Expansion of the combined GNSS component of the Community Geodetic Model for the Statewide California Earthquake Center

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1. Abstract

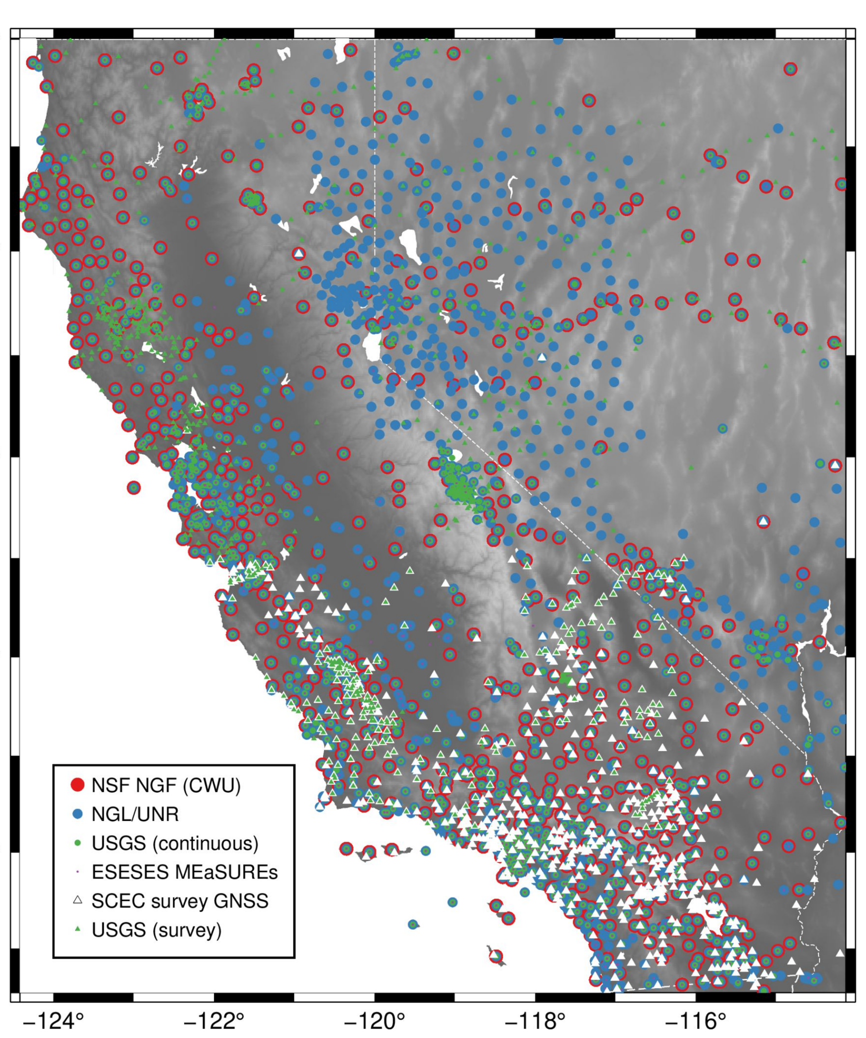
We present the latest combination of statewide GNSS products for the Community Geodetic Model (CGM), using, realigning and combining publicly available velocity products from six sources (four continuous GNSS only, one survey GNSS only and one continuous and survey GNSS) to generate a comprehensive superset. We use the no-net-rotation (NNR) reference frame versions of analysis centers' velocity products (IGS20 for NGL/UNR and ITRF2014 for GAGE/CWU, JPL and SOPAC) except for the USGS velocity solution, for which we use the North America reference frame version rotated to an NNR reference frame using the appropriate ITRF2014 plate motion model. Once transformed into a consistent reference frame, we combine the velocity solutions by calculating the weighted mean, using inverse variances quoted in each analysis center product as the weight, for each station. We test definitions of the associated uncertainties in three ways: using the inverse of the sum of the weights,equivalent to the formal uncertainties from weighted least-squares inversions; using the standard weighted unbiased sample standard deviation; and using the variance sum of these two. We then rotate the GNSS velocities into various common reference frames used to describe and study the North America-Pacific plate boundary, relative to North America and the Pacific plate defined by the ITRF2020 plate motion model, the ITRF2014 plate motion model, the Global Strain Rate Model, and another common definition of North America. We also produce velocities in "half-plate" reference frames, by taking the average rotation rate vectors of the North America-Pacific plate pairs, where simultaneously defined, which minimizes the velocities along the plate boundary itself rather than in the far-field on either side. This approach is similar to that of Y. Zeng for the 2023 National Seismic Hazard Model. Compared to their compilation, within the same region and for velocities with sigmas less than or equal to 4.143 mm/yr in both horizontal components, the largest for any site within the region of interest from the Zeng solution, we present about 3320 sites, 450 more than the 2870 from the Zeng solution within the same criteria. The GNSS velocity solution products presented here will be available through the CGM Explorer soon. Finally, we derive a statewide strain rate field by colocation, which we anticipate being included as a candidate methodology in the CGM's Community Velocity Field Exercise.

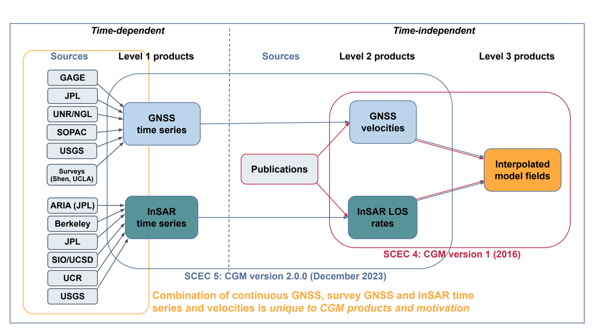
2. Introduction

The Community Geodetic Model (CGM) is one of the Community Earth Models (CEMs) and seeks to generate, provide and combine geodetic (currently GNSS and InSAR) products and derived surface motion fields. Here we expand the comprehensive GNSS velocity solution statewide, including more sources (e.g. USGS surveys, mostly in central and northern California).

GNSS velocity solution	Unique stations	NNR reference frame	Plate reference frame	Reference
ESESES MEaSUREs	1145 (JPL) 1145 (SOPAC)	IGS14 (ITRF2014)	None	Bock et al. (2025)
NSF NGF (formerly GAGE)	756	IGS14 (ITRF2014)	ITRF2014 Plate Motion Model (Altamimi et al., 2017)	Herring et al. (2016)
NGL/UNR	1753	IGS20 (ITRF2020)	Global Strain Rate Model (Kreemer et al., 2014)	Blewitt et al. (2018)
NGS NCN "MYCS3" [not used]	324	IGS20 (ITRF2020)	None	
USGS	1076 (continuous) 890 (survey) 11 (semi-permanent)	IGS14 (ITRF2014)	ITRF2014 Plate Motion Model (Altamimi et al., 2017)	Murray and Svarc (2017)
SCEC survey GNSS	803	None	SNARF (SNARF Working Group,)	Shen et al. (2011), Shen (2020)
SCEC CGM update (this study)	**3390 1821 (continuous) 1569 (survey)**	**IGS20 (ITRF2020)**	**Mutiple, e.g. all the above and ITRF2020 Plate Motion Model (Altamimi et al., 2023)**	
NSHM 2023 update	*2870*	*None*	*ITRF2014 Plate Motion Model (Altamimi et al., 2017)*	*Zeng (2022)*

Table 1: Summary of contributing (continuous and survey) GNSS solutions, the latest CGM (GNSS) superset from this study and the GNSS velocity solution for comparison. Numbers of unique stations are limited to within the geographic boundary shown in Figures 2 and 3, and, in the case of this study versus the NSHM 2023 update (Zeng, 2022), limited to horizontal velocity sigmas less than or equal to 4.143 mm/yr, the maximum reported in Zeng (2022).





↑ **Figure 1:** Elements of the CGM (GNSS and InSAR) combination, including publicly available products from analysis centers (currently GNSS) as well as contributions from the CGM Working Group (mostly InSAR). This study iterates the combination of GNSS sources of velocities (Level 2 products) for statewide coverage.

← **Figure 2:** Locations of continuous and survey GNSS stations processed by the analysis centers who provide publicly available.

3. New Statewide GNSS Velocity Solution

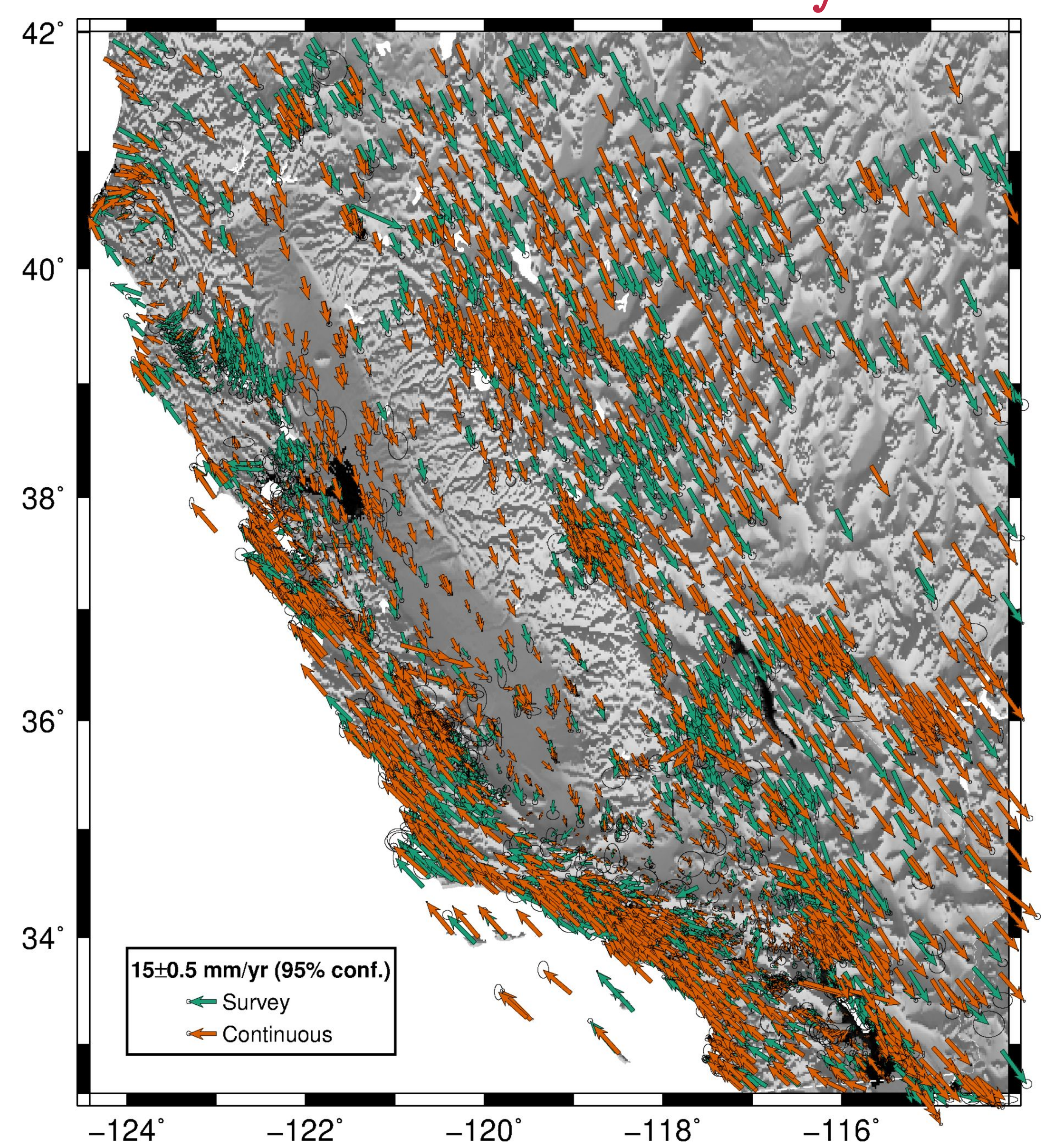


Figure 3: Updated "superset" (or "union") CGM GNSS velocity product, combined from the sources shown in Table 1 and Figure 2. Uncertainties are estimated as described below.

4. Treatment of Uncertainties

Uncertainties derived from the inverse of the sum of the weights (equivalent to the formal uncertainties from weighted least-squares inversions), σ, are based on the variances of solutions' velocity estimates but do not take into account the variance *between* solutions' estimates. We therefore use the weighted unbiased sample standard deviation, *s*:

$$\bar{s}_j = \sqrt{\frac{\sum_{i=1}^{n} \frac{v_i - \bar{v}_j}{\sigma_i^2}}{\sum_{i=1}^{n} \frac{1}{\sigma_i^2} - \frac{\sum_{i=1}^{n} \left(\frac{1}{\sigma_i^2}\right)^2}{\sum_{i=1}^{n} \frac{1}{\sigma_i^2}}}} \quad \text{where} \quad \bar{v}_j = \frac{\sum_{i=1}^{n} \frac{v_i}{\sigma_i^2}}{\sum_{i=1}^{n} \frac{1}{\sigma_i^2}} \quad \text{versus} \quad \bar{\sigma}_j = \sqrt{\frac{1}{\sum_{i=1}^{n} \frac{1}{\sigma_i^2}}}$$

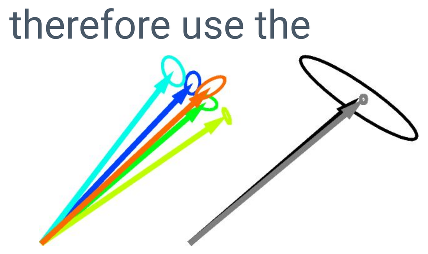


Figure 4: Demonstration of *s* (black) versus σ (gray) for five schematic solutions (left)

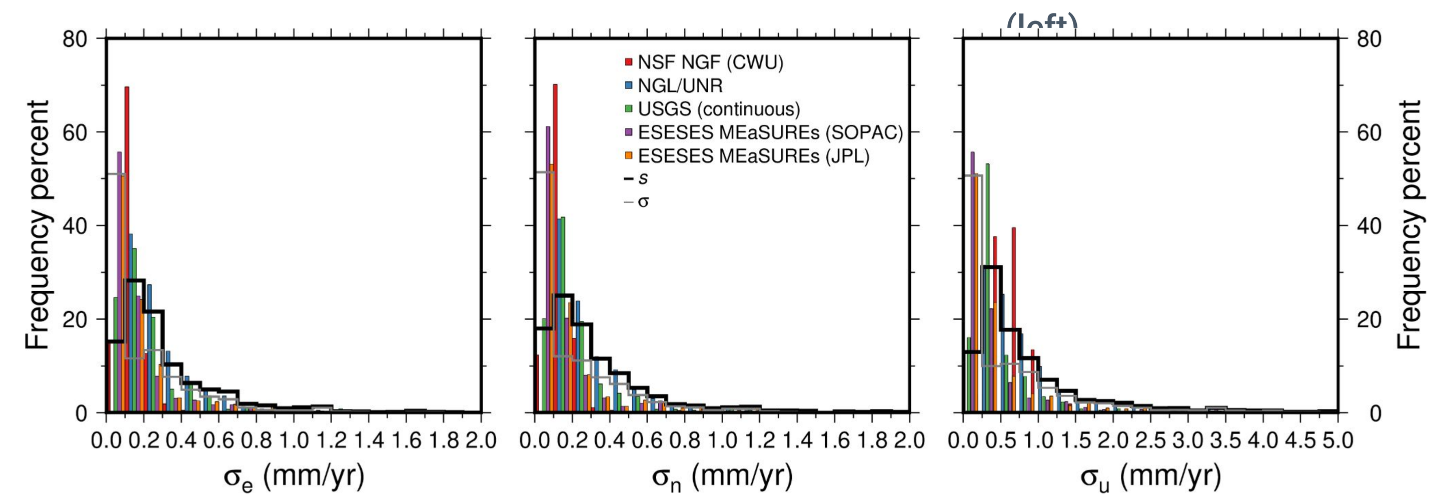


Figure 5: Histogram showing the distribution of velocity uncertainties in each contributing solution (bars) versus the distribution of the two approaches to velocity uncertainties in the CGM combination (lines). The inverse of the sum of the weights, σ, is over-optimistic whereas *s* represents the distribution of any individual solution (e.g. aleatoric uncertainty) and the variance between them (e.g. epistemic uncertainty).

5. Spatial Interpolation by Colocation

The ultimate goal and derived quantity of the CGM is a continuous field of surface (geodetic) velocity and strain rate (e.g. CGM version 1; Sandwell et al., 2016). Here we show the results of one classic method, colocation, using the GNSS velocity solution shown in Figure 3, which may be used to contribute to the CGM Community Velocity Exercise (e.g. Tymofyeyeva et al., Poster 087).

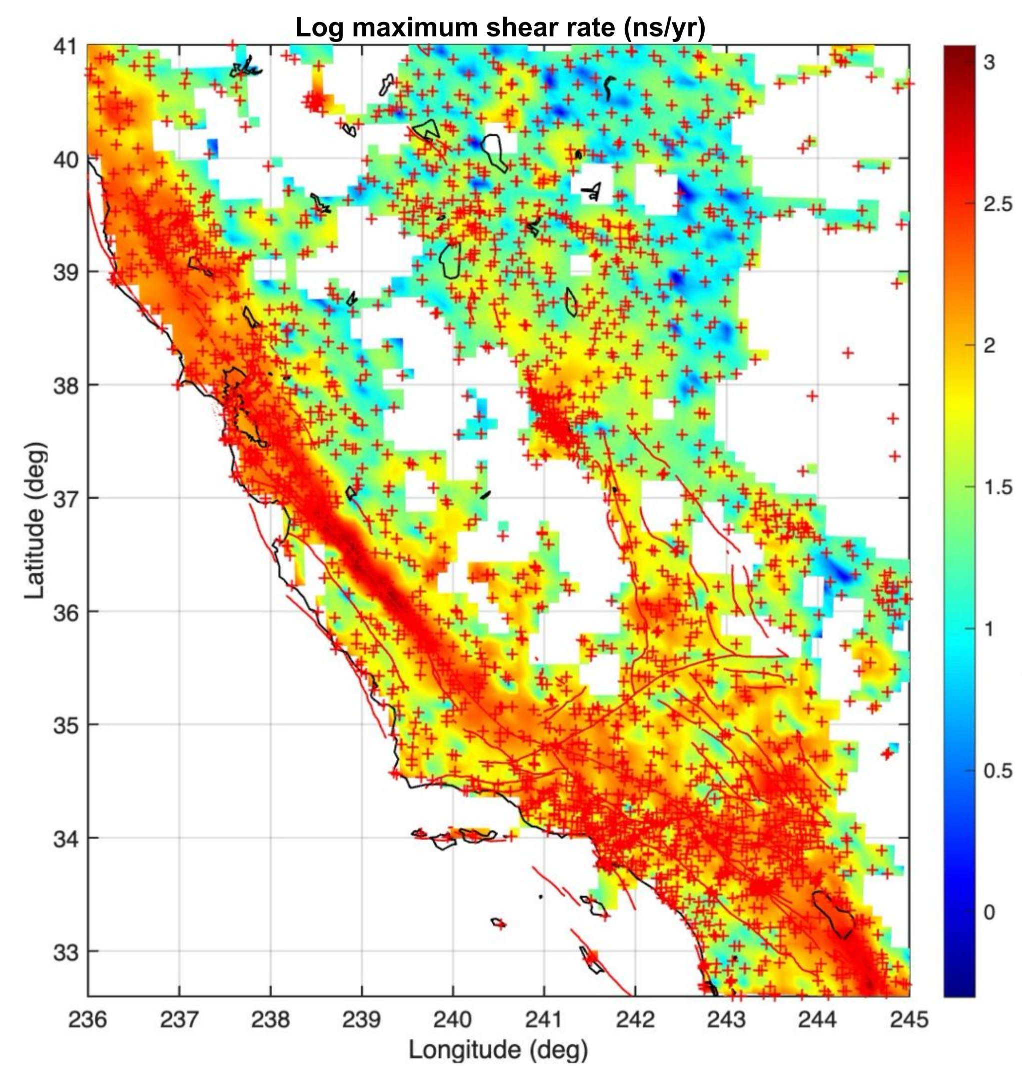


Figure 6: Map of shear strain rate component estimated from interpolation of the GNSS velocities shown in Figure 3 by colocation. Velocity fields and other components of the velocity gradient tensor may also be calculated. GNSS station locations are shown with red plus symbols. Areas not colored are beyond the limits of the distance over which interpolation is allowed. Spatial density may be enhanced by the inclusion of denser GNSS solutions and InSAR.

6. Future Updates

- Add **more survey solutions** throughout California, e.g. McGill et al. (2015) in San Bernardino Mountains, and Floyd and Funning work in northern California (currently unpublished but available).
- **Extend to Baja California**, e.g. González-Ortega et al. (2018) for survey stations and González-Ortega (pers. comm.) for continuous stations.
- **Detect and remove outliers** to facilitate use as fundamental data for CGM Community Velocity Exercise (e.g. see Tymofyeyeva et al., Poster 087) and/or combination with InSAR.
- **Release and publish** an update to the CGM (e.g. Floyd, Tymofyeyeva, et al., 2023) and through the CGM Explorer (http://moho.scec.org/cgm-explorer).
- Expand corresponding combined **time series statewide** with a similar approach (e.g. Floyd, Tymofyeyeva, et al., 2023, for southern California).

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