GPSVEL Project: Towards a Dense Global GPS Velocity Field

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Abstract. The "Global Velocity Synthesis Working Group" (GPSVEL) is a new initiative by the University NAVSTAR Consortium (UNAVCO), and falls under IAG commission XIV for Crustal Deformation. The goal of GPSVEL is to synthesize velocity vectors from international GPS campaigns into a consistent global reference frame. This effort will build on the densification projects of the International GPS Service (IGS) and the International Earth Rotation Service (IERS) Terrestrial Reference System, which incorporates over 200 continuous GPS stations around the world. The result will be a "benchmark" global solution to which geophysical models such as NUVEL-1A can be compared. GPSVEL will be a primary input into the Global Strain Rate Map Project initiated in 1998 by the International Lithosphere Program. From the Principal Investigator's perpective, GPSVEL will allow different experiments to be compared in a consistent way, and would make existing solutions more accessible and interpretable to future investigators. GPSVEL will enable P.I.s to design their experiments to more fully exploit current data sets. GPSVEL will also provide realistic error scaling based on self-consistency checks in overlapping networks.

Introduction

The Global Strain Rate Map project was initiated in 1998 by the International Lithosphere Program (ILP). Under the guidance of W. Holt, the first steps toward the establishment of such a map have been made (Kreemer et al., 2000), using a variant on the method introduced by Haines and Holt (1993). A completed Global Strain Rate Map, determined by combining geodetic data, seismic moment tensors and Quaternary fault slip rates, will provide a large amount of information that is vital for our understanding of continental dynamics and for the quantification of seismic hazards.

A key input to the Global Strain Rate Map project will be GPS velocity data being compiled as part of the GPS Global Velocity Synthesis Working Group (GPSVEL). GPSVEL is a new initiative by the University NAVSTAR Consortium (UNAVCO), a U.S. National Science Foundation-funded community-based organization for solid Earth science using GPS. The goal of this working group, co-chaired by G. Blewitt and W. Holt, is to synthesize data from various studies to produce a combined, consistent, high quality global GPS velocity field expanding on the new UNAVCO Community GPS Site Motions Project (Meertens et al., 2000).

This effort will build on the densification projects of the International GPS Service (IGS) and the International Earth Rotation Service (IERS) International Terrestrial Reference System, which coordinate over 200 continuous GPS stations around the world (Zumberge and Liu, 1995). IGS analysis centers routinely produce daily estimates of GPS station positions and hence provide a robust global velocity solution. The IGS provides a methodology and standards that will be applied to the GPSVEL project (e.g., SINEX files with full documentation of *a priori* constraints and antenna heights). Considerable additional data will be needed, however, because IGS stations are geographically sparse and often not well located to address tectonic issues.

This task is extremely ambitious, but clearly needed. While the UNAVCO Facility (at Boulder, Colorado) will participate by helping to gather solutions and disseminating results and software tools on the Web, the GPSVEL Working Group will work towards the technical objective of actually producing a consistent set of velocity vectors. One goal of this project is to solicit participation in the Working Group, and to encourage the international GPS community to contribute data from their networks and campaigns. Such a high quality, self-consistent solution for station kinematics will be useful as a tectonic tool, giving motions in a rigorous global kinematic frame. The project will also ensure the quality and documentation of present GPS data for use by future generations of scientists. Already a wide range of scientists from different countries have expressed a desire to participate, and we anticipate that as this effort progresses, others will join.

As discussed and generally accepted at the 1999 UNAVCO community meeting, and as reflected in the funded UNAVCO proposal to the National Science Foundation (NSF), the goal of this work is to synthesize velocity vectors from UNAVCO and non-UNAVCO international GPS campaigns into a consistent global reference frame. The result will be a "benchmark" global solution to which geophysical models such as NUVEL-1A can be compared. It would also allow P.I.s of different experiments to compare and interpret their own and other vectors in a consistent way. This process would add value to investigators' solutions, making them more accessible and interpretable to future investigators. GPSVEL will allow investigators to design their experiments to more fully exploit current data sets and will also provide realistic error scaling based on self-consistency checks in overlapping networks.

Methodology

As part of this IGS ITRF Densification Project, the IGS Global Network Associate Analysis Center at Newcastle has been producing a weighted combination of several Analysis Center solutions on a weekly basis since 1995. The resulting coordinate RMS is typically at the level of 2 mm horizontal, and 7 mm vertical.

Our methodology (Davies and Blewitt, 2000) features a free network approach and use of full covariance information in a five step process: (i) weekly station coordinate solutions from the IGS Analysis Centres are rigorously combined, using Koch/Baarda generalized outlier elimination for coordinate triplets, and Helmut variance component estimation for realistic relative weighting; (ii) 5.5 years of our weekly combined solutions from 1995 to 2001 are fit to a station coordinate and velocity model including the estimation of annual and semi-annual periodic signal parameters. Only sites with at least 2.5 years of data are included since this is the minimum for reliable velocity estimates (Blewitt and Lavallée, 2001). Sites requiring estimated offsets due to co-seismic displacement and station configuration changes are accounted for and attached in a separate step so not to perturb the quality of the core solution. Such offsets and all related information will be archived alongside the GPSVEL solution.

Weekly regional IGS permanent network solutions for EUR, AUS and SIR are processed using the same criteria. In addition to deconstraining regional solutions the effect of the fixed IGS ITRF constrained orbit (not present in the global solution) is removed by allowing the epoch solutions to rotate and translate by augmenting the stochastic model. This process improves both the RMS and the velocity agreement between the regional and more reliable and fully fiducial-free global results. For example deconstraining the EUR solutions before combination changes the vertical RMS velocity agreement with the global solution from 1.03 to 0.64 mm/yr, augmenting the stochastic model reduces this to 0.48 mm/yr. The regional solutions are attached to the global solution using back-substitution via at least 3 anchor stations (Davies and Blewitt, 2000); this ensures the global frame is not affected by the less precise regional results.

The formal errors of the solution are updated using a colored noise model estimated from fitting lines to the time series power spectrum. The reference frame of the solution is then assigned in a final step via a 12 parameter Helmert transformation to ITRF2000. The kinematic origin of the frame is hence defined by a combination of SLR results and should be better centered at the center of mass of the Earth, Oceans and Atmosphere. Although relative plate Euler vectors and plate velocity residuals are invariant to the 3D rotation rate they are not invariant to the 3D translation rate due to the spherical aspect of the model so the definition of the origin is important.

Such a previous solution: GPSVEL 0.0 (Lavallée and Blewitt, 2000) forms the underlying frame for the current global strain map produced by Kreemer et al. (2000). The latest solution: GPSVEL 0.1 is based on more data and will form the core for GPSVEL. A greater number of permanent networks will be added into later versions, using wherever possible the methods outlined above to ensure consistency.

To define plate fixed frames, Euler vectors are estimated for the major plates, removing stations which are not adequately fit by the rigid-plate model; residual velocities are used to investigate intra-plate deformation. Plate interiors in GPSVEL 0.1 are defined to less than a millimeter, the RMS of inter-site arc-extension rates between sites within plate interiors (which is not affected by weighting like Euler vector estimation) is 0.85 mm/yr. As an example, Figure 1 shows plate residuals in Europe to a model defined by 32 sites with an RMS of 0.6 mm/yr. In cases where sites within plate interiors do not fit the plate model, more often than not, the velocity formal error is large due to the need to estimate offsets for site equipment changes. For this reason it is intended that all aspects of GPSVEL be well documented so those interpreting tectonics can have access to all the information.

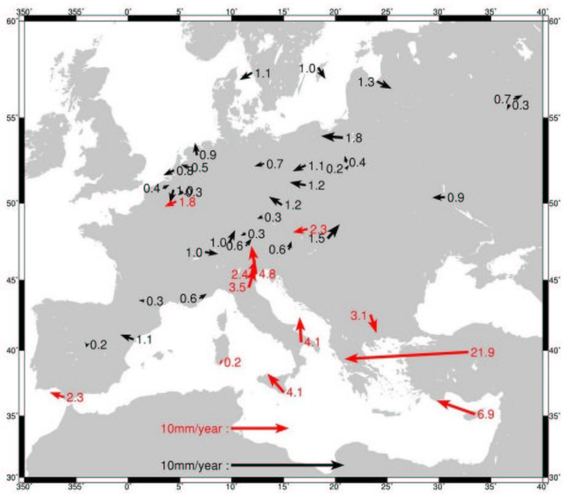

Fig 1. The Eurasian plate model velocity residuals in Europe. Sites with vectors in black were used to define the model along with a site on Ny-Alesund in Norway.

As a first glimpse into the potential of this project, initial results from GPSVEL Version 0.1, there are beginning to appear some significant deviations from NUVEL-1A. For example, the South America-Nazca pole of rotation lies more to the south than the NUVEL-1A pole. This results in significantly slower convergence at Peru. The North America-Pacific relative velocity vector computed in California has a magnitude of 50 mm/yr (faster than NUVEL-1A) and lies more parallel to the San Andreas fault north of the big bend than NUVEL-1A predicts. Our results also show the remarkable stability of the North American plate (with the exception of the Basin and Range province), ranging from Alaska across to Greenland and Iceland, and down to Bermuda. This lies in contrast with broadly deforming Eurasia. Moreover, there is preliminary evidence of deformation at Diego Garcia, in the presumed diffuse plate boundary zone between India and Australia.

Initial tests with Central Greece 1989-1997 epoch campaigns

For preliminary tests of the GPSVEL procedures with respect to campaign solutions we have attempted to include velocity solutions from the 1989-1997 Central Greece Campaigns (Clarke et al., 1998). The epoch campaigns were originally processed by fixing the coordinates of one site (Dionysos) to it's ITRF92 position. Velocities were then estimated while simultaneously estimating network translations and fixing the velocity of Dionysos to its velocity relative to stable Europe (Clarke et al., 1998). Additionally co-seismic offsets due to the June 15 1995 Egion event were removed with an elastic dislocation model. The estimation of network translations and the use of minimal constraints (1 site) preserve the inner geometry of the solution. The solution is therefore attached to GPSVEL 0.1 in its current form without the need to remove distortions of the network due to over constraint.

Inclusion of the kinematic solution for the Central Greece campaigns in GPSVEL presents an interesting challenge since there is no overlap between the two solutions. The velocity of Dionysos fixed in the solution was obtained by subtracting the NUVEL 1A NNR velocity for Europe at Dionysos from the ITRF92 velocity (from SLR). To place the solution into the GPSVEL 0.1 frame we first remove the Dionysos NUVEL 1A NNR velocity from all sites. Since there is no overlap between GPSVEL and the Greece solution we rely on GPSVEL being a realization of the ITRF2000 frame, which includes a velocity for Dionysos (from both SLR and GPS). The orientation of ITRF92 and ITRF2000 is identical so we then translate the network by the difference between the Dionysos ITRF92 and ITRF2000 velocities. This ensures the velocity tie takes advantage of the improved ITRF2000 velocity for Dionysos. As a final step the solution can be placed in the European frame by rotating by the GPSVEL 0.1 Euler vector for Europe. The process changes the velocity of Dionysos by -0.4 mm/yr in the North component and -2.0 in the East component. The difference varies only slightly for the other sites since the European rotation pole is far away. Figure 2 plots the velocities in the original and new European frame.

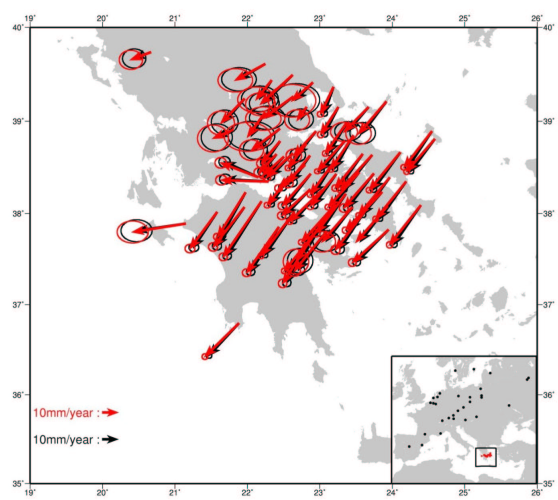

Fig. 2 Velocities of sites within the Central Greece network before (black arrows) and after (overlapping red arrows) inclusion into the GPSVEL frame. Inset shows location of sites used to define the GPSVEL stable European frame.

This process demonstrates how campaign solutions, particularly older ones can be included in GPSVEL even with the minimum of velocity information. Such a process might not be as rigorous as the 3-site attachment method outlined earlier but still allows a reasonable frame definition. For future definitions of GPSVEL we are hoping nearby and overlapping Mediterranean campaign solutions will provide a stronger tie for the Central Greece campaigns than this initial test. An important conclusion to be drawn from this test however is that a good number of "global" sites should be processed alongside campaigns wherever possible so a more rigorous approach can be taken.

Participation

Table 3 shows a list of more than 70 people who have personally indicated their interest in participation. There are several possible things that investigators might be able to contribute (1) GPS data and/or solutions, (2) technical expertise, and (3) the authority to direct any resources which may be necessary to accomplish this task. If you are interested in participating, please let us know as soon as possible by email, with a short note on how you'd like to contribute, to **gblewitt@unr.edu**.

For more information on GPSVEL on the web, go to:

http://www.unavco.ucar.edu/science_tech/crustal_motion/

Conclusions

The first steps towards the goal of producing a dense, self-consistent, and well-documented GPS global velocity field have been made. A high quality frame solution: GPSVEL 0.1 is complete. Initial tests indicate that campaigns can be incorporated with even only one linking site although it is recommended that more "global" sites are processed alongside campaign results wherever possible.

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Table 3: Current GPSVEL Participants. (*Indicates co-authors of this paper)

Name	**Contribution**
David Lavallee*	GPSVEL solution synthesis, internal QA
Geoffrey Blewitt*	Co-chair: "input coordination". synthesis, geodetic methodology & frame, internal QA, standards
Bill Holt*	Co-chair: "end user coordination". synthesis, velocity modeling, external QA, interpretation
Corne Kreemer*	Grad student: Strain modeling, external QA, interpretation
Peter Clarke*	Greece campaign analysis, reference frame-related errors
Konstantin Nurutdinov*	Global and regional IGS network synthesis
Chuck Meertens*	UNAVCO Facility support, P.I. liason, database, software tools
Wayne Shiver*	UNAVCO Facility Manager at Boulder, Colorado
Seth Stein*	UNAVCO Scientific Director (until September 2000)
Susanna Zerbini*	Europe tide gauge (SELF) network GPS analysis, coordination of WEGENER campaign GPS solutions
Luisa Bastos*	GPS solutions from Iberian peninsula
Hans –G. Kahle*	GPS solutions in Mediterranean region
David Jackson	Western North America network and campaign GPS analysis
Donald Argus	Western North America and campaigns synthesis, global plate motion analysis
Mark Murray	Western North America GPS analysis and synthesis
Mikhail Kogan	Siberia (Eurasia-N.A. boundary) network and campaign GPS analysis
Rick Bennett	North America synthesis
Roland Burgmann	Northern California GPS analysis
Tom Herring	Global and regional IGS network synthesis, geodetic methodology, reference frame, standards
Robert King	Solutions from Central Asia
Tonie vanDam	Reference frames for vertical motion, vertical motion interpretation, end user analysis
Wayne Thatcher	Western North America network and campaign GPS analysis
Will Prescott	Western North America network and campaign GPS analysis
Alessandro Caporali	Italy-Alpine region, network and campaign GPS analysis
Boudewijn Ambrosius	GPS campaign analysis: south east Asia, etc
Carine Bruyninx	Europe network (EUREF) station configuration control and data archives
Cecilia Sciarretta	Italy network GPS analysis
Claude Boucher	Reference frame definition and precision
Francisco Suárez Vidal	Mexico GPS analysis
Grenerczy Gyula	Central Europe (CERGOP) campaign GPS analysis
Herb Dragert	Western North America (WCDA) network and campaign GPS analysis
Ian Whillans	Transantarctic Mountains campaign GPS analysis
Istvan Fejes	Hungarian Geodynamic Reference Network (HGRN) GPS analysis
James Kellogg	Northern Andes, Central America, and Caribbean campaign GPS analysis
John Beavan	GPS campaign synthesis and velocity modeling
Ken Hudnut	Southern California GPS analysis and synthesis (SCEC), modeling of temporal variations
Kristine Larson	Global and regional network and campaign analysis, global plate motion analysis
Kurt Feigl	Pyrenees campaign GPS analysis
Mike Bevis	Reference frame analysis
Richard Snay	North America network GPS analysis, kinematic modeling
Rosa Pacione	Italy network GPS analysis
Wim Spakman	Velocity modeling, end user analysis
Zuheir Altamimi	Geodetic quality analysis, reference frame definition and precision, comparison w/VLBI, SLR, DORIS
David Wiltschko	Taiwan GPS campaign analysis
Eric Calais	GPS campaign analysis: Baikal rift zone, Western Mongolia, Northeastern Caribbean, French Alps
Kazuro Hirahara	Japan Nagoya University GPS network analysis
Kosuke Heki	Assistance with Japanese partners
Mike Pearlman	Liason with potential non-UNAVCO partners
Seiichi Shimada	Regional Japanese solutions, Eastern Asia and Western Pacific.
Zinovy Malkin	Solutions investigating postglacial rebound in Baltic region, plus 40 permanent European stations
Janusz Sledzinski	Solutions from Central European Geodynamics Project, SAGET, and EUREF
David V. Wiltschko	GPS campaign data from Taiwan (approx. 40 stations)
Fu Yang	Solutions from China, > 1000 epoch campaign stations plus 26 permanent stations
Salah Mahmoud	Egypt network and campaign data

Table 3: (continued)

Name	Contribution
E. C. Malaimani	Permanent GPS station at Hyderabad, India
Abdullah ArRajehi	Solutions from permanent GPS in Saudi Arabia
Jose Martin Davila	GPS solutions from Iberian Peninsula – North Africa
Paul Segall	Use of the results for geophysical analysis, and technical issues with GPSVEL
Glenda Besana	Kyoto University-Philippine Institute of Volcanology and Seismology GPS network in the Philippines
Raymundo Punongbayan	Kyoto University-Philippine Institute of Volcanology and Seismology GPS network in the Philippines
Ludwig Combrinck	Permanent stations in Africa
Fran Boler	GPS solution archive support at UNAVCO
Anthony Qamar	PANGA array in Washington State, plus standardized methods to compare GPS solutions
Rob McCaffrey	Campaigns in Indonesia, Papua New Guinea, and continuous data in Oregon
Shinichi Miyazaki Duncan Agnew Minoru Kasahara Satoshi Miura Takao Tabei	Regional velocity field in Japan
T. Kanazawa	
Zheng-Kang Shen	
Kenneth Hurst	
Jeff Freymueller	
Gerald Bawden	