Development of an Interferometric Laser Ranging System for a Follow-On Mission to GRACE

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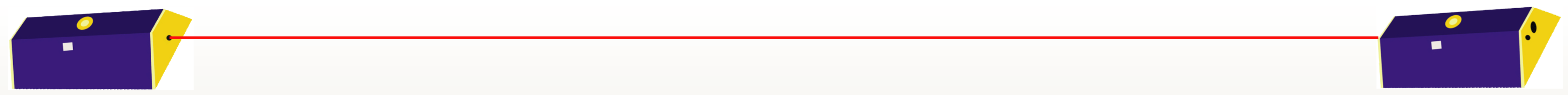


Abstract

The Gravity Recovery and Climate Experiment (GRACE) has ushered in a new era for satellite measurements of the Earth system. The tremendous advances made by GRACE have led to an interest in launching a follow-on mission with even better spatial resolution. The spatial resolution can be improved by improving the ranging performance, implementing a drag-free control system, and flying at a lower altitude. This presentation will focus on an effort, funded by NASA's Instrument Incubator Program, to develop an interferometric laser ranging system that we expect to perform near the 1 nm/sec level or better over 5 second intervals, which when coupled with other mission improvements, would improve the spatial resolution to ~100 km for 1 cm water equivalent accuracy. We report progress towards building an engineering model of the instrument, with which we will demonstrate its accuracy in the laboratory over the next few years. The laser system will range directly to the proof mass of the drag-free system, eliminating many of the difficulties associated with post-processing the accelerometer data on GRACE. In addition, we will show new results from our successful laboratory tests of the breadboard design in both ambient and vacuum conditions.

What limits GRACE?

- The GRACE measurement errors are limited at low frequencies by the accelerometer errors and at high frequency by the microwave phase noise.
- To get improved spatial resolution from space:
  - Must decrease phase noise, probably by moving from a microwave to an optical instrument
  - Should improve accelerometer for best performance
  - Flying at a lower altitude also is desired to improve performance
- Improvements in the geophysical models used in the data analysis are also needed.

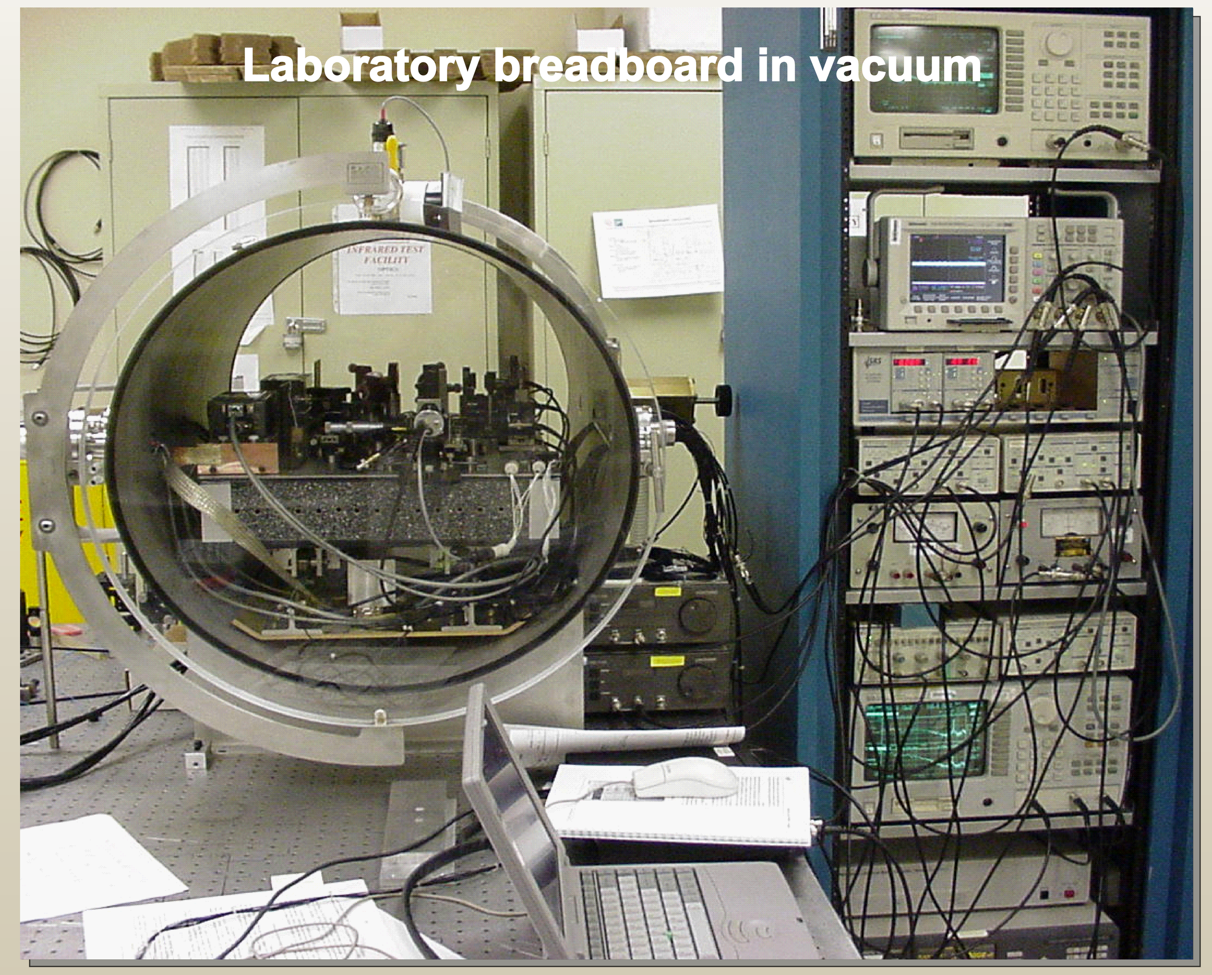
An improved GRACE mission

- Frequency stabilized laser interferometric ranging system (also eliminates multipath, RF interference)
- Improved Gravitational Reference Sensor coupled with direct ranging to the proof mass
- Drag-free propulsion using proportional electric thrusters
- Fly at a lower altitude (250-350 km) and possibly with a smaller spacecraft separation (50 km)
- Ranging performance improves from ~0.2 micron/sec to ~0.5 nm/sec for 5 second averages.
- Temporal gravity spatial resolution improves to ~100 km for 1 cm water equivalent accuracy.

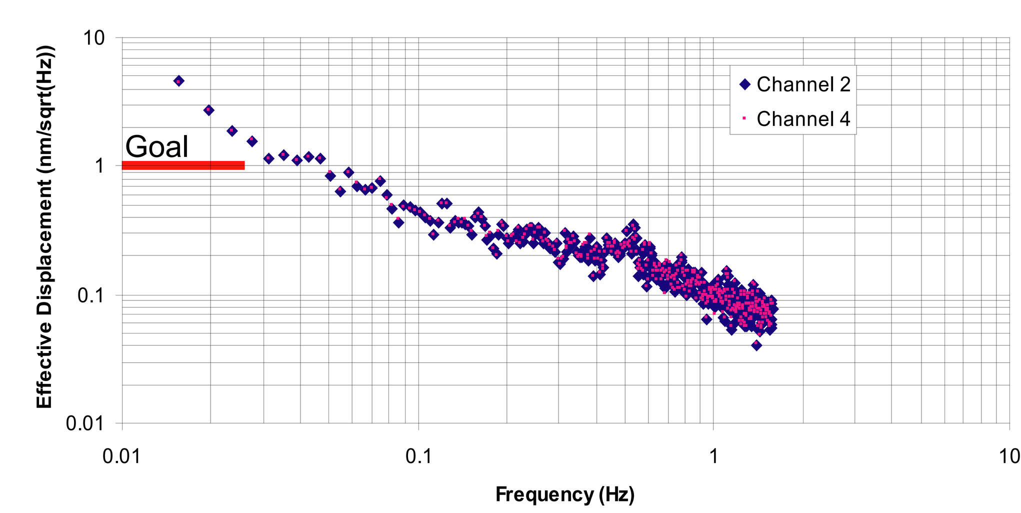
Investigation goals

- The goal of this investigation is to develop a laboratory demonstration of a laser interferometric ranging system suitable for a GRACE Follow-On mission.
  - Demonstrate a ranging measurement with 1 nm/sqrt (Hz) displacement sensitivity from 0.01 to 0.1 Hz
  - Demonstrate capability for pointing acquisition
- This work will include verifying the performance of the system relative to the science requirements, and environmental testing of the system sufficient for a rating of TRL 6.
- In addition, the performance of the system for recovering the gravity field will be ascertained through simulations using the instrument error budget and assumptions about the mission design.

Laboratory breadboard in vacuum



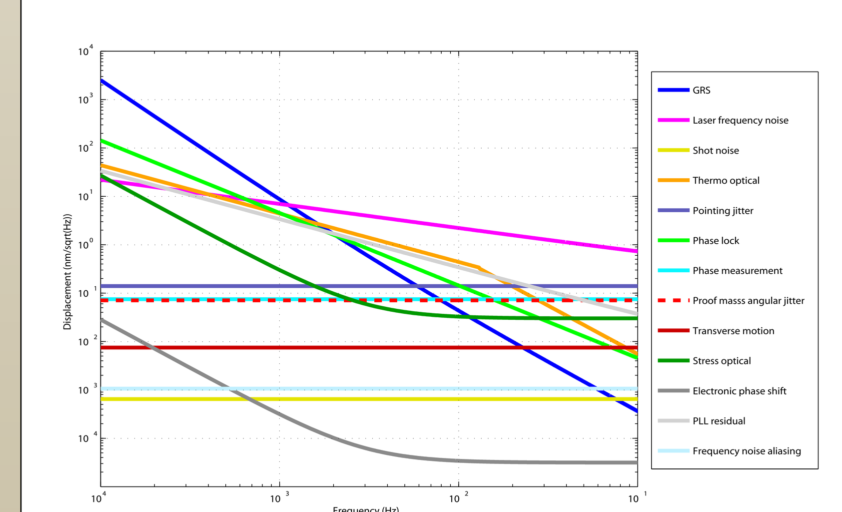
System (IRT) noise performance in vacuum



Instrument error sources considered

- Gravitational Reference Sensor (GRS) Noise
- Laser frequency noise
- Photodetector shot noise
- Thermo-optic effect
- Stress-optical effects
- Pointing jitter and wavefront distortion
- USO noise from phase lock
- Signal phase measurement error
- Angular jitter of the proof mass
- Transverse displacement of the proof mass

Power spectrum of errors



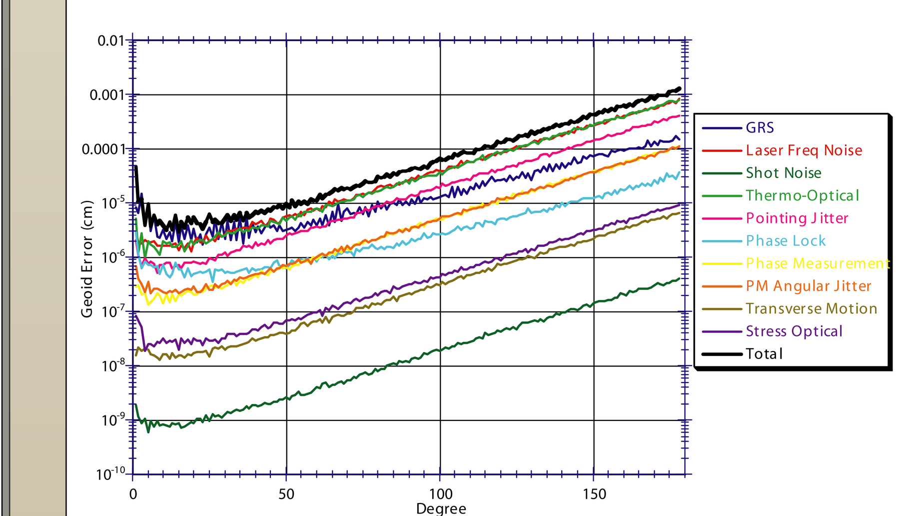
Geoid error simulation

$$\sigma_n^2(\delta N) = \frac{1}{1-P_n(\cos\theta)} \frac{R_e^3}{GM} \left(\frac{r}{R_e}\right)^{2n+1} \sigma_n^2(\delta\rho)$$

$\sigma_n^2(\delta\rho) =$ degree variance of range-rate errors
$\theta =$ spacecraft separation angle
$r =$ spacecraft orbit radius
$\sigma_n^2(\delta N) =$ geoid degree error variance

[Kim, 2000]

Geoid errors

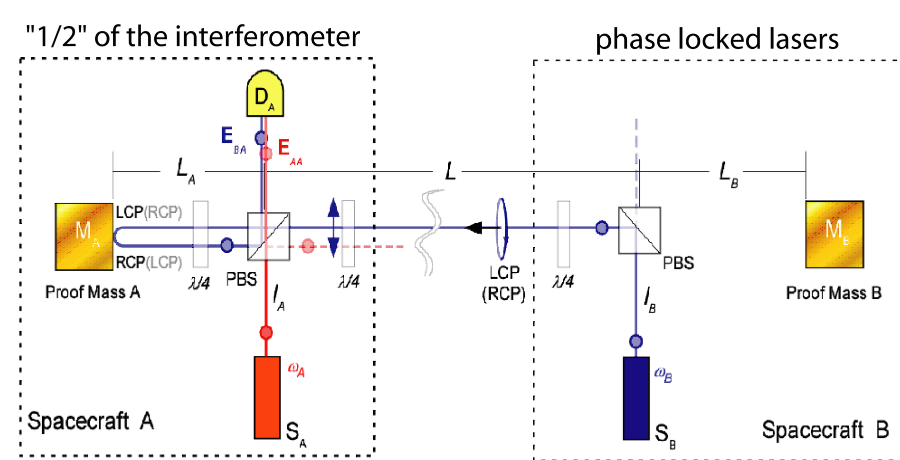


The Instrument

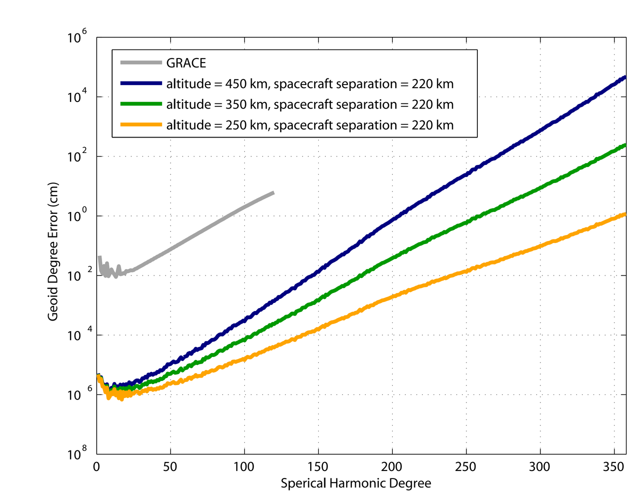
- Simple heterodyne interferometer - extremely simplified version of the LISA Design.
- The laser on Spacecraft 2 is phase-locked with an offset frequency to the laser on Spacecraft 1.
- Spacecraft pointing signal derived from quadrant photodiode at the output of the interferometer.
- Two flat mirrors to simulate proof masses of the GRS, one proof mass can actively rotate at radian level.
- JPL Blackjack receiver for measuring phase.
- We are not currently developing improved methods for laser frequency stabilization (cavity vs iodine, 2 vs 3 s/c, etc.).

Measurement Concept

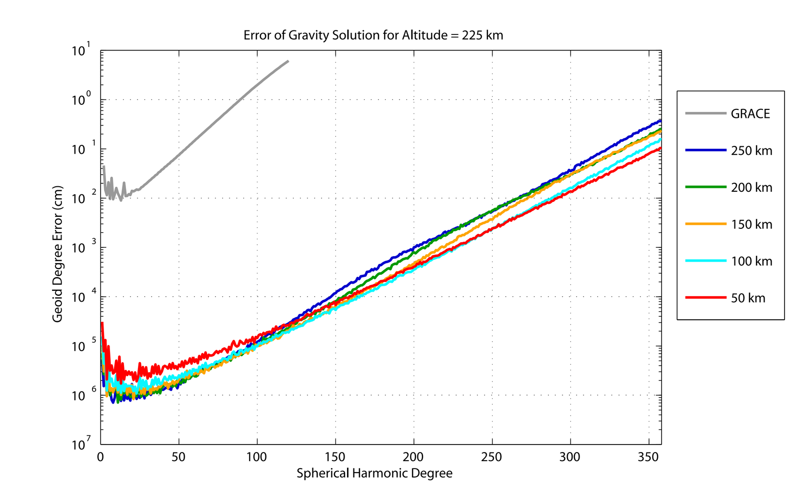
- Interferometric ranging between spacecraft
- Drag-free operation of each spacecraft
- Proof-mass-to-proof-mass measurement
- Laser B is phase-locked to Laser A (optical transponder)



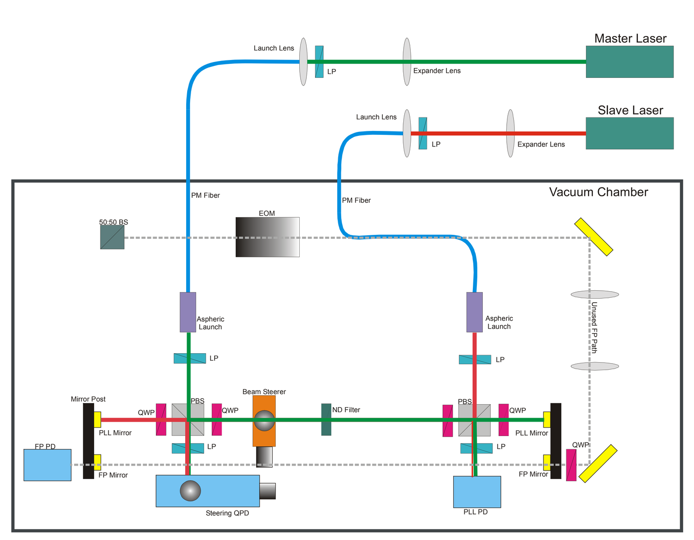
Geoid error for different mission altitudes



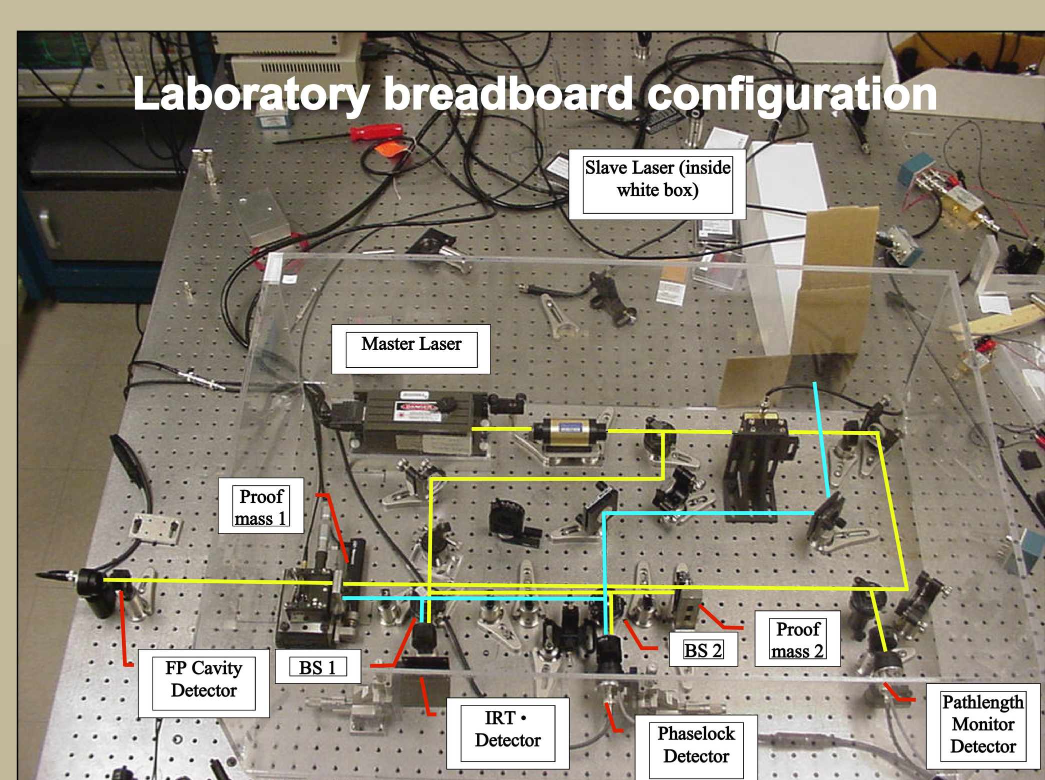
Geoid error for different spacecraft separations



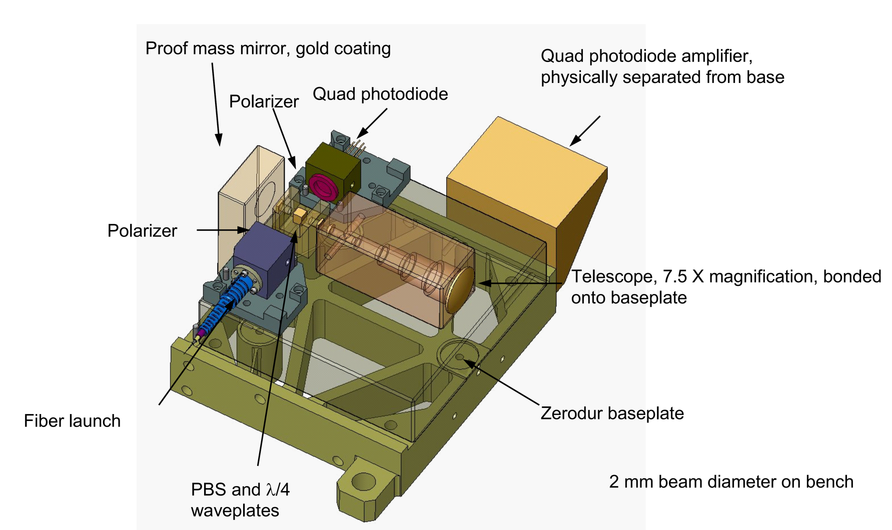
IRT breadboard design



Laboratory breadboard configuration



Brassboard concept



Current Status

- Investigation initiated in October 2003.
- Successfully completed Concept (3/2004) and Design (4/2004) Reviews.
- Breadboard is completed.
- Breadboard testing in vacuum chamber is completed.
- Brassboard preliminary design is completed.
- Test interferometer system in relevant space environment.
- Achieve TRL 6 by December 2006.

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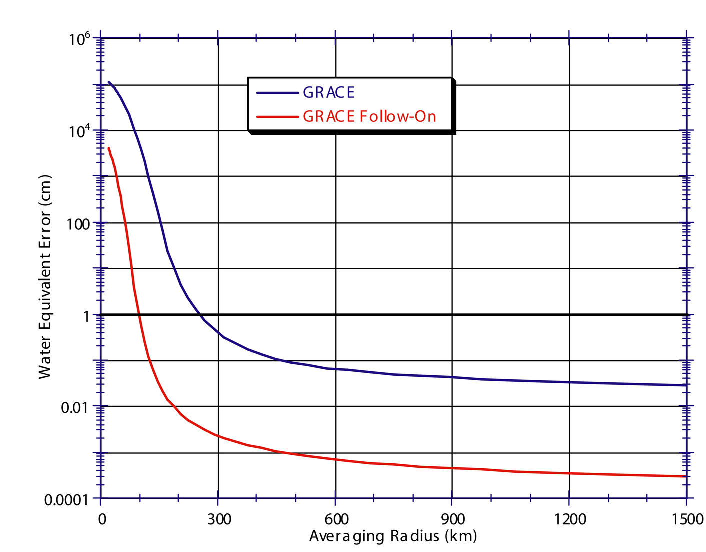
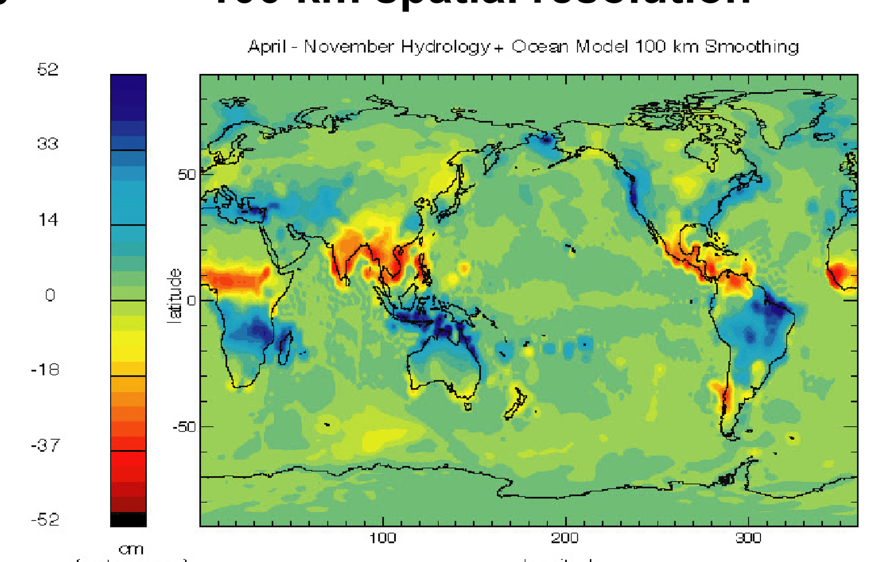
Recovery of surface water mass



Courtesy of John Wahr

100 km spatial resolution



Courtesy of John Wahr & Sean Swenson