Development Status and Preliminary Results for the CrossRate LORAN/GPS Integration Filter

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LG Integration Objectives

LG Integrator Design Objectives

- To integrate GPS position and velocity signals with LORAN pseudo-range and bearing measurements to produce an optimally combined position/velocity/heading solution.
  - Combined solution should be commensurate with the robustness (LORAN) and accuracy (GPS) associated with the individual resources without degradation of either
  - Algorithm should provide resistance to accuracy degradation in the face of GPS dropout
  - Algorithm should be robust to a range of enabled/disabled resources, partial measurements, etc.

Integrator Simulink-Based Development Simulation

Development Simulation

Key Model Blocks

- GPS Receiver Model produces (noise) corrupted Lat/Lon/Alt and ECEF velocity vectors as well as UTC time-tag

- Loran Truth Model (Produces "True" TOAs)
  - Computes true ranges to stations using Vincenty Method
  - Applies primary (PF), secondary and ASF factor effects
  - Adds process noises due to path and local weather and spatial uncertainty effects

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Development Simulation

Key Model Blocks

- Loran Receiver Ranging Model (Produces "Measured" Pseudo-Ranges)
  - Corrupts true TOA with clock error model (Measured TOA)
  - Compensates TOA with nominal PF, SF and ASF terms (using estimated position)
  - Converts TOA to ranges
  - Also models "Range Hits"; short term bad range measurements (Integrator monitors for this)
  - Simple SNR model using desired STD

Development Simulation

Key Model Blocks

- Loran H-Field Bearing Measurement Model
  - Corrupts true bearings using circular error-map
  - Generates "BearingValid" Indicator for each candidate station
  - Currently only single bias term is accounted for in Integrator

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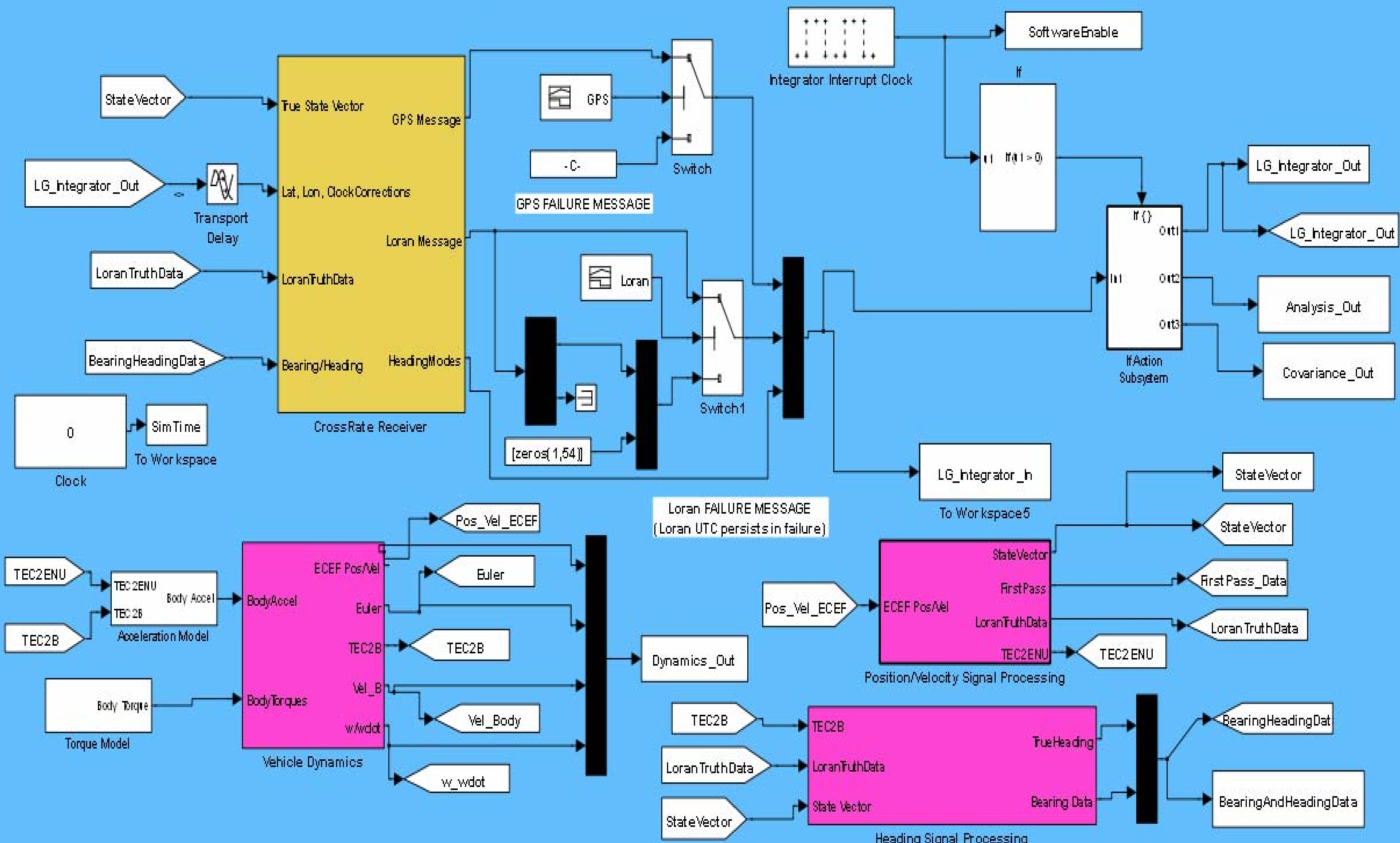
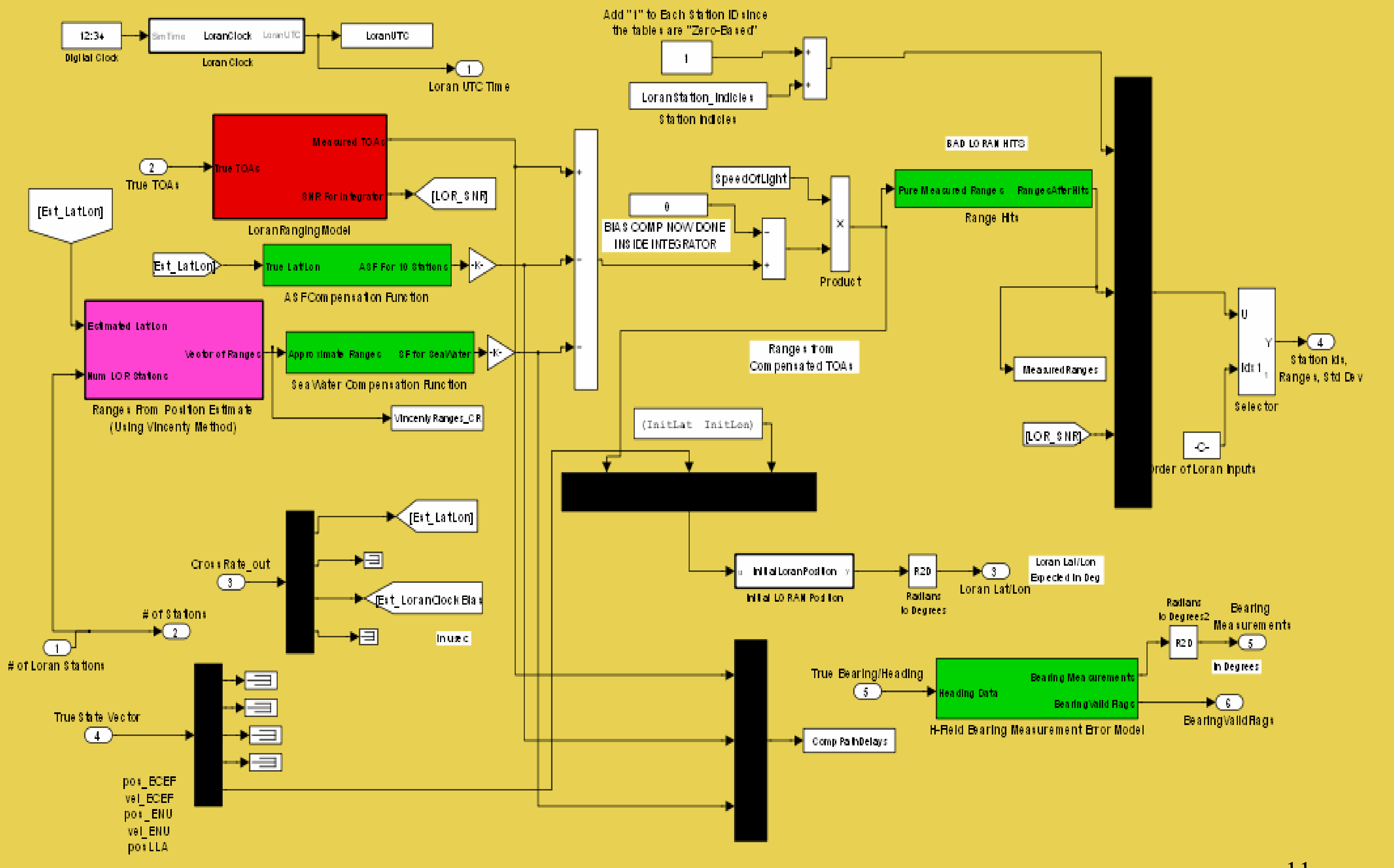
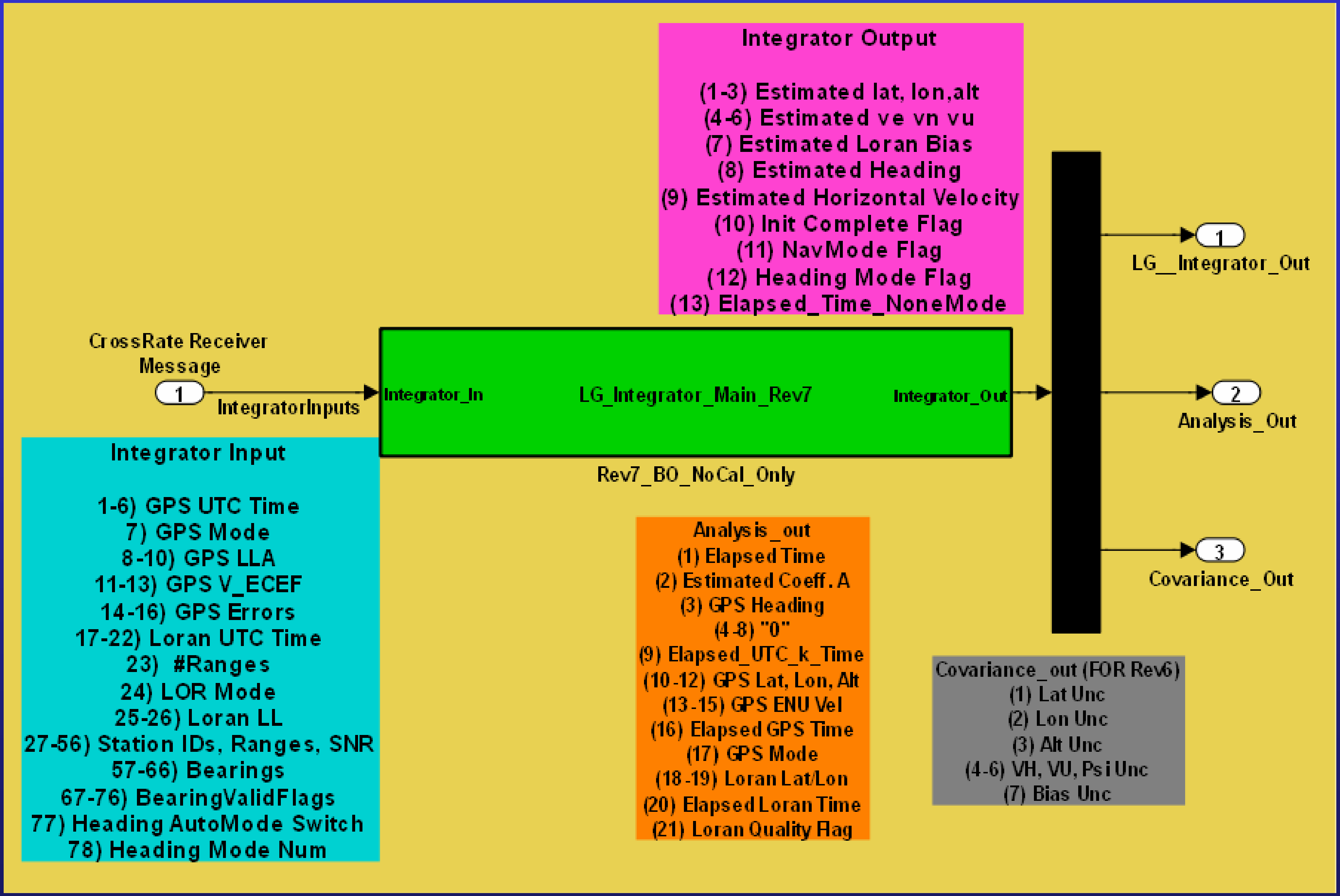
CrossRate eLoran/GPS/ Blending Software Development Simulation (REV 4 With Heading/Bearing)



eLoran Receiver Model



Integrator Processing Block (With Actual I/O)



PVH Heading Modes

Heading Modes in PVH Integrator

- Integrator must accommodate two primary scenarios in estimating the heading:
  - **Scenario #1**: Fluid velocity is negligible when compared with velocity of receiver relative to fluid. *EN velocity may be included in heading estimation.*
  - **Scenario #2**: Fluid velocity is substantial when compared with velocity of receiver relative to fluid. *EN velocity should be excluded in heading estimation.*

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Heading Modes in PVH Integrator

- BearingAndVelocity (BAV) Mode
  - Blends velocity information with bearing measurements to produce heading estimates
  - Utilizes GPS-generated pseudo-heading measurements (from ECEF velocity measurements)
  - Will also incorporate velocity states, implicit to the integrator, in the heading estimation
  - Velocity and heading states are coupled in filter

Heading Modes in PVH Integrator

- BearingOnly (BO) Mode
  - Uses H-Field bearing measurements only to obtain insight into heading
  - No heading information derived directly from GPS
  - No direct heading/velocity correlation in filter

Heading Modes in PVH Integrator

- Calibration Mode
  - Generate correction parameters for Loran bearing measurements
  - Must be manually selected by user
  - Will require a TBD calibration procedure to refine accuracy in the bearing measurements

Heading Modes in PVH Integrator

- Heading mode can be selected manually by user or autonomously selected by software
  - Autonomous selection done based on magnitude of horizontal velocity, V_H
  - If V_H is small than risk of large velocity-derived heading error

Heading Modes Drive Integrator State-Spaces

State-Spaces in PVH Integrator

- Non-Calibration State-Spaces
  - BearingOnly_NoCal (**BO_NoCal**)
  - BearingAndVelocity_NoCal (**BAV_NoCal**)
  - BearingOnly_PostCal (**BO_PostCal**)
  - BearingAndVelocity_PostCal (**BAV_PostCal**)

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State-Spaces in PVH Integrator

- Calibration State-Spaces
  - BearingOnly_Cal (**BO_Cal**)
  - BearingAndVelocity_Cal (**BAV_Cal**)
  - PositionAndVelocity (**PosVel**)

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PVH Filter Implementation

State Vector for BAV Mode (with No Calibration)

- BAV_NoCal Mode Error-State Space

$$\breve{x} = \begin{bmatrix} \delta_{\phi} & \delta_{\lambda} & \delta_{h} & \delta_{V_H} & \delta_{V_U} & \delta_{\psi} & \delta_{B_L} & \delta_{A_\theta} \end{bmatrix}$$

  - Latitude, longitude and altitude error states
  - Horizontal and vertical velocity error states
  - Heading error state

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PVH Filter Implementation

BAV_NoCal (Continued)

- BAV_NoCal Mode Error-State Space

$$\breve{x} = \begin{bmatrix} \delta_{\phi} & \delta_{\lambda} & \delta_{h} & \delta_{V_H} & \delta_{V_U} & \delta_{\psi} & \delta_{B_L} & \delta_{A_\theta} \end{bmatrix}$$

  - LORAN bias correction error state (A Gauss-Markov process with correlation time (τ_{BL})
  - Bearing bias error correction state (A Gauss-Markov process with correlation time (τ_{A})
  - Assumes no calibration was done

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PVH Filter Implementation

State Vector for BO Mode (with No Calibration)

- BO_NoCal Mode Error-State Space

$$\breve{x} = \begin{bmatrix} \delta_{\phi} & \delta_{\lambda} & \delta_{h} & \delta_{V_E} & \delta_{V_N} & \delta_{V_U} & \delta_{\psi} & \delta_{B_L} & \delta_{A_\theta} \end{bmatrix}$$

  - Latitude, longitude and altitude error states
  - East, North, Up velocity error states
  - Heading error state

PVH Filter Implementation

BO NoCal (Continued)

- BO_NoCal Mode Error-State Space

$$\hat{x} = \begin{bmatrix} \delta_{\phi} & \delta_{\lambda} & \delta_{h} & \delta_{V_E} & \delta_{V_N} & \delta_{V_U} & \delta_{\psi} & \delta_{B_L} & \delta_{A_\theta} \end{bmatrix}$$

  - LORAN bias correction error state (A Gauss-Markov process with correlation time (τ_{BL})
  - Bearing bias error correction state (A Gauss-Markov process with correlation time (τ_{A})
  - Assumes no calibration was done

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Key Remaining Integrator Design Tasks

Remaining Design Tasks

Conductivity Model Uncertainty Compensation

- Will accommodate *individual* LORAN ranging errors in estimator (for each active tower)
- Provide corrections as feedback to ensuing range measurements (within integrator)
- Objective is to provide robust positioning solution for static or dynamic receiver and during GPS outage periods

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Integrator Design Issues

Heading Integration with Autonomous Transitions

- Allow for BAV and BO mode capabilities in single Integration software
- S/W will have the ability to automatically transition between the various heading modes – states, covariances, etc.
- User can also control this manually

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Integrator Design Issues

State-Space Transition Concepts

- Need to provide for smooth transitions between Heading Modes
- Need to accommodate BAV-to-BO and BO-to-BAV transitions
- Some overlapping states, some different states, different dimension state spaces, etc.

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PVH Filter Implementation

State-Space Transition Concepts

- Transition processing must be done not only with states but variances and covariances as well
- Want to avoid spikes or otherwise discontinuous output trajectories
- Some methods exist for transformations between state spaces and covariances
- Similar issue common in autonomous vehicles for incorporation of "features"

Integrator Design Issues

Calibration Mode Design and Procedure

- Calibration mode can be manually selected only upon power-up
- User can opt to utilize stored set of model coefficients upon power-up through heading mode selection
- Estimated corrections will remain constant throughout LG Integration processing
- New Calibration can be run upon reset, generating updated error corrections

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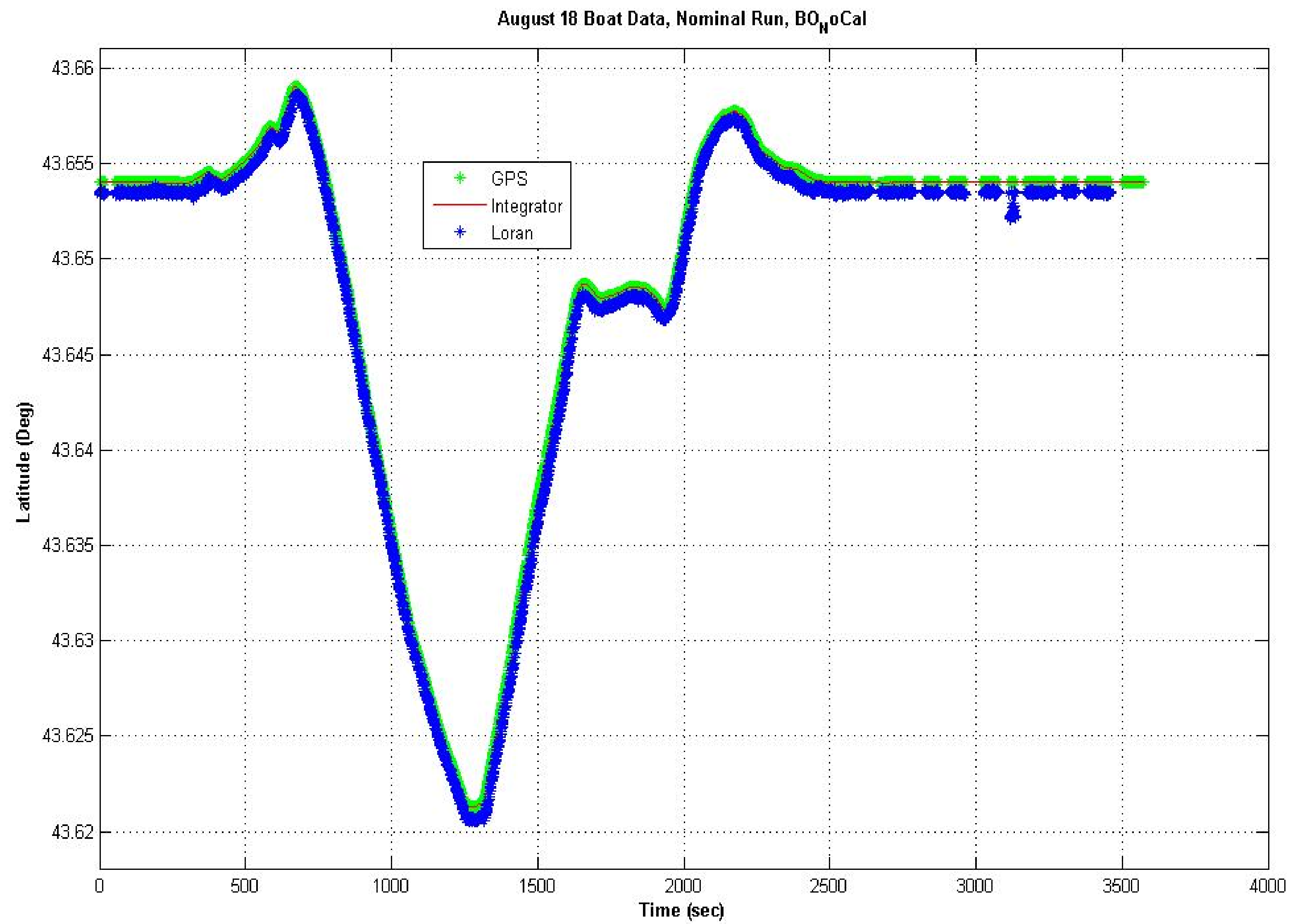
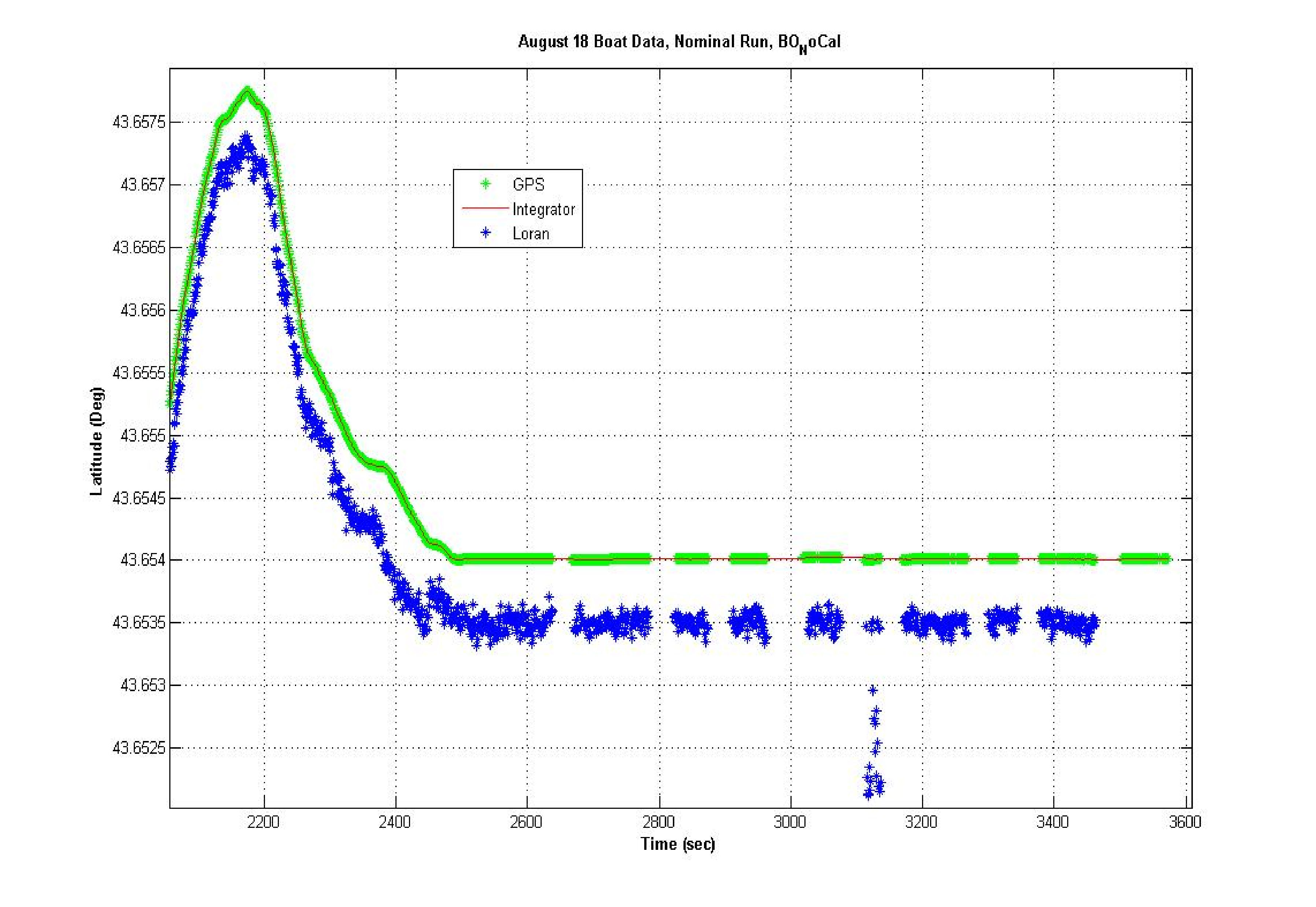
Actual Integration Results
(August 18 Test Data)

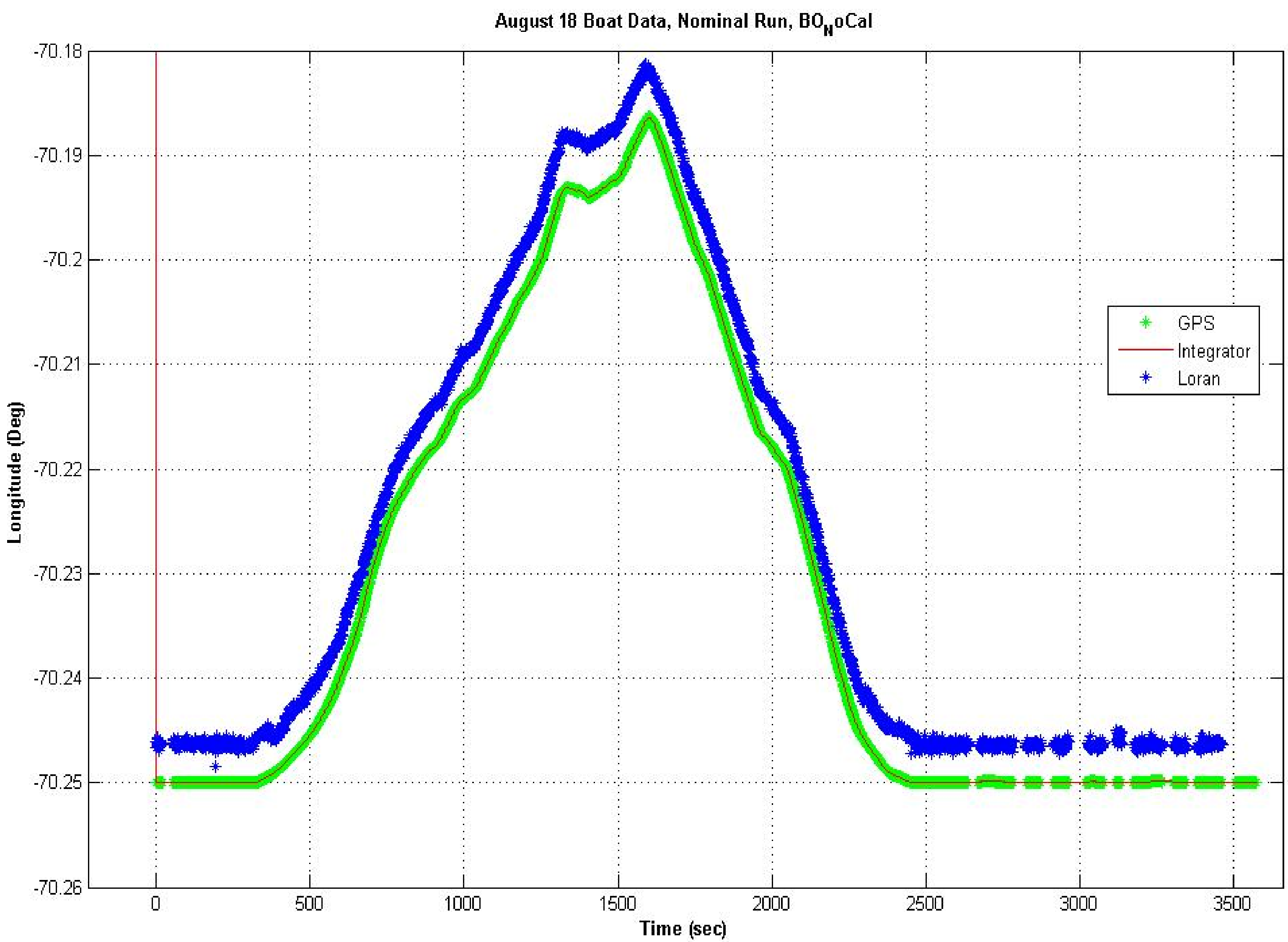
Latitude (GPS vs. Loran vs. Integrator



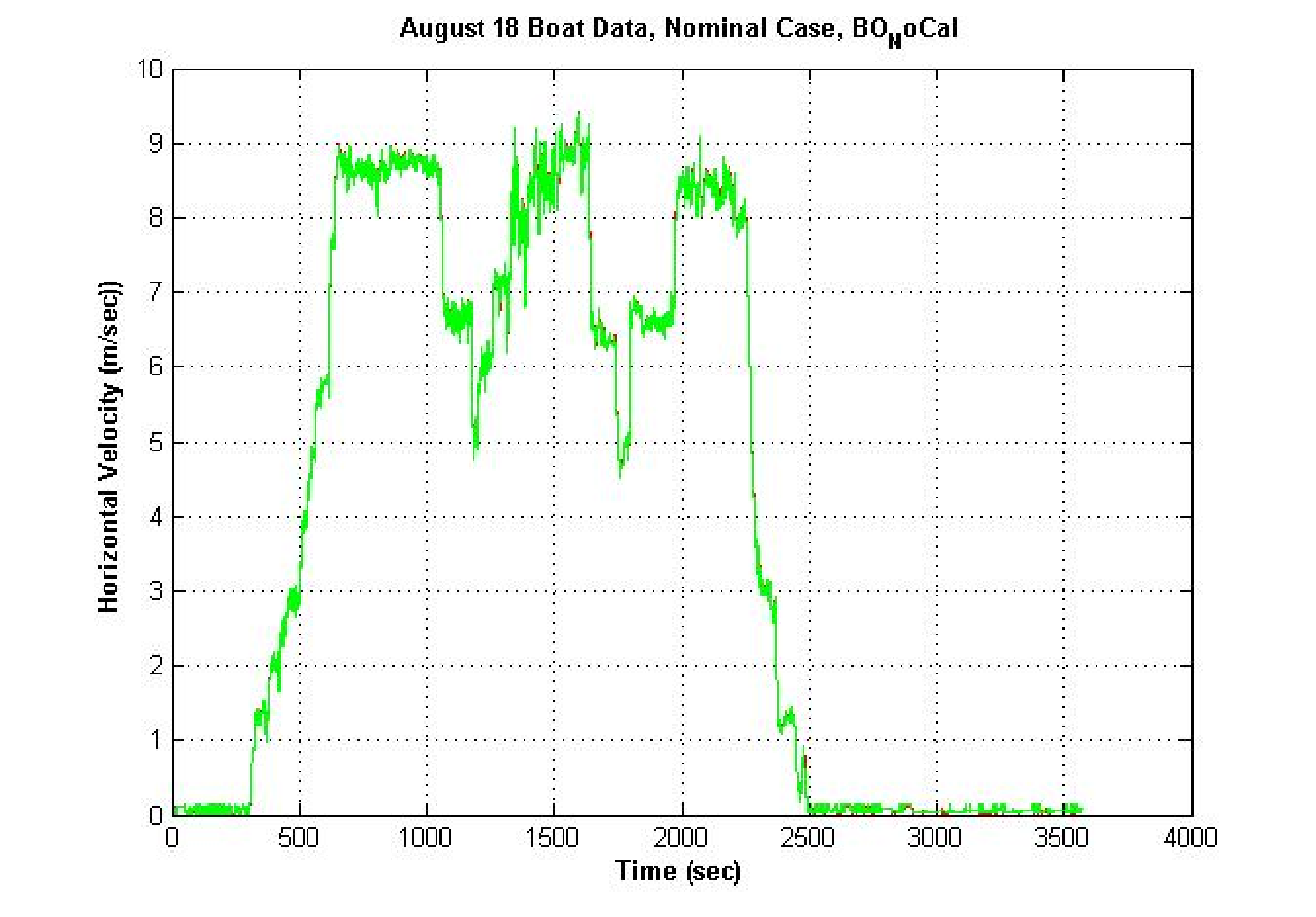
Latitude (Blow-up)



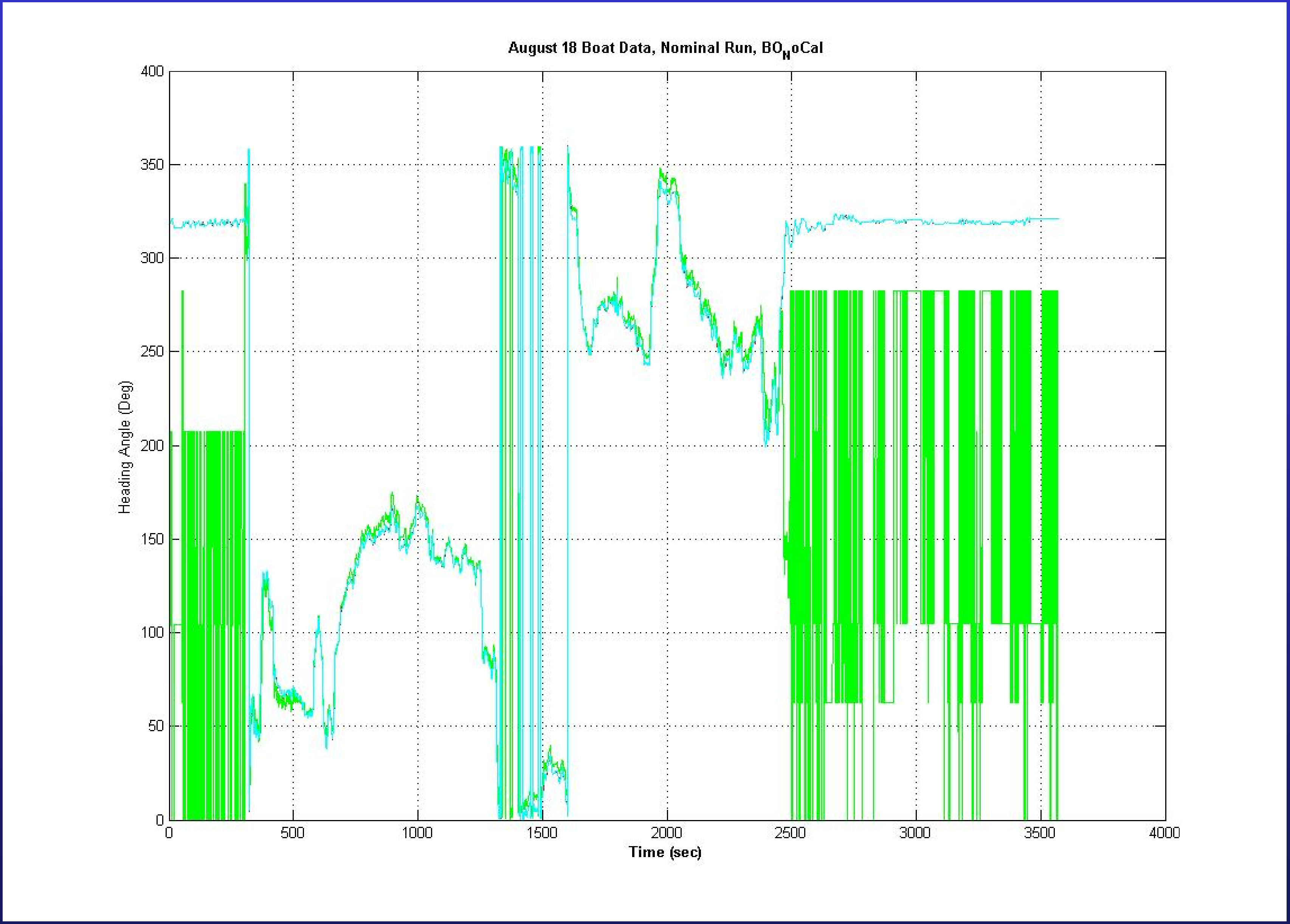
Longitude (GPS vs. Loran vs. Integrator



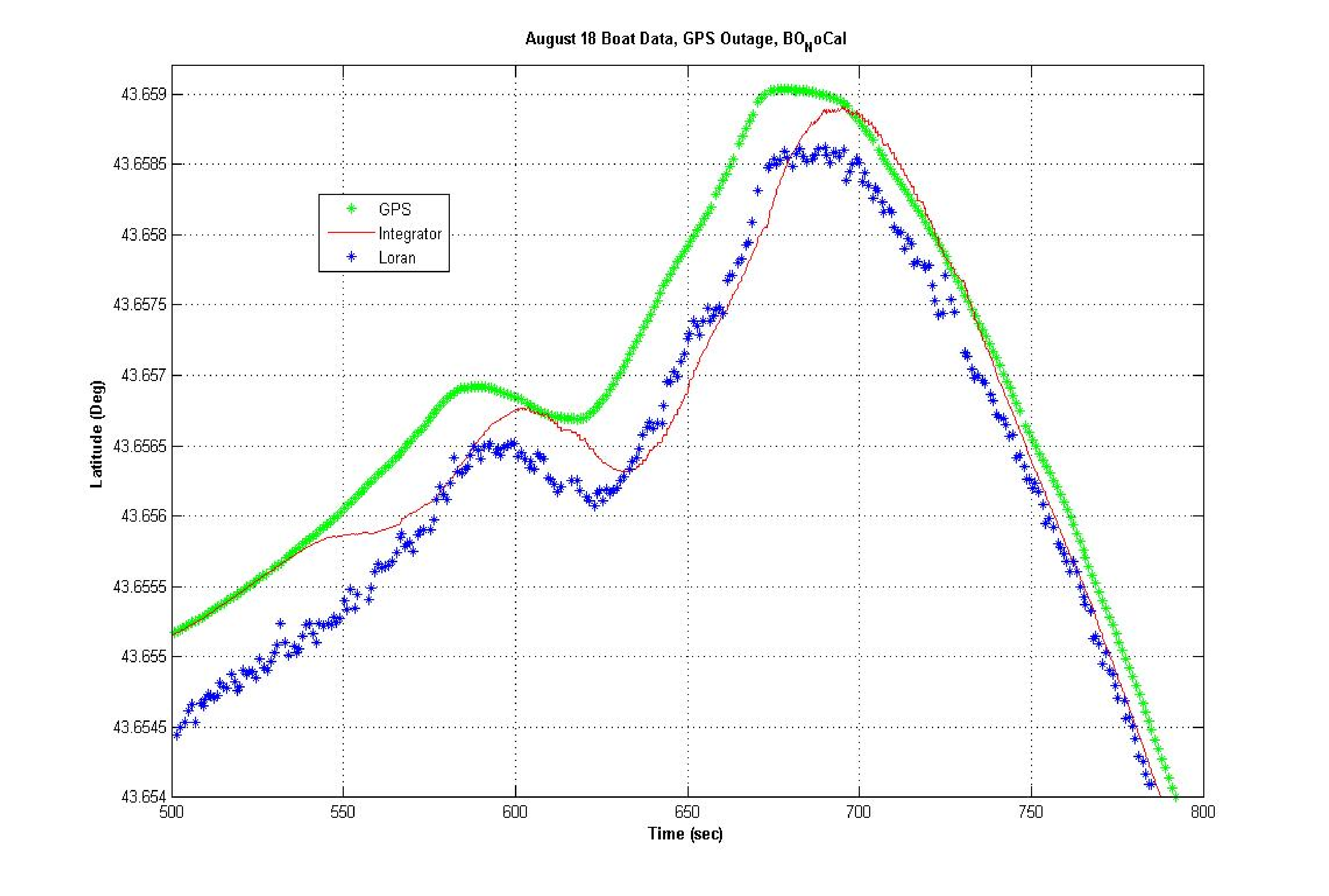
V_{HOR} (GPS vs. Integrator)



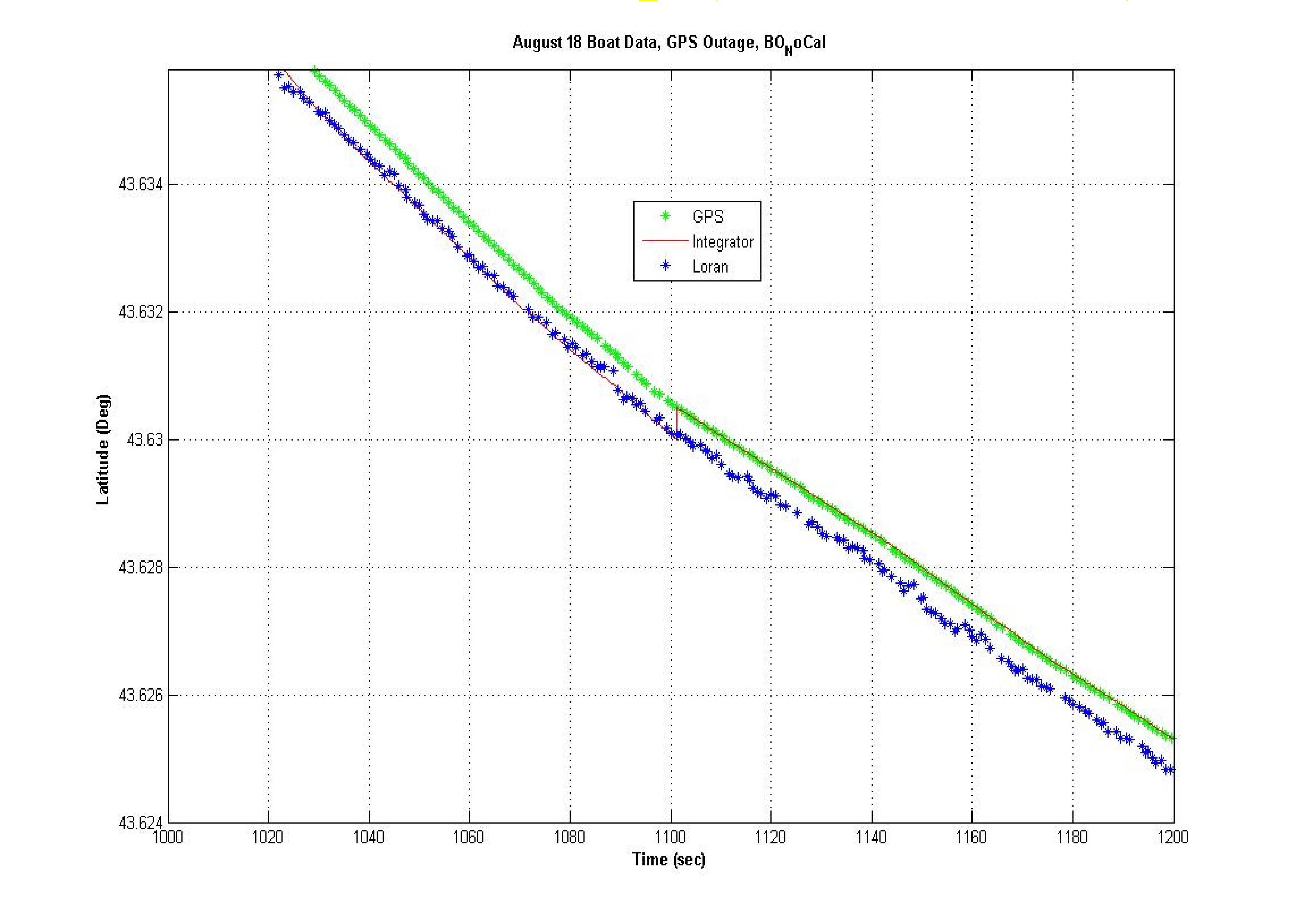
Heading (GPS vs. Loran vs. Integrator)



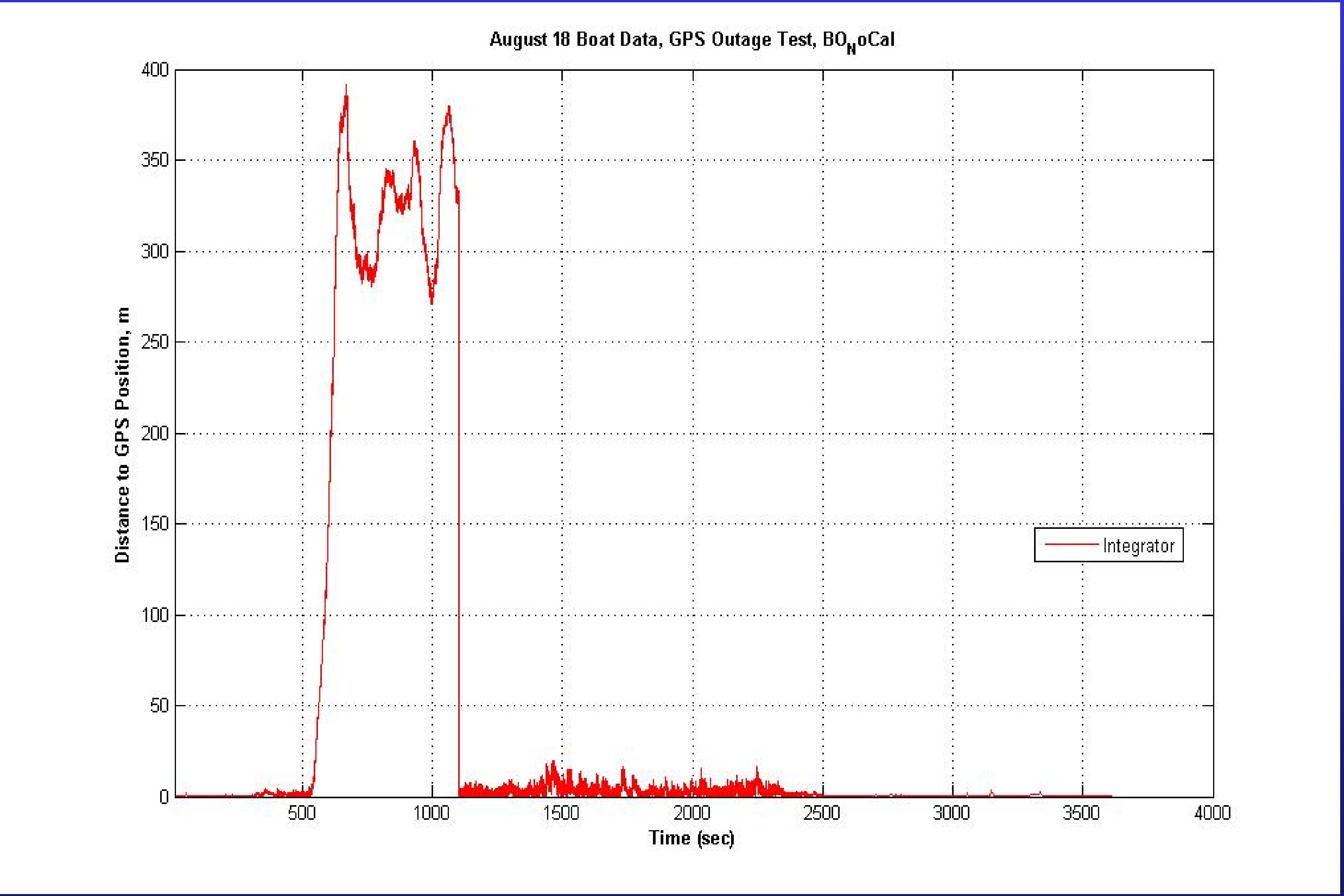
Latitude Blow-up (GPS Outage Test)



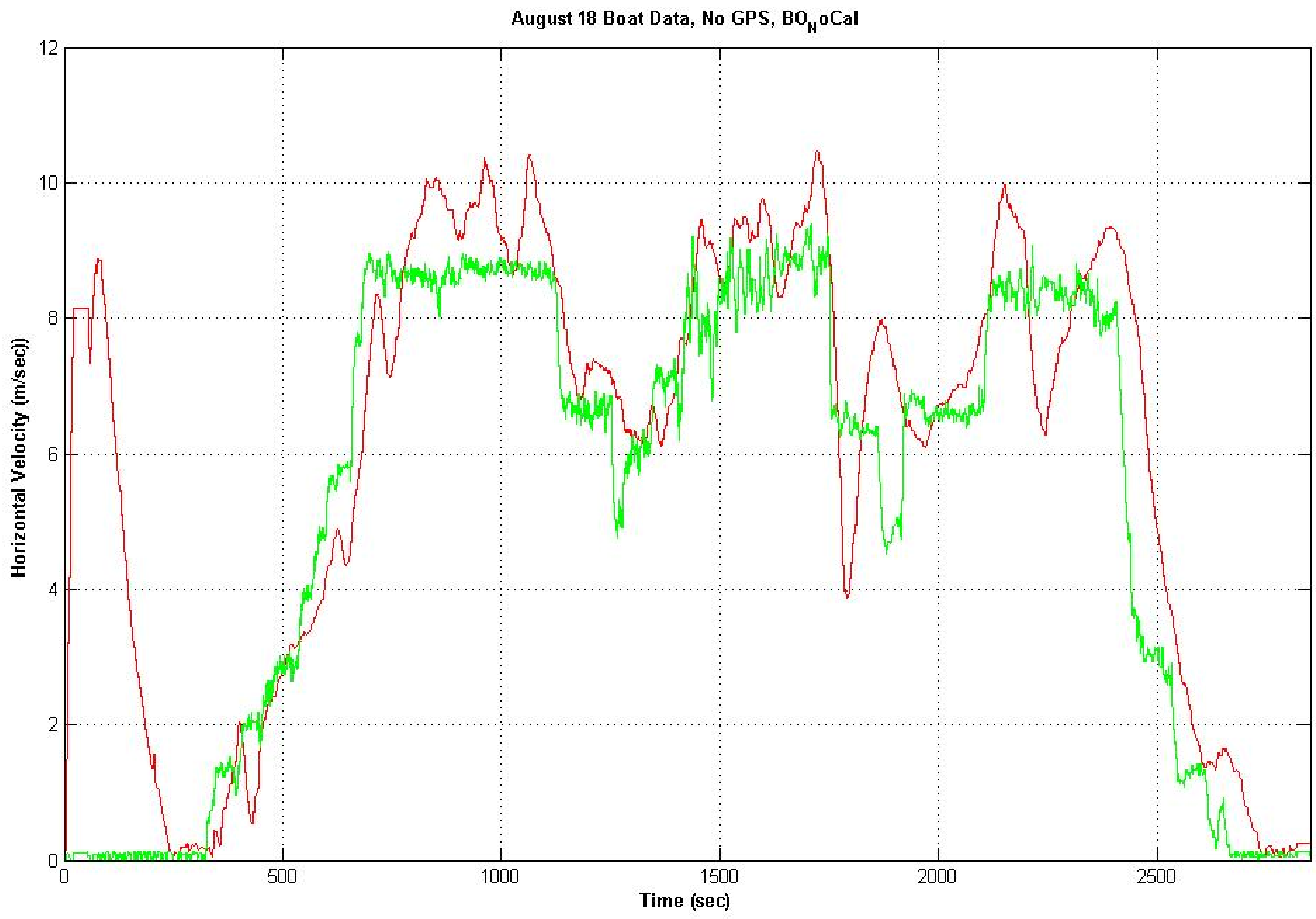
Latitude Blow-up (GPS Returns)



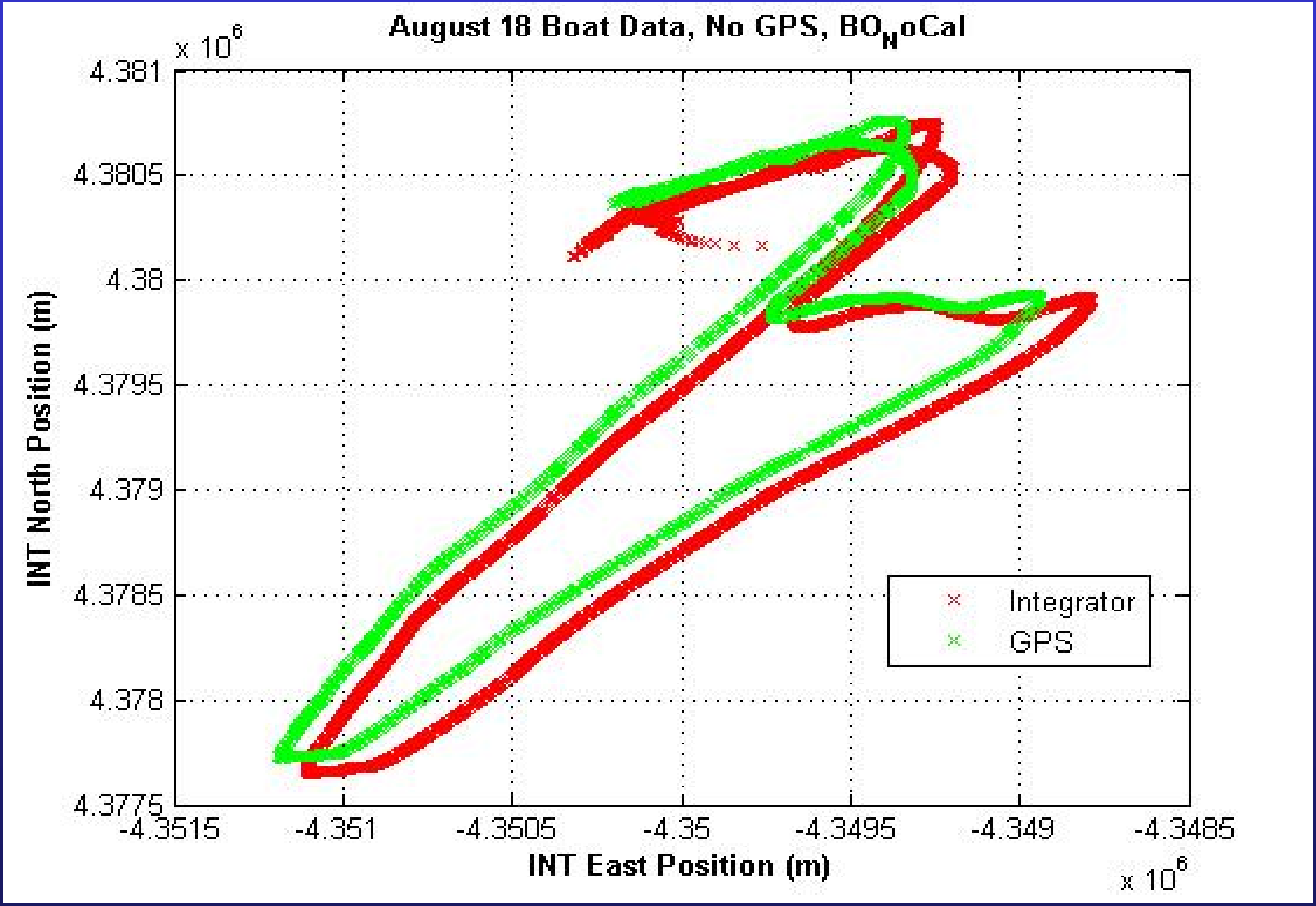
Distance-to-GPS (GPS Outage)



V_{HOR} (No GPS for Entire Run)



Hor. Plane Motion Map (No GPS)



Preliminary Integrator

Results Summary

- Integrated position – mean distance-to-GPS ≈ 2 meters
- Loran-only integrator – mean distance-to-GPS of ≈ 330 meters
- Loran-only velocity error 10-15%
- Simple Loran clock bias correction improves results by 10-15 %

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THE END