STATE OF CALIFORNIA • DEPARTMENT OF TRANSPORTATION

TECHNICAL REPORT DOCUMENTATION PAGE

TR-0003 (REV 04/2024)

1. REPORT NUMBER CA26-4317	2. GOVERNMENT ASSOCIATION NUMBER N/A	3. RECIPIENT'S CATALOG NUMBER N/A
4. TITLE AND SUBTITLE Statewide 3-Dimensional Motion Analysis for Optimal CTSRN Performance and Geospatial Data Management		5. REPORT DATE 03/31/2026
		6. PERFORMING ORGANIZATION CODE 95-6006144
7. AUTHOR Dr. Yehuda Bock, Distinguished Researcher and Senior Lecturer Director, Scripps Orbit and Permanent Array Center (SOPAC)		8. PERFORMING ORGANIZATION REPORT NO. N/A
9. PERFORMING ORGANIZATION NAME AND ADDRESS The Regents of the University of California, U.C. San Diego 9500 Gilman Drive MC. 0210 La Jolla, CA 92093-0210		10. WORK UNIT NUMBER N/A
		11. CONTRACT OR GRANT NUMBER 65A1210 Task 4317
12. SPONSORING AGENCY AND ADDRESS California Department of Transportation P.O. Box 942873, MS #83 Sacramento, CA 94273-0001		13. TYPE OF REPORT AND PERIOD COVERED Final Report June 30, 2024 to January 29, 2026
		14. SPONSORING AGENCY CODE Caltrans

15. SUPPLEMENTARY NOTES
N/A

16. ABSTRACT

The California Spatial Reference Center (CSRC), operating within Scripps Institution of Oceanography, University of California, San Diego will leverage results of previous Caltrans funded efforts to develop regional boundaries for the Caltrans Spatial Reference Network (CTSRN) subnetworks using Continuous Global Navigation Satellite System (CGNSS) station data, that take geology, landforms, subsidence, and plate tectonics into consideration, and develop configurations that will minimize maintenance and maximize the relative accuracy of the subnetworks.

17. KEY WORDS GNSS, Optimal subnetwork boundaries, CTSRN, CRTN, geodetic control	18. DISTRIBUTION STATEMENT No restrictions	
19. SECURITY CLASSIFICATION *(of this report)* Unclassified	20. NUMBER OF PAGES 25	21. COST OF REPORT CHARGED N/A

Reproduction of completed page authorized.

DISCLAIMER

The research reported herein was performed by the California Reference Center at Scripps Institution of Oceanography, University of California San Diego, for the Division of Right of Way and Land Surveys, Office of Land Surveys at the California Department of Transportation.

This document is disseminated in the interest of information exchange. The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California or the Federal Highway Administration. This publication does not constitute a standard, specification or regulation. This report does not constitute an endorsement by the Department of any product described herein.

The contents of this report do not necessarily reflect the official views or policies of the University of California. This report does not constitute an endorsement by the University of California of any product described herein.

For individuals with sensory disabilities, this document is available in alternate formats. For information, call (916) 654-8899, TTY 711, or write to California Department of Transportation, Division of Research, Innovation and System Information, MS-83, P.O. Box 942873, Sacramento, CA 94273-0001.

Institute of Geophysics and Planetary Physics

Scripps Institution of Oceanography

University of California San Diego

Yehuda Bock and Aubrey Bennett

Report Number CA26-4317

March 31, 2026

Contract Manager: Arvern Lofton, P.E.
California Department of Transportation
Division of Research, Innovation and System Information
Office of Safety Innovation and Cooperative Research

Prepared for: Kevin C. Maxwell, PLS
California Department of Transportation
Division of Right of Way and Land Surveys
Office of Land Surveys

Executive Summary

This research provided to the California Department of Transportation includes a set of optimal regional boundaries (subnetworks) for the Caltrans Spatial Reference Network (CTSRN) to support highway improvement projects and increase efficiencies by Survey Department staff. The design, which takes geology, landforms, subsidence, and plate tectonics into consideration, minimizes maintenance and maximizes the relative accuracy of the subnetworks by providing a schedule for updating station coordinates for Caltrans projects and real time kinematic (RTK) users of the CTSRN.

Problem, Need and Purpose of the Research

California is situated on major fault lines (tectonic plate boundary) along with numerous other earthquake fault zones causing significant horizontal and vertical ground displacements over time. This ground motion requires periodic update of coordinates of GNSS stations to stay within specified survey accuracy – 1 cm in the horizontal and 2 cm in the vertical.

The Caltrans Spatial Reference Network (CTSRN) provides access to a geodetic reference system used by Caltrans divisions within Project Delivery to plan, design, and construct highway improvement projects. The accuracy of this system and the resulting, collected data meeting Federal Highway Administration (FHWA) mapping accuracy requirements for all federal aid projects is critical. Also, the Federal Office of Management and Budgets (OMB) Circular No. A-16 Revised, requires that all federal aid projects must be aligned to a common reference system or geodetic datum. Defined by Public Resources Code (PRC) Sections 8850 – 8861, the official geodetic datum and reference network for California provides the California Spatial Reference Center (CSRC) legislative authority to define and maintain these systems.

The purpose is to ensure that the CTSRN can maintain horizontal and vertical accuracies in the presence of crustal deformation by creating optimal subnetworks to meet the needs of Caltrans' Districts and their partners.

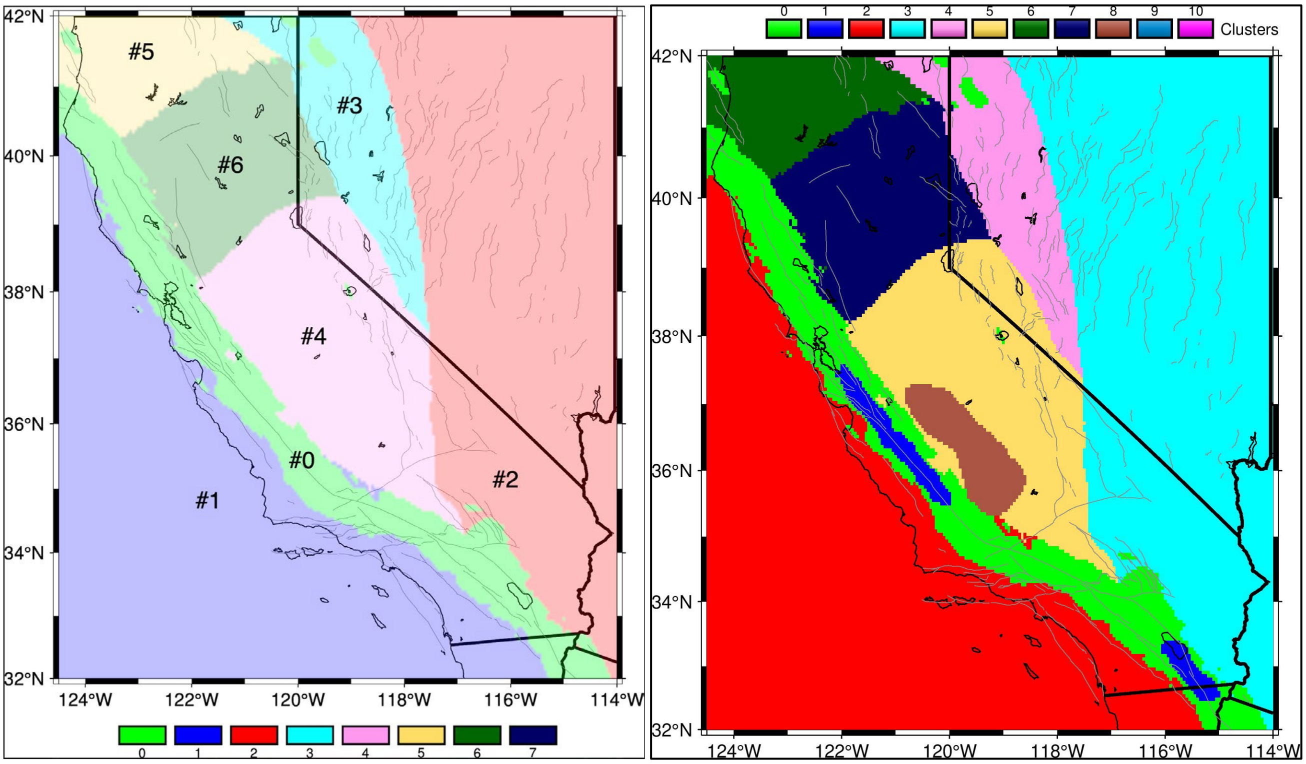
Overview of the Work

The overall objective is to define optimal regional boundaries and coordinate reset times for CTSRN subnetworks. The Scripps Orbit and Permanent Array Center (SOPAC) research team used a machine learning algorithm, K-Means clustering, to meet this objective. SOPAC created accompanying weekly 3-D and 4-D digital maps of crustal deformation. The project comprised of four tasks:

Task 1: Investigate Strategies for Regional Boundaries
Task 2: Compile Digital Maps of 4-D Crustal Motions (space and time)
Task 3: Compile Digital Maps for CTSRN Design
Task 4: Reporting

Major Results and Recommendations

SOPAC researchers tested various subnetwork designs and configurations summarized in the figure and table below, which highlight the main results and recommendations. SOPAC recommends the use of the nearest neighbor approach (described in the body of the report) for the current CTSRN configuration and the corresponding coordinate reset times. The California Real Time Network (CRTN) configuration with a much larger number of stations provides comparable reprocessing times except for Cluster #5, which indicates significantly reduced time between coordinate updates. Therefore, adding more CRTN stations to the CTSRN in Cluster #5, if feasible, might be useful.



Optimal subnetworks. Final subnetwork design for CTSRN and CRTN configurations (nearly identical and represented by a single map). (Left) Horizontal clusters; (Right) Horizontal and vertical clusters, which includes Cluster #8 in the Central Valley. The distinct blue regions along the San Andreas fault are folded into Cluster #0 covering the San Andreas fault system in the (Right) map. Cluster #3 is outside of California's boundaries, so its sliver in the northeast corner of the state is folded into Cluster #5 in the (Left) map.

Table 1. Summary of optimal coordinate reset times for CRTN and CTSRN

Cluster #	CRTN # of Stations in Cluster	CRTN Nearest Neighbor Reprocessing Times	CTSRN # of Stations in Cluster	CTSRN Nearest Neighbor Reprocessing Times
0	321	0.65 years	63	1.25 years
1	162	3.6 years	36	2.5 years
2	49	4.35 years	20	4 years
4	134	3.23 years	46	4.2 years
5	28	2.33 years	12	+7.6 years
6	58	+7.6 years	24	+7.6 years

Acronyms and Abbreviations

Acronym	**Definition**
ADA	Americans with Disabilities Act
Caltrans	California Department of Transportation
CGNSS	Continuous Global Navigation Satellite System
CRTN	California Real Time Network
CSRC	California Spatial Reference Center
CTSRN	California Spatial Reference Network
FHA	Federal Highway Administration
GIS	Geographic Information System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
NAD	North American Datum
NOTA	Network of the Americas
OMB	Office of Management and Budgets
PRC	Public Resources Code
RTK	Real Time Kinematic
SCEC	Statewide California Earthquake Center
SCIP	SOPAC Coordinate Interpolator Prompt
SIO	Scripps Institution of Oceanography
SOPAC	Scripps Orbit and Permanent Array Center

Table of Contents

Introduction

The California Spatial Reference Center (CSRC), operating within Scripps Institution of Oceanography, University of California, San Diego, developed regional boundaries (subnetworks) for the Caltrans Spatial Reference Network (CTSRN) of continuous GNSS stations. The design considers secular deformation due to crustal deformation across the transition between the North America and Pacific plates and subsidence due mainly to groundwater withdrawal and replenishment. In addition, we considered instantaneous coseismic offsets and postseismic deformation that require a reset of all coordinates at affected stations and may reduce the time between coordinate updates, using the 2019 Mw7.1 Ridgecrest earthquake and subsidence in the Central Valley as case studies.

The SOPAC research team applied a machine learning K-Means clustering algorithm to create the subnetworks and to estimate the time required for coordinate updates within each subnetwork when survey precision is exceeded: 1 cm in the horizontal components and 2 cm in vertical coordinate. SOPAC provided a schedule for updating station coordinates for real time kinematic (RTK) users of the CTSRN and the various Caltrans infrastructure projects.

The SOPAC researchers examined two network configurations: (1) utilizing the current CTSRN stations that include Caltrans and affiliate stations (e.g., from EarthScope's NOTA infrastructure) (Figure 1); (2) utilizing the entire CRTN network of over 769 stations (Figure 2).

Problem

The Caltrans Spatial Reference Network (CTSRN) is the Department's real-time GNSS positioning system used by Caltrans districts within Project Delivery to plan, design, and construct highway improvement projects. The CTSRN is a collection of active GNSS reference stations that receive, process, and transmit satellite information to provide real-time positioning solutions, which include geospatial data collection, engineering surveys, as-built surveys, construction layout, automated machine guidance, autonomous vehicle research, and other positioning needs. The accuracy of this system and the resulting data collected meeting Federal Highway Administration (FHWA) mapping accuracy requirements for all federal aid projects is critical. Also, the Federal Office of Management and Budgets (OMB) Circular No. A-16 Revised, requires that all federal aid projects must be aligned to a common reference system or geodetic datum. The official geodetic datum and reference network for California is defined by PRC sections 8850 – 8861 and provides the CSRC legislative authority to define and maintain these systems.

Because California is situated on a major fault line (tectonic plate boundary) along with numerous other earthquake fault zones, the internal accuracy and integrity of the State's geodetic reference network deteriorate by as much as a few inches per year. California is also subject to areas of severe subsidence due to natural and resource extraction and replenishment. The primary task is to identify regions/areas of consistent relative movements that fall within survey precision requirements (1 cm in the horizontal and 2 cm in the vertical) and design subnetworks to take the motions into account, that is, to maintain geodetic control within the constraints of crustal motions. The primary goal is to provide Caltrans' surveyors and engineers with increased efficiencies, minimize maintenance and provide

RTK and static users of the CTSRN with survey precision, with respect to California's latest geodetic reference system (CSRN 2025.00 NAD83(2011).

Objectives and Scope

To address the problem described above, the CSRC has provided:

(1) A digital map that includes velocity data, regional boundaries, time intervals, and source data locations. The data from the digital map will support Caltrans with preparing recommendations for optimal CTSRN subnetwork boundaries within California, which may also incorporate political/district boundaries and other factors.
(2) A companion digital map with modified regions that displays idealized time intervals. The subsequent time intervals from the companion map will yield the necessary adjustments for Caltrans to maintain relative accuracy of the CTSRN, with considerations of district boundaries.
(3) A complete project report on 2-D, 3-D, and 4-D assessments. This report with the resulting, multi-dimensional assessments will serve as a valuable reference and resource to support our recommendations for optimal subnetwork boundaries.

Benefits

The following benefits will be realized by understanding the State's underlying geodetic reference network and isolating reference stations in the more stable regions of the State from the reference stations in its more active regions:

(1) Improved accuracy in the geodetic reference network will increase efficiencies in collecting and producing digital and geospatial data products, thus improving functions of Project Delivery.
(2) Scientifically designed CTSRN subnetworks will improve accuracy and increase efficiencies when using the CTSRN to collect and layout digital and geospatial data, therefore improving functions of Project Delivery.
(3) Improved accuracy and maintenance of geospatial data contained in a statewide common data environment – Geographic Information System (GIS) and other digital data based upon the State's official geodetic reference network.
(4) Cost savings by identifying focus areas (regions) and regular time intervals for reference network re-adjustments and reducing wasted efforts spent on areas that are less impacted by ground motion.

Identifying these regions can reduce the amount of work needed to maintain the State's geodetic reference network and the CTSRN by reducing adjustment intervals in stable areas, increasing adjustment intervals in volatile areas, and defining the boundaries between areas.

The results of this project align with the Caltrans Strategic Management Plan:

(1) Safety First: With more users utilizing the Caltrans Spatial Reference Network, Department employees will have less exposure to the traveling public and other hazards associated with conventional geospatial data collection and positioning.
(2) Stewardship and Efficiency: Defined regions with similar motion will require less field re-work, maintenance, and/or adjustments to accommodate the effects of ground motion. These efficiencies will be realized by many divisions within Caltrans. Support current digital delivery and geospatial lifecycle management initiatives currently under development statewide.
(3) Equity and Livability: Benefit all public and private sectors that are involved with land ownership and infrastructure improvements through the application of high-accuracy GNSS data. This research will benefit the integration of connected vehicle technology with the state highway system.
(4) Innovation: More effectively utilize satellite-based technology to its full potential in the dynamic environment of California to enable comprehensive planning and decision making to improve the lives of all Californians.
(5) Climate Action: Create a highly accurate geodetic control network, requiring minimal re-work to reduce the amount of CO_2 emissions by reducing vehicle miles travelled. Accurately monitor and mitigate for the impacts of sea-level rise on transportation projects in coastal areas.

Research Methodology

Overview

The overall objective is to define regional boundaries for the CTSRN subnetworks (Figure 1) using CGNSS station data in the presence of geology, landforms, subsidence, and plate tectonics, and develop configurations that will minimize maintenance, maximize the relative accuracy of the subnetworks in space and time, and provide the times to reset coordinates to maintain stated survey accuracies.

The project was conducted under four tasks:

Task 1: Investigated Strategies for Regional Boundaries

- Used a K-means clustering approach to divide the CTSRN into clusters corresponding to subnetworks described as velocity, velocity gradient, and strain rate grids.
- Considered the current CTSRN stations including Caltrans-owned stations and affiliates (e.g., EarthScope NOTA stations), http://sopac-adj.ucsd.edu/caltrans/ (Figure 1).
- Considered the complete California Real Time Network (CRTN, http://sopac-adj.ucsd.edu/crtn-map/) (Figure 2).
- Finalized horizontal subnetwork boundaries for CTSRN (Figure 3 – right panel).
- Finalized horizontal and vertical subnetwork boundaries for CTSRN (Figure 3 – left panel).
- Compared CTSRN and CRTN configurations (Figure 4).
- Compared clusters derived from center point or nearest neighbor criteria (Figure 5).
- Calculated time to reset coordinates for each cluster (Table 1 and Figure 6).
- Evaluated the impact of coseismic and postseismic motions on the reset of subnetwork coordinates (Figure 7).

Table 1. Summary of all scenarios considered in this report[1]

Cluster #	CRTN # of Stations in Cluster	CRTN Center Point Reprocessing Times	CRTN Nearest Neighbor Reprocessing Times	CTSRN + Affiliates # of Stations in Cluster	CTSRN Center Point Reprocessing Times	CTSRN Nearest Neighbor Reprocessing Times
0	321	0.4 years	0.65 years	63	0.4 years	1.25 years
1	162	1.2 years	3.6 years	36	1.25 years	2.5 years
2	49	1.64 years	4.35 years	20	1.8 years	4 years
4	134	1.71 years	3.23 years	46	2.2 years	4.2 years
5	28	1.1 years	2.33 years	12	2.2 years	4.8 years
6	58	4.6 years	7.6 years	24	4.75 years	7.6 years

[1] *SOPAC recommends the use of the nearest neighbor approach for the current CTSRN configuration. The CRTN configuration with a much larger number of stations provide comparable reprocessing times except for Cluster #5, which indicates a longer coordinate reset time. Cluster #3 was folded into Cluster #5.*

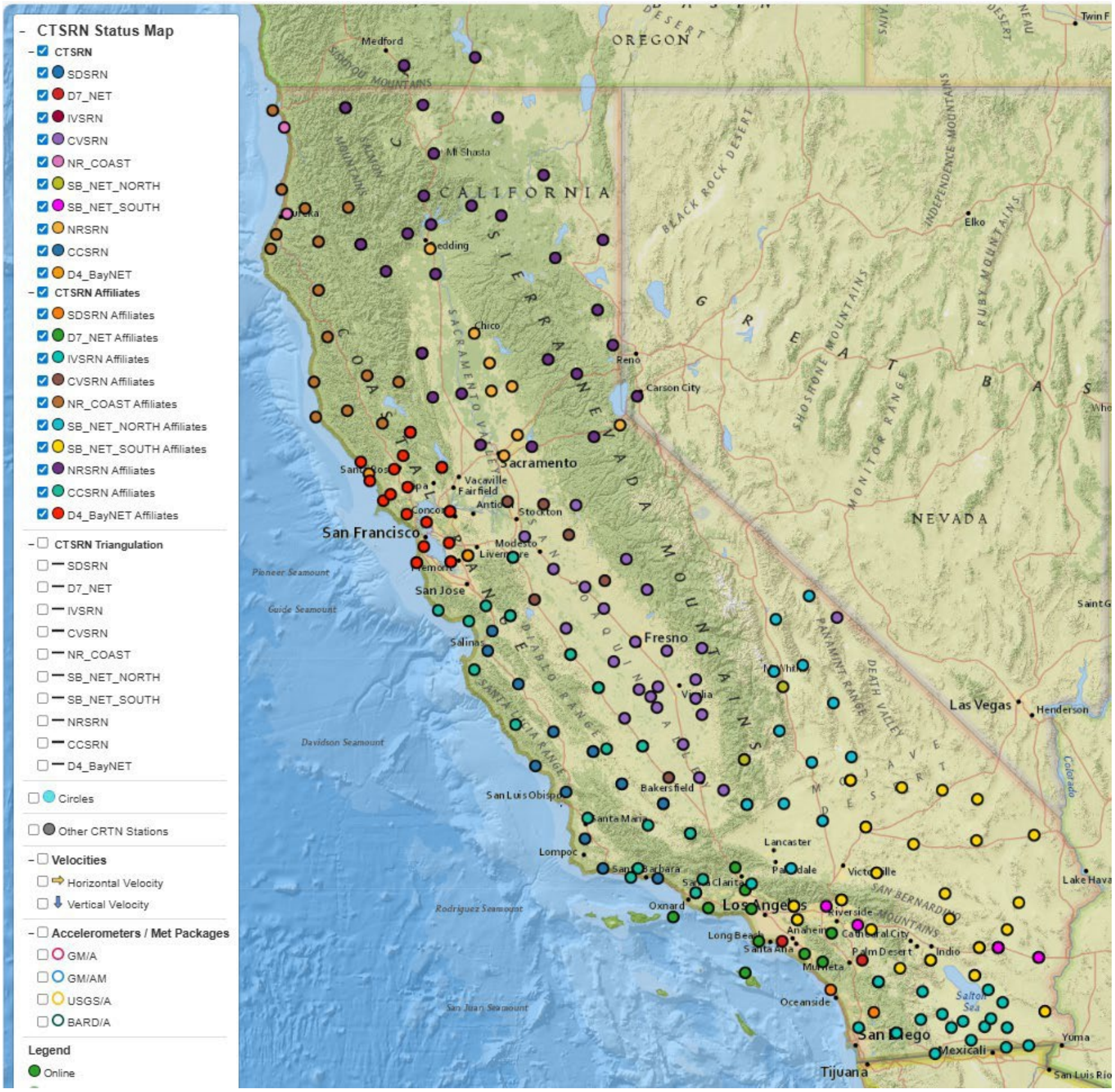


Figure 1. CTSRN stations (http://sopac-adj.ucsd.edu/caltrans/)

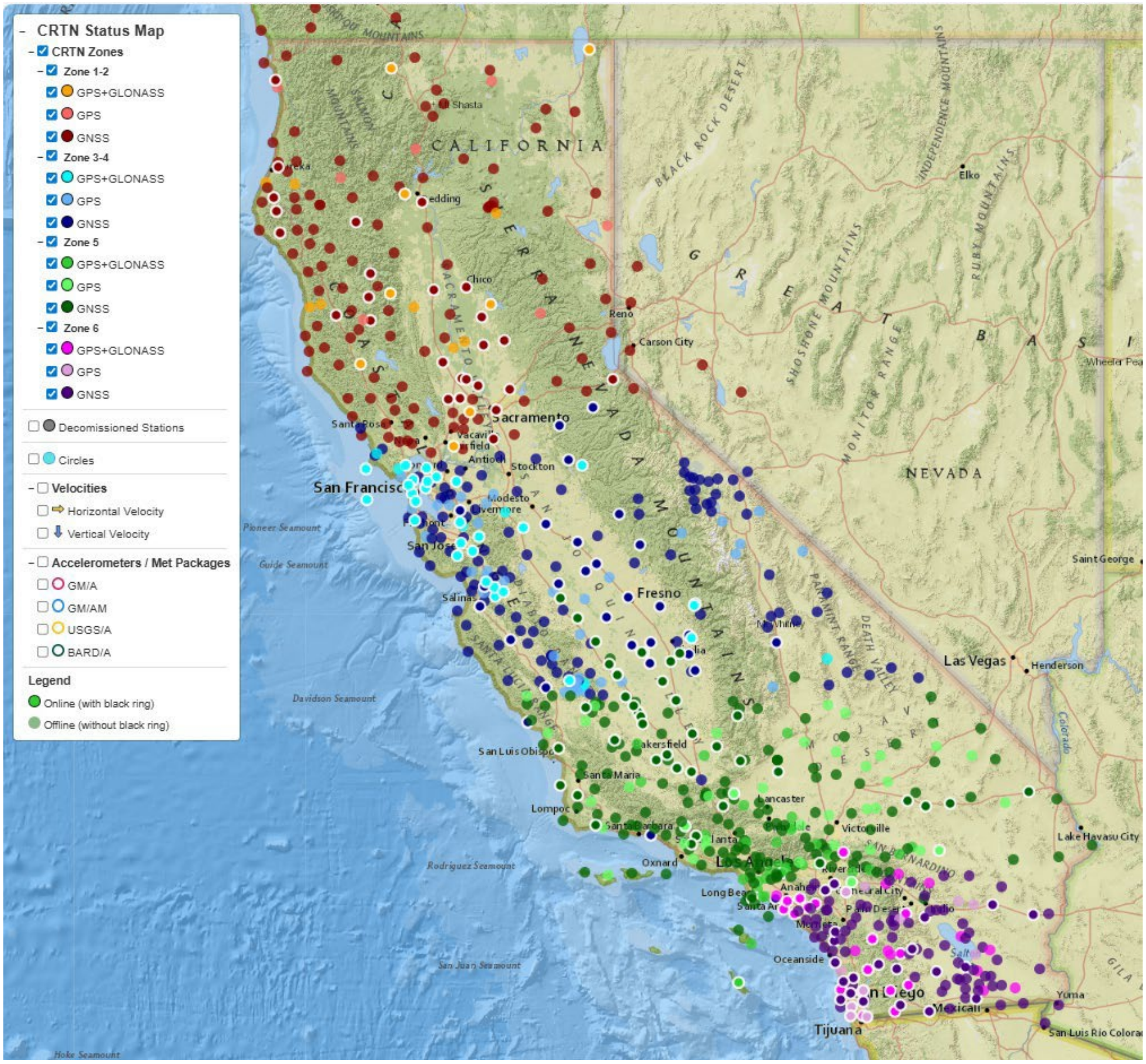


Figure 2. CRTN stations (http://sopac-adj.ucsd.edu/crtn-map/)

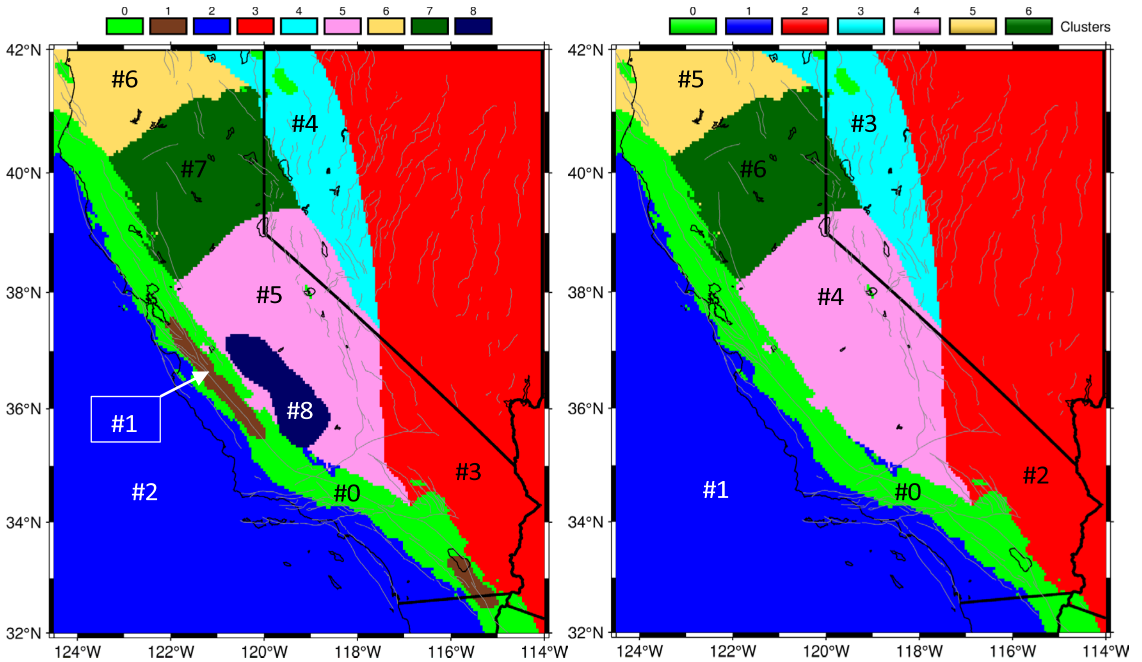


Figure 3. Final network boundaries for CTSRN. (Left) Horizontal and vertical. Vertical requires a separate cluster in the Central Valley; (Right). Horizontal only. Consolidated the disparate blue regions, indicating regions of fault creep, into the San Andreas fault Cluster #0.

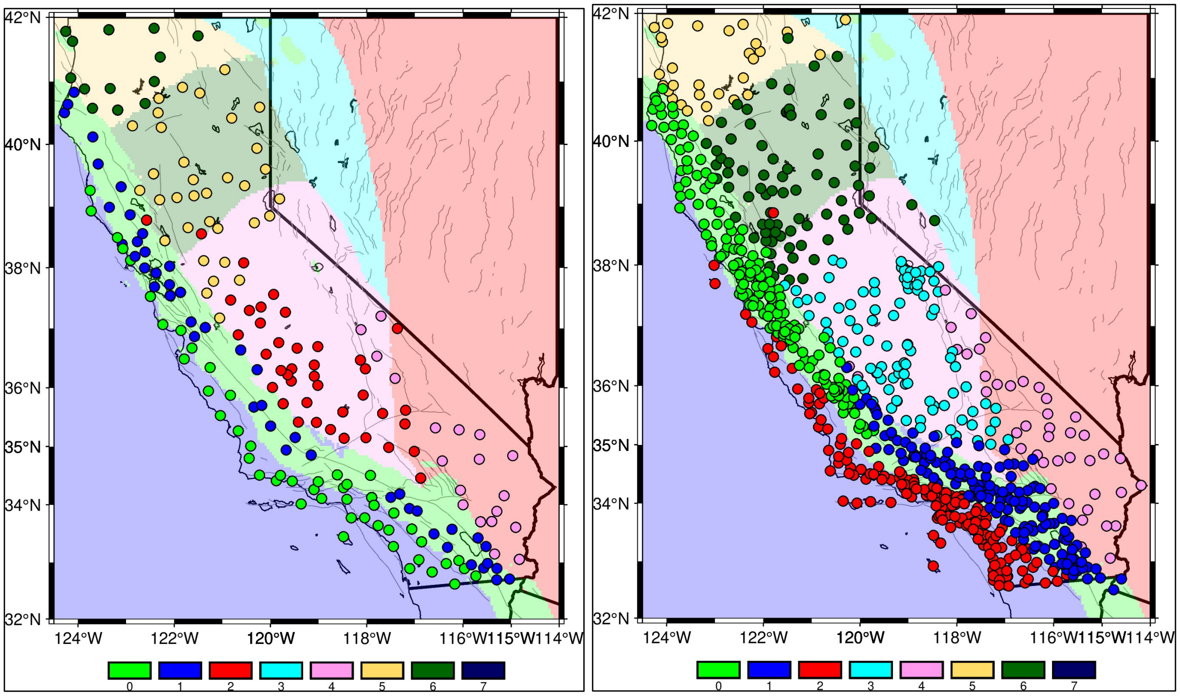


Figure 4. Comparison of two networks and clustering results. (Left) CTSRN; (Right) CRTN. *The clustering is nearly identical for the two networks.*

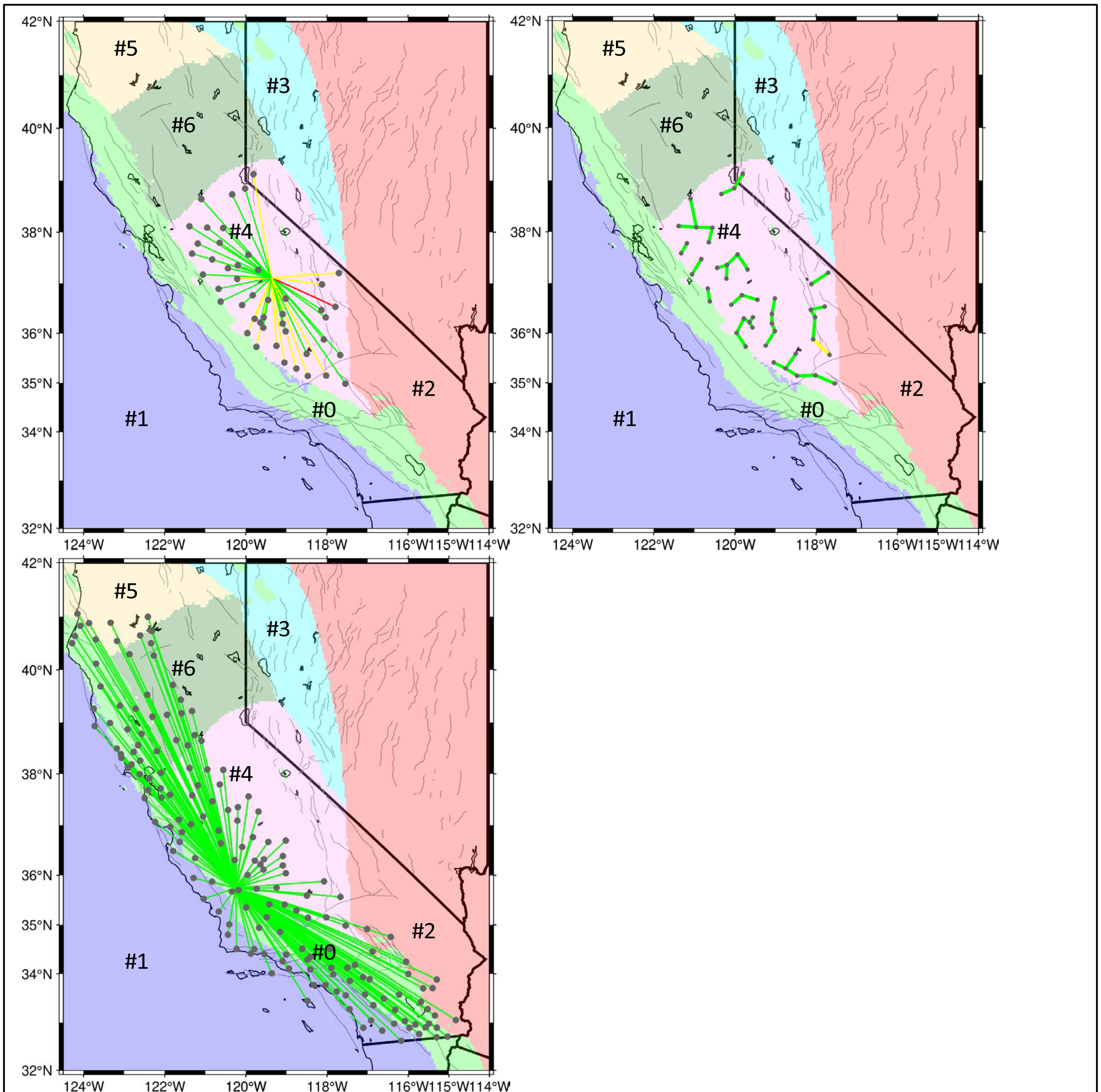


Figure 5. Criteria to calculate coordinate update times for CTSRN. (Left) Center point; (Right) Nearest neighbor. Nearest neighbor approach is more plausible. Refer to Table 1 and Figure 6. (Bottom) Broader area of deformation for Cluster #0 (San Andreas fault).

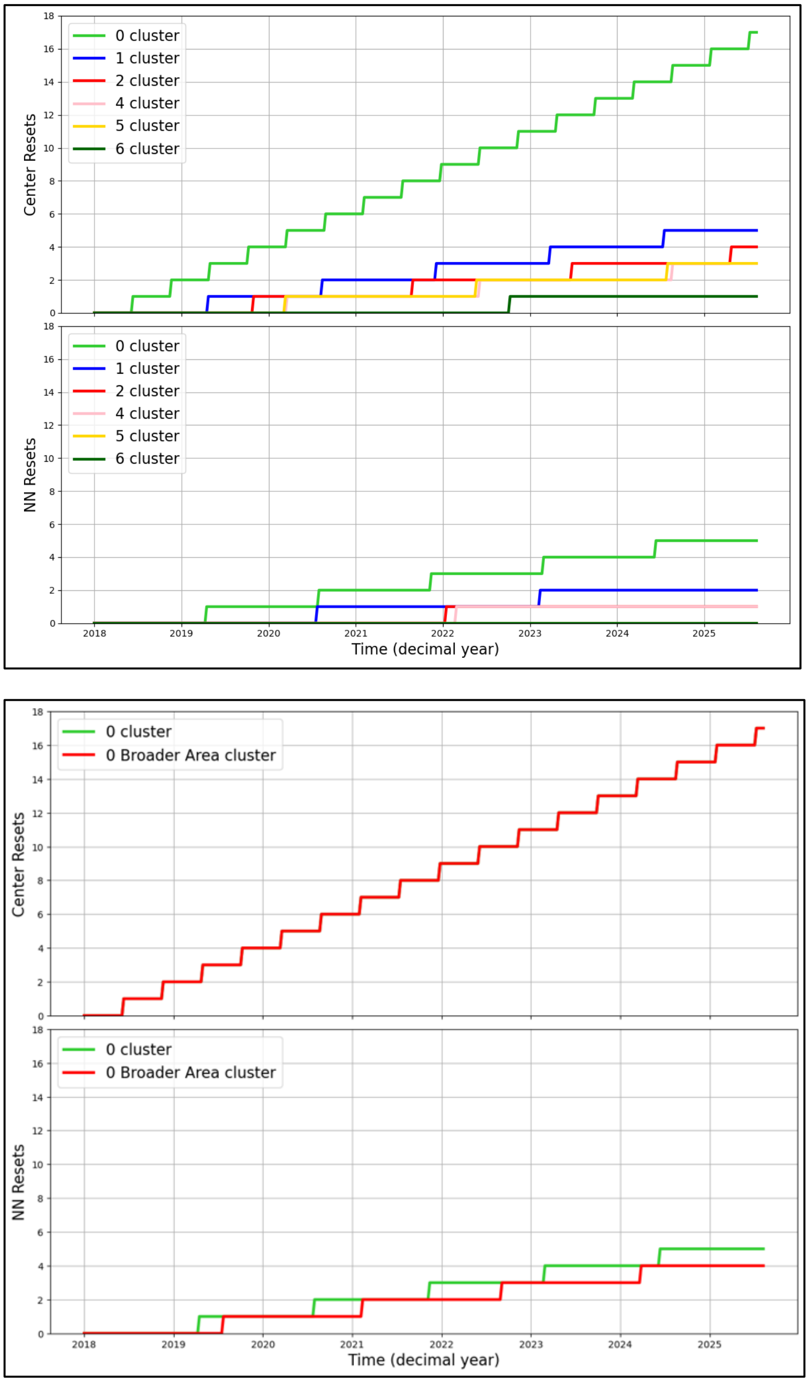


Figure 6: Coordinate resets. (Top) The number of resets over time given a center point (top) and nearest neighbors (bottom). Refer to Table 1 and Figure 5. (Bottom) The number of resets over time for the original San Andreas Cluster #0, and a broader area of deformation (refer to Figure 5 bottom panel). The resets were referenced to a given a center point (top) and nearest neighbor distance (bottom).

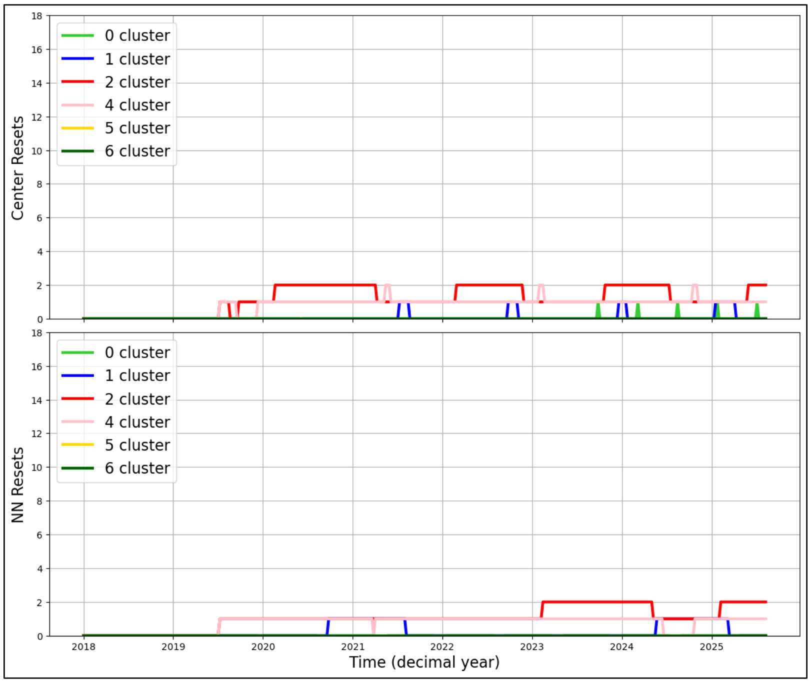


Figure 7: Effects of coseismic offsets and postseismic deformation. Difference in the number of resets between secular + coseismic + postseismic displacement and secular displacement for the CRTN stations. After a coseismic event, for example the 2019 Mw7.1, Ridgecrest earthquake, there would have been an immediate need to reset subnetworks #2 and #4. The subnetworks adjacent to the mainshock need to be monitored for perturbations in the time series due to postseismic motion.

Task 2: Digital Maps of 4-D Crustal Motions

- Compiled Digital Maps of 4-D Crustal Motions (in space and time).
- Finalized database of GPS-derived deformation grids (through SCIP utility - http://sopac-adj.ucsd.edu/scip/) (Figure 8).

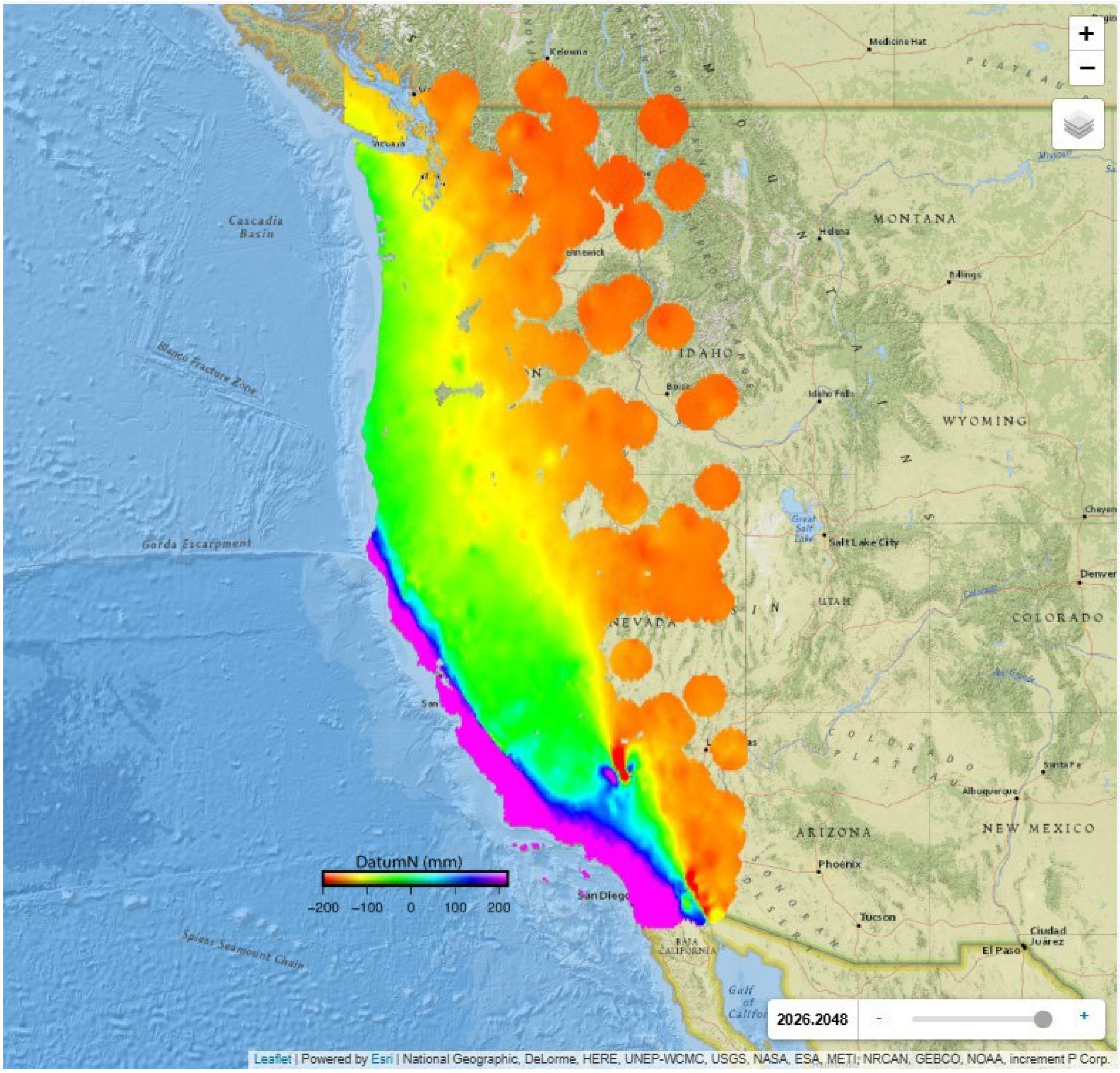


Figure 8: Example of a weekly deformation grid. North direction centered on March 16, 2026. The east and up components provide a 3-D picture, while the sequence of grids provides the time dimension (i.e., 4-D).

Task 3: Digital Maps for CTSRN Design

- Compiled Digital Maps for CTSRN Design (provided to Caltrans staff).
- Compiled kmz files and cluster boundary coordinates for final subnetworks (provided to Caltrans staff).

Task 4: Reporting

- Presented posters at the 2025 Statewide California Earthquake Center (SCEC) Meeting, Palm Springs (Figure 9) and the 2025 American Geophysical Union (AGU) Meeting, New Orleans by [Bennett et al. (2025)](#).
- Met repeatedly with Caltrans personnel to review progress and receive feedback.
- Met with Caltrans personnel for final project briefing.
- Prepared this Final Report.

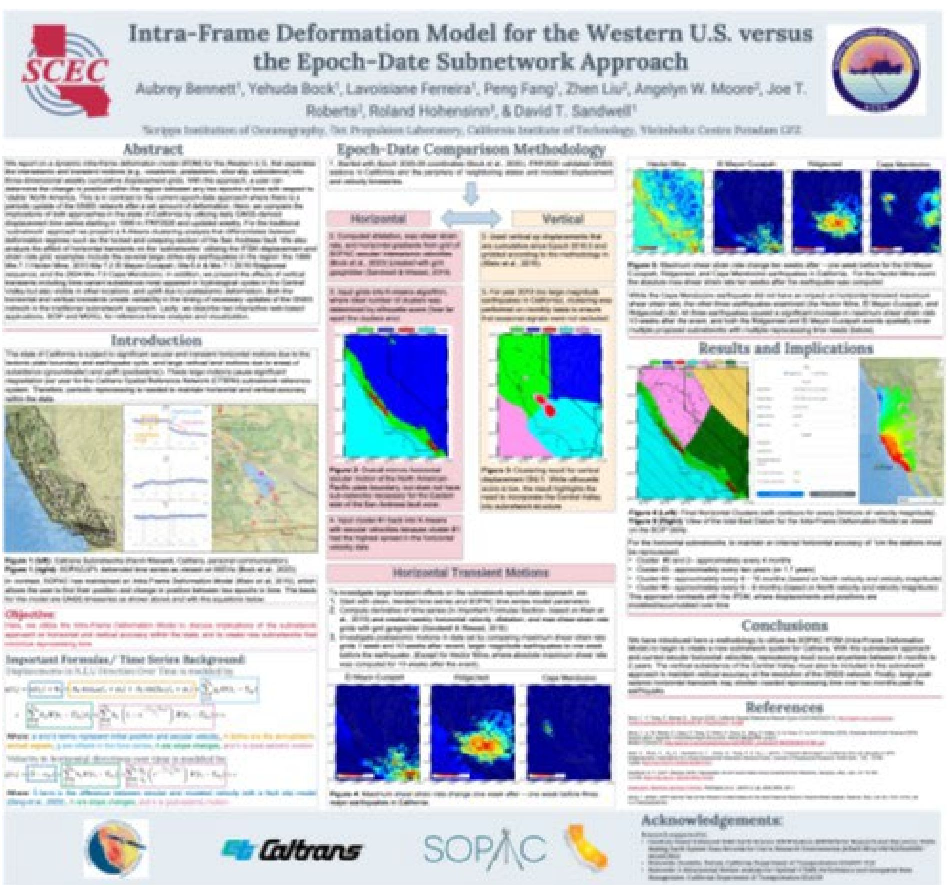


Figure 9: Poster presented at SCEC Fall Meeting September 7-10, 2025, by Bennett et al.

K-Means Analysis

The K-means clustering algorithm from scikit-learn (Pedregosa et al., 2011) was used to create the suggested subnetwork boundaries for CTSRN and CRTN.

Horizontal Subnetwork Boundaries

To create the horizontal subnetwork boundaries, validated Epoch 2025.00 SOPAC GNSS velocities (https://sopac-csrc.ucsd.edu/index.php/velocities/) were analyzed. The workflow was as follows:

1. Created interpolated velocity grids with gpsgridder (Sandwell & Wessel, 2016) assuming a minimum velocity uncertainty of 0.5 mm/yrs. Then, dilatation rate, max shear strain rate, and the four velocity gradient grids were created from the interpolated velocity grids.
2. Performed K-Means clustering (Pedregosa et al., 2011), on the grids listed in step 1, and determined the best number of clusters with a silhouette test (a measure of cluster separations).
3. To increase cluster separation, K-Means was iteratively performed on the cluster on the Eastern side of the San Andreas. The clustering was stopped when further clustering only separated deformation patterns outside of California. The final horizontal clustering is shown in Figure 4.

Vertical Subnetwork Boundaries:

To create the vertical subnetwork boundaries, we used displacement grids from the SCIP utility (http://sopac-adj.ucsd.edu/scip/). The vertical displacement grids were constructed from validated SOPAC GNSS displacements. The workflow performed is as follows:

1. Monthly 2018 vertical displacement grids were clustered independently. The year 2018 was chosen due to the lack of large magnitude earthquakes in California during that time.
2. Each cluster result was analyzed to find clusters that were due to GNSS signal, not just spatial dependence. The only subnetwork boundary necessary to account for vertical accuracy degradation is around the Central Valley (Figure 3).

The final clustering result combining horizontal and vertical velocities is shown in Figure 3 (right panel) and the reset times for coordinates, satisfying the 2 cm accuracy specification.

Horizontal Accuracy Degradation

To begin determining the reprocessing time necessary for the horizontal subnetworks, the locations of a subset of CTSRN stations were used. The clusters were analyzed according to two subnetwork distances: the distance to a central point and the distance to each station’s nearest neighbor (Figures 5 and 6). North and East secular velocity values were found for each station utilizing an interpolated interseismic grid (Zeng et al., 2022). The velocity values were converted to weekly displacements over the years 2018.00 to 2025.60. The distances between either the center point to the station or the nearest neighbor to the station were computed at each time step. If the change in distance exceeded 1 cm for more than two stations, a subnetwork reset was declared and the change in distance was reset to 0 cm.

Horizontal Accuracy Degradation- Ridgecrest Case Study

To determine the impact of a large earthquake with significant coseismic offsets and postseismic motions on subnetwork reprocessing time, additional displacements were added to the time series. Interpolated displacement grids were created for the years 2018.00 to 2025.60 given the SOPAC GNSS time series parameters (methodology in Bock et al., 2023), and the equation:

$$y(t_i) = a(t_0) + bt_i + A_0 \sin(\omega_0 t_i + \phi_0) + A_1 \sin(2\omega_1 t_i + \phi_1) + \boxed{\sum_{j=1}^{n_g} g_j H(t_i - T_{gj})}$$
$$+ \boxed{\sum_{j=1}^{n_h} h_j H(t_i - T_{hj})\, t_i} + \boxed{\sum_{j=1}^{n_k} k_j \left(1 - e^{\frac{-(t_i - T_{kj})}{\tau_j}}\right) H(t_i - T_{kj})} + \epsilon$$

where only coseismic and postseismic parameters (highlighted in blue) were added to the secular displacement values. Then, the change in distances was again computed weekly between the center point or the nearest neighbor to the station (Figure 7).

Horizontal Cluster Validation- Comparison of CTSRN and CRTN configurations

In order to validate the K-Means clustering approach for the horizontal velocities, K-Means ran on both the CTSRN (Figure 1) and CRTN (Figure 2) station locations. These were used to create velocity, velocity gradient, and strain rate grids, using the same gmt gpsgridder methodology (Sandwell & Wessel, 2016).

The optimal number of clusters was determined with a silhouette test. K-Means was iteratively performed on the Eastern most cluster, which had too large of a spatial extent for subnetwork purposes. The clustering was stopped at the same number of subcluster processes as the CTSRN workflow.

For the CRTN stations (Figure 4, right panel), the initial clustering result picked out similar tectonic signals to the CTSRN values such as the creeping and locked sections of the San Andreas fault zone. The final result largely captures similar boundaries and tectonic motions (such as that of the Sierra Nevada microplate). However, in zones of broad deformation such as the Basin and Range or the Eastern California Shear Zone, the boundaries of the subnetworks differ slightly between the CTSRN and CRTN configurations. For the CRTN (Figure 4, right panel), the San Andreas fault zone is one coherent cluster (not separated into North/South or creeping/locked clusters). The boundaries of the subnetworks differ only slightly between CTSRN and CRTN for broader zones of deformation (Clusters 4 and 6).

CRTN Horizontal Reprocessing Times

The same horizontal accuracy degradation test was applied to the CRTN stations within the subnetwork boundaries as determined by the interpolated CTSRN grids. The clusters were analyzed from 2018.00 to 2025.60 according to two subnetwork distances: the distance to a central point and the distance to each station’s nearest neighbor, weekly. The distances between either the center point to the station or the nearest neighbor to the station were computed based on secular velocity values. If the change in distance exceeded 1 cm for more than two stations, a subnetwork reset was declared and the change in distance was reset to 0 cm.

The results comparing the CRTN and CTSRN reprocessing times are shown in Figures 4-6. The nearest neighbor results are different between the two scenarios. The nearest neighbor test was dependent on localized deformation (or the area between nearest neighbor stations). Unless station coverage was uniform across the state or the reset time was independent of station number, the reprocessing time will depend on the geometry of the subnetwork. For the center point test, Cluster #5 yielded a shorter reprocessing time than the CTSRN center point test. This difference in reprocessing times was due to stations located along the boundary between Cluster #5 and Cluster #0 (the San Andreas cluster). The difference in reprocessing times due to the San Andreas cluster boundary demonstrates the benefits of utilizing a 'broader dynamic zone' for Cluster #0 (Table 1 and Figure 5 bottom).

Horizontal Reprocessing Times CRTN- Ridgecrest Case Study

Coseismic and postseismic displacements were also added to the secular time series (velocities) to determine if the impact on the subnetworks was the same as the CTSRN scenario. Interpolated displacement grids were created for the years 2018.00 to 2025.60 given the SOPAC coseismic and postseismic parameters. The change in distances was again computed weekly between the center point to the station or the nearest neighbor to the station. The results are shown in Table 1. The effective impact on subnetwork health is the same as in the CTSRN run. After a coseismic event, e.g., 2019 Mw7.1 Ridgecrest earthquake, there is an immediate need to reset the subnetworks. Then, the subnetworks adjacent to the mainshock need to be monitored for perturbations in the reset time series due to postseismic motion.

Main Conclusions

Table 1 summarizes the number of resets for each of the clusters over time within the various configurations. The difference between the number of resets needed for a central point versus the nearest neighbor highlights the fact that there are still small variations in how each subnetwork internally deforms over time. Therefore, the intended scope of projects contemplated by Caltrans in each cluster could be used to determine the reprocessing needs of a subnetwork at a given point in time.

A broader zone of deformation was considered for sub-networking purposes (Figure 5 bottom panel). The reprocessing needs for this larger cluster did not change from the original Cluster #0 to the center point (Figure 6 bottom panel). However, due to the stations available in this broader cluster, the reprocessing time increased for nearest neighbor points.

Lastly, the impact of coseismic and postseismic motions is shown in Figure 7 with the difference in number of resets, in this case versus the secular displacements only case. For Clusters #2 and #4, additional resets were needed after the Ridgecrest coseismic event. Additionally, the coseismic and postseismic displacements perturbated the reset time for Cluster #4 for several years.

Potential Future Work

Because the gridded and station clustering results slightly deviated over broad zones of deformation, one follow-on study could investigate where subnetwork boundaries should be placed precisely in broad deformation zones. Another future avenue of work could look at subnetwork geometry's effect on nearest neighbor's reprocessing times. Reprocessing times utilizing a single nearest neighbor are inherently dependent on the number of stations and the geometry of the subnetwork. Future work could also focus on finding the ideal number of nearest neighbors that make the reprocessing times independent of station number/geometry.

A potential deliverable could be a user interface where secular reprocessing times could be given for a user defined location and cluster number. The horizontal accuracy degradation test could also run with an evenly spaced subnetwork geometry that considers uncertainties in the secular velocity grid.

Acknowledgments

The authors and co-authors thank Kevin Maxwell, David Olander with District 11 Surveys for conceiving this project and providing important feedback, and Arvern Lofton with the Division of Research, Innovation and System Information for his able management and support. Thanks to members of the SOPAC team for providing the infrastructure in support of this project: Maria Turingan, Peng Fang, Anne Sullivan, Songnian Jiang and Sean King.

References

Bennett, A. et al. (2025), Intra-Frame Deformation Model for the Western U.S. versus the Epoch-Date Subnetwork Approach, poster presented at SCEC Annual Meeting, G43C-0336, Sept. 7-10, Palm Springs. https://sopac-csrc.ucsd.edu/wp-content/uploads/2026/05/Bennett_AGUPoster.pdf

Bock, Y., A. W. Moore, D. Argus, P. Fang, D. Golriz, K. Guns, S. Jiang, S. Kedar, S. A. Knox, Z. Liu & A. Sullivan (2023), Extended Solid Earth Science ESDR System (ESESES): Algorithm Theoretical Basis Document, http://garner.ucsd.edu/pub/measures ESESES_products/ATBD/ESESES-ATBD.pdf

Klein, K., Y. Bock, X. Xu, D. Sandwell, D. Golriz, P. Fang, L. Su (2019), Transient deformation in California from two decades of GPS displacements: Implications for a three-dimensional kinematic reference frame, J*. Geophys. Res*., https://doi.org/10.1029/2018JB017201

Sandwell, D. T. and P. Wessel, 2016, Interpolation of 2-D Vector Data Using Constraints from Elasticity, Geophys. Res. Lett., 43, 10,703 10,709, https://doi.org/10.1002/2016GL070340

Pedregosa et al., Scikit-learn: Machine Learning in Python, JMLR 12, pp. 2825-2830, 2011.

Zeng, Y. (2022). GPS Velocity Field of the Western United States for the 2023 National Seismic Hazard Model Update, Seismol. Res. Lett. 93, 3121–3134, doi: 10.1785/0220220180.