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Simulations of the Ocean Calibration Approach for Correcting for Spurious Accelerations

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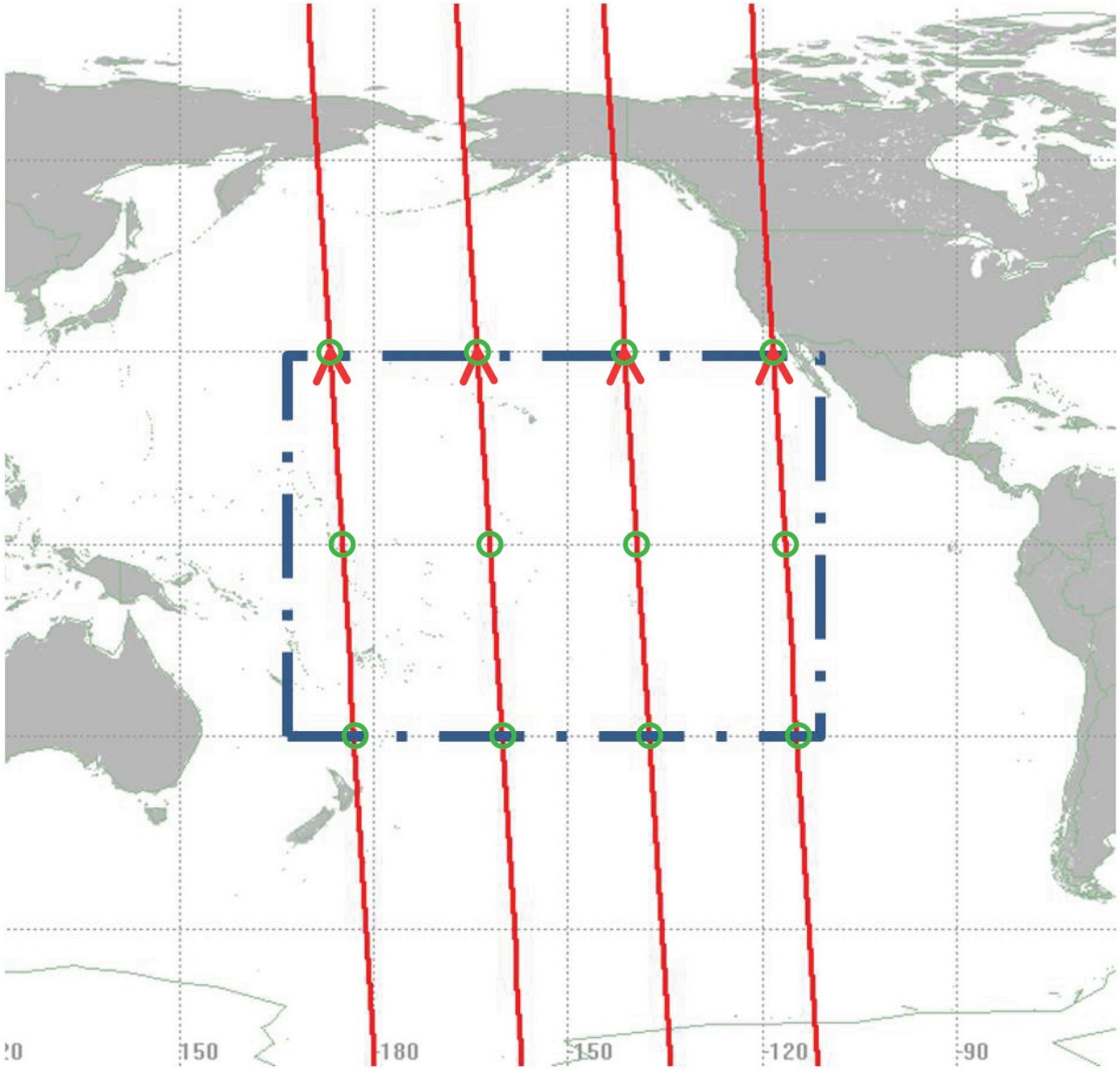
Empirical Parameter Corrections

- Because of spurious accelerations of the GRACE satellites and other possible error sources, empirical corrections to the relative accelerations or velocities are usually made about once every two revolutions.
- These corrections usually include once/rev accelerations, a constant term, and possibly other terms.
- In determining the empirical parameters for these corrections, the best available models from other data sources for geopotential variations along the orbits are used.
- However, whatever errors there are in the geopotential time-variation models used will effect the GRACE results through the resulting errors in the empirical parameters and through the incompleteness of the fitting procedure.

Satellite Ground Tracks Across the Central Pacific



Ocean Calibration Approach

- For the GRACE follow-on mission, the spurious acceleration noise is expected to be reduced by a factor 3 or more. However, some form of empirical correction still will be needed.
- In the highly simplified analysis model we are using, the satellite separation varies only with the height of the geopotential at the satellite altitude, except for noise in the separation due to spurious accelerations. This model is based on the constant energy approximation.
- The uncertainties in the geopotential height variations over the central Pacific, and over portions of the Indian and Atlantic Oceans, are believed to be substantially less than over most of the rest of the globe. For this reason, the use of satellite separation data over these regions to calibrate out the effects of differential along-track spurious accelerations appears to be desirable.
- If arc lengths of 4 revolutions are used, the total time involved for the calibration procedure will be about 6.3 hours. Thus, for polar orbits, the changes in the geopotential heights at satellite altitude between crossings of the South Pole will be small. In view of this, including measurements at the South Pole in the calibration procedure seems useful.
- Thus it seems worthwhile to investigate whether the present empirical parameter correction approach can be replaced by a procedure where most of the weight in determining the correction is placed on comparisons of the measured satellite separation with the values expected at locations over the central Pacific, at a few points in the Indian and Atlantic Ocean, and at the South Pole.

Simulation of the Ocean Calibration Approach

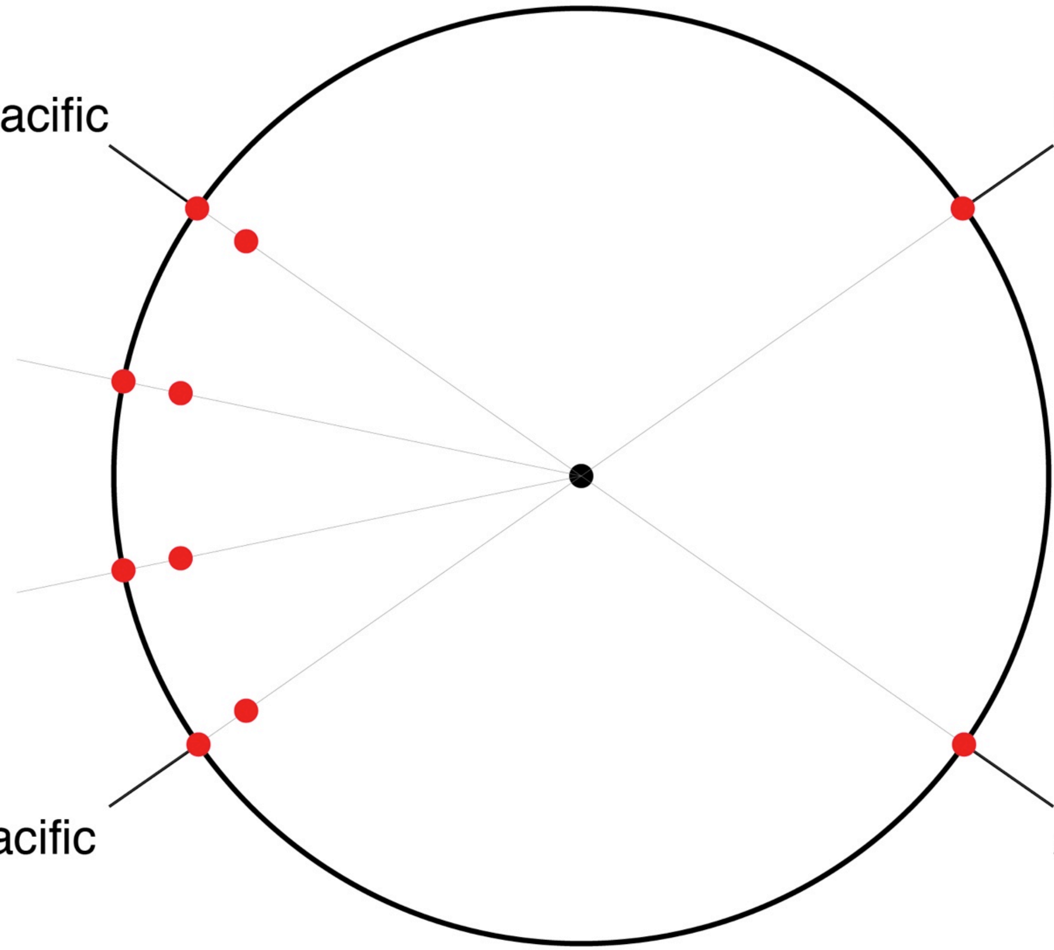
- For polar orbits, there are two times each day that 4 successive revolutions cross the central Pacific. The ocean calibration approach involves solving for a "correction function" based on comparing the satellite separations with those expected from the a priori geopotential variation data at a number of calibration points over favorable regions of the oceans and over the South Pole during these 4 revolution arcs.

- For each revolution, the data from the central Pacific is approximated by one point each at -30 deg, 0 deg, and +30 deg latitude. In addition, one measurement over the Indian Ocean during the 1st revolution and one over the Atlantic during the 4th revolution usually can be included. With 5 South Pole crossings, this gives 19 measurement points during the 4 revolutions.

- For 100 km satellite separation, the errors in the satellite separation variations due to the errors in the a priori geopotential height variation data will be about a factor 70 less.

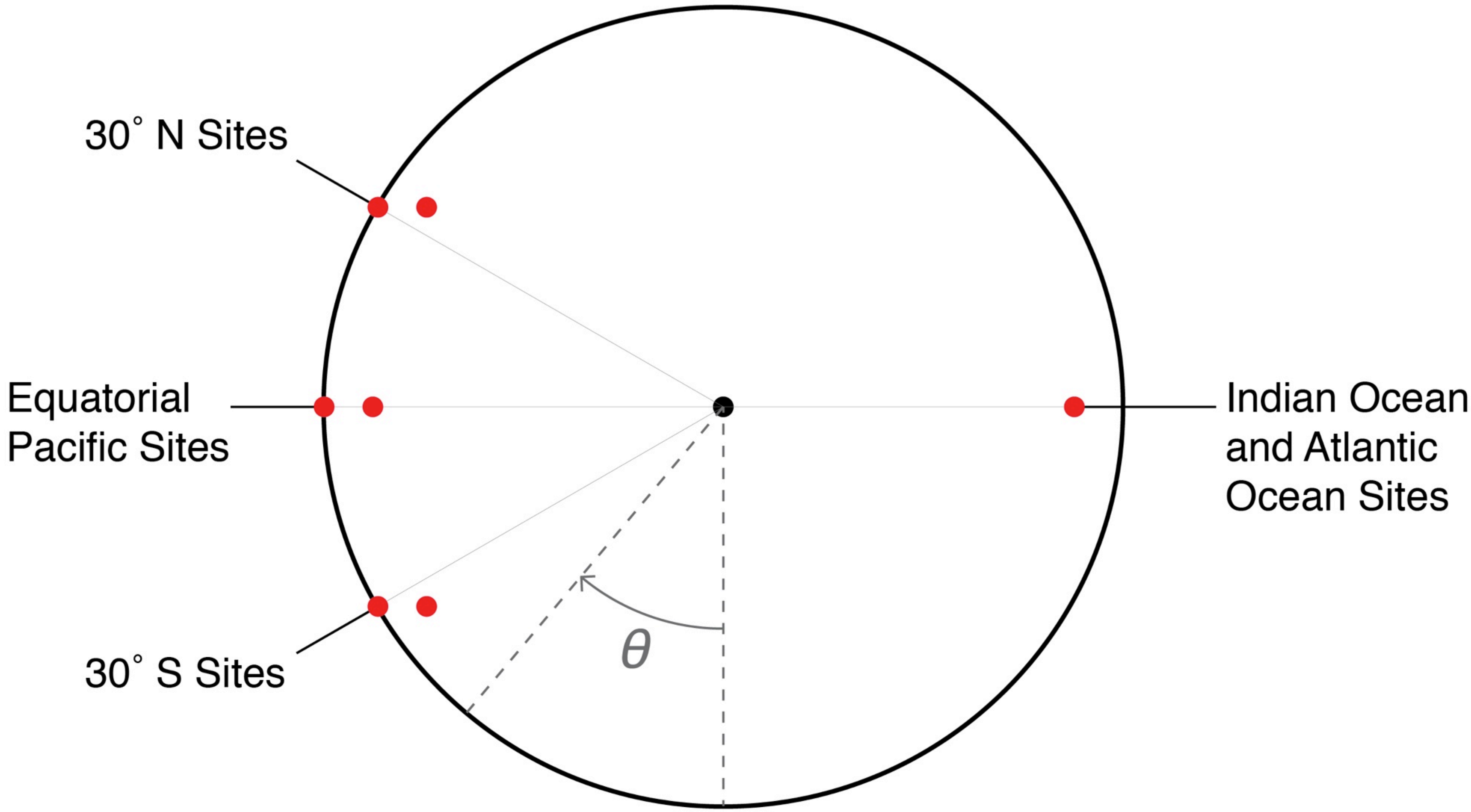
- Thus for a 1 mm contribution to the uncertainty in the geopotential heights, the corrections to the satellite separation need to be fit to about 15 microns.

Distribution of Calibration Sites in Longitude



View from above the North Pole
of the Earth.

Geometry for Determining *cosθ* Variation in the Satellite Separation over 6 Hour Periods



View from perpendicular to the satellite orbit plane
(θ = angular separation from the South Pole)

Model for Fitting Spacecraft Separation Noise due to Spurious Accelerations

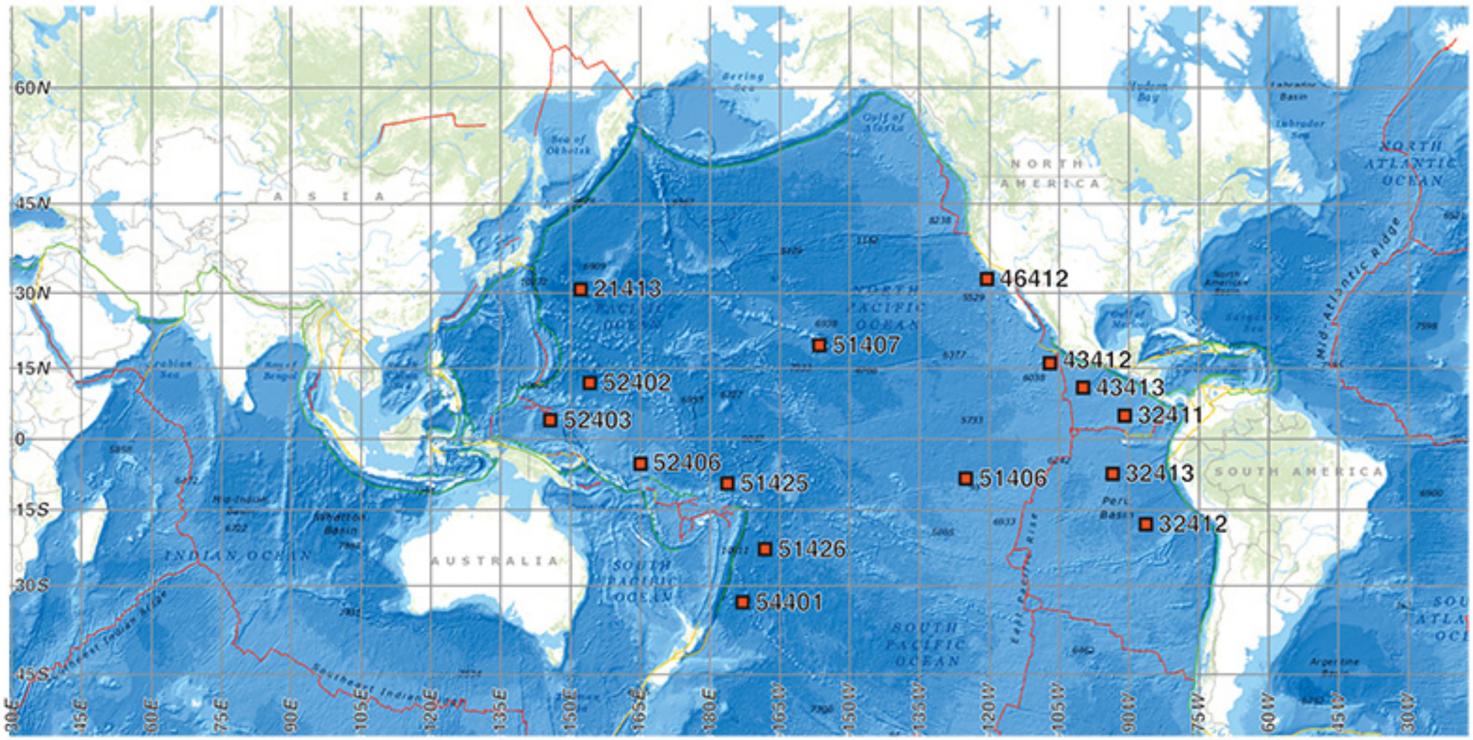
- Based on:
  - 3.3 x 10^{-11} m/s^2/√Hz acceleration noise above 5 mHz, and increasing as 1/√f at lower frequencies.
  - With approximate allowance for resonance
- Separation noise amplitudes in 1/8 cycle/revolution frequency bands:
  - Rising from 40 microns at 1.75 cy/rev to 0.6 mm at 1 cy/rev
  - Only changing slowly from 1 to 0.5 cy/rev
  - Increasingly rapidly to 5 mm at 0.25 cy/rev and at lower frequencies
- Basis functions that are being fit to observations at the calibration sites:
  - Constant and linear terms
  - Sines and cosines of 1, 7/16, 7/32, and 3/128 cycles/revolution
  - Constant offset at 5 South Pole crossings

Current Simulation Limitations from the Spurious Acceleration Noise Model

- RMS errors in geopotential height variations at 500 km altitude during the 4 revolutions, but on the side of the orbit away from the Pacific, in mm.

	1^{st} Rev.	2^{nd} Rev.	3^{rd} Rev.	4^{th} Rev.
60° N. Lat.	1.2	1.8	3.1	0.9
30° N. Lat.	1.1	2.2	3.4	0.8
30° S. Lat.	1.0	2.2	2.9	1.2
60° S. Lat.	1.8	1.8	2.1	0.8

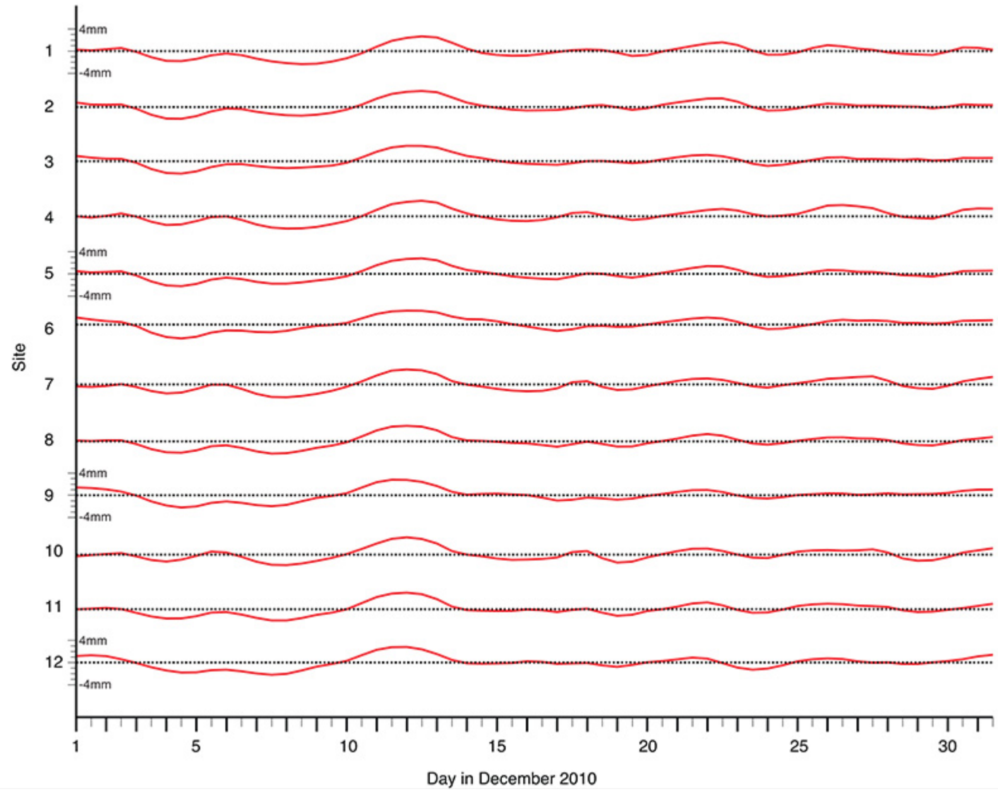
- Overall RMS value: 1.9 mm



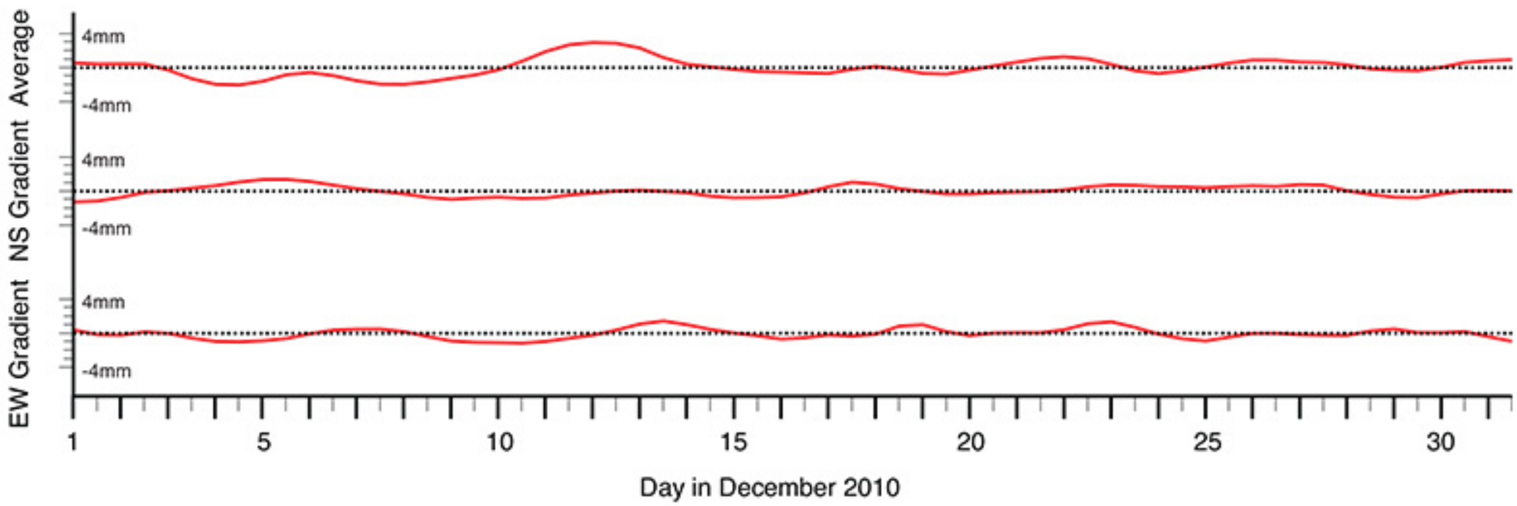
Locations of the NOAA Deep-ocean Assessment and Reporting of Tsunamis (DART) ocean bottom pressure gauges used in the comparison with values from the ECCO-JPL ocean model.

Comparison of ECCO-JPL and DART Results for Ocean Bottom Pressure Variations from Mean for December, 2010

- Sites compared: 15 sites in the Pacific between -30^{o} and $+30^{o}$ latitude
- RMS variations at DART sites: 1.6 cm H_20
- RMS variations at ECCO sites: 0.93 cm H_20
- Correlation coefficients: 0.38 to 0.85; mean = 0.57



Variations at the 12 calibration sites in the geopotential height at satellite altitude from the ECCO-JPL ocean model.



Variations in three statistical quantities based on the geopotential height variations from prior slide figure. These quantities are: (1) the mean variations for the 12 calibration sites; (2) a measure of the variations in the N-S gradient across the 12 sites; and (3) a measure of the variations in the E-W gradient (see text).

Ad Hoc Model for Geopotential Height Data Errors at Altitude at Calibration Sites

Pacific sites	
Uniform error at 12 sites:	2 mm
Random error at sites:	2 mm
Linear N-S gradient: 30^{o}N – 30^{o}S:	1.5 mm
Linear E-W gradient: 1st rev – 4th rev	1.5 mm
Random errors at Indian Ocean and Atlantic Ocean sites:	3 mm
Random errors at South Pole crossings due to time variations:	1 mm

(A 2 mm geopotential height error at 500 km altitude corresponds to a 1 cm error in water height over a 78^{o} radius region.)

Limitations from Geopotential Height Variation Uncertainty Model

- RMS errors in geopotential height variations at 500 km altitude during the 4 revolutions, but on the side of the orbit away from the Pacific, in mm.

	1st Rev.	2nd Rev.	3rd Rev.	4th Rev.
60^o N. Lat.	0.74	0.93	0.84	0.74
30^o N. Lat.	0.62	0.87	0.81	0.62
30^o S. Lat.	0.59	0.77	0.80	0.59
60^o S. Lat.	0.70	0.79	0.84	0.69

- Overall RMS value: 0.75 mm

Conclusions

- For the GRACE Follow-On Mission, the use of a new approach to correct for spurious accelerations of the spacecraft appears likely to limit errors in the geopotential height variations at satellite altitude to 3 mm or less during two 6-hour periods each day.
- This approach, called Ocean Calibration, would rely mainly on comparing the measured spacecraft separation variations with those given by an ocean model, such as ECCO-JPL.
- A model for geopotential height variations at 500 km altitude at calibration sites over the central Pacific based on the ECCO-JPL model has been established.
- The ECCO-JPL values of ocean bottom pressure variations have been compared with those from ocean bottom pressure gauges at 15 sites in the central Pacific for a one month period in 2010.
- Collaboration on improved simulations of the suggested approach would be welcome.