Project: NOAA CRUSTAL MOTION MODEL
DG133C06RQ0830

PROJECT REPORT

SUMMARY

An analytical model representing horizontal crustal motion in the western conterminous United States was developed. The model predicts the instantaneous surface horizontal velocity and its uncertainty (optional) given the input of a geographic surface coordinate. The products of the work comprised a number of velocity grid files that were integrated into the HTDP software.

WORK PERFORMED

The scope of this requested work was to develop a model of horizontal surface velocities for the western United States. While there are many ways to go about doing this, here we have chosen to generate a geologic block model, constrained by observations from geodesy, seismology and geology. The parameters of the block model are constrained by non-linear least-squares inversion and then are used to predict surface velocity at any point within the model domain.

In the past few years McCaffrey has developed a Fortran computer code called *DEFNODE* that utilizes GPS velocities, fault slip rates, earthquake slip vectors and strain rate data to estimate the modern day surface velocities. In this approach the Earth's surface is represented by a series of elastic, rotating blocks that are separated by faults along which friction causes elastic strain within the blocks. In addition, permanent strain within the blocks, possibly due to small-scale faulting, is represented by a uniform strain rate tensor. In this manner the deformation even within a tectonically complex region as the western US can be represented by only a relatively few geologically relevant parameters.

The block inversion method is described in McCaffrey (1995, 2002) and is available on the website www.rpi.edu/~mccafr/defnode. The technique was applied separately to the southwestern US (McCaffrey, 2005) and to the Northwestern US (McCaffrey et al. 2007). These models were based on thousands of GPS velocities and hundreds of geologic fault slip rates, earthquake slip vectors and surface strain rates. In both cases the simple models comprising rotating blocks subject to elastic and anelastic strains were able to match the observations within the uncertainties. Other researchers have used the free *DEFNODE* software to generate block models for several parts of the world (see citations on software website). The work performed here expanded those western US studies by changes to the block model to combine the southwest and northwest regions and updating the data.

Western US crustal velocity field

This work combined the two western US models to produce a block model of the entire western US, covering the area requested. Most of the effort involved refining the model and assessing new data. The block model satisfies the available data (Tables 1 and 2). From this model a continuous, predicted surface velocity field in the form of four grids was generated. The output of the model includes formal uncertainties on both the model parameters and on the surface velocities predicted by it. All data used and misfits (residuals) resulting from the inversion are provided.

Per the email from R. Snay of 11/21/2006, the inversion was done in and output is in the ITRF2005 reference frame (Altamimi et al., 2007). In this work, the reference frame was realized by fixing the velocities of 55 sites within the model area and rotating other velocity fields into that reference frame; the fits to the 55 ITRF2005 sites was Nrms = 1.23 and Wrms = 0.66 mm/yr (Tables 1 and A1).

The data comprise 4890 horizontal GPS velocities, 170 fault slip rates inferred from geologic and paleomagnetic studies and 258 fault slip vectors taken from both earthquakes and geologic fault studies. All data are listed in the Appendices. Slip vector and fault slip data were those used in McCaffrey (2005) and McCaffrey et al. (2007).

Horizontal GPS velocities were derived from 13 separate velocity fields (Table 1). Other than the ITRF2005 velocity field (see below), all were transformed into the ITRF2005 reference frame by least squares, simultaneously with the other model parameters. The transformation involved only 3 free parameters since the velocities are tangential to the surface of the Earth and no scaling is applied. In some cases the velocities were down-weighted if I thought the uncertainties did not reflect the actual scatter in them. It should be noted that three of the fields, CMM4, CEA1 and PBO7 (Table 1), are soon to be updated (R. W. King, personal communication, 9/11/2007).

Of the 6462 original velocities contained in the 13 velocity fields, 1570 were removed from the inversion for the following reasons: either near volcanoes or unmodeled faults (244), high uncertainties (754), anomalous velocities (343), or not within the model region (228).

Table 1. GPS velocity fields and fits.

Code	Num Used	Num Total	Weight Factor	SigMin, mm/yr	SigMax, mm/yr	Nrms	Wrms, mm/yr	Sum of Weights	Data Source
ITR5	55	290	0.44	0.5	3.0	1.23	0.66	377.0	Altamimi et al. 2007
SNRF	18	22	1.00	0.3	3.0	1.12	0.43	246.0	SNARF website
DXB2	16	16	1.00	0.3	5.0	0.67	0.85	19.6	Dixon et al 2002
HT04	67	67	1.00	0.5	3.0	0.90	0.86	146.0	Hammond & Thatcher 2004
HT05	94	110	1.00	0.5	3.0	0.87	1.01	139.0	Hammond & Thatcher 2005
WILL	36	71	0.25	0.5	3.0	1.19	1.14	78.3	Williams et al. 2006
CEA1	1285	1403	1.00	0.3	2.5	1.21	1.33	2150.0	California Earthquake Authority
CMM4	1195	1318	1.00	0.3	2.5	1.15	1.22	2130.0	Shen et al. 2007
DMEX	12	14	0.44	0.5	3.0	0.75	1.07	11.8	Marquez-Azua et al 2003
PBO7	437	795	0.25	0.4	3.0	1.07	0.95	1100.0	PBO 4/2007
PNW7	578	670	1.00	0.3	2.5	1.16	0.58	4590.0	McCaffrey, 2007; Payne, 2007
USGS	306	501	0.44	0.4	3.0	1.09	1.00	729.0	USGS website
RWK7	791	1185	0.25	0.4	2.5	1.17	1.06	1910.0	King, 2007; D'allesio, 2005

Weight Factor is multiplied by the weight of each observation; weight = σ^{-2}. SigMin and SigMax are the minimum and maximum uncertainties allowed. If the assigned σ < SigMin then σ = SigMin; if σ > SigMax then the observation is removed. Nrms is the normalized rms misfit. Wrms is the weighted rms misfit.

The statistics of the overall fits to the data are:

Table 2. Fits to data.

Data Type	Num. Data	Nrms	Wrms	Sum Weights
GPS	9780	1.15	0.98 mm/yr	13600
Slip rates	170	1.41	1.23 mm/yr	225
Slip vectors	258	0.94	12.9º	1.4
Total	10208	1.16	---	13825

The overall fit is described by the reduced chi-squared statistic; the weighted residual variance divided by the degrees of freedom. The final model had a reduced chi-squared of 1.38 (DOF = 9779, number of free parameters = 429, final misfit variance = 13,542). The data are fit to within their level of uncertainties and the system is highly overdetermined.

The simultaneous inversion for angular velocities, strain rates and fault locking is non-linear and is solved by an iterative procedure (downhill simplex). Due to the non-linearity and the *a priori* constraints placed on parameter values, the formal uncertainties in the parameters are not exactly determined, and are probably underestimated. Derivatives are estimated by finite differences and a linear system of equations is assumed. The formal uncertainties in velocities are typically less than 1 mm/yr throughout the region (see figures). Other measures of uncertainties, such as the weighted rms misfits, also indicate an uncertainty at the mm/yr level.

The process estimates vertical velocities but these are very unreliable and should not be used, as the physical model for the vertical is not robust, particularly around crustal faults.

Since the forward computation of the velocities with *DEFNODE* is computationally intensive (i.e., slow) due mainly to the computation of the elastic strain component from numerous faults, the output of the model supplied to interface with the *HTDP* software comprises four grid files. These grids cover different regions with different cell sizes in order to obtain higher accuracy in regions of higher velocity gradients (Table 3). The grids were designed in consultation with NGS (R. Snay, email of 11/29/2006).

Table 3: Grid regions used

Longitude range	Latitude range	Cell spacing (minutes)	Grid dimensions	Region
125º to 100ºW	31º-49ºN	15.0	101 x 73	Entire region
125º to 122ºW	40º-49ºN	3.75	49 x 145	Pacific NW
125º to 119ºW	36º-40ºN	3.75	97 x 65	Northern CA
121º to 114ºW	31º-36ºN	3.75	113 x 81	Southern CA

In addition to the grids, I am providing to NGS scientists the *DEFNODE* software plus input and output files related to the final model (those velocity fields that are subject to intermittent updates should be obtained from the primary sources for future calculations). In this way the Crustal Motion Model can be revised by NGS personnel with addition of new data if they so desire. I am providing maps of the velocity field, data and residuals in digital form (PDF) along with a map of the reliability of the predicted velocity field based on the *a posteriori* parameter covariance matrix.

Citations

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Table A1. ITRF2005 Velocities and residuals (in mm/yr).

Longitude	Latitude	Ve	Vn	Re	Rn	Se	Sn	Site
167.73	8.722	-70.38	29.46	-0.89	-0.60	0.50	0.50	KWJ1
189.278	-14.326	-63.83	33.93	0.62	-0.23	0.57	0.50	ASPA
200.335	22.126	-63.20	34.25	-1.21	-0.17	0.50	0.50	KOKB
200.661	21.985	-62.41	35.17	-0.43	0.76	1.32	1.19	LHUE
202.135	21.303	-62.52	34.22	-0.54	-0.12	0.50	0.50	HNLC
203.743	20.707	-61.83	33.82	0.09	-0.42	0.50	0.50	MAUI
204.544	19.801	-63.38	34.97	-1.19	0.78	0.50	0.50	MKEA
210.394	-17.577	-66.16	34.53	0.79	0.98	0.50	0.50	THTI
226.473	68.306	-12.27	-15.24	1.48	0.02	0.50	0.50	INVK
231.865	50.640	-12.77	-10.10	-0.04	-0.86	0.50	0.57	HOLB
234.458	48.926	-3.12	-3.79	0.10	0.15	1.32	1.30	UCLU
234.75	71.990	-16.31	-13.71	-0.38	-0.66	0.50	0.57	SACH
235.914	49.295	-8.35	-8.24	0.41	-0.76	0.50	0.50	NANO
236.513	48.390	-7.63	-7.59	0.18	-0.57	0.50	0.50	ALBH
237.832	52.237	-13.85	-11.38	-0.31	-0.49	0.50	0.50	WILL
239.056	39.975	-21.30	-4.27	-0.56	0.50	0.50	0.50	QUIN
239.318	34.469	-42.46	24.86	-0.47	-0.18	0.63	0.68	HARV
240.317	48.132	-12.69	-9.81	0.28	-0.40	0.50	0.50	BREW
240.375	49.323	-12.73	-10.05	0.51	0.12	0.50	0.50	DRAO
241.827	34.205	-37.27	14.51	-0.39	0.63	0.50	0.50	JPLM
242.239	70.736	-16.87	-11.31	0.45	-0.49	0.50	0.50	HOLM
243.111	35.425	-17.48	-3.90	0.46	0.25	0.50	0.50	GOLD
243.334	31.871	-40.10	20.88	-0.19	0.02	0.50	0.50	CIC1
243.578	32.892	-38.53	17.44	-1.15	-0.02	0.50	0.50	MONP
245.519	62.481	-16.42	-11.02	0.58	-1.24	0.50	0.50	YELL
245.707	50.871	-13.86	-10.48	1.25	-0.83	0.50	0.50	PRDS
251.881	34.302	-12.93	-7.39	-0.27	-0.62	0.50	0.50	PIE1
255.475	38.803	-14.32	-6.00	-0.72	0.42	0.50	0.50	AMC2
255.985	30.681	-11.99	-5.52	-0.55	0.73	0.50	0.50	MDO1
258.022	54.726	-17.26	-6.76	-0.02	-1.20	0.50	0.50	FLIN
262.941	27.838	-11.81	-3.79	-0.98	0.02	2.10	1.26	ARP3
263.998	64.318	-18.59	-4.58	0.58	-1.15	1.56	1.50	BAKE
264.134	50.259	-17.40	-4.57	-0.66	-1.19	0.50	0.50	DUBO
265.911	58.759	-18.09	-3.77	0.33	-1.03	0.50	0.50	CHUR
268.425	41.772	-15.06	-1.02	-0.16	0.81	0.50	0.50	NLIB
270.132	16.916	-8.56	-0.90	-1.15	0.31	1.22	0.72	ELEN
279.838	25.735	-10.35	3.46	-0.07	1.14	0.50	0.50	AOML
281.929	45.956	-16.13	2.48	-0.31	-0.59	0.50	0.50	ALGO
282.934	38.919	-14.70	4.04	-0.67	0.60	0.50	0.50	USNO
283.173	39.022	-14.69	4.09	-0.64	0.57	0.50	0.50	GODE
283.521	38.983	-14.74	3.88	-0.71	0.23	0.50	0.50	USNA
283.546	38.319	-14.16	4.41	-0.31	0.75	0.55	0.58	SOL1
283.87	38.589	-13.89	2.61	0.02	-1.16	0.57	0.66	HNPT
284.193	45.585	-15.81	3.39	-0.17	-0.50	0.78	0.63	CAGS
284.376	45.454	-15.91	3.89	-0.31	-0.06	0.50	0.50	NRC1

288.507	42.613	-14.81	5.59	-0.12	0.17	0.50	0.50	WES2
291.778	44.395	-15.45	7.06	-0.58	0.50	0.52	0.61	BARH
293.008	44.909	-15.26	7.60	-0.37	0.62	0.50	0.57	EPRT
293.167	54.832	-17.63	7.31	-0.75	0.27	0.50	0.50	SCH2
293.358	45.950	-15.93	7.46	-0.84	0.36	0.50	0.61	UNB1
295.304	32.370	-11.61	9.36	-0.05	1.59	0.50	0.50	BRMU
296.389	44.684	-14.94	8.12	-0.42	-0.01	0.90	0.98	HLFX
298.311	56.537	-16.35	10.04	0.23	1.27	0.77	1.05	NAIN
307.322	47.595	-14.36	12.71	-0.61	1.08	0.50	0.50	STJO
309.055	66.987	-17.34	11.53	-1.17	-0.62	0.50	0.50	KELY

Ve and Vn are east and north velocities. Re and Rn are east and north residuals. Se and Sn are east and north sigmas.

Attached figures

Map file explanations. All maps use large page .pdf format. All include 70% confidence ellipses on the GPS vectors. In some cases black vectors are predicted velocities.

itrf_model - block boundaries and faults (red lines with tics on the hanging wall side. Each block is named in red. Blue dots show GPS sites used.
itrf_model_north – north half of model.
itrf_model_south – south half of model.

itrf_all_data - Shows all data used, including on the Pacific and North American plates. Dots are color coded by source.
itrf_wus_data - Western US close-up of the data map.
itrf_grid_N - Shows the number of GPS sites within each 30 x 30 minute cell.

itrf_wus_vel - Observed velocities in ITRF2005 frame. Vectors are color-coded according to source.
itrf_wus_vel_block - Observed velocities in ITRF2005 frame. Vectors are color-coded according to source. Fault model included.
itrf_wus_res - Residual velocities in ITRF2005 frame. Vectors are color-coded according to source.

itrf_err_tot - Estimated velocity uncertainties based on the a posteriori covariance matrix (parameter uncertainties) for 15 minute grid. Fault outlines are shown. Note that uncertainties increase in regions near faults due to the uncertainties on fault coupling parameters.
itrf_grid_res - Shows the weighted average GPS residual within each 30 x 30 minute cell.
itrf_grid_nrms - Shows the normalized rms GPS residual within each 30 x 30 minute cell.
itrf_grid_wrms - Shows the weighted rms GPS residual within each 30 x 30 minute cell.

itrf_grid_vec_1 - Grid of estimated velocities in ITRF2005 frame at 15 minute intervals.
itrf_grid_vec_2 - Same as itrf_grid_vec_1 but includes block model overlain.

Close-up maps are made of the regions below. Each has the format of the itrf_wus_vel and itrf_wus_res maps.
San Francisco Bay Area (**itrf_bay_vel** and **itrf_bay_res**);
Southern California (**itrf_socal_vel** and **itrf_socal_res**);
Pacific Northwest (**itrf_pnw_vel** and **itrf_pnw_res**).

Attached files

cmm_summary.data – contains all data and fits, angular velocities and strain rates for blocks, and the uncertainties.

cmm_final.dfn – input file for the program defnode.

defnode.f (plus defcomm.h, defiles.h, defconst.h, …) **–** source code for defnode.

defnode.html – instruction manual for defnode.

Original Data files in ‘data’ directory; other data are in the .dfn file

itrf directory contains output of defnode.