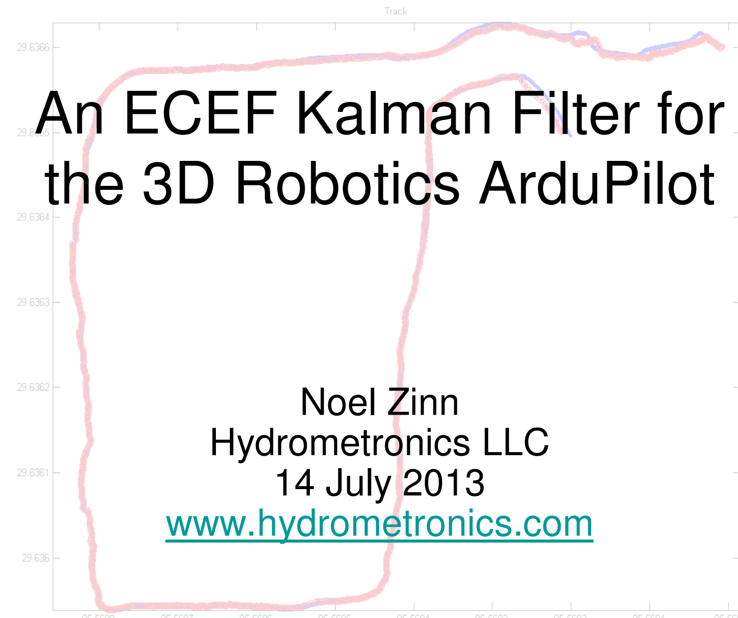

An ECEF Kalman Filter for the 3D Robotics ArduPilot

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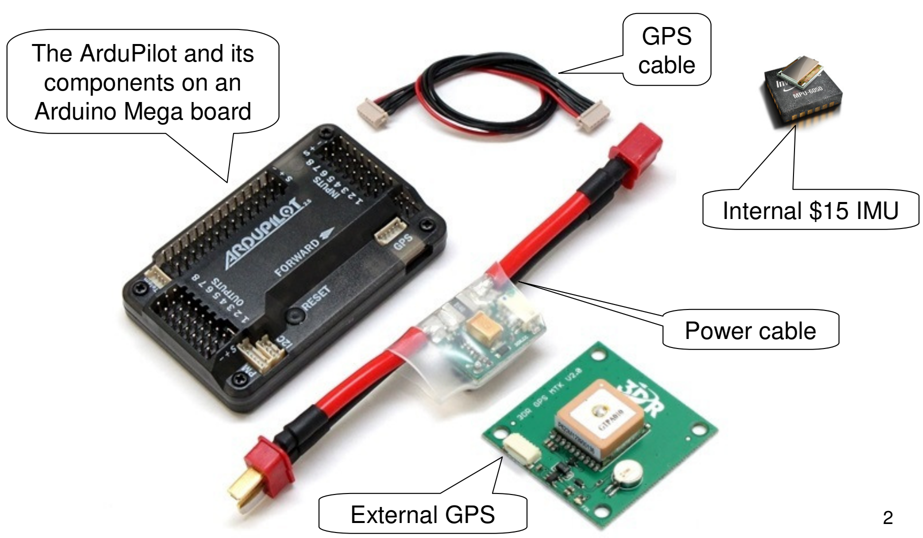
14 July 2013
www.hydrometronics.com

3D Robotics ArduPilot, a $316 IMU with Upgraded GPS and Radio Telemetry, Which Fits in the Palm of Your Hand. The Internal, Consumer-Grade MPU-6000 IMU Itself Costs $15.



2

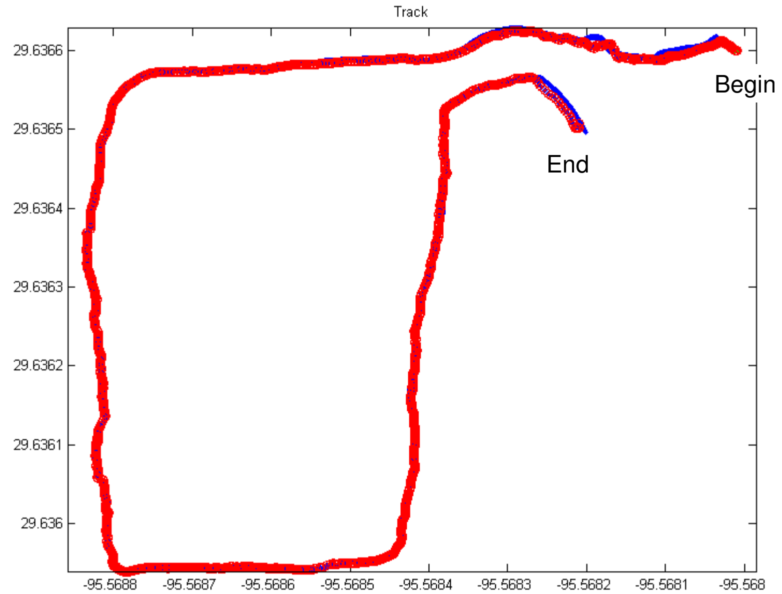
Overview

- Hydrometronics has developed 15-state, loosely- and tightly-coupled Kalman filters (Kf) coordinated in ECEF for the integration of IMU (inertial) and GPS (or acoustic) data
- In anticipation of testing the Kf with low-cost, consumer-grade, MEMS sensors, Hydrometronics purchased a 3D Robotics ArduPilot (shown in the previous slide)
- In collaboration with NCS Subsea personnel Eddie Majzlik and Tommy Rosa, who is skilled in Arduino programming, we conducted a walk-around test of the ArduPilot (hand held) near the NCS office. Thanks to both of them!
- This report presents initial results filtering some of that data (the first half) using an error profile appropriate for a consumer-grade IMU
- A later report exhibits performance on a car and in a lake
- With appropriate error profiles this Kf can be used with tactical- and aviation-grade IMUs
- Aiding sensors other than GPS position can be used, e.g. GPS Doppler velocity (which the ArduPilot does not supply), acoustics, DVL, other velocity meters, strain gauges (depth)

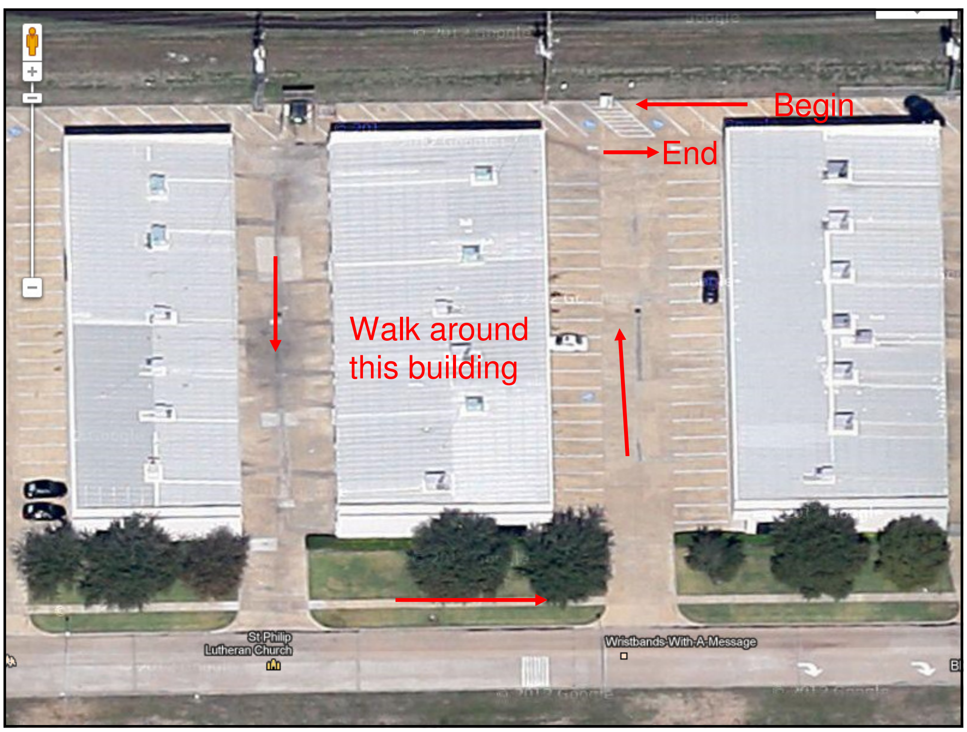
Development Resources

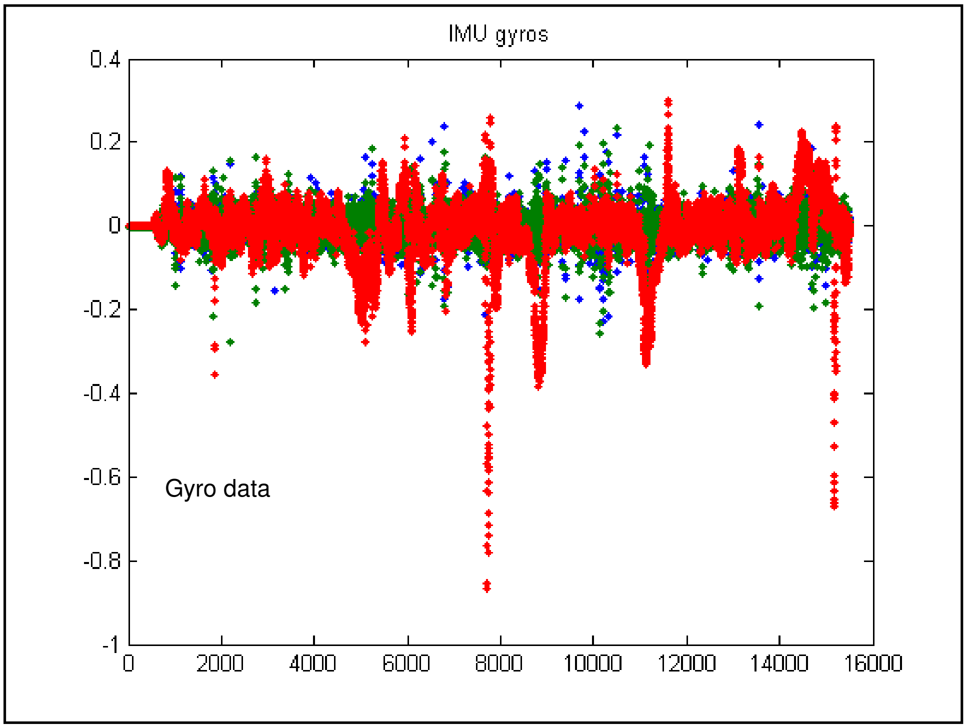
- Paul D. Groves, *Principles of GNSS, Inertial, and Multisensor Integrated Navigation Systems*, Second Edition, April 2013, an excellent text with excellent, well-documented Matlab code
- Yigiter Yuksel, excellent Matlab code at http://www.instk.org/, *Open Source Inertial Navigation Toolkit*, but scantily documented
- Jay A. Farrell, *Aided Navigation: GPS with High Rate Sensors*, 2008, with sparse Matlab code
- Mohinder S. Grewal, Application of Kalman Filtering to GPS, INS, & Navigation, Short Course Notes, January 2013, with sparse Matlab code
- David Titterton and John Weston, *Strapdown Inertial Navigation Technology*, 2nd Edition, 2004

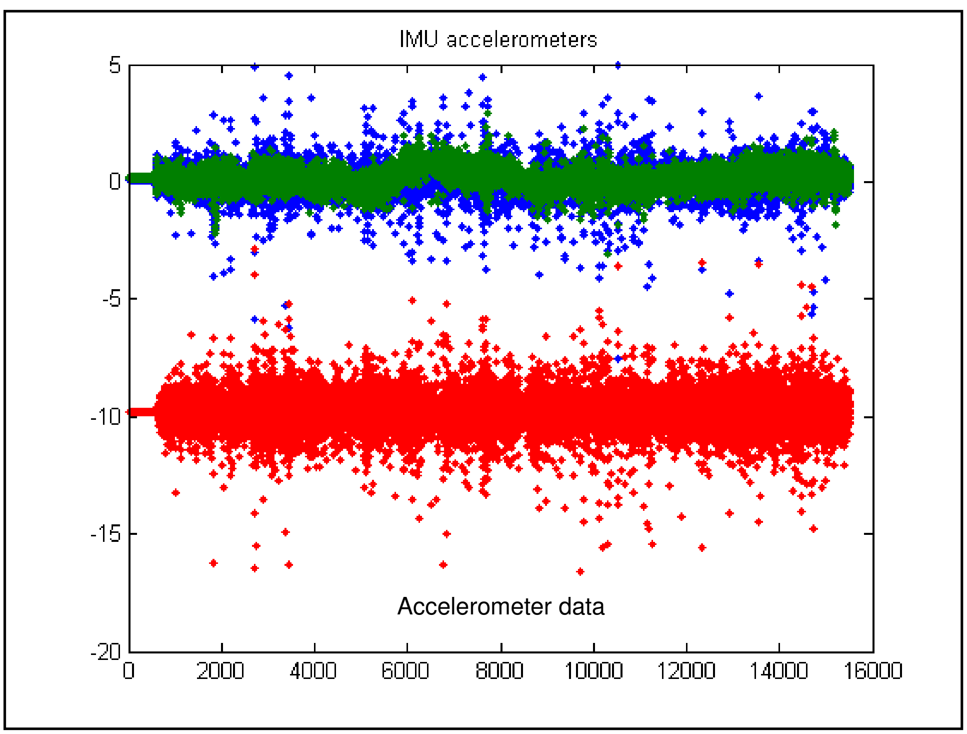
Track Analyzed (Half of Data Collected)

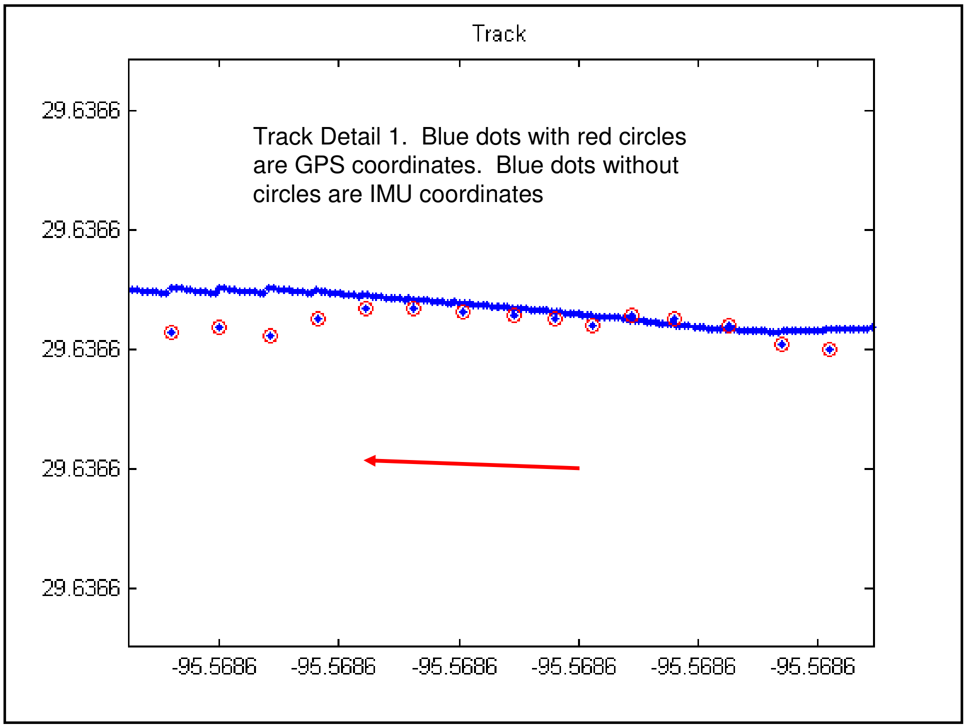


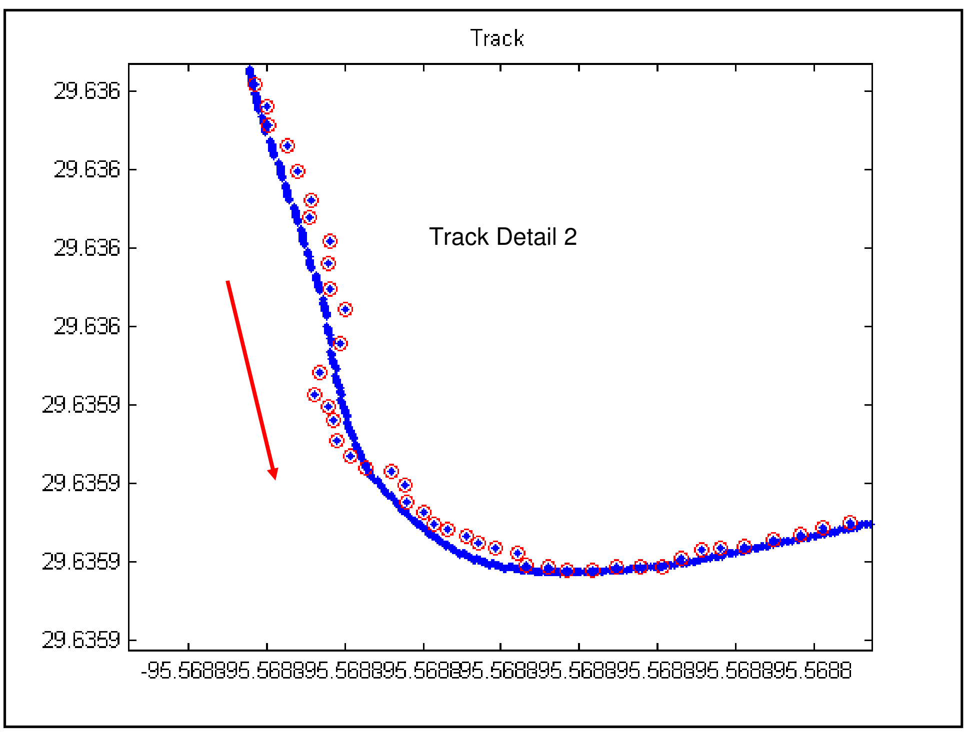
5

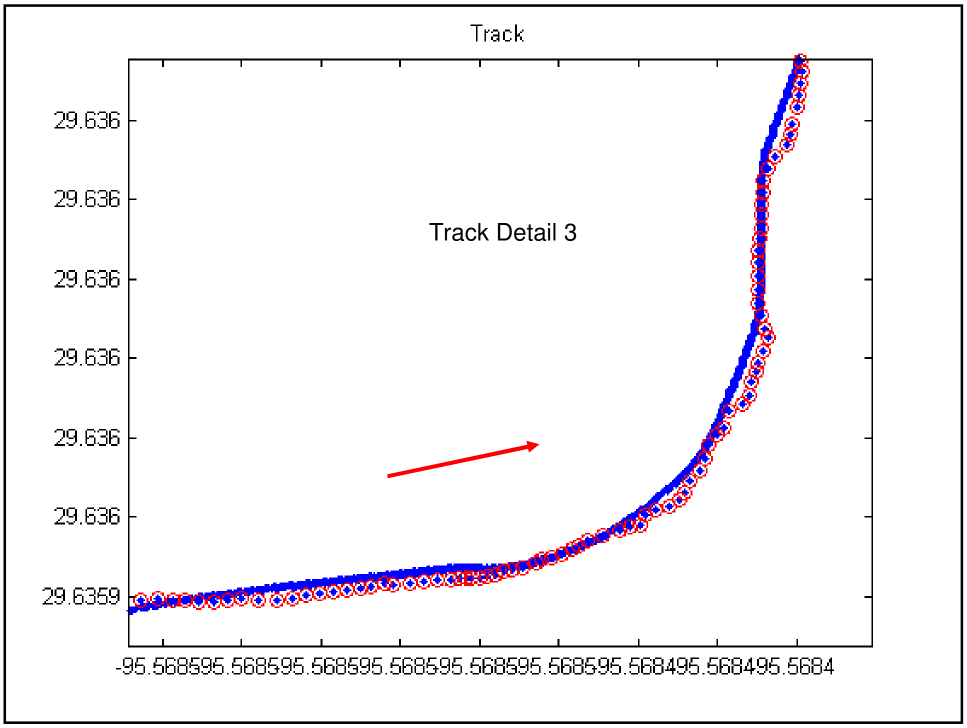


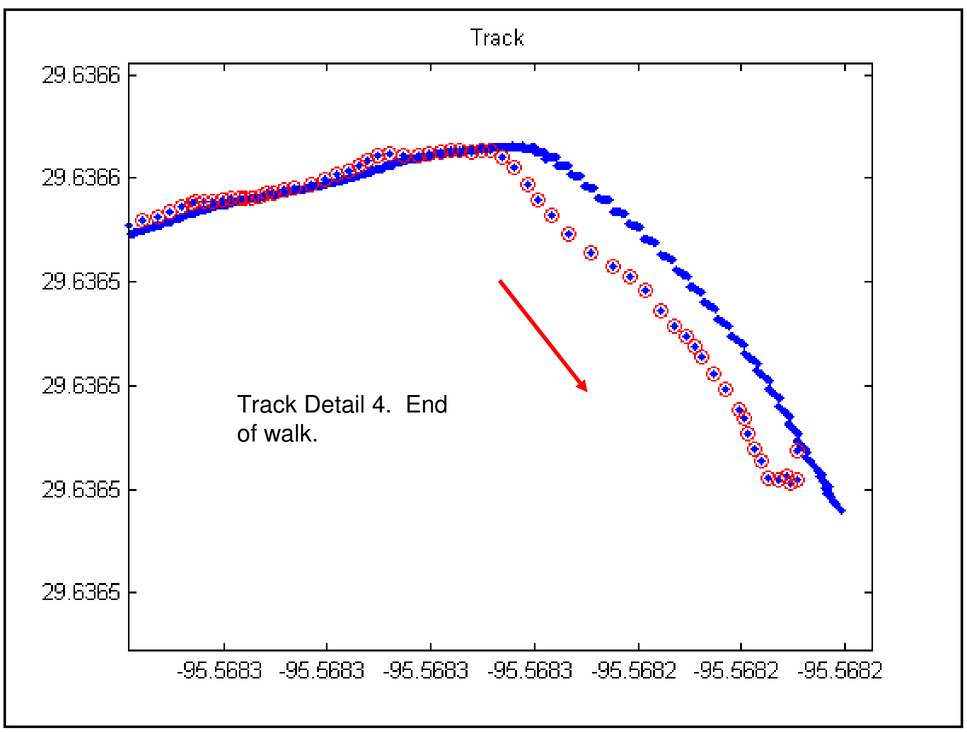

IMU gyros
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
0
2000
4000
6000
8000
10000
12000
14000
16000
Gyro data

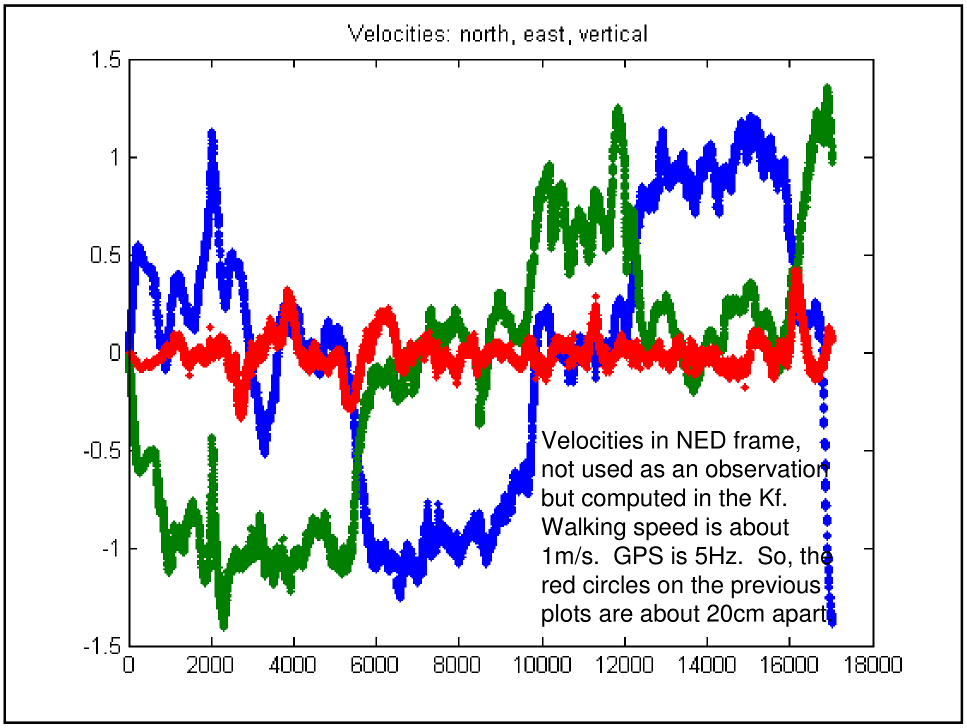

IMU accelerometers
5
0
-5
-10
-15
-20
0
2000
4000
6000
8000
10000
12000
14000
16000
Accelerometer data

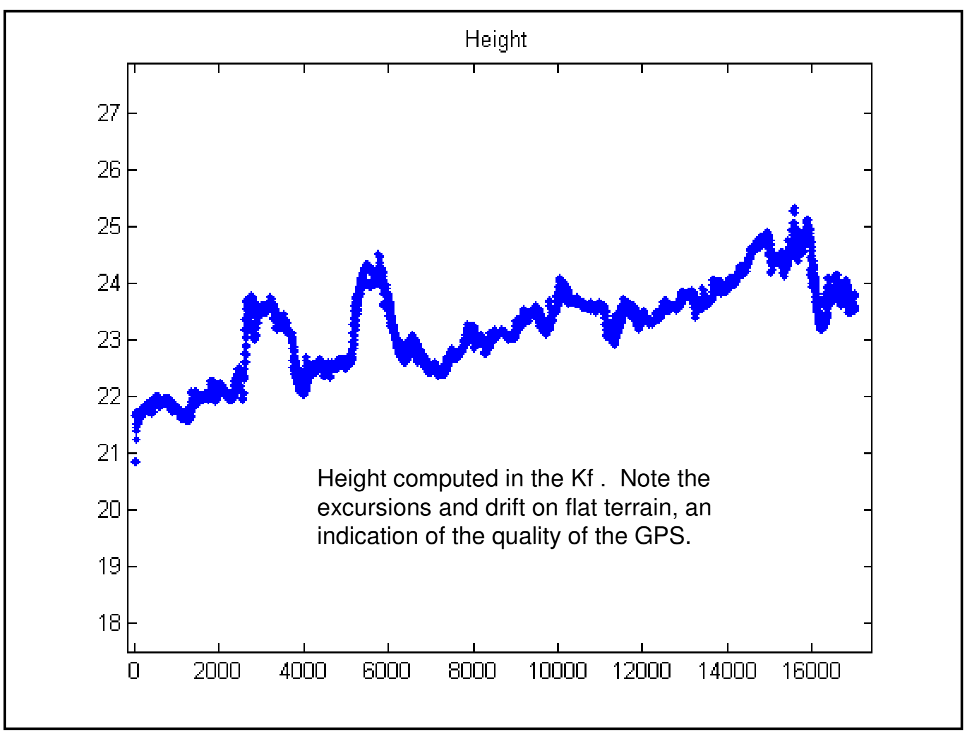

Track
Track Detail 1. Blue dots with red circles
are GPS coordinates. Blue dots without
circles are IMU coordinates
29.6366
29.6366
29.6366
29.6366
29.6366
-95.5686
-95.5686
-95.5686
-95.5686
-95.5686
-95.5686

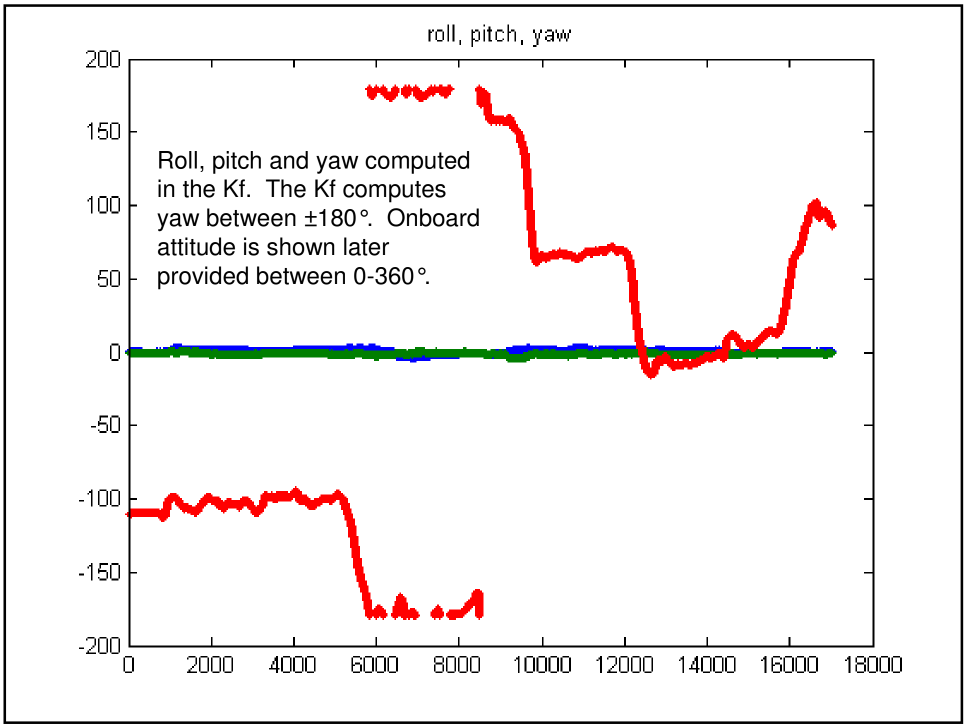

Track
Track Detail 2
29.636
29.636
29.636
29.636
29.6359
29.6359
29.6359
29.6359
-95.568895.568895.568895.568895.568895.568895.568895.568895.5688

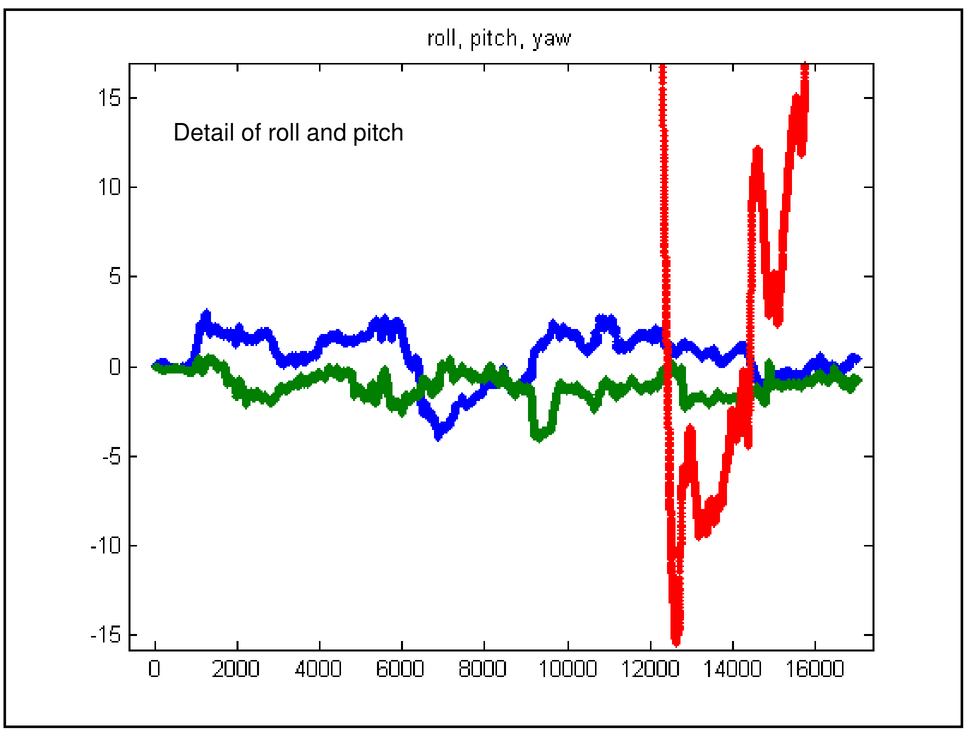

Track
Track Detail 3
29.636
29.636
29.636
29.636
29.636
29.636
29.6359
-95.568595.568595.568595.568595.568595.568595.568495.568495.5684

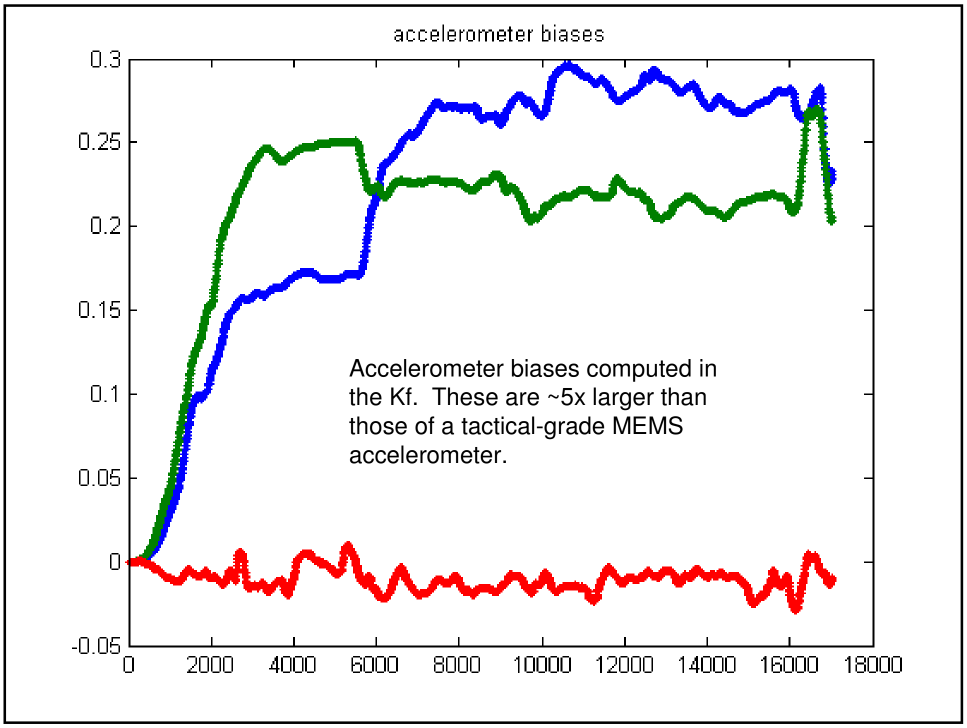

Track
Track Detail 4. End of walk.
29.6366
29.6366
29.6365
29.6365
29.6365
29.6365
-95.5683 -95.5683 -95.5683 -95.5683 -95.5682 -95.5682 -95.5682

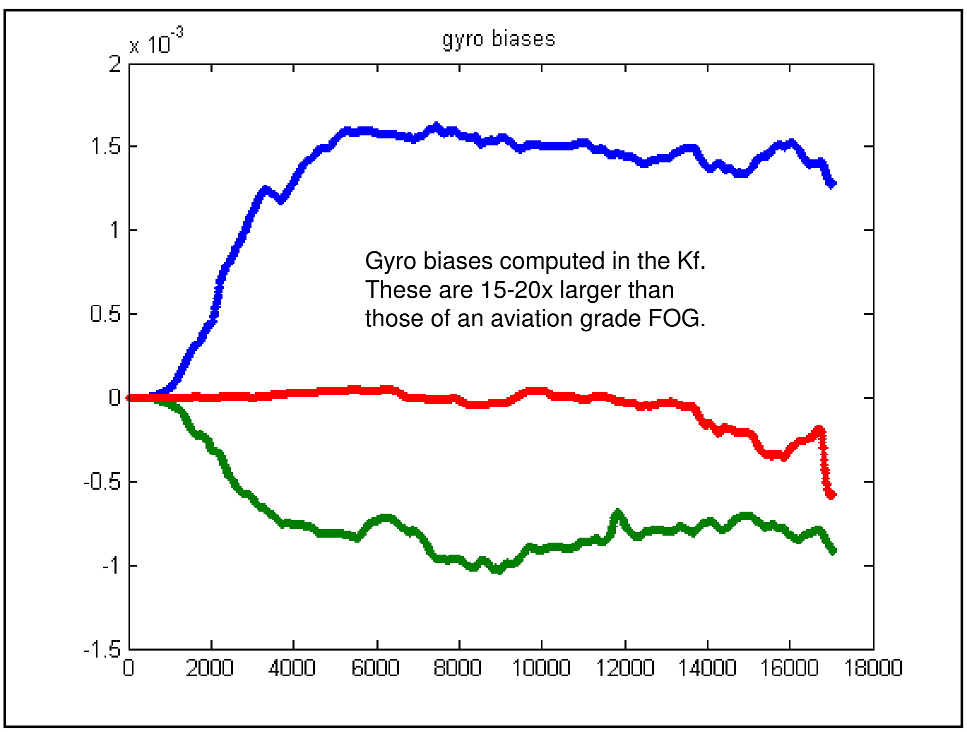

Velocities: north, east, vertical
1.5
1
0.5
0
-0.5
-1
-1.5
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
Velocities in NED frame, not used as an observation but computed in the Kf. Walking speed is about 1m/s. GPS is 5Hz. So, the red circles on the previous plots are about 20cm apart

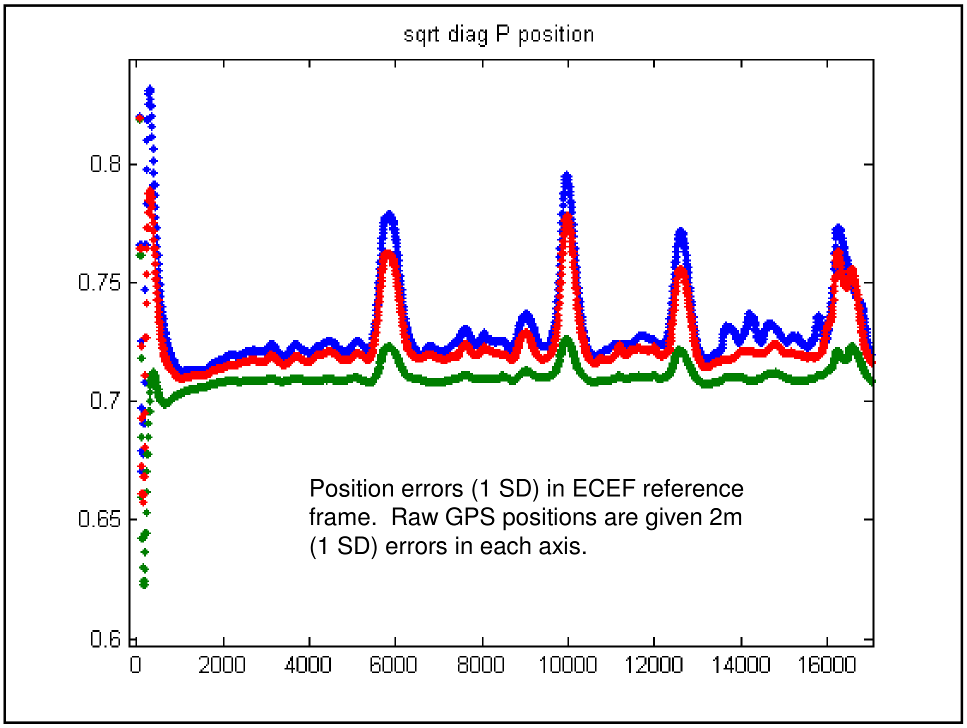

Height
27
26
25
24
23
22
21
20
19
18
0
2000
4000
6000
8000
10000
12000
14000
16000
Height computed in the Kf . Note the excursions and drift on flat terrain, an indication of the quality of the GPS.

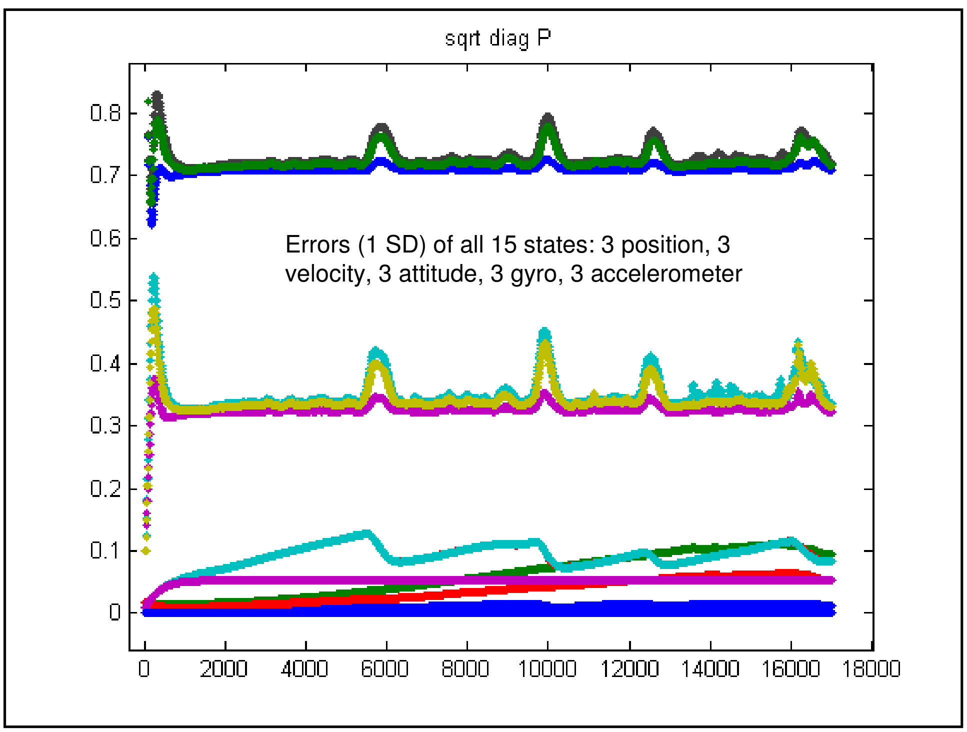

roll, pitch, yaw
Roll, pitch and yaw computed
in the Kf. The Kf computes
yaw between ±180°. Onboard
attitude is shown later
provided between 0-360°.
200
150
100
50
0
-50
-100
-150
-200
0
2000
4000
6000
8000
10000
12000
14000
16000
18000

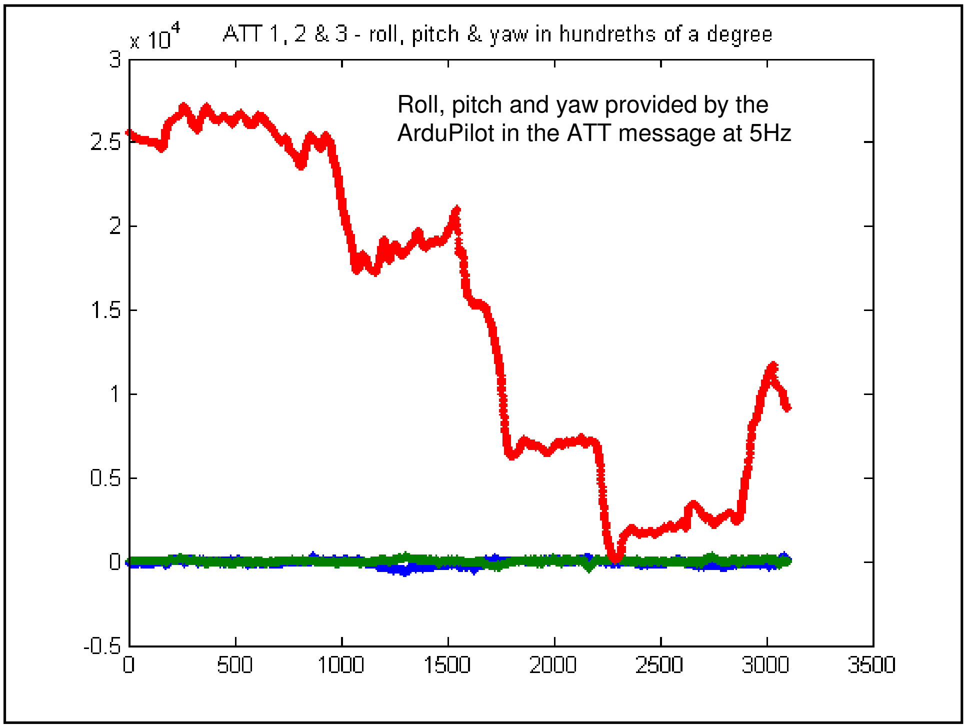

roll, pitch, yaw
Detail of roll and pitch
15
10
5
0
-5
-10
-15
0
2000
4000
6000
8000
10000
12000
14000
16000

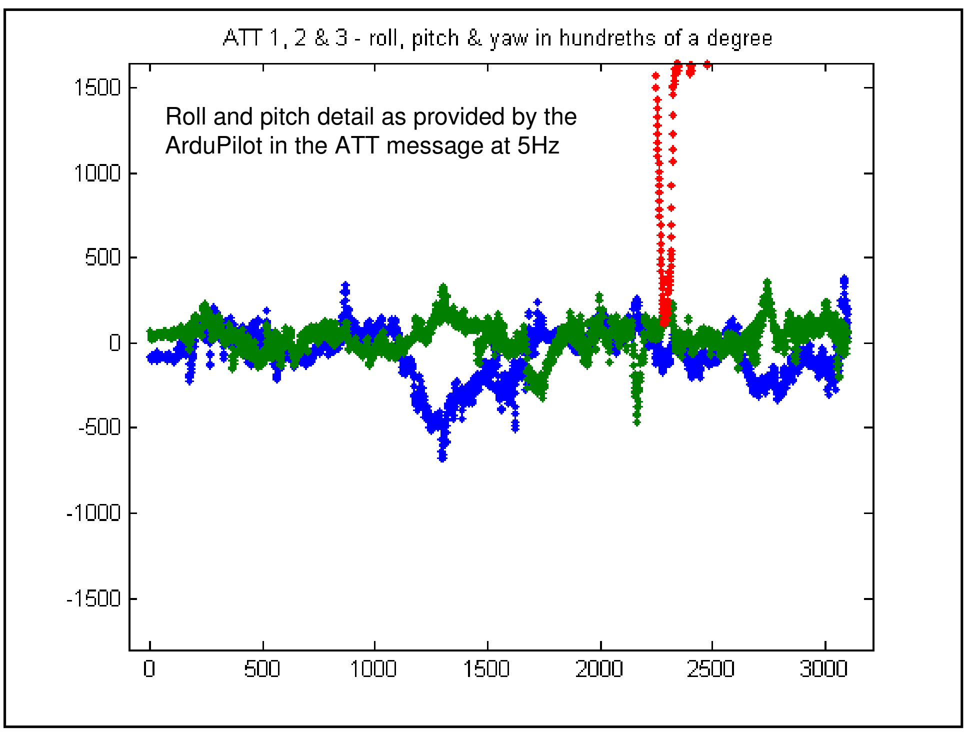

accelerometer biases
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
Accelerometer biases computed in the Kf. These are ~5x larger than those of a tactical-grade MEMS accelerometer.


x 10^-3
gyro biases
2
1.5
1
0.5
0
-0.5
-1
-1.5
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
Gyro biases computed in the Kf. These are 15-20x larger than those of an aviation grade FOG.


sqrt diag P position
Position errors (1 SD) in ECEF reference frame. Raw GPS positions are given 2m (1 SD) errors in each axis.
0.8
0.75
0.7
0.65
0.6
0
2000
4000
6000
8000
10000
12000
14000
16000


sqrt diag P
Errors (1 SD) of all 15 states: 3 position, 3 velocity, 3 attitude, 3 gyro, 3 accelerometer
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
2000
4000
6000
8000
10000
12000
14000
16000
18000


ATT 1, 2 & 3 - roll, pitch & yaw in hundreths of a degree
x 10^4
Roll, pitch and yaw provided by the
ArduPilot in the ATT message at 5Hz
3
2.5
2
1.5
1
0.5
0
-0.5
0
500
1000
1500
2000
2500
3000
3500


ATT 1, 2 & 3 - roll, pitch & yaw in hundreths of a degree
Roll and pitch detail as provided by the
ArduPilot in the ATT message at 5Hz
1500
1000
500
0
-500
-1000
-1500
0
500
1000
1500
2000
2500
3000

Comments

- The appearance of the raw gyro and accelerometer data is similar in character (if not RMS) to higher grade sensors
- The (almost) unmodified Kf will process GPS Doppler velocity, but that observation, which is independent of code pseudo-range positions and which improves results, is not provided by the onboard GPS
- The Kf can be modified to solve for sensor scale factors (in addition to biases), but that may be overkill with MEMS devices of this quality
- The track details exhibit a lagging responsiveness in the IMU due, in part, to slow data rates: 5Hz for GPS and 50Hz for IMU
- The tuning of the Kf (selection of *a priori* errors) also affects responsiveness
- This Kf was tuned to achieve steady states for the IMU sensor biases
- GPS was given SDs of 2m in each axis
- Resulting position errors are 70-75cm in each axis
- The Kf-derived height, roll, pitch and yaw appear to be better defined (less RMS noise) than the onboard results, but this may be due to the higher frequency of the IMU than the ATT message
- A more stable platform than a pair of hands (e.g. rigid mounting in a vehicle or vessel) provides better results
- Nevertheless, it works!

Appendix: Recorded Raw Data

```
GPS,76471, 422606000, 10, 29.6365880, -95.5680083, 21.0100, 21.1500, 1, 35235
IMU,76477,0.0002, -0.0006, 0.0019, 0.0056, 0.0096, -9.8100
IMU,76482,0.0002, -0.0004, 0.0017, -0.0088, 0.0024, -9.7956
IMU,76487,0.0007, -0.0006, 0.0017, -0.0154, 0.0156, -9.8190
IMU,76493,0.0007, -0.0001, 0.0011, -0.0160, 0.0270, -9.7926
IMU,76498,0.0012, -0.0001, 0.0006, -0.0064, 0.0054, -9.8118
ATT,76504, -23, -20, 15827
GPS,76506, 422606000, 10, 29.6365880, -95.5680083, 20.9400, 21.1500, 1, 35235
IMU,76513,0.0012, -0.0006, 0.0006, -0.0124, -0.0221, -9.8166
IMU,76518,0.0015, -0.0006, 0.0006, -0.0172, -0.0269, -9.7986
IMU,76523,0.0015, -0.0004, 0.0006, -0.0040, -0.0293, -9.7849
IMU,76528,0.0002, -0.0006, 0.0014, -0.0058, -0.0305, -9.8106
IMU,76533,0.0007, -0.0012, 0.0017, 0.0038, -0.0341, -9.8291
ATT,76538, -67, 4, 15830
GPS,76540, 422606200, 10, 29.6365880, -95.5680085, 21.0100, 21.1700, 23, 35235
IMU,76548,0.0012, 0.0002, 0.0017, 0.0073, -0.0209, -9.8238
IMU,76553,0.0004, 0.0004, 0.0025, 0.0265, -0.0065, -9.8064
IMU,76558,-0.0004, 0.0004, 0.0011, 0.0367, 0.0132, -9.8244
IMU,76563,0.0010, 0.0004, 0.0001, 0.0265, 0.0276, -9.8118
IMU,76568,0.0015, 0.0004, -0.0005, 0.0253, 0.0204, -9.7801
ATT,76573, -85, 16, 15833
GPS,76575, 422606200, 10, 29.6365880, -95.5680085, 21.0500, 21.1700, 23, 35235
IMU,76582,-0.0004, -0.0004, -0.0005, 0.0175, 0.0012, -9.7998
IMU,76588,-0.0006, -0.0001, -0.0002, 0.0032, -0.0095, -9.8028
IMU,76593,-0.0001, -0.0020, 0.0006, 0.0097, -0.0065, -9.8166
IMU,76598,0.0018, -0.0004, 0.0009, -0.0016, -0.0107, -9.8016
IMU,76603,0.0020, 0.0007, 0.0017, -0.0268, -0.0137, -9.7998
ATT,76609, -84, 22, 15837
```