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Spaceborne Gravity Sensors for Continental Hydrology and Geodynamic Studies

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Abstract : The currently operating NASA/GFZ Gravity Recovery and Climate Experiment (GRACE) mission is designed to measure small mass changes over a large spatial scale, including the mapping of continental water storage changes and other geophysical signals in the form of monthly temporal gravity field. The European Space Agency's Gravity field and steady state Ocean Circulation Explorer (GOCE) space gravity gradiometer (SGG) mission is anticipated to determine the mean Earth gravity field with an unprecedented geoid accuracy of several cm (rms) with wavelength of 130 km or longer. In this paper, we present a summary of present GRACE studies for the recovery of hydrological signals in the Amazon basin using alternative processing and filtering techniques, and local inversion to enhance the temporal and spatial resolutions by two-folds or better. Simulation studies for the potential GRACE detection of slow deformations due to Nazca-South America plate convergence and glacial isostatic adjustment (GIA) signals show that these signals are at present difficult to detect without long-term data averaging and further improvement of GRACE measurement accuracy.

Key Words : Gravity, Temporal Gravity, Hydrology, Geodynamics, Plate Convergence, Earthquakes, Glacial Isostatic Adjustment.

1. Introduction

The complicated dynamic processes of the Earth system are linked with phenomena of global climate change and processes potentially associated with natural hazards. The NASA/GFZ Gravity Recovery and Climate Experiment (GRACE) mission is designed to measure small mass changes over a large spatial scale. The scientific objectives of GRACE include the mapping and understanding of climate-change signals associated with mass variations within solid Earth-atmosphere-ocean-cryosphere-hydrosphere system with unprecedented accuracy and resolution in the form of time-varying gravity field (Wahr *et al.*, 1998; Tapley *et al.*, 2004a, 2004b). GRACE was launched in March 2002 for a mission span of 5 years or longer. The satellite mission is consisted of two identical co-orbiting spacecrafts with a separation of 220 ± 50 km at a mean initial orbital altitude of 500 km with a circular orbit and an inclination of 89^0 for near-global coverage (Bettadpur and Watkins, 2000; Tapley *et al.*, 2004a). The dual-one way K- (24.5 GHz) and Ka- (32.7 GHz) band microwave inter-satellite

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ranging system with a precision of 0.1 μm/sec (in range-rate) (Kim *et al.*, 2001), the Ultra-Stable Oscillator (USO) accurate to within 70 picosecs of time-tagging, the 3-axis super-STAR accelerometers with a precision of 4×10^{-12} m/s^2 (Davis *et al.*, 1999) and the dual-frequency 24-channel Blackjack GPS receivers comprise the instrument suite for GRACE's mapping of the global gravity field with unprecedented accuracy and resolution (Tapley *et al.*, 2004a).

European Space Agency's Gravity field and steady state Ocean Circulation Explorer (GOCE) space gravity gradiometer (SGG) mission, scheduled to launch in 2006, is anticipated to determine Earth's mean gravity field with an unprecedented geoid accuracy of several cm with wavelength of 130 km or longer. The mission duration is about 20 months. In a sun-synchronous near-polar orbit and at an altitude of 250 km, the GOCE onboard space gravity gradiometer (SGG) will measure primarily 4 components (3 diagonals and 1 off-diagonal) of the Earth gravity tensor (ESA, 1999; Schrama, 2003). The onboard GPS receiver (high-low SST) will be used to determine the precise orbit, the long wavelength component of the gravity field, and to register the gravity tensor observables within a few cm of accuracy. Although SSG's noise characteristics prohibit the precise determination of lower degree coefficients, it is expected to have significant improvement in higher degree geopotential coefficients (i.e., $N_{max} = 300$ or higher). GOCE senses not only static gravitational forces but also tides and other temporal signals resulting from mass variations of various Earth processes. These signals manifest as gravity field changes and include effects such as atmospheric loading on the Earth, ground water movement, oceanic mass variations, and ice mass fluxes. Simulated gravity field recovery study using GOCE SSG and SST indicates that effects of errors in atmospheric and tides, and hydrological signals are largely below the instrument noise in a 2-month solution (Han *et al.*, 2005b).

This paper presents summaries of current research using GRACE for the study of continental hydrology and alternate processing methodologies capable of enhancing localized regional hydrological signals, and simulation studies to use GRACE for potential detection of several solid Earth "slow" deformation processes including the Nazca-South America plate convergence and the Glacial Isostatic Adjustment (GIA).

2. Hydrology

The measurements of terrestrial water storage (soil moisture, snow, lake, ground water, river, and vegetation) variation with regional scale (several hundreds to thousands km) are difficult to acquire using the ground-based sensors (Alsdorf *et al.*, 2003). Space-borne remote sensing technique (i.e., GRACE) offers the promise of allowing one to monitor hydrological change at regional scales with homogeneous accuracy as well as spatial and temporal resolutions. One of the important scientific objectives from the GRACE mission includes monitoring of the regional continental water mass variation (Wahr *et al.*, 1998). Previous investigations (Wahr *et al.*, 1998; Rodell and Famiglietti, 1999) developed methods to extract the hydrological signals and presented promising results using simulations via analysis of GRACE observed Earth's gravity changes. The methods primarily use the time-series of Stokes' coefficients, which are one of the so-called Level-2 science data products of the GRACE mission (Tapley *et al.*, 2004a; Wahr *et al.*, 2004). For the temporal variation of the Earth gravity fields, relatively well-known geophysical effects such as tides, atmospheric mass redistribution, and barotropic ocean response due to atmospheric forcing are forward modeled in the analysis of the GRACE observations to isolate the observed climate-sensitive signals such as hydrology, ice sheet mass balance, and ocean mass change.

Wahr *et al.* (2004) show that the current GRACE gravity field solutions can be used to recover monthly changes in water storage, both on land and in the ocean, to accuracies of 1.5 cm of water thickness when smoothed over 1000 km spatial scale, and that the annual amplitude of large hydrological basins including the Amazon could be determined to accuracies of 1.0-1.5 cm. Ramillien *et al.* (2004) developed an inversion method to invert GRACE data to constrain continental hydrology models in 71 world drainage basins and claimed a 1-cm accuracy for GRACE monthly hydrology observations. It should note that the current GRACE accuracy is approximately 40 times worse than the prelaunch estimate (Wahr *et al.*, 2004), however, it is anticipated that the accuracy will improve with refining of instrument model and other parameters.

Alternate methods of GRACE data processing which show improvement include the use of a non-isotropic filter to enhance latitudinal spatial resolutions up to 200 km (Shum *et al.*, 2004); the use of the *in situ* approach employing the conservation of energy principle (Han, 2004) to process the K-band inter-satellite range-rate (the so-called Level 1B data) directly (Han *et al.*, 2004b), and the use of local inversion techniques to enhance spatial and temporal resolutions up to 200 km and sub-monthly, respectively (Han *et al.*, 2005a; Han *et al.*, 2004b). Fig. 1 shows simulation results (Han *et al.*, 2005a) for the annual variations estimated from the local inversion method (left), which have much higher frequency signal recovery than the global spherical harmonic approach (right). Fig. 2 shows real GRACE monthly observed hydrological signals over the Amazon basin (N_{max} = 15) from the Level 2 (L2) data product (Tapley *et al.*, 2004a) (left), while higher resolution signal is observed using non-isotropic filtering instead of the classical isotropic Gaussian smoothing (Shum *et al.*, 2004) (right).

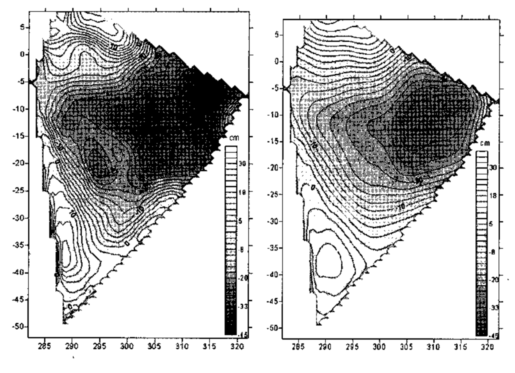

Fig. 1. The annual variations estimated from the local inversion method (left), which shows much higher frequency signal recovery than the global spherical harmonic coefficients (right) in a GRACE simulation (Han *et al.*, 2005a).

Fig. 3 shows the recovered hydrological signals in terms of water storage anomaly from the local inversion method with 15-day sampling in the Amazon basin: (a) the first half of July 2003, (b) second half of July 2003, (c) first half of August 2003, and (d) second half of August 2003 (Han *et al.*, 2004b). These results show an improvement of GRACE processing for hydrological signal observations with enhanced temporal (15 days instead of monthly) and spatial (500 km or finer instead of 1,000 km) resolutions.

3. Geodynamics

Tectonically driven spatio-temporal signals manifest from complex geophysical processes. These processes include convergent plate boundaries, earthquake deformation cycle, mantle convection and intra-plate deformations. GIA, which is the visco-elastic response of the solid Earth to deglaciation of current and ancient ice sheets, is another slow deformation process. These processes generate small but measurable signals at present by using GPS or gravimeters, or using InSAR. Spaceborne gravimetry including GRACE and GOCE have the potential to detect some of these slow deformation signals. Fig. 4 shows the geoid or geoid change signals (mm) as a function of spherical harmonic degrees or spatial scales for the GRACE prelaunch

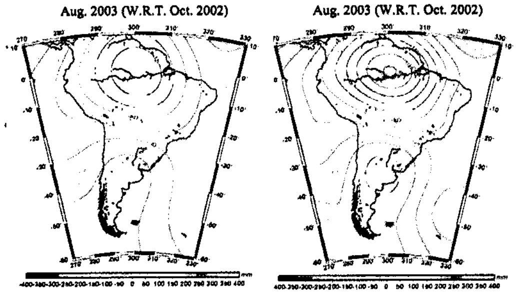

Fig. 2. GRACE monthly observed hydrological signal over the Amazon basin (N_{max} = 15) from the L2 data product (Tapely *et al.*, 2004a) (left). A higher resolution signal is observed using the non-isotropic filtering (Shum *et al.*, 2004) (right).

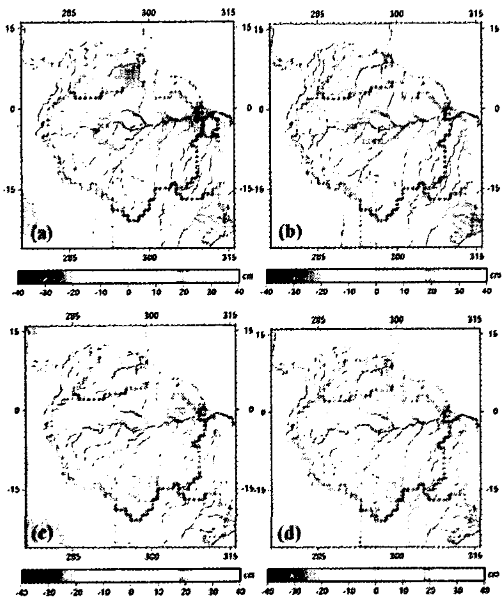

Fig. 3. The water storage anomaly from the local inversion method with 15-day sampling in the Amazon basin: (a) the first half of July 2003, (b) second half of July 2003, (c) first half of August 2003, and (d) second half of August 2003 (Han *et al.*, 2004b).

error, monthly error (Tapley *et al.*, 2004a), yearly error, atmosphere error and aliasing (ECMWF-NCEP) (Han *et al.*, 2004a), ocean tide error and aliasing (CSR4.0-NAO99) (Han *et al.*, 2004a), signals associated with the 1960 Chile earthquake, Nazca-South American plate convergence (accumulated over 1 year and 5 year), and

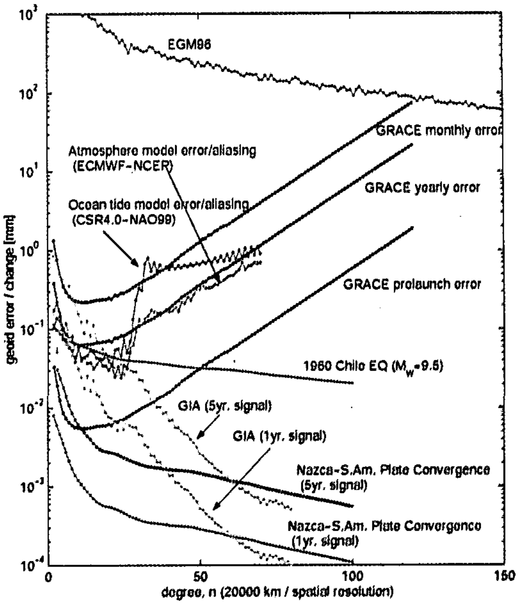

Fig. 4. (from Shum *et al.* (2005)) shows the geoid or geoid change signals (mm) as a function of spherical harmonic degrees or spatial scales for the GRACE prelaunch error, monthly error (Tapley *et al.*, 2004a), yearly error, atmosphere error and aliasing (ECMWF-NCEP) (Han *et al.*, 2004a), ocean tide error and aliasing (CSR4.0-NAO99) (Han *et al.*, 2004a), signals associated with the 1960 Chile earthquake, Nazca-S. American plate convergence (accummulated over 1 year and 5 year), and GIA (1 year and 5 years). EGM96 gravity model (Lemoine *et al.*, 1996) is used as a reference.

GIA (1 year and 5 years). EGM96 gravity model (Lemoine *et al.*, 1997) is used as a reference. Fig. 4 shows that the largest recorded earthquake, the 1960 Chile earthquake (M_W = 9.5) is observable based on prelaunch GRACE noise to degree 50 or longer. However, it is barely detectable even after averaging 1 year of GRACE data at the present GRACE accuracy (Tapley *et al.*, 2004a; 2004b).

Fig. 5 (from Shum *et al.* (2005)) shows the simulated disturbing potential (in units of $10^{-3}m^2/s^2$, N_{max} = 120) at the Earth surface due to 5 years of accumulated slow deformation using a simplified model due to the Nazca-South America plate convergence and assuming

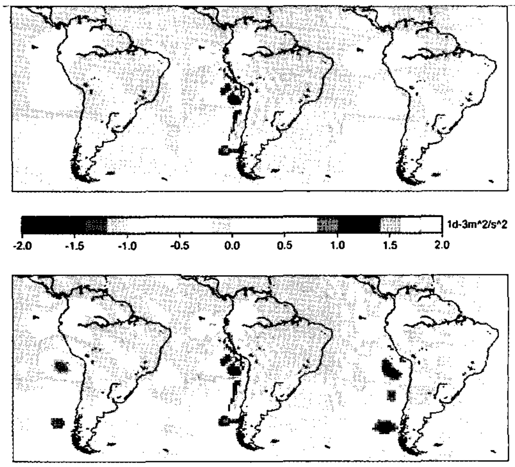

Fig. 5. (from Shum *et al.* (2005)) shows simulated results that GRACE is able to recover 5 year accumulated deformation (middle panels) due to Nazca-South America plate convergence, assuming prelaunch GRACE accuracy. Both spherical harmonics and spherical wavelets (Schmidt *et al.*, 2004) are able to recover the deformation using signal using GRACE simulated observations with the wavelets achieved enhanced resolutions.

GRACE prelaunch accuracy (Shum *et al.*, 2005). Both spherical harmonics and spherical wavelets (Schmidt *et al.*, 2004) have been used to recover the simulated plate convergence deformation using GRACE simulated observations. Fig. 5 (Top left) shows the recovered (long wavelength) deformation signal represented by spherical harmonics (N_{max} = 15); the middle panels show the "truth signal" (N_{max} = 100); top right: recovered signal in wavelets (Level = 4, degree 15). Fig. 5 (bottom left) shows recovered signal in spherical harmonics (N_{max} = 31); bottom middle: "truth" signal (N_{max} = 100); bottom right: recover signal in wavelet (Level = 5, degree 31). In both cases it is shown that the spherical wavelets enhanced the recover signals, and that the deformation signal is recoverable assuming GRACE prelaunch accuracy estimate and that this is noise-only simulation.

Fig. 6 (from Shum *et al.* (2005)) shows the recovery of simulated GIA signal using GRACE data and assuming prelaunch GRACE accuracy. Fig. 6 (top-left) shows five years of GIA signal based on the ICE4G

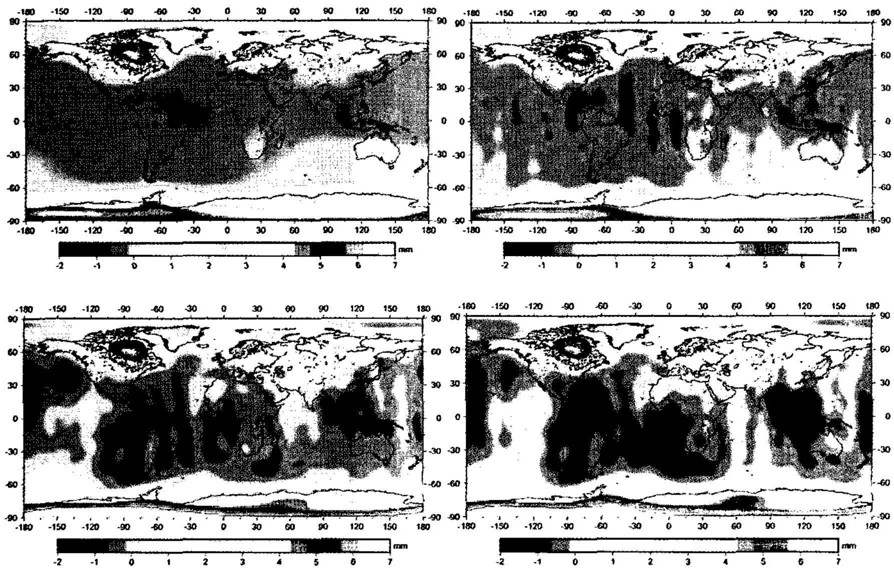

Fig. 6. (from Shum *et al.* (2005)). (Top-left) five years of GIA signal based on ICE4G model; (Top-right) its recovery in the presence of measurement noise-only (Bottom-left) its recovery in the presence of measurement noise and atmosphere modeling error; (Bottom-right) its recovery in the presence of measurement noise, atmosphere modeling error, and ocean tide modeling error.

model. Fig. 6 (top-right) shows its recovery in the presence of measurement noise-only (bottom-left) its recovery in the presence of measurement noise and atmosphere modeling error. Fig. 6 (bottom-right) shows its recovery in the presence of measurement noise, atmosphere modeling error, and ocean tide modeling error (Shum *et al.*, 2005).

4. Conclusions

This paper presents results of current research using GRACE for the study of continental hydrology and alternate processing methodologies capable of enhancing localized regional hydrological signals, and simulation studies to use GRACE for potential detection of several solid Earth "slow" deformation processes including Nazca-South America plate convergence and Glacial Isostatic Adjustment (GIA) signals. It is concluded that GRACE has the ability to observe basin-scale hydrological signals and that alternate processing techniques could enhance the spatial and temporal resolutions. Solid Earth deformation processes such as plate convergence, large earthquakes and its co-seismic cycles, and GIA at present are difficult to detect using GRACE unless data is averaged over a long span (e.g., several years) and that the data accuracy will be improved.

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References

Bettadpur, S., and M. Watkins, 2000. GRACE gravity science & its impact on mission design, *EOS Trans AGU*, May 2000.

Davis, A., C. Dunn, R. Stanton, and J. Thomas, 1999. The GRACE mission: meeting the technical challenges, 50th International Astronautical Congress, October 4-8, 1999, Amsterdam, Netherlands.

ESA, 1999. *Gravity Field and Steady-State Ocean Circulation Mission*, Rep. SP-1233, European Space Agency, Noordwijk.

Han, S-C., 2004. The efficient determination of global gravity field from satellite-to-satellite tracking mission, *Celestial Mechanics and Dynamical Astronomy*, 88: 69-102.

Han, S., C. Jekeli, and C. Shum, 2004a. Time-variable aliasing effects of ocean tides, atmosphere, and continental water mass on monthly mean GRACE gravity field, *J. Geophys. Res.*, 109(B4), B04403, 10.1029/2003JB002501.

Han, S., C. Shum, D. Alsdorf, K. Seo, and C. Wilson, 2004b. High-resolution recovery and validation of GRACE hydrological signals, *Eos Trans. AGU*, 85(47), Fall Meet. Suppl., Abstract C22C-01, San Francisco, December 13-17.

Han, S., C. Shum, and A. Braun, 2005a. High-Resolution Continental Water Storage Recovery from Low-Low Satellite-to-Satellite Tracking, *J. Geodynamics*, 39(1): 11-28.

Han, S., C. Shum, P. Ditmar, P. Visser, C. van Beelen, and E. Schrama, 2005b. Effect of high-frequency mass variations on GOCE recovery of the Earth's gravity field, in review, *J. Geodynamics*.

Kim, J., P. Roesset, S. Bettadpur, B. Tapley, and M. Watkins, 2001. Error analysis of the Gravity Recovery and Climate Experiment (GRACE), *IAG Symposium Series*, M. Sideris (eds), 123, 103-108, Springer-Verlag Berlin Heidelberg.

Lemoine, F., D. Smith, L. Kunz, R. Smith, E. Pavlis, N. Pavlis, S. Klosko, D. Chinn, M. Torrence, R. Williamson, C. Cox, K. Rachlin, Y. Wang, S. Kenyon, R. Salman, R. Trimmer, R. Rapp, and R. Nerem, 1997. The development of the NASA GSFC and NIMA joint geopotential model, *International Association of Geodesy Symposium No. 117*, Tokyo, Japan, September 30-October 5, 1996, J. Segawa, H. Fujimoto, and S. Okubo, Editors, 461-469, Springer.

Ramillien, G., A. Cazenave and O. Brunau, 2004. global timem variations of hydrological signals from GRACE satellite gravimetry, *Geophys. J. Int.*, 158: 813-826, doi: 10.1111/j.1365-246X. 2004.02328.x.

Rodell, M., and J. Famiglietti, 1999. Detectibility of Variations in Continental Water Storage from Satellite Observations of the Time-variable Gravity Field, *Wat. Resour. Res.*, 35(9): 2705-2723.

Schmidt, M., O. Fabert and C. Shum, 2004. Towards the estimation of a multi-resolution gravity field representation based on spherical harmonics and wavelets, *IAG Springer Symposia*, in-press.

Schrama, E., 2003. Error characteristics estimated from CHAMP, GRACE and GOCE derived geoids and from satellite altimetry derived mean dynamic topography, *Earth Gravity Field from Space*, Kluwer Space Sciences Reviews Journal (Beutler, Drinkwater, Rummel and Steiger, Editors).

Shum, C. S. Han, C. Kuo, K. Seo and C. Wilson, 2004. Assessment of GRACE time-variable gravity observables: A new filtering technique to enhance signal spatial resolutions, *Eos Trans. AGU*, 85(47), Fall Meet. Suppl.,Abstract G31C-0814, San Francisco, December 13-17.

Shum, C., S. Han, C. Kuo, L. Potts, A. Braun, M. Schmidt, and M. Lai, 2005. Study of potential GRACE detection of solid Earth slow deformations, submitted, *Advances in Geosciences.*

Tapley, B. D., S. Bettadpur, M. Watkins, and Ch. Reigber, 2004a. The Gravity Recovery and Climate Experiment; Mission Overview and Early Results, *Geophys. Res. Lett.*, 31(9), 10.1029/2004GL019920.

Tapley, B. D., S. Bettadpur, J. Ries, P. Thompson, and M. Watkins, 2004b. GRACE Measurements of Mass Variability in the Earth System, *Science*, 305: 503-505.

Wahr, J., M. Molenaar, and F. Bryan, 1998. Time variability of the Earth's gravity field: hydrological and oceanic effects and their possible detection using GRACE, *J. Geophys. Res.*, 103: 30205-30229.

Wahr, J., S. Swenson, V. Zlotnicki, and I. Velicogna, 2004. Time-variable gravity from GRACE: First results, *Geophys. Res. Lett.*, 31, L11501, doi:10.1029/2004GL019779.