Advances in GIPSY GNSS/IMU Integrated Positioning and Application to UAVs

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Emerging Developments in Airborne Gravimetry

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Goals & Motivation

- Study Goals:
  - *Validate INS Integration in RTGx using real flight data*.
  - Assess when and how much INS matters for Kinematic Precise Point Positioning (K-PPP) Applications
- *Motivations*
  - Tight-INS in RTGx will provide better K-PPP and potentially open the software to new applications (e.g. ocean buoys, GNSS/INS ground reference sites, airborne PPP)
  - Share with community that JPL's Latest GIPSY has an integrated INS capability

Brief Historical Overview of GIPSY

~1990s

Developed and Maintained by JPL

- ***GIPSY***: **G**NSS **I**nferred **P**ositioning **S**ystem
  - >~25 years in development, ***post-processing*** for:
    - Station Precise Point Positioning (PPP);
    - Precise Orbit Determination (POD) for LEOs;
    - JPL's IGS Orbit/Clock Products
- ***Real Time GIPSY*:**
  - >~16 years in development, ***real-time***
    - Real-time GPS Orbits/Clocks NASA JPL Global Differential GPS (GDGPS)
    - Near Real-time POD for LEOs
    - K-PPP for NASA JPL's Airborne SAR (UAVSAR, AirMoss)
- ***Real-Time GIPSY-x:***
  - >~5 years in development, ***real-time*** or ***post-processed***
    - Navigation software for GPS OCX project
    - Supports all GNSS, not just GPS, Modernized C++/Python OOP Software
    - JPL's IGS Orbit/Clock Products
    - **Integration of Inertial Navigation Capability**

2016

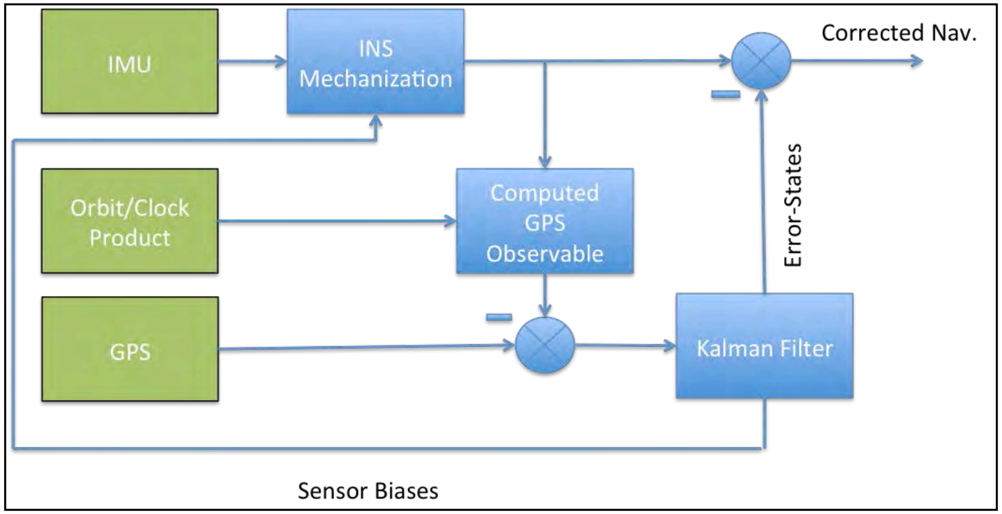
UAVSAR Application

K-PPP vs. RTK

- Has used RTG & GDGPS for real-time K-PPP since 2006;
- Requires real-time solution with global availability
  - Remote locations (e.g. lack of base station);
  - Rapid response;
- In practice: abrupt change in attitude → loss of lock / phase breaks → degraded real-time K-PPP

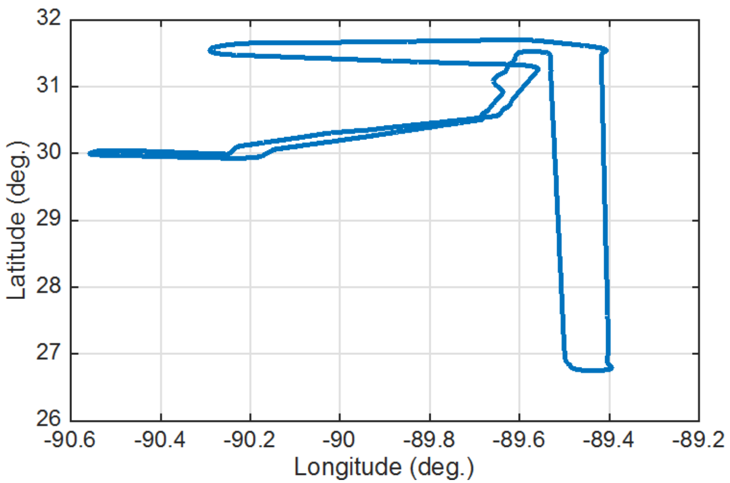
INS Formulation Adopted

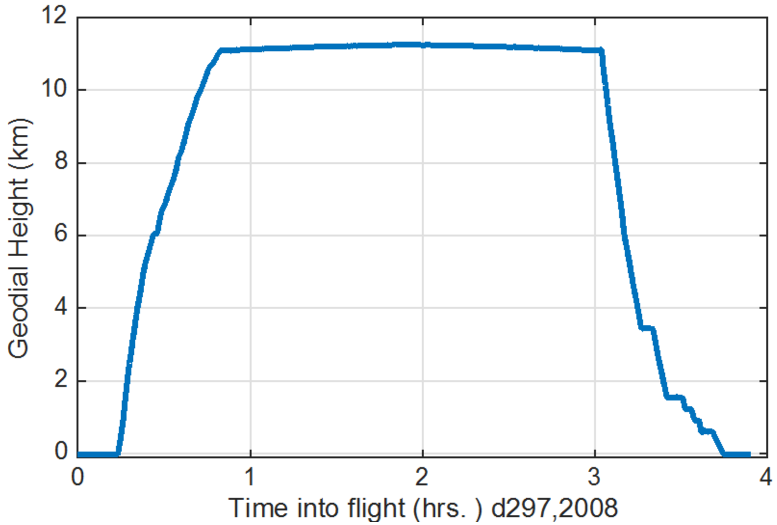
- INS mechanized in Inertial frame;
- 3rd order RK-integration used for quaternion update (Jekeli, 2001);
- Error-state model adopted from (Groves, 2013);
  - 15-INS error states:
    - 3 Attitude
    - 3 Position
    - 3 Velocity
    - 3 Accelerometer Biases
    - 3 Gyro Biases



- **<u>Other considerations</u>**
  - GPS/INS Time Stamp Misalignment
  - Lever Arm/ IMU Rotation

Flight Data: NGS Kinematic Challenge & GRAV-D Data





- 1 Hz Dual-Freq. Range/Phase GPS
- 200 Hz raw IMU data
- Lever-arm
- Smoothed attitude reference solution;

- 6 flight in total
  - Kinematic Challenge, Louisiana
  - New York 2011: 2 Different IMUs
  - Alaska 2015
- ~3.5 hours;
- Sea-level to ~11 km and back;
- Due N/S and E/W legs;

Strategy & Reference Solutions

Baseline Processing Strategy

- Forward filter-only;
- Solve for residual wet zenith delay as a tightly constrained random walk process;
  - Provide Trop Dry Z Nominal
- Solve for GPS receiver clock as a random walk process;
- For GPS-only K-PPP, provide an a priori nominal position solution from a pseudorange only run;
- Use JPL final orbit/clocks;

Reference Solutions

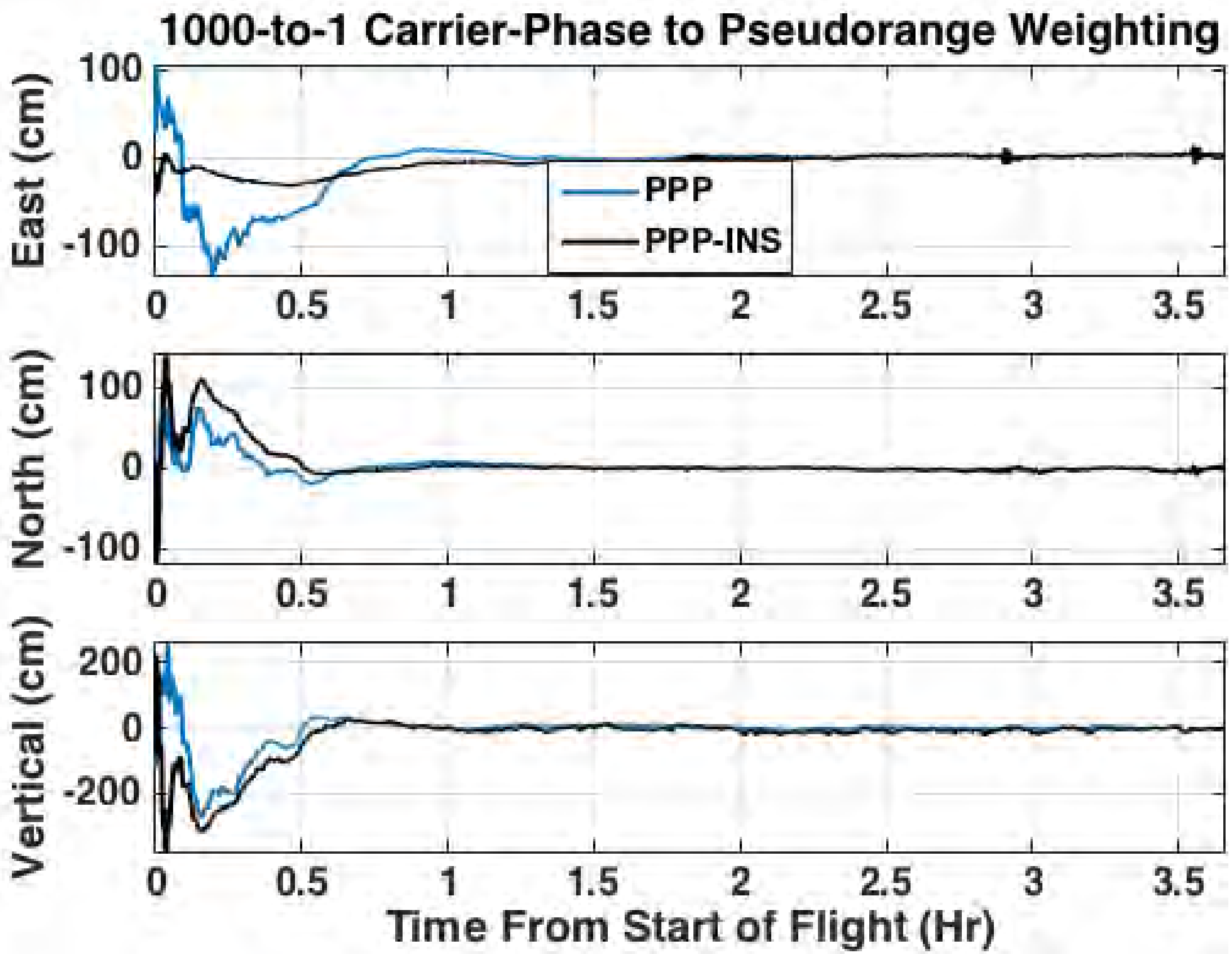
Position:

- These were JPL's submissions and/or strategy to the NGS Kinematic Challenge;
- Iteratively filtered/smoothed post-processed GIPSY-OASIS II solution w/ outlier deletion;
- Uses JPL's wide-lane phase-bias (WLPB) products for single receiver integer ambiguity resolution;

Attitude:

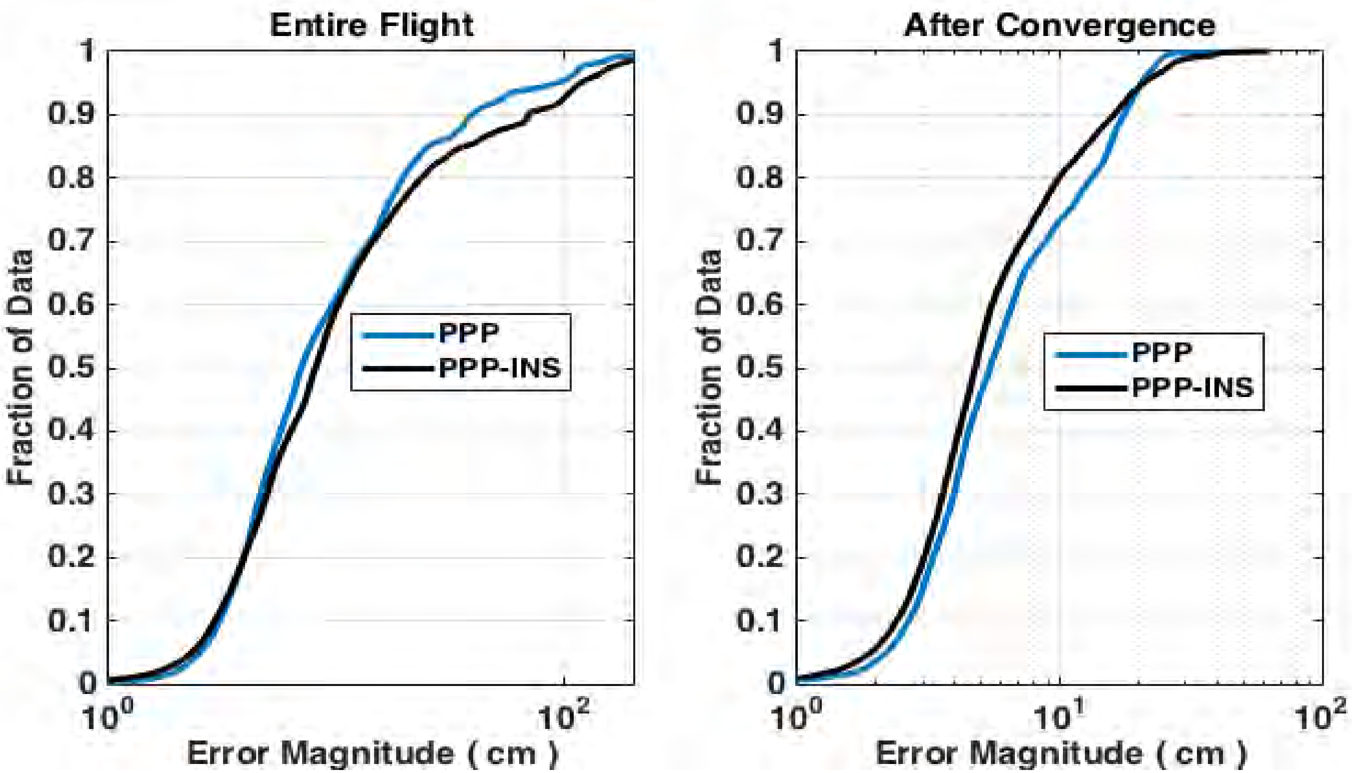
- Applanix PosAV of Novatel SPAN 'smoothed best estimate' solution

Example Positioning Performance AKF07



Positioning Performance All Flights

Cumulative Distribution Position Errors wrt Reference for all 8 data sets

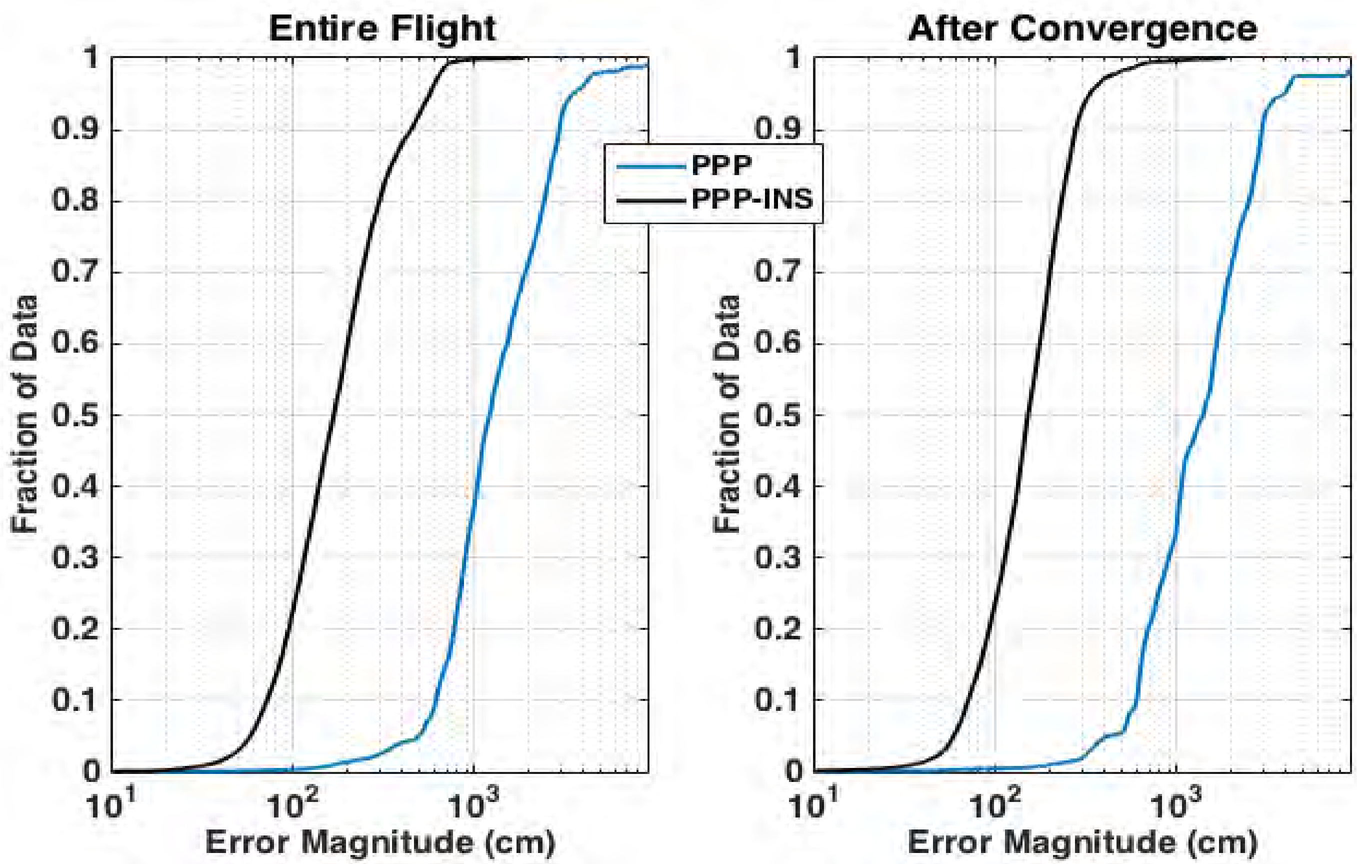


Integrated solution has ***<u>very slight</u>*** advantage for positioning accuracy after solution convergence.

- **PPP-INS Median 3D Error = 4.74 cm**
- **PPP Median 3D Error = 5.4 cm**

When does Integrated INS help?

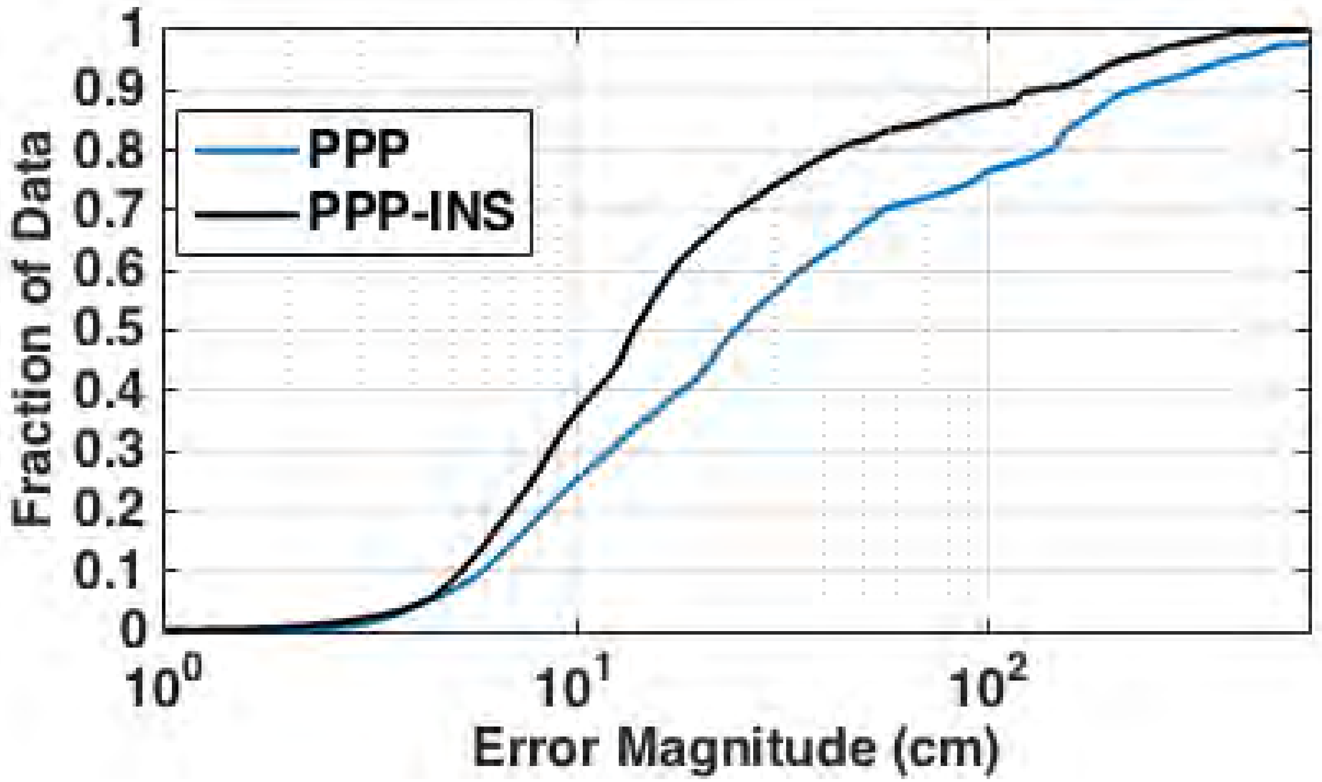
***Case Study*: Test Limit of Poor Data Quality by Processing a Pseudorange only Solution**



- **PR-INS Median 3D Error = 1.5 m**
- **PR Median 3D Error = 13.9 m**

When does Integrated INS help? (cont.)

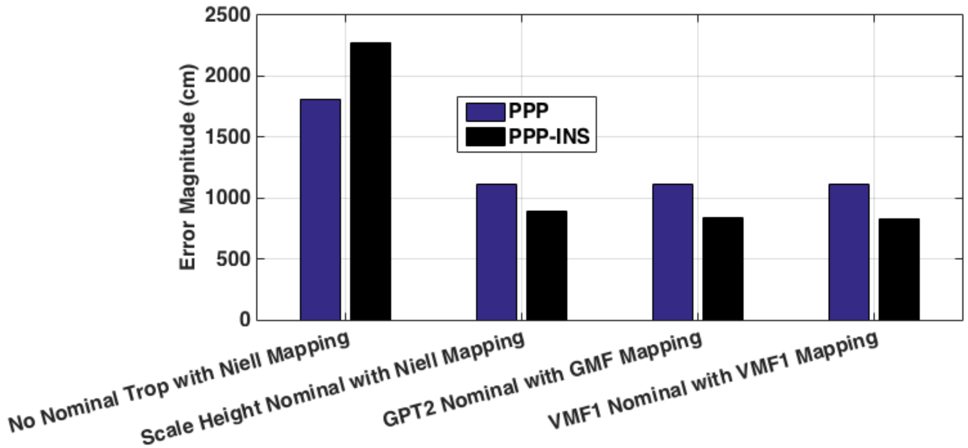
Case Study*:** ***Test Limit of Poor Nominal Position Solution $x_k = x_{k-1}$

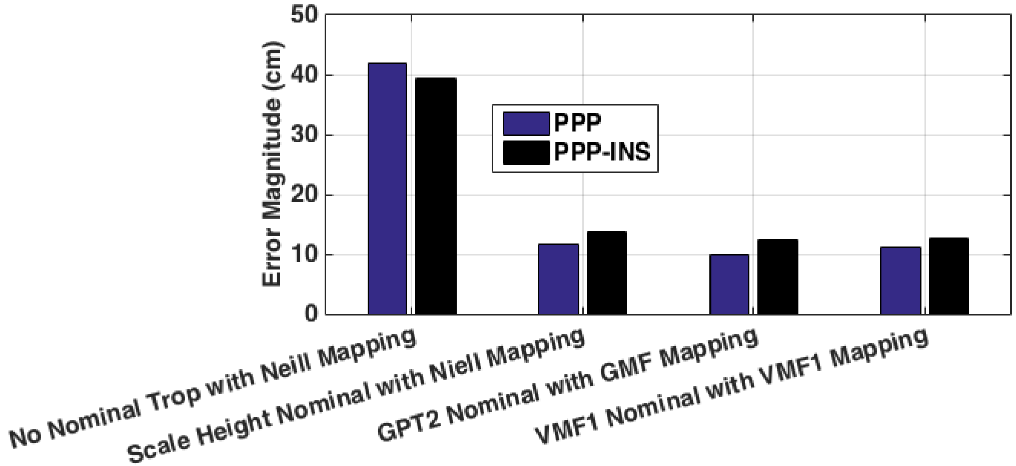


- **PPP-INS Median 3D Error = 13.6 cm**
- **PPP Median 3D Error = 24 cm**

When does Integrated INS help a lot? (cont.)

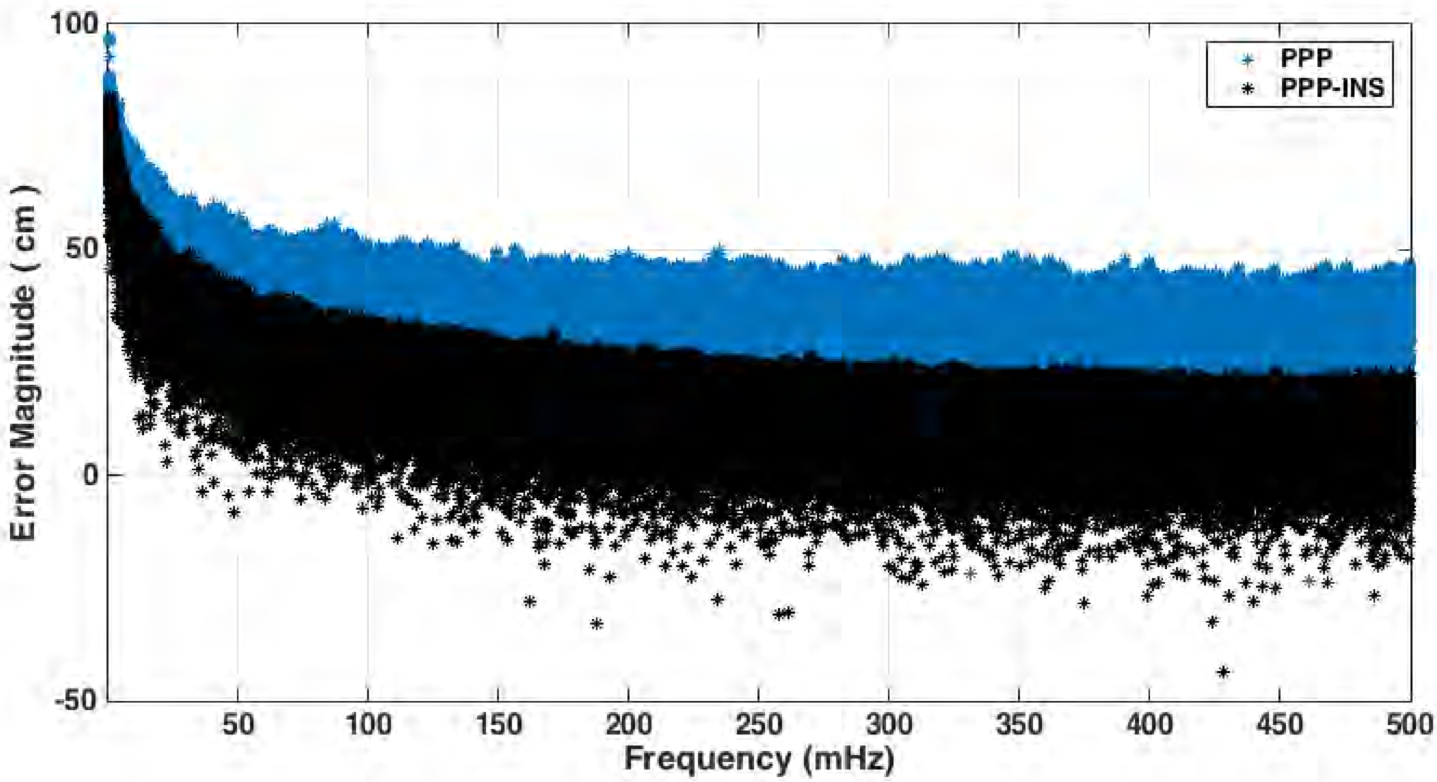
***Case Study*: Test quality of troposphere error model**





When does Integrated INS help? (cont.)

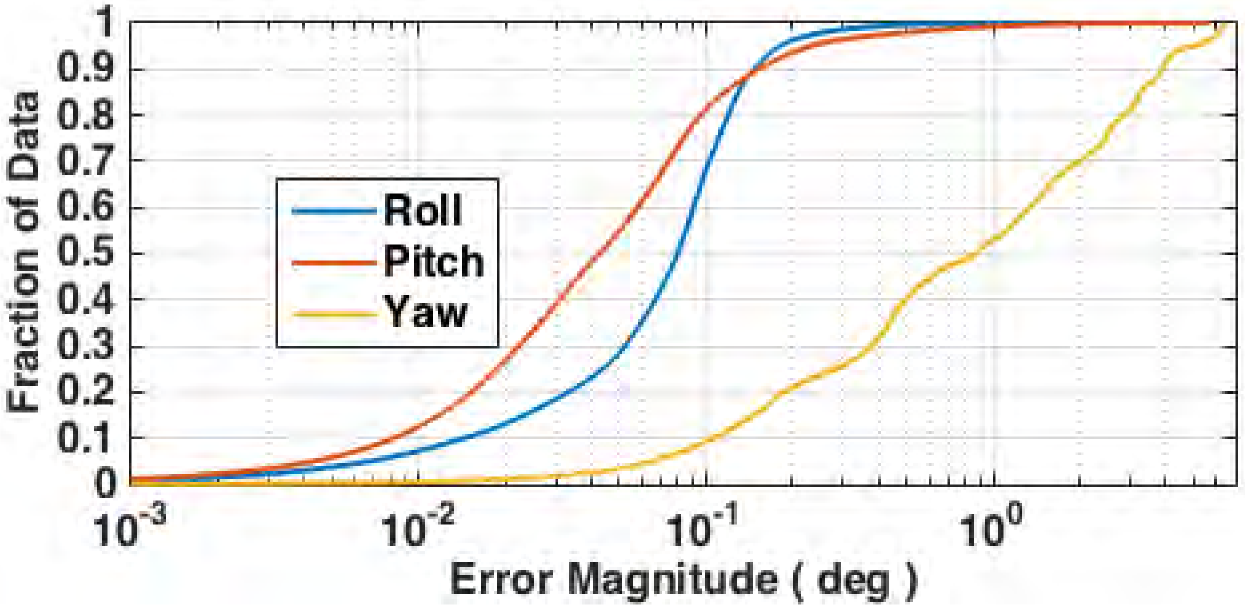
Obtain a 100 Hz vs. 1 Hz Smoother Position Solution



Nominal Position Solution vs. Estimated Position Solution

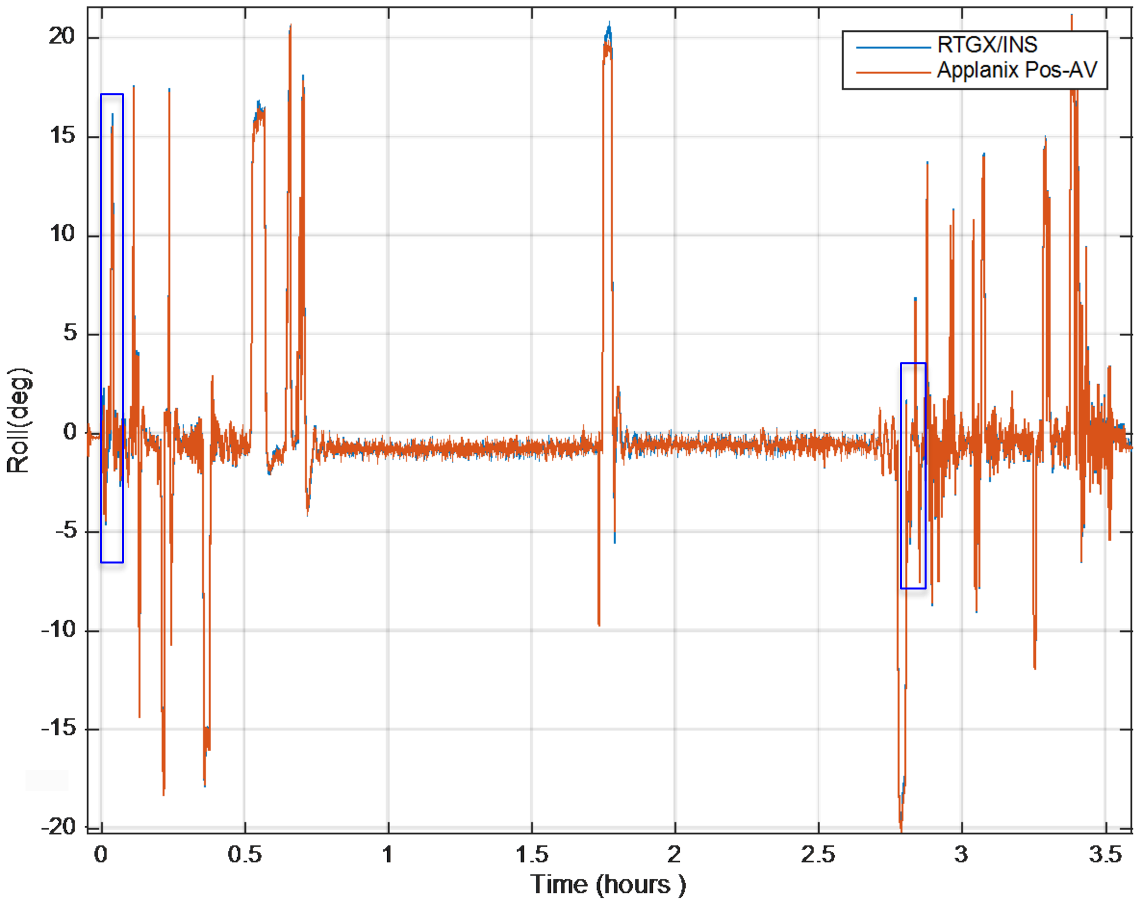
When does Integrated INS help a lot? (cont.)

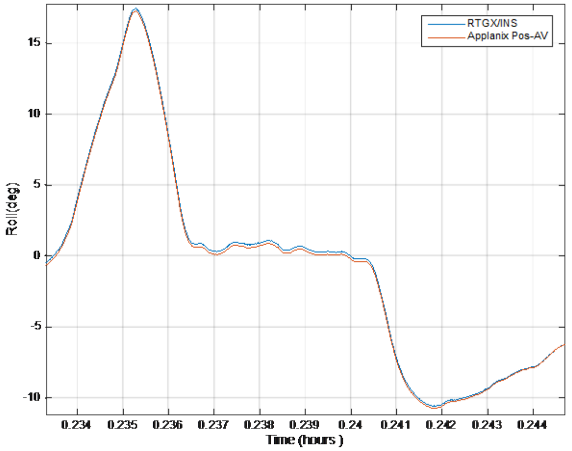
100 Hz attitude solution

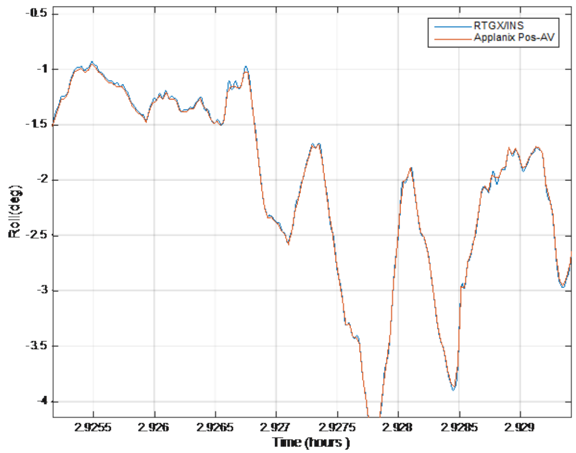


- **Median Roll Error = 0.08 deg.**
- **Median Pitch Error = 0.04 deg.**
- **Median Yaw Error = 0.87 deg.**

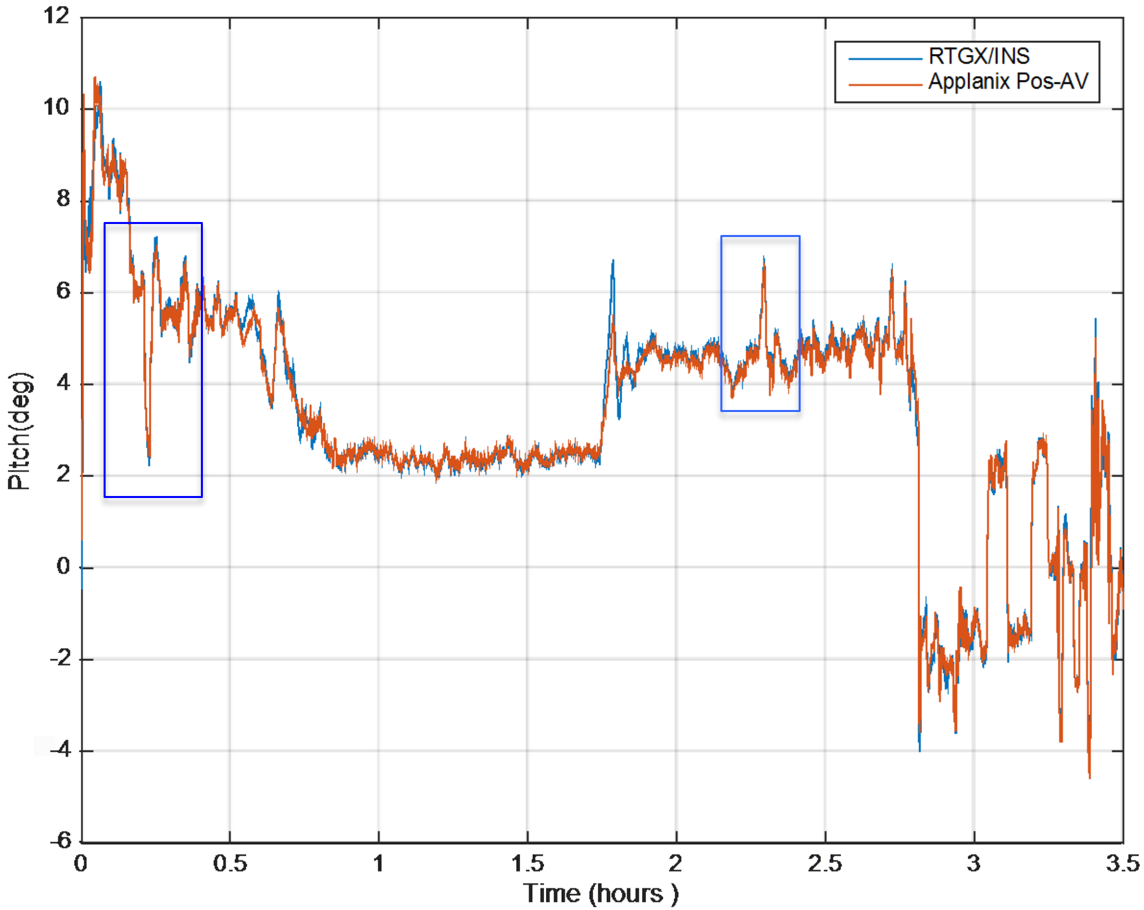
Example Roll Estimation vs. Applanix

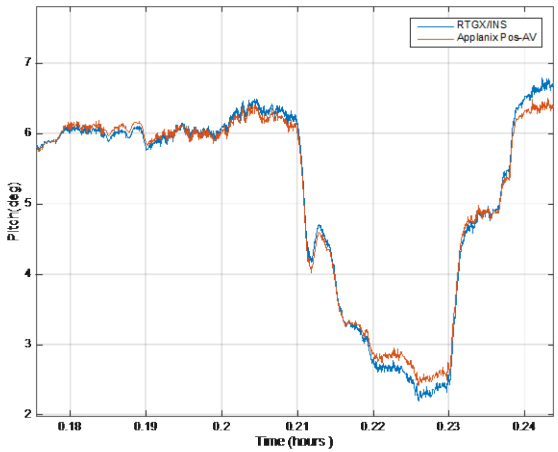


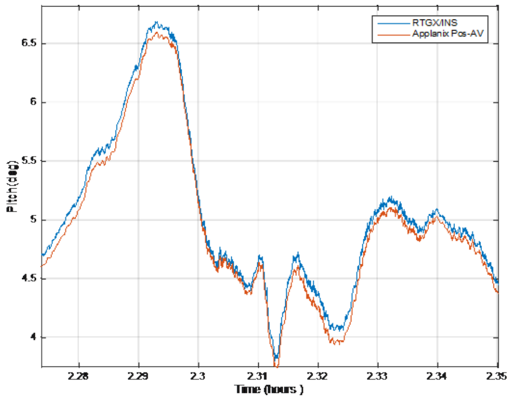




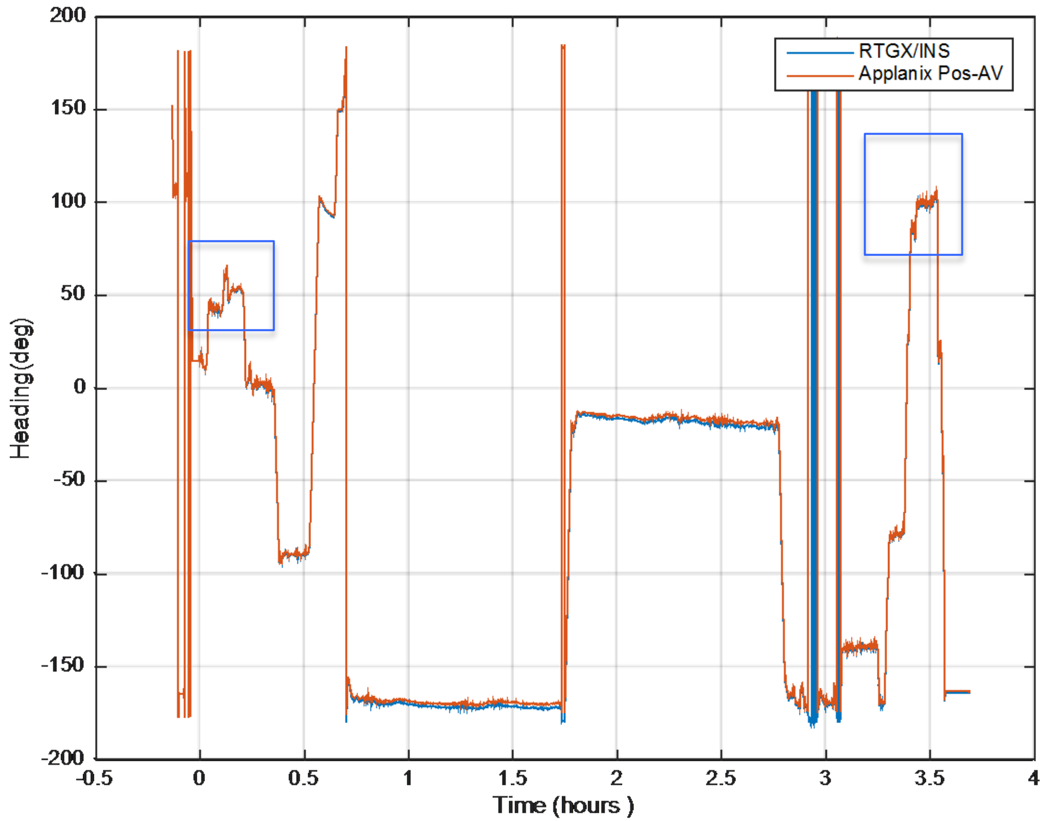
Example Pitch Estimation vs. Applanix

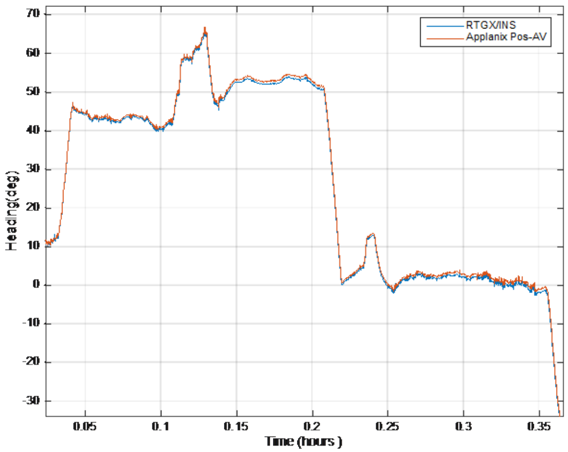


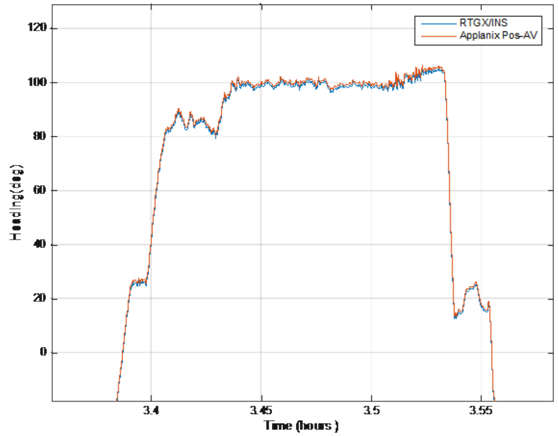




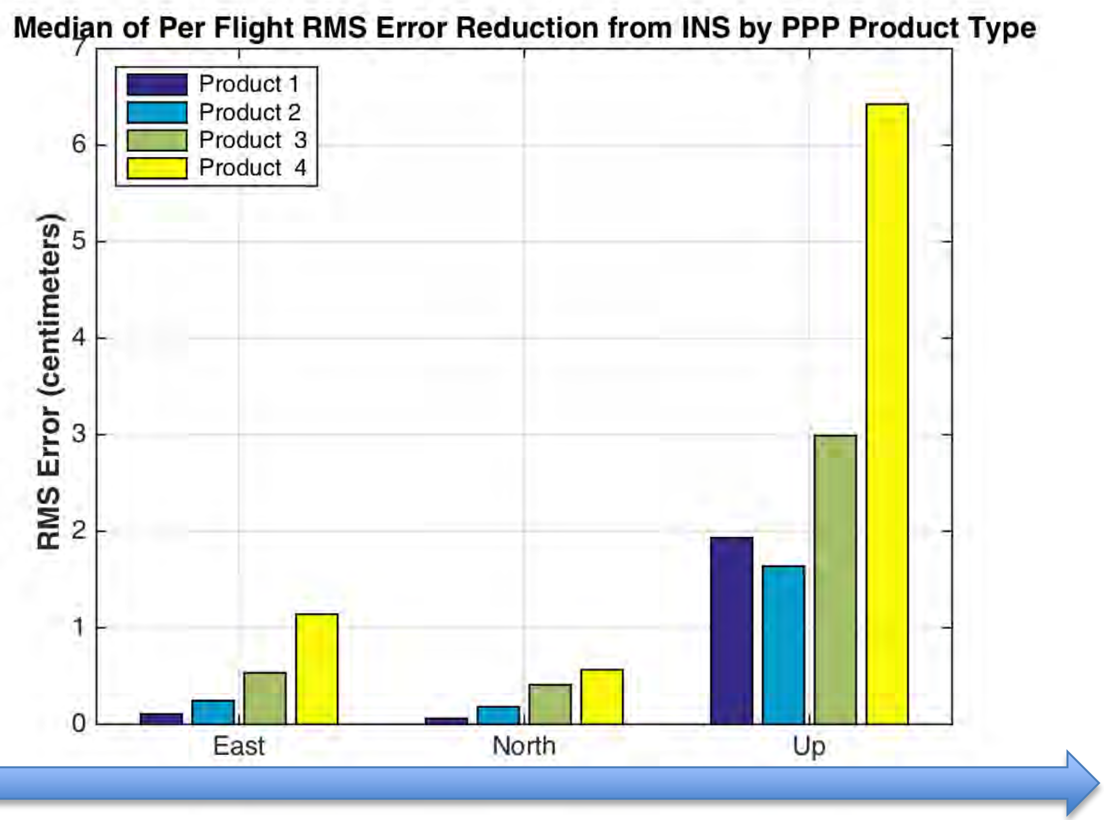
Example Heading Estimation Vs. Applanix







Simulated Results: ENU Error Reduction from INS vs. Orbit Quality



Decreasing Orbit Quality
[.05 0.1 0.2 0.3] m RMS

K-PPP for Small UAV Applications

Receiver	Flight 1				Flight 2				Flight 3			
	Front		Back		Front		Back		Front		Back	
Algorithm	μ (m)	σ (m)	μ (m)	σ (m)	μ (m)	σ (m)	μ (m)	σ (m)	μ (m)	σ (m)	μ (m)	σ (m)
PR2P-PP	1.98	1.32	3.11	2.80	3.20	3.82	2.57	0.85	1.85	0.84	2.27	0.96
RTKLIB-PP	1.77	1.17	3.68	2.23	3.57	3.75	2.99	1.80	1.69	0.64	2.05	0.83
GD2P-PPP	0.61	0.038	0.91	0.20	0.63	0.03	0.99	0.082	1.391	0.029	1.33	0.026
RTKLIB-PPP	1.99	0.048	2.23	0.18	0.59	0.013	0.65	0.066	0.97	0.018	1.013	0.025

	Overall Average	
Algorithm	μ (m)	σ (m)
PR2P-PP	2.50	1.76
RTKLIB-PP	2.62	1.74
GD2P-PPP	0.98	0.067
RTKLIB-PPP	1.23	0.058

~6 cm precision with PPP, despite ~ 5 min flight

Conclusions

- INS has been integrated for tightly-coupled processing in RTGx and vetted experimentally;
- For real-time aircraft PPP INS vs. PPP:
  - very slight positioning benefit when everything is working well;
  - smoother and more robust positioning solution (e.g. more tolerant to poor nominal and data quality)
  - High-rate solution with precise attitude solution
- INS in RTGx opens the software to new application domains;

Acknowledgements

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- Thanks for Bruce Haines at JPL for providing input on his GIPSY reference solution strategy.

Questions?

References

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