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Workshops to Establish a Stable North American Reference Frame for EarthScope

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PART 2: PROJECT FINDINGS

The following summarizes, some of the key findings of the SNARF project. More details can be found in the Appendices, and in the references listed at the end of this section. Many of the references refer to presentation and posters that can be found on the SNARF web page

http://www.unavco.org/research_science/workinggroups_projects/snarf/snarf.html

(1) GIA can cause systematic error in pole of rotation that leads to ~ 1 mm/yr velocity bias. A significant cause of potential bias arises from lateral heterogeneity, such as the plate boundaries themselves (Figure 1). On this basis, the SNARF WG decided that a different approach was needed than simply adopting a specific GIA model. Instead, a stochastic data-assimilation approach was developed and applied.

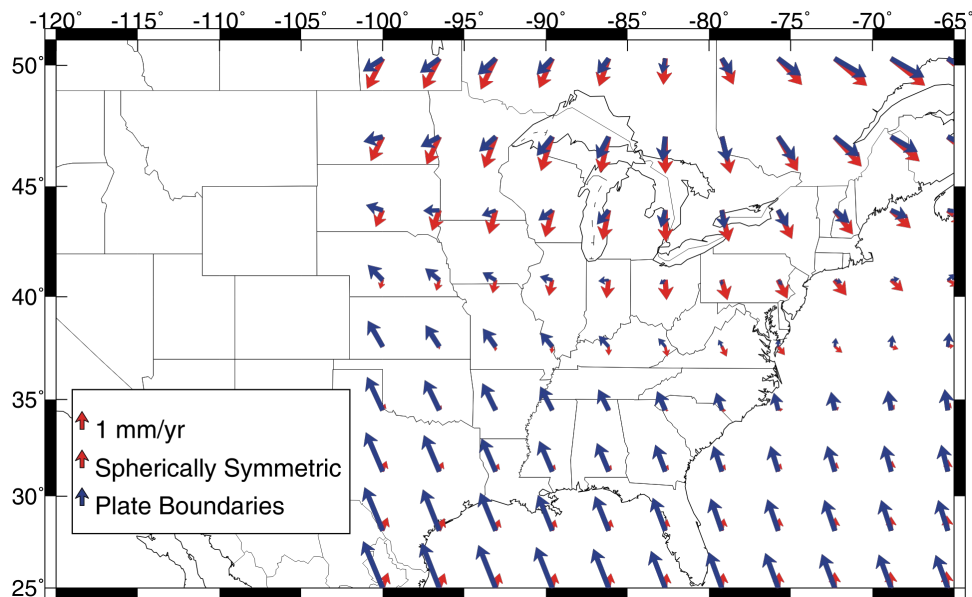


Figure 1: Modeled effect of plate boundaries on GIA-induced horizontal velocities (Tamisiea, 2006).

(2) In the global reference frame ITRF2005, the pattern of GIA uplift (Hudson Bay) and peripheral bulge (Canada-US) is clearly delineated in the GPS velocity solutions. This is first-order evidence that ITRF is

suitably accurate. The SNARF WG decided to adopt the ITRF2005 origin and scale as the reference frame for vertical motions. In all contributing GPS solutions, vertical motions beyond the peripheral bulge are consistently < 1 mm/yr, including the plate boundary regions spanning the Basin and Range, the Sierra Nevada, and the NA-Pacific transform.

(3) In a non-rotating reference frame, there exists a plate interior (east of Rockies/Rio Grande Rift) which is clearly stable in all contributing GPS velocity solutions to < 1 mm/yr. Bermuda is clearly on stable North America (with no apparent passive margin deformation, as expected). However, Greenland, Alaska, Siberia motions appear to be significant in some GPS solutions (1-3 mm/yr), as compared to sites in the stable plate interior. This may be in part due to a mix of GIA, current ice (de-)loading, and permafrost effects.

(4) Monument stability and jumps in time series remains an issue for many sites, but the best sites have 0.1 mm/yr monument stability (inferred by local baselines).

(5) Daily transformations into SNARF are recommended versus rotation of velocity field.

(6) SNARF has been successfully adopted by the operational analysis centers of the Plate Boundary Observatory. Also, it is now clear that operational analysis of GPS data throughout Stable North America (in Canada and USA) can be performed successfully by the national geodetic agencies, NRCAN and NGS, thus leading the way to the future adoption of a legal North American Reference Frame (NAREF) that is based on SNARF concepts and data.

(7) A new SNARF version 2.0 is currently undergoing final adjustment and testing and is scheduled for public release in Spring 2008. Some small remaining site edits are needed to remove sites with local subsidence and monument instability. Once the new GIA model is available, the final version should be generated quickly. The whole SNARF system will need to be re-done once the IGS analysis using absolute phase center models is completed. The IGS re-analysis will take at least another year.

In summary, the SNARF project has successfully met its key objectives, in that we have defined a vertical and horizontal reference frame which significantly enhance geophysical interpretation of GPS velocities in the Plate Boundary Observatory. We find that future improvements are currently limited by the accuracy of GIA models and the quality of existing geodetic stations in stable North America (versus the relatively higher quality of stations in PBO). We therefore recommend that future research efforts be directed to improved GIA models and their impact on reference frame definition, and into improving the quality and density of geodetic infrastructure within stable North America, far from the tectonically active plate boundary.

Appendix A1. Analysis of GPS solutions submitted for SNARF Version 2.0 contributed by Tom Herring

Introduction

Five GPS analyses have been submitted for inclusion in SNARF version 2.0. The characteristics of these solutions are given in Table A1.1. For the initial constructions of SNARF version 2.0, only stations that appear in at least two analyses are included in the reference frame. This approach allows us to check the agreement between different analyses and in some cases eliminate stations that have discordant velocity and position estimates. With this condition applied, there are 465 stations at 283 unique locations included in the combination.

A critical step in the combination of the analyses submitted to SNARF version 2.0 is the calculation of the scale factors that must be applied to the submitted covariance matrices so that all the analyses are given the appropriate weight in the combination. The scale factors are computed from the chi-squared-per-degree of the fit of the analysis center solution the ITRF2005 velocities of sites in North America. The re-weighting scale factors are given in Table A1.1. After these factors are applied and the analyses combined, there are 222 unique locations with height rate sigmas less than 5 mm/yr, 213 locations less than 4 mm/yr, 167 locations less than 2 mm/yr and 59 locations less than 1 mm/yr.

The final step in the generation of SNARF version 2.0 will be the synthesis of current velocity estimates in the glacial isostatic adjustment (GIA) ensemble model and the final alignment of estimated velocity on the stable North America sites in the GIA model.

Table A1.1: Submissions to SNARF Version 2.0

Code	AC	File	#Stations	#Unique Stations	Re-weight
CBN	CBN/NRCAN	CBN06P30v4uc.snx	200	190	8.8
NAR	NAREF/NRCAN	NAR06P44v6uc.snx	724	578	621
PUR	EC/Purdue	calais nov06.snx	677	675	3.6
UAF	JF/UAF	UAF SNARF.stacov	132	132	7236
UNR	GB/UNR	UNR SNARF 0208.stacov	45	45	2653

The table entries are: Code: Code to denote the analysis; AC: Analysis and center. The codes are CBN Canadian Backbone Network, NAREF North America Reference Frame, EC Eric Calais, JF Jeff Freymueller, GB Geoff Blewitt, NRCAN National Resources Canada, Purdue Purdue University, UAF University Alaska Fairbanks, and UNR University Nevada Reno. #Stations and #Unique Stations are the number of stations and unique locations included in the analysis. These two entries differ due to offsets in stations positions that arise from antenna and radome changes and sometimes monument reconstruction. Re-weight is the scale factor applied to the submissions variance-covariance matrix to generate standard deviations for velocity estimates that are consistent across the analyses (see text for discussion).

Analysis Method

The submissions from each center are converted from SINEX or STACOV to the GLOBK binary format. Centers which have their frames constrained have a ± 10 mas rotation and ± 1 m translation covariance added to the submitted covariance matrix. These covariance matrices are computed such that the stations rotate and translate in a consistent fashion. As noted in Table 1, variance-scaling factors are determined by velocity RMS fits of each center's velocity field to IGS05. During the combination of the results from each center, rotations, translation and scale values and rates are estimated. At the end of the combination, the reference frame is realized by rotation/translation and scaling onto a chosen reference system. This reference system will ultimately be a GIA ensemble estimated model. At this stage while the inputs to SNARF version 2.0 are being validated we have used SNARF version 1.0 GIA model, IGS05 or SNARF

version 2.0 (for comparing analysis center results). During the combination, we also check for position inconsistencies between the analysis centers, which sometimes arise in heights or from different treatments of antenna and radome changes. In a final step of the combination, velocities at collated sites are equated by constraints to the covariance matrix.

In current combination, the UAF analysis is not used due to numerical stability problems. These problems could be related to the de-constraining method used and should be easily rectified. The final version of SNARF version 2.0 will use a GIA model derived from the current combination when the UAF analysis can be added.

As part of the evaluation of the combination we compare each of the input analyses to the combined analysis. The results are shown in Table A1.2.

Table A1.2: RMS Velocity difference between contributions and combined version 2.0

Code	#	Weight Root-Mean-Square difference (mm/yr)			Normalized Root-Mean-Square difference		
		N	E	U	N	E	U
CBN	73	0.23	0.55	0.61	0.29	0.51	0.13
NAR	311	0.55	0.58	1.51	0.34	0.37	0.25
PUR	204	0.17	0.15	0.44	0.33	0.34	0.41
UAF	96	0.78	0.75	2.59	0.18	0.24	0.29
UNR	36	0.29	0.33	1.96	0.56	0.66	1.09

is the number of common stations and the normalized RMS difference is the square root of chi-squared per degree of the freedom of the differences. These values should be near unity. All values are less than unity which may indicate some systematic differences between the SNARF input solutions and ITRF05 in North America.

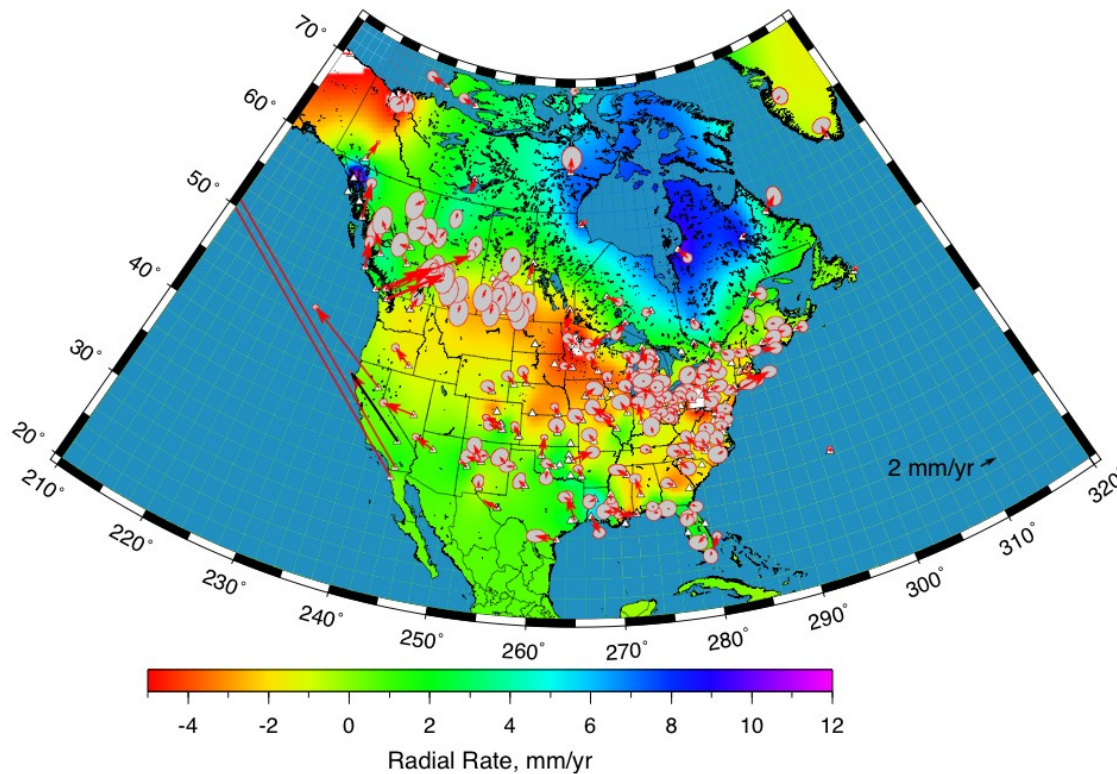


Figure A1.1: Preliminary SNARF version 2.0 aligned with version 1.0 GIA Model. Sites with horizontal velocity uncertainties of less than 1 mm/yr are shown (with 95% confidence ellipses). Only the sites with horizontal motions due to GIA will be used in the final version 2.0 alignment.

Preliminary results

Figure A1.1 shows the current horizontal and interpolated vertical velocities of SNARF version 2.0 when the reference frame is aligned with the GIA model used in the alignment of SNARF version 1.0.

To indicate the effects of reference frames, we show in Figure A1.2, the preliminary SNARF model aligned with ITRF 2005 sites in North America rotated to the North American plate using the ITRF2005 Euler pole. In this case much larger horizontal motions can be seen and these magnitude motions are seen in some GIA models. The GIA ensemble model for SNARF version 2.0 should ensure that most consistent set of horizontal and vertical motions are obtained.

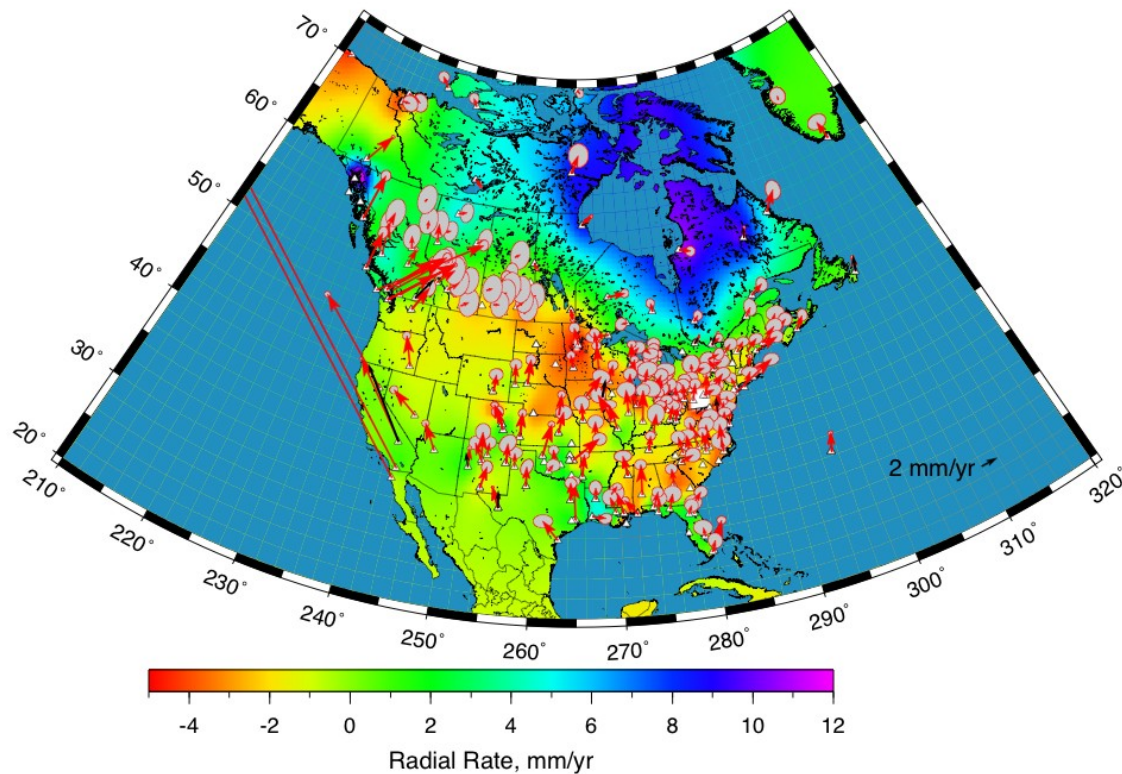


Figure A1.2: Preliminary SNARF version 2.0 aligned with the North American sites in ITRF 2005. Other aspects of the figure are the same as figure A1.1.

Summary

The current SNARF version 2.0 combination is in good shape with some small remaining site edits needed to remove sites with local subsidence and monument instability. Once the new GIA model is available, the final version should be generated quickly. The whole SNARF system will need to be re-done once the IGS analysis using absolute phase center models is completed. The IGS re-analysis will take at least another year.

APPENDIX 2: Purdue Contribution to SNARF

contributed by Eric Calais

The Purdue contribution to SNARF is a combination of two independent solutions, one produced by Univ. Wisconsin (C. DeMets) using the GIPSY-OASIS software, the other produced by Purdue Univ. (E. Calais) using the GAMIT-GLOBK software. Both solutions include up to 14 years of continuous data at about 500 continuous GPS sites in the central and eastern U.S. and Canada (Calais et al., 2006).

The GIPSY-OASIS solution follows the precise point positioning analysis strategy (Zumberge et al., 1997). No attempt was made to resolve integer phase ambiguities. Site coordinates determined from the analysis of the GPS phase and pseudo-range observables are initially defined in a fiducial-free reference frame and subsequently transformed into the International Terrestrial Reference Frame 2000 (ITRF2000; Altamimi et al., 2002) using 7-parameter Helmert transformations that align the daily coordinates of a selected subset of ITRF2000 fiducial sites with the fiducial-free coordinates of the same subset of sites. Station velocities are calculated by a linear fit to the position time series, including estimation of antenna phase center offsets where such offsets are not specified in station site logs. Station velocity uncertainties are estimated using the Mao et al. (1999) uncertainty estimation algorithm, site-specific estimates of white and flicker noise, and an assumed $1 \text{ mm yr}^{-0.5}$ of random monument walk.

The GAMIT-GLOBK solution uses double-differenced GPS phase measurements to estimate daily station coordinates, satellite state vectors, 7 tropospheric delay parameters per site and day, horizontal tropospheric gradients, and phase ambiguities using IGS final orbits and Earth orientation parameters. For processing time considerations, we divided the network into regional subnetworks of about 25 sites each. All subnetworks share 6 common IGS sites (AOML, USNO, ALGO, NLIB, MDO1, AMC2) well determined in ITRF2000. These sites serve to tie the subnetworks together and with the ITRF. We then produce position time series that we use to estimate site-specific parameters for a noise model that includes white and random-walk processes. We finally combine the (unconstrained) daily solutions for each subnetwork into a single, unconstrained, position-velocity solution while accounting for site-specific noise parameters.

In addition to the GAMIT and GIPSY solutions described above, we use (1) the global solutions provided by the IGS, which results from the combination of individual solutions from IGS analysis centers, goes back to February 1999, and (2) the full definition (i.e., estimates and complete covariance matrix) of the ITRF2000 (Altamimi et al., 2002).

We then combined the minimally constrained individual solutions mentioned above using the combination algorithm developed by Altamimi et al. (2002). The combination consists of simultaneously estimating, for each site in each solution (GAMIT, GIPSY, IGS, ITRF2000), its velocity, position, and a 14-parameter transformation between the individual and the combined solution.

The reference frame definition in the combination can be implemented by imposing the 14-parameter transformation between ITRF2000 and the combined solution to be zero to express the resulting velocity field in ITRF2000. For the purpose of SNARF, we however provided a loosely constrained solution.

APPENDIX 3: UNR Contribution to SNARF

contributed by Geoff Blewitt and Corné Kreemer

The contribution of University of Nevada, Reno (UNR) to SNARF was produced using the GIPSY-OASIS software. The solution is a subset of a solution of 3790 GPS sites worldwide (~2,600 continuous), with up to 14 years of continuous data from 1994-2008 (Figure A3.1).

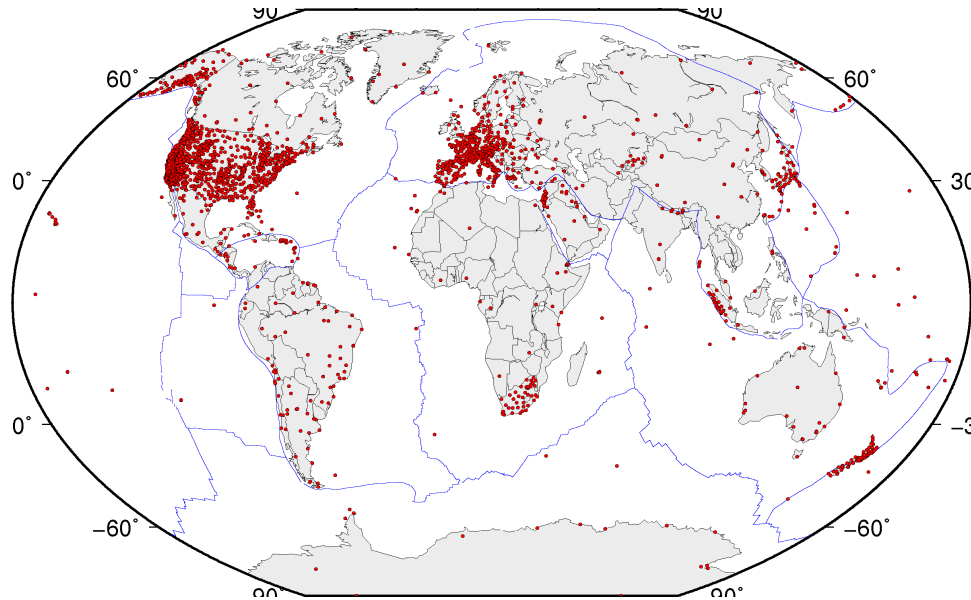


Figure A3.1: Global ambiguity-resolved solution of 3790 stations from UNR

As for the Purdue solution, the GIPSY-OASIS analysis follows the precise point positioning analysis strategy (Zumberge et al., 1997), however, integer phase ambiguities were resolved using the new “Ambizap” algorithm (Blewitt, 2006). Site coordinates determined from the analysis of the GPS phase and pseudo-range observables are initially defined in a fiducial-free reference frame and subsequently transformed into the International Terrestrial Reference Frame 2005 using a 7-parameter Helmert transformations provided by JPL. No scaling was applied to error bars, which are overly optimistic.

A subset of 45 sites was selected to define a kinematic frame with a linear motion (constant velocity) model. These sites spanned the region from Hawaii to Alaska, to Greenland and to Bermuda (Figure A3.2). A loosening transformation was applied to the PPP covariance matrices prior to station velocity estimation, which effectively allows a further small transformation (rotation, translation and scale) of individual daily solutions relative to the kinematic frame defined by the linear motion model. These 45 sites were selected on the basis of geographical distribution, continuous time series since January 2000, and no known jumps in the timeseries (resulting from equipment configuration changes). A linear model was fit to data from these 45 sites using only data since January 2000.

Finally, a no-net rotation constraint was applied using a subset of 18 sites within the stable NA continent that were deemed to be sufficiently far from tectonic and horizontal GIA effects (Figure A.3.3). This last step has no effect on the final SNARF combination, but does provide an independent check on the realization of a non-rotating frame. This rotational constraint then applied to the 45 station frame, and then transformation files (“x-files” in GIPSY parlance) were generated to transform daily non-fiducial solutions into a stable NA reference frame (SNARF). UNR is now aiming to make these NA x-files publicly available.

The resulting horizontal velocities (Figures A3.2 and A3.3) show that Bermuda is indeed attached to stable North America, however, Greenland and northern Alaska have significant velocities (at the few mm/yr level).

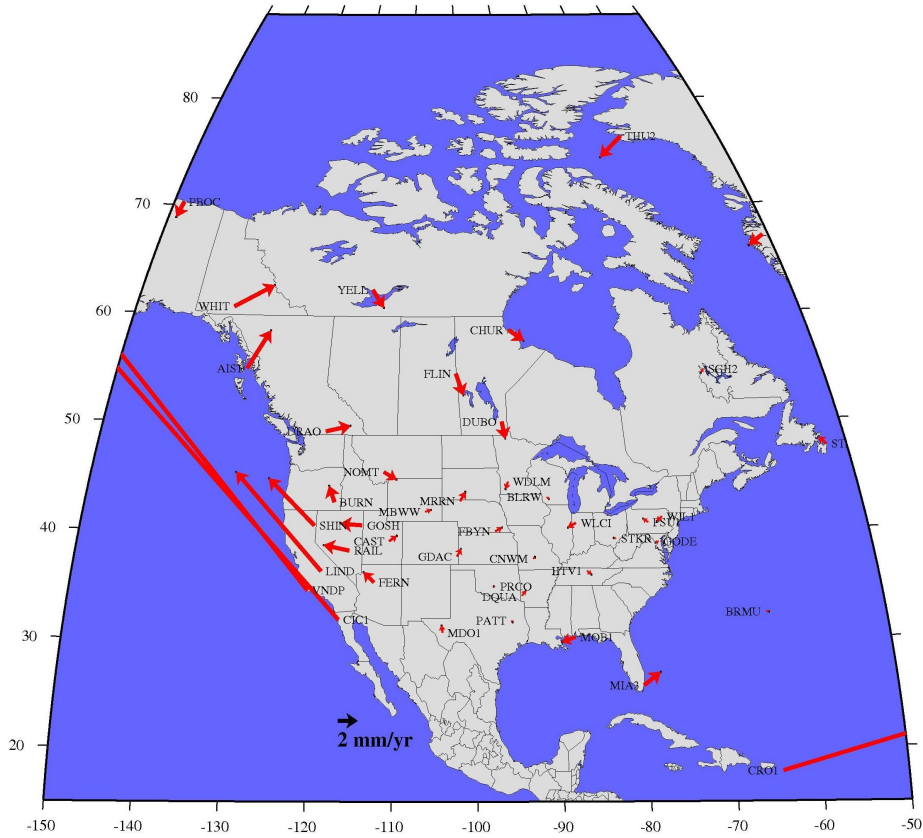


Figure A3.2: Horizontal velocities of the UNR solution for the 45 sites defining a constant velocity kinematic frame (nominally in ITRF2005, then with no-net rotation constraint applied to subset described in Figure A3.3).

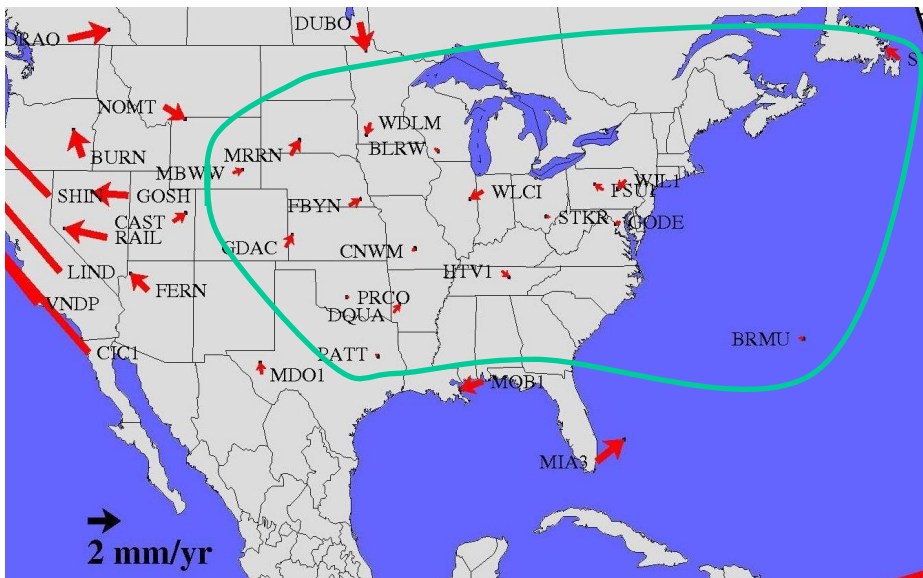


Figure A3.3: Horizontal velocities zoomed in to show details. Stations within the closed curve were used to define a no-net rotation frame.

The resulting vertical velocities (Figures A3.4 and A3.5) clearly delineate a vast vertically stable area from the areas of GIA uplift and peripheral bulge collapse. Generally, the magnitude of vertical velocities for sites beyond the peripheral bulge are < 1 mm/yr, including sites in the Basin and Range province, and in the region of the San Andreas transform, including the Sierra Nevada.

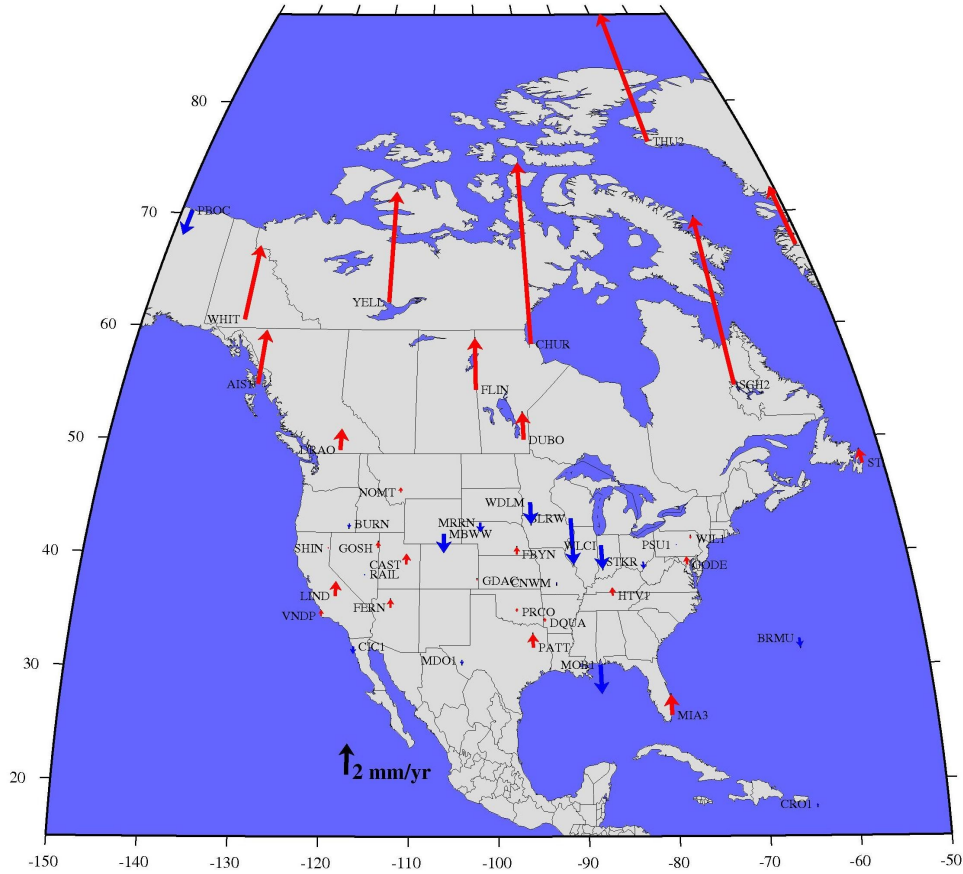


Figure A3.4: Vertical velocities of the UNR solution for the 45 sites defining a kinematic frame.

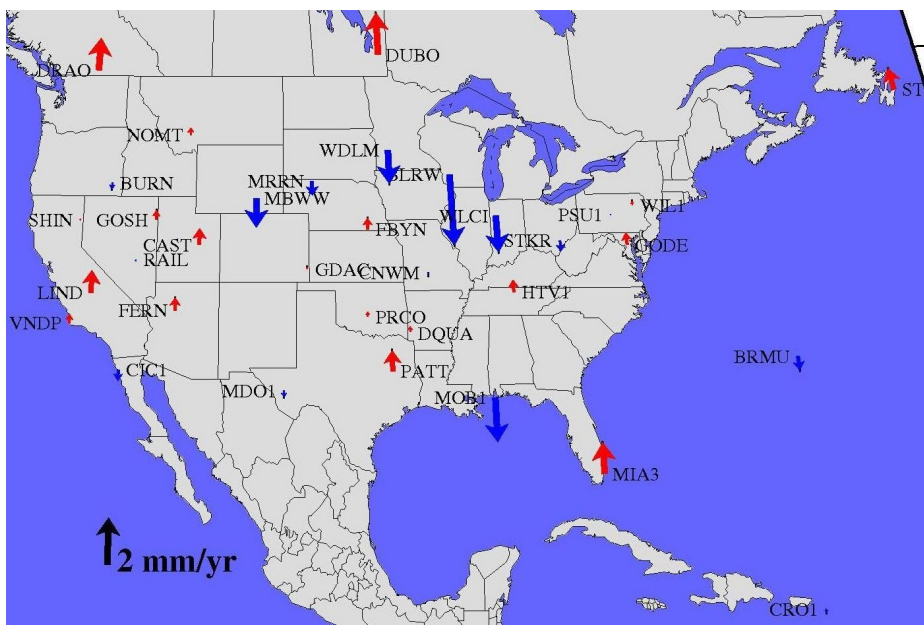


Figure A3.5: Vertical velocities of the UNR solution in detail.

REFERENCES

SNARF-Related Research by Members of the SNARF Working Group (2006-2008).

Argus, D.F. (2006), Defining translational velocity of Earth's reference frame, 6th SNARF Workshop, held in Ottawa, Canada, November 2006.

Bennett, R.A., S. Hreinsdottir, M.S. Velasco, and N.P. Fay (2007), GPS constraints on vertical crustal motion in the northern Basin and Range, *Geophys. Res. Lett.*, doi:10.1029/2007GL031515.

Blewitt, G. (2006). The fixed point theorem of ambiguity resolution for precise point positioning of GPS networks: Theory and applications, *Eos Trans. AGU*, 87(52), Fall Meet. Suppl., Abstract G43A-0977.

Blewitt, G., Z. Altamimi, J. Davis, R. Gross, C. Kuo, F. Lemoine, R. Neilan, H.P. Plag, M. Rothacher, C.K. Shum, M.G. Sideris, T. Schöne, P. Tregoning, and S. Zerbini (2006). Geodetic observations and global reference frame contributions to understanding sea level rise and variability (pp. 127-143). Paris: Understanding Sea-level Rise and Variability, A World Climate Research Programme Workshop and a WCRP contribution to the Global Earth Observation System of Systems, World Climate Research Program.

Blewitt, G. (2007), GPS and Space Based Geodetic Methods, chapter in *Treatise on Geophysics*, Vol. 3., pp. 351-390, Ed. Thomas Herring, Ed.-in-chief Gerald Schubert, Academic Press, Oxford, UK, ISBN: 0-444-51928-9.

Blewitt, G., J. Price, W. Hammond, C. Kreemer, H.-P. Plag, B. Wernicke, K. Mahan, B. Guest, N. Niemi, J. Davis, S. Bisnath, and E. Malikowski (2007), Geodetic monitoring of the Yucca Mountain region using continuous GPS measurements, NSHE Cooperative Agreement Interim Progress Briefings, Desert Research Institute, Reno.

Blewitt, G., and C. Kreemer (2007), Mega-network GPS solutions: Producing a consistent, global-scale, and high-resolution view of plate tectonic stability, rotation, and deformation, *Eos Trans. AGU*, Vol. 88, Fall Meet. Suppl., Abstract.

Blewitt, G., (2007) Software development: massive, rapid network processing with ambiguity resolution, 7th SNARF Workshop, EarthScope National Meeting, Monterey, CA, March 27, 2007.

Blewitt, G., (2007) Plate Boundary Observatory analysis using the Ambizap GPS processing algorithm, poster presented at EarthScope National Meeting, Monterey, CA, March 27, 2007.

Blewitt, G., and Z. Altamimi (2007), Providing a stable reference frame for observing the effect of global climate change on sea level, presented at The Global Geodetic Observing System (GGOS) Workshop, Frascati, Italy

Blewitt, G. (2008) Overview of the SNARF Working Group, its activities, and accomplishments, 9th SNARF workshop, UNAVCO Science Workshop 2008, Boulder, CO, March 13, 2008.

Bock, Y. (2006), Various projects related to SNARF objectives, presentation given at the 5th SNARF Workshop, held in Denver, CO, March 2006.

Blewitt, G., Hammond, W.C., Kreemer, C. (in press). Geodetic observation of contemporary strain in the northern Walker Lane: 1, Semi-permanent GPS strategy. *Late Cenozoic Structure and Evolution of the*

Great Basin – Sierra Nevada Transition, Geological Society of America.

Calais, E. (2006), Deformation of the North American plate interior from a decade of continuous GPS measurements, *J. Geophys. Res.*, Vol. 111, B06402, doi:10.1029/2005KB-004253.

Calais, E., J.Y. Han, C. DeMets, and J.M. Nocquet (2006), Deformation analysis in the North American plate's interior, presentation given at the 6th SNARF Workshop, held in Ottawa, Canada, November 2006.

Calais, E. (2007), DeMets, CD., Han, J., A velocity field for the North American plate interior, *Eos Trans. AGU*, 88(52), Fall Meet. Suppl., 2007.

Clarke, P.J., D.A. Lavallée, G. Blewitt, and T. van Dam (2007), Basis functions for the consistent and accurate representation of surface mass loading, *Geophys. Journ. Int.*, 10 pp., doi:10.1111/j.1365-246X.2007.03493.x

Craymer, M., J. Henton, M. Piraszewski (2006). Measuring crustal motion and sea level change in the Canadian Arctic. GPS in the IPY: The POLENET Project Workshop, Dresden, October 3-5, 2006.

Craymer, M., J. Henton, M. Piraszewski (2006). NRCan velocity fields for SNARF. 6th SNARF Workshop, Ottawa, November 16, 2006.

Craymer, M., J. Henton, M. Piraszewski (2006). Sea level change and vertical crustal motion in the Canadian Arctic using GPS and tide gauges: Challenges and preliminary results. *Eos Transactions, AGU*, 87(52), Fall Meeting Supplement, Abstract G23B-1288, 2006.

Craymer, M. (2006), NRCan velocity fields and comparison with some NA plate motion estimates, presentation given at the 5th SNARF Workshop, held in Denver, CO, March 2006.

Craymer, M. (2006), Reprocessing of continuous and campaign data in Canada, Greenland, and northern US, presentation given at the 5th SNARF Workshop, held in Denver, CO, March 2006.

Craymer, M., J. Henton, and M. Piraszewski (2006), NRCan velocity fields for SNARF, presentation given at the 6th SNARF Workshop, held in Ottawa, Canada, November 2006.

Craymer, M.R (2006). The evolution of NAD83 in Canada. *Geomatica*, Vol. 60, No. 2, pp. 151-164.

Craymer, M.R. (2006). The evolution of NAD83 in Canada: Addendum. *Geomatica*, Vol. 60, No. 4.

Davis, J.L., B.L. Wernicke, S. Bisnath, N.A. Neimi, and P. Elosegui (2006), Subcontinental-scale crustal velocity changes along the Pacific-North America transform plate boundary from BARGEN GPS data, *Nature*, Vol. 441, 1131, doi:10.1038.nature0478112/2006.

Craymer, M. (2006). Making Sense of Evolving Datums: WGS84 and NAD83. *Hydroscan 2006*, Saskatoon, September 22, 2006.

Craymer, M., G. Blewitt, D. Argus, Y. Bock, E. Calais, J. Davis, J. Freymueller, T. Herring, G. Sella, R. Snay, M. Tamisiea (2006). SNARF 1.0: A regional reference frame for North America. *Geodetic Reference Frames GRF2006*, International IAG/FIG Symposium, Munich, October 9-14.

Craymer, M.R., M. Piraszewski, J.A. Henton (2007). The North American Reference Frame (NAREF) project to densify the ITRF in North America. Proceedings of ION GNSS 2007, Fort Worth, Texas, September 25-28, 2007.

Craymer, M., D. Forbes, J. Henton, M. Piraszewski (2007). Integrating GPS and tide-gauge data with geological evidence and geophysical models to estimate sea-level change and vertical motion in the western Arctic. CMOS/CGU/AMS Congress, St. John's, NL, May 28 - June 1, 2007.

Craymer, M., J. Henton, M. Piraszewski (2007). NRCan velocity fields for SNARF. 7th SNARF Workshop, EarthScope National Meeting, Monterey, CA, March 27, 2007.

Craymer, M., J. Henton, M. Piraszewski (2007). NAREF & CBN velocity fields for a new version of SNARF, 8th SNARF Workshop, AGU 2007 Fall Meeting, San Francisco, December 11, 2007.

Craymer, M. and G. Sella (2007). Making sense of evolving reference frames for North America. Eos Transactions, AGU, 88(23), Joint Assembly Supplement, Abstract G32A-01, 2007.

Craymer, M. and R. Snay (2007). Regional reference frames for North America: Status and future plans of sub-commission 1.3c. IUGG XXIV General Assembly, Perugia, Italy, July 2-13, 2007.

Dixon, T.H., F. Amelung, A. Ferretti, F. Novali, F. Rocca, R. Dokka, G. Sella, S.W. Kim, S. Wdowinski, and D. Whitman (2006), New Orleans subsidence and relation to flooding after Hurricane Katrina as measured by space geodesy, *Nature*, Vol. 441, pp. 587-588.

Dokka, R.K., G.F. Sella, and T.H. Dixon (2006), Tectonic control of subsidence and southward displacement of southeast Louisiana with respect to stable North America, *Geophys. Res. Lett.*, Vol. 33, L23308, doi:10.1029/2006GL027250, 2006.

Dong, D., P. Fang, Y. Bock, F. Webb, L. Prawirodirdjo, S. Kedar, and P. Jamason (2006), Spatiotemporal filtering using principal component analysis and Karhunen-Loeve expansion approaches for regional GPS network analysis, *J. Geophys. Res.*, 111, B03405, doi:10.1029/2005JB003806.

Fang., P. and Y. Bock (2007), SOPAC reanalysis for SNARF and web-based analysis tools, 8th SNARF Workshop, San Francisco, CA, December 11, 2007.

Fang., P. and Y. Bock (2007), SOPAC reprocessing and webtool development, 7th SNARF Workshop, EarthScope National Meeting, Monterey, CA, March 27, 2007.

Freymueller, J.T. (2006), Motion of Bering Plate? presentation given at the 6th SNARF Workshop, held in Ottawa, Canada, November 2006.

Freymueller, J.T. (2006), Seasonal position variations and regional reference frame realization, presentation given at the 6th SNARF Workshop, held in Ottawa, Canada, November 2006.

Freymueller, J.T., and J. Elliott (2007), Uncertainty in the motion of the North American Plate and its impact, 8th SNARF Workshop, San Francisco, CA, December 11, 2007.

Freymueller, J.T., and J. Elliott (2007), How well do we know the North American frame today? Differences between recent realizations and implications, 7th SNARF Workshop, EarthScope National Meeting, Monterey, CA, March 27, 2007.

Gross, R.S., D.A. Lavallée, G. Blewitt, and P.J. Clarke (in press), Consistency of Earth rotation, gravity, and shape measurements, International Association of Geodesy Symposia, Volume 131, 8 pp., Springer Verlag, Berlin

Hammond, W.C., Z. Li, H.-P. Plag, G. Blewitt, and C. Kreemer (2006). Results of InSAR and GPS measurement of tectonic deformation of the Eastern California Shear Zone and Yucca Mountain, Nevada", Eos Trans. AGU, 87(52), Fall Meet. Suppl., Abstract G53D-0931.

Hammond, W.C., G. Blewitt, C. Kreemer, H.-P. Plag, J.G. Anderson, K. Smith (2006), Recent seismicity and surface deformation at Lake Tahoe: An update on lower crustal magma movement, UNAVCO Science Meeting, Denver. (March 2006).

Hammond, W.C., H.-P. Plag, G. Blewitt, and C. Kreemer (2007), Postseismic relaxation at the Central Nevada Seismic Belt observed with vertical GPS time series, Eos Trans. AGU, Vol. 88, Fall Meet. Suppl., Abstract.

Hammond, W.C., G. Blewitt, C. Kreemer, H.-P. Plag (2008), Walker lane tectonic deformation and fault slip rates constrained by GPS data, UNAVCO Science Workshop, Boulder, CO, March 11-13.

Hammond, W.C. and W. Thatcher (2007), Crustal Deformation across the Sierra Nevada, Northern Walker Lane, Basin and Range Transition, Western United States Measured with GPS, 2000-2004, J. Geophys. Res., 112, B05411, doi:10.1029/2006JB004625.

Hammond, W.C., C. Kreemer, G. Blewitt (2008), Geodetic vs. geologic measures of fault slip rates in the northern Walker Lane, Basin and Range province, western United States, AGU Joint Assembly, Ft. Lauderdale, FL, May 27-30, 2008.

Hammond, W. C., Kreemer, C. W., Blewitt, G. (in press). Geodetic observation of contemporary strain in the northern Walker Lane: 3, Central Nevada Seismic Belt postseismic relaxation. Late Cenozoic Structure and Evolution of the Great Basin – Sierra Nevada Transition, Geological Society of America.

Henton, J., M. Craymer, R. Ferland, H. Dragert, S. Mazzotti (2006), D. Forbes. Crustal motion and deformation monitoring of the Canadian landmass. Geomatica, Vol. 60, No. 2, pp. 151-164.

Henton, J., M. Craymer, E. Lapelle, M. Piraszewski (2007). Contributions of the North American Reference Frame Working Group to the next realization of the Stable North American Reference Frame (SNARF). Eos Transactions, AGU, 88(52), Fall Meeting Supplement, Abstract G21B-0498, 2007.

Herring, T.A. (2006), SNARF realization for PBO processing, presentation given at the 5th SNARF Workshop, held in Denver, CO, March 2006.

Herring, T.A. (2006), PBO Frame definition using SNARF 1.0, presentation given at the 6th SNARF Workshop, held in Ottawa, Canada, November 2006.

Herring, T.A. (2007), SNARF Version 2.0 construction: Current status, 9th SNARF workshop, UNAVCO Science Workshop 2008, Boulder, CO, March 13, 2008.

Herring, T.A. (2007), SNARF Version 2.0 construction, 8th SNARF Workshop, San Francisco, CA, December 11, 2007.

Hill, E.M., and G. Blewitt (2006), Testing for fault activity at Yucca Mountain, Nevada, using independent GPS results from the BARGEN network, *Geophys. Res. Lett.*, Vol 33, L14302, doi:10.1029/2006GL026140, 2006.

Hill, E. (2007), Investigation of site-dependent GPS errors and monument stability using a short-baseline network of braced monuments, 8th SNARF Workshop, San Francisco, CA, December 11, 2007.

King, N. E., D. Argus, J. Langbein, D. C. Agnew, R. S. Dollar, G. Bawden, Z. Liu, E. Reichard, A. Yong, F. H. Webb, Y. Bock, K. Stark, and D. Barseghian (2007), Space geodetic observation of expansion of the San Gabriel Valley, California, aquifer system, during heavy rainfall in winter 2004-2005, *J. Geophys. Res.*, 112, B03409, doi:10.1029/2006JB004448.

Kreemer, C., D. A. Lavallée, G. Blewitt, and W. E. Holt (2006), On the stability of a geodetic no-net-rotation frame and its implication for the International Terrestrial Reference Frame, *Geophys. Res. Lett.*, Vol. 33, L17306, doi:10.1029/2006GL027058.

Kreemer, C. (2006), Using SNARF: Lessons Learned, 6th SNARF Workshop, held in Ottawa, Canada, November 2006.

Kreemer, C., W.C. Hammond, G. Blewitt (2006). On the motion and geometry of the Sierra Nevada – Great Valley micro-plate: Implications for Walker Lane tectonics, *Eos Trans. AGU*, 87(52), Fall Meet. Suppl., Abstract G42A-05.

Kreemer, C., D.A. Lavallée, G. Blewitt, and W.E. Holt (2006). On the stability of a geodetic no-net rotation frame, effects of frame translation, and implications for the ITRF, *Eos Trans. AGU*, 87(52), Fall Meet. Suppl., Abstract G33C-04

Kreemer, C., D. Lavallée, G. Blewitt, and W.C. Holt (2006). Constraining no-net rotation of the Terrestrial Reference Frame, International Association of Geodesy, Geodetic Reference Frames 2006 Symposium, Munich (October 2006).

Kreemer, C., G. Blewitt, W.C. Hammond, and H.-P. Plag (2006), Global Deformation from the Great 2004 Sumatra-Andaman Earthquake Observed by GPS: Implications for Rupture Process and Global Reference Frame, *Earth Planets and Space*, Vol. 58, pp. 141-148, 2006.

Kreemer, C., and G. Blewitt (2007), Finding and defining the edges of stable North America: Reference frame effects versus real tectonics, *Eos Trans. AGU*, Vol. 88, Fall Meet. Suppl., Abstract.

Kreemer, C. and W.C. Hammond (2007), Geodetic constraints on areal-changes in the Pacific-North America plate boundary zone: What controls Basin and Range extension? *Geology* v. 35, no 10: p.943-947, doi:10.1130/G23868A.1.

Kreemer, C. W., Blewitt, G., Hammond, W.C. (in press). Geodetic observation of contemporary strain in the northern Walker Lane: 2, Vector and strain rate tensor analysis. *Late Cenozoic Structure and Evolution of the Great Basin – Sierra Nevada Transition*, Geological Society of America.

Kreemer, C. (2007), Using SNARF: Lessons Learned, 7th SNARF Workshop, EarthScope National Meeting, Monterey, CA, March 27, 2007.

Lavallée, D.A., T. Van Dam, G. Blewitt, and P.J. Clarke (2006), Geocenter Motions from GPS: A

Unified Observation Model, *Journ. Geophys. Res.*, Vol. 111, B05405, doi:10.1029/2005JB003784, 2006.

Lavallée, D.A., G. Blewitt, P.J. Clarke, P. Moore, T. van Dam, and Q. Zhang, (2006). The terrestrial reference frame and surface mass loading, *Geophys. Res. Abs.*, Vol. 8, 07154.

Luttrell, K., D. Sandwell, B. Smith-Konter, B. Bills, and Y. Bock (2007), Modulation of the earthquake cycle at the southern San Andreas fault by lake loading, *J. Geophys. Res.*, 112, B08411, doi:10.1029/2006JB004752.

Noll, C., Y. Bock, H. Habrich, and A. Moore (2008), Development of data infrastructure to support scientific analysis for the International GNSS Service, *J. Geod.*, Submitted.

Pearson, C., and R. Snay (2007) Updating HTDP for two recent earthquakes in California. *Surveying and Land Information Science*, 67(3), 149-158.

Pearson, C. (2007) HTDP: A tool to correct survey data for tectonic motion, 8th SNARF Workshop, San Francisco, CA, December 11, 2007.

Plag, H.-P. (2006), Special Bureau of Loading status report: Towards a standard model for present-day signals due to postglacial rebound, presentation given at the 5th SNARF Workshop, held in Denver, CO, March 2006.

Plag, H.-P. (2007), Effect of Surface Loading on Regional Reference Frame Realization, 8th SNARF Workshop, San Francisco, CA, December 11, 2007.

Plag, H.-P. (2007), Combination of GPS-observed vertical motion with absolute gravity changes constrain the tie between reference frame origin and Earth center of mass, 7th SNARF Workshop, EarthScope National Meeting, Monterey, CA, March 27, 2007.

Plag, H.-P., C. Kreemer, W.C. Hammond, and Blewitt, G. (2007). Vertical motion observed with GPS: What can we learn about regional geophysical signals, Earth structure, and rheology? *EarthScope National Meeting Abstracts*, p. 165, Monterey, CA.

Prawirodirdjo, L., Y. Ben-Zion, and Y. Bock (2006), Observation and modeling of thermoelastic strain in Southern California Integrated GPS Network daily position time series, *J. Geophys. Res.*, 111, B02408, doi:10.1029/2005JB003716.

Sella, G.F. (2006), Site monumentation information, presentation given at the 5th SNARF Workshop, held in Denver, CO, March 2006.

Sella, G. (2007), The CORS network and improved understanding of "Stable North America", 8th SNARF Workshop, San Francisco, CA, December 11, 2007.

Sella, G., S. Stein, T. Dixon, M. Craymer, T. James, S. Mazzotti, R.K. Dokka (2007). Constraints on Glacial Isostatic Adjustment (GIA) Motion in North America Using GPS. *IUGG XXIV General Assembly*, Perugia, Italy, July 2-13, 2007.

Sella, G.F., S. Stein, T.H. Dixon, M. Craymer, T.S. James, S. Mazzotti, and R.K. Dokka (2007), Observation of glacial isostatic adjustment in "stable" North America with GPS, *Geophys. Res. Lett.*, Vol. 34, L02306, doi:10.1029/2006GL027081, 2007.

Snay R. (2006), NGS reanalysis of all CORS data in the context of IGS reanalysis, presentation given at the 5th SNARF Workshop, held in Denver, CO, March 2006.

Snay, R., M. Cline, W. Dillinger, R. Foote, S. Hilla, W. Kass, J. Ray, J. Rohde, G. Sella, T. Soler (2007) Using global positioning system-derived crustal velocities to estimate rates of absolute sea level change from North American tide gauge records. *J. Geophys. Res.*, 112, B04409, doi:10.1029/2006JB004606.

Szeliga, W., T. Melbourne, M. Santillan, and M. Miller (in press), GPS constraints on 34 slow slip events within the Cascadia subduction zone, 1997 – 2005, *Journ. Geophys. Res.*

Tamisiea, M. E., J. L. Davis, and E. M. Hill (2006), Observationally-derived estimates of glacial isostatic adjustment, GRACE Science Team Meeting, San Francisco, CA, December, 2006.

Tamisiea, M.E. and J. Davis (2006), Assessing the GIA contribution to SNARF, presentation given at the 6th SNARF Workshop, held in Ottawa, Canada, November 2006.

Tamisiea, M.E. (2006), Update on GIA models, presentation given at the 5th SNARF Workshop, held in Denver, CO, March 2006.

Tamisiea, M.E. (2007), Assimilated GIA field, 8th SNARF Workshop, San Francisco, CA, December 11, 2007.

Tamisiea, M. E., J. L. Davis, and E. M. Hill (2007), Estimation of GIA over Fennoscandia from combined observations, GRACE Science Team Meeting, Potsdam, October, 2007.

Tamisiea, M.E. (2008), Assessing the GIA contribution to SNARF, 9th SNARF workshop, UNAVCO Science Workshop 2008, Boulder, CO, March 13, 2008.

Wdowinski, S., B. Smith, Y. Bock, D. Sandwell (2007), Diffuse interseismic deformation across the Pacific-North America plate boundary, *Geology*, 35(4), doi:10.1130/G22938A.1, 311-314.