# GPS/INS Kalman Filter Design for Spacecraft Operating in the Proximity of ISS

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# Acknowledgments / Corrections

- This work was partially funded by the Navigation Systems & Technology Lab at the NASA Johnson Space Center
- The software used in this work is part of the Java Astrodynamics Toolkit (JAT), an open source software library founded by UT grad students: http://jat.sourceforge.net
- SIGI is tightly integrated, embedded GPS/INS
  - Combined GPS/INS solution not used in orbit [Goodman, 2002]
- ** indicates new since paper was submitted

# Introduction

- Previous studies have concluded that GPS relative navigation is feasible for rendezvous [Ebinuma, 2001], [Um, 2001]
  - Don't account for GPS outages or degradation due to:
    - signal blockage
    - multipath effects
    - delta-v and attitude maneuvers

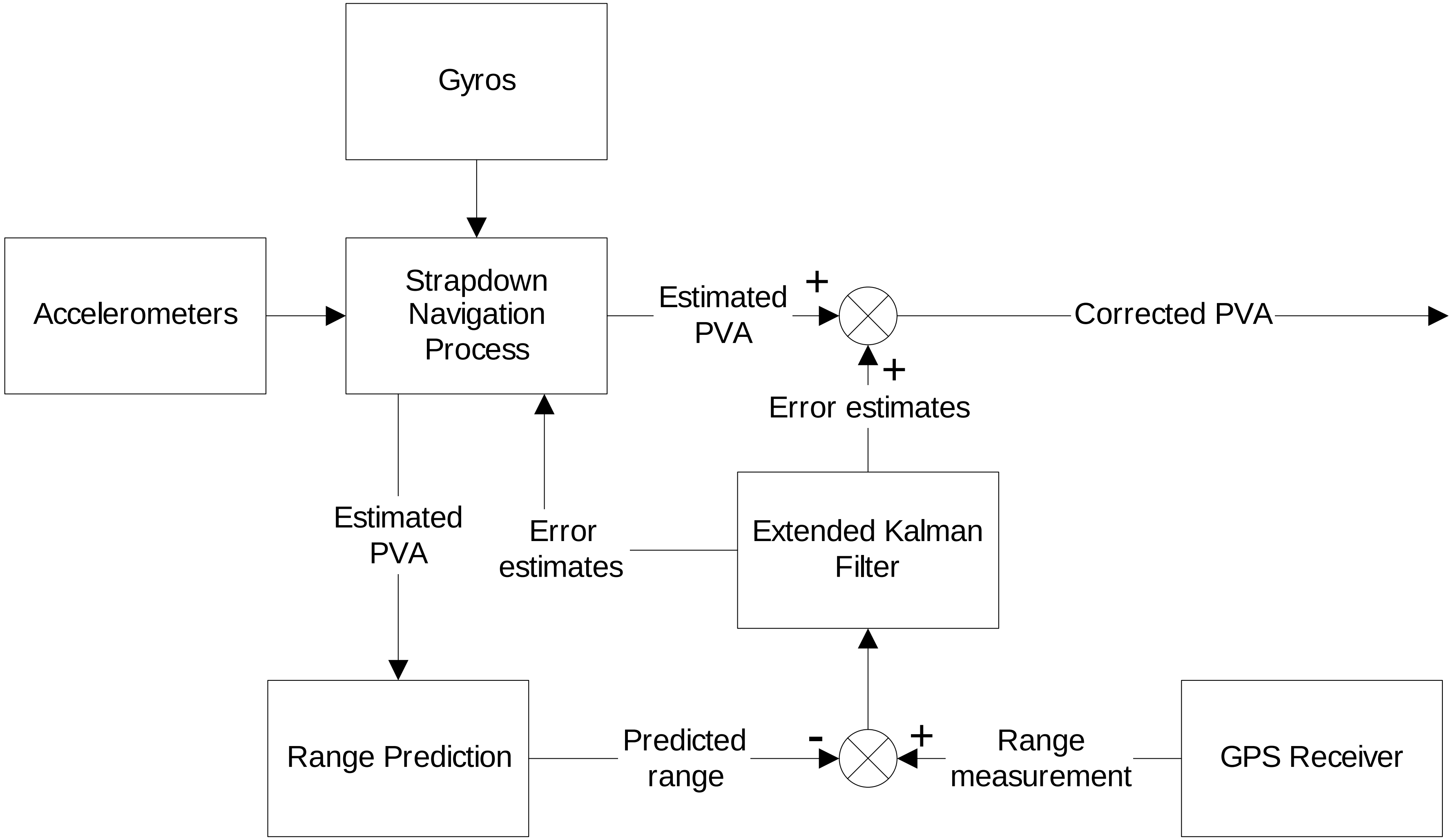
# Introduction (cont.)

- Can GPS/INS provide navigation for all flight phases?
  - INS only is currently used during ascent [Goodman]
    - GPS/INS could be used if GPS antennas were added
    - GPS and GPS/INS currently used by commercial LVs
  - GPS/INS has been studied for entry and landing and shown to be adequate [Goodman], [Braden, et al, 1990]
  - Rendezvous is the remaining unknown
- Role of INS for rendezvous application
  - Provide trajectory during GPS outages
  - Measure maneuvers

# Filter Architecture

- Indirect feedback Kalman filter
  - Kalman filter estimates error states (indirect)
  - Gyro and accelerometer measurements are used to obtain reference trajectory
  - State estimates are used to correct the reference trajectory (extended Kalman filter formulation)
  - Absolute Navigation Filter
  - **Relative Navigation Filter

# Filter Architecture



# Absolute Navigation Filter

- States:
  - ECI Position (3)
  - ECI Velocity (3)
  - Body to ECI Quaternion (4)
  - Gyro Biases (3)
  - Accelerometer Biases (3)
  - GPS Receiver Clock Bias and Drift (2)
  - **Ionospheric Delay (1)
  - **GPS SV Clock and Ephemeris (n)
  - **Integer Ambiguity (n) – carrier phase only
- Measurements
  - Gyros and Accelerometers (provide reference trajectory)
  - GPS C/A Code or **Carrier Phase

# Relative Navigation Filter

- **States
  - Chaser ECI Position and Velocity (6)
  - Chaser Body to ECI Quaternion (4)
  - Chaser Gyro and Accelerometer Biases (6)
  - Chaser GPS Receiver Clock Bias and Drift (2)
  - Ionospheric Delay (1)
  - GPS SV Clock and Ephemeris (n)
  - ISS ECI Position and Velocity (6)
  - ISS Drag Coefficient (1)
  - ISS GPS Receiver Clock Bias and Drift (2)
  - Single Difference Integer Ambiguity (n)
- **Measurements
  - Chaser Gyros and Accelerometers (chaser ref trajectory)
  - Chaser and ISS GPS C/A Code
  - Single Difference Carrier Phase (between chaser and ISS)

# Trajectory Generation

- Currently: Two Body Orbit Model
  - Rendezvous trajectory computed using CW equations (two impulse solution)
  - Simulation begins just after Ti burn
- Coming Soon
  - JGM3 Gravity, Harris-Priester Drag
    - Already exists in JAT
  - Finite burn modeling
  - Simulation of Twice Orbit Rate V-bar Approach (TORVA) used by Shuttle

# GPS Measurement Generation

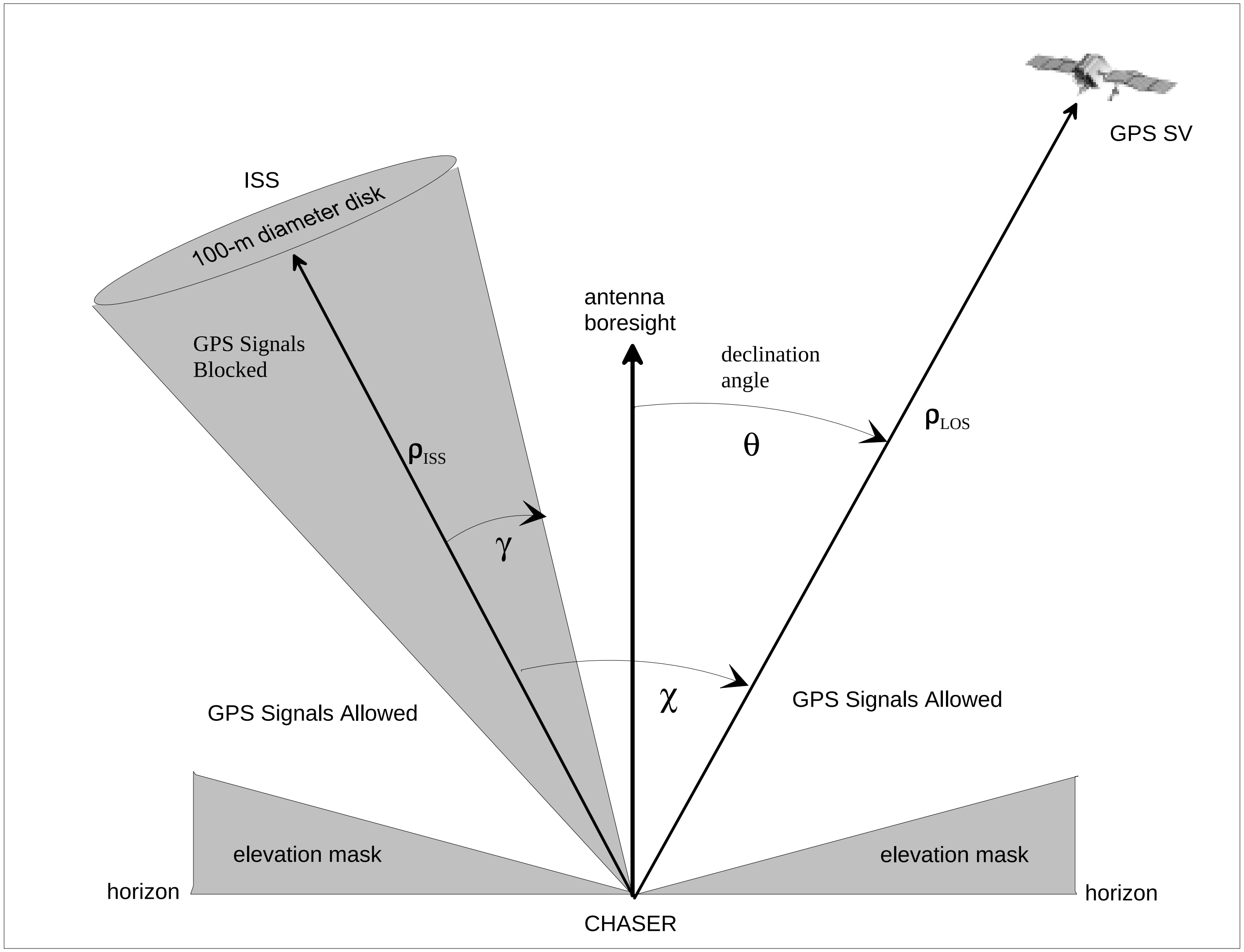
- GPS C/A Code and Carrier Phase
  - Receiver Clock Bias and Drift
    - Two state random walk model
  - **Ionospheric Delay
  - **SV Clock and Ephemeris Errors
    - Constant radial, along track, cross track and clock errors
    - Projected onto the line of sight vector
  - **Integer Ambiguity (carrier phase)
    - Constant random number for each SV, no cycle slips
  - ISS Blockage and Multipath
  - All-in-view GPS receiver (Not the SIGI receiver)
    - Single nadir-pointed GPS antenna (no attitude maneuvers)

# INS Measurement Generation

- SIGI Gyros and Accelerometers Modeled
  - Honeywell Q-Flex QA-2000 accels and GG1320 RLGs
  - First order Gauss-Markov bias processes
  - Scale Factor and Misalignments (planned)
    - Data from [Um]

| | | |
|---|---|---|
| Gyro | Bias $\sigma$ | 0.0035 deg/hr |
| | Bias $\tau$ | 1 hr |
| | Noise | 0.002 deg/rt-hr |
| | Scale Factor | 2 ppm |
| Accelerometer | Bias $\sigma$ | 30 $\mu$g |
| | Bias $\tau$ | 1 hr |
| | Noise | 0.00075 m/s/rt-hr |
| | Scale Factor | 40 ppm |

# Blockage Model



# Multipath Environment Model

- Statistical model based on rural and indoor multipath models
- Generates amplitude, phase and time delays for N (user selectable) multipath rays
- Conjectures
  - Amplitudes are Rayleigh distributed
  - Phases are uniformly distributed
  - Time delays form a Poisson Process
  - Multipath power decays exponentially with time delay
- More details in paper

# Multipath Range Error Models

- Computes the range error for C/A code and carrier phase measurements
  - Based on amplitudes, phases and time delays of multipath rays from multipath environment model
  - Details of carrier phase range error in paper
  - Details of C/A code range error in upcoming ION GPS 2003 paper [Gaylor, Lightsey and Key]

# Results

– Rendezvous scenario with blockage

– **All GPS error sources except multipath

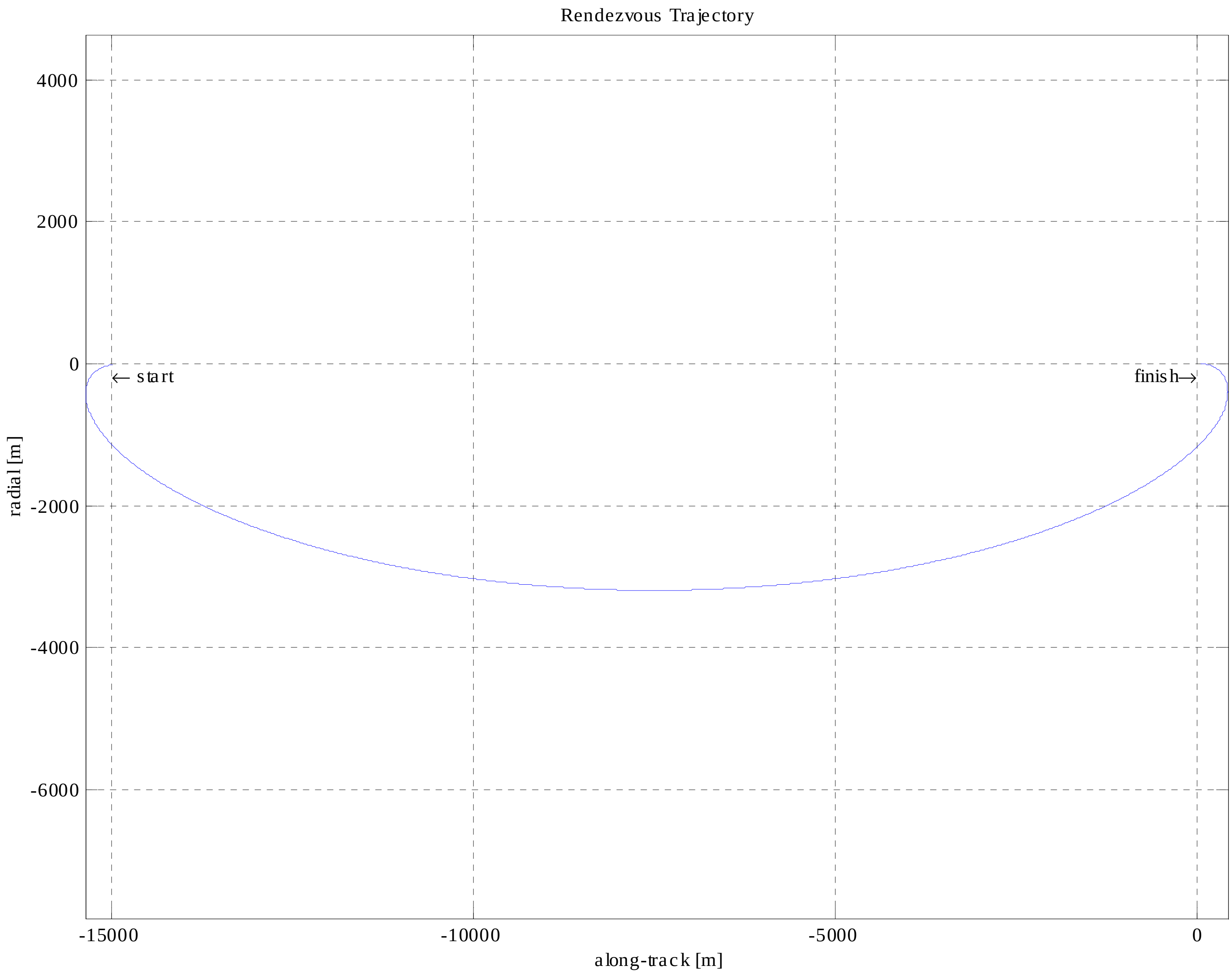
– **Absolute navigation results

  - C/A code pseudorange measurements
  - Iono-free carrier phase measurements
    – Assuming the use of dual frequency receiver

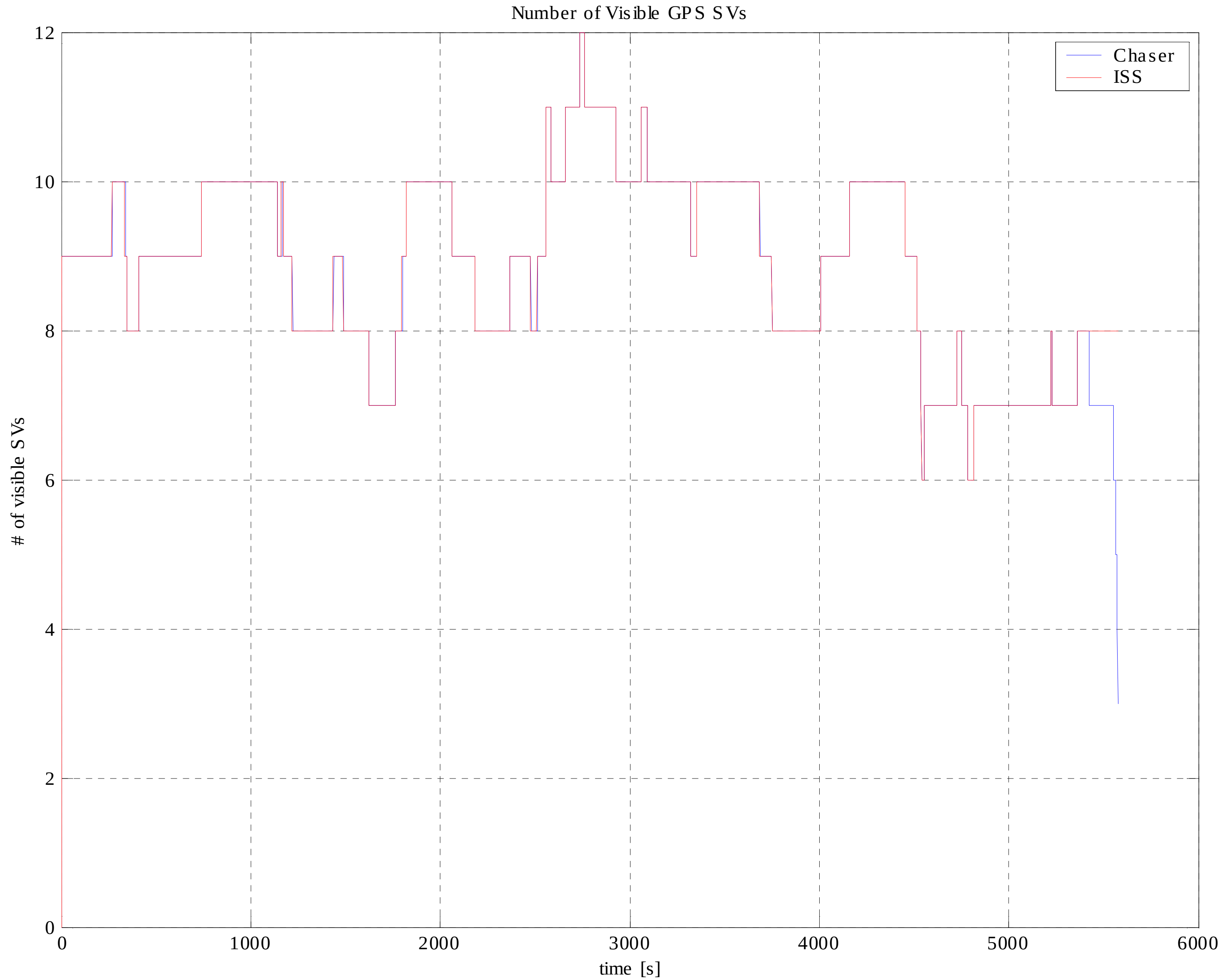
– **Relative navigation results

  - Differencing Chaser and ISS GPS/INS Absolute Navigation Filter States
  - Differencing Chaser and ISS Carrier Phase Measurements in Relative Navigation Filter

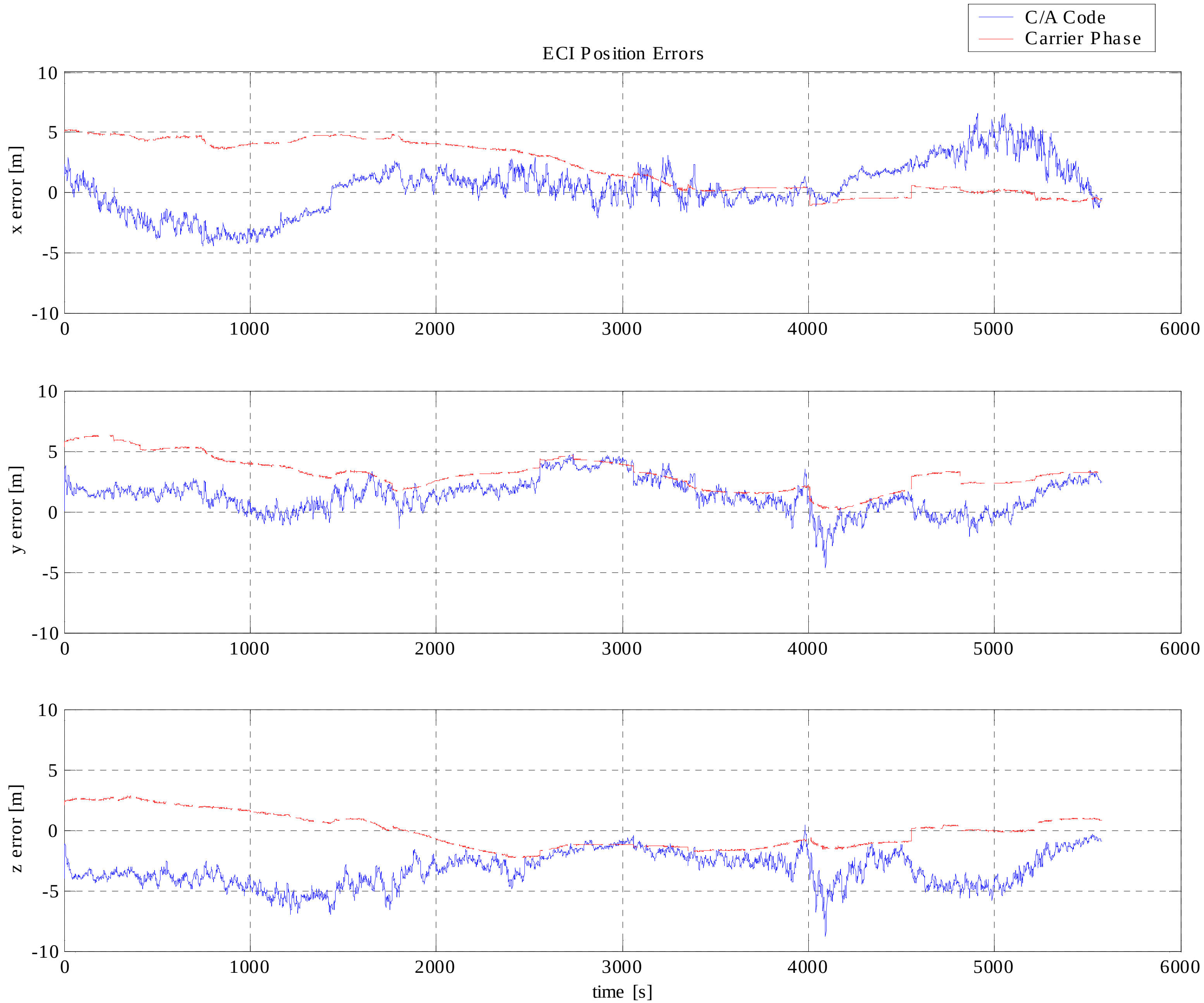
# Rendezvous Trajectory



# Number of Visible GPS SVs



# Absolute Navigation Results



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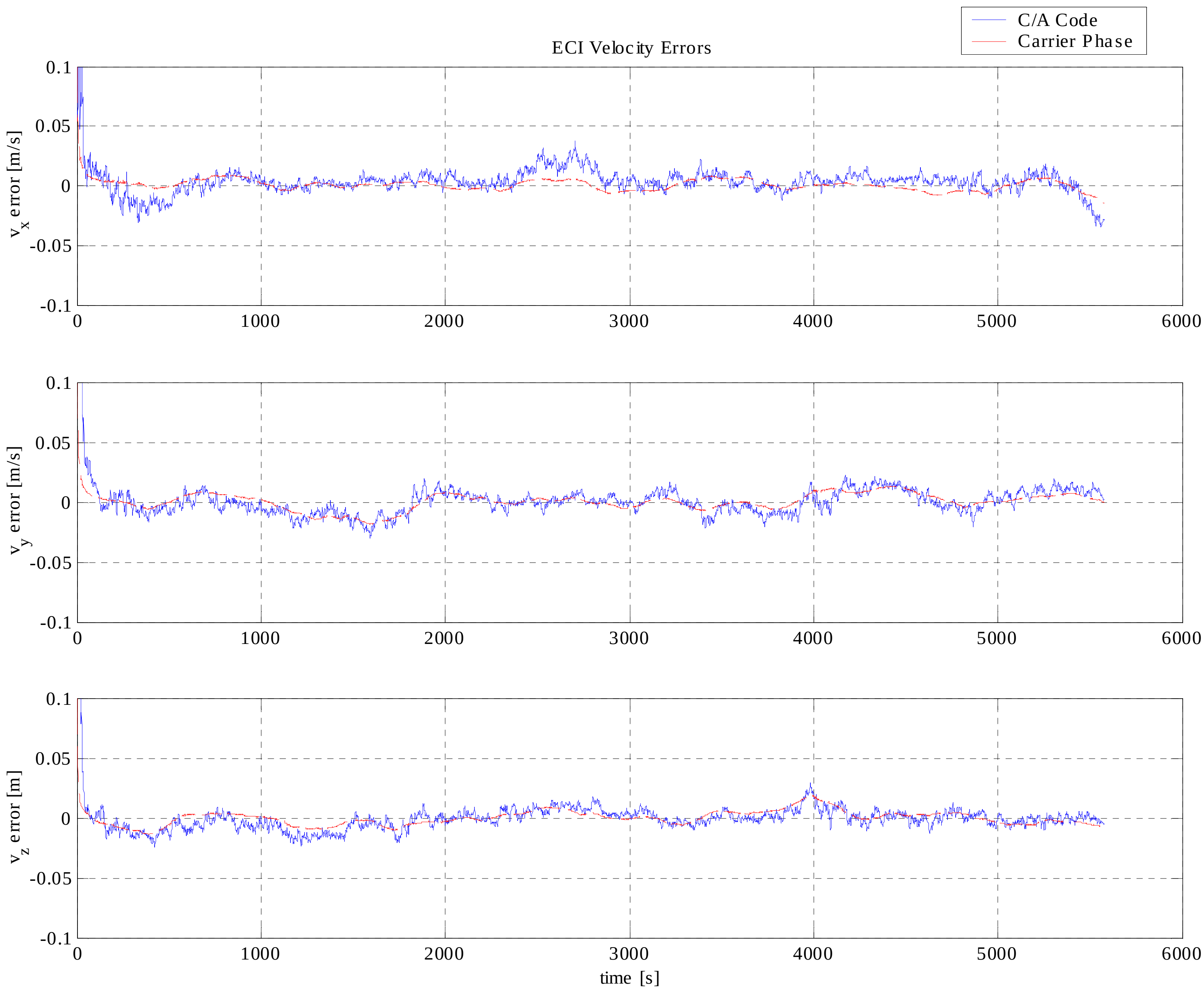
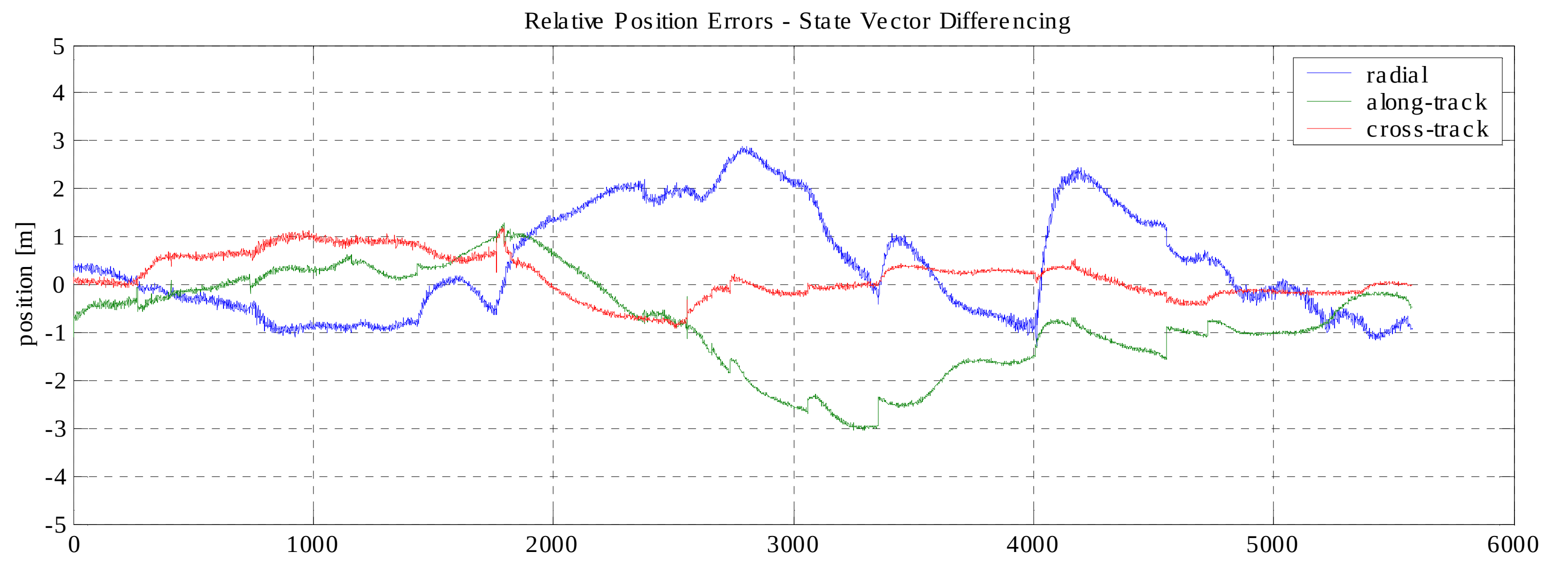
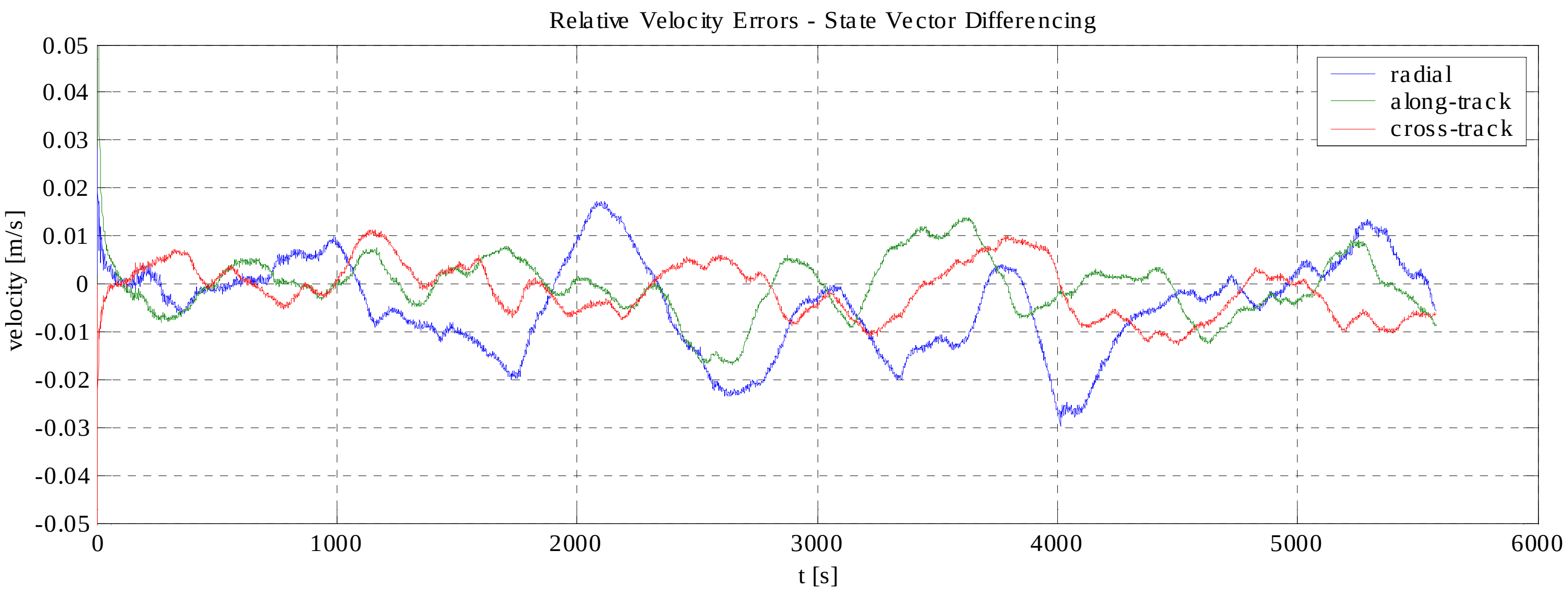


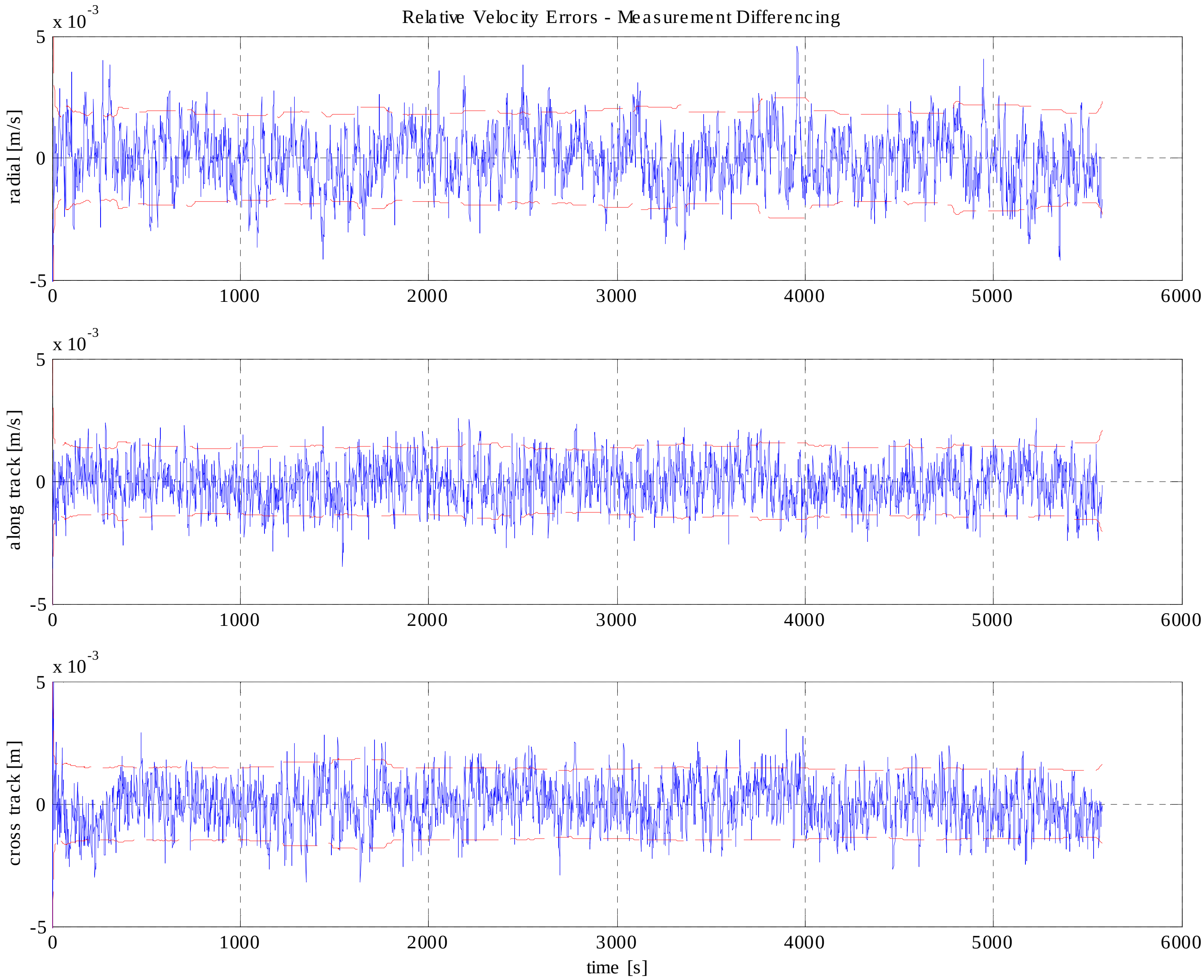
# Relative Navigation Results
## (State Vector Differencing)



# Relative Navigation Results
## (Measurement Differencing)

# Relative Navigation Results
## (Measurement Differencing)



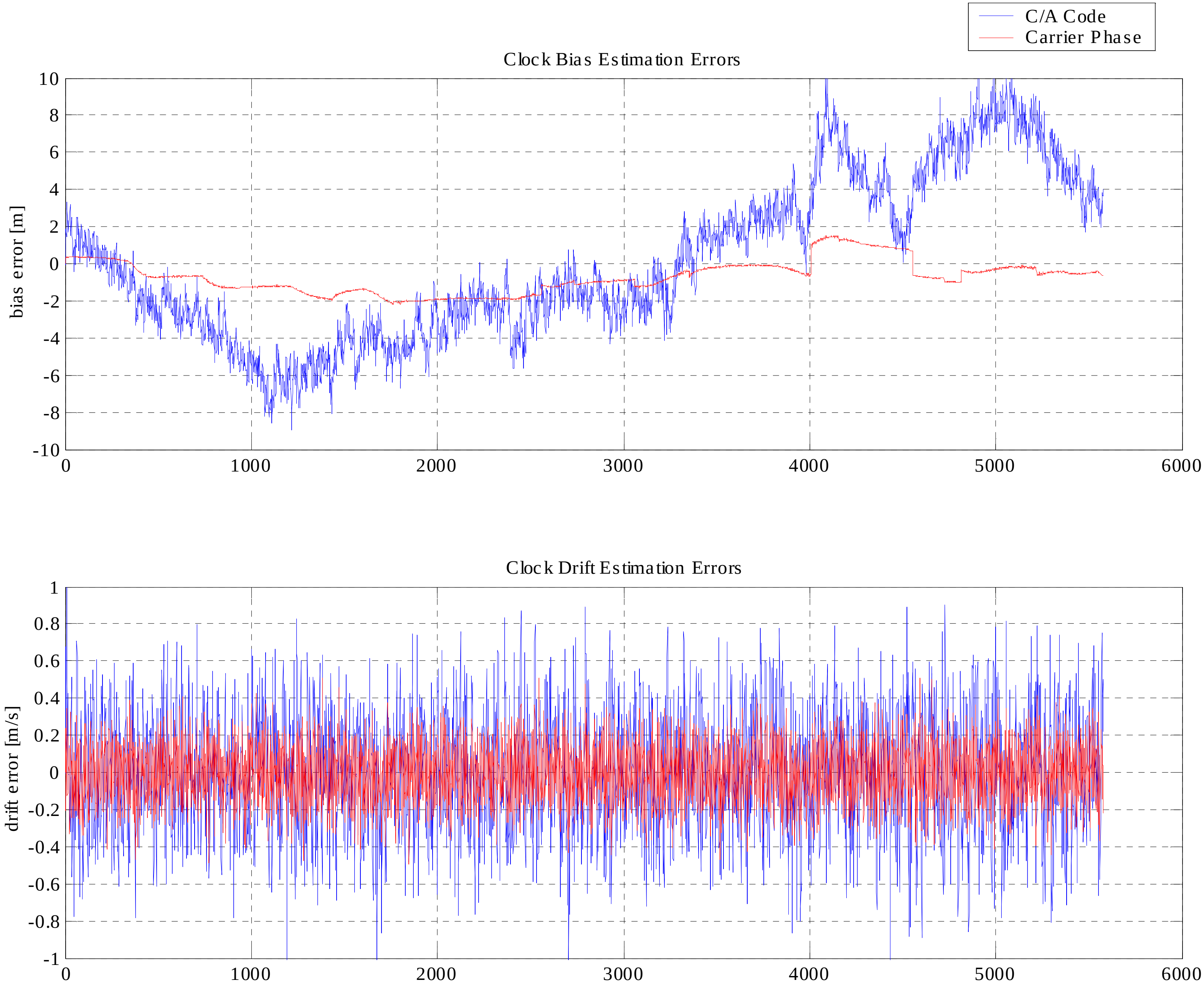
# Conclusions

- GPS/INS Extended Kalman Filter simulation has been developed. More fidelity will be added in the next few months
- Capabilities to study
  - Relative navigation architectures
    - State vs Measurement Differencing
  - GPS and INS sensor requirements
    - Dual frequency vs Single frequency GPS receiver
    - Code vs Carrier Phase
    - Accelerometer and Gyro requirements
  - Various ISS final approach concepts
  - Additional sensor integration

# References


- Goodman, John L., “GPS in Earth Orbit: Experiences from the Space Shuttle, International Space Station and Crew Return Vehicle Programs”, Core Technologies for Space Systems Conference, Nov 2002.
- Ebinuma, Takuji, “Precision Spacecraft Rendezvous Using Global Positioning System: An Integrated Hardware Approach”, Ph.D. dissertation, University of Texas, Aug 2001.
- Um, Jaeyong, “Relative Navigation and Attitude Determination Using a GPS/INS Integrated System Near the International Space Station”, Ph.D. dissertation, University of Texas, Dec 2001.
- Braden, K., et al, “Integrated Inertial Navigation System/Global Positioning System (INS/GPS) for Manned Return Vehicle Autoland Applications”, Proceedings of IEEE PLANS, Mar 1990.
- Gaylor, Lightsey and Key, “Effects of Multipath and Signal Blockage on GPS Navigation in the Vicinity of the International Space Station”, Proceedings of ION GPS-2003, Sep 2003.

# Absolute Navigation Filter Results



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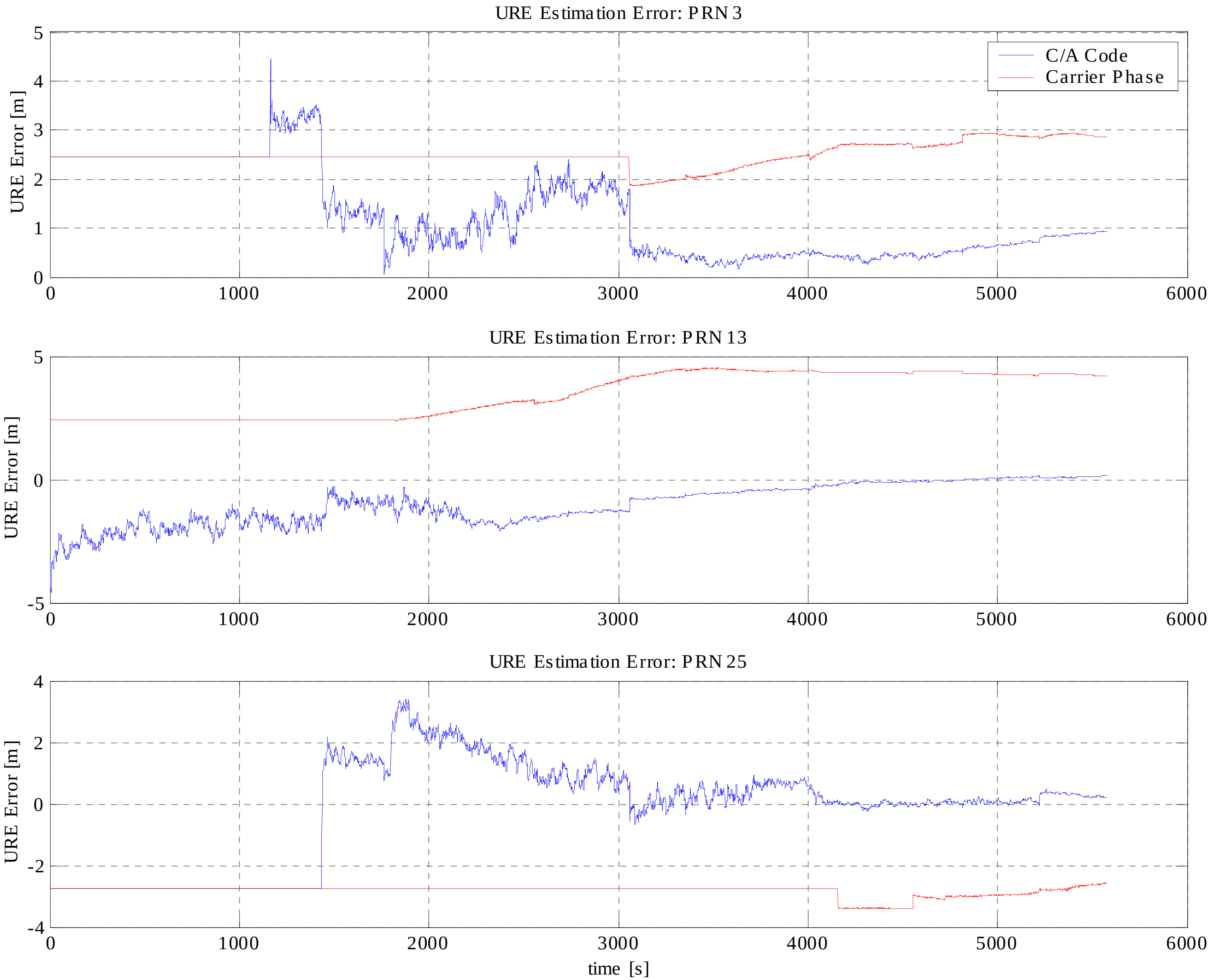

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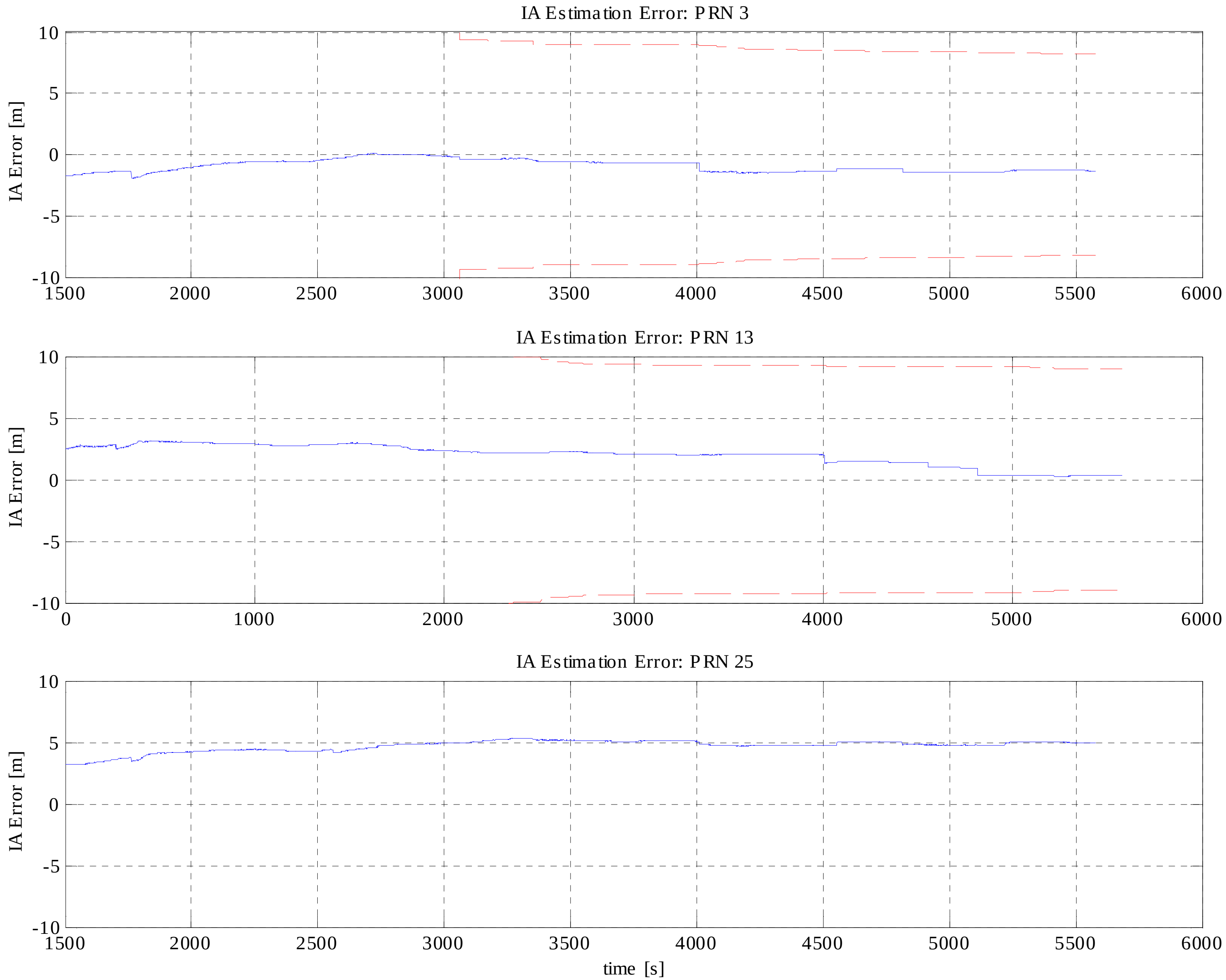

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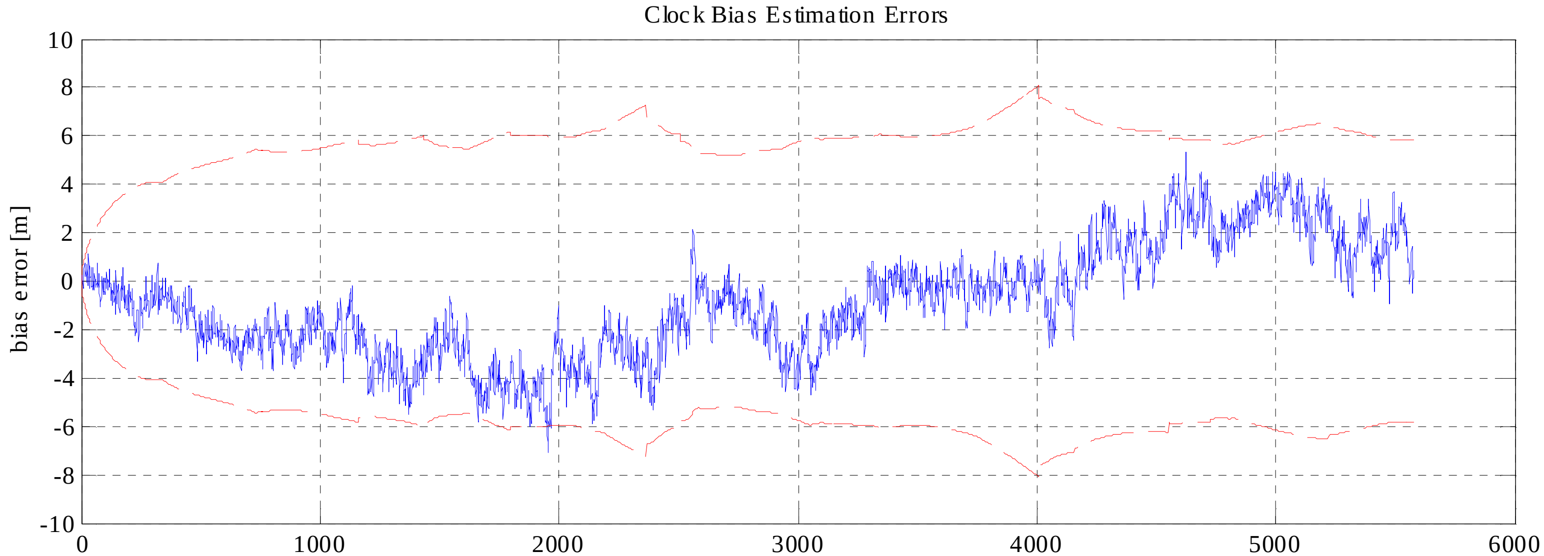


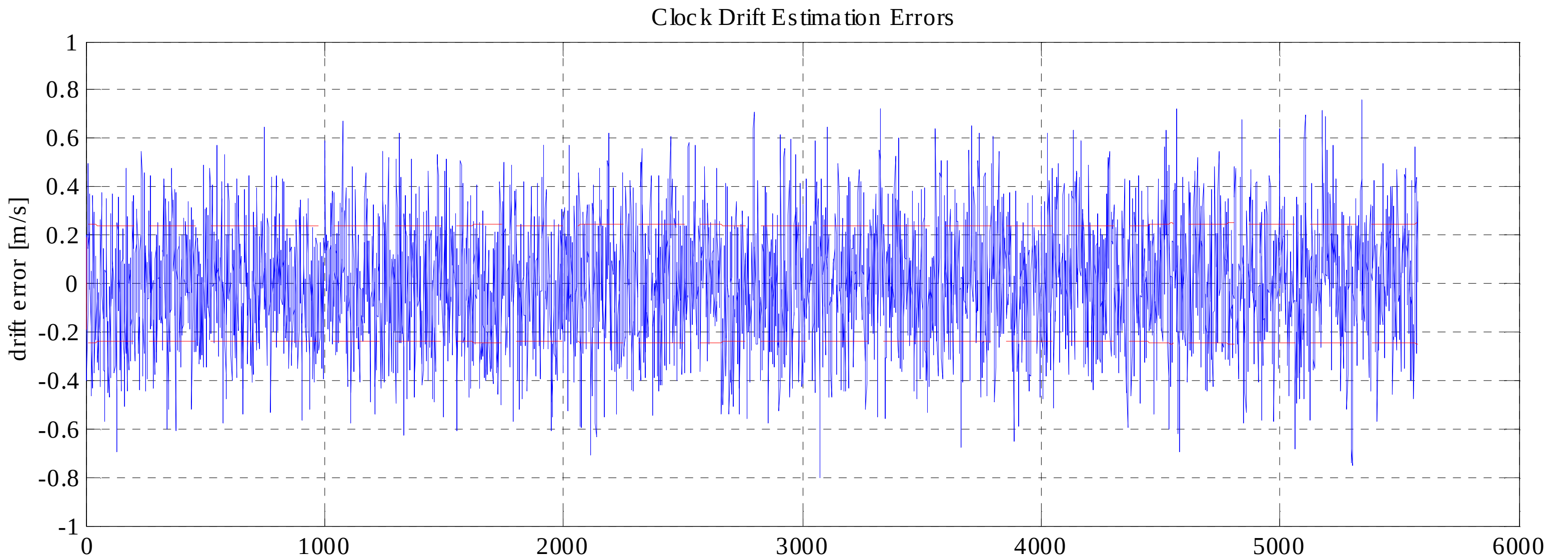

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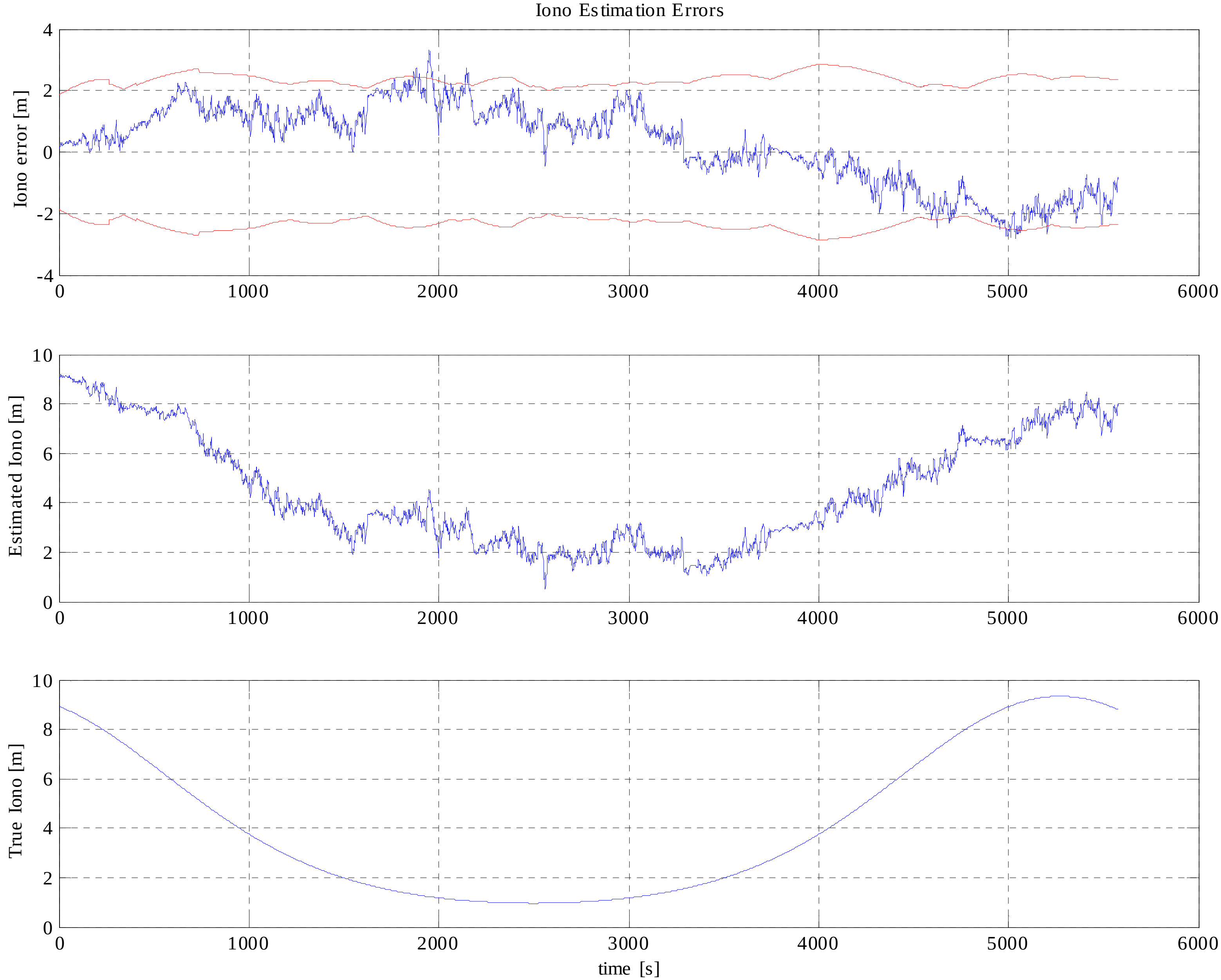

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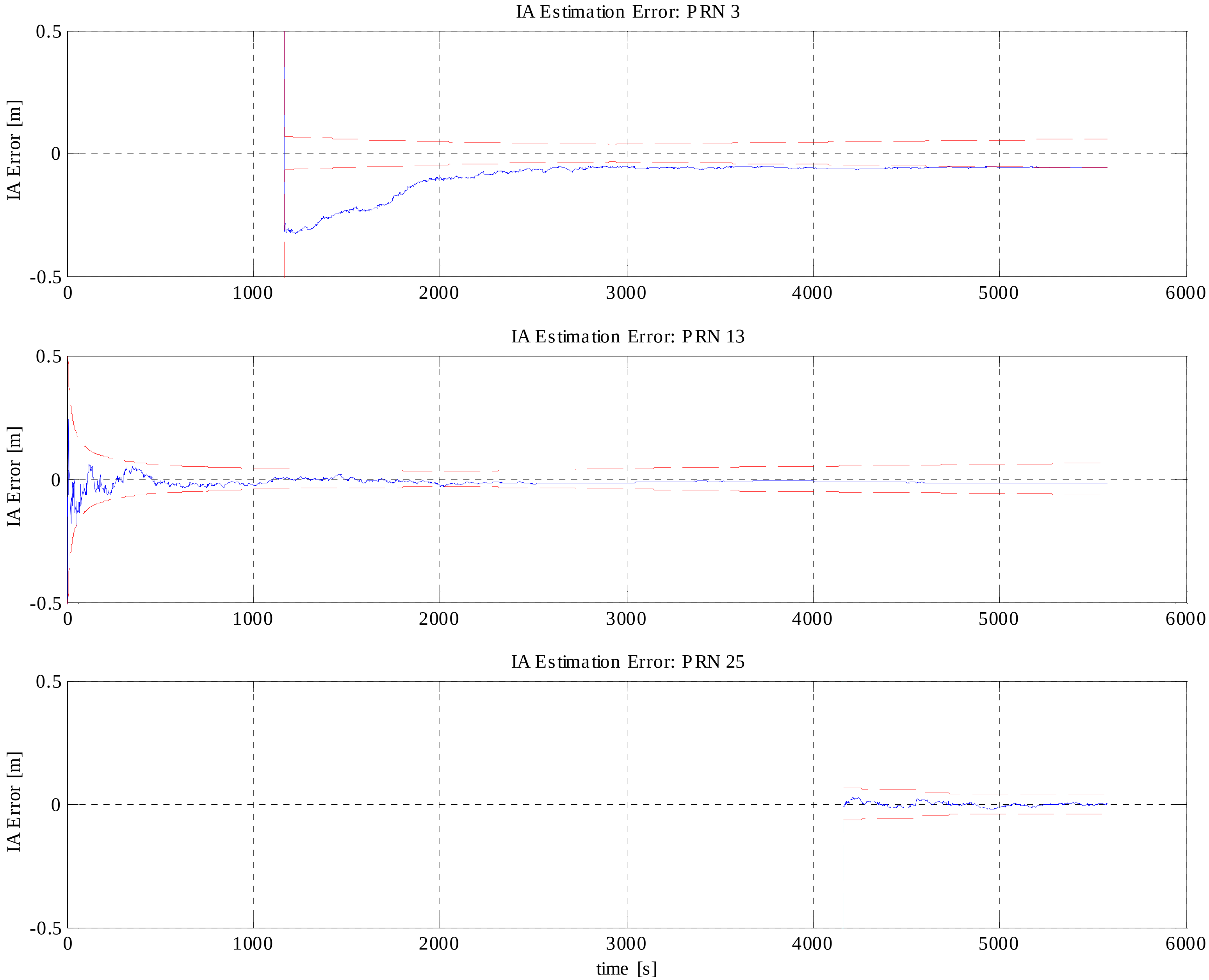

# Relative Navigation Filter Results