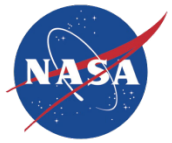


Project Orion Abort Flight Test

The Best Estimated Trajectory Analysis for Pad Abort One

Prasad Kutty, Meghan Noonan
Analytical Mechanics Associates, Inc.
NASA Dryden Flight Research Center, Edwards, CA

Christopher Karlgaard
Analytical Mechanics Associates, Inc.
NASA Langley Research Center, Hampton, VA

Roger Beck
Analytical Mechanics Associates, Inc.
Huntsville, AL

PA-1 BET Overview

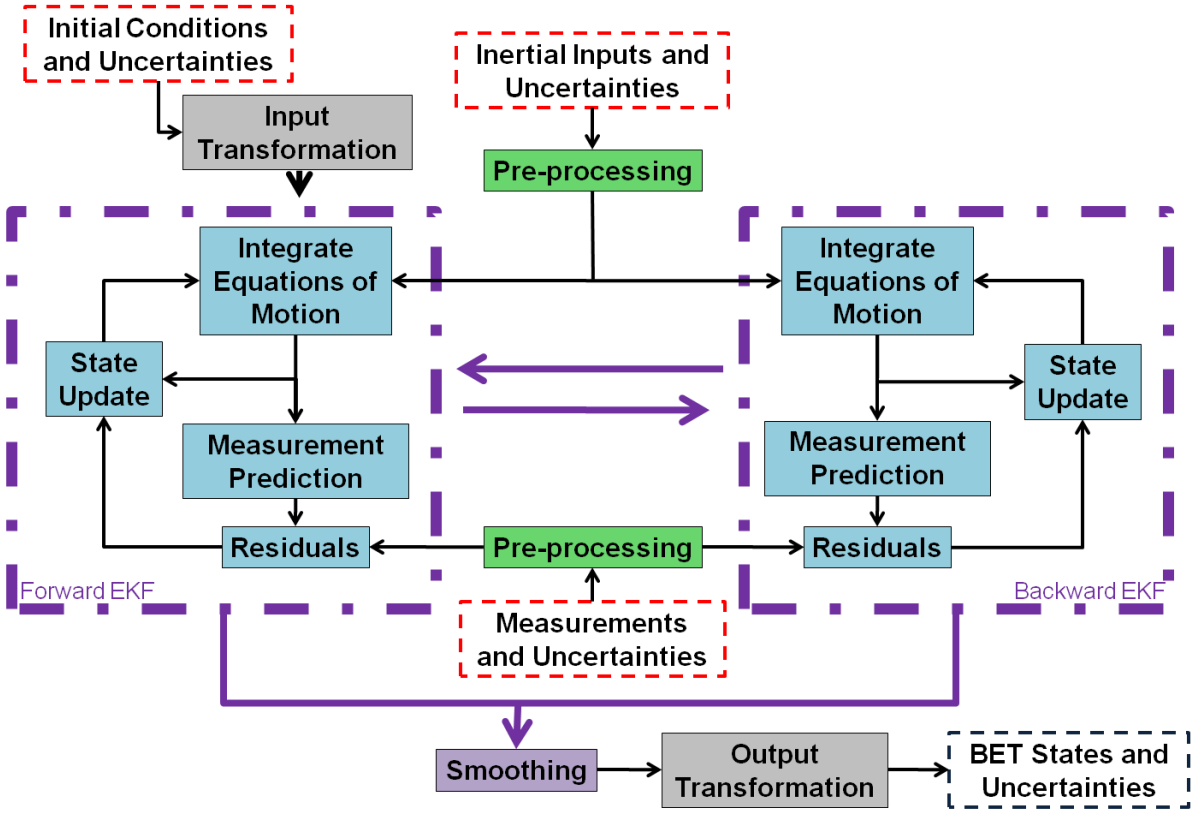
- Best Estimated Trajectory (BET) objective:
  - Produce reconstructed trajectory of the PA-1 flight to understand vehicle dynamics and aid other post flight analyses
  - Leverage all measurement sources taken of vehicle during flight to produce the most accurate estimate of vehicle trajectory
  - Generate trajectory reconstructions of the Crew Module (CM), Launch Abort System (LAS), and Forward Bay Cover (FBC)
- BET analysis was started immediately following the PA-1 mission and was completed in September, 2010
  - Quick look version of BET released 5/25/2010: initial repackaging of SIGI data
  - Preliminary version of BET released 7/6/2010: first blended solution using available sources of external measurements
  - Final version of BET released 9/1/2010: final blended solution using all available sources of data

NewSTEP

- Numerical approach used in STEP (Statistical Trajectory Estimation Program) applied extensively in 1960s-1980s (X-23A PRIME, Viking, Pioneer Venus, Shuttle)
- AMA developed NewSTEP with numerous enhancements including:
  - MATLAB Based
  - Additional Measurements
  - Numerical Improvements
  - Updated filters
- NewSTEP successfully used for trajectory reconstruction in recent flight projects:
  - Mars Exploration Rover (MER)
  - X-43A (Hyper-X) Mach 7 and Mach 10 Flights
  - Ballistic range data reduction for CEV
  - ARES-1X
  - MSL MEADS

NewSTEP Flow Chart

- Based on Iterative Extended Kalman Filter (IEKF) code to compute optimal 6-DOF trajectory based on all available measurements taken during flight
- IEKF is a recursive weighted least-squares estimation that optimally blends sensor data and mathematical models to produce minimum variance estimates of the system state and uncertainty



Sources of Measurement Data

- SIGIs provide primary source of acceleration and rate information used to derive a deterministic trajectory solution
- Measurements from SIGI-1 and SIGI-2 are filtered through low pass frequency algorithm before use in NewSTEP
- Additional external sources of data:
  - Radar measurements taken by WSMR range assets
  - Optical measurements taken by WSMR range assets
  - Atmospheric model derived from day of flight balloon measurements (winds, pressure, density, temperature)
  - Mass properties model derived from Abort Motor burn curve (AM mass known as function of time)
- FADS data measurements were unavailable at time of Final BET release

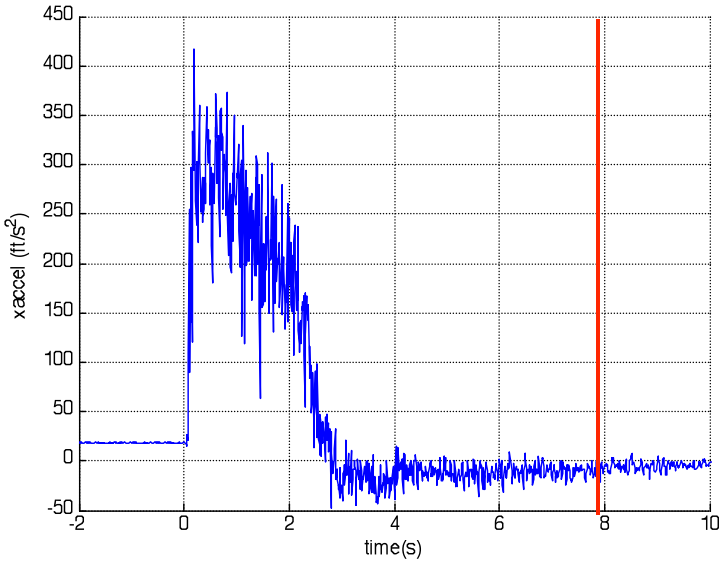
SIGI Data Acquisition

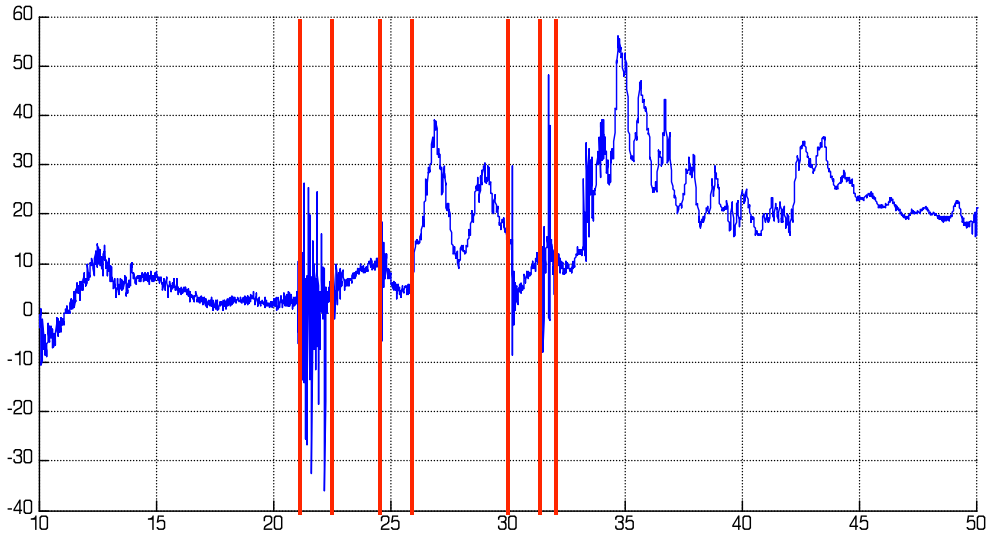
- Linear acceleration and angular rate measurements were taken from SIGI-1 and SIGI-2 using the Dryden Flight Data Archive System (FDAS)
- SIGI data recorded at 100Hz
- Acceleration data provided to NewSTEP was derived from recorded SIGI velocities through differentiation
- When integrated, derived accelerations provided a strong match to the SIGI navigated position solution
- Velocities were corrected for lever-arm offset between SIGI and center of gravity using the day of flight mass properties model:

$$V_{NED,CG} = V_{NED,SIGI} - (\omega \times r)_{NED}$$

Windowing Raw Data

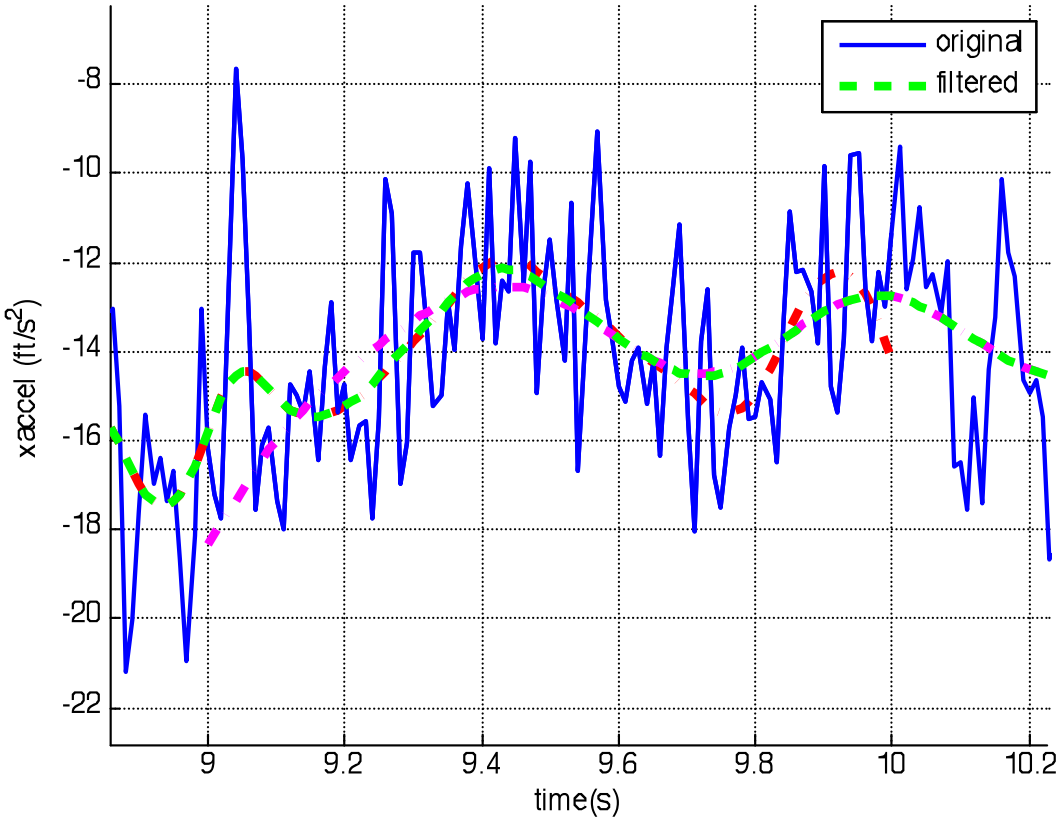
- SIGI data filtered using a low-pass frequency domain filter
- Filtering technique applied using the System Identification Program for Aircraft (SIDPAC) toolbox
- Different regions of trajectory were filtered at different frequencies depending on dynamic behavior during region
- Retain dynamics of vehicle while filtering out acoustics, structural, sensor noise, etc.
- High dynamic windows: Ignition, Sep Events (LAS, Drogue, Main)
- Low dynamic windows: Reorientation, Under chutes





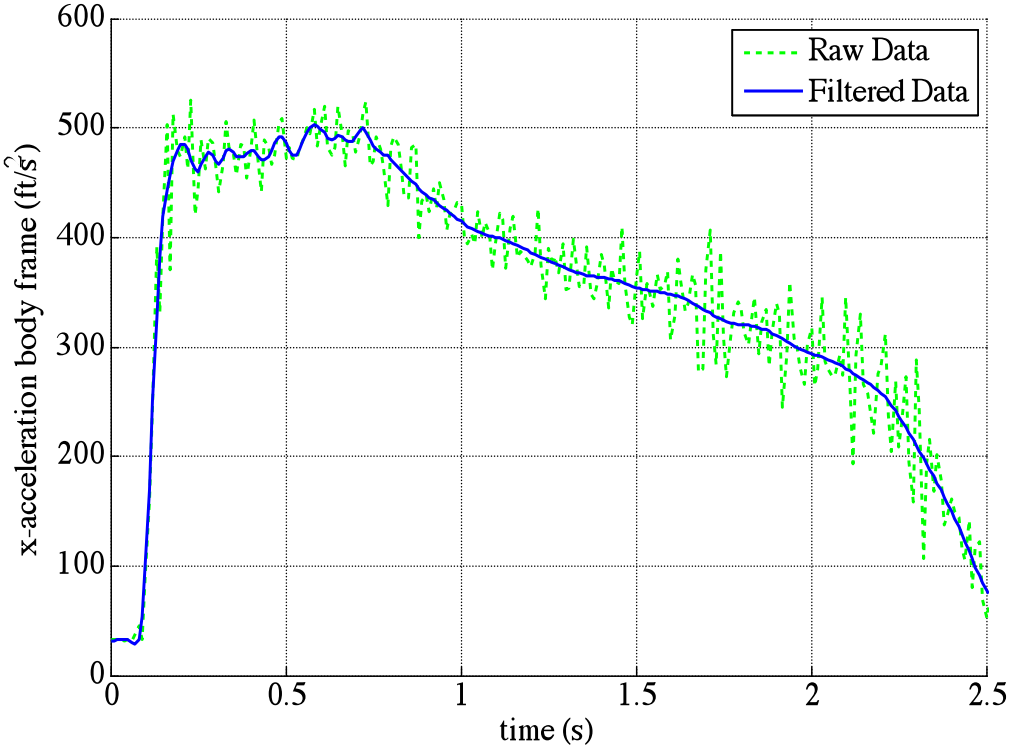
Transition Between Windows

- Fourier filtering method produces anomalous behavior at beginning and end of data
- To prevent undesired effects due to filtering, windows are overlapped and filtered data in overlapping region is computed by weighted average



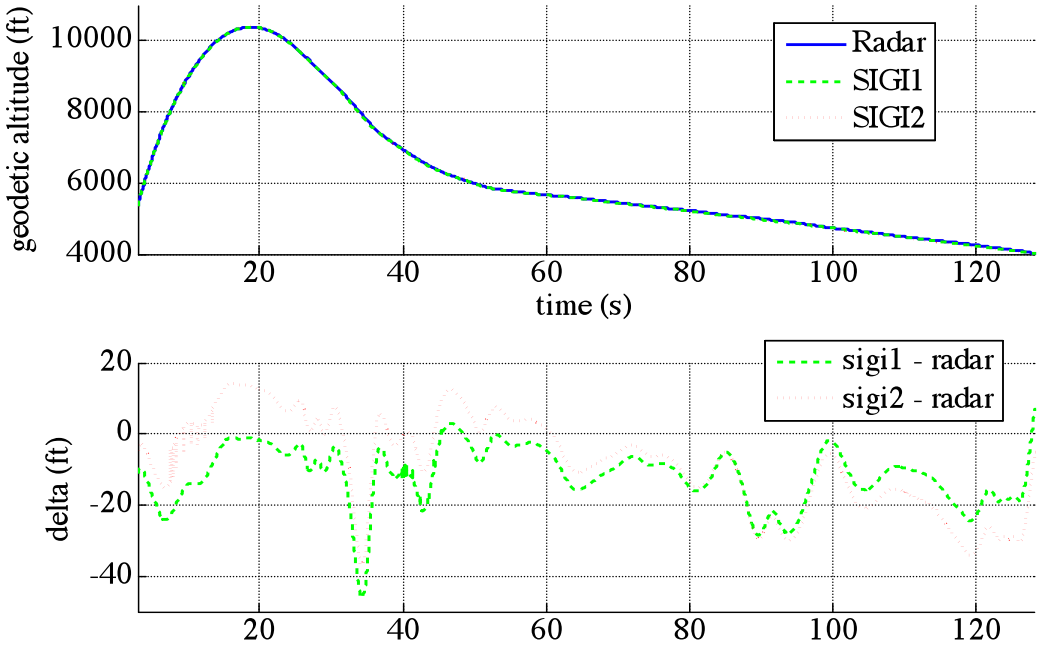
Ignition Acceleration

- Filtering acceleration at ignition produced high frequency oscillations between 0.25 and 0.75 seconds
- Oscillations caused by the high filtering frequency required to capture the rise rate in x-body acceleration
- Undesired frequency content passed through filter as a result



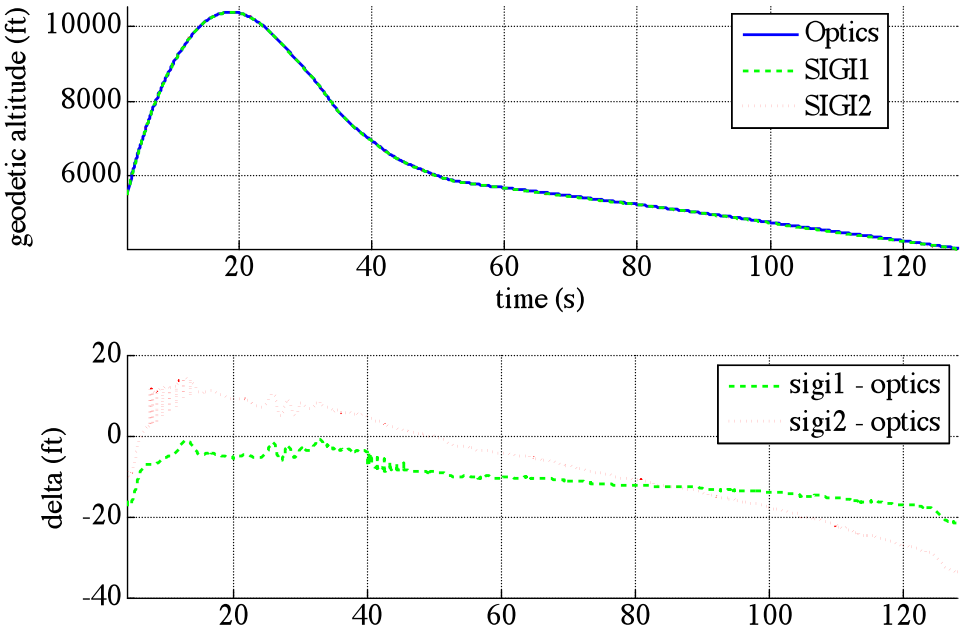
Radar Measurement Data

- Fourteen track assignments via C-band ground based radars
- Three radars provided good track quality of the CM
- One radar provided good track quality of the LAS (10 sec after jettison)
- No radars adequately tracked the FBC
- Radar data at low elevation angles (liftoff and landing) were not used due to multipath errors

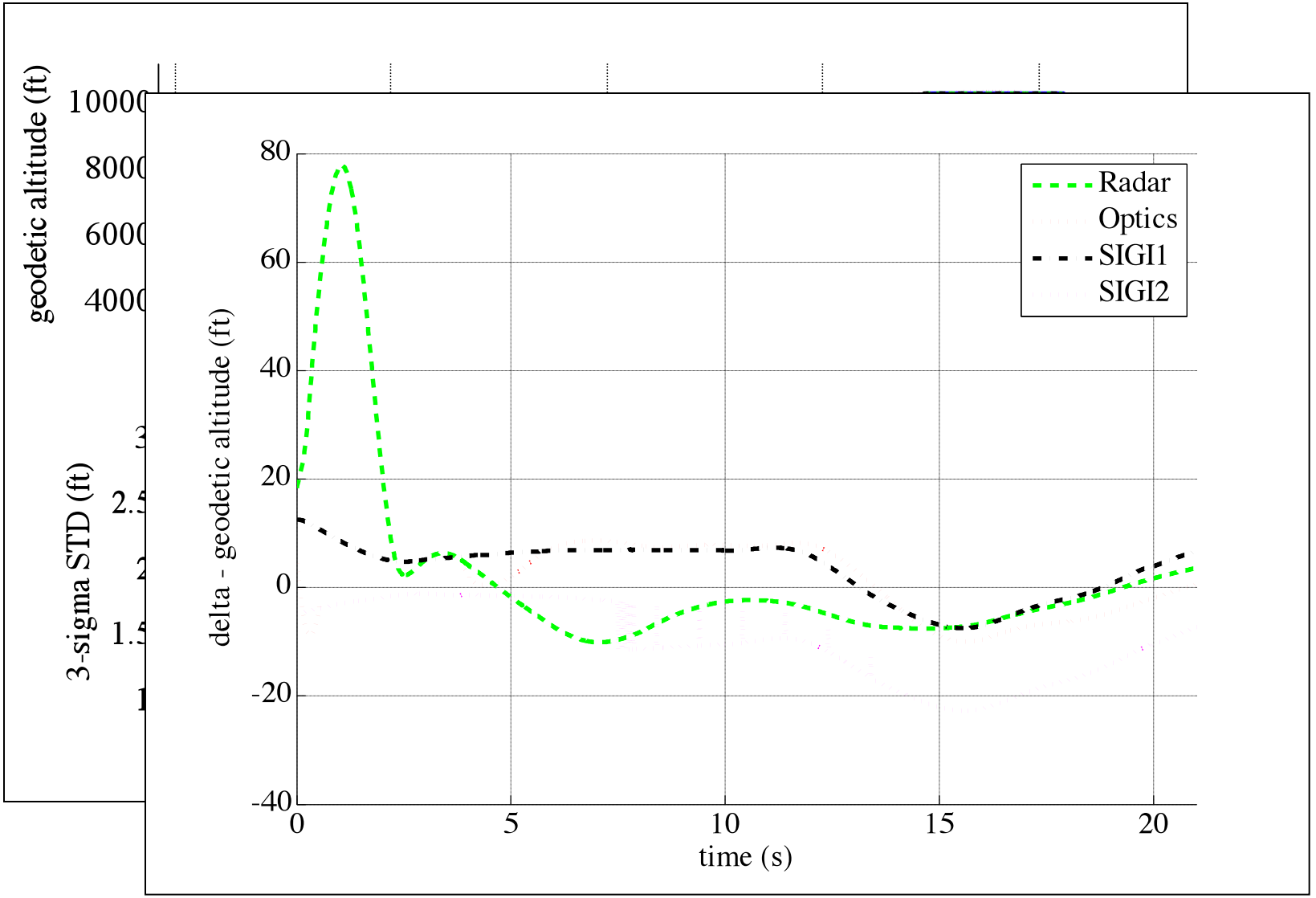


Optical Measurement Data

- Optical cameras tracked the LAV/CM flight for a majority of the mission
- As many as 10 tracking stations captured LAV/CM flight providing a highly accurate position solution with very low uncertainties
- Lever-arm offset correction was made to account for shift between optical tracking location and vehicle center of gravity



Final BET Results - LAV



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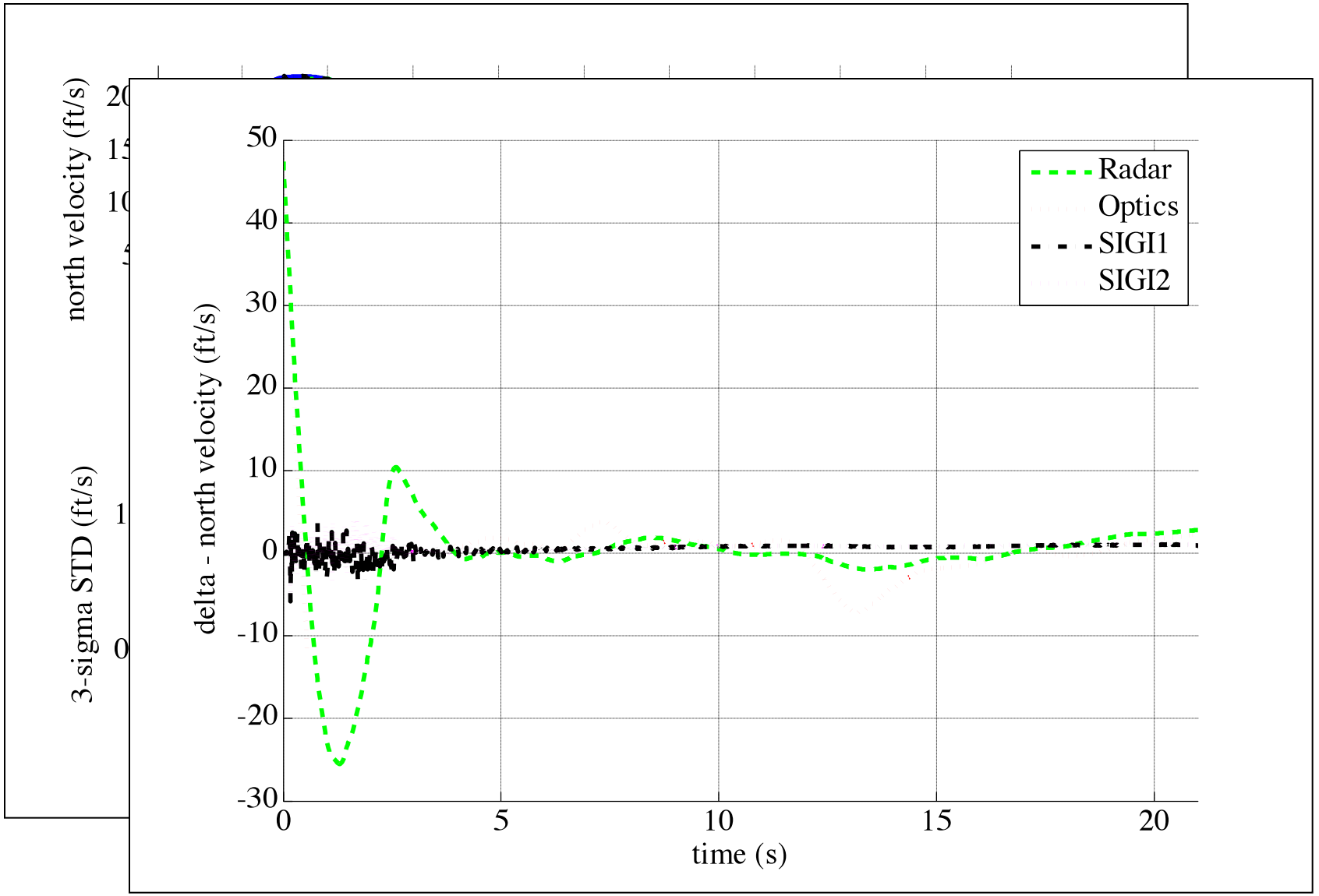

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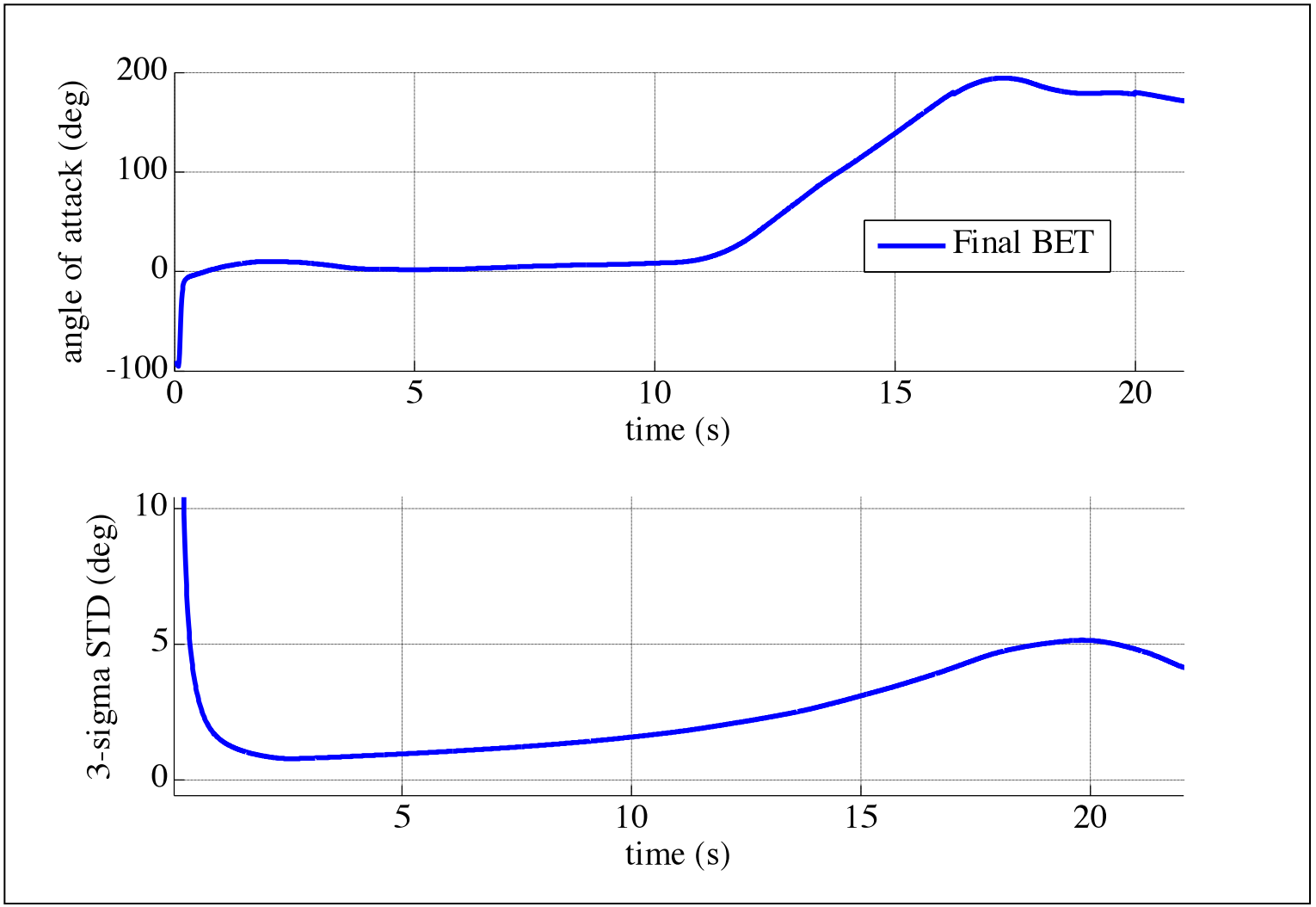
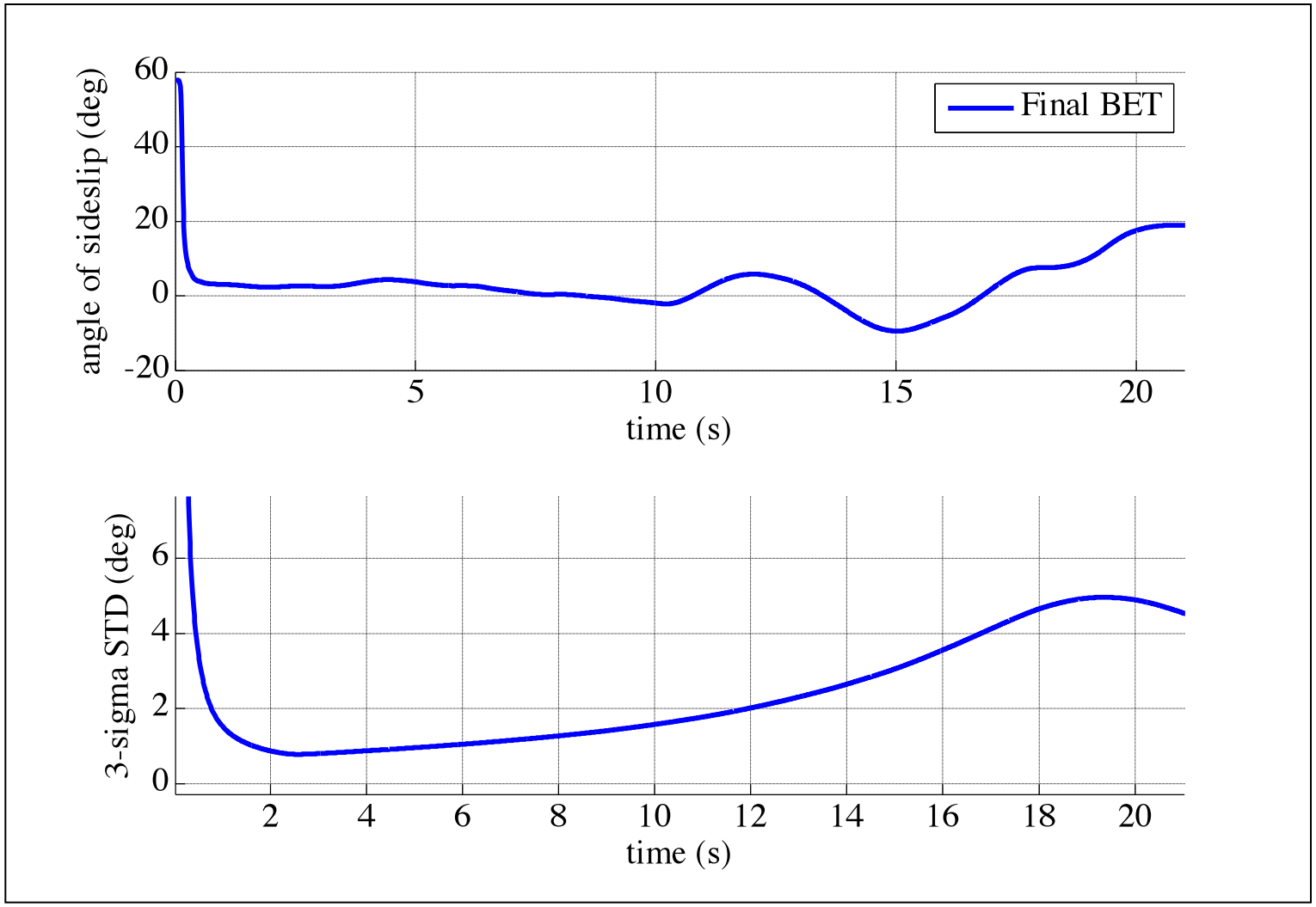
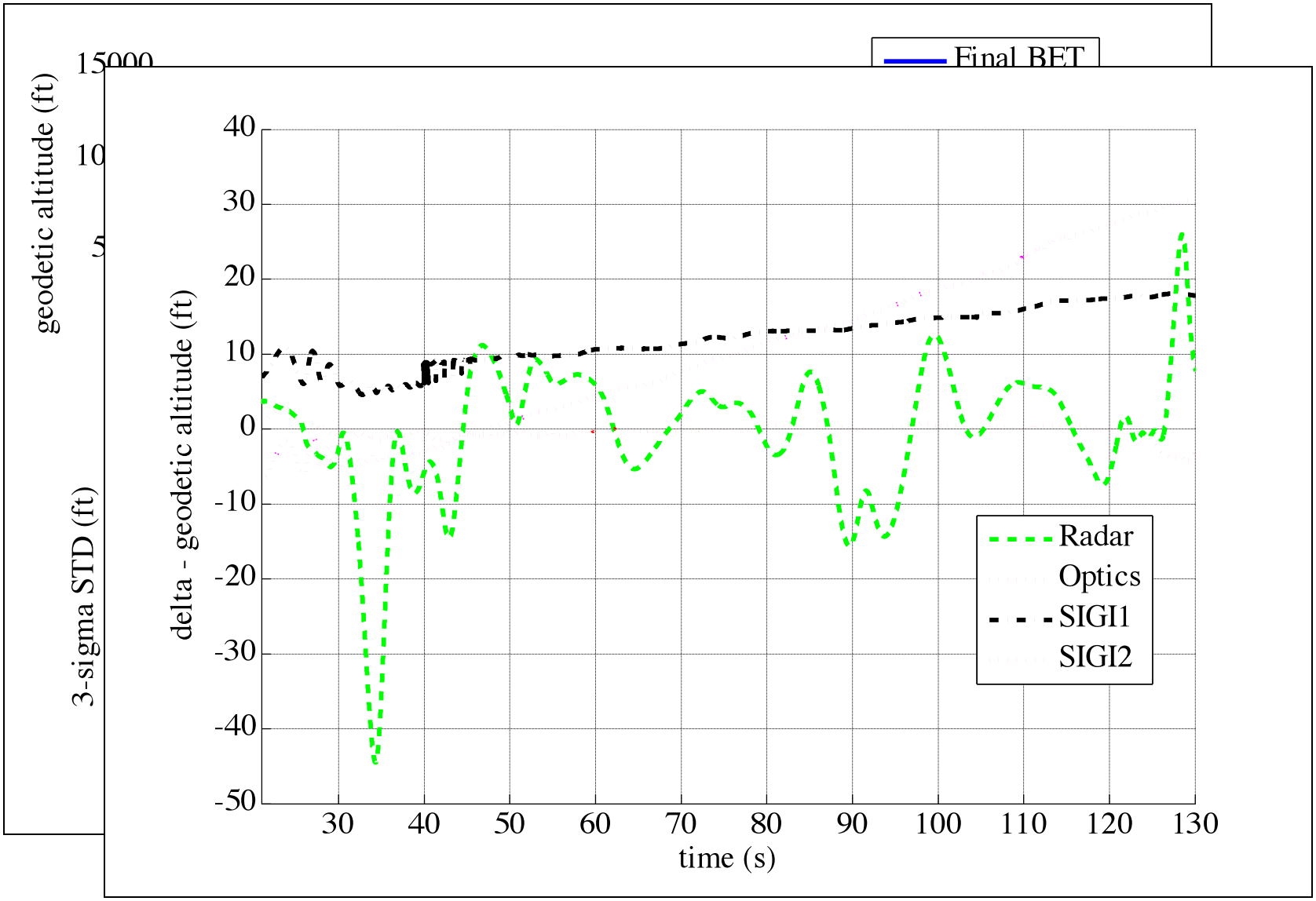


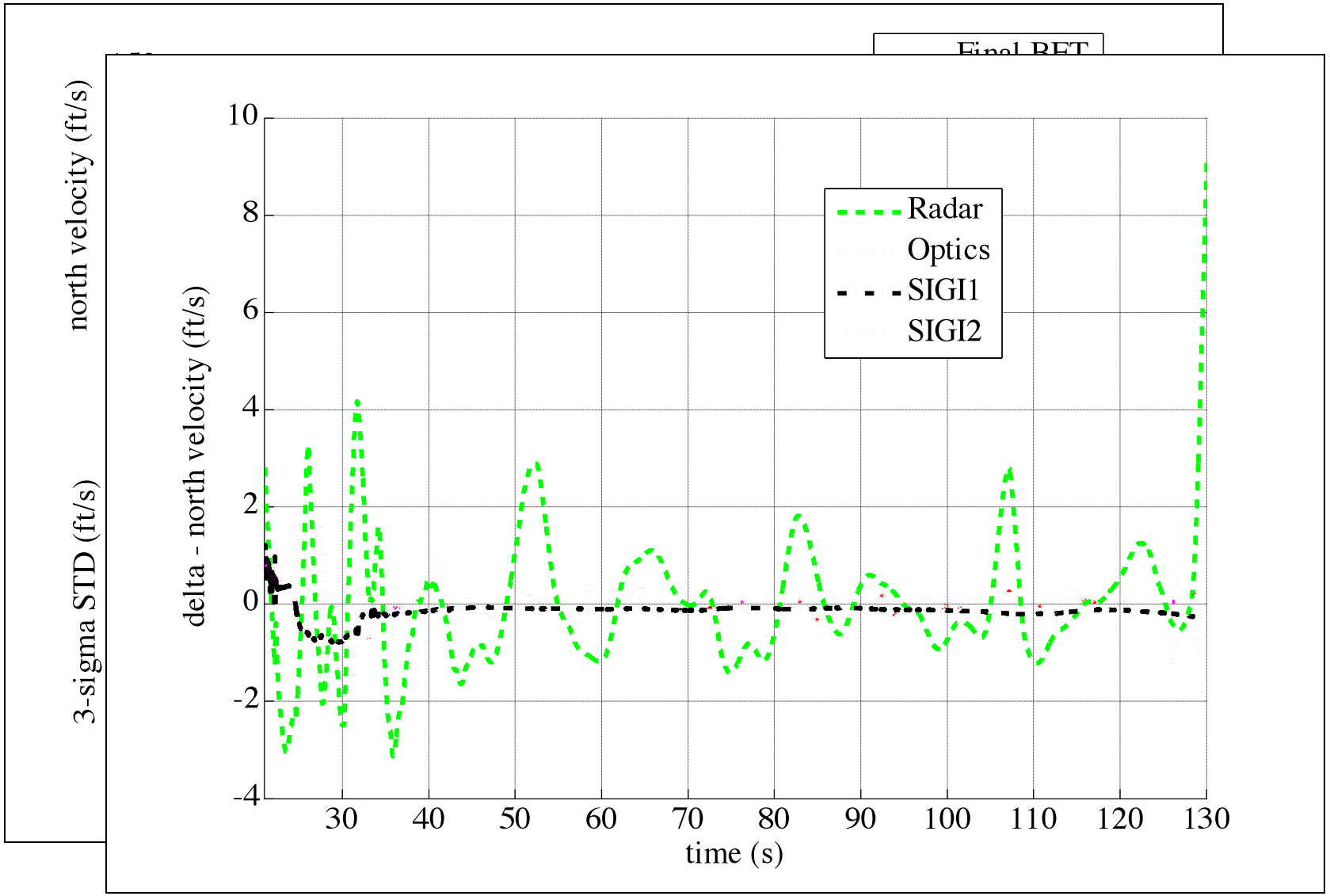
Final BET Results - LAV



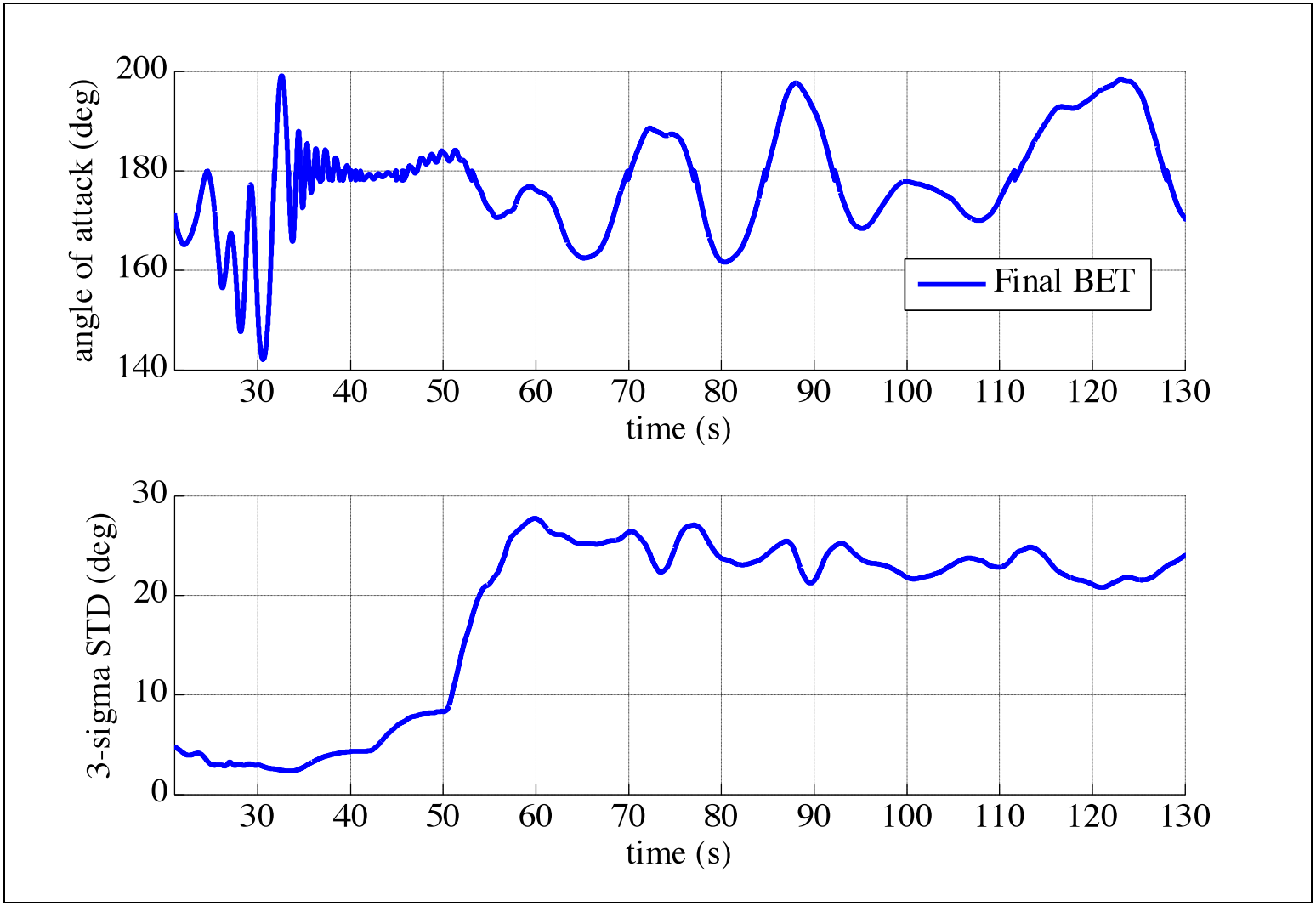
Final BET Results - CM



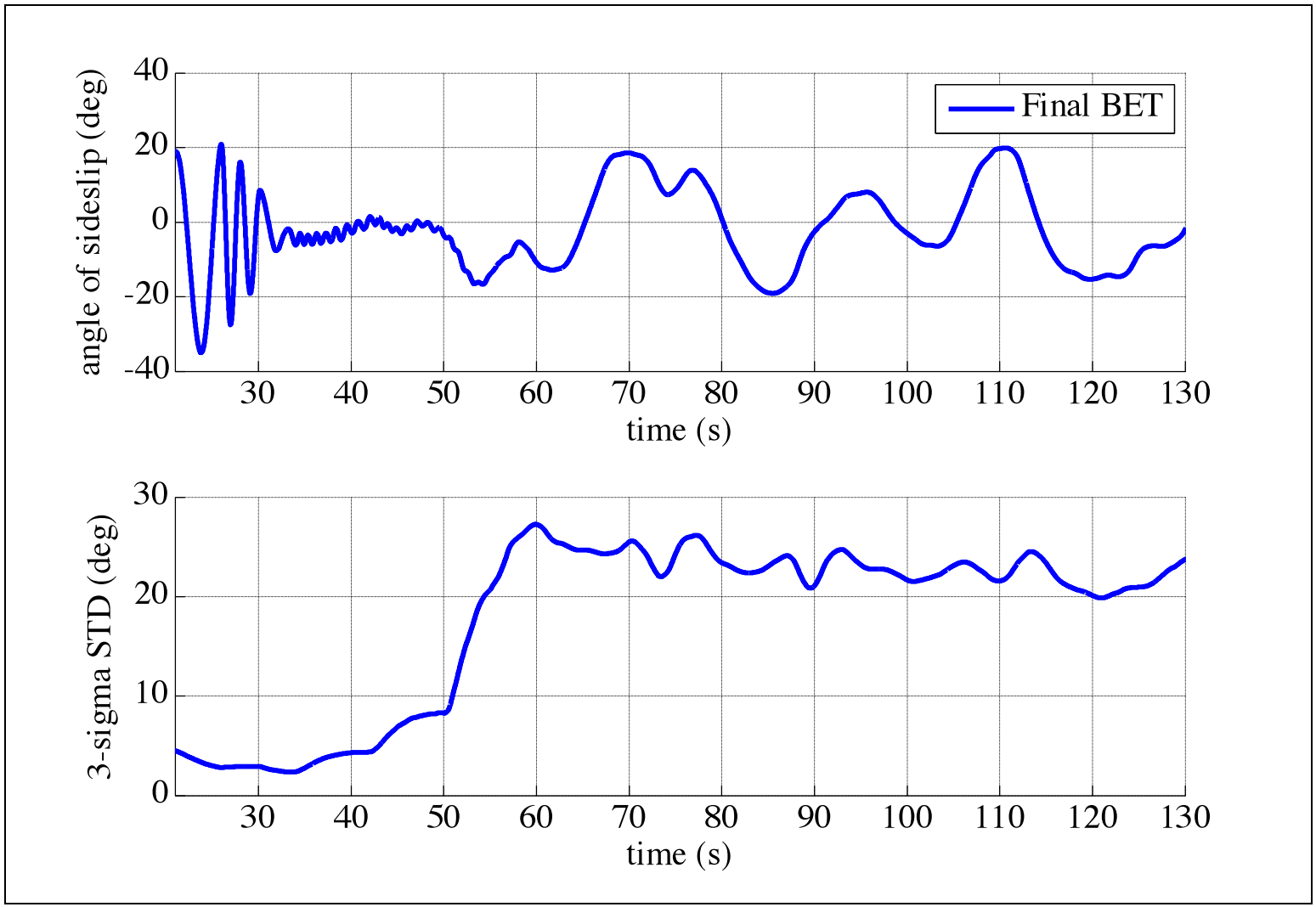
Final BET Results - CM



Final BET Results - CM



Final BET Results - CM



Summary Slide

- PA-1 BET provided high fidelity reconstruction of trajectory using all available sources taken onboard and externally
  - SIGI sensor data
  - Radar data
  - Optical data
  - Day of flight atmosphere model and mass properties model
- Sources of data not used:
  - FADS
  - Vibration accelerometers
- Comprehensive analysis and NewSTEP heritage provides strong confidence in final results

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Questions?