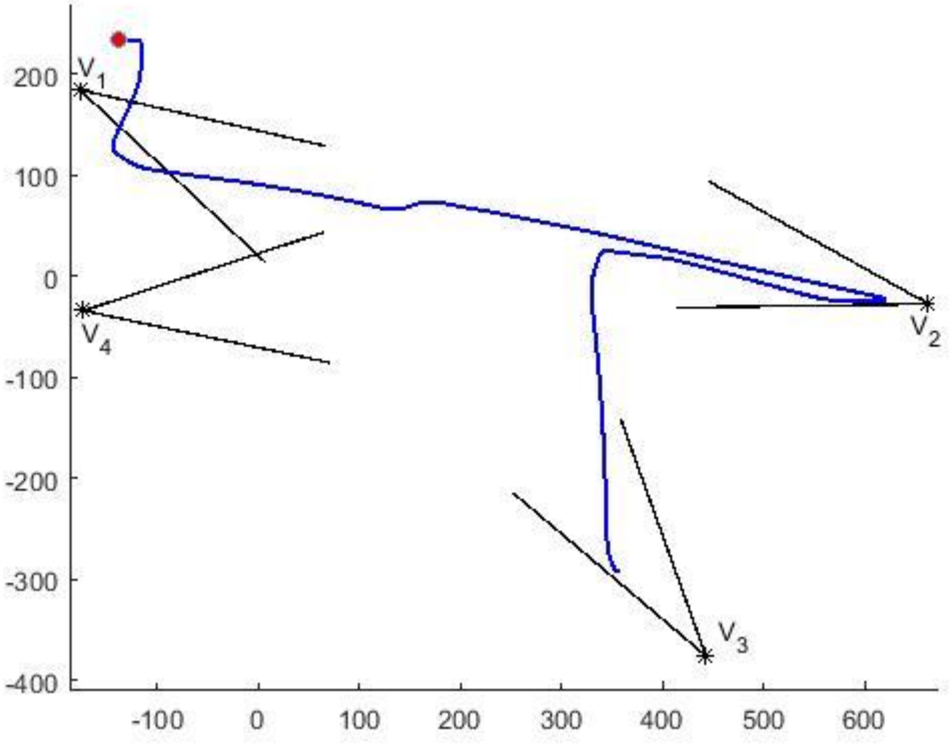
Simulation Setup



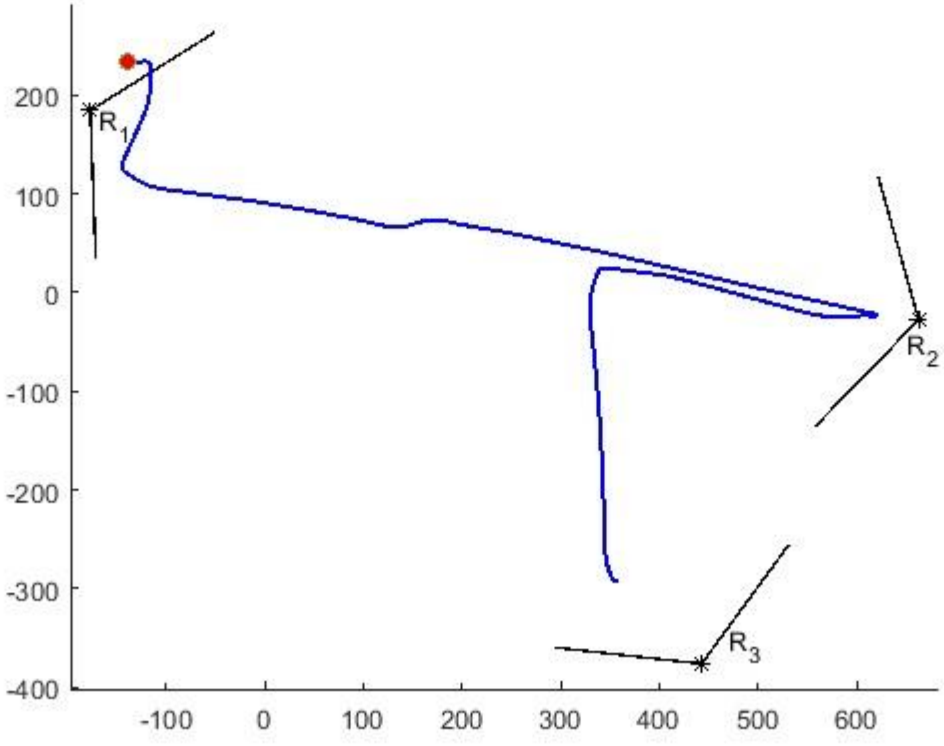
- Sensor stations
- Computing centers
- Communication towers

- Smart Mobility's flight test scenario at NASA ARC DART site
- Target's flight simulated in Reflection Sim Environment
- Generated data stored at 100Hz
- Ground based sensors distributed at NASA ARC DART site
  - Camera readings at 30 Hz, radar readings at 10Hz
  - At least two cameras and two radars see the target
  - Sensors readings generated along the stored trajectory
- Computing centers distribution
  1. Cloud computing with virtually unlimited capabilities
     - Example -NASA supercomputing facility
  2. Edge computing - laptop computer at sensor stations 1, 3
- Communication network deployed
  - Limited wireless data transmit rate and distance
  - Fast Ethernet or VLAN between Station 3 and Center 1

Sensors Layout and Target's Trajectory in 2D



Visual sensors



Radars

Simulation Results for Migration

Communication setup

- Communication protocol for data transmission from sensors to towers
  - Non-orthogonal multiple access - allows all users to utilize the entire system bandwidth
  - simultaneously with a multiple access interference in the coverage area
- Communication protocol for data transmission between towers
  - Orthogonal frequency-division multiple access – no interference
- Ambient white Gaussian noise at the receiver
- Maximum distance for wireless transfer – 500m
- Sensor stations S_1 and S_3 are wired to towers T_1 and T_3 respectively

Computing centers setup

- Computing center C_1 is wired to tower T_3
- Computing centers C_2 and C_3 are wired to towers T_1 and T_3 respectively
- Computing center C_1 is 400 times faster than C_2 and C_3

Communication delay from sensors to computing centers in time steps

V_1	V_2	V_3	V_4	R_1	R_2	R_3
3	2	0	4	0	0	0

Optimal location C_1

Simulation Results for Tracking

Filter Initialization

- Position variables at fires available radar measurement translated into inertial frame
- Velocity variables at zero
- Unknown constant (same for all radars) estimate at zero
- Error covariance matrix P at Q

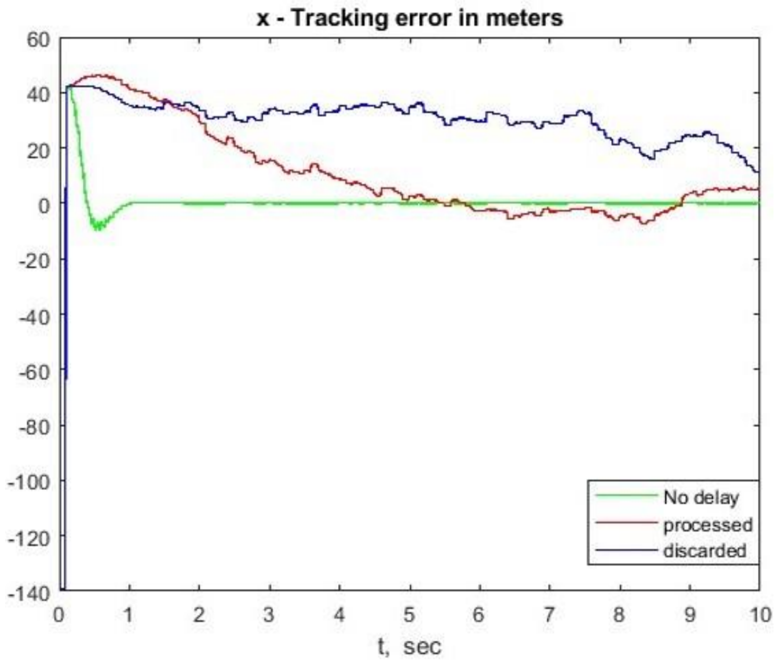
Root-mean-square (RMS) values of errors comparison (entire simulation time)

Tracking case	$RMS(e_x)$	$RMS(e_y)$	$RMS(e_z)$	$RMS(P_{tr})$
No delayed measurements	2.3380	3.6198	0.3731	14.9456
Slow measurements discarded	5.9840	4.9586	4.1202	88.3366
Slow measurements processed	4.0234	3.7562	0.4136	18.3418

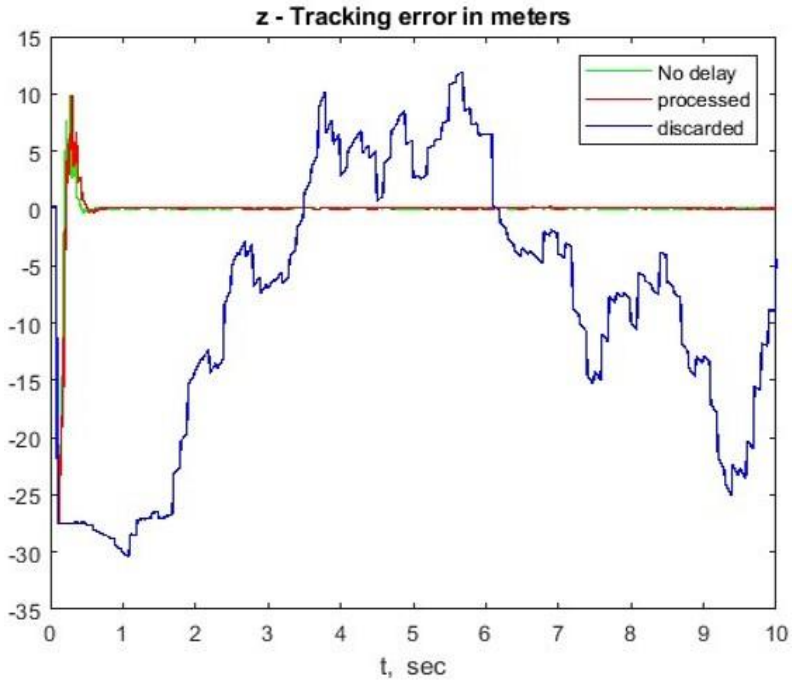
Root-mean-square (RMS) values of errors evolution as simulation progresses

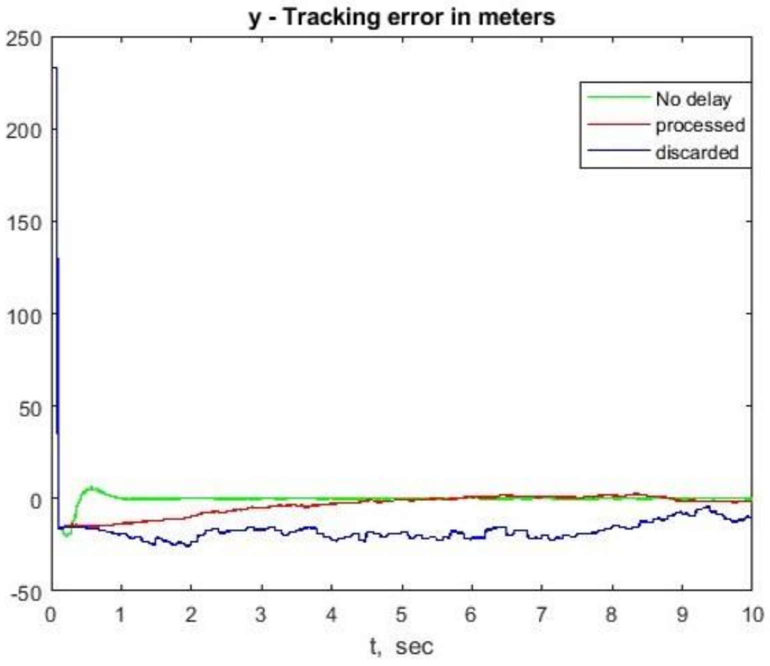
Time inreval	$RMS(e_x)$	$RMS(e_y)$	$RMS(e_z)$	$RMS(P_{tr})$
$0 < t \leq 10$	23.2430	21.8229	2.4052	52.7483
$10 < t \leq 321$	0.4975	0.2005	0.0163	15.4578
$321 < t \leq 331$	0.5317	0.4193	0.0079	26.2248

Simulation Results (Cont.)



Tracking errors at takeoff

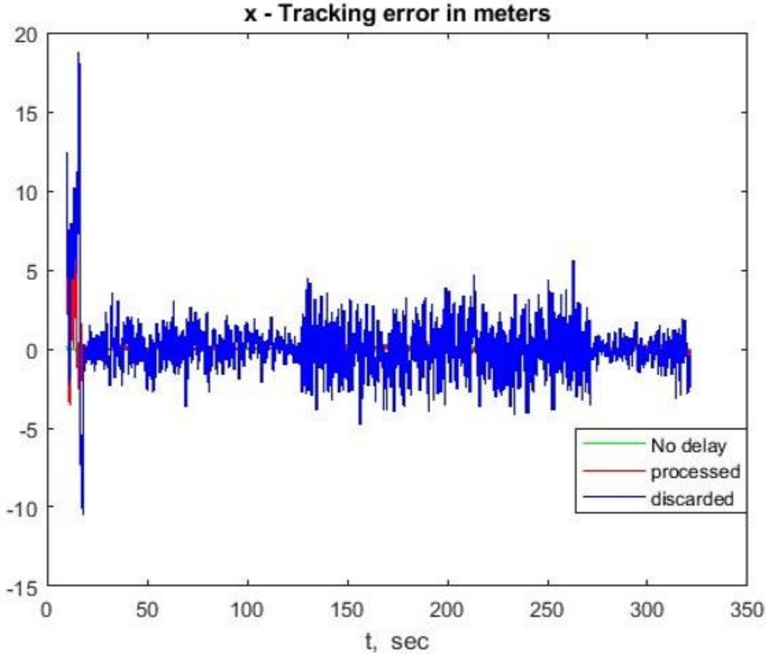


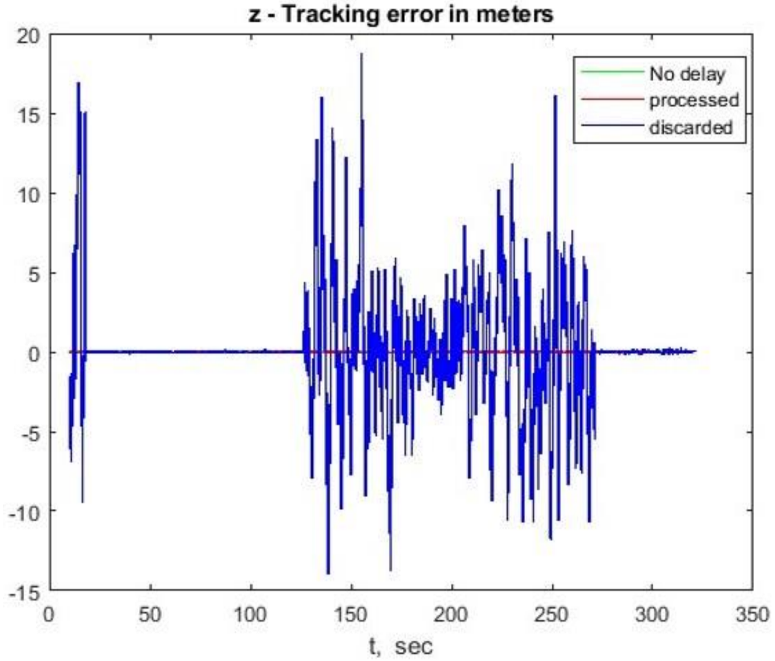


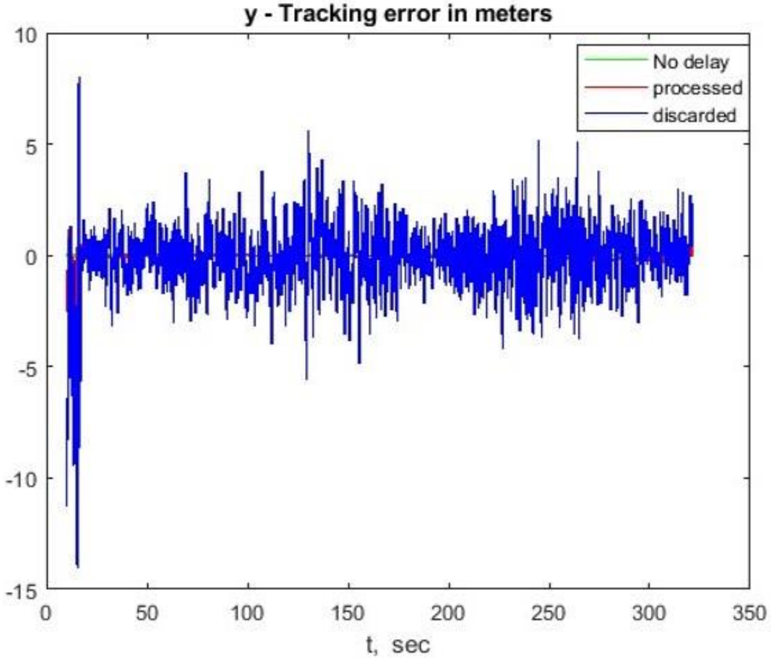
- Ideal case -no delay meas.
- Processed delayed meas.
- Discarded delayed meas.

Simulation Results (Cont.)

Tracking errors in cruise







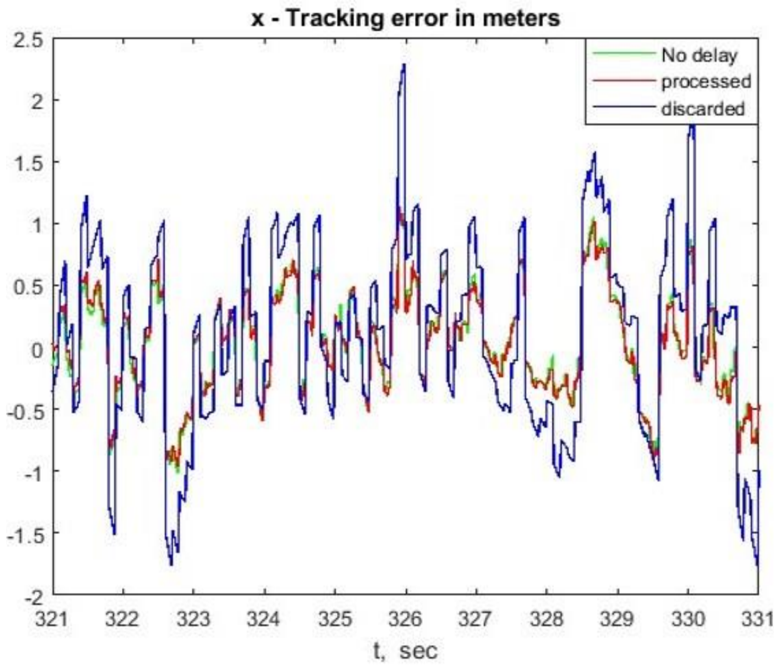
Ideal case -no delay meas.

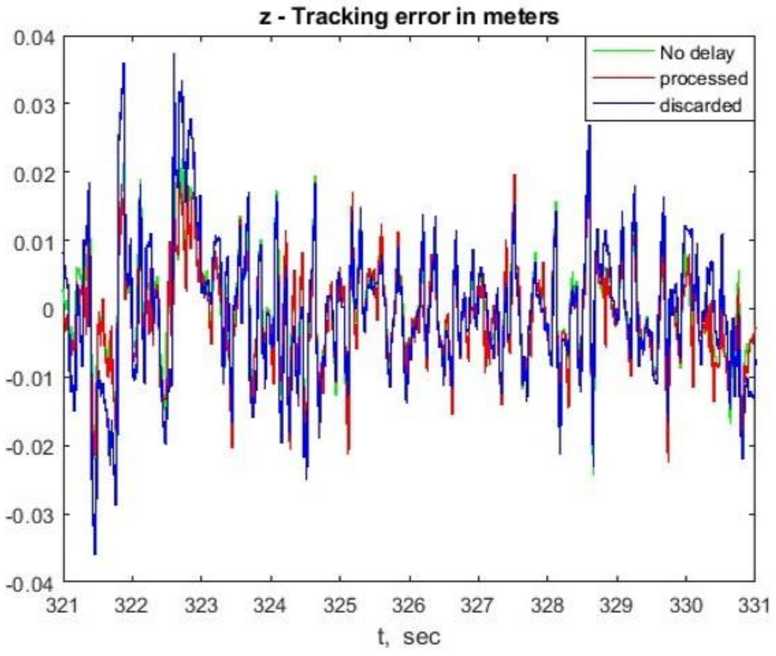
Processed delayed meas.

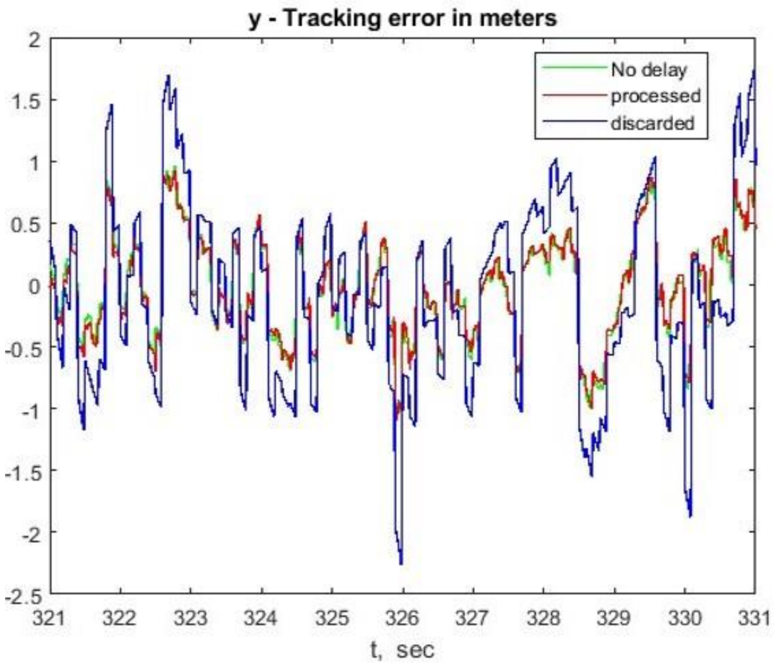
Discarded delayed meas.

Simulation Results (Cont.)

Tracking errors in landing





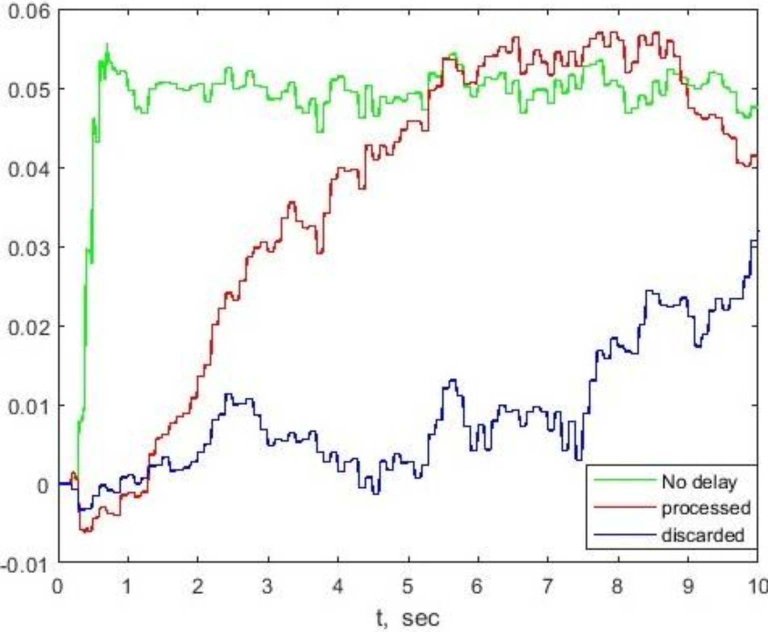


- Ideal case -no delay meas.
- Processed delayed meas.
- Discarded delayed meas.

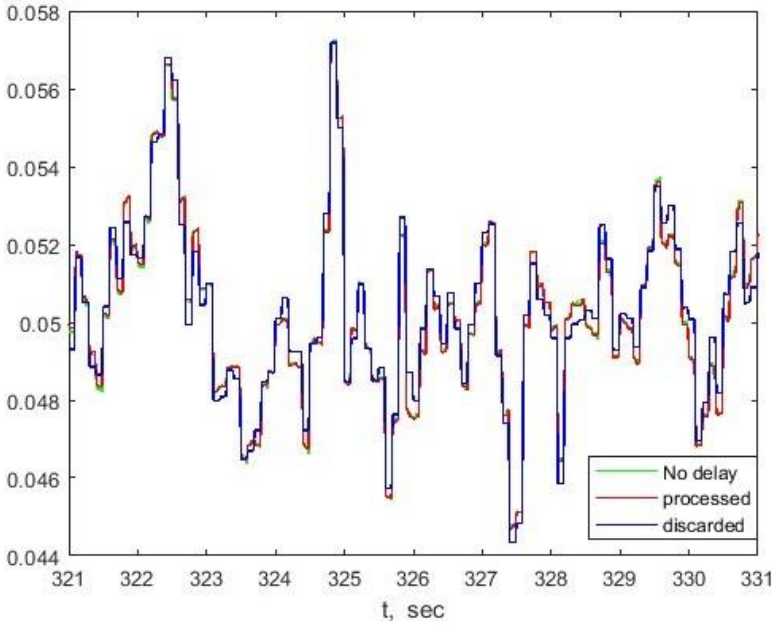
Simulation Results (Cont.)

Estimate of unknown constant

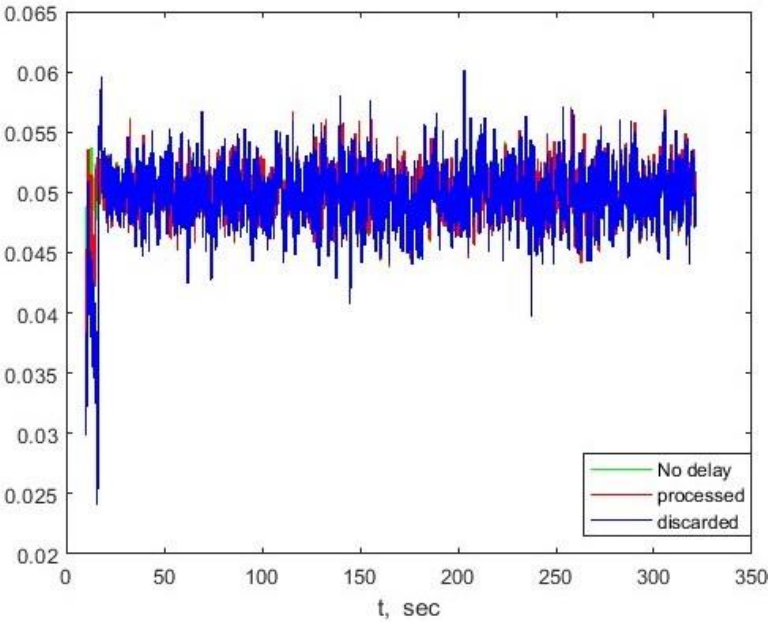
Take-off



Landing



Cruising



- Ideal case -no delay meas.
- Processed delayed meas.
- Discarded delayed meas.

Future Research

Mobility of sensors, antennas, computing platforms

- Sensors mobility design for optimized sensing
- Aircraft as network node for data transfer
- Optimal network topology for fast and efficient data transfer
- Optimal trajectory design for network nodes
- Edge computing on moving platforms
- Optimal edge motion design
- Navigation and control of mobile edges for optimal information processing
- Estimation of atmospheric disturbances with distributed sensing
- Complexity in the network design
- Joint optimization may be beneficial but expensive