G43C-09 1615h

Spaceborne Laser Altimetry

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A new spaceborne geodetic tool was launched on ICESat in January 2003 into a 600 km altitude, near polar orbit. ICESat carries a laser altimeter, the Geoscience Laser Altimeter System, designed to generate high accuracy profiles of the polar ice sheets that enable detection of surface change. A variety of other applications have been demonstrated, which include land topography, vegetation canopy height, atmospheric and ocean. The laser altimetry uses a 1064 nm wavelength with a beam divergence that produces an illuminated surface spot of approximate 70 meters in diameter. With a pulse repetition rate of 40 Hz and the orbital motion, successive spots on the Earth's surface are separated by 170 m. This new geodetic tool has a precision of a few centimeters on flat surfaces and horizontal knowledge of the illuminated spot location has been shown to approach the requirement of 4.5 meters. A variety of calibration/validation techniques have been applied since laser operations began in February 2003 and numerous examples of high accuracy surface profiles have been collected. This paper will summarize the current operational status and illustrate the variety of applications to Earth science.

G43C-10 1630h

Photon Counting Airborne Laser Swath Mapping

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During the past decade airborne laser swath mapping (ALSM) has brought topographic mapping to the forefront of geodesy. ALSM has made it possible, for the first time, to study natural geo-surficial processes on spatial scales extending from meters to hundreds of kilometers, all in a consistent geodetic frame of reference. The conventional approach to ALSM has been to use lasers with enough energy per pulse, and optics with large enough collecting areas, to obtain returns of thousands of photons per shot. This approach minimizes the impact of spurious range values caused by noise, such as background solar radiation and sensor thermal noise, but also constrains the minimum size, weight and power consumption of the hardware. Current systems typically operate at rates approaching 100,000 pulses per second, and another order of magnitude increase would be needed to provide contiguous coverage with a spatial resolution of 30 cm or better. This high signal-to-noise ratio approach affords little scalability for significantly downsizing the hardware, or reducing the costs. University of Florida (UF) researchers are developing an ALSM unit based on a different paradigm, which we refer to as photon counting ALSM, or simply PC-ALSM. The approach is to transmit relatively low energy laser pulses, and to illuminate a surface patch' about an order of magnitude larger than the typical footprint of a conventional ALSM system. The returning signal will have far fewer photons per unit area of the receive optics, making it more difficult to discriminate between return signal and noise. If a single channel detector were used, the spatial resolution would also be degraded. However, by using a multi-channel photomultiplier tube to detect the returns, the surface patch can be divided into an array of groundals, and by using a multi-stop timing system false ranges can be filtered out of the data during post flight processing. Researchers at NASA GSFC have already tested a first generation system based on this new paradigm, operated from a high altitude aircraft, to develop a satellite based instrument. Details of the preliminary UF design for a second generation system that will operate from a light aircraft flying less than 1000 meters above local ground level and providing contiguous coverage of the terrain with 30 cm spatial resolution will be presented.

G43C-11 1645h

Multi-mission mean sea surface and geoid models for ocean monitoring within the GOCINA project

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A major goal of the EU project GOCINA (Geoid and Ocean Circulation In the North Atlantic) is to develop tools for ocean monitoring using satellite altimetry combined with satellite gravimetry. Furthermore, the project will determine an accurate geoid in the region between Greenland and the UK and, hereby, create a platform for validation of future GOCE Level 2 data and higher order scientific products. The central quantity bridging the geoid and the ocean circulation is the mean dynamic topography, which is the difference between the mean sea surface and the geoid. The mean dynamic topography provides the absolute reference surface for the ocean circulation. The improved determination of the mean circulation will advance the understanding of the role of the ocean mass and heat transport in climate change. To calculate the best possible synthetic mean dynamic topographies a new mean sea surface (KMS03) has been derived from nine years of altimetric data (1993-2001). The regional geoid has furthermore being updated using GRACE and gravimetric data from a recent airborne survey. New synthetic mean dynamic topography models have been computed from the best available geoid models (EGM96, GRACE, GOCINA) and the present mean sea surface models (i.e. CLS01, GSFC00, KMS03). These models will be compared with state of the art hydrodynamic mean dynamic topography models in the North Atlantic GOCINA area. An extended comparison in the Artic Ocean will also be presented to demonstrate the impact of improved geoid and mean sea surface modeling. Particularly using the GRACE derived geoid models, and the KMS03 mean sea surface.

URL: http://www.gocina.dk

G51A CC: 516 D Friday 0830h

Pleistocene Ice-Mass Change, Displacement and Gravity Change, and Their Interpretation With 3-D Earth Models II *(joint with H, OS, S, T, C, GC, PP, SEDI)*

Presiding: **V Klemann,** GeoForschungsZentrum Potsdam**; A Lambert,** Geological Survey of Canada**; P Wu,** University of Calgary

G51A-01 0830h INVITED

Laurentide Deglaciation

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An updated sequence of maps illustrating the deglaciation of North America was recently released as Geological Survey of Canada Open File 1574. These represent extensive revisions of the Dyke and Prest (1987; Géographie physique et Quaternaire, 41: 237-263) ice margin reconstructions. Age control on ice margins and glacial lake shorelines is provided by a chronological data set of about 4000 radiocarbon dates as well as key varve and tephra dates. Dates on problematic materials, such as marl, freshwater shells, lake sediment with low organic carbon content, marine sediment, bulk samples yielding probable blended ages, and most deposit-feeding marine molluscs from calcareous substrates were excluded. These culled samples, many of which had been used in previous reconstructions, yield ages that are too old. Retained marine shell dates were adjusted for regionally variable marine reservoir effects, based on a new set of radiocarbon measurements on pre-bomb molluscs from Pacific, Arctic, and Atlantic shores. These corrections range from 800 years in the Pacific Ocean and the Champlain Sea to 450 years in the SW Gulf of St. Lawrence, and hence are larger than the previous "conventional" correction, a uniform 400 years. The net effect is that deglaciation ages are diminished in most places by 1000-2000 years in comparison to Dyke and Prest (1987). However, the spatial pattern remains similar to previous reconstructions, being guided by the continental scale glacial geology. The revised deglaciation chronology places most of the major mid-deglaciation moraines into the Younger Dryas interval and brings the deglaciation of Hudson Bay into correlation with the 8200 cal yr BP event (Barber et al., 1999; Nature 400: 344-348).

G51A-02 0850h INVITED

The Time Rate of Change of Gravity in Canada: New Results and Insights.

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Gravimetry in Canada plays a significant role in many different areas of scientific interest including geophysical prospecting, structural interpretation and imaging of the vast Canadian landmass. Although the first gravity measurements in Canada date back in the early 1900 using pendulum and torsion balance devices, it was in the mid 1940 when the first gravimeters (Worden and LaCoste-Romberg) were used to form what it became later the Canadian Gravity Standardization Network (CGSN). The re-observation of CGSN continued ever since, following stringent standards both in methodology and instrument calibration. Over the last few decades absolute and superconducting instruments have enhanced the accuracy of gravity measurements and when combined with high precision geodetic observations, including those from the recent satellite gravity missions, can provide important information and constraints on geodynamic phenomena such as plate tectonics and glacial isostatic adjustment. The long history of CGSN along with repeated high precision absolute gravity measurements have recently been considered carefully in anticipation to estimate the time rate of change of gravity (g-dot) in Canada that is probably dominated by the glacial isostatic adjustment. Results of these analyses have been presented in the past and most recently in JGR Solid Earth (S. Pagiatakis and P. Salib, 2003). Research in this area continues as more observations are acquired. The long series from the Canadian Superconducting Gravimeter Installation (CSGI) combined with absolute measurements as well as with atmospheric and hydrological records enhance our knowledge on g-dot at the Canadian Absolute Gravity Site (CAGS) and offer new constraints and insight in the analysis of CGSN. In this contribution we will present new results on g-dot and will make comparisons with other geophysical studies in an effort to stimulate discussion and multidisciplinary research that will enhance our knowledge on the glacial isostatic adjustment and climate change.

G51A-03 0910h

Global Glacial Ice Volume: The Eustatic Sea Level Constraint

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Although the classical oxygen isotope derived inference of the rise of eustatic sea level across the glacial-interglacial transition of 120m has been confirmed by direct observations of the LGM depression of relative sea level at several locations, the validity of this inference has been questioned recently by several authors. The basis for the suggestion that the ice-equivalent eustatic depression of RSL at LGM must be greater than the Del-18O dervided estimate has been provided by an implementation of the theory of post glacial relative sea level change. In this paper I will employ the refined model of planetary deglaciation denoted ICE-5G(VM2) together with an extremely detailed analysis of the impact of changing coastline upon the theoretical predictions of RSL history, to show that these suggestions of the existence of a significant error in the oxygen isotope derived estimate of LGM land ice volume (eustatic sea level depression) are unfounded. These analyses demonstrate that the LGM depression of eustatic sea level was very near the classical estimate of 120m. This result provides strong support for the newly developed ICE-5G model of planetary deglaciation.

G51A-04 0925h INVITED

A glaciologically consistent model of northern hemisphere ice loading since the LGM

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The chronology of northern hemisphere ice-sheet extent during the last deglaciation is now fairly well known from glacial-geological observations. The thickness and volume of the ice sheets is however much harder to reconstruct from the geomorphological evidence and generally needs to be inferred from indirect evidence and modelling. One approach consists of glacio-isostatic modelling of relative sea-level changes in regions far away and in the vicinity of the former ice sheets to both determine the time-dependent change in global ice volume and the source contributions from individual ice sheets from some inverse modeling scheme.

One problem is however that the resulting ice-sheet geometries are often at odds with the conventional understanding of ice dynamics. Here we report on another approach that aims to produce a glaciologically, climatologically, and geomorphologically consistent ice-loading history on the continents of the northern hemisphere since the LGM. We use a 3-D thermomechanical ice-sheet model applied to a northern hemisphere domain, which was upgraded from earlier versions to include more sophisticated mass-balance and glacial-isostatic components and a new treatment for marine calving. The climatic forcing was derived from a time-dependent experiment with the atmosphere/ocean/sea-ice model of intermediate complexity ECBILT/CLIO, which is fast enough to be able to model the period from LGM to present-day in a logistically reasonable period of time. Boundary conditions imposed on ECBILT/CLIO consist of changes in ice sheet area (albedo), ice sheet elevation, solar insolation and greenhouse gas concentrations. We expect that using the resulting ice loading histories as input in visco-elastic earth models may put better constraints on postglacial rebound and current rates of land uplift.

G51A-05 0945h

Modeling Postglacial Rebound and Laurentide Ice-Mass Change in the North American Mid-continent Using Multiple Observational Constraints

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A variety of different types of observations are now available in mid-continental North America to constrain postglacial rebound models. We have compared theoretical model results with absolute gravity rates (8 to 12 yrs of data; 6 sites), GPS rates (4 to 8 years of data; 10 to 20 sites), lake gauge tilt rates (> 30 yrs of data; 10 to 20 gauge pairs), Lake Agassiz strandline tilt data and other published geodetic data. Except for the Churchill site, absolute gravity change rates are generally lower than previously published, as a result of longer data series and the application of corrections for previously undetected, inter-annual variations. In an attempt to fit all four data types, we have used a slightly altered ICE-3G loading history on a spherically symmetric Earth model with fluid outer core, compressible Maxwell viscoelastic mantle and elastic lithosphere. Meltwater is globally redistributed in a gravitationally self-consistent fashion, and includes provisions for formerly-glaciated marine regions. Reasonable agreement can be obtained north of 49°N by adjustments to ICE-3G north-west of Churchill and by small adjustments to lower mantle viscosity. However, south of 49°N both gravity rates and Lake Agassiz strandline tilts diminish much less rapidly with distance southward than predicted by the model. Available GPS vertical rates from different sources exhibit a significant scatter but on average show the model-predicted peripheral subsidence. We notice, however, that shifting the GPS results by about +1 mm/yr would bring the gravity and GPS rates into better agreement in this study area but would have the effect of shifting the zero uplift line further south than predicted by the present model. Comparisons between gravity and vertical GPS rates are needed at a larger number of sites to resolve the zero-line question.

G51A-06 1030h

Millennial Timescale Variations of Azimuthal Flows in the Earth's Core

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Changes in the length of day at decade timescales and parts of the secular variation of the magnetic field can be both consistently explained by torsional oscillations in the Earth's fluid core. This type of flow is predicted by theory and consists of azimuthal oscillations of rigid cylindrical surfaces aligned with the rotation axis. In this work, we apply the same concept to investigate variations in azimuthal flows at millennial timescales. Variations in the length of day reconstructed from ancient records of eclipses contain an oscillating component with a periodicity of roughly 1500 years. The dominant variations observed in archaeomagnetic field models are episodic eastward and westward drifts with a similar periodicity. We show that the time-dependent azimuthal flows that can consistently explain both the magnetic field variations and the changes in angular momentum of the core are characterized by a shear in the axial direction, in contrast to the decade timescales variations. We interpret these as oscillations in the thermal winds and discuss the implications for the geodynamo and core-mantle coupling at millennial timescales.

G51A-07 1045h

Simultaneous inversion of the Earth's mantle viscosity and ice mass imbalance in Antarctica and Greenland

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A self-consistent inversion procedure, based on the Levenberg-Marquardt method, has been used to invert simultaneously for the lower and upper mantle viscosity and for present-day ice mass loss in Antarctica and Greenland, within the framework of forward viscoelastic, stratified Earth's models based on an analytical, normal mode theory and on Satellite Laser Ranging data. The observational data are the even and odd zonal time variations of the Earth's gravity field, which we attribute to both Pleistocene deglaciation and present-day ice mass instabilities in Antarctica and Greenland. If Antarctica is considered as the only source of present-day melting, the lower mantle viscosity is about one order of magnitude higher than the upper mantle one and ice loss in Antarctica is -228 Gt/yr. If Greenland is also considered as a contributor to present-day melting, ice loss is partitioned between Antarctica and Greenland, with ice loss of -190 Gt/yr and -90 Gt/yr, respectively. The chi-square analysis show that Pleistocene deglaciation cannot be the only contributor to the time variations of the long-wavelength gravity field up to the harmonicdegree 8 and mass redistribution between the polar andf equatorial regions of the Earth is ongoing.

G51A-08 1100h INVITED

GIA-Induced 3-D Crustal Velocities Predicted Using a New Generation of Viscoelastic Earth Models

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In recent work we have described a new finite-volume, time-domain numerical scheme for predicting the response of a complex (Maxwell) viscoelastic Earth model to arbitrary surface mass loads. The method permits the incorporation of 3-D variations in mantle viscoelastic structure including, for example, heterogeneities in elastic plate strength and mantle viscosity. To address these complexities numerically, we have developed our code for a distributed (parallel) computer environment such as a Beowulf PC cluster. In this talk we apply the numerical formulation to compute a suite of predictions of present-day 3-D crustal deformation rates driven by the glacial isostatic adjustment process (GIA). These predictions are generated using an input global ice model and an ocean load computed using a solution to the governing 'sea-level equation'. The latter is obtained in a numerical calculation that utilizes the same space-time discretization as in the main solver. Our goal is to assess the sensitivity of previous predictions of GIA-induced 3-D crustal rates based on spherically symmetric Earth models to the introduction of: (1) elastic plate thickness variations within oceanic regions and across the ocean-continent interface; and (2) variations in mantle viscosity inferred, indirectly, from a tomographic model of seismic velocity heterogeneity.

G51A-09 1120h

Postglacial Induced 3-D Surface motion, Sealevels and Gravity change on a Spherical, Self-gravitating, Laterally Heterogeneous Maxwell Earth

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Previous studies of postglacial sealevels and surface motion often assume lateral homogeneity. However, studies of lateral heterogeneity on postglacial sealevels and surface motion often neglect the spherical shape of the Earth and self-gravity of the solid earth and oceans. In this paper, the gravitationally self-consistent Sea level Equation is solved by the Coupled Laplace-Finite Element method for a spherical, self-gravitating incompressible Maxwell earth. Relative sea level rate, land uplift rate, tangential velocity and rate of change of geoid height are computed for earth models with lateral heterogeneities - including lithospheric thickness, asthenospheric and lower mantle viscosity variations. One goal is to see if these rate-related observations can resolve the lateral structures. Another goal is to determine the optimal location where such observations can be used to resolve such lateral structures. It is found that all these rate-related observations are capable of detecting lateral viscosity contrast in the lower mantle underneath the load. However, geoid rates are not very useful in detecting lateral variations in lithospheric thickness and asthenospheric viscosity but tangential velocity is robust in distinguishing such lateral heterogeneity. Combined lateral variations in lithospheric thickness and asthenospheric viscosity can be detected by RSL data near the ice margin and land uplift rate or RSL rate data near the center of rebound. For lateral variations involving lithospheric thickness alone, the optimal place for detection is near the ice margin for both RSL, land uplift rate and RSL rate.

G51A-10 1135h

Post-Glacial Rebound Constraints on Radial Viscosity Structure and the Influence of 3D Variations

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Observations of isostatic adjustment of the earth's surface due to transient loading provide important constraints on the mantle viscosity structure. In this study, we investigate how well post-glacial rebound (PGR) observations are able to constrain the spherically symmetric (1D) viscosity structure of the earth. Computation of the earth's response includes realistic glacial loading, the gravitationally self-consistent Sea Level Equation, and the effects of polar wander. The computation is performed with a Green's Function method for 1D viscosity models, and with the spherical finite element software CitcomSVE [Zhong et al., 2002] for 3D viscosity models. Following a Monte Carlo algorithm, the responses of thousands of 1D viscosity models are computed. Their resulting PGR observables are compared to synthetic measurements generated from a specified viscosity model. How well the Monte Carlo inversion is able to constrain the 1D viscosity depends on the measure of misfit between a given forward model and the synthetic measurements. We consider measures of misfit which include different combinations of the following PGR observables: relative sea level (RSL) change at various locations in North America, $\dot{J}_2$, polar wander, and the rate of change of higher order gravity Stokes coefficients (anticipated Grace data). We find that, considering only the misfit in RSL and $\dot{J}_2$, it is difficult to constrain even a 4-layer viscosity model (that is, we find high variability among those 4-layer models that fit the data well). Inclusion of polar wander observations in the misfit function is found to improve constraints on lower mantle viscosity. Further inclusion of Stokes coefficients up to degree and order 10 can greatly improve constraints at all depths. The Monte Carlo inversion is performed for synthetic data taken from 1D viscosity models, and redone for synthetic data taken from a realistic 3D viscosity model (derived from shear wave tomography). When searching for 1D models that best fit the 3D synthetic data,

we find poorer constraints on the resulting best fit, suggesting the complicating influence of lateral inhomogeneity.

G51B CC: 516 A Friday 0830h

Heights and Geoid Modeling: North America II *(joint with OS, T, SEDI)*

Presiding: **D R Roman,** U.S. National Geodetic Survey**; M Veronneau,** Geodetic Survey Division, National Resources Canada

G51B-01 0830h

A Gravimetric Geoid Model for Vertical Datum in Canada

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The need to realize a new vertical datum for Canada dates back to 1976 when a study group at Geodetic Survey Division (GSD) investigated problems related to the existing vertical system (CGVD28) and recommended a redefinition of the vertical datum. The US National Geodetic Survey and GSD cooperated in the development of a new North American Vertical Datum (NAVD88). Although the USA adopted NAVD88 in 1993 as its datum, Canada declined to do so as a result of unexplained discrepancies of about 1.5 m from east to west coasts (likely due to systematic errors). The high cost of maintaining the vertical datum by the traditional spirit leveling technique coupled with budgetary constraints has forced GSD to modify its approach. A new attempt (project) to modernize the vertical datum is currently in process in Canada. The advance in space-based technologies (e.g. GPS, satellite radar altimetry, satellite gravimetry) and new developments in geoid modeling offer an alternative to spirit leveling. GSD is planning to implement, after stakeholder consultations, a geoid model as the new vertical datum for Canada, which will allow space-based technology users access to an accurate and uniform datum all across the Canadian landmass and surrounding oceans. CGVD28 is only accessible through a limited number of benchmarks, primarily located in southern Canada. The new vertical datum would be less sensitive to geodynamic activities (post-glacial rebound and earthquake), local uplift and subsidence, and deterioration of the benchmarks. The adoption of a geoid model as a vertical datum does not mean that GSD is neglecting the current benchmarks. New heights will be given to the benchmarks by a new adjustment of the leveling observations, which will be constrained to the geoid model at selected stations of the Active Control System (ACS) and Canadian Base Network (CBN). This adjustment will not correct vertical motion at benchmarks, which has occurred since the last leveling observations. The presentation provides an overview of the "Height Modernization" project, and discusses the accuracy of the existing geoid models in Canada.

G51B-02 0845h INVITED

Recent Progress Towards New Australian Geoid Models

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The members of the Western Australian Centre for Geodesy and our collaborators in Australia and around the world are active in the determination of future generations of the Australian geoid model and its relation to the Australian Height Datum (AHD). As part of ongoing Australian Research Council grant funding, we continue to improve our geoid determination theories, techniques and computer software for provision to the National Mapping Division of Geoscience Australia (formerly AUSLIG). We aim to release a new geoid model this year, called AUSGeoid2004. This paper summarises our work over the last few years on several key aspects to produce a new generation of geoid model for Australia that will better support the direct transformation of GPS-derived heights to the 1971 realisation of the AHD. These activities include:
· Experiments with global geopotential models derived from the new dedicated satellite gravity field missions, which seem to identify long-wavelength errors in the Australian land gravity data;
· Optimisation of the kernel modification so as to high-pass filter out these long-wavelength errors;
· Computation of new high-resolution grid of gravimetric terrain corrections from version 2 of the GEODATA 9-arc-second digital elevation model;
· Identification of erroneous ship-track gravity data using multi-mission satellite altimetry, and the selection of the best grid of altimeter-derived gravity anomalies around Australia;
· Trials of the University of New Brunswick's approach to regional geoid determination, and its comparison with the classical remove-compute-restore technique and the approaches that were used for AUSGeoid98;
· Experiments on griding different types of terrestrial gravity anomalies prior to regional gravimetric geoid computation;
· Investigation of various methods to fit the gravimetric geoid model to the AHD with regional GPS data, to produce a geoid-type' surface that will support the more direct transformation of GPS-derived heights to the AHD. Results of experiments on all these facets will be presented, together with some coarse estimates of the improved precision that can be expected from future releases of the Australian geoid models in relation to the AHD.

G51B-03 0905h INVITED

Using Energy Integrals for Airborne Geoid Profiling With GPS/INS

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Traditional geoid determination from airborne gravimetric data is based on the conventional space-wise approach that transforms the vertical gravitational acceleration to gravitational potential (and the geoid) in the form of a solution to a boundary-value problem in potential theory. The combination of 3-D airborne GPS and an inertial navigation system (INS) (consisting of accelerometers and gyros) has recently also been used to transform the horizontal gravitational acceleration into potential (and geoid) differences by simple line integration (essentially a time-wise approach), thus enabling geoid profiling without extensive areal survey coverage. In both cases, GPS positions must be numerically differentiated twice (or Doppler velocities once) to obtain the kinematic acceleration. We have developed a new profiling technique for geoid determination from airborne GPS/INS that utilizes velocities rather than accelerations to yield potential (and geoid) differences on the basis of conservation of energy. This eliminates an essentially redundant differentiation with subsequent integration of GPS velocities. Preliminary tests on airborne GPS/INS data show that this new technique, borrowed from recent satellite gravity mapping data processing methods, yields relative geoid accuracy that is better than 10 cm, and is comparable to the alternative profiling method.

G51B-04 0925h INVITED

The role of spaceborne gravimetry in height definition and unification

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The basic height equation, $h = H + N$, connects physical and geometric heights through the geoid. The equation is violated for several reasons: choice of height datum definition, height systems used, synoptic character of leveling and gravity data sets, extent and geography of leveling network, and others. Moreover, evaluation of the height equation occurs on discrete benchmarks, whereas the geoid and the gravity field are inherently field quantities with certain spectral characteristics. On top of these problems, we are now entering an era in which height systems must be regarded fundamentally as time-variable. This presentation attempts to identify and quantify the error sources that cause discrepancies in the height equation. It will then discuss how spaceborne gravimetry can contribute to the definition and establishment of a continental or even global height system. The discussion will include classical satellite-only models and the gravity satellite missions CHAMP, GRACE and GOCE.

G51B-05 0945h

Dynamic geoid modelling - A general overview

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Since the deloading of the ice at the end of the last ice age the Earth exerts continuous viscous rebound driven by the disequilibrium due to the mass imbalance in the initially ice covered areas. The process of the glacial isostatic adjustment (GIA) is identified by the geological and geophysical observations. In addition, a variety of geodetic measurements, such as time variations of gravity and geopotential, vertical and horizontal displacement rates, sea level variations measured by altimetry, etc., provide increasingly important constraints for GIA modelling. Vertical displacement rates over Laurentia predicted by the contemporary rebound models point to the necessity for the realization of a time-dependent reference surface for orthometric heights. An indispensable part of this is the determination of a time-dependent geoid, which raises the questions: (i) what kinds of data can be used and (ii) how they can be combined in an optimal way. In view of this problem, a cursory qualitative and quantitative analysis of the data available in Canada has been performed. The application of the classical geodetic techniques, such as Stokes integration and least squares collocation in time-varying gravity field modelling has been examined. Special attention has been paid to least squares collocation as a traditional technique for combining heterogeneous data. This paper presents an overview of the required analysis and recommends further studies that will contribute to the definition and realization of a dynamic geoid model for Canada.

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Arctic Ocean Geoids from GRACE and Surface Gravity Data: Comparisons with Altimetric sea Surface Topography

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Altimetric observations of much of the Arctic Ocean's sea-surface and sea-ice topography continue flowing from the ICESat and ENVISAT satellites. In addition, altimetric observations from CryoSat - scheduled for launch this November - should greatly enhance matters by extending coverage of the Arctic poleward to 88N. All these observations need to be referred to a highly accurate geoid in order to properly estimate the dynamic ocean heights as well as the 'freeboard' heights of sea ice. Thus we are developing suitable high-accuracy, high resolution gravimetric geoids of the Arctic Ocean. We have completed a preliminary "hybrid" geoid by combining data from the GRACE mission with detailed gravity from the international Arctic Gravity Project (ArcGP). This hybrid geoid will be compared with altimetric mean sea surfaces (ERS, ICESat etc) and evidence of dynamic topography (amplitudes on order of decimeters) will be presented. Such geoids will enable satellite altimeters to help monitor and comprehensively map thickness plus mass flux of Arctic sea ice. Moreover, these geoids will allow the application of satellite altimetry to mapping of the Arctic Ocean circulation and surface geostrophic currents. In addition, they will provide a reference against which absolute measurements of time-varying oceanographic features, such as dynamic topography and sea ice cover, can be repeatedly calculated through comparison with altimetric height measurements.

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Estimation of Systematic Errors in the Canadian Terrestrial Gravity Data From GRACE Gravity Results

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