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), a U.S. Government-funded community-based organization for solid Earth science using GPS. 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. Towards these goals, it is proposed that GPSVEL be sanctioned as a joint UNAVCO-WEGENER project to facilitate international participation, project leadership, direction, and coordination, and the development of a product that will have genuine utility to the community.

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 could 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 (e.g., under WEGENER) 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.

Towards these goals, it is proposed that GPSVEL be sanctioned as a joint UNAVCO-WEGENER project to facilitate international participation, project leadership, direction, and coordination, and the development of a product that will have genuine utility to the community.

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. To ensure the highest standards of reliability, one of the rules imposed is that the "global solution" only includes stations for which there are at least 3 Analysis Center solutions. 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) our weekly combined solutions from 1995 to 1999 are fit to a station coordinate and velocity model, with careful accounting for co-seismic displacement and station configuation changes; (iii) no-net rotation and translation constraints are applied to account for Chasles' theorem; (iv) Euler vectors are estimated for the major plates, removing stations which are not adequately fit by the rigid-plate model; (v) residual velocities (for all stations) are computed to investigate intraplate deformation, and (vi) differences between pairs of Euler vectors are used to compute bounds on the kinematics integrated across key plate boundaries

Such a solution [*Lavallee and Blewitt, 2000*] forms the underlying frame for the current global strain map produced by *Kreemer et al.* [2000], and is archived at UNAVCO as GPSVEL Version 0.0 to indicate that it is a necessary first step towards more densified solutions. As a first glimpse into the potential of this project, initial results from GPSVEL Version 0.0, 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.

Practicalities

As centers of activity, the Unversity of Nevada, Reno will coordinate the integration of campaign and permanent array data, while the University of Newcastle will provide IGS combinations of global and regional networks to provide the underlying reference frame. Ideally, the standards of solution exchange and bookkeeping (e.g., SINEX files with full documentation of a priori constraints and antenna heights) and the analysis methods could follow the IGS example. As a test case, the University of Newcastle is currently working towards providing a series of campaign solutions in SINEX format from Greece, which will then be incorporated into the IGS combination solution.

Nevertheless, there are several technical issues that will need resolving, given that much campaign data is not likely to be in the desired form at present. Table 1 outlines anticipated problems faced by the project, along with suggested solutions. One challenge will be to persuade the Principal Investigators of campaigns that it will be worth their effort to produce fully documented SINEX files, and just as importantly, to produce fiducial-free solutions (or constrained solutions together with the reference station coordinates and a priori standard deviations).

To effect this, it is clear that some help should be provided to P.I.s, ranging from advice, software tools, and in some cases, reanalysis of original data according to guidelines. The GPSVEL Working Group will be looking at these issues, with the goal of producing a "GPSVEL" all-encompassing GPS kinematic solution, while at the same time preserving geodetic-quality campaign and network solutions in a standard, fully documented, quality assured way for future generations of researchers. Table 2 provides a timeline of events for the 3-4 yr duration of the project.

Outcomes of the Project

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 contributing P.I.' 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.

Table 1: GPSVEL Project Troubleshooting Analysis

Problem	Possible Solutions	WG/Facility Action
Format*:* A specific input solution may be available but is not currently in SINEX format	1. P.I. converts data into SINEX format 2. P.I. provides solutions to facility in an alternative format which has sufficient information to construct appropriate SINEX files	1. WG develops, makes available, and documents set of SINEX conversion tools 2. WG provides information to P.I.'s on format converters in GAMIT, GIPSY, BERNESE software packages. 3. Facility produces SINEX files from alternative formats, working with P.I. to ensure accurate and complete documentation in SINEX file.
Content: Input solutions come in different frames and with different modeling strategies	1. GPSVEL should only include solutions which meet certain model and frame specifications to enhance homogeneity and accuracy of resulting solution 2. P.I. produces a SINEX file with full a priori constraint information so that free network solution can be constructed 3. P.I. reprocesses data exactly the same way except that no fiducial constraints are applied 4. P.I. reprocesses RINEX data to meet specifications 5. P.I. makes RINEX data and station configuration data available to facility.	1. WG decides on and distribute specifications that balance inclusiveness, homogeneity, and accuracy. 2. Facility gathers information on specific solutions and assesses suitability for combination (pre- and post-analysis assessment). WG to review input solutions and suggest courses of action to P.I.'s and/or facility. 3. WG produces and distributes a P.I.'s guide to these specifications and how they can be met. 4. Facility provides individual assistance to P.I.'s. 5. Facility processes RINEX files and produces SINEX files.
Content: Input solutions assumed incorrect station configuration (e.g., antenna heights, antenna phase centers), or incorrect/incomplete information is provided in SINEX file	1. A definitive station configuration database is used to find and correct errors 2. Redundancy can be used to find problems (i.e., solutions from different analysis groups of same station data).	1. WG develops and makes available station database based on existing IGS "loghist" file, but also including regional networks and campaigns 2. Facility uses database for SINEX creation, and checks incoming SINEX files with database. 3. Facility uses consistency checks between various spatially overlapping solutions to flag problems. 4. Facility uses station coordinate time series to detect possible problems. 5. Detected discrepancies are resolved through consultation, and database is upgraded.
Availability: P.I. does not make solution available, or solution has not retrievable in a useful form	1. Data is not included in GPSVEL 1. P.I. makes RINEX data and station configuration data available to facility. 2. Construct solution based on published results (e.g., from plotted velocity vectors and error ellipses).	1. WG attempts to persuade P.I. as to the benefits of participating, or as to the benefits of reprocessing data. 2. Facility processes RINEX, produces SINEX. 3. Facility develops and carries out procedures to construct solutions from publications, and assesses utility of such solutions
Accuracy: Epoch of input solution was pre-IGS (1992.5).	1. Pre-IGS data not included in GPSVEL unless crucial to providing a velocity solution for specific stations. 2. Accept pre-IGS and lower accuracy solutions, but scale covariance matrix.	1. WG assesses which pre-IGS data is "crucial" 2. Facility includes crucial data and assesses methods of covariance scaling.
Reliability: Input network solution does not overlap significantly (≥3 stations) with other network solutions (e.g., IGS network),	1. If solutions for same stations do not overlap at some epochs, use kinematic solution to tie the epoch solution. 2. If tie is still insufficient, take care to model the covariance matrix such that it may reflect strong "inner precision", but weak "outer precision."	Facility adopts rigorous stochastic modeling in network combination procedure.
Reliability: Only one analysis group has processed specific stations	1. Use time series for internal reliability (assuming epoch solutions are available). 2. Use velocity modeling for external reliability.	1. Facility implements suite of methods for internal reliability analysis, and computes "marginal detectable error" on velocity solutions. 2. Facility computes residual velocity to rigid plate motion as an external check. 3. WG assesses velocity modeling as a method of detecting problem stations.

Table 2: GPSVEL Timeline of Events

Mar 2000	Deliverable: "Prototype" GPSVEL version 0.0: reference frame solution based on 4-5 years of IGS combination time-series solutions, by Blewitt and Lavallée. Will deliver to Facility for graphic display on UNAVCO web pages.
Apr 2000	GPSVEL Working Group meeting at UNAVCO community meeting Goal: Community and Facility discuss and commit to required tasks. Discuss software development to assist participation of P.I.'s, and establish a clearing house for software tools. Tune the GPSVEL plan to best meet community needs and expectations.
Jun 2000	Development of GPSVEL software toolkit in collaboration with Newcastle. Peter Clarke (from Newcastle) visits UNR (under NASA funding).
Jul 2000	Blewitt visits Newcastle (under NASA funding).
Sep 2000	GPSVEL presentation at WEGENER meeting, Cadiz, Spain. Goal: solicit and encourage participation and commitment of international P.I.s
Sep 2000	Deliverable: Prototype GPSVEL version 0.1: refined global reference frame solution
Jan 2001	David Lavallée begins 2-yr appointment of as full-time Postdoctoral R.A. at UNR
Jan 2001	Lavallée and Blewitt visit Boulder facility to discuss Facility collaboration on GPSVEL software tools
Mar 2001	Deliverable: P.I. participation toolkit.
Mar 2001	Deliverable: Prototype GPSVEL version 0.2, including non-IGS regional permanent network solutions, and test with Newcastle to incorporate Greek epoch campaigns
Apr 2001	GPSVEL Working Group meeting at UNAVCO community meeting with Facility-funded travel for some international participants. Goal: Consolidate international participation, and present tutorial to all P.Is on how to participate (use of tools, etc.).
Sep 2001	Deliverable: Prototype GPSVEL version 0.3, including more selected UNAVCO experiments, and a selected WEGENER experiment.
Sep 2001	GPSVEL presentation and Working Group meeting at WEGENER, location t.b.d.
Mar 2002	Deliverable: First "Preliminary" GPSVEL version 1.0 including several UNAVCO and WEGENER experiments.
Apr 2002	GPSVEL Working Group meeting at UNAVCO community meeting. Goal: Review preliminary GPSVEL solution. Assess P.I. participation and any problems. Solicit further participation where "holes" might exist in GPSVEL.
Sep 2002	Deliverable: Preliminary GPSVEL version 1.1, including more experiments.
Sep 2002	GPSVEL status presentation at WEGENER meeting, location t.b.d.
Jan 2003	Possible start of future NSF/NASA funds to augment support for GPSVEL.
Mar 2003	Deliverable: First "official" GPSVEL version 2.0
Apr 2003	GPSVEL Working Group meeting at UNAVCO community meeting. Goal: GPSVEL "near final report" presentation. Fine tune plan to enhance utility of final results to the community.
Sep 2002	GPSVEL final report presentation at WEGENER meeting, location t.b.d.
Sep 2003	Deliverable: "Final" GPSVEL version 2.1
Nov 2003	End of current UNAVCO 4-year funding cycle.

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

Name	**Contribution**
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
David Lavallee*	Grad student, to be full-time Postdoctoral R.A. on GPSVEL solution synthesis, internal QA
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)
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 modelling
Rosa Pacione	Italy network GPS analysis
Susanna Zerbini	Europe tide gauge (SELF) network GPS analysis, coordination of WEGENER campaign GPS solutions
Wim Spakman	Velocity modelling, 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
Salah Mahmoud	Egypt network and campaign data
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

Table 3: (continued)

Name	**Contribution**
David V. Wiltschko	GPS campaign data from Taiwan (approx. 40 stations)
Fu Yang	Solutions from China, > 1000 epoch campaign stations plus 26 permanent stations
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
Hans –G. Kahle	GPS solutions in Meditteranean region
Rob McCaffrey	Campaigns in Indonesia, Papua New Guinea, and continuous data in Oregon
Shinichi Miyazaki	Regional velocity field in Japan
Duncan Agnew	
Minoru Kasahara	
Satoshi Miura	
Takao Tabei	
T. Kanazawa	
Zheng-Kang Shen	
Kenneth Hurst	
Jeff Freymueller	
Gerald Bawden	

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

As can be seen from the current list of participants, many are investigators active in WEGENER, as well as UNAVCO. Towards the goal of producing a dense, self-consistent, GPS global velocity field, it is proposed that GPSVEL be sanctioned as a joint UNAVCO-WEGENER project to facilitate international participation, project leadership, direction, and coordination, and the development of a product that will have genuine utility to the community.

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