

2001 and 2003 from two seafloor precision transponder arrays at 12S off the coast of Peru. The geodetic positioning technique uses two reference points located 20 km and 50 km upslope from the Peru-Chile trench to characterize the updip limit of locking between the downgoing Nazca plate and the South America plate. Stick slip behavior is thought to cause the majority of interseismic activity between the convergent plates. Absolute and relative horizontal deformation was determined with 1-cm uncertainty and may help in understanding the cause and location of stick slip behavior between the plates. Combined with land based geodetic stations, this study presents the first observations of convergent plate motion above the entire subduction thrust zone. We will report preliminary results and their implications for models of thrust fault behavior.

G21C CC: 220 C-E Tuesday 0830h Toward a Stable North America-Fixed Reference Frame II Posters (joint with S, T)

Presiding: G Blewitt, University of Nevada, Reno; M Craymer, Natural Resources Canada; W E Holt, State University of New York at Stony Brook

G21C-01 0830h POSTER

First Report of the Stable North America Reference Frame (SNARF) Working Group

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We report on the first SNARF Workshop funded by NSF EarthScope, held on Jan 27, 2004. The initial SNARF Working Group membership was approved by the UNAVCO Board and is charged with producing a standard reference frame (for studies in North America) and specifying standard procedures to realize such a frame to meet the needs of EarthScope and the UNAVCO community. SNARF is an official IAG working group under the North America Reference Frame (NAREF) sub-commission. There is also a public service element to these activities in that one objective is for SNARF to become part of the definition of the legal reference frame used in the USA and Canada (NAD83), a natural spin-off demanded by society's increasingly sophisticated needs following on the heels of scientific progress. Through the first workshop, the SNARF WG has already begun to address the pressing needs for a North America-fixed reference frame that is stable at the sub-millimeter level, and what is involved in defining a frame with such stability. Velocity solutions from GPS networks covering the North America-Pacific plate boundary (including the Plate Boundary Observatory under construction) are most naturally expressed with respect to the stable interiors of either the North America or Pacific plates. As well as providing a common

frame by which to compare results from different analysis groups, such a system makes it easier to interpret the data in terms of where the total budget of relative plate motion is accommodated, and how deep plate boundary dynamics penetrate into the plate interior. Defining a stable frame at the sub-millimeter level requires adequate characterization of kinematics at that level across a sufficiently broad expanse of what may be termed the "plate interior," which deforms due to GIA and other mantle processes, coupled with lithospheric heterogeneity. A dynamically defined velocity datum (as opposed to a purely kinematic choice) is preferable to add interpretive value to site velocities. We summarize initial findings of the workshop that begin to address these issues, and present a roadmap of what is required to realize a reference frame for stable North America.

G21C-02 0830h POSTER

The NAREF Perspective on a New Plate-Fixed Reference Frame for North America

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In collaboration with the IAG community, its service organizations and the national geodetic organizations of North America, the IAG's Sub-Commission 1.3a on Regional Reference Frames for North America (NAREF) provides international focus, cooperation and coordination for issues involving the geodetic reference frames and control networks of North America. Some of these issues include the maintenance and future evolution of reference frames for North America and the setting of standards and guidelines. To this end, NAREF has coordinated the densification of the ITRF reference frame in North America and has been providing regular weekly coordinate solutions for most of the permanent GPS receivers on the continent since 2001. Work is now progressing on providing regular cumulative solutions with velocities estimates for all stations. More recently, a new initiative has begun, underwritten by UNAVCO, Inc. in support of the EarthScope project, to establish a stable, plate-fixed reference frame for North America that would serve the broad scientific and geomatics communities. The goal is to provide a consistent reference system, including velocity models, procedures and transformations, tied to a "stable" North America in which scientific and geomatics results (e.g., positions in tectonically active areas) can be produced and compared. This paper focuses on the requirements that such a reference frame would need to satisfy from the perspective of NAREF. We also make some suggestions for how such a new reference frame could be implemented for the benefit of the general public and discuss some pitfalls learned from the ITRF densification work.

URL: <http://www.naref.org>

G21C-03 0830h POSTER

Test of a Center of Lateral Figure (CL) reference frame for a global GPS network

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Seasonal degree-one deformation related to loading effects are a source of significant misfit between observed site coordinates and assumed positions that are based on a linear center of surface figure (CF) reference frame. This discrepancy is partly absorbed by apparent annual variations in the GPS "scale" parameter which, in turn, spreads annual deformation artifacts to sites elsewhere on the Earth's surface. In the presence of degree-one deformation, a suitable reference frame model should allow for non-linear site motion. The Center of Lateral Figure (CL) reference frame is one possible solution. With the CL model, station motions are constrained to move with constant horizontal velocities, and the vertical velocities are unconstrained. This confines degree-one deformation to the unconstrained vertical component. A CL reference frame model is demonstrated here using the results of a GIPSY/OASIS II fiducial-free analysis of over 100 globally distributed GPS sites. The reference frame model utilizes only the horizontal component of site positions and the GPS "scale" parameter is neglected in the initial solution. Preliminary results show that seasonal deformation is placed in the vertical component, as expected, and that the geographical distribution of seasonal signals is consistent with degree-one loading models. An additional finding from this test is that the

WRMS scatter in daily horizontal site positions is reduced. This is likely due to reliance on the precise horizontal component, and omission of the noisier vertical component. The result is that the horizontal scatter for stations in a global solution approaches the quality of a regionally-filtered solution. For analysis on a plate-wide to global scale, as is the case for SNARF, use of a CL frame with the vertical component unconstrained may be useful. With the vertical component unconstrained, horizontal positions are not biased by seasonal vertical motion and noisy vertical motion at sites located 90 degrees around the side of the earth. In turn, a precise datum for the local vertical component is realized using horizontal data from the same sites a quarter turn around the Earth.

G21C-04 0830h POSTER

New Constraints on Crustal Deformation in the New Madrid Seismic Zone From Continuous GPS Geodesy.

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Preliminary results from the first determination of crustal velocities in the area of the New Madrid seismic zone based on two years of continuous GPS geodetic measurements indicate that velocities with respect to stable North America are small (less than 3mm/yr) and not significantly different than zero. Our results are significantly stronger than previous campaign results, which while also not statistically different from zero, yielded velocities with respect to stable North America from near zero to several cm/yr. They also rule out velocities determined by campaign measurements that are "statistically significant" with magnitudes larger than a few mm/yr. The continuous GPS results are also the first to suggest tectonically reasonable deformations, in terms of both rates and geologically and seismologically defined structures in the New Madrid seismic zone. The relatively undurated pile of Mississippi Embayment sediments, may also act as a filter to displacements at its base, which may be significantly larger than those observed at the surface. Our results strengthen the argument against models based on conventional, plate boundary style dynamics for the generation of large earthquakes in the New Madrid seismic zone. With respect to the development of new models for New Madrid tectonics, we stress both the preliminary nature of our results and the sparse sampling provided by the continuous network. Our results can clearly be used to reject models that do not produce small or no surface deformation but are currently less useful to additionally constrain or distinguish among competing tectonic models that meet the stringent limitations placed on surface deformation. The upper bound, of a few mm/yr, on the velocity of our stations with respect to a stable North America shows the importance, timeliness and necessity of improving the definition of stable North America to further our understanding of intraplate earthquakes.

G21D CC: 516 B Tuesday 0830h Toward a Stable North America-Fixed Reference Frame I (joint with S, T)

Presiding: G Blewitt, University of Nevada, Reno; M Craymer, Natural Resources Canada; W Holt, State University of New York at Stony Brook

G21D-01 0830h INVITED

Evolving from NAD 83

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The development of a stable North American reference frame should influence future positioning activities on our continent not only for scientists; but also for land surveyors, GIS professionals, remote sensing professionals, and others. Although our current spatial reference system, the North American Datum of 1983 (NAD 83), may seem sufficiently adequate for most positioning activities in North America, history has revealed that reference systems need to evolve to keep pace with the ever-increasing accuracy with which we are able to locate points on and near the Earth. These accuracy improvements are driven by advances in geodetic technology and geophysical theory. Indeed, the development of electronic distance measurement (EDM) instrumentation in the 1960s and satellite-based Doppler positioning in the 1970s compelled the North American positioning community to supersede the North American Datum of 1927 (NAD 27) with NAD 83 in the mid-1980s. In particular, the EDM and Doppler observations revealed that NAD 27 positional coordinates contained regional distortions exceeding several meters. The Doppler observations also revealed that the NAD 27 origin was more than 100 km from the Earth's center of mass. NAD 83 was introduced to correct these NAD 27 shortcomings. No sooner was NAD 83 adopted, than newer geodetic technologies (GPS, VLBI, SLR) and newer geophysical theories (plate tectonic and glacial isostatic adjustment) came along to expose some of its shortcomings. For example, it is now known that NAD83 is offset from the geocenter by about 2 m. Here we examine the status of NAD 83 to consider how we may develop a better reference system for North America.

G21D-02 0850h INVITED

The Hunting of the SNARF

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Establishing a Stable North American Reference Frame (SNARF) is important to understand the processes that occur in plate boundary zones and that affect the stable plate itself. Stable North American defined as the area east of the Rocky Mountains has a number of seismically active areas including New Madrid Seismic Zone and the Charevoix region of Quebec whose causal mechanisms remain poorly understood. For the last 10 years we have been characterizing the kinematics of present day deformation of the stable plate interior using both Global Positioning System (GPS) data and seismic data. As the number of continuous GPS (CGPS) sites in Eastern North America and the lengths of data have increased we have seen a steady improvement in the root mean square misfit of site velocities to those expected for a perfectly rigid plate to less than 1mm/yr. However further reductions in the misfit are challenging since simply increasing the number of sites results in little to no improvement probably reflecting systematic errors. These errors include in order of importance: characterizing propagation delays caused by water vapour in the atmosphere, glacial isostatic adjustment (GIA) due to glacial unloading, regional site motions due to hydrologic effects, local site motions, reference frame, and satellite orbit errors. Obtaining site, temporally and azimuthally specific estimates of the water vapour content would result in a significant improvement to current mapping functions. Although we believe that we can identify sites that are most affected by GIA and exclude these sites from our stable plate definition, we are still unable to remove the GIA signal from the remaining sites. Global annual and semiannual hydropheric signals can be successfully removed, but regional to local ones are still poorly understood. Part of the understanding of this signal will emerge through high-density networks being built with 50-100km spacing. Local site motions and equipment biases are very difficult to identify unless they are very large, althoughwwh integrating spatially continuous data such as INsAR may help identify these effects. Reference frame, ITRF 2000, and satellite orbital errors are probably much smaller than any of the other error sources.

G21D-03 0905h INVITED

The Plausible Range of GIA Contributions to 3-D Motions at GPS Sites in the SNARF Network

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A significant contribution to the secular crustal deformation across North America is the continued recovery from loading effects caused by the Late Pleistocene ice sheets (glacial isostatic adjustment or GIA). The crustal motions driven by this process are quite large (horizontal motions on the order of 1 mm/yr across the plate and vertical motions of over 1 cm/yr near the loading centers). Unfortunately, both the Late Pleistocene ice history and the viscosity model of the solid Earth remain uncertain. The range of model predictions derived by considering reasonable variations in these inputs can be as large as the signals. In this talk, we first consider reference frame and orientation issues that arise when comparing model predictions to GPS observations. We then examine a suite of model predictions using both ICE-1 (a history based on geological data alone) and ICE-3G (constrained, in part, from geophysical data sets) as well as viscosity models that include a range of lithospheric thicknesses and mean upper and lower mantle viscosities. We compare these results at GPS sites that may be included in SNARF to determine if a subset of these stations exhibit consistent or small GIA contributions; this consistency could be used as a site selection criteria for SNARF.

G21D-04 0920h INVITED

Realization of a Stable North America Reference Frame

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In this paper we address the realization of a stable North American frame (SNARF). The long term realization can be achieved through the positions and velocities of a set of sites on a stable part of the Northern American plate that will have zero average velocity in the reference frame combined with sites which have well defined velocities relative to this stable region. These other sites may be on different tectonic plates with a rigid body rotation rate between the plates. The estimated velocities of realizations of this type using GPS data collected over the last decade differ from zero or the predicted motion with root-mean-square (RMS) scatter of 0.6 mm/yr for the horizontal components of motion. Vertical motion RMS scatters are around the 1 mm/yr level. The greater challenge for SNARF is the day-to-day realization of the frame. For this application, deviations of sites from zero or secular motion will introduce daily rotations and translations of the frame. These deviations arise from atmospheric pressure loading which should be well modeled with high temporal resolution and water loading variations which are not well modeled currently. Other complications arise from instrument failures and equipment changes. The net effect of these deviations is that frame realizations over small regions (such as Southern California) are more precise (daily position RMS of 0.6 mm) while continental scale realizations have RMS position deviations of 1-2 mm. We discuss methods that could be used to achieve day-to-day continental frame accuracy similar to regional realization precision.

URL: <http://geoweb.mit.edu/~tah/AGUS04>

G21D-05 0935h

SOPAC's Instantaneous Global Plate Motion Model: Contributions to a North-America Fixed Reference Frame

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We have implemented at the Scripps Orbit and Permanent Array Center an automated procedure whereby an instantaneous global plate motion model is updated on a regular (monthly) basis to improve its precision and reliability as new data become available, and as a baseline against which anomalous motions can be detected. The global plate motion model is for seventeen major and minor tectonic plates based solely on

analysis of data from 133 globally distributed continuous GPS stations, spanning the period from January 1991 to the present. Site positions estimated from 24-hour segments of data are aligned day-by-day to the IGS realization of the ITRF2000 reference frame using a similarity transformation, thereby ensuring that the ITRF2000 No-Net-Rotation condition is preserved and that our plate motion model is absolute. Linear velocities of a carefully selected set of stations are estimated from the position time series, along with annual and semi-annual fluctuations and position offsets due to GPS instrument changes. A white noise plus flicker noise model is applied to estimate realistic uncertainties for the site velocities, which are then propagated into the derived plate motion model parameters. We also examine the vertical velocities in the site selection process. Here we consider the stability of a North-America fixed reference frame, in terms of changes in the monthly updates of the global plate motion model. We discuss the implications and limitations of this frame for PBO, the new definition of a North America datum, and the California Spatial Reference System maintained by the California Spatial Reference Center.

URL: <http://sopac.ucsd.edu/processing/coordinates>

G21D-06 0950h

Application of a North America Reference Frame to Regional GPS Arrays in the Deforming Plate Boundary Region: Examples From the Pacific Northwest Geodetic Array (PANGA)

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Global and regional solutions for GPS (Global Positioning System) networks are typically analyzed in the International Terrestrial Reference Frame (ITRF), derived from a mathematically powerful and self-consistent reference system that, for non-specialists, is non-intuitive and poorly understood. Such regional solutions in the ITRF can then be transformed into "stable plate" or other physically meaningful reference frames, either by using published Euler vectors that describe plate motions in the ITRF or by including stations in an analysis that can be used to define a "rigid" plate or block. The PANGA network has used this latter technique to define a GPS determined "North America" reference frame through several generations of solutions. Our approach consists of generating fiducial-free, ambiguity resolved daily solutions that are stabilized to ITRF2000 using JPL data products such as fixed orbits, fixed clocks, and daily frame files. These are then stabilized to a reference file in ITRF2000 that also contains regional stations with well-determined linear velocities. This results in negligible change in velocities but much greater resolution of the time series. Finally, the ITRF velocities are stabilized to a subset of stations that may characterize a more stable continental interior. We explore the stability of this reference frame over annual solutions generated since 2000. Enhancements to the data analysis strategy, a more robust set of stations from the continental interior, better regional GPS coverage, and concomitant improvements in precision improve resolution of time series but have little effect on stability of the reference frame at the millimeter level. We propose approaches for optimization of a Stable North America Reference Frame (SNARF) that will provide a plate scale regional stabilization, steps towards a physically meaningful reference frame, and better resolution of time series.