G21A MCC: 2010 Tuesday 0800h

Reference Frame Definition and Modeling and Influence of Geophysical Fluids I *(joint with A, H, OS)*

Presiding: **T A Herring,** Massachusetts Institute of Technology; **M Feissel-Vernier,** Institute Geographique National

G21A-01 0800h INVITED

Requirements for Improved Definitions and Realizations of the ITRF Origin and Geocenter Motion

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The International Terrestrial Reference Frame (ITRF) currently assumes a framework of points rigidly attached to a hypothetical solid Earth surface wherein the points move only due to linear tectonic motions and accurately predictable tidal (periodic) effects. The ITRF origin is specified as coincident with the the geocenter, the center of mass of the entire Earth system, and is realized by long-term dynamical solutions of satellite laser ranging (SLR) data. Within this otherwise secular framework, small relative motions of the geocenter and the ITRF origin due to large-scale mass redistributions within the Earth system can be treated empirically as pure translations if the ITRF retains its rigidity. This approach has been used in analyses of SLR, DORIS, and GPS data to demonstrate "geocenter motions" at the few-mm level, roughly consistent with models for geophysical fluid variations. Effects are most significant at semi-diurnal and diurnal tidal periods, and at seasonal timescales. However, differences among observing techniques and analysis groups imply that important systematic errors remain, and insufficiently robust data exist to accurately quantify the expected geophysical mass effects. These realities complicate efforts to observationally realize a reliable time series of geocenter motions. Difficulties apply at a conceptual level, as well. For instance, the assumption of ITRF rigidity is inconsistent with the actual surface deformations expected due to large-scale mass motions. The International Earth Rotation and Reference Systems Service is considering more accurate definitions and specifications to provide a more consistent framework for the expression of measured ITRF quantities, including satellite orbits and Earth orientation.

G21A-02 0815h

Geocenter Variability and its Excitation: Insight From Geodetic and Global Geophysical Fluid Model Comparisons

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Changes in the Earth's geocenter are caused by mass redistribution of global geophysical fluids, such as the atmosphere, oceans, continental hydrology, glaciers and ice sheets. We have analyzed geocenter variations, as determined from satellite laser ranging (SLR), on a variety of timescales and compared them to excitation sources derived from various geophysical fluid models. We shall present the results of these analyses and discuss the implications of our findings.

G21A-03 0830h INVITED

Satellite Laser Ranging Observations of the TRF Origin

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The origin of the Terrestrial Reference System (TRS) is realized through the adopted coordinates of its defining set of positions and velocities at epoch, constituting the conventional Terrestrial Reference Frame (TRF). Since over two decades now, these coordinates are determined through space geodetic techniques, in terms of absolute or relative positions of the sites and their linear and episodic motions. The continuous redistribution of mass within the Earth system causes concomitant changes in the Stokes' coefficients describing the instantaneous terrestrial gravity field, including its longest wavelength components. Seasonal changes in these coefficients have been closely correlated with mass transfer in the atmosphere, hydrosphere and the oceans. The new gravity-mapping missions, CHAMP and GRACE, and to a lesser extent the future mission GOCE, address these temporal changes from the gravimetric point of view. For the very low degree and order terms, there is also a geometric effect that manifests itself in ways that affect the origin and orientation relationship between the instantaneous and the mean reference frame. Satellite Laser Ranging (SLR) data, especially that from LAGEOS 1 and 2, contributed the most accurate observations of this effect yet, demonstrating millimeter level accuracy for weekly averages. Other techniques, like GPS and DORIS, have also contributed and continue to improve their results with better modeling and more uniformly distributed (spatially and temporally) tracking data. We will present the results from the latest analysis of over a decade of LAGEOS 1 and 2 data, discuss their accuracy and compare them to results from other techniques. Finally, we will look into potential improvements in the future, which will likely lead us to even finer resolution and higher accuracy through the constructive combination of the individual time series.

G21A-04 0845h INVITED

Comparison of Geometric and Gravimetric Estimates of Surface Mass Transfer: Constraints on Geocenter Motion and Low-degree Love Numbers

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Mass redistribution on the surface of the Earth causes deformation of the solid Earth and translation of the solid Earth with respect to the whole Earth-ocean-atmosphere system ("geocenter motion"). These phenomena can be observed by tracking Earth-orbiting satellites from terrestrial observatories. For SLR tracking (generally of geodetic, LAGEOS-type satellites), non-gravitational forces are well modelled and so the orbit parameters and geocenter translation can be recovered quite precisely, despite the relative sparseness of the satellite constellation and tracking network. Conversely, in GPS tracking the forces acting on the satellites are less well modelled, and so direct estimates of geocenter translation are less precise. However, the greater density of the GPS constellation and tracking network allows the degree-1 deformation of the solid Earth to be estimated. Because the deformation and geocenter motion arise from the same surface mass distribution, comparison of the two constrains the ratio of Love numbers $h_1'/(1+k_1')$ applicable at periods from weeks to years. At degrees 2 and higher, multi-satellite SLR analyses have sufficient strength to solve for the time-varying zonal gravitational potential field. As at degree 1, this potential field must arise from the same surface mass redistribution that causes deformation of the solid Earth. We compare GPS estimates of higher-degree zonal deformation with recent SLR estimates of zonal gravitational potential change (Cox and Chao, Science 297, 2002). This method is in principle capable of constraining the degree-n Love number ratio $h_n'/(1+k_n')$ applicable at fortnightly to interannual periods.

G21A-05 0900h INVITED

Improvements in understanding the Earth's nutations and the roles of solid and fluid layers

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Continuing improvements in the precision of nutation estimates from observational data necessitate a fresh look at recent theoretical treatments with the twin objectives of achieving a better accounting of the data and possibly obtaining more insights into the geophysical properties and processes that affect nutations. Against this background, we make a reassessment of the geophysical model underlying the MHB2000 theory and of the approximations employed. For instance, could the viscosity of the core fluid have a nonneglible influence on nuation, and if so, could inclusion of viscosity in the modeling help to reduce the electrical conductivity required for the lowermost mantle layer or magnetic field at the boundaries of the fluid core? Conversely, could the nutation data help to place useful bounds on the fluid viscosity? The last question is of particular interest in view of the very high values inferred in the recent past from studies on Slichter (translational) modes of the inner core. Other possibilities for fine tuning nutation theory relate to the potential for better modeling of the effects of ocean tides and of the atmosphere. Besides considering these, a review of the effects arising from nonlinear terms in the equations of nutation theory will be made. Finally, one needs to consider whether estimates for nutations might be "contaminated" by "leakage" from other phenomena (e.g., tides) due to possible deficiencies in their modeling in the VLBI data processing software, or for other reasons.

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G21A-06 0915h

Geophysical Use Of The New Parametrization Of The Earth Orientation

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The increase of the accuracy of the space and geodetic techniques giving access to the Earth orientation, as well as the improvement of the terrestrial and celestial reference systems, require, for the best scientific benefit, a more accurate modelisation of the Earth rotation. In the framework of the IAU 2000 Resolutions (especially Resolution B1.8 recommending the use of the Celestial Ephemeris Origin), analysis centers are asked to produce X, Y coordinates of the CIP in the ICRS instead of the classical parameters dpsi, depsilon. The aim of this paper is to provide the transformation formulae in order to extract geophysical parameters from the observed EOP. In particular, we provide expressions to transform the CIP coordinates X, Y into prograde and retrograde nutation amplitudes. We also provide realistic evaluation of coupling effects between precession-nutation and variations in the Earth's angular velocity.

G21A-07 0930h INVITED

Expected Improvements in VLBI Measurements of the Earth's Orientation

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Measurements of the Earth's orientation since the 1970s using space geodetic techniques have provided a continually expanding and improving data set for studies of the Earth's structure and the distribution of mass and angular momentum. The accuracy of current one-day measurements is better than 100 microarcsec for the motion of the pole with respect to the celestial and terrestrial reference frames and better than 3 microsec for the rotation around the pole. VLBI uniquely provides the three Earth orientation parameters (nutation and UT1) that relate the Earth to the extragalactic celestial reference frame. The accuracy and resolution of the VLBI Earth orientation time series can be expected to improve substantially in the near future because of refinements in the realization of the celestial reference frame, improved modeling of the troposphere and nonlinear station motions, larger observing networks, optimized scheduling, deployment of disk-based Mark V recorders, full use of Mark IV capabilities, and e-VLBI. More radical future technical developments will be discussed.

G21A-08 0945h INVITED

Sub-Daily to Interannual Geocenter Motion - Direct and Inverse GPS Results

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The motion of center-of-mass (CM) of the entire Earth system with respect to the surface of the solid Earth is a consequence of mass redistribution on the surface and in the interior. Understanding of such motion is important for the definition and maintenance of the origin of global geodetic reference frames. Accurate measurements of such motion can also provide us with a window of opportunity to infer a global mode of mass variation with the largest spatial scale. In certain cases, determination of geocenter motion is essential when the goal is to know the complete mass variation spectrum. Driven by surface mass variation, the motion of CM with respect to the center-of-figure (CF) of the solid Earth surface has a one-to-one correspondence with degree 1 surface mass load. However, geodetic tracking networks have only finite number of stations, and can be very sparse in many cases. The motions of CM with respect to various networks therefore will be different from that with respect to CF and different among themselves. The network-based measurements will be further complicated by higher degree surface load induced deformation. These issues will be examined as we report our direct and inverse measurements of sub-daily to interannual geocenter motions through GPS orbit dynamics and relative surface deformation. We will also discuss implications of geocenter motion on the study of surface mass variations using time-variable gravity data.

G21B MCC: Level 1 Tuesday 0830h

Insights Into the Earthquake Cycle I Posters *(joint with OS, S, T)*

Presiding: **S L Hamilton,** University of Durham**; J T Freymueller,** University of Alaska, Fairbanks

G21B-0257 0830h POSTER

Interseismic Displacements: Cycle Invariance, Slip Rate, and Rheology

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Geodetic data are commonly interpreted in terms of strain accumulation on faults. Often such interpretations are guided by simple models of interseismic displacements near an infinite strike slip fault (e.g. Savage and Prescott, 1978). These models assume relatively simple rheologies and that the system is in a cycle invariant state, with periodic ruptures such that the displacements throughout the seismic cycle do not vary from one cycle to the next. The displacements are given by perturbations to an average arctangent displacement profile, parameterized by the slip rate and locking depth of the fault. We explore the relationship between cycle invariance, changes in slip rate, and rheology to inferences of slip rate, locking depth, and rheology in models of infinite faults with given histories and sizes of ruptures. The number of seismic cycles required to attain cycle invariance is a function of the strength of the system (parameterized by the Maxwell relaxation time, τ_M) and the recurrence time of the ruptures (period, T). In systems with $\tau_M \ll T$ the invariant average arctangent curve is established over very few seismic cycles. However, for $\tau_M \approx T$ or $\tau_M > T$, it takes many seismic cycles to establish cycle invariance. A consequence of this is that it is easy to confuse a large postseismic relaxation signal (low τ_M) calculated ignoring all but the latest earthquake with a periodic system and a small post-seismic relaxation signal (high τ_M). During transition to cycle invariance, the average stress level of the system changes by an amount $\Delta\sigma$, determined by τ_M, T, and the stress drop in a rupture (σ_{eq}); $\Delta\sigma$ is independent of the magnitude of the initial background stress. For low τ_M, $\Delta\sigma$ is negligible compared to σ_{eq}, but may be much larger than σ_{eq} for high τ_M. A change in slip rate on a fault, accommodated by a change in recurrence time or σ_{eq}, tends to force the system toward a new average stress. For weak rheologies, changes in slip rate are negligible as the system establishes cycle invariance quickly. However, for stronger rheologies, it takes many seismic cycles to attain cycle invariance, and during the non-invariant transitional time, inferences of slip rate, locking depth, and rheology will be incorrect.

G21B-0258 0830h POSTER

Stress-Driven Earthquake Cycle Model of the Active Taiwan Collision Zone

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We have developed a 2-D earthquake cycle model for compressional deformation in Taiwan in which active faults slip in response to the stresses in the lithosphere. The earth is modeled as an elastic lithosphere overlying a Maxwell viscoelastic asthenosphere. Slip on major earthquake-producing faults is modeled with sudden periodic slip at a specified recurrence interval. Coseismic rupture is modeled as a full stress-drop. Creeping faults slide at zero resistive shear stress throughout the earthquake cycle. The purpose of our modeling is to infer the geometry of active faults and partitioning of slip-rates among the faults. We seek a model that is consistent with surface deformation measured by GPS, deformation patterns at depth inferred from earthquake focal mechanisms, and longer-term geologic data such as paleoseismology and subsurface structure revealed by reflection seismology. Our study focuses on central Taiwan where an extensive GPS network has recorded preseismic, coseismic, and postseismic deformation associated with the Mw = 7.6, 1999 Chi-Chi earthquake. Active deformation in central Taiwan is concentrated mainly in two regions: the Longitudinal Valley of eastern Taiwan, which is thought to be the suture zone between the Philippine Sea Plate and the Eurasian continental margin, and the western fold and thrust belt. Interseismic deformation recorded with GPS for seven years leading up to the Chi-Chi earthquake displays high shortening rates of about 35 mm/yr across the Longitudinal Valley and subsidence of up to 15 mm/yr. About 25 mm/yr of shortening is occurring across the western fold and thrust belt. We model this deformation with slip on an eastward dipping Longitudinal Valley Fault and slip on a ramp-decollement geometry under the western fold and thrust belt. We find that the data is best explained with a decollement that dips about 10° under the western foothills and then dives down at a steeper angle of approximately 40° under the Central Ranges. In our model the decollement creeps continuously throughout the earthquake cycle and the frontal ramp breaks periodically in large earthquakes and is locked interseismically. The Longitudinal Valley fault creeps between 0 and 11 km depth and between 20 and 30 km. The fault is locked interseismically between 11 and 20 km. The long-term slip rate on the Longitudinal Valley fault is nearly twice the long-term slip rate on the frontal ramp under the western foothills. This viscoelastic cycle model explains the horizontal and vertical interseismic GPS data and deformation patterns at depth inferred from focal mechanisms of earthquakes occurring just before and just after the Chi-Chi earthquake. The long-term uplift rates are also consistent with the general patterns inferred from dated uplifted terraces. We also compare the fault geometry obtained form the stress-driven cycle model with inversions of GPS data for fault geometry using standard kinematic dislocation models in which the slip is prescribed as a displacement discontinuity rather than solved for as in the stress-driven cycle model. A bootstrap analysis is performed using the kinematic model to identify a range of solutions that fit the data satisfactorily. We show that many of the fault geometry models, which fit the data using the kinematic model, do not fit the data with the stress-driven model. This indicates that we can better constrain the range of possible models by enforcing stress boundary conditions on the faults.

G21B-0259 0830h POSTER

Seven big strike-slip earthquakes

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We examine seven large ($M_w > 7$) strike-slip earthquakes that occurred since the beginning of ERS 1 and 2 missions. We invert GPS observations and InSAR interferograms and azimuth offsets for coseismic slip distributions. We explore two refinements to the traditional least-squares inversion technique with roughness constraints. First, we diverge from the usual definition of "roughness" as the average roughness over the entire fault plane, and allow "variable smoothing" constraints. Variable smoothing allows our inversion to select models that are more complex in regions that are well-resolved by the data, while still damping regions that are poorly resolved. Second, we choose our smoothing parameters using the $_jR_i$ criterion. The $_jR_i$ criterion draws on the theory behind cross-validation and the bootstrap method. We examine the theoretical basis behind such methods and use an analytical approximation technique for linear problems. We provide maps of model variance and spatial averaging scale over the fault plane, to explicitly show which features in our slip models are robust. We examine the 1992 Landers (CA), 1995 Sakhalin (Russia), 1995 Kobe (Japan), 1997 Ardekul (Iran), 1997 Manyi (Tibet), 1999 Hector Mine (CA), and 2001 Kunlun (Tibet) earthquakes. We compare features of the slip distributions such as the depth distribution of slip, the inferred magnitude and the degree of heterogeneity of slip over the fault plane, as resolved by the available InSAR and GPS data. We end with a brief description of the data coverage required for future earthquakes of similar size if we want to infer some of the above quantities to within a given confidence interval. We describe both the number of InSAR scenes and the distribution of GPS points that would be required, based on theoretical treatments of the fault plane/data point geometry using the $_jR_i$ method.

G21B-0260 0830h POSTER

3-D Viscoelastic FEM Modeling of Postseismic Deformation Caused by the 1964 Alaska Earthquake, Southern Alaska

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To complement previous modeling efforts to understand the postseismic deformation following the 1964 Alaska earthquake, we are implementing a three-dimensional viscoelastic model using the Finite Element Method. Rapid postseismic uplift, as much as 125 cm, occurred on the central part of the Kenai Peninsula over the 35 years following the earthquake. Recent precise GPS observations show heterogeneous plate coupling, and a vigorous ongoing postseismic response to the 1964 earthquake. Past models of the postseismic deformation have focused on afterslip models because earlier viscoelastic-only models did a poor job at predicting the cumulative uplift observations, but this might be due to unrealistic assumptions for the model geometry. We are working toward a realistic 3D viscoelastic model that, in concert with afterslip models, can be used to understand how much each component contributes to the total postseismic deformation. Our model suggests that viscoelastic relaxation contributes to the total 30 years postseismic uplift moderately in the Kodiak region (40 %), slightly in the western Kenai Peninsula (<20 %) and not significantly in the northern Kenai Peninsula (<10 %). Most of the observed total uplift in Kenai Peninsula must be explained by afterslip. The depth of afterslip (30-70 km) is deeper than that of coseismic rupture (10-25 km). Some recently observed trenchward horizontal deformation far inland from the trench is explained by the viscoelastic response of the 1964 earthquake. But transient slip is required to explain the large trenchward motion in the northern and western Kenai Peninsula.

G21B-0261 0830h POSTER

Spatio-temporal distribution of interplate coupling in southwest Japan deduced from inversion analysis

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