The Best Estimated Trajectory Analysis for Pad Abort One

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PA-1 BET Overview

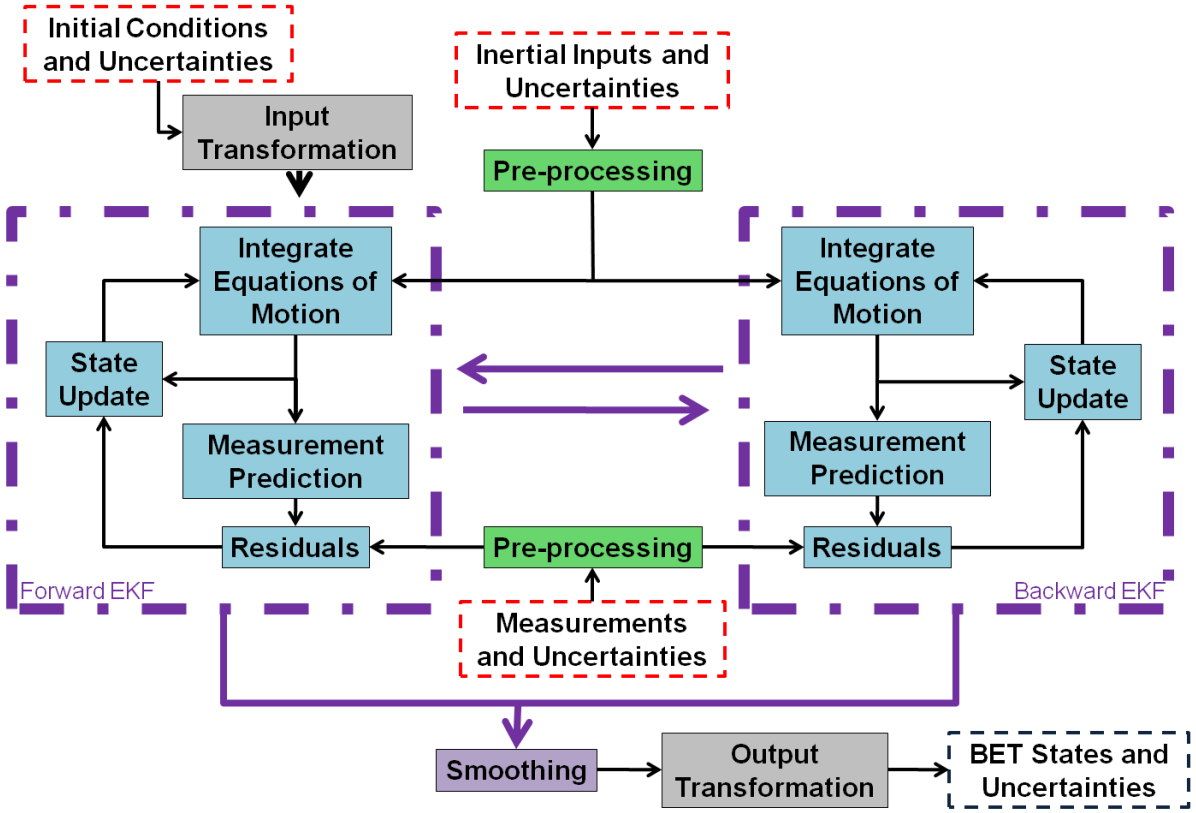
- Best Estimated Trajectory (BET) objective:
  - Produce reconstructed trajectory of the PA-1 flight to understand vehicle dynamics and aid other post flight analyses
  - Leverage all measurement sources taken of vehicle during flight to produce the most accurate estimate of vehicle trajectory
  - Generate 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

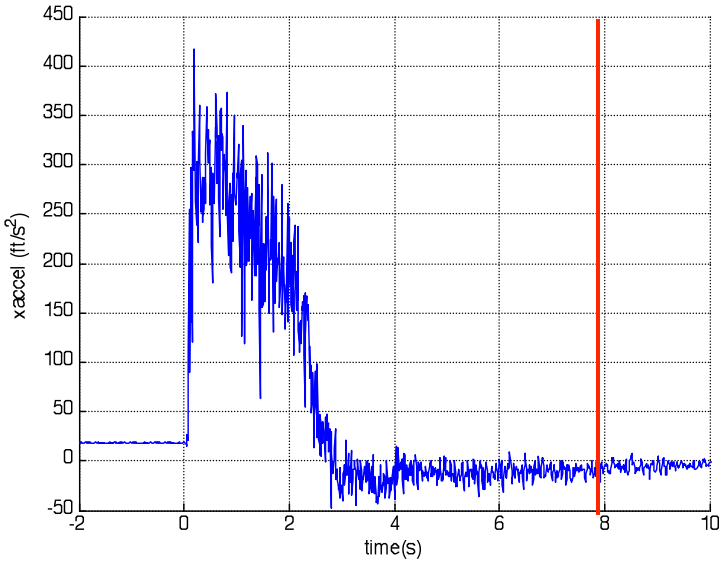
SIGI Data Acquisition

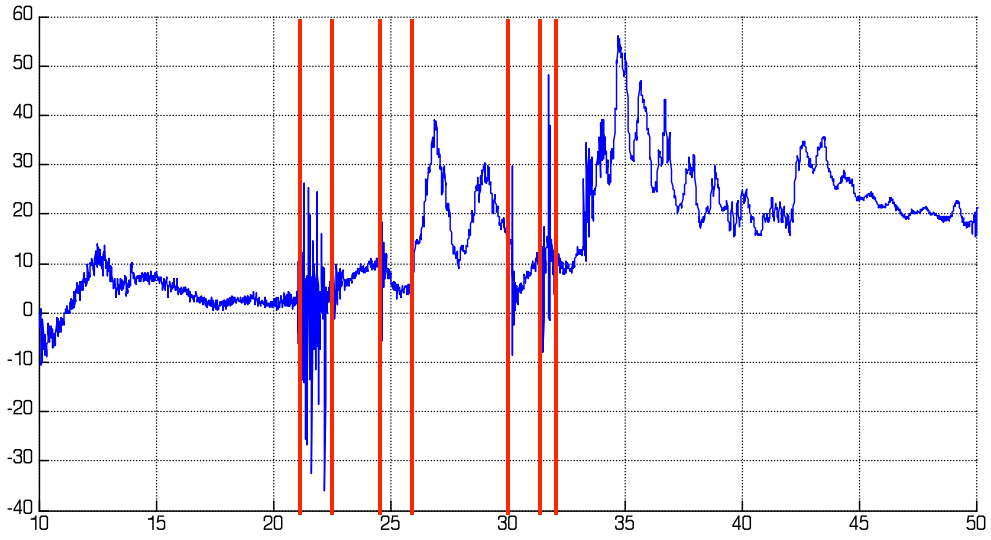
- Linear acceleration and angular rate measurements were taken from SIGI-1 and SIGI-2 using the Dryden Flight Data Archive System (FDAS)
- SIGI data recorded at 100Hz
- Acceleration data provided to NewSTEP was derived from recorded SIGI velocities through differentiation
- When integrated, derived accelerations 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

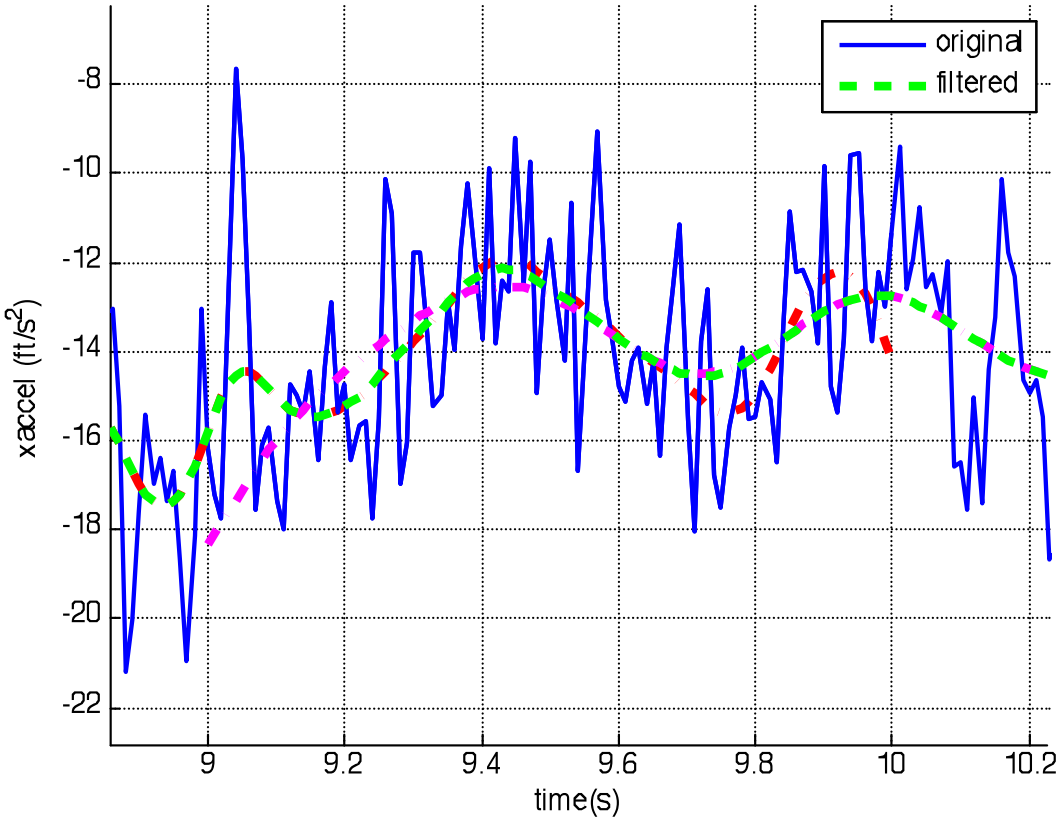
- SIGI data filtered using a low-pass frequency domain filter
- Filtering technique applied using the System Identification Program for Aircraft (SIDPAC) toolbox
- Different regions of trajectory were filtered at different frequencies depending on dynamic behavior during region
- Retain dynamics of vehicle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





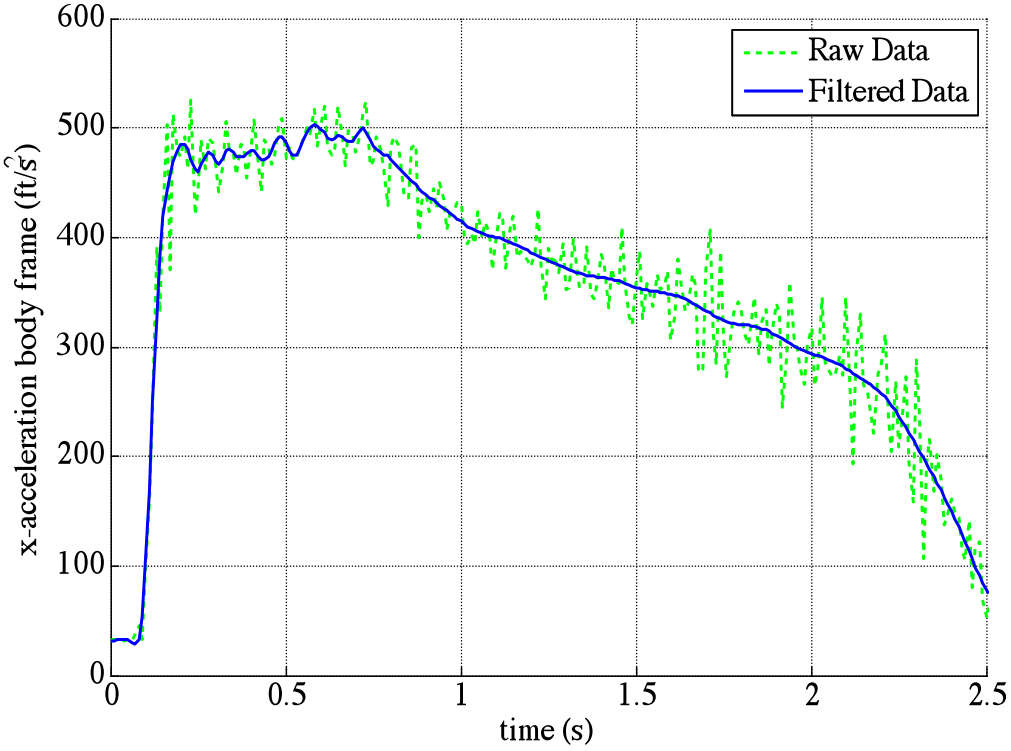
Transition Between Windows

- 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



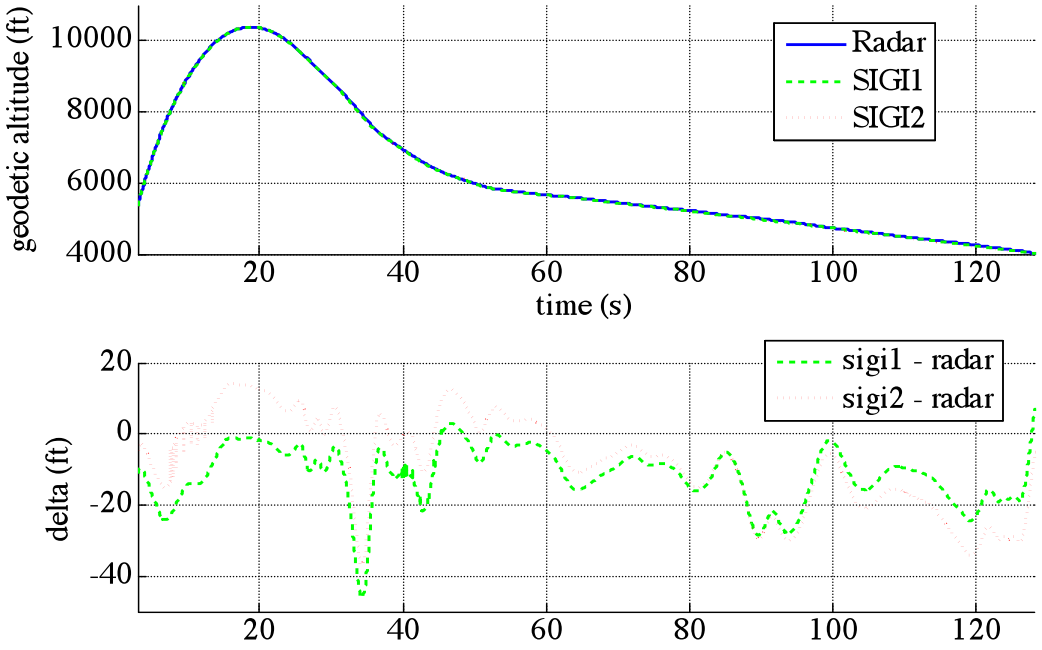
Ignition Acceleration

- 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



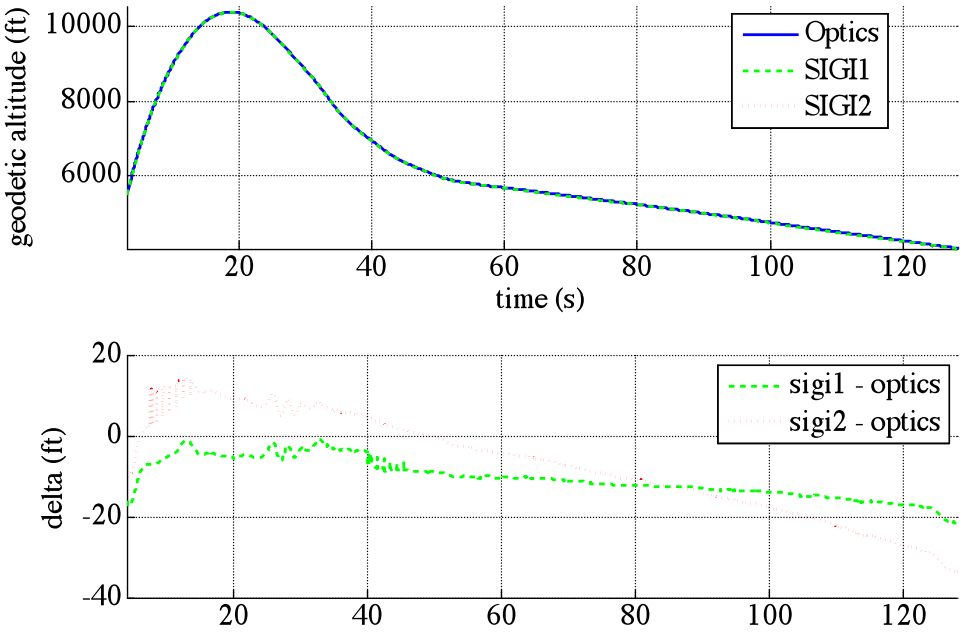
Radar Measurement Data

- 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

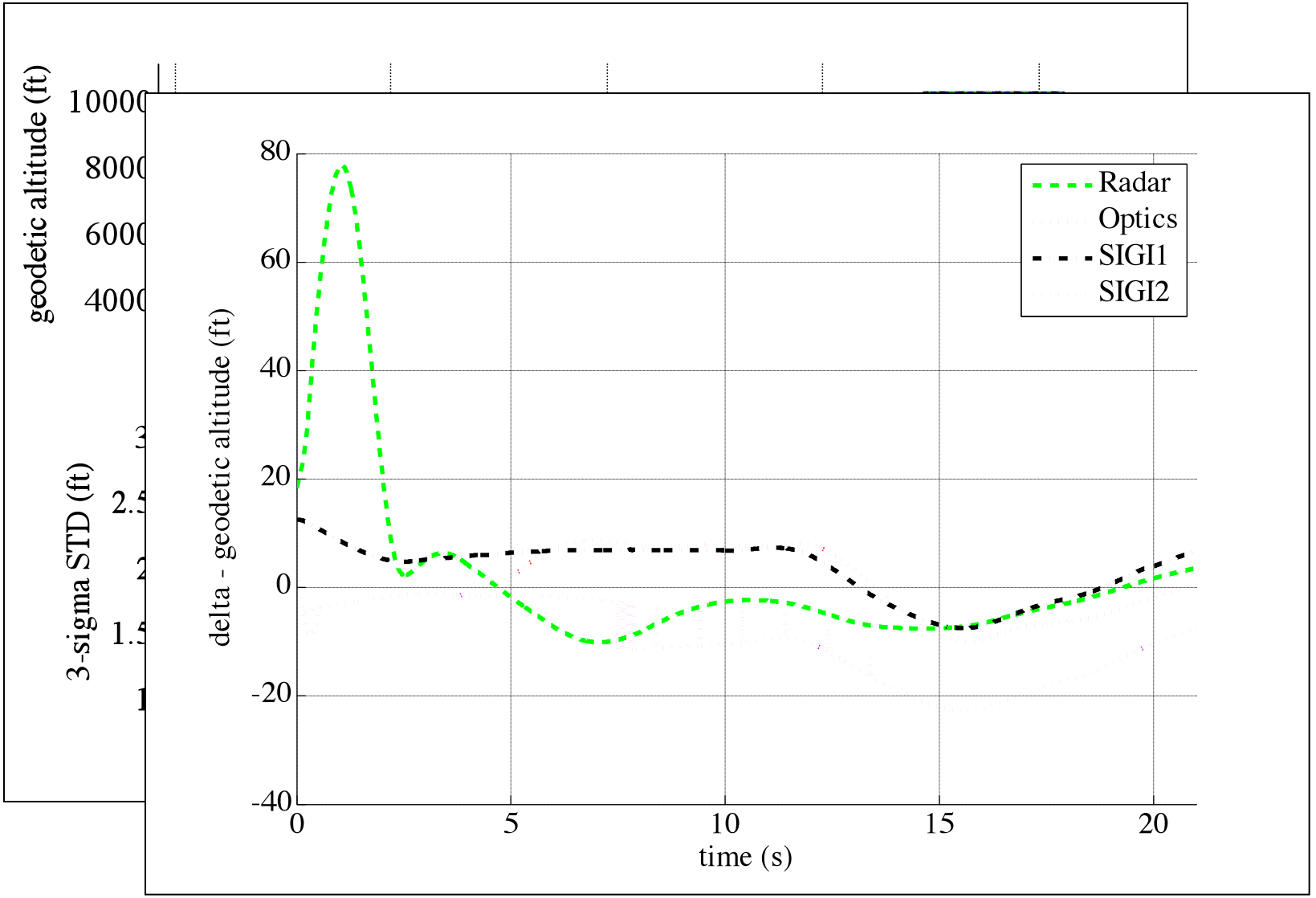


Optical Measurement Data

- 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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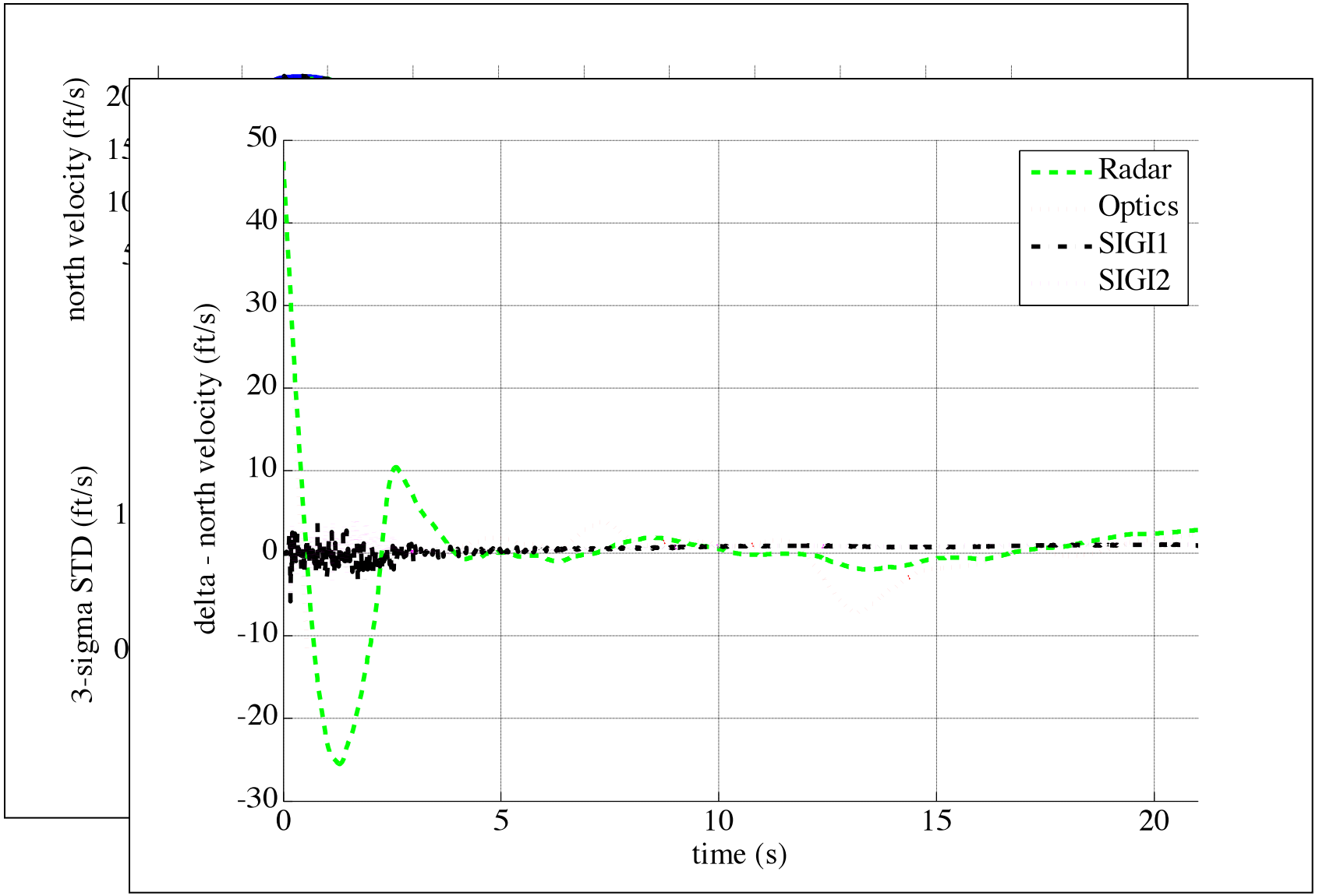

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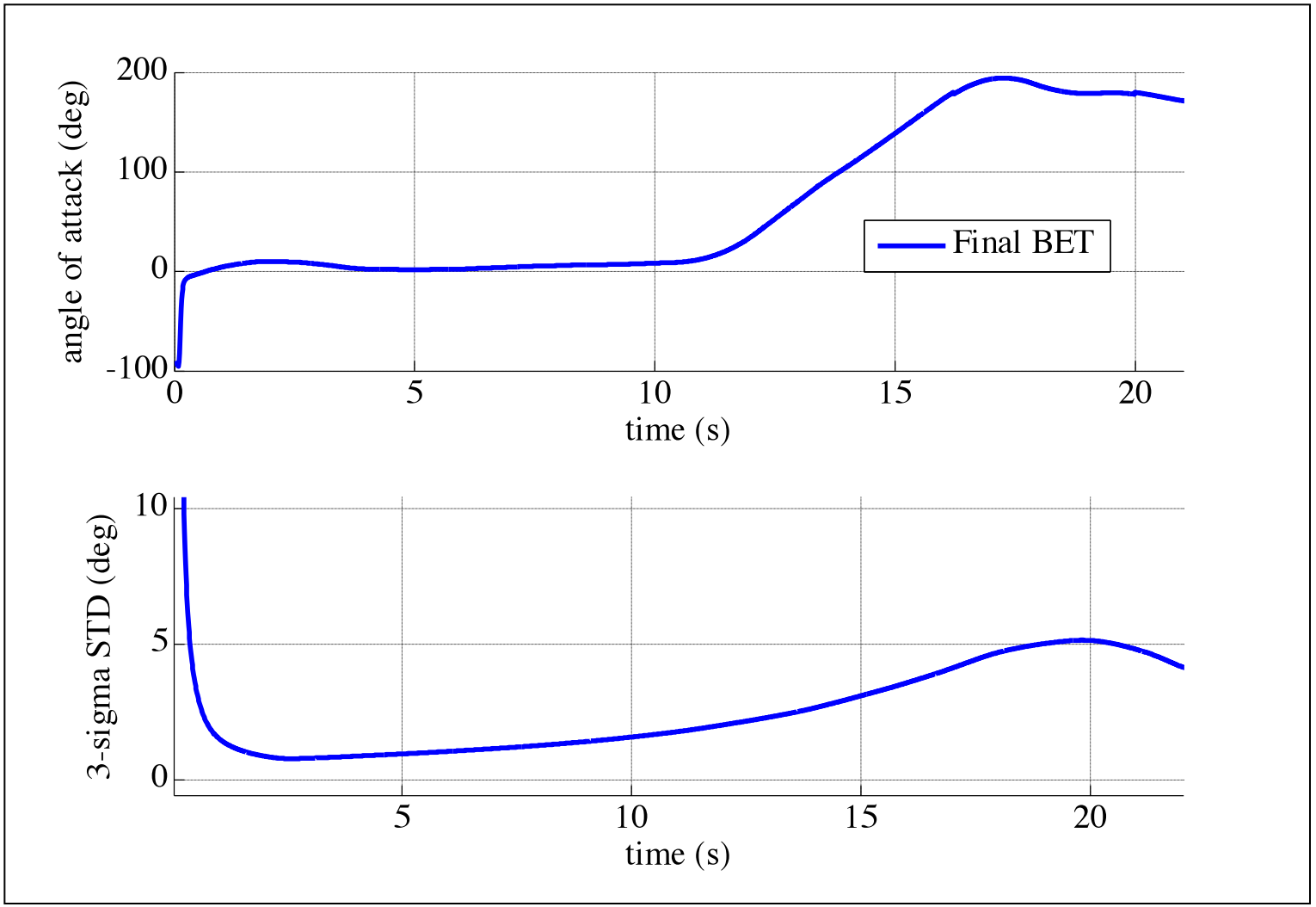

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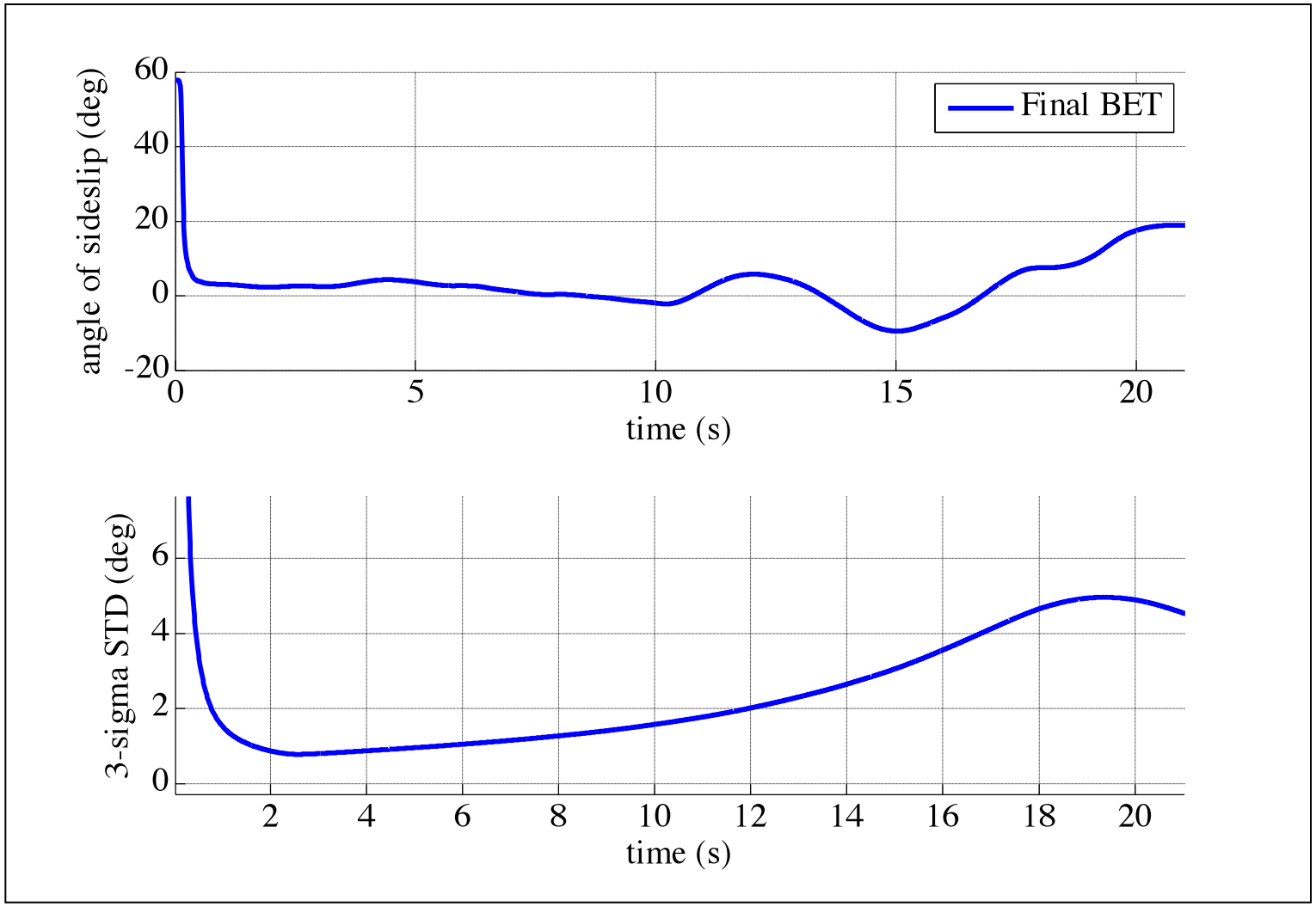
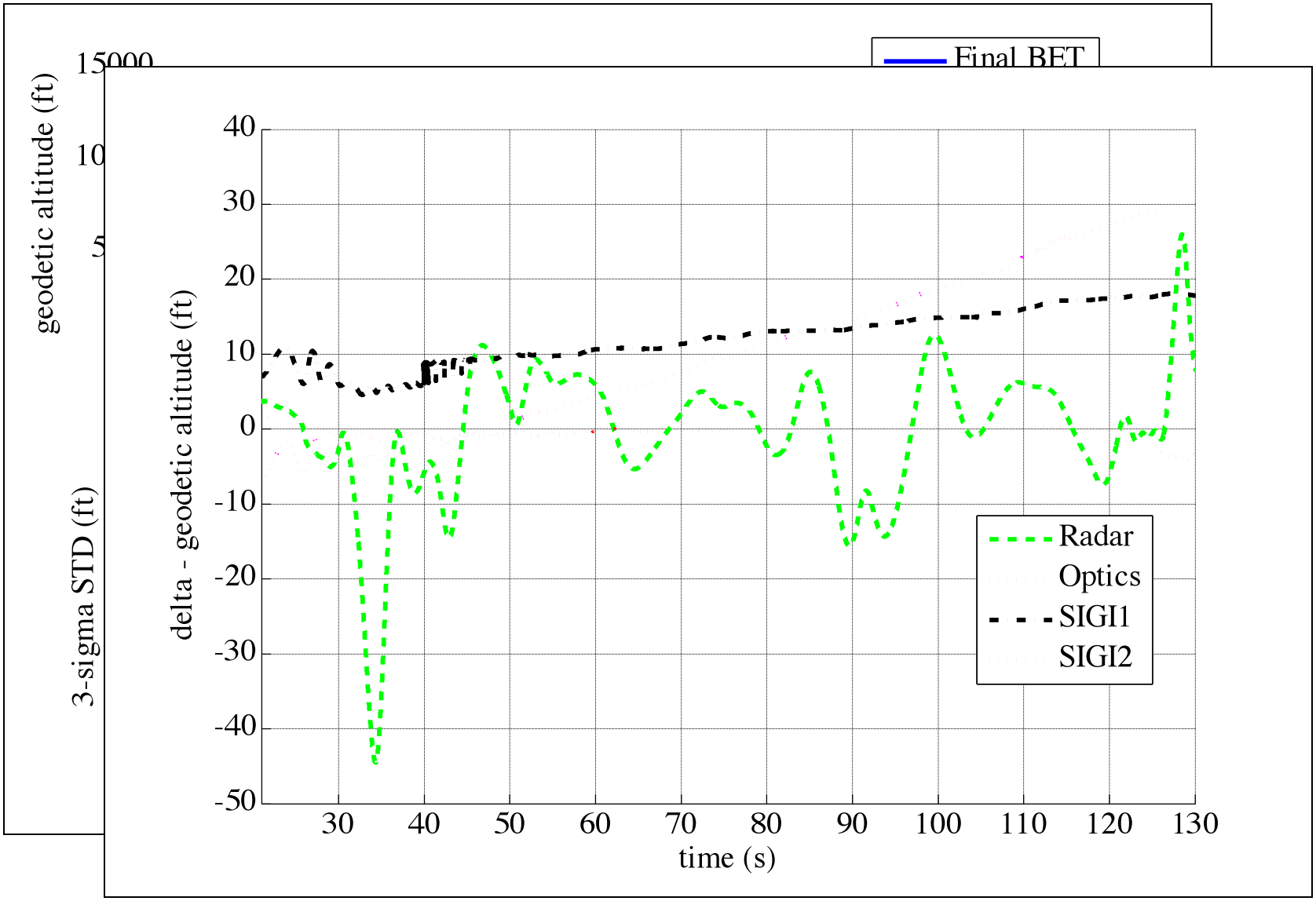
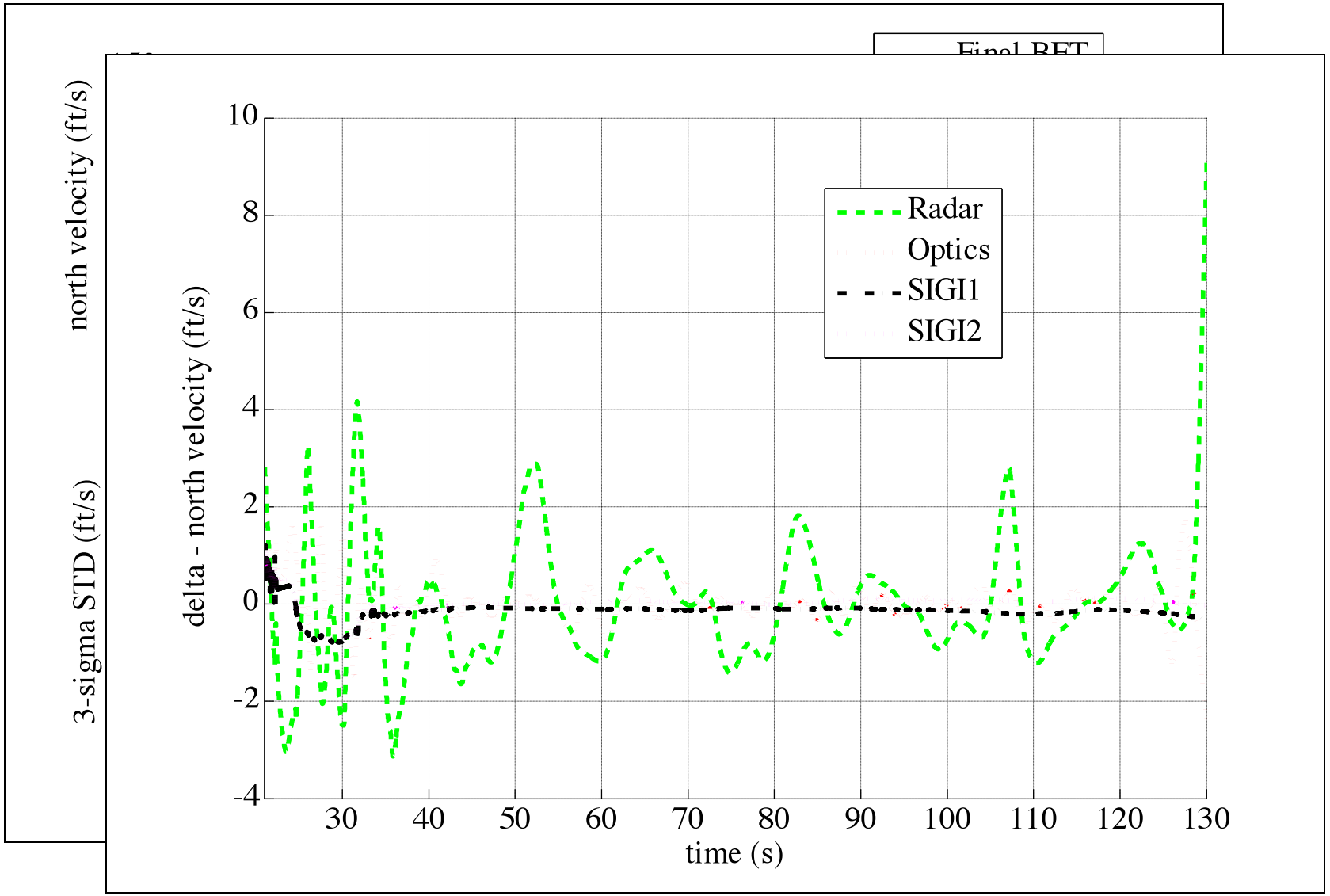


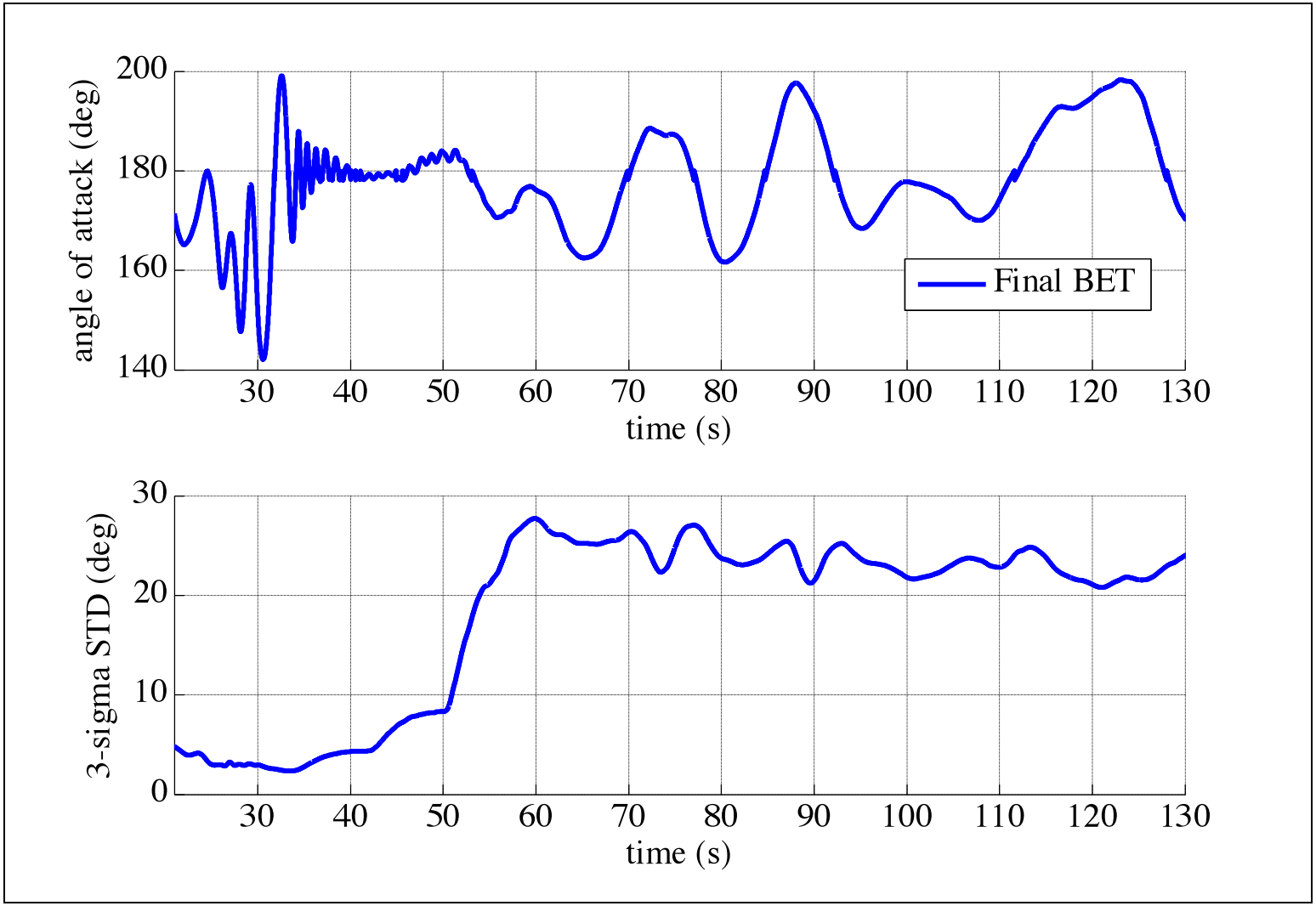
Final BET Results - CM



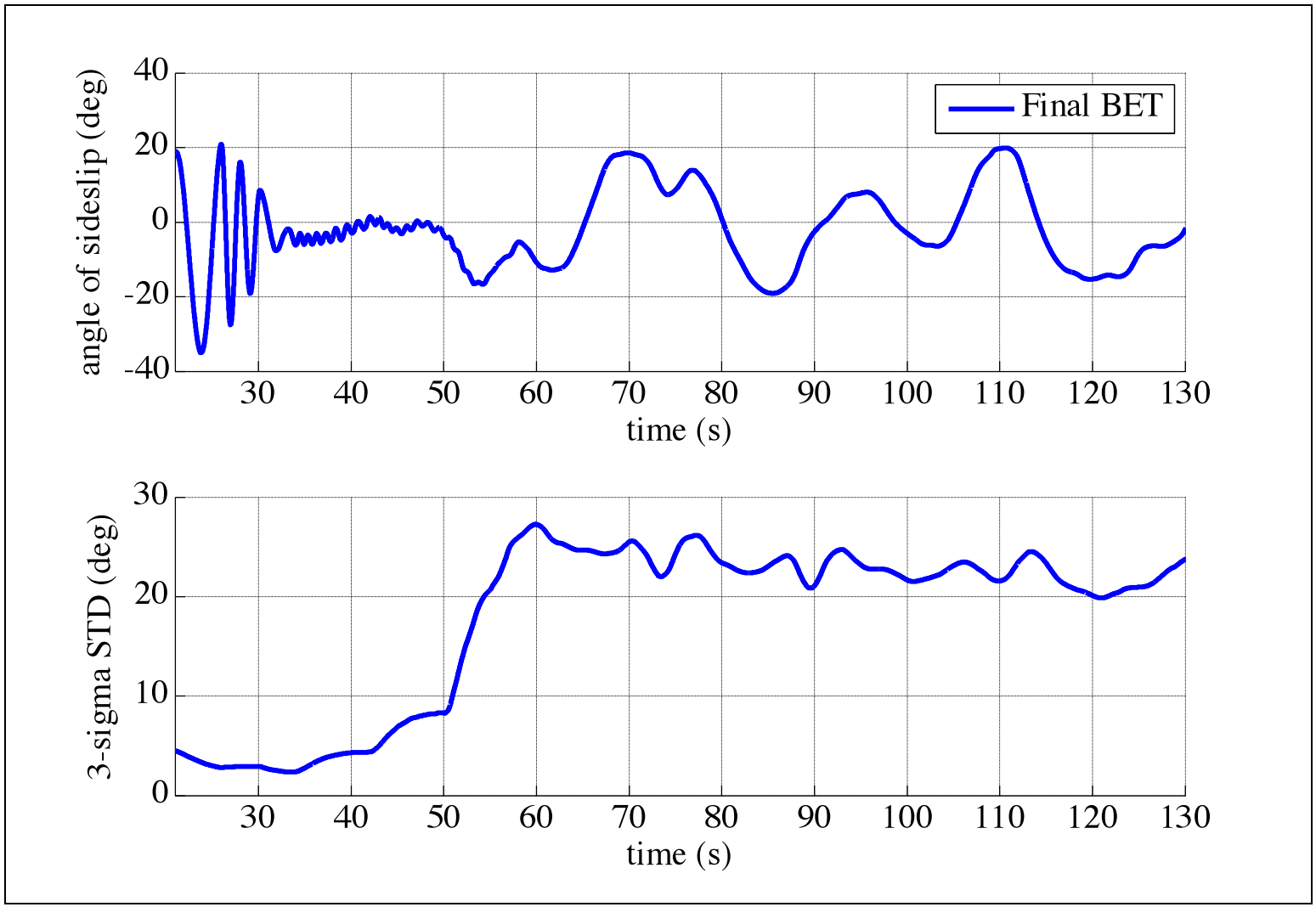
Final BET Results - CM



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?