MONDAY 2 AUGUST 2004 AM/PM

Space Geodetic Techniques and Tides

Conveners: R. Haas, S. Bettadpur

PRESIDING

R. Haas, *Onsala Space Observatory, Chalmers University of Technology, Sweden.*

Paper No	Time	Type	Title	Authors
ETS-02-01	10:30-11:00	I/O	The significance of tides in GRACE gravity field determination	R. Eanes, S. Bettadpur, J. Bonin, J. Ries, M. Cheng
ETS-02-02	11:00-11:15	C/O	Seasonal time changes of the Earth's gravity field from GRACE: a comparison with ground measurements from superconducting gravimeters and with hydrology model predictions	J. Hinderer, O. Andersen, F. Lemoine, D. Crossley, J.-P. Boy
ETS-02-03	11:15-11:30	C/O	Effect of High-Frequency Mass Variations on GOCE Recovery of the Earth's Gravity Field	S.-C. Han, C.K. Shum, C. Kuo, P. Ditmar, P. Visser, E.J.O. Schrama, C. van Beelen
ETS-02-04	11:30-11:45	C/O	Oceanic Mass Constraint Studies in East Antarctica Ocean	C.Y. Kuo, A. Braun, S-C Han, C. K. Shum, Y. Yi
ETS-02-05	11:45-12:00	C/O	Combined analysis of VLBI and superconducting gravimeter	L. Petrov, J- Hinderer, J.-P. Boy
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ETS-02-08	14:15-14:30	C/O	Deficiencies in monitoring global crustal deformation with GPS	P.J. Mendes Cerveira , R. Weber, H. Schuh
ETS-02-09	14:30-14:45	C/O	Global Tidal Displacements Measured by GPS	X. (Frank) Wu, M.B. Heflin, D.C. Jefferson, F.H. Webb, H.-G. Scherneck
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ETS-02-11		C/P	GPS Observations of Ocean Tide Loading in the British Isles	C.R. Allinson, P. Clarke, M.A. King, S.J. Edwards,T.F. Baker, P. Cruddace
ETS-02-12		C/P	Antarctic Ocean Tide Loading: GPS Estimates Compared to Gravity and Models	M.A. King, T.F. Baker
ETS-02-13		C/P	Deficiencies in monitoring global crustal deformation with GPS	P.J. Mendes Cerveira , R. Weber, H. Schuh
ETS-02-14		C/P	Subdiurnal Earth rotation variations from VLBI CONT campaigns	R. Haas, J. Wünsch
ETS-02-14		C/P	Comparison of Superconducting Gravimeter and GRACE Satellite Derived Temporal Gravity Variations	J. Neumeyer , P. Schwintzer, C. Reigber, F. Barthelmes, O. Dierks, F. Flechtner, J. Hinderer, Y. Imanishi, C. Kroner, B. Meurers, S. Petrovic, R. Schmidt, H.-P. Sun, H. Virtanen, M. &G. Harnisch

C: *Contributed*; **I:** *Invited*; **O:** *Oral*; **P:** *Poster*

ETS-02-01

The significance of tides in GRACE gravity field determination

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Tidal variability of the geopotential at periods less than one month or so is of great significance to the quality of monthly geopotential estimates from GRACE. Errors in the a priori models for the tides is recognized one of the larger contributors to GRACE estimate errors. This paper presents a discussion of the mechanisms by which tidal model errors affect GRACE seasonal gravity estimates. Following this, comparisons of GRACE estimates using different ocean tidal models is presented - as a first step towards articulating some accuracy and resolution requirements on ocean tide models for GRACE gravity estimation. Finally, the prospects for the determination of tides from GRACE data will be briefly discussed.

ETS-02-02

Seasonal time changes of the Earth's gravity field from GRACE: a comparison with ground measurements from superconducting gravimeters and with hydrology model predictions

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(3) National Survey and Cadastre, Copenhagen, Denmark
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We investigate the time-variable gravity changes retrieved from the initial GRACE monthly solutions spanning a 20-month duration from April 2002 to December 2003. Gravity anomaly maps are retrieved from the monthly satellite solutions from which we compare the fields according to various truncation levels (typically between degree 10 and 20) of the initial fields (expressed in spherical harmonics up to degree 120). We first show that there is a clear seasonal signal worldwide which is in agreement in amplitude and phase with models of continental hydrology. We focus then more specifically to Central Europe and, for different truncation degrees, an empirical orthogonal function (EOF) decomposition of the time-variable gravity field leads us to its main spatial and temporal characteristics. We confirm that the dominant signal is indeed annual with both amplitude and phase in agreement with predictions in Europe modeled using snow and soil-moisture variations from recent hydrology models. We compare these GRACE gravity field changes to surface gravity observations from 6 superconducting gravimeters of the GGP (Global Geodynamics Project)! European sub-network, with a special attention to loading corrections. Initial results suggest that all 3 data sets (GRACE, hydrology and GGP) are responding to annual changes in near-surface water in Europe of a few microGal (at length scales of ~1000 km) that show a high value in winter and a summer minimum. The GRACE gravity field evolution indicates that there is a trend in gravity between summer 2002 and summer 2003. We tentatively try to relate this to the 2003 heat wave in Europe and its hydrological consequences (increased dryness).

ETS-02-03

Effect of High-Frequency Mass Variations on GOCE Recovery of the Earth's Gravity Field

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European Space Agency's GOCE space gradiometer mission is anticipated to recover the mean gravity field model of the Earth with an unprecedented cumulative geoid accuracy of several cm with wavelength at 150 km or longer. Even though such a high spatial resolution of the geopotential solution can be expected solely from the space-borne gradiometer, the latter is not sensitive to low degree and order harmonics. The traditional high-low satellite-to- satellite (GPS tracking) data will be incorporated to constrain the low degree and order geopotential recovery. In a sun-synchronous, near-polar orbit and at an orbital altitude of 250 km, GOCE gradiometer and GPS receiver will sense not only static gravitational forces but also tides and other time-varying mass signals, including atmosphere, ocean, and hydrological mass, at commensurate temporal and spatial resolutions. In this simulation study, we extended the study by Han et al. [2004] by further investigating and quantifying the respective and combined effects of the high-frequency temporal mass variations and their model errors on the GOCE geopotential model (complete to degree 300) recovery using the gradiometer and GPS tracking data.

ETS-02-04

Oceanic Mass Constraint Studies in East Antarctica Ocean

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In modern climate, ocean circulation is responsible for some half of the poleward heat transport, the remaining half is contributed by the atmosphere. The Southern Ocean provides a major link among the world oceans and link associated with the melting and accumulation of the vast Antarctic ice sheet and its adjacent sea ice. While satellite altimetry such as TOPEX/POSEIDON or JASON is limited in geographical coverage outside of ±66° latitude, high-latitude covering radar and laser altimeters (Geosat, GFO, ERS- 1/-2, ENIVSAT, IceSat and CryoSat) provide a complete coverage of the Southern Ocean, including sea ice covered seas, in unprecedented spatial and temporal coverage. In situ data such as tide gauges remain sparse, with Syowa station in East Antarctica represent the only long-term (longer than a decade) and carefully calibrated instrumentation in Antarctica. In addition, in situ temperature and salinity measurements are not homogeneously distributed and limited in accuracy, and consequently, the steric sea level is not well known, particularly in the Southern ocean. This paper presents a study to assess the role of GRACE observed long-wavelength mass variations in potentially improving the steric sea level estimates over East Antarctica Ocean near Syowa. Using multiple mission satellite altimetry, GRACE gravimetry, steric sea level from in situ measurements and an altimetry-assimilated general ocean circulation model (ECCO, Fukumori et al., 1999), we examine the low (spatial) frequency variations of steric effect and mass redistribution over the East Antarctica Ocean near Syowa. In situ temperature and salinity measurements used are from NOAA's WOD01 and potentially from PALACE and ARGO floats.

ETS-02-05

Combined analysis of VLBI and superconducting gravimeter data

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We have processed a full dataset of 20 years of global VLBI data from 40 stations and 5 years of global superconducting gravimeter (SG) data from 18 stations. We have estimated 3D tidal displacements of VLBI stations at 32 frequencies and determined gravity changes at the same frequencies from SG data. After subtracting theoretical signal computed on the basis of the solid Earth tides model and models of tidal ocean, atmospheric and hydrology loadings we obtain the residual signals for both techniques. Since geodetic and gravimetric techniques are sensitive to different combinations of Love numbers expressing the Earth's (in-)elastic transfer function and have different sensitivity to mass loading, the analysis of a combined dataset of residuals has certain advantages. We discuss possible approaches to an optimal combined analysis of VLBI/SG residuals and present preliminary results.

ETS-02-06

Geodynamics from Space: VLBI Observations of the Free Core Nutations

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Very Long Baseline Interferometry (VLBI) nutation measurement series, both in excess of twenty-three years length, from Goddard Space Flight Center and the United States Naval Observatory, have been analyzed in the spectral domain for Free Core Nutation Resonances.

The Discrete Fourier Transforms of the non-equispaced records are found by minimizing an objective function which weights the squared error between the DFT representation and the measured values in inverse proportion to the square of their standard errors. In common with other large least squares problems, the coefficient matrix of the resulting conditional equations is poorly conditioned, and we employ the Singular Value Decomposition Technique for their solution. A novel feature of our procedure is the use of the Parseval relation as an objective criterion to determine the number of singular values of the coefficient matrix to be eliminated.

We report the observation for the first time of the prograde mode predicted by Jiang (1993) in addition to the classical retrograde mode. The long series permit the determination of the time evolution of the two Free Core Nutations (FCNs). Both are found to be closely in free decay. Simple Ekman boundary layer theory allows the viscosity at the top of the core to be found from the decay rates. An average value of $800\;Pa\cdot s$ results.

The series we analyze are residuals with respect to the IAU1980 nutation model. In contrast to the IAU2000 model of Herring, Mathews, Buffett (2000) (HMB), this model is not adjusted to the observations, or to conform to any preconceived excitation mechanism. HMB use a moving box car

window in their adjustment and, by the shifting theorem of Fourier Transforms, this results in a sinusoidal modulation of the deduced FCNs, which appears to have been mistaken by them, for renewed excitation, as it obscures the free exponential decay found in residuals with respect to the unadjusted IAU1980 model. They, in turn, invoke a very highly conducting layer above the core-mantle boundary to explain this artifact of their analysis as due to electromagnetic core-mantle coupling. The free exponential decay we observe eliminates continuous excitation mechanisms such as electromagnetic or, as often suggested, atmospheric coupling.

ETS-02-07

Constraints on Mantle Anelasticity from Geodetic Observations, and implications

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Using geodetic observations of the Earth, such as Satellite laser ranging (SLR) measurements of the 18.6 year Earth Tide, length of day observations (LOD) of the M2, Mf and Mm Earth and ocean tides, and measurements of the Chandler Wobble (CW), we can constrain anelasticity in the Earth's mantle at periods between 12 hours and 18.6 years. The results confirm the conclusions of earlier studies that the anelastic parameter Q is smaller for those periods than for seismic waves. We interpret this as evidence that Q is frequency dependent. We find that the frequency dependence suggested by the geodetic observations is reasonably consistent with laboratory measurements. These results impact the interpretation of the 1998-2002 J2 anomaly detected in SLR observations by Cox and Chao (2002).

ETS-02-08/ ETS-02-13

Deficiencies in monitoring global crustal deformation with GPS

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The GPS space geodetic technique should not only be precise, but also highly accurate to correctly interpret observed global site motions with respect to tidal and non-tidal loading effects. The objective of this paper is to point out several deficiencies of GPS-derived station coordinates, which may lead to erroneous deductions. Actually, nine Analysis Centers (ACs) of the International GPS Service (IGS) contribute to the final weekly station coordinates in the common IGb00 or IGS00 (the precursor of IGb00) terrestrial reference frame, respectively. The determination of seasonal variations of IGS stations would essentially contribute to improve the stability and accuracy of the IGS reference frame. The time span of the data used for this investigation ranges from July 1999 till July 2004. A detailed study and comparison of the station coordinate time series provided by each AC shows many irregularities and discrepancies of all coordinate components. Although each AC produces a weekly solution, the reference epoch may vary up to 4 days between the various ACs. In addition, some coordinate solutions produced by the ACs, after alignment to IGb00 (or IGS00, respectively), differ in the range of 2 cm (3D), indicating that these solutions are contaminated by systematic errors. Nevertheless, comparing the nine individual ACs solutions with the moving average, it is possible to extract similar patterns for many sites e.g., apparent periodic signals on seasonal time scales in the vertical station coordinate component, with amplitudes of up to 9 mm and a standard deviation of unity weight of up to ±1 cm. These apparent

periodic site motions are partly caused by atmospheric, oceanic, and hydrological surface loading effects, and coincide at nearby sites. Yet, a comparable large contribution stems from systematic deviations of the analysis models used by the different ACs, due to different software packages and strategies (e.g. constraints on parameters etc.). In general, trends of horizontal (north and east) station coordinate components agree well, but temporal variations of the coordinate components show differences of more than 1 cm between the various ACs. It is notable, that individual ACs observe similar signals at nearby sites. We may conclude with these results that at present, GPS can hardly detect surface mass redistribution effects on terrestrial station coordinates with an accuracy of better than ±5 mm at a global level.

ETS-02-09
Global Tidal Displacements Measured by GPS

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We study tidal displacements using globally distributed continuous GPS data and models of ocean and solid earth tides. For reference frame consistency, data from 45 well-distributed stations are used in global network analyses where tidal displacements are estimated simultaneously with orbital and other geodetic parameters. Precise point positioning is then applied to a large number of tracking sites individually and efficiently with fixed orbits. More than 900 days of data have been processed to estimate amplitudes and phases of 3-dimensional displacements due to M2, S2, N2, K2, K1, O1, P1, and Q1 tides. The results are further decomposed into geocenter motion, earth orientation variations and relative displacements. In general, purely lunar tides, M2, N2, O1, and Q1 are determined very well at the level of 1 mm. Results for S2, K2, K1, P1 are a factor of 2-3 noisier.

ETS-02-10
The High Frequency Variations of the Atmospheric Angular Momentum and the Earth Rotation

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Spectral analysis of the components of the relative atmospheric angular momentum (AAM) vector and the Earth Orientation Parameters (EOP) is performed. These series have been computed in the International Earth Rotation Service for the 6-hour intervals within the period of 1958--2003. The basic harmonics of diurnal tides (S_1, P_1, K_1, π_1, ψ_1, φ_1, O_1) and semidiurnal tides (S_2, T_2, R_2, K_2, P_2) are determined.

The tides transformation mechanisms in the atmosphere are discussed. It is shown that the main mechanism of the zonal tides effect on the atmospheric variability is the amplitude, frequency and phase modulation of diurnal and sub-diurnal oscillations of the AAM and the EOP. The durations of the natural synoptic periods in the atmosphere coincide with the periods of the zonal tides oscillations and of the Earth rotation regimes. The synoptic processes and of the Earth rotation regimes controlled by zonal tides vary with periods continuously varying within 5 -- 9 days. The synoptic processes govern the amplitude of diurnal and sub-diurnal oscillations of the AAM components. This means that the amplitude, frequency and phase modulations of diurnal and sub-diurnal oscillations of the AAM are occurred. Because of it in spectrum of the AAM there are the powerful wide maxima near to frequencies 0.85 and 1.70 cycles/day.

New results on the fortnight's and week's duration oscillations of the EOP and equatorial components of the AAM are obtained. The effects of the atmospheric tides on the Earth rotation are discussed.

ETS-02-11

GPS Observations of Ocean Tide Loading in the British Isles

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The intricate shape of the coastline, coupled with the interaction of the tides in the open oceans and shallower coastal regions makes ocean tide loading (OTL) prediction difficult in the British Isles. Model predictions for the south-west area of England illustrate how large the loading effect can be, where total OTL can reach 9cm in amplitude (FES99). However, current models have only been tested by using sparse gravimetric and short-term GPS data, and discrepancies between these can be sizable. In an attempt to validate or improve existing OTL models, we have devised a method of directly solving for OTL using data gathered from a network of continuously operating GPS receivers on a point-by-point basis.

We observe OTL at diurnal and semi-diurnal periods by directly estimating fixed- period harmonic motions within individual daily GIPSY/OASIS GPS analyses. An iterative Kalman Filter approach to combine the multiple daily solutions enables us to isolate the principal near-diurnal (K1, O1, P1, Q1) and near-semi- diurnal (M2, S2, N2, K2) OTL components, to which we later apply nodal corrections. A preliminary test using data from a number of UK sites shows that our estimates are in good agreement with OTL predicted by the FES99 model, where values vary from 342 mm in amplitude (M2). The TPXO.2 model consistently gives the lowest level of agreement, with M2 amplitude misfits typically ~8 mm and phase misfits ~25 degrees. Our final estimates are generated using approximately 1000 days of data in the solution, resulting in amplitude standard deviations of approximately 1 mm per component (compared with an RMS difference between OTL models of 2 mm per component). Phase estimate! s of the OTL components generally take longer to converge. The phase standard deviations for M2 remain ~5-15 degrees after 1000 days (compared to the phase RMS between OTL models of 117 degrees) and 2040 degrees for the remaining smaller magnitude components. We also show that our estimates are stable for the M2, S2, N2, O1 OTL components (at the majority of locations) when data from at least ~90 days are stacked, with an amplitude standard deviation of approximately 2 mm (for M2). Exceptionally, the K2, K1 and P1 components require at least 2000 days of data before similar confidence levels are achieved. This is however site dependent, as multipath and other sources of noise have a detrimental effect on the stability of our estimates.

ETS-02-12

Antarctic Ocean Tide Loading: GPS Estimates Compared to Gravity and Models

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We present three-dimensional ocean tide loading (OTL) estimates for Antarctica based on direct estimates from GPS observations and compare with several numerical tide models. Accurate estimates of the ocean tides in the Antarctic region are difficult to obtain from numerical ocean tide models due to the lack of bathymetric information and direct tidal observations in the sub ice shelf regions in particular. Consequently, independent measurements, such as from GPS, with an extensive spatial distribution are extremely important to ensure geodetic and altimetric (e.g, ICESat) measurements are not biased by mismodelled OTL.

In order to provide an external validation of the model estimates we estimated the eight major diurnal and semi-diurnal harmonic loading terms directly in our GPS analysis of data from approx. 15 sites distributed mainly around the perimeter of the continent. By combining estimates from up to several thousand days at each site constituent amplitudes were determined with formal uncertainties generally less than 1 mm (= ~0.3 microgals). Phase uncertainties are dependent on the constituent amplitude but are generally 5-20 degrees.

We show that while large misfits are evident with some tide models (CSR3, TPXO.2 and NAO.99b), especially near the very large Ross and Filchner-Ronne ice shelves, more recent models provide very good fits with the data. In the non ice shelf regions the models are typically in agreement at the 1-2 mm level. In particular, Q1 and N2 have extremely good agreements, with mean misfits of ~0.2 mm in the horizontal components and ~0.35 mm in the vertical components. As found in other studies, K1 and K2 have a significantly worse agreement than the other constituents.

Also shown are comparisons with long-term gravity measurements at two sites (South Pole and Swoya Station) made available by the International Centre for Earth Tides. Again, sub-mm agreements are found with several constituents, demonstrating the accuracy of the GPS technique for making three dimensional loading estimates and we discuss ways to further improve the accuracy of GPS-based estimates of K1 and K2.

Based on these comparisons, we recommend optimal numerical tide models to be used in OTL computations for geodetic and altimetric measurements in Antarctica.

ETS-02-14

Subdiurnal Earth rotation variations from VLBI CONT campaigns

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High-frequent Earth rotation variations are studied based on empirical determinations using VLBI CONT data theroretical and corresponding theoretical considerations. The high quality VLBI data CONT94 and CONT02 are analysed with several signal analysis tools, e.g. fourier analysis, wavelet analysis, Clean algorithm. In particular we study the amplitude spectra of EOP to investigate ter-diurnal variations. The results are compared to theoretical predictions based on a hydrodynamical ocean tidal model.

ETS-02-15

Comparison of Superconducting Gravimeter and GRACE Satellite Derived Temporal Gravity Variations

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The recovery of temporal Earth gravity field variations is one objective of the satellite gravity mission GRACE. The gravity resolution is in µgal range for a half wavelength spatial resolution of 2000km (l_{max} = 10) and the temporal resolution is 1 month.

Of fundamental interest is the combination of satellite-based and terrestrial time varying gravity measurements. On the Earth surface high-precision gravity measurements are carried out with Superconducting Gravimeters forming the SG network of the Global Geodynamic Project (GGP). These measurements have a gravity resolution in ngal range and a linear drift of some µgal per year. GRACE derived temporal gravity variations are compared with ground measurements at selected SG stations. Therefore both data sets are reduced for the same known gravity effects (Earth and ocean tides, pole tide, atmosphere) by using the same models. The atmospheric pressure reduction of the SG data is carried out with a new 3D model. Because of GRACE's limited spatial resolution all known local gravity effects are removed from the SG measurements. The influence of local groundwater table variation on the SG data is shown. GRACE and SG gravity variations show a quite good agreement within their estimated error bars for most of the stations.

The remaining gravity variations of both data sets are mainly caused by hydrological effects. For comparison the loading Love numbers h' and k' are used to adapt satellite and ground gravity variation measurements. Additionally a comparison is performed with gravity variations derived from global hydrological models. The adjustment to the GRACE and SG data sets is shown.