Better Aircraft Positioning for Airborne Gravimetry:
Results from GRAV-D's "Kinematic GPS Challenge" Issued to the GPS Community

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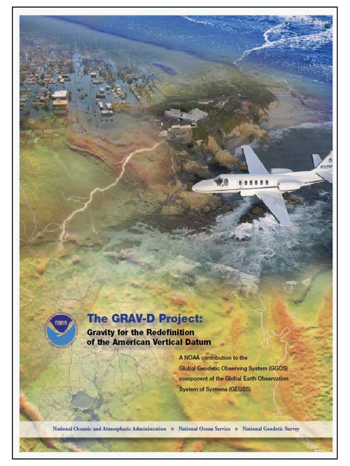
1. What is GRAV-D?

The GRAV-D (Gravity for the Redefinition of the American Vertical Datum) Project of the U.S. National Geodetic Survey plans to collect airborne gravity data across the entire U.S. and its holdings over the next decade. The goal of the project is to create a gravimetric geoid model to use as the national vertical datum by 2021.



It is NGS' mission to define and maintain a spatial reference system for the U.S. Part of this mission is to provide access to heights useful for measuring water flow (particularly for flood hazard estimation) and for construction/transportation projects. Based on current errors and requirements in the era of GPS, a new datum with 1-2 cm accuracy is needed.

The project plan and more details are available: http://www.ngs.noaa.gov/GRAV-D

2. Kinematic GPS Challenge

To achieve the best airborne gravity data accuracy possible, the GPS position solutions must provide not just accurate and precise positions, but accurate and precise velocities and accelerations to be used in calculating gravity corrections. To our knowledge, no head-to-head comparisons have been done of available kinematic processing techniques with a focus on producing good airborne gravity results.

ORIGINAL GOALS:

1. 0.5 mGal or less two-sigma values (precision) for free-air disturbances calculated with different GPS position solutions, but the same gravity processing.

2. Close comparisons to EGM08 (accuracy), the best available global gravity model (Pavlis, et al., 2010), in an area where EGM08 is well-constrained.

Thus, in Fall 2010 the National Geodetic Survey announced the "Kinematic GPS Challenge" to the entire GPS community. The Challenge solicited position solutions for two GRAV-D airborne gravity flights done in Louisiana in Fall 2008. The flights are described in the data section below. The response of the community was outstanding, with some groups submitting multiple solutions:

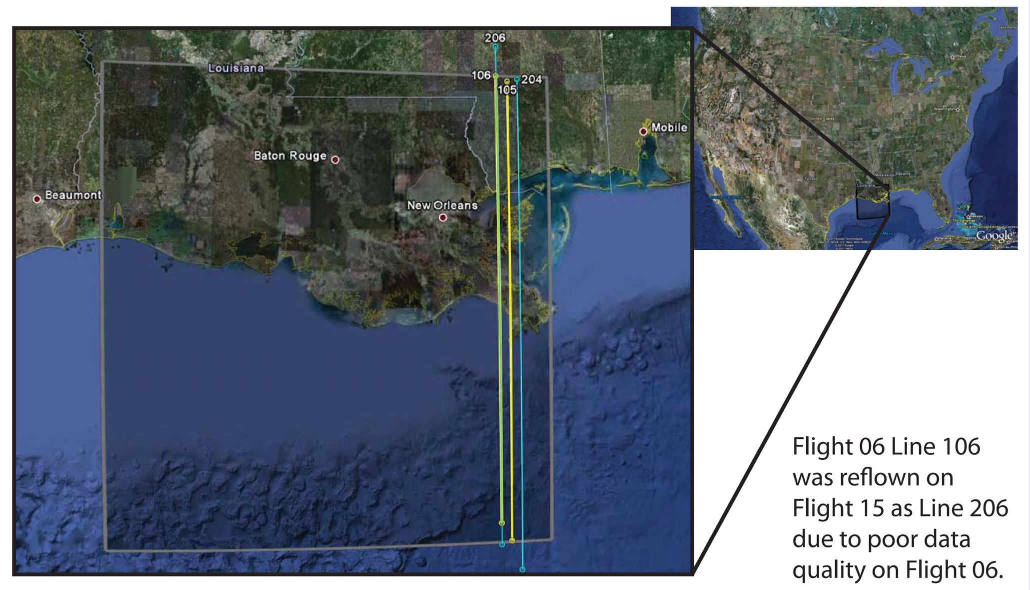
Participating groups: 10 Solutions for each flight: 16 Total solutions (for 4 gravity lines): 64

GPS processing types span the range of differential and PPP solutions, with different methods developed by each group. The results are presented anonymously here (each solution presented with a unique f## designator rather than the software's & developer's names), protecting the GPS participants while they discuss these results but allowing the airborne gravity community to benefit from the early conclusions.

3. Challenge Data

Data Block Name	CS02
Location	Eastern Louisiana
Gravimeter	Micro-g LaCoste TAGS
Aircraft	NOAA Cessna Citation II
Altitude	35,000 ft/10 km
Data Line Spacing	10 km
Datums	WGS84 and ITRF00
Public Release Date	February 2012

Flight Number	F06	F15
Date Completed	23 Oct 2008	19 Nov 2008
Lines Flown	105, 106	204, 206
Color on Map	Yellow	Cyan



Flight 06 Line 106 was reflown on Flight 15 as Line 206 due to poor data quality on Flight 06.

7. References

Pavlis, Nikolaos (2010). "Earth Gravitational Model 2008 (EGM2008)." Online: http://earth-info.nga.mil/GandG/wgs84/gravitymod/egm2008/

Harlan, Raymond (1968). "Eotvos Corrections for Airborne Gravimetry." Journal of Geophysical Research, 73 (14), pp. 4675-4679.

Hackney, R. I. and W. E. Featherstone (2003). "Geodetic vs. geophysical perspectives of the 'gravity anomaly'." Geophysical Journal International, 154, pp. 35-43.

Peters, Mary F. and John M. Brozena (1995). "Methods to Improve Existing Shipboard Gravimeters for Airborne Gravimetry." Proceedings of the IAG Symposium on Airborne Gravity Field Determination, IUGG Assembly, Boulder, CO. pp. 39-45.

4. Tests and Methods

A. Ensemble, Quality, and EGM08

1. Calculate an "ensemble" gravity solution, which is the average of all free-air gravity disturbances (FAD) calculated from the submitted GPS Challenge position solutions.

2. Calculate the difference between the Ensemble average FAD and each individual Challenge FAD.

3. Determine the quality of the ensemble gravity solution by comparing with EGM08 and field-determined quality.

4. Calculate statistics to determine whether the gravity solutions meet the precision and accuracy targets of the GRAV-D project.

B. GPS-only vs. GPS+IMU Positions

1. Calculate the difference in the FAD gravity solution when an GPS+IMU (inertial measurement unit) loosely-coupled position solution is used, instead of a GPS-only.

2. Calculate statistics to determine which position solution produces a FAD most like the EGM08 FAD.

C. Analysis of Reflown Line (106/206)

1. Filter, at four reasonable filter lengths, the FAD of the original line (F06 L106) and its reflight (F15 L206) for each set of lines submitted by an individual Challenge participant. Then calculate the RMS Difference and Cross Correlation (%) of the two lines. This tests FAD repeatability. The two lines would be 100% correlated and have an RMS Difference of zero if they were perfectly flown and perfectly processed.

D. Gravity Correction Sensitivity Testing, GPS-only vs. GPS+IMU

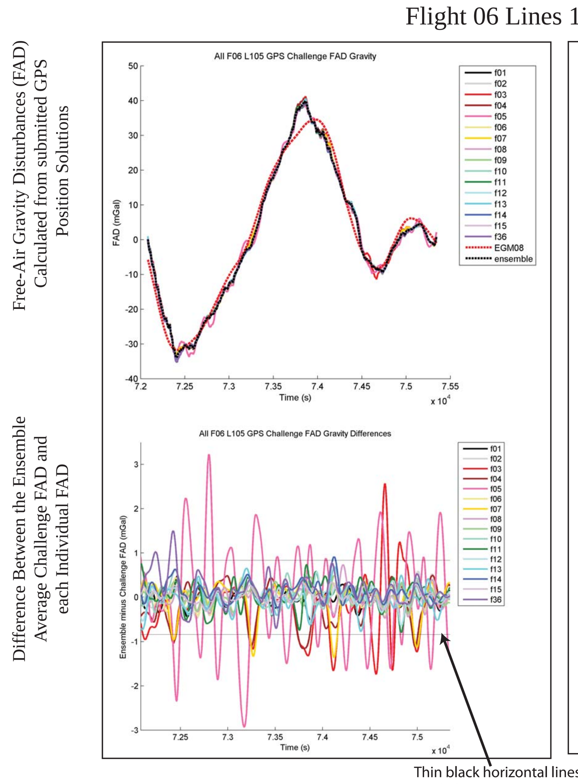
1. Filter all corrections applied to the airborne gravity data with the same 120 s filter.

2. Calculate the ensemble average of each of the gravity corrections for each of the submitted Challenge solutions:
  a. *Simple Eotvos Correction* (1st order approximation) from Harlan (1968). Commonly Used.
  b. *Vertical Acceleration Correction*, calculated using a 3-pt central difference discrete derivative applied twice.
  c. *Normal Gravity Correction*, also called Latitude Correction, Somigliana-Pizetti formula exact to 1 microGal (Hackney and Featherstone, 2003).
  d. *Offlevel Correction*, Peters and Brozena (1995).
  e. *Free-Air Correction*, 2nd order (Hackney and Featherstone, 2003)

3. Calculate the differences between GPS-only corrections and GPS+IMU correction, to see which corrections are most affected by the inclusion of IMU data.

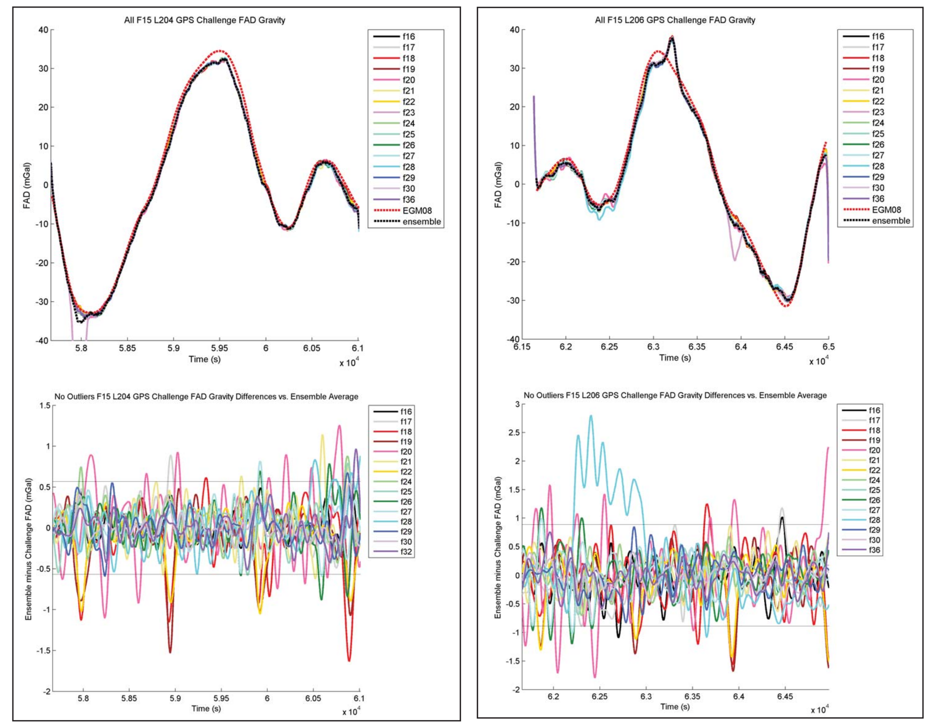
5. Results

Flight 06 Lines 105 and 106



Thin black horizontal lines on all plots mark the +/- 2-sigma (2 * Standard Deviation) values

Flight 15 Lines 204 and 206



Statistics

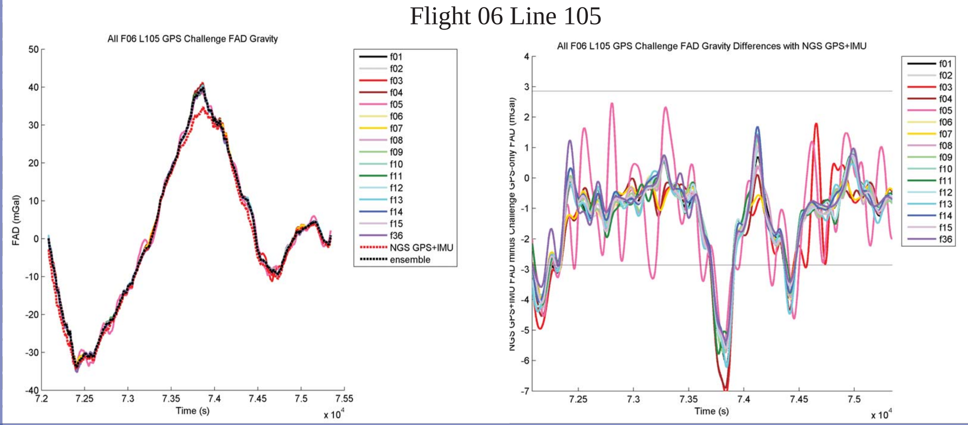
FAD Gravity Quality Determined in the Field and Statistics of Difference between EGM08 and Ensemble

Line Number	Minimum (mGal)	Maximum (mGal)	Mean (mGal)	Standard Deviation (mGal)	Field-Determined Quality
L105	-4.17	7.31	-0.28	2.68	Acceptable, Some Noise
L106	-7.58	8.70	-0.43	2.80	Poor, Very Noisy
L204	-5.19	7.42	-1.29	1.04	Excellent
L206	-4.41	7.77	-0.75	1.71	Very Good

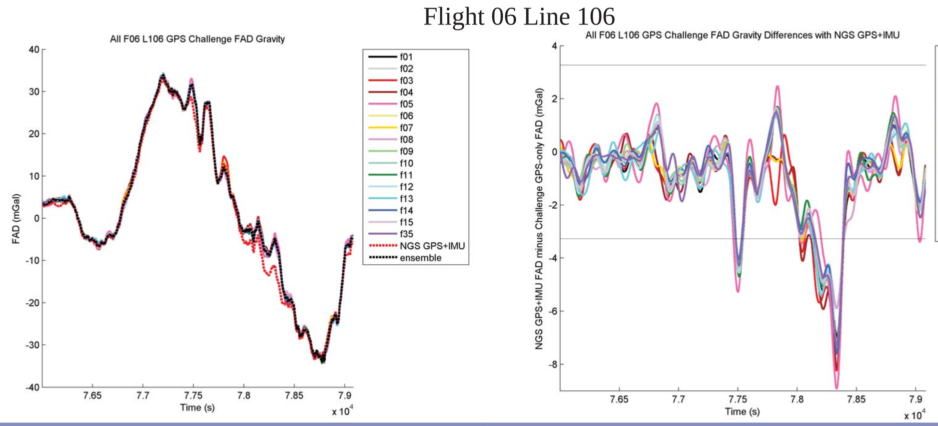
FAD Gravity Individual Solutions Compared to the Ensemble Average

Line Number	Standard Deviation of All (mGal)	Standard Deviation, No Outliers (mGal)	Outlier Solutions	Most Different from Average Solution (But Not Outliers)
L105	0.42	N/A	N/A	f03, f05, f36
L106	0.35	N/A	N/A	f03, f04, f05, f07, f15
L204	1.71	0.24	f23	f18, f19, f20, f22
L206	0.56	0.44	f23	f19, f18, f20, f22, f28

Flight 06 Line 105

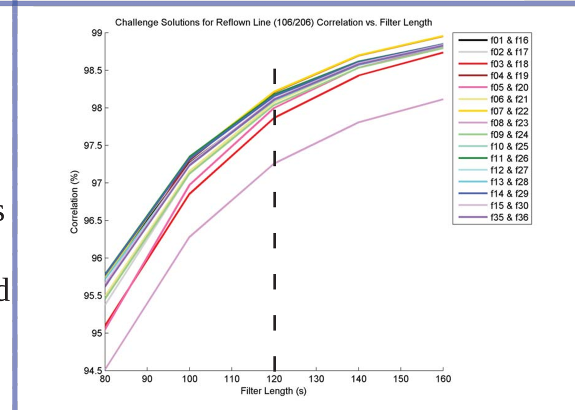


Flight 06 Line 106



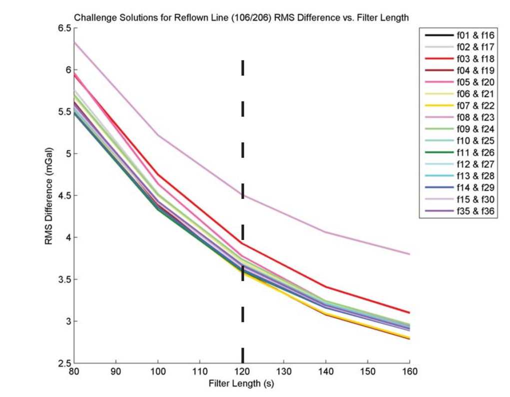
Statistics

Line Number	Comparison	Min (mGal)	Max (mGal)	Mean (mGal)	Std Dev (mGal)
L105	(NGS GPS+IMU)-EGM08	-5.329	2.944	-1.6248	1.5424
L105	Ensemble-EGM08	-4.173	7.3122	-0.2842	2.6782
L105	Ensemble-(NGS GPS+IMU)	-0.7738	5.7965	1.3406	1.3657
L106	(NGS GPS+IMU)-EGM08	-8.1974	6.0649	-1.4826	2.1009
L106	Ensemble-EGM08	-4.173	7.3122	-0.2842	2.6782
L106	Ensemble-(NGS GPS+IMU)	-1.1474	7.4421	1.0522	1.5967



For both plots, the dashed vertical black line indicates the triple time-domain Gaussian filter length (120 s) used for all other analyses. 120 s is the smallest reasonable filter that gives good noise suppression on the less turbulent flight (F15). Longer filter lengths are expected to further smooth the data (especially for the more turbulent flight, F06) and provide a better overall match between the reflown lines.

However, some processing packages improve more than others at longer filter lengths; the best ones yield the highest correlation percentages and the lowest RMS Differences.



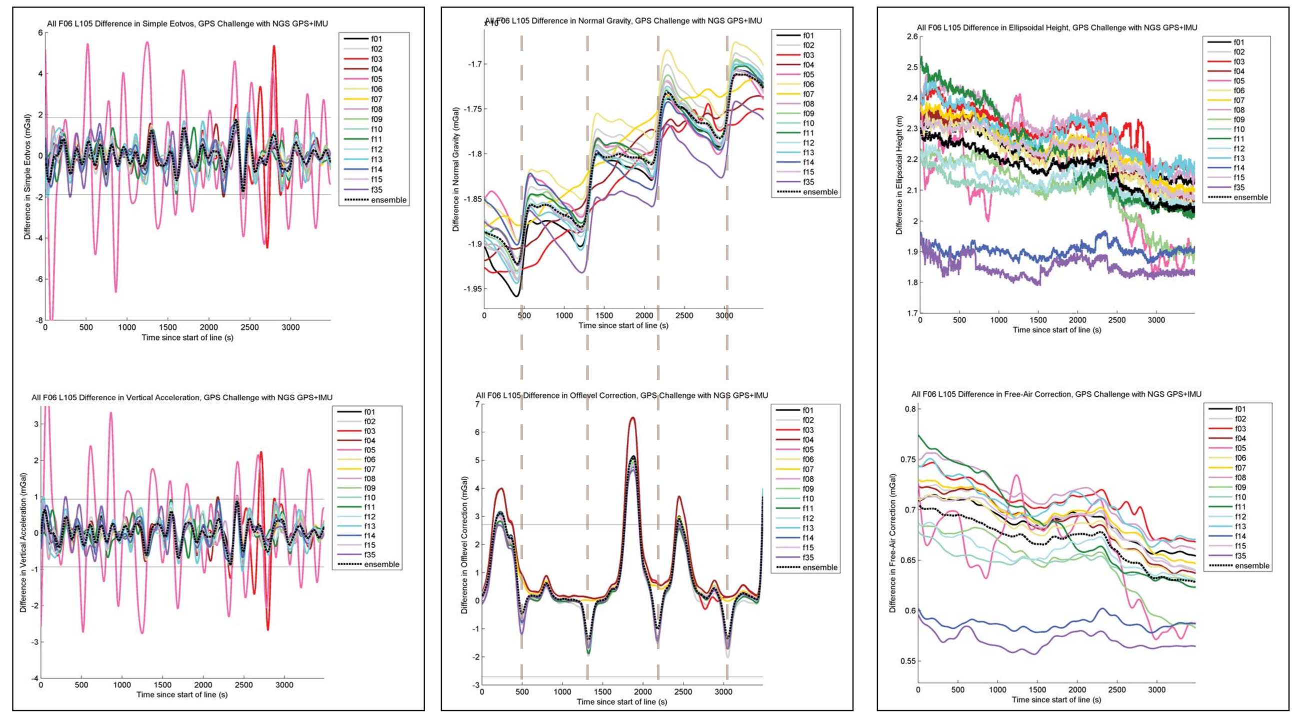
Statistics

Three Pairs of Solutions with the Best Match, by Filter Length

Filter Length	Solution 1	Solution 2	RMS Difference (mGal)	Correlation (%)
120	f07	f22	3.58	98.2142
120	f04	f19	3.59	98.2063
120	f11	f26	3.6	98.1768
140	f07	f22	3.09	98.6986
140	f04	f19	3.08	98.6957
140	f11	f26	3.16	98.6168
160	f07	f22	2.8	98.9558
160	f04	f19	2.79	98.9537
160	f02	f17	2.9	98.8571

Three Pairs of Solutions with the Worst Match, by Filter Length

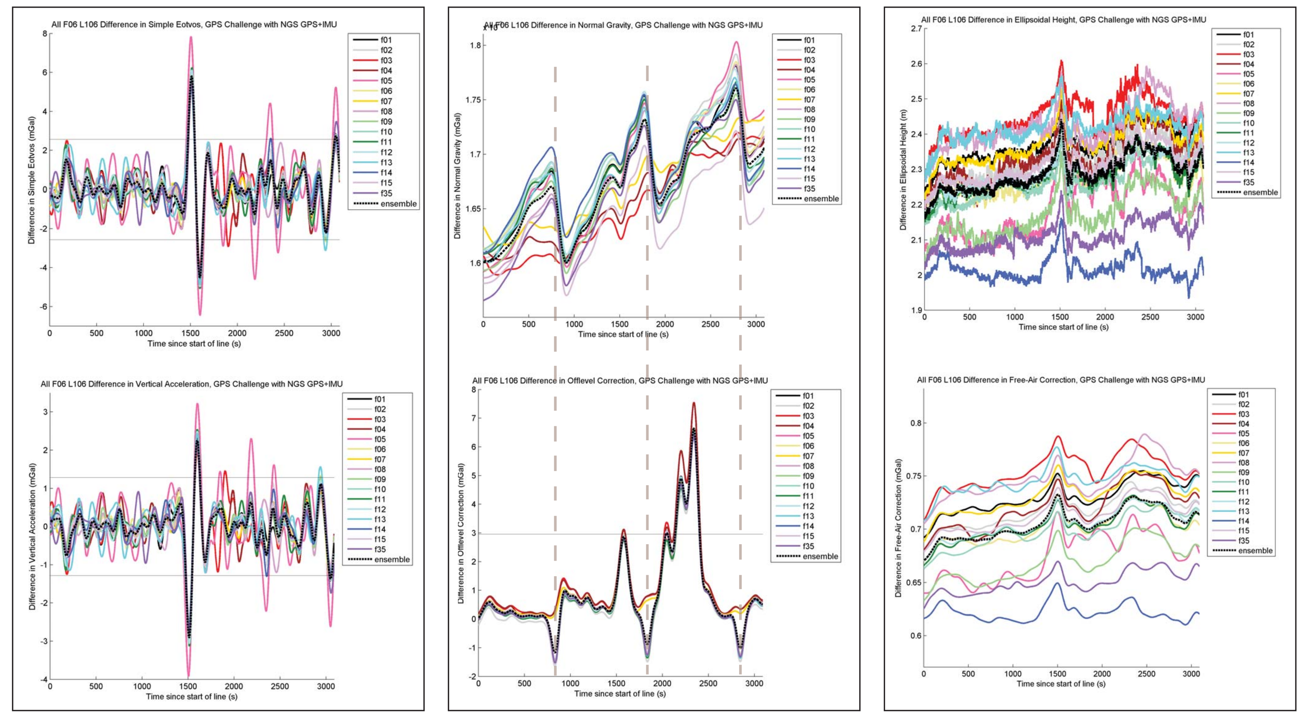
Filter Length	Solution 1	Solution 2	RMS Difference (mGal)	Correlation (%)
120	f05	f20	3.78	97.9976
120	f03	f18	3.93	97.8642
120	f08	f23	4.51	97.257
140	f09	f24	3.24	98.5315
140	f03	f18	3.41	98.4295
140	f08	f23	4.06	97.8053
160	f09	f24	2.96	98.7918
160	f03	f18	3.1	98.7345
160	f08	f23	3.8	98.1115



Flight 06 Line 105

Statistics for Challenge GPS-only Ensemble Minus NGS GPS+IMU), by Correction

Correction	Min (mGal)	Max (mGal)	Mean (mGal)	Std Dev (mGal)
Offlevel Correction	-1.40	5.07	0.73	1.32
Simple Eotvos Correction	-1.75	1.75	-0.02	0.57
Vertical Acceleration Correction	-0.88	0.87	0.01	0.28
Full Eotvos Correction	-0.87	0.88	-0.01	0.28
Free-Air Correction	0.63	0.71	0.67	0.02
Normal Gravity	0.00	0.00	0.00	0.00



Flight 06 Line 106

Statistics for Challenge GPS-only Ensemble Minus NGS GPS+IMU), by Correction

Correction	Min (mGal)	Max (mGal)	Mean (mGal)	Std Dev (mGal)
Offlevel Correction	-1.17	6.62	0.88	1.46
Simple Eotvos Correction	-4.51	5.81	0.04	1.16
Vertical Acceleration Correction	-2.91	2.26	-0.02	0.58
Full Eotvos Correction	-2.25	2.90	0.02	0.58
Free-Air Correction	0.67	0.73	0.71	0.01
Normal Gravity	0.00	0.00	0.00	0.00

6. Conclusions

1. There is one FAD for F15 that is an obvious outlier (f08), but the rest cluster well. The outlier may be due to a timing issue. A few FADs are different from the others, notably f04/f19, f05/f20, and f07/f22 that follow each other most closely.

2. With the outlier removed, the precision of the Challenge FADs meets or comes close to meeting the 0.5 mGal 2-sigma precision goal.

3. The calculated statistical qualities of the gravity solutions, when compared to the best available global gravity model, agree with the expected qualities from field observations.

1.The GPS+IMU solution is consistently, statistically much closer to the global gravity model, based on standard deviations.

2. GPS-only solutions are not adequate for GRAV-D accuracy requirements; combined GPS+IMU solutions are needed.

1. The same three solutions that stood out as different in Test A are two of the best and one of the worst in terms of repeatable gravity solutions.

2. The majority perform equally well for repeatability, with some notable exceptions for the worst.

1. Corrections most affected by the lack of IMU data are the Offlevel Correction, Eotvos Corrections (Simple and Full), and Vertical Acceleration Correction.

2. The magnitude of the differences between using and not using IMU data are very large and indicate that GPS+IMU solutions are required for accurate airborne gravimetry.

3. Although there is statistically zero difference to the normal gravity calculation, the differences have large slopes that indicate horizontal positioning sensitivity (resets?), since latitude is the only variable used here. This impacts the off-level correction. However, three solutions (f07, f04, and f03) are a close match to the GPS + IMU solution and do not have the problem.

4. Line 105's ellipsoidal height and free-air correction show that most solutions have a slope (two do not) that is not in the GPS+IMU solution. Biases and slopes are very important to remove for geodetic uses.