PROJECT REPORT

California Spatial Reference System

CSRS Epoch 2017.50 (NAD83)

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Summary

This report prepared under contract with the California Department of Transportation (Caltrans) serves as the official publication of a new geodetic datum for California called "CSRS Epoch 2017.50 (NAD83)," for short "Epoch 2017.50." The California Spatial Reference System (CSRS) is realized by the geodetic coordinates and uncertainties on the date of 2017.50 (July 2, 2017; GPS week 1956, day 0) of 948 stations (839 active and 109 defunct stations) comprising the California Spatial Reference Network (CSRN) in California and at the borders of Arizona, Nevada, Oregon and Baja California (Table 1).

The CSRS is the official geodetic datum in California, as published by the California Spatial Reference Center (CSRC) according to the Public Resources Code (PRC) Sections 8850-8861. It is rigorously aligned with the National Spatial Reference System (NSRS) as published by the National Geodetic Survey (NGS). As an example, all surveys performed by Caltrans using the California Coordinate System (CCS83), including all transportation projects, must be tied to control stations that are part of the CSRN, or meet the specifications for inclusion in the CSRN. PRC Sections 8801-8808 define CCS83 and PRC Sections 8812-8819 define the application and documentation of using and establishing CCS83 coordinates with the CSRS.

The new datum is fundamentally tied to the global Cartesian International Terrestrial Reference Frame 2014 (ITRF2014) through reanalysis of the raw GPS data and metadata collected at the CSRN stations from 1995 to September 30, 2017, and data from about 400 global tracking stations of the International GNSS Service (IGS). All of these data and their metadata are archived at the Scripps Orbit and Permanent Array Center (SOPAC).

The ITRF2014 coordinates (X,Y,Z) of the 948 CSRN stations are transformed into geodetic coordinates, latitude, longitude and ellipsoidal height, using the ellipsoidal parameters (semi-major axis, a = 6378137 m and inverse flattening, 1/f = 298.257 223 563) of the World Geodetic System 1984 (WGS84 – different from the GRS80 ellipsoid with a slightly modified 1/f = 298.257 222 101). The WGS84 is maintained by the U.S. Department of Defense (DoD) to be globally consistent with ITRF, to within ±1 m. The DoD has adopted ITRF for the GPS and it is the frame in which the GPS broadcast ephemeris and the precise IGS orbits are provided. The latest realization of WGS84 by the DoD on January 6, 2014 is called WGS84 G1762 (http://www.wsmr.army.mil/testcenter/nga/Documents/SNSH-G1762-Upgrade-01Jan2014.pdf), consistent with ITRF2008 (a future change to ITRF2014 should be insignificant at the cm level).

CSRS Epoch 2017.50(NAD83) replaces the previous "CSRS Epoch 2011.00 ITRF2005 NAD83(NSRS2007)" that included coordinates for 830 CSRN stations. Epoch 2017.50 is related to the current definition of the National Spatial Reference System (NSRS) through a set of coordinate transformations from ITRF2014 to NAD83(2011), published by the NOAA/NOS National Geodetic Survey (NGS).

Geoid heights from the latest NGS-published model, GEOID12B, have been applied to develop Derived California Orthometric Heights (Table 1) for all of the CSRN stations, in accordance with PRC §§8890-8902.

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1. Publication / Deliverables

(1) CSRS Epoch 2017.50 (NAD83) adjustment (Table 1)
(2) Selection and evaluation of CSRN stations (Table 2)
(3) Project report (this document)
(4) Auxiliary data and files (http://garner.ucsd.edu/pub/projects/CalTrans_repro/) (username: "anonymous"; password: your email address)

2. Timeline Record

3/6/2016	Task Order 002 of Contract 52A0103 Authorized
5/5/2016	CSRC Coordinating Council Spring meeting, La Jolla - report on Epoch 2017.50
8/29/2016	Completed backfill of CVSRN RINEX data
10/6/2016	CSRC Coordinating Council Spring meeting, Sacramento - report on Epoch 2017.50
12/30/2016	Provided list of 969 CSRN candidate stations to Greg Helmer, Chair station selection committee
1/6/2017	Received final station recommendations from Greg Helmer
1/17/2017	Added 28 USGS stations in southern California for a total of 997 CSRN candidates
1/29/2017	IGS migrates to ITRF2008 to ITRF2014, marking the end date for the Epoch 2017.50 reprocessing
2/10/2017	Revise station list after visual inspection of ITRF2008 time series (977 stations, including 83 defunct)
2/15/2017	Began GAMIT global station reprocessing in ITRF2014
3/31/2017	Completed GAMIT global station reprocessing in ITRF2014
4/1/2017	Began GAMIT CSRN regional reprocessing
5/4/2017	CSRC Coordinating Council Spring meeting, La Jolla - report on Epoch 2017.50
9/15/2017	Completed GAMIT CSRN regional reprocessing
9/23/2017	Refined CSRN list (996 stations, including 83 defunct)
10/2/2017	Began GLOBK analysis
10/10/2017	Completed GLOBK analysis
10/11/2017	Began time series analysis
10/19/2017	CSRC Coordinating Council Fall meeting, Sacramento - report on Epoch 2017.50
11/1/2017	Completed time series analysis and perform final QC
11/5/2017	Tabulated final CSRN list (949 stations, including 75 defunct) and Epoch 2017.50 coordinates
11/20/2017	Completed draft of project report

3. Objectives

A new California geodetic datum is needed to ensure that all Caltrans surveys are using modern, accurate, and up to date coordinates with known uncertainties to remain in compliance with the California Public Resources Code. To this end, Caltrans through a task order has tasked Scripps Institution of Oceanography (SIO) to produce a new geodetic datum to replace CSRS Epoch 2011.00 ITRF2005 NAD83(NSRS2007). The process is to be performed by the Scripps Orbit and Permanent Array Center (SOPAC) with oversight by

Caltrans and in coordination with the California Spatial Reference Center (CSRC) Executive Committee, the National Geodetic Survey (NGS) Pacific Southwest Region Advisor in residence at SIO, and the California Geodetic Coordinator.

The task order requires the selection of a group of continuous GPS (cGPS) stations in California and in the border areas of neighboring States to define the California Spatial Reference Network (CSRN). Once the network is selected in consultation with a CSRC committee assigned to this task, the steps to meet the objectives include: (1) Re-process the SOPAC daily coordinate time series for the chosen CSRN stations in the ITRF2014 reference frame (previously in ITRF2008) from their inception to the date of transition of the International GNSS Service (IGS) from ITRF2008 to ITRF2014; (2) Concatenate the re-processed time series with the operational SOPAC time series after the ITRF2008 to ITRF2014 transition date; (3) Perform a time series analysis of the full data set to estimate ITRF2014 coordinates and their uncertainties at Epoch Date 2017.50; (4) Convert the ITRF2014 global Cartesian (X,Y,Z) coordinates and uncertainties to geodetic latitude, longitude and height with respect to the WGS84 ellipsoid (semi-major axis, a = 6378137 m and inverse flattening, 1/f = 298.257 223 563); (5) Transform the coordinates and uncertainties to the most recent NAD83(2011) frame as published by the National Geodetic Service (NGS). The set of coordinates and uncertainties in ITRF2014 and NAD83 (2011) at Epoch 2017.50 will define the geodetic component of the CSRS Epoch 2017.50 (NAD83) datum, and provide the connection between the CSRS and the National Spatial Reference System (NSRS).

Lastly as a value-added product, geoid heights from the latest NGS-published model, GEOID12B, will be applied to develop Derived California Orthometric Heights for all of the CSRN stations in accordance with PRC §§8890-8902.

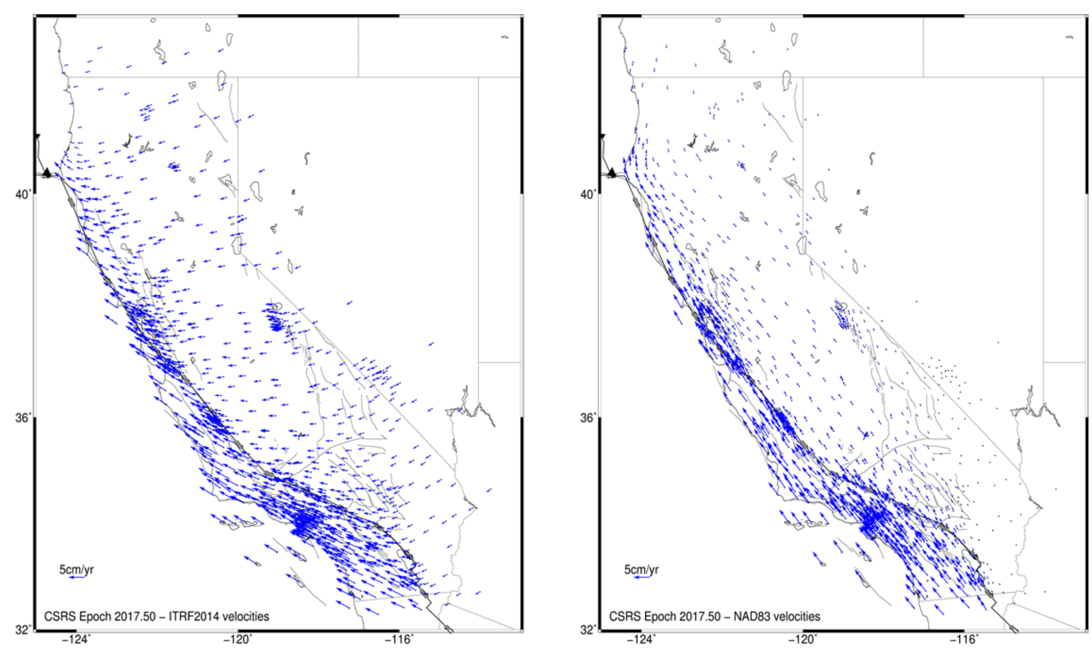


Figure 1. (Left) CSRS 2017.50 ITRF2014 velocities for 948 stations comprising the California Spatial Reference Network; (Right) Station velocities transformed to the North America fixed NAD83(2011) system using the NGS HTDP program. Prepared by Dara Goldberg.

4. Background and Motivation

Much of California's crust is subject to a variety of motions at various spatial and temporal scales that complicate the maintenance of a fixed geodetic datum. These motions are the result of tectonic and magmatic processes and vertical land motion (subsidence and uplift) due to natural (e.g., drought) or anthropogenic (e.g., water and oil extraction) effects. California sits on the boundary of the North America and Pacific plates resulting in a steady, primarily horizontal, motion on the order of up to 50 mm/yr (0.16 ft/yr) distributed over a width of hundreds of kilometers (Figure 1). This steady motion is punctuated by significant earthquakes that may instantaneously cause up to several feet of motion followed by significant postseismic motion (Figure 2) over a period of months to years until the crust returns to its steady state. For example, the April 4, 2010 Mw 7.2 El Mayor-Cucapah in northern Baja California, Mexico caused significant coseismic motion throughout southern California (from 0.03 - 0.8 ft) (with a further aftershock on June 15, 2010 that affected 7 stations), and an additional cumulative postseismic motion of about 50% over the last 7 years. In addition to the 2010 El-Mayor Cucapah event, California has experienced seven earthquakes greater than magnitude 5.1 that significantly affected station positions since the publication of Epoch 2011.00 (Table 3).

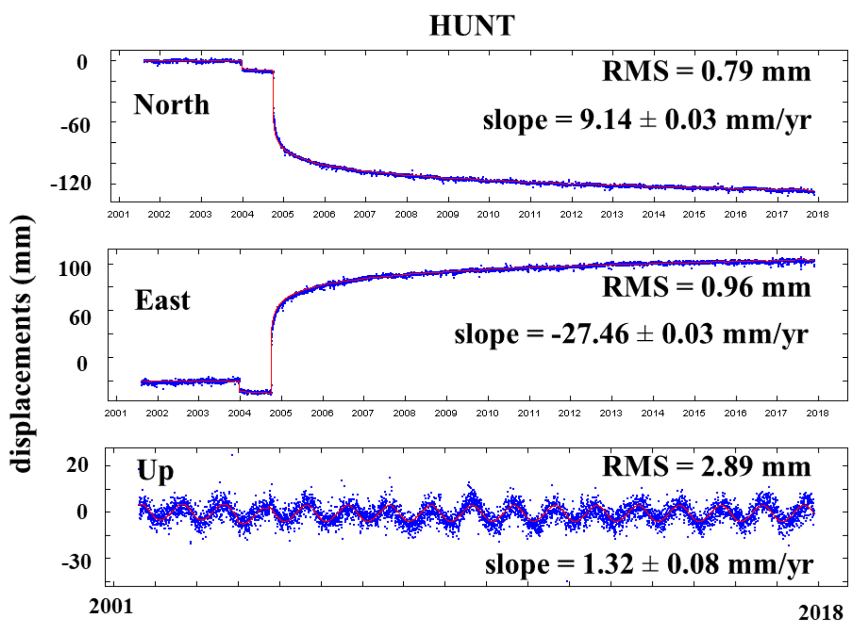


Figure 2. Typical CSRN ITRF2014 detrended modeled daily displacement time series ("detrended" indicates that the estimated slopes have been removed for display purposes). The station HUNT experienced two earthquakes, 2003 Mw6.5 San Simeon and 2004 M6.0 Parkfield (Table 3) with significant coseismic and postseismic motion. Station HUNT is located near the town of Parkfield on the San Andreas fault in Central California. Source: GPS Explorer Time Series Applet (http://geoexp01.ucsd.edu/gridsphere/gridsphere).

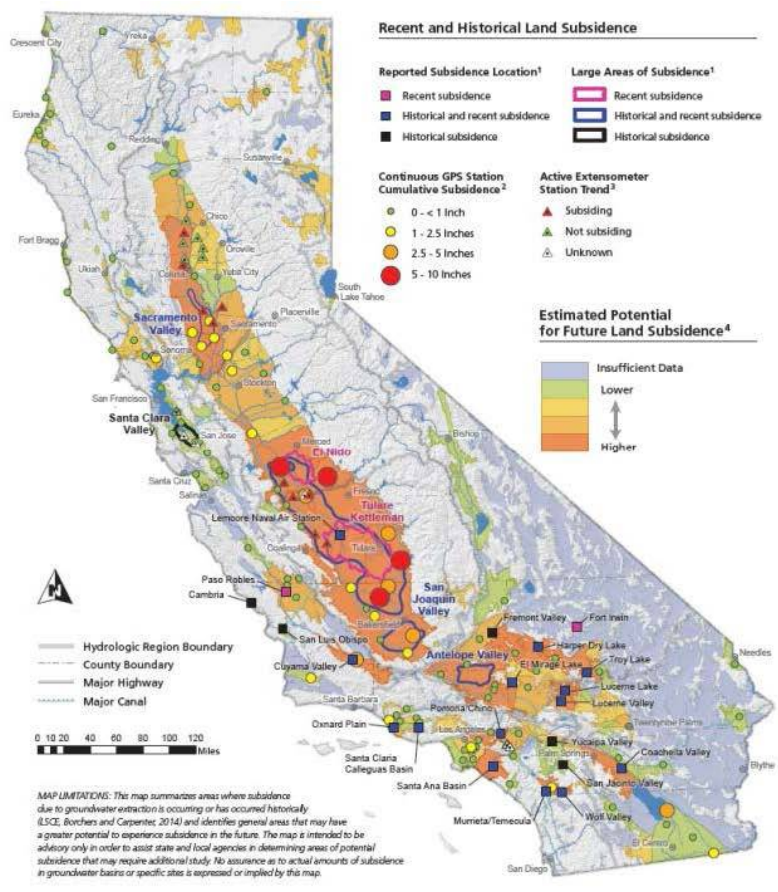
Table 3. Significant earthquakes since publication of Epoch 2011.00

Date	UTC	Name	Mw	Depth	Latitude (N)	Longitude (W)	Sites Affected
4/4/2010	22:40:43	El Mayor-Cucapah, Mexico	7.2	10	32.259	115.287	221[1]
6/15/2010	4:26:59	Aftershock, El Mayor-Cucapah	5.7		32.698	115.924	7
7/7/2010	23:53:33	Borrego Springs	5.4		33.417	116.483	3
8/26/2012	19:31:22	Brawley Seismic Swarm	5.3, 5.4	9.2	33.019	115.546	4
10/21/2012	6:55:09	Central California	5.3		36.31	120.856	4
3/10/2014	5:18:13	Offshore Ferndale	6.8	7	40.821	125.1277	18
3/30/2014	4:09:42	La Habra, NW Orange County	5.1	7.5	33.92	117.940	1
8/24/2014	10:20:44	Napa	6.1	10.7	38.215	122.318	15

[1] Of these, 165 stations had measurable postseismic motion

Table 1 lists the cumulative coordinate changes for each of the CSRN stations from Epoch 2011.00 to Epoch 2017.50. With the new datum realization, the coordinates published at Epoch 2011.00 have changed up to 0.6 meters (~2 feet), primarily due to accelerated subsidence in the Central Valley during drought conditions (Figure 3); one station in the Central Valley experienced nearly 1.5 meters (~5 feet) of subsidence.

Figure 3. Areas of land subsidence in California and drought response. Source: California Department of Water Resources, Fall 2014.



California Department of Water Resources; Drought Response Update Fall 2014

To minimize the deviations in station coordinates due to crustal and other motions in California, the CSRC has previously published several coordinate "Epoch Dates." The last three were at 2007.00 (for 551 stations), 2009.00 (for 766 stations) and 2011.00 (for 830 stations). Epoch 2011.00 was based on GPS observations up to April 17, 2011 (2011.2918). The published geodetic coordinates (latitude, longitude and height above the reference ellipsoid) included uncertainties (two-sigma, 95% confidence level) to comply with the California Public Resources Codes. The new datum CSRS Epoch 2017.50 (NAD83) supersedes all previous Epoch dates.

Provisional coordinates were previously estimated for new stations (e.g. in the San Francisco Bay Area, San Diego County, Central Valley) established since publication of Epoch 2011.00. The new stations have been added to the CSRN and are now part of Epoch 2017.50.

Since Epoch 2011.00, several groups operating real-time networks for field surveys have upgraded their base station coordinates through a variety of procedures with no central coordination. Surveyors throughout the State are using a variety of datums with different epoch dates, depending on the procedures of their real-time service provider. CSRC's California Real Time Network (CRTN) has been transmitting coordinates at Epoch 2011.00. Epoch 2017.50 will facilitate a unified datum for precise real-time applications.

5. History

The CSRN now includes 948 cGPS stations within California and at the borders of Arizona, Nevada, Oregon and Baja California, Mexico. The first stations were built in 1991 as part of the Permanent GPS Geodetic Array (PGGA), a collaboration of SIO's Institute of Geophysics and Planetary Physics (IGPP) and the Jet Propulsion Laboratory (JPL), and a forerunner of the Southern California Integrated GPS Network (SCIGN) and Plate Boundary Observatory (PBO) projects. The bulk of the stations were specifically established by academic institutions, government research laboratories and research consortia, many in collaboration with the surveying community, to monitor crustal deformation and seismic hazards. Others were specifically established for geodetic control, primarily by Caltrans District 6, water and utility districts (Metropolitan Water District – MWD, East Bay Municipal Utility District – EBMUD, Riverside County Flood Control and Water Conservation District – RCFCWCD) and California Counties (Los Angeles, Orange, San Diego, and Riverside). The bulk of the cGPS stations are now maintained by several groups, including UNAVCO's PBO, SCIGN (The U.S. Geological Survey's office in Pasadena and SOPAC in SIO), the Bay Area Regional Deformation Array (BARD – UC Berkeley and USGS), and Caltrans District 6 (CVSRN).

Traditionally and historically, California users have depended on the National Geodetic Survey (NGS), and its predecessor agencies, for geodetic control – 18,000 horizontal stations and 50,000 benchmarks were established by NGS in California. About 25 years ago, the direction of NGS changed (largely due to budget constraints and emerging GPS geodetic surveying capabilities) from maintaining relatively dense control networks to maintaining a basic "framework" system consisting primarily of GPS-based Continuously Operating Reference Stations (CORS) at a spacing of one degree in latitude by one degree in longitude. Any geodetic control would be maintained either through cooperative agreements with NGS or by independent, local efforts.

At the time, specific critical issues for geodetic control in California were identified that would then not be addressed by the new NGS policies.

- Secular crustal motions – throughout the State. NGS has maintained the Horizontal Time-Dependent Positioning (HTDP) software (https://www.ngs.noaa.gov/TOOLS/Htdp/Htdp.shtml) to approximate secular motions due to movement on geological faults.
- Episodic crustal motions (coseismic deformation) – California has experienced several significant earthquakes since the inception of cGPS. HTDP has to be updated to accommodate these events, requiring significant turnaround time.
- Aseismic deformation (fault creep) – Coastal Range east of Paso Robles, Imperial Valley, San Jacinto fault, etc.
- Large areas of subsidence – Central Valley (San Joaquin and Sacramento Valleys), Los Angeles basin, Santa Ana basin, Lancaster/Edwards Air Force Base, Long Beach, and Antelope Valley. For example, an NGS station (benchmark) near Mendota in the San Joaquin Valley had a measured subsidence of 24 feet from 1943 to 1966.
- No releveling in much of California, including the Central Valley, since the 1970's.
- Two vertical datums in use in California: NGVD29 and NAVD88.
- Incomplete implementation of NAVD88 – only 30 percent of California's NGVD29 benchmarks were included in the NAVD88 readjustment and many of these have been either lost to construction or unreliable because of subsidence.
- Extensive coastal infrastructure facilities (harbors, international boundaries, offshore leases, etc.) – these facilities generally are referenced to tidal datums, which are not necessarily referenced to a national geodetic vertical datum.
- Use of numerous local vertical datums – information from different sources cannot be related.
- Incorrect (obsolete) published values for many geodetic control stations – due to crustal motions, subsidence, etc.
- Limited or no station maintenance during the last 20 to 30 years (monitoring, updating values, station replacement, etc.).

The CSRC was established due to the need to be self-sufficient in areas that NGS was no longer active. Drawing on the relationships of geodesists and geophysicists with the surveying community in California garnered in constructing and maintaining cGPS stations, a grass roots effort led to the establishment of the CSRC in 1997 with the goal of "Establishing and maintaining an accurate state-of-the-art network of GPS control stations for a reliable spatial reference system in California." The CSRC was formally dedicated at SIO on February 20, 2001 (http://csrc.ucsd.edu/csrcDedication.shtml) as a Support Group of the University California San Diego (UCSD). In 2002 a committee of CSRC members prepared a Master Plan (http://csrc.ucsd.edu/docs/csrcMasterPlan.pdf) to guide its activities, which was approved by the NGS on March 12, 2003. The initial focus of the Master Plan was the expansion and maintenance of geodetic monuments for horizontal and vertical control throughout the State and several large projects were sub-contracted by the CSRC to the private sector for this purpose. With the rapid expansion of the permanent geophysical networks, the focus shifted to permanent cGPS stations.

Started by SOPAC with a handful of SCIGN stations, the cGPS stations in California began to be upgraded to real-time operations (~1 second latency) in the early 2000's for two purposes: (1) to research earthquake early warning and rapid response systems, and (2) to provide active base stations in support of real-time kinematic (RTK) positioning. Previously, cGPS stations sampled at 15-30s with downloads every 6-24 hours. The real time stations collect data at a frequency of 1 sample per second (sps, or 1 Hz) or greater, which are downloaded continuously with a latency of less than a second through a variety of communication methods (radio modems, microwave, cell phones, direct Internet). SOPAC and some PBO stations in southern California are supported by UCSD's dedicated communications network HPWREN (http://hpwren.ucsd.edu/).

CRTN was established by SOPAC in 2003, specifically to provide base station support for RTK surveys by rebroadcasting real-time data to registered users. CRTN is overseen by the CRTN Consortium (http://csrc.ucsd.edu/docs/Consortium_FAQs.pdf) with input from the CSRC Executive Committee. It provides a clearinghouse of high-rate real-time data obtained from multiple Networked Transport of RTCM via Internet Protocol (NTRIP) servers, at UNAVCO (PBO), UC Berkeley/USGS Menlo Park (BARD), USGS Pasadena (SCIGN), Caltrans (CVSRN), Orange County Public Works (OCRTN), MWD, and SOPAC (SCIGN). CRTN provides GPS (and where available GNSS) data in RTCM 3.0 format at 1 sps in NTRIP protocol from 420 stations and 2 CRTN servers at SOPAC (Southern California: 207 stations; Northern California: 213 stations) (http://csrc.ucsd.edu/docs/csrsEpoch2011.00.xls). Currently, the RTCM streams contain NAD83(NSRS2007) 2011.00 coordinates and station metadata (antenna and receivers models, antenna height and reference point). The intention is to transmit coordinates in CSRS Epoch 2017.50 (NAD83).

6. SOPAC Infrastructure

The Scripps Orbit and Permanent Array Center (SOPAC) was established in 1991 with the goal of "processing and archiving high-precision GPS data for the study of earthquake hazards, tectonic plate motion, crustal deformation and meteorology." SOPAC was a founding member of the IGS serving until today as a Global Data Center and a Global Analysis Center (http://www.igs.org/). SOPAC also played a major role in establishing the PGGA, SCIGN and CRTN, and supported NOAA's GPS meteorology program for over 20 years, until it was privatized by NOAA in 2016. Today, SOPAC is working with NOAA's Tsunami Warning Centers (National and Pacific) on a local tsunami warning system for the Nation using GNSS and seismogeodetic data (combination of GNSS and seismic data).

SOPAC serves as the operational arm of the CSRC and the CRTN Consortium with oversight by its Executive Committee (http://csrc.ucsd.edu/executiveCommittee.shtml).

GPS Data Analysis

SOPAC analyzes daily ITRF positions for about 3000 global and regional stations, including all of the CSRN stations, some established as early as 1992, using the methodology described in sections 7 and 8. It collaborates with the Jet Propulsion Laboratory on a NASA-funded project to merge the SOPAC daily positions estimated with GAMIT/GLOBK software and those estimated by the Jet Propulsion Laboratory (JPL) using the GIPSY software. For the Epoch 2017.50 project, only the SOPAC analysis was used since JPL had not yet reprocessed their data in ITRF2014.

Data Archive and Database

SOPAC maintains a global archive of continuous GNSS data (in RINEX format at 15-second intervals, and 1 second intervals for CRTN) back to 1992, accessible through anonymous ftp (ftp://garner.ucsd.edu/) (username: "anonymous"; password: your e-mail address). It also archives a number of data products, e.g., daily coordinate time series and satellite orbits. The archive is linked to an Oracle 11g database. The SOPAC database is the repository of the CSRN station metadata, e.g., antenna and receiver models, and antenna heights that are critical for the accuracy of the Epoch 2017.50 coordinates.

Web Presence

SOPAC: http://sopac.ucsd.edu
CSRC: http://csrc.ucsd.edu

Web Applications

SOPAC maintains a number of Web applications that have been useful extensively for this project, for example:

SECTOR – A tool to retrieve true-of-date coordinates and uncertainties in ITRF and NAD83 coordinates for all cGPS stations analyzed by SOPAC, including the CSRN stations (http://sopac.ucsd.edu/sector.shtml).

GPS Explorer – An interactive user-customizable interactive data portal, including a map interface, position time series applet, access to station coordinates and velocities. It also includes a private administrator page for editing and viewing time series model parameters that was used extensively for this project (http://geoexp01.ucsd.edu/gridsphere/gridsphere).

Equipment and Software

The following software and equipment were available to the project:

- GAMIT and GLOBK software for the analysis of daily station positions, precise satellite orbits and Earth rotation parameters (Herring et al., 2008).
- Array of post-processing computers; 212 CPU cores for processing in the form of a two high speed quad-node servers (192 cores) and 10 standalone processing hosts (20 CPU cores).
- High-speed LSI storage array with 32 terabytes of online storage for the data archive.
- Dedicated servers for public access to products and data, isolated and installed on virtual servers for increased availability and security.
- Oracle 11g relational database to store metadata pertaining to nearly all aspects of SOPAC operations, including GNSS site metadata and data archive holdings.
- Internet access. Equipment in the SOPAC computer room are connected through a 1 Gbit ethernet network, with a 10 Gbit uplink to the internet.
- Rack-mounted systems held in a secured, temperature controlled server room and protected by high-capacity uninterruptible power supply (UPS) system.
- Fiber-connected Storage Area Network (SAN) backed up to a dedicated NAS providing disk-to-disk redundant backup of the main storage archive and critical configuration data.
- Real-time data collection and initial processing of geodetic data for CRTN is handled by five dedicated systems, with two additional servers collecting and processing accelerometer and meteorological data from a limited number of stations. Currently, we receive data from our field stations and from other real-time servers (UNAVCO/PBO, SCIGN, BARD, PANGA networks) and rebroadcast 1 Hz data from over 600 real-time GNSS stations in the Western U.S. and Canada comprising the Real-Time Earthquake Analysis for Disaster mItigation network (READI).
- Precise point (PPP) positioning software for real-time analysis and high-rate post-processing, and Kalman filtering software for GNSS/seismic (seismogeodetic) integration. Processes run on virtual servers for reliability, security and business continuity (quick recovery in case of disaster).

7. Methodology

Choice of CSRN stations for Epoch 2017.50

The CSRC assigned a station selection committee to advise the CSRC Director on the choice of CSRN stations for Epoch 2017.50. The intent was to identify the existing and historical cGPS stations in California and at the borders of Arizona, Nevada, Oregon and Baja California, Mexico. Historical stations are defunct but with sufficient data to warrant inclusion, in order to support any surveys previously done using these stations as geodetic control. In most cases, compiling this list was straightforward and automatically included all stations in the geophysical networks (PBO, BARD/USGS, SCIGN/USGS/SOPAC/CRTN) and partner agencies' real-time networks (RTNs) (CVSRN, OCRTN, SDCRTN, MWD, EBMUD). With the encouragement of the CSRC, many but not all of these stations have been incorporated into the NGS CORS network and there are a few other CORS stations that were chosen. A requirement was that every station have a complete and accurate record of metadata stored in the SOPAC database (section 6). After further review by the CSRC Director, other stations were excluded (Table 2). Added to the original list were several CVSRN stations, requested by Caltrans and a list of relatively new USGS Pasadena stations along the length of the southern section of the San Andreas fault. Stations that were suggested by the committee but not included are listed in Table 2 with an explanation of why. The final list of CSRN stations for Epoch 2017.50 is given in Tables 1 and 2 and plotted in Figure 1 along with their velocities in ITRF2014 and NAD83.

In the next subsections, we review the factors that are important is building a cGPS network and how they impacted the choice of CSRN stations and the accuracy of the Epoch 2017.50 datum.

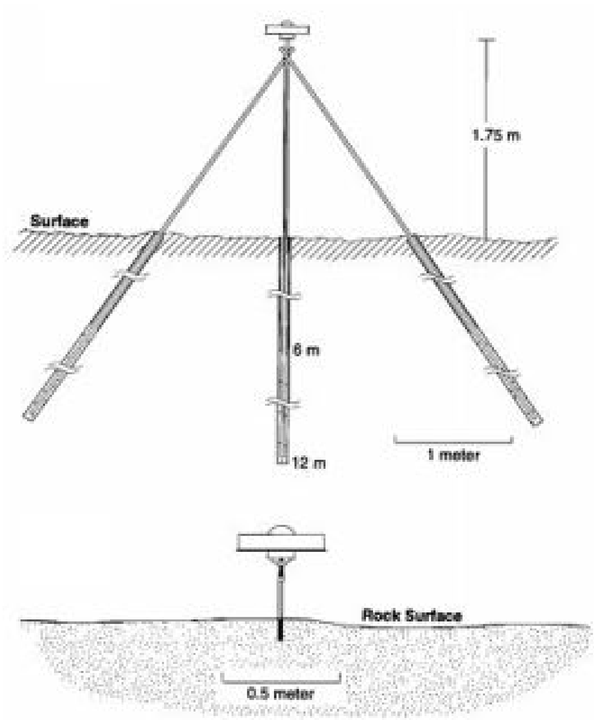


Figure 4. Two types of geodetic monuments (Top) deeply-anchored drill-braced designed by D. Agnew and F. Wyatt; (Bottom) shallow-anchored rock pin monument in bedrock. Source: Bock et al. (1997).

Monumentation and Non-tectonic Effects

Long records of pre-GPS geodetic measurements including spirit leveling, electronic distance measurements and tiltmeters indicated significant temporal correlations ("colored" noise) that over time result in positional uncertainties that are higher than would be expected with just random ("white") noise, which is primarily due to instrumental noise. Time series analysis of these pre-GPS observations indicated that the colored noise resembles a random walk process (sometimes called "red" noise or "Brownian motion"). The temporal correlations were primarily attributed to the instability of geodetic monuments caused by soil contraction, desiccation, or weathering, e.g., by expansive clays in near-surface rocks. Based on this earlier geodetic record, a permanent and rigid (but quite expensive) monument was designed by the PGGA and

SCIGN projects for crustal deformation monitoring, in order to reduce non-tectonic local surface deformation. The monument consists of five deeply-anchored drill-braced stainless steel rods, one vertical and four slanted (~10 m) rods, isolated from the surface down to ~3 m (Figure 4). The SCIGN monument has been adopted by other geophysical networks, including PBO and parts of BARD. Also, developed and installed at numerous stations were less expensive shallow-braced monuments that were particularly suitable in rock outcroppings. Thus, the bulk of the CSRN stations are well anchored.

Less expensive and supposedly less stable monuments were incorporated into the early network, in particular in the early densification of the Los Angeles region as part of the “Dense GPS Geodetic Array” (DGGA) (Hensley, 2000) – the PGGA and DGGA were eventually subsumed by the SCIGN project. The monuments include rock pins, pillars, masts and building mounts. At the start of the SCIGN project a decision was made not to include new stations situated on buildings. In later years, some new installations did include building mounts for stations installed by our CSRC/CRTN partners, and other types of monuments such as masts. For example, the CVSRN operated by Caltrans District 6 and NGS CORS has a mix of monument types.

Regardless of the monument type there are other critical issues that affect the geodetic position time series and complicate the development of the new California datum. Non-tectonic vertical land motions (uplift and subsidence) are due to anthropogenic sources (e.g., water, mineral and oil extraction, geothermal fields) and natural changes (e.g., drought, magmatic processes such as in the Mammoth Lakes region, snow accumulation). Furthermore, these motions often bleed into non-tectonic horizontal motions, for example at the edges of aquifers. Although the Central Valley is the prime example, there are other areas of significant subsidence in California, e.g., in the San Joaquin and Sacramento Valleys, Los Angeles basin, Santa Ana basin and Antelope Valley (Figure 3). Reduction in precipitation, i.e., the drought conditions that occurred in the western US from 2012-2016, resulted in diminished winter-spring subsidence, enhanced late summer uplift, and long-term trends. The recent California drought also induced a regional-scale uplift of the Sierra Nevada Mountains and other areas in the western U.S.

Figure 5. Custom GPS equipment for continuous GPS monitoring stations. (Top) SCIGN short antenna radome covering a GPS chokering antenna; (Bottom) Adjustable antenna adapter/mount. Source: SCIGN project.

The overriding factors for the stability of geodetic marks in many locales in California is the hydrology or freeze thaw cycle, anthropogenic effects and natural effects over an area much larger than their footprint. The CSRN does benefit from large areas of the State that have dry climates. See a further discussion of these issues in the review paper by Bock and Melgar (2016).

Centering, Leveling and Geodetic Mark

Centering of the GNSS antenna is another important factor for achieving mm-level accuracy, especially re-centering when an antenna is replaced. For this purpose, the SCIGN project designed a precision antenna adapter (mount) with leveling capabilities (Figure 5). The adapter is permanently welded at the meeting point of the four slanted and one vertical rods that make up the monument. The GPS antenna is then mounted on a standard 5/8 inch threaded bolt. This adapter as well as protective SCIGN (short and tall) antenna covers ("radomes") (Figure 5) have been adopted by all the geophysical monitoring networks in California. In addition, the SCIGN adapter has a fixed "antenna height" (0.0083 m) above a clearly defined point within the adapter, which serves as the Geodetic Reference Mark (GRM). Not all stations have this arrangement so antenna heights above the GRM may vary from zero (when there is no adapter) to a few feet. The SOPAC database maintains a complete record of relevant metadata and metadata changes over the lifetime of the CSRN, and is a critical resource for the accuracy of the geodetic datum.

Antenna Phase Centers

It is also necessary to clearly identify the antenna phase centers and their exact relationship to the antenna height reference point and the GRM, both horizontally and vertically. Absolute phase center offsets and variations with and without radomes are estimated by single robot-mounted calibration by collecting thousands of observations at different orientations (e.g., Rothacher, 2001). This information in maintained in tables compiled by the IGS; these were used as part of our analysis – all antennas in the CSRN have been calibrated. In the field, antennas are oriented to true north to reduce azimuthal effects and to be consistent with the calibration corrections. In practice, the corrections are imperfect and changes in antenna types will often result in spurious offsets in position time series so changes in antennas are avoided to the extent possible. Nevertheless, a number of stations in the CSRN with long time series (>20 years) have multiple antenna changes.

Offsets in Displacement Time Series: Real and Artifacts

It is critical to identify and correct/compensate for offsets in displacement time series, which could bias the Epoch 2017.50 coordinates and their uncertainties. The offsets are of two categories: coseismic and non-coseismic offsets. Coseismic offsets are sudden displacements caused by an earthquake, which can be on the order of a meter for stations near the earthquake's epicenter. For example, the 2010 Mw7.2 El Mayor-Cucapah earthquake in northern Baja California significantly displaced all stations in southern California. The timing of the coseismic offsets is straightforward and available from seismic catalogues. The extent of an offset can be estimated through geophysical modeling and validated through visual inspection. The magnitudes of the offsets are estimated as part of the time series analysis of the daily displacement time series analysis (section 8).

Non-coseismic offsets are more complicated to deal with since they are not physical, but artifacts of local changes at the CSRN stations. The most common are a result of a replacement of an antenna with one of a different model, or trimming the trees at an overgrown station that are obstructing the view to the satellites. In this case, accurate and complete access to metadata is critical to identify the timing of the offset. Often, we are dependent on other groups who are responsible for maintaining station logs. As part of the analysis of Epoch 2017.50, we performed an extensive accounting and estimation of non-coseismic offsets. Although there are algorithms to automatically detect non-coseismic offsets, considerable manual effort is still required to detect all offsets and to minimize the number of false detections. False detections, if left uncorrected/compensated, can significantly increase the position and velocity uncertainties.

RINEX Files / Metadata

SOPAC maintains a long-term archive of RINEX data and metadata for all geophysical stations in the Western U.S., including all of the CSRN stations. As part of the new datum, we have scoured other archives to ensure that we have a complete record of RINEX data and associated metadata. We back-filled RINEX data from several CVSRN stations that were not previously archived or analyzed at SOPAC. To attain mm-level position precision it is essential to accurately record station "metadata" including, antenna type and serial number, receiver type, serial number and firmware version, antenna eccentricities (height and any horizontal offsets), antenna phase calibration values, and dates when changes in any of these have occurred. SOPAC stores its metadata in an Oracle 11g relational database. The RINEX headers for the SOPAC-operated stations in San Diego and Orange Counties are directly created from the database. For other sources of RINEX data, we are dependent on the responsible group and some are more conscientious than others. For this reason, we generally ignore metadata in RINEX headers from outside sources. Instead we use the metadata from IGS-type site logs provided by the responsible groups that have been ingested into the SOPAC database. Note that there are data gaps of various lengths in the RINEX files for a large number of stations due to station failures and other reasons. We have included general information about data gaps in Table 2. All RINEX data used for this project are publicly available from the SOPAC archive (http://garner.ucsd.edu/pub/rinex) (username: "anonymous"; password: your e-mail address). The RINEX files contain 24 hours (0-24 hours, GPS day) of GPS phase and pseudorange data sampled at 15-30 s, and with a cutoff elevation angle assigned by the station operator.

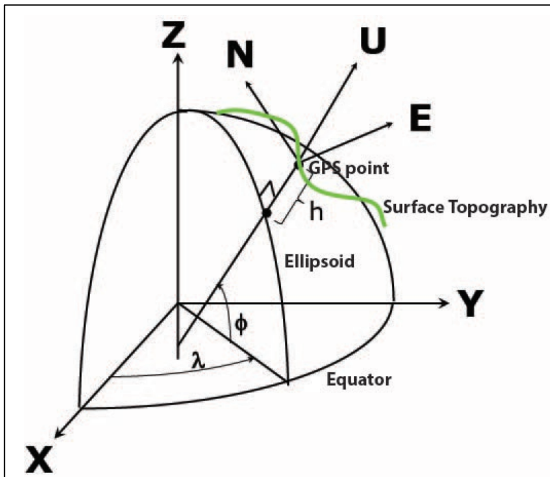


Figure 6. Coordinate systems used for deriving Epoch 2017.50. Analysis of GPS phase and pseudorange data is carried out in a global Earth-centered Earth-fixed reference frame (X,Y,Z) – here in ITRF2014. The ITRF2014 coordinates are transformed to geodetic latitude, longitude and ellipsoidal height (ϕ, λ, h) with respect to a geocentric oblate ellipsoid of revolution (one octant shown) – here the WGS84 ellipsoid. Transformation of positions in the right-handed (X,Y,Z) frame to displacements in a left-handed local frame ($\Delta N, \Delta E, \Delta U$) is a function of geodetic latitude and longitude (equation 1). Source: Bock and Melgar (2016).

8. ITRF2014 Processing

The most time consuming part of the project is to reprocess, in ITRF2014, the SOPAC RINEX data holdings for the chosen (948) CSRN stations and the IGS global stations (~400). The global stations are required to estimate a new set of satellite orbits that are consistent with ITRF2014.

Since the IGS analysis centers, including SOPAC, transitioned from ITRF2008 to ITRF2014 on GPS week 1934 (January 29, 2017), reprocessing in ITRF2014 ended one day earlier. We started the reprocessing on January 1, 1995. Although we have data for some stations prior to that date, they are of lesser quality, primarily because of the limited global coverage of satellites and stations at the time, and hence precision of the estimated satellite orbits. This is reflected in the larger scatter for the earlier ITRF2008 displacement time series that were processed starting in 1992. In summary, the reprocessing included data from the beginning of 1995 up to and including January 29, 2017.

The reprocessing starts with the estimation of a new set of daily (X,Y,Z) positions for each of the CSRN and global stations in ITRF2014 (Figure 6) using the GAMIT/GLOBK software (http://www-gpsg.mit.edu/~simon/gtgk/; Herring et al., 2008). These positions are then converted to displacements in North, East and Up directions (ΔN, ΔE, ΔU) relative to the (X,Y,Z) positions at the first time series epoch, using the geodetic latitude and longitude of the station (ϕ, λ) (Figure 6) according to equation (1). The output is called the "raw daily displacement time series."

The resulting raw daily displacement time series are merged with the already processed ITRF2014 time series since the start of the transition of the IGS from ITRF2008 to ITRF2014, as part of SOPAC's ongoing normal operations. Epoch 2017.50 coordinates are estimated in the next step using the complete set of raw daily displacement time series, by means of a time series analysis using JPL's analyz_tseri software (https://qoca.jpl.nasa.gov/). The result of this process are the "modeled daily displacement time series", the model parameters, and the residual time series (the deviations from the model) (Figure 7). An example is shown in Figure 2. We describe in detail the complete process in the following subsections.

True-of-date Coordinates

It is instructive to describe the operational GPS analysis at SOPAC (Figure 7) for a fuller understanding of the methodology used for Epoch 2017.50. The raw daily displacement time series are continuously improved, updated and extended every week to maintain a consistent long-term data record, using the "true-of-date" station coordinates of the previous week. The "true of date" coordinates estimated by time series modeling of the entire data record for each station then seed the next week's analysis. This is an iterative process that includes an analysis of all the position data to date, validation of relevant metadata, automatic and manual quality control for the individual time series, identification of instrumental offsets, appropriate fitting/modeling of the time series and an administrator web interface to perform detailed quality control and to improve the position time series models. This approach is taken to best account for seismic events with significant coseismic offsets and significant postseismic deformation, and to take into account non-coseismic offsets. The archived true-of-date a priori positions from the operational analysis (formerly in ITRF2008) were used to seed the daily reprocessing in ITRF2014 for the new geodetic datum.

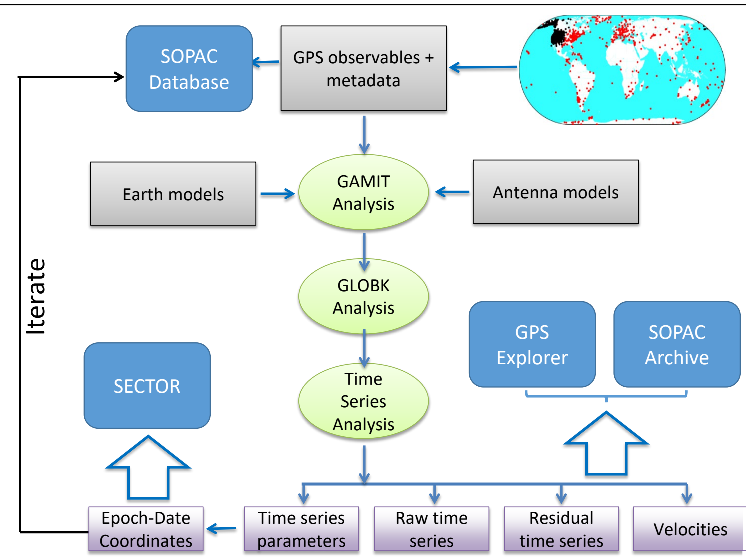


Figure 7. GNSS processing diagram indicating basic methodology used to estimate the new geodetic datum for California, CSRS Epoch 2017.50 (NAD83) at SOPAC.

GAMIT/GLOBK Analysis

The GAMIT/GLOBK software (http://www-gpsg.mit.edu/~simon/gtgk/; Herring et al., 2008) is based on network positioning (as compared to precise point positioning - PPP) and described in the review paper by Bock and Melgar (2016). Since the total number of stations for this project and for SOPAC's normal operational analysis are in the thousands, the CSRN and global stations are divided into sub-networks of about 50 stations, with overlaps of 3-6 stations. Each network is then analyzed separately with the GAMIT software. The GLOBK software is then used to perform a network adjustment of all the sub-networks to effectively reconstitute the larger network. This is referred to as the distributed processing approach (Zhang, 1996). In the GAMIT/GLOBK approach, the subnetworks include both global and CSRN stations. (PPP requires an initial network analysis of global stations to estimate satellite orbits and satellite clocks. Then using this information, positions are estimated for each station in a particular region).

The GAMIT analysis reads the GPS phase and pseudorange data from the RINEX files and proceeds as follows (no other GNSS data were used for the new datum). The first order ionospheric effects and the satellite and receiver clock errors are eliminated through double differencing of the GPS observations between all stations in each sub-network. The elevation cutoff is set to 10°. The observations are weighted according to satellite elevation angle – data at lower elevations are down weighted.

The parameters estimated in GAMIT include:

1. GPS satellite orbits (per 24 hour)
2. Earth orientation parameters (EOP) (per 24 hour)
3. Station positions (per 24 hour)
4. Tropospheric zenith delay parameters (per hour for each station)
5. Tropospheric delay gradients per station (per 12 hours in north-south and east-west directions)
6. Phase ambiguities

A GAMIT solution consists of four-steps:

1. Coordinates and orbits constrained, phase ambiguities are free
2. Coordinates and orbits constrained, phase ambiguities are fixed to integer values
3. Coordinates and orbits loosely constrained, phase ambiguities are free
4. Coordinates and orbits loosely constrained, phase ambiguities are fixed to integer values.

Steps 3 and 4 are required when the output files are to be combined with other solutions through the GLOBK analysis (next section), as was required for this project. The results of Steps 1 and 2 are used for local processing.

GAMIT Solution Physical Models:

1. Solid Earth tides (IERS Conventions, 2010)
2. Ocean tidal loading (FES04 model with Earth center of mass correction) (https://igppweb.ucsd.edu/~agnew/Spotl/spotlmain.html)
3. Pole tide (IERS Conventions, 2010)
4. Satellite yaw model (Bar-Sever, 1996)
5. Vienna Mapping Function for hydrostatic and wet components of the troposphere (Boehm et al., 2006)

6. Absolute IGS phase center and offset models for receiver antenna and satellite transmitting antenna (ftp://ftp.igs.org/pub/station/general/igs14.atx)
7. General relativity effect (IERS Conventions, 2010)
8. IGS differential code biases (DCB) (ftp://cddis.gsfc.nasa.gov/pub/gps/products/mgex/dcb)
9. BERN 15 parameter solar radiation model (Springer et al, 1999)
10. IGS ionospheric grid model for higher-order ionospheric correction (ftp://cddis.gsfc.nasa.gov/gnss/products/ionex)
11. TUME1 albedo mode (http://acc.igs.org/orbits/albedo-gps_Rodriguez_Solano_MS09.pdf).

A priori information and constraints:

1. IGS orbits and solar radiation parameters constrained to 10 cm.
2. IERS series A Earth orientation parameters. Polar motion X and Y components are constrained to 3 mas (~10 cm) in position, and to 0.1 mas/day in rate. UT1 is constrained to 0.02 ms in epoch, 0.1 ms/day in rate.
3. ITRF2014 stations positions. The positions of the IGS global stations are constrained to 2-3 mm horizontally, and 5-10 mm vertically.
4. Nominal tropospheric zenith delay estimation, nominal meteorological parameters are set to 1023 mb for pressure at sea level, 20°C for temperature, and 50% for relative humidity. The pressure is adjusted according to the site elevation. The zenith delays are constrained to 0.5 m within each estimation interval (hourly), and their variations are constrained to 10 cm between intervals with a random walk correlation time set to 100 hours.

All observations are used at a specified sampling interval, currently 30 seconds for automatic data cleaning. To save computational time, at the stage of solving the normal equations the pre-fit solution only uses every 10th double-difference observable epoch (=300 s sampling interval). The post-fit solutions uses every 4th epoch (=120 s sampling interval).

GLOBK

The GAMIT-computed raw displacement time series including the solutions for all the sub-networks are adjusted using the GLOBK software to reconstruct the entire network. The output in IGS SINEX format contains the ITRF2014 position estimates and their variance-covariance matrices from the GAMIT unconstrained ambiguity fixed solution (Step 4) for each 24-hour period.

The ITRF (X,Y,Z) coordinates for each station are then converted to local displacements by:

$$\begin{bmatrix} \Delta N(t_i) \\ \Delta E(t_i) \\ \Delta U(t_i) \end{bmatrix} = \begin{bmatrix} -sin\phi cos\lambda & -sin\lambda sin\phi & cos\phi \\ -sin\lambda & cos\lambda & 0 \\ cos\lambda cos\phi & cos\phi sin\lambda & sin\phi \end{bmatrix}_{t_i} \left\{ \begin{bmatrix} X(t_i) \\ Y(t_i) \\ Z(t_i) \end{bmatrix} - \begin{bmatrix} X(t_0) \\ Y(t_0) \\ Z(t_0) \end{bmatrix} \right\}$$

$$= \boldsymbol{G}_{t_i} \left\{ \begin{bmatrix} X(t_i) \\ Y(t_i) \\ Z(t_i) \end{bmatrix} - \begin{bmatrix} X(t_0) \\ Y(t_0) \\ Z(t_0) \end{bmatrix} \right\} \qquad (1)$$

where t_0 is the time of the first observation and t_i is the current (true-of-date) time of observation. The geodetic latitude and longitude (ϕ, λ) are computed from the (X,Y,Z) coordinates at time t_i, using the WGS ellipsoid parameters: semi-major axis, *a* = 6378137 m, and inverse flattening, *1/f* = 298.257 223 563. The covariance matrix of (N,E,U) is derived from the covariance matrix of (X,Y,Z) by error propagation,

$$\boldsymbol{C}_{(N,E,U)_i} = \begin{bmatrix} \sigma_N^2 & \sigma_{NE} & \sigma_{NU} \\ \sigma_{NE} & \sigma_E^2 & \sigma_{EU} \\ \sigma_{NU} & \sigma_{EU} & \sigma_U^2 \end{bmatrix} = \boldsymbol{G}_{t_i}\boldsymbol{C}_{(X,Y,Z)_i}\boldsymbol{G}_{t_i}; \boldsymbol{C}_{(X,Y,Z)_i} = \begin{bmatrix} \sigma_X^2 & \sigma_{XY} & \sigma_{XZ} \\ \sigma_{XY} & \sigma_Y^2 & \sigma_{\text{YZ}} \\ \sigma_{XZ} & \sigma_{YZ} & \sigma_Z^2 \end{bmatrix} \quad (2)$$

Daily Time Series Analysis

A time series analysis of the GLOBK output positions is then performed on the raw daily displacement time series, station by station and component by component (north, east and up). Time series analysis can be performed component by component since the correlations between them are small (Zhang 1996, Amiri-Simkooei 2009). Using the analyz-tseri program, the following parameters were estimated:

(1) Velocity (linear trend)
(2) Amplitude and phase of annual and semiannual signal
(3) Coseismic offsets
(4) Postseismic relaxation (either exponential decay or logarithmic decay)
(5) Non-coseismic offsets (artifacts due, for example to antenna model changes at a station)

The output from this adjustment are the modeled daily displacement series, the model parameters and their uncertainties and the model residuals (deviations from the model). Note that the velocity uncertainties that are part of the Epoch 2017.50 definition are scaled in order to take into account the colored (time-correlated) noise in the displacement time series (Williams, 2003) – see monumentation discussion in section 7). The CSRN residuals are then filtered to remove a spatially-coherent signal over California due to non-tectonic artifacts outside of the region, which is subtracted from the "unfiltered" modeled displacement time series resulting in the "filtered" modeled displacement time series, as described in detail below.

An individual component time series (ΔN, ΔE, or ΔU) at discrete epochs t_i can be modeled by (Nikolaidis 2002)

$$y(t_i) = a + bt_i + csin(2\pi t_i) + dcos(2\pi t_i) + esin(4\pi t_i) + fcos(4\pi t_i) +$$

$$+ \sum_{j=1}^{n_g} g_j\, H\left(t_i - T_{g\,j}\right) + \sum_{j=1}^{n_h} h_j\, H\left(t_i - T_{h\,j}\right) t_i +$$

$$+ \sum_{j=1}^{n_k} k_j e^{\left[1-\left(\frac{t_i - T_{k\,j}}{\tau_j}\right)\right]} H\left(t_i - T_{k\,j}\right) + \varepsilon_i\,. \quad (3)$$

H denotes the discrete Heaviside function (a discontinuous step function),

$$H = \begin{Bmatrix} 0, & t_i - T_{k\,j} < 0 \\ 1, & t_i - T_{k\,j} \geq 0 \end{Bmatrix}$$

The coefficient *a* is the value at the initial epoch t_0 ("y-intercept"). The t_i denote the interval of time between a particular point in the time series and the initial point t_0 in units of years. The linear rate (slope) *b* represents the interseismic secular tectonic motion, typically expressed in mm/yr. The coefficients *c*, *d*, *e*, and *f* denote unmodeled annual and semi-annual variations present in GPS position time series. The magnitudes *g* of n_g jumps (offsets, steps, discontinuities) are due to coseismic deformation and/or non-coseismic changes at epochs T_g. Most non-coseismic discontinuities are due to replacement of GPS antennas with different phase center characteristics (although like antennas may also introduce offsets). Possible n_h changes in velocity are denoted by new velocity values *h* at epochs T_h (there were no multiple velocities assigned for this project, which is an issue for areas of subsidence – see Discussion). Postseismic coefficients k are for n_k postseismic motion events starting at epochs T_h and decaying exponentially with a time constant τ_j. Alternatively, some earthquakes were assigned a logarithmic decay

$$\sum_{j=1}^{n_k} k_j log\left(1+\frac{t_i-T_{k\,j}}{\tau_j}\right) H\left(t_i-T_{k\,j}\right) \tag{4}$$

A number of stations experienced two large earthquakes, requiring multiple coseismic and postseismic parameters. The significant earthquakes since Epoch 2011.00 are shown in Table 3.

The event times *T* (*g,h,k*) are determined from earthquake catalogs, station sites logs, automatic detection algorithms, or by visual inspection. The postseismic decay times τ_j are typically estimated separately, so that the estimation of the remaining time series coefficients can be expressed as a linear adjustment problem,

$$\boldsymbol{y} = \boldsymbol{Ax} + \boldsymbol{\varepsilon}\text{;}\; E\{\boldsymbol{\varepsilon}\} = \boldsymbol{0};\; D\{\boldsymbol{\varepsilon}\} = \sigma_0^2 \boldsymbol{C}_{\boldsymbol{\varepsilon}} \tag{5}$$

where **A** is the design matrix and $\boldsymbol{x}$ is the parameter vector,

$$\boldsymbol{x} = (a\; b\; c\; d\; e\; f\; \boldsymbol{g}\; \boldsymbol{h}\; \boldsymbol{k})^T. \tag{6}$$

The operator *E* denotes statistical expectation, *D* denotes statistical dispersion, $\boldsymbol{C}_{\boldsymbol{\varepsilon}}$ is the covariance matrix of observation errors, **P=** C_ε^{-1} is the weight matrix, and σ_0^2 is an *a priori* variance factor.

The model parameters are estimated by weighted least squares. In its basic form, the weighted sum of the squares of the residual vector $\boldsymbol{\varepsilon}$ is minimized such that

$$min[\![\boldsymbol{\varepsilon}^T \boldsymbol{P\varepsilon}]\!] = min\|(\boldsymbol{l}-\boldsymbol{AX})^T \boldsymbol{P}(\boldsymbol{l}-\boldsymbol{AX})\| \tag{7}$$

with the weighted least squares solution $\hat{\boldsymbol{x}}$ and the estimated covariance matrix $\hat{\Sigma}_{\hat{x}}$ given, respectively, by

$$\hat{\boldsymbol{x}} = (\boldsymbol{A}^T\boldsymbol{PA})^{-1}\boldsymbol{A}^T\boldsymbol{P}\hat{\boldsymbol{l}}\,; \tag{8}$$

$$\hat{\boldsymbol{\Sigma}}_{\hat{x}} = \hat{\sigma}_0^2(\boldsymbol{A}^T\boldsymbol{PA})^{-1}; \hat{\sigma}_0^2 = \frac{\hat{\boldsymbol{\varepsilon}}^T\boldsymbol{P}\hat{\boldsymbol{\varepsilon}}}{n-u}. \tag{9}$$

The hat denotes an estimated quantity. The *a posteriori* variance factor $\hat{\sigma}_0^2$ is often called the "*a posteriori* variance of unit weight," "chi-squared per degrees of freedom," or "goodness of fit," where the degrees of freedom is $n-u$; n is the number of observations and u the number of parameters. Other inversion methods are often used as a variation of the above, such as the Kalman filter in the analyz_tseri software.

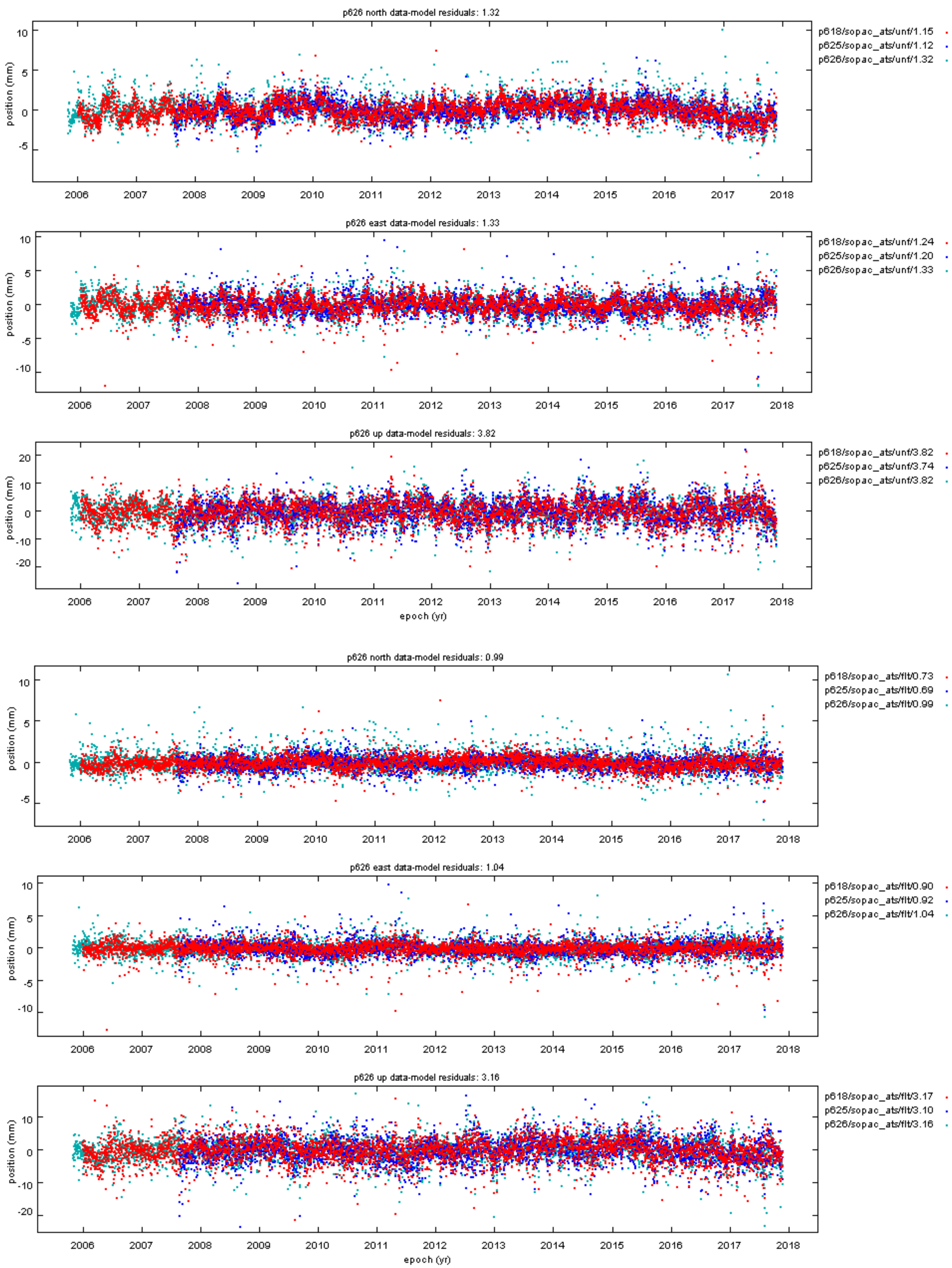


Figure 8. (Top) Overlain unfiltered displacement time series for 3 CSRN stations showing "common-mode" periodic features; (Bottom) Filtered displacement time series showing a significant decrease in scatter (wrms) in the horizontal components and less so for the vertical component Source: Source: GPS Explorer Time Series Applet (http://geoexp01.ucsd.edu/gridsphere/gridsphere).

Filtered time series

Examination of the post-fit residuals $\hat{\boldsymbol{\varepsilon}} = \boldsymbol{y} - \boldsymbol{A}\hat{\boldsymbol{x}}$ of the modeled daily displacement time series reveals a similar periodic signature at all stations referred to as "common-mode error" (CME) (Figure 8). This is typical for any regional network and is due to global sources outside the region. Filtering of the residuals in space (over all CSRN stations) and time (the entire time interval) called "spatio-temporal filtering" can be used to estimate and remove the common-mode allowing for improved discernment of tectonic signals by lowering the model parameter uncertainties and the scatter in the displacements (weighted rms – equation 12). An early study suggested a stacking procedure (Wdowinski et al., 1997), a simple form of principal component analysis (PCA) applied to displacement time series (Dong et al., 2006). We used PCA to create the "filtered modeled daily displacement time series" from the "unfiltered model daily displacement time series." In the PCA process the post-fit residuals are stored column-wise in a matrix **X** according to displacement components in north, east and up directions for epoch *m* (*m*=1, M) and station *n* (*n*=1, N) assuming *m*>*n* (this is always the case in geodetic analysis). The "covariance" matrix is defined by

$$\boldsymbol{B} = \frac{1}{M-1}\boldsymbol{X}^T\boldsymbol{X}, \tag{10}$$

which is decomposed by

$$\boldsymbol{B} = \boldsymbol{V}\boldsymbol{\Lambda}\boldsymbol{V}^T. \tag{11}$$

B is a full rank matrix of dimension N, **V** is the eigenvector matrix and $\boldsymbol{\Lambda}$ has *k* non-zero eigenvalues along its diagonal ($N \geq k$). Then, using **V** as an orthonormal basis at epoch *i*

$$X(t_i, x_n) = \sum_{k=1}^{N} a_k(t_i)v_k(x_m)$$

$$a_k(t_i) = \sum_{n=1}^{N} X(t_i, x_j)v_k(x_n) \tag{12}$$

The eigenvalue $a_k(t_i)$ is the *k*th principal component representing the temporal variations and $v_k(x_n)$ is the corresponding eigenvector representing the spatial responses to the principal components. The largest principal component corresponds to the primary contributor to the variance of the network-wide residual time series and it is used to create the filtered time series, while the smallest principal component has the least contribution.

QA/QC

As indicated in Figure 7, the overall analysis is performed in an iterative manner. As part of this process there are several procedures applied for quality analysis/quality control (QA/QC). The entire process, including the QA/QC process, consists of the following steps:

(1) Identify all archived stations in California and border areas as candidates for the CSRN – this was performed in collaboration with the CSRC station selection committee.
(2) Backfill missing RINEX files in the archive from the relevant agencies (e.g., the UNAVCO and CVSRN archives).
(3) Check for updated site logs from the responsible agencies and update SOPAC database with any missing metadata.
(4) Examine earlier SOPAC ITRF2008 displacement time series:

a. Flag defunct stations
b. Identify and categorize any deviations from linearity, outliers, anomalies
c. Document gaps in the data
d. Identify and exclude outliers
e. Assign simple QC rating (Excellent, Very Good, Fair to Good, Fair, Poor)
f. Refine CSRN station list

(5) Perform GAMIT/GLOBK ITRF2014 analysis (global stations) – identify and repair problematic solutions (large adjustments, failed solutions).
(6) Examine and repair ITRF2014 global displacement time series (raw, unfiltered, filtered, residuals, weighted root mean square errors - wrms) for remaining problems – repeat step (4) above.
(7) Convert ITRF2014 Epoch 2017.50 values to NAD83(2011) and evaluate.
(8) Create and troubleshoot the Epoch 2017.50 results for all CSRN stations (Table 2).
(9) Audit an independently-determined sample as described in section 11.

9. Orthometric Heights

The latest hybrid geoid model GEOID12B published by NGS https://www.ngs.noaa.gov/GEOID/GEOID12B/ was used to interpolate geoid heights for each of the stations. Geodetic coordinates (latitude, longitude, ellipsoid height) at CSRS Epoch 2017.50 (NAD83) were input into the online interpolation software on the NGS website. A second interpolation was run with the same coordinates and same GEOID12B model in Trimble Business Center desktop software for confirmation. The resulting geoid heights were intended to develop Derived California Orthometric Heights (DOCH) on the NAVD88 datum in accordance with the California Public Resources Code §§8850-8861 Geodetic Datums §§8870-8880 Geodetic Coordinates §§8890-8902 Heights. The DOCH, *H*, on the NAVD88 datum were determined by the formula:

$$H = h - N \quad (13)$$

where *h* = the ellipsoid height on NAD83(2011), and *N* = the geoid height in GEOID12B (Table 1).

"The relative accuracy of GEOID12B to NAVD88 is characterized by a misfit of +/-1.7 centimeters nationwide" (https://www.ngs.noaa.gov/GEOID/GEOID12B/GEOID12B_TD.shtml). Therefore, accuracy estimates for the DOCH in Table 1 should be augmented by a similar appropriate geoid uncertainty applied to the ellipsoid height 2-sigma uncertainty. This augmentation to derive a 2-sigma uncertainty for the DCOH is specific to the local characteristics of the GEOID12B model within the area of interest and should be derived from observation data on known local California Orthometric Heights (COH) (i.e. confirmed local bench marks). The NGS statement "+/-1.7 centimeters nationwide" is a realistic guideline, and any augmentation value should be reasonably close to this number.

Several of the stations had previously been included in precise leveling projects on the NAVD88 datum (Table 4). Leveling projects included CSRC CORS leveling and network RTK projects: CSRC Lv - 2005 and 2006, Metropolitan Water District of Southern California leveling projects (MWD - 2004 to 2009), County of Orange leveling (OCS - 2000 to 2010), County of San Diego Record of Survey 21787 (CoSD RoS21787), Riverside County Flood Control leveling (RCFC), City and County of San Francisco Record of Survey (8080 CCSF RoS8080), and the Port of Long Beach in 2016 (POLB 2016). While the subset is predominantly from Southern California projects, it serves as a valuable independent testing of the DCOH. Table 4 provides a comparison between the leveled COH and the derived COH. The entire sample exhibits a standard deviation of 37 mm. Considering some suspect stations in subsidence areas as outliers, the sample exhibits a standard deviation of 27 mm. Considering the known issues with the NAVD88 datum in California, and the extensive areas of subsidence and vertical crustal motion, the DCOH in Table 1 likely represent the most consistent realization of the NAVD88 datum in the State.

Table 4. Comparison of 2017.50-Derived NAD2011 and Leveled Orthometric Heights

Station	COH-Derived 2017.50 (m)	COH88-Leveled (m)	Difference (m)	Leveling Source
BILL	503.154	503.154	0.000	CSRC Lv
BKAP	283.430	283.418	0.012	CSRC Lv
BLSA	13.054	13.137	-0.083	OCS 2005
BRAN	280.931	280.947	-0.016	MWD
BSRY	645.612	645.632	-0.020	CSRC Lv
BVPP	158.029	158.139	-0.110	CSRC Lv
CCCC	845.127	845.141	-0.014	CSRC Lv
CCCS	67.429	67.428	0.001	OCS 2006
CLAR	407.515	407.532	-0.017	MWD
CLBD	55.896	55.897	-0.001	CoSD RoS21787
CNPP	334.814	334.817	-0.003	CSRC Lv
COPR	13.860	13.823	0.037	CSRC Lv
COTD	61.028	61.177	-0.149	CSRC Lv
CRBT	240.132	240.134	-0.002	CSRC Lv
CRHS	13.032	13.060	-0.028	POLB 2016
CSDH	27.435	27.424	0.011	CSRC Lv
CSN1	296.648	296.660	-0.012	CSRC Lv
DSME	91.415	91.413	0.002	CoSD RoS21787
ELSC	97.058	97.150	-0.092	CSRC Lv
EWPP	364.089	364.123	-0.034	CSRC Lv
FVPK	24.436	24.460	-0.024	OCS 2005
GLRS	-13.991	-13.984	-0.007	CSRC Lv
GVRS	190.015	190.103	-0.088	MWD
HBCO	9.668	9.711	-0.043	CSRC Lv
HNPS	427.149	427.135	0.014	MWD
IID2	45.109	45.162	-0.053	CSRC Lv
LAPC	243.275	243.277	-0.002	CSRC Lv
LBC1	14.475	14.502	-0.027	POLB 2016
LBC2	8.016	8.004	0.012	POLB 2016
LBCH	8.919	8.904	0.015	POLB 2016
LORS	482.651	482.713	-0.062	MWD
LVMS	1575.138	1575.127	0.011	CSRC Lv
MAT2	432.232	432.213	0.019	CSRC Lv
MHMS	33.989	34.020	-0.032	POLB 2016

MLFP	506.555	506.546	0.009	CSRC Lv
MVFD	1222.578	1222.649	-0.071	CSRC Lv
NDAP	272.704	272.705	-0.001	CSRC Lv
NOCO	221.219	221.240	-0.021	RCFC
OCSD	77.969	77.986	-0.017	CoSD RoS21787
OEOC	393.581	393.606	-0.025	OCS 2002
P478	405.160	405.162	-0.002	CoSD RoS21787
P799	61.407	61.431	-0.024	POLB 2016
PPBF	461.425	461.418	0.007	CSRC Lv
PVRS	96.413	96.432	-0.019	MWD
RSTP	745.498	745.501	-0.003	CSRC Lv
SACY	24.518	24.582	-0.064	OCS 2010
SBCC	123.852	123.764	0.088	OCS 2000
SNHS	102.048	102.075	-0.027	OCS
TORP	31.421	31.431	-0.010	MWD
TOST	309.983	310.016	-0.033	CSRC Lv
TRAK	150.931	150.970	-0.039	OCS 1993
UCSF	187.698	187.770	-0.072	CCSF RoS8080
USLO	169.786	169.783	0.003	CSRC Lv
VDCY	352.706	352.715	-0.010	CSRC Lv
VIMT	589.182	589.169	0.013	CSRC Lv
VNCX	363.520	363.504	0.016	CSRC Lv
VNDP	25.401	25.428	-0.027	CSRC Lv
VNPS	994.449	994.432	0.017	CSRC Lv
VTIS	96.097	96.091	0.006	CSRC Lv
VTOR	414.202	414.212	-0.010	CoSD RoS21787
WHYT	300.038	300.047	-0.008	OCS 2002
WIDC	477.864	477.849	0.015	CSRC Lv
WRHS	44.478	44.471	0.007	CSRC Lv

10. CSRS Epoch 2017.50 (NAD83)

The results of the CSRS Epoch 2017.50 analysis on ITRF2014 and NAD83(2011) are shown in Table 1 for each CSRN station. The Epoch date is 2017.50 (2017-07-02; 2017, day of year 183; GPS week 1956, GPS day 0). It provides ITRF2014 and NAD83(2011) coordinates, velocities, and their uncertainties for 948 CGPS stations in California and border regions, identified by their four-character id's and full station name. It is based on SOPAC filtered position time series up to epoch 2017.8234 (10/28/2017; GPS week 1976, GPS day 6; 2017 day of year 301). All coordinates refer to the geodetic reference mark (GRM), after consideration of antenna L1 and L2 phase center models and antenna height. All uncertainties are given at the 95% confidence level (using a 1-D factor 1.96).

The modeled coordinates and uncertainties of the CSRN stations at Epoch 2017.50 in ITRF2014 are the realization of the CSRS. They are consistent with the frame in which GNSS satellite orbits (broadcast, IGS rapid and precise) and auxiliary products that are provided by the IGS.

The following describes the data fields in Table 1, which constitute the results of the Epoch 2017.50 solution:

ITRF_X(m), ITRF_Y(m), ITRF_Z(m)

ITRF2014 global Cartesian coordinates (X,Y,Z) per station in meters, based on a GAMIT/GLOBK analysis of CSRN and global stations (section 7), and time series analysis of the entire data holdings for each station (section 8). They refer to the model trace resulting from the time series analysis (section 8), at Epoch 2017.50. An example of the model trace is shown in Figure 9 – it is the line that best fits the modeled (unfiltered and filtered) daily displacement time series. The model trace can be viewed in the GPS Explorer time series application (http://geoexp01.ucsd.edu/gridsphere) for all CSRN stations. It is also the basis for epoch-date coordinates available through the SECTOR application (http://sopac.ucsd.edu/sector.shtml).

Stations that are no longer operational are extrapolated based on the estimated time series model parameters to Epoch 2017.50.

ITRF_X2sig(m), ITRF_Y2sig(m), ITRF_Z2sig(m)

ITRF2014 global Cartesian coordinates (X,Y,Z) uncertainties per station in meters. Since the 2017.50 ITRF2014 coordinates are based on the model fit, we use the GAMIT/GLOBK estimated uncertainties (scaled by the goodness of fit) at that date as the X,Y,Z uncertainties, in meters. It should be noted that the cross-covariances between different stations are negligible and can be ignored. We do retain the X,Y,Z variances and covariances for each station (there are 3 variance and 3 covariance values since the variance-covariance matrix is symmetric). These are used for the propagation from X,Y,Z to N,E,U variance-covariance matrices according to equation (2).

ITRF_Lat (dms), ITRF_Lon (dms), ITRF_Hgt (m)

ITRF2014 geodetic coordinates (latitudes, longitudes, ellipsoidal heights, in d/m/s and meters) at epoch 2017.50 transformed from X,Y,Z coordinates using equation (1) and the WGS84 ellipsoidal parameters (semi-major axis, a = 6378137 m and inverse flattening, 1/f = 298.257 223 563).

Lat2sig(mm), Lon2sig(mm), Hgt2sig(mm)

ITRF2014 and NAD83 geodetic coordinates uncertainties. The geodetic uncertainties provide a more intuitive representation of the errors. Note that they are provided in millimeters, while the coordinates are expressed in meters. The X,Y,Z variance-covariance matrix is transformed to the N.E,U variance-covariance matrix by error propagation by means of equation (2). The uncertainties are the square root of the variances on the matrix diagonal expressed at the 95% confidence level (multiplied by 1.96). As expected the north and east uncertainties are about three times smaller than the vertical uncertainties. It should be noted that the N,E,U covariances are negligible and not shown. Recall that the presence of low correlations is the rationale for performing separate time series analysis for each of the geodetic coordinates (Zhang, 1996). Using the same logic, the uncertainties are one dimensional, for each component. Note that we assumed that the coordinate uncertainties for ITRF2014 and NAD83 values are equivalent, since the transformation between the two is assumed to be without error.

N_wrms, E_wrms, U_wrms

Another measure of uncertainty is the scaled weighted root mean square (wrms) of each modeled displacement time series (expressed in mm), which represents the scatter about the model trace weighted by the estimated component uncertainties at each epoch. These are computed from the modeled ΔN,ΔE,ΔU displacement time series residuals, $\boldsymbol{y} - \boldsymbol{A}\hat{\boldsymbol{x}}$ (equations 7-9), per component, where *n* is the number of data points

$$wrms = \sqrt{\frac{\sum_{i=1}^{n}[(\boldsymbol{y}-\boldsymbol{A}\hat{\boldsymbol{x}})^T(\frac{1}{\sigma_i^2})(\boldsymbol{y}-\boldsymbol{A}\hat{\boldsymbol{x}})]}{n}} \quad (12)$$

It is notable that the 95% confidence geodetic coordinate uncertainties are similar to the wrms values.

ITRF_N Vel(mm/yr), ITRF_E Vel(mm/yr), ITRF_U Vel(mm/yr)

ITRF2014 velocity estimates from the time series model fit in millimeters/year. It is insufficient to apply the velocities to transform between epochs, since that would neglect the other model parameters, in particular earthquake-related displacements and offsets. Also note that these velocities are not with respect to stable North America, but with respect to the global Cartesian reference frame (ITRF2014) (Figure 1).

N vel2sig(mm/yr), E vel2sig(mm/yr), U velsig2(mm/yr)

ITRF2014 and NAD83 velocity uncertainties in north, east and up directions in millimeters/year. Note that the velocity uncertainties take into account the colored noise in the displacement time series (section 8). The uncertainties are expressed at the 95% confidence level (multiplied by 1.96). Note that we assumed that the velocity uncertainties for ITRF2014 and NAD83 values are equivalent, since the transformation between the two is assumed to be without error and the velocity azimuths have only a small rotation (Figure 1).

NAD_X(m), NAD_Y(m), NAD_Z(m)

Global Cartesian X,Y,Z coordinates of the stations after transformation from ITRF2014 to NAD83(2011) at Epoch 2017.50 using the application the NGS HTDP application ("beta htdp 3.2.6"). We used the beta version because it includes the ITRF2014 transformation.

NAD_Lat(dms), NAD_Lon(dms), NAD_Hgt(m)

These are the geodetic coordinates of the stations after transformation from ITRF2014 to NAD83(2011) using the "beta htdp 3.2.6" software.

NADvelN(mm/yr), NADvelE(mm/yr), NADvelU(mm/yr)

These are the north, east and up velocities in NAD83(2011) referenced to North America (Figure 1).

3DposDif (m)

The difference in coordinates between the new Epoch2017.5 (E2) and the previous Epoch2011.00 (E1) in meters. The 3DposDif is defined by

$$\sqrt{(X_{E2}-X_{E1})^2+(Y_{E2}-Y_{E1})^2+(Z_{E2}-Z_{E1})^2}. \quad (13)$$

Start(year), End(year)

Start and end dates of the displacement time series used to derive Epoch 2017.50. For all active stations the end date should be equal to the last day of displacements. That is, epoch 2017.8233 (10/28/2017; GPS week 1976, GPS day 6; 2017 day of year 301).

Op(2017.50)(Y/N)

Denotes the stations that were operational at 2017.50.

Geoid12B(m)

Denotes interpolated geoid heights for each of the stations derived from the latest hybrid geoid model GEOID12B published by NGS (https://www.ngs.noaa.gov/GEOID/GEOID12B/) (section 9).

Cal_Ortho_Hgt(m)

The geoid heights were used to estimate Derived California Orthometric Heights (DOCH) on the NAVD88 datum (DCOH) in accordance with the California Public Resources Code §§8850-8861 Geodetic Datums §§8870-8880 Geodetic Coordinates §§8890-8902 Heights (section 9).

It is important to note that the ellipsoid and orthometric heights in Table 1 are to the geodetic reference mark (GRM) on each of the stations. Use of these heights requires verification of the current antenna model and antenna height for the selected station, as equipment is changed over time. The GRM, however, remains fixed.

11. Survey/GeoSpatial Independent Checking

As stated in the CSRC/CLSA joint publication, *GNSS Surveying Standards and Specifications, Ver. 1.1* http://csrc.ucsd.edu/docs/CLSA_CSRC_GNSS_Standards_and_Specifications_v1.1.pdf to achieve an accuracy level for geodetic control networks *"testing of the final results must be addressed by auditing an independently-determined sample"*. Ten sites, distributed across the State, were processed independently using three different online processors, with three days of observations spanning the 2017.50 epoch:

1. Jet Propulsion Laboratory Automated Precise Positioning Service http://apps.gdgps.net/
2. Natural Resources Canada Precise Point Positioning https://webapp.geod.nrcan.gc.ca/geod/tools-outils/ppp.php
3. National Geodetic Survey OPUS https://www.ngs.noaa.gov/OPUS/

These independent solutions lack the historical solution series and rigorous crustal motion modeling used for the CSRN 2017.50 solution, but exhibit precision suitable for independent checking. All three independent solutions are oriented to the ITRF08 reference frame, and therefore should not be considered absolute comparisons. The apparent bias in comparisons (dX = -5 mm, dY = -2 mm, dZ = -4 mm) are partly a result of the difference in reference frames. Regardless, the independent checking serves as evidence to substantiate the accuracy claims in Table 1. The comparisons between the combination of the three independent solutions and the CSRN 2017.50 solution exhibit a standard deviation of dX = 2.8 mm, dY = 1.9 mm, and dZ = 3.0 mm. Table 5 provides a summary of the solutions used for independent checking.

Table 5. Comparisons of CSRC 2017.50 ITRF 2014 coordinates to JPL, NRCan and OPUS solutions

Station	ITRF_X(m)	ITRF_Y(m)	ITRF_Z(m)	ITRF_X2sig(m)	ITRF_Y2sig(m)	ITRF_Z2sig(m)
BLYT	-2223206.8910	-4830299.7890	3510587.5215	0.0035	0.0046	0.0042
MODB	-2399442.7634	-4105688.0651	4238581.9266	0.0050	0.0057	0.0059
MUSB	-2491802.7532	-4438642.3413	3833672.5438	0.0035	0.0045	0.0043
P150	-2474961.3098	-4280914.9374	4019149.1724	0.0037	0.0044	0.0044
P475	-2460343.9634	-4778294.7760	3422858.2530	0.0032	0.0041	0.0036
P580	-2372609.8161	-4618139.9265	3695056.9400	0.0031	0.0039	0.0037
UCSF	-2709557.2168	-4260015.6128	3884773.3635	0.0034	0.0041	0.0041
VNDP	-2678090.5235	-4525436.9533	3597431.9500	0.0037	0.0046	0.0044
VTIS	-2517409.4944	-4676543.7623	3520010.4652	0.0028	0.0035	0.0033
YBHB	-2576448.0281	-4011576.3364	4224116.9497	0.0043	0.0054	0.0051

ITRF2008(2017.50) JPL PPP Solution						Comparisons (JPL - CSRC Solutions)			
Station	X	Y	Z	X_2sig	Y_2sig	Z_2sig	dX	dY	dZ
	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)
BLYT	-2223206.889	-4830299.783	3510587.520	0.008	0.015	0.011	0.002	0.006	-0.001
MODB	-2399442.756	-4105688.052	4238581.923	0.015	0.019	0.021	0.007	0.013	-0.003
MUSB	-2491802.747	-4438642.337	3833672.548	0.010	0.017	0.014	0.007	0.004	0.004
P150	-2474961.307	-4280914.925	4019149.174	0.010	0.014	0.013	0.003	0.013	0.001
P475	-2460343.954	-4778294.765	3422858.252	0.010	0.016	0.011	0.009	0.011	-0.001
P580	-2372609.812	-4618139.921	3695056.944	0.008	0.013	0.011	0.004	0.006	0.004
UCSF	-2709557.212	-4260015.609	3884773.369	0.009	0.013	0.012	0.005	0.004	0.006
VNDP	-2678090.514	-4525436.945	3597431.963	0.009	0.013	0.010	0.010	0.008	0.013
VTIS	-2517409.490	-4676543.758	3520010.469	0.008	0.015	0.011	0.005	0.004	0.004
YBHB	-2576448.022	-4011576.332	4224116.951	0.014	0.022	0.019	0.006	0.004	0.001

ITRF2008(2017.50) Natural Resources Canada PPP Solution					Comparisons (NRCan - CSRC Solutions)				
Station	X	Y	Z	X_2sig	Y_2sig	Z_2sig	dX	dY	dZ
	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)
BLYT	-2223206.893	-4830299.791	3510587.516	0.010	0.014	0.009	-0.002	-0.002	-0.005
MODB	-2399442.772	-4105688.065	4238581.931	0.010	0.013	0.012	-0.008	0.000	0.004
MUSB	-2491802.749	-4438642.343	3833672.543	0.009	0.013	0.010	0.004	-0.001	-0.001
P150	-2474961.314	-4280914.935	4019149.172	0.009	0.012	0.010	-0.005	0.002	0.000
P475	-2460343.960	-4778294.776	3422858.251	0.009	0.012	0.008	0.003	0.000	-0.002
P580	-2372609.815	-4618139.930	3695056.941	0.008	0.011	0.008	0.001	-0.003	0.001
UCSF	-2709557.213	-4260015.615	3884773.363	0.009	0.011	0.009	0.003	-0.002	0.000
VNDP	-2678090.517	-4525436.951	3597431.954	0.008	0.011	0.008	0.007	0.002	0.004
VTIS	-2517409.496	-4676543.770	3520010.469	0.008	0.010	0.007	-0.002	-0.007	0.003
YBHB	-2576448.024	-4011576.335	4224116.943	0.011	0.012	0.012	0.004	0.002	-0.007

ITRF2008(2017.50) NaNGS OPUS					Comparisons (OPUS - CSRC Solutions)				
Station	X	Y	Z	X_2sig	Y_2sig	Z_2sig	dX	dY	dZ
	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)
BLYT	-2223206.879	-4830299.787	3510587.530	0.008	0.011	0.006	0.012	0.002	0.008
MODB	-2399442.755	-4105688.066	4238581.934	0.015	0.012	0.008	0.008	-0.001	0.008
MUSB	-2491802.740	-4438642.347	3833672.550	0.017	0.019	0.013	0.013	-0.006	0.006
P150	-2474961.305	-4280914.940	4019149.180	0.006	0.008	0.007	0.005	-0.003	0.008
P475	-2460343.951	-4778294.782	3422858.265	0.009	0.008	0.006	0.012	-0.006	0.012
P580	-2372609.813	-4618139.922	3695056.949	0.009	0.004	0.009	0.003	0.005	0.009
UCSF	-2709557.216	-4260015.609	3884773.386	0.005	0.015	0.012	0.001	0.004	0.022
VNDP	-2678090.514	-4525436.952	3597431.958	0.005	0.006	0.006	0.010	0.001	0.008
VTIS	-2517409.488	-4676543.763	3520010.465	0.012	0.024	0.014	0.007	0.000	0.000
YBHB	-2576448.022	-4011576.337	4224116.957	0.011	0.008	0.005	0.006	-0.001	0.007

12. Discussion

We have created a new datum for California in ITRF2014 and NAD83(2011) at Epoch 2017.50 to replace Epoch 2011.00. During this time the coordinates of the CVSRN stations significantly changed by 0.06 to 1.6 meters (due to subsidence in the Central Valley at station LEMA, the next largest change is 0.6 meters) as shown by the entry 3DposDif (m) in Table 1, even without a large earthquake since April 2010 (Table 3). In addition, a comprehensive set of California Orthometric Heights on the NAVD88 datum were established for each station.

The question remains is how often to repeat the process of publishing new Epoch dates. It is partly a function of the occurrence of large earthquakes that will significantly affect the positions of a large number of stations. For example, the extent of motion during the 2010 Mw7.2 El Mayor-Cucapah earthquake affected all stations in southern California (Table 3). Another option is to transition to a dynamic datum – this is a topic of discussion, and a report is now being prepared by SOPAC for Caltrans. As NGS implements a new horizontal and vertical datum in 2022 (https://www.ngs.noaa.gov/datums/newdatums/index.shtml) this question will become even more pronounced. The CSRN Epoch 2017.50 will provide the comprehensive and reliable geodetic data from which to address such challenging issues.

Another consideration for a dynamic datum is the presence of significant subsidence in the State (Figure 3), which is problematic for vertical control and may require special treatment. In particular, since the Epoch 2011.00 the Central Valley has experienced significant changes in the rate of subsidence due to drought conditions and a subsequent increase in water extraction. The daily displacement time series from PBO station P304 in the Central Valley illustrate this problem (Figure 9) – the model trace from the time series analysis (section 8) does not fit the data well. Another illustration of the problem can be seen in the residuals of the time series model for station CRCN (Figure 10). Note that at about epoch 2017.50 the deviation in the up component is about 0.4 feet. Thus, Caltrans may need to update its CVSRN station coordinates on a more frequent basis using SOPAC's SECTOR utility (http://sopac.ucsd.edu/sector.shtml).

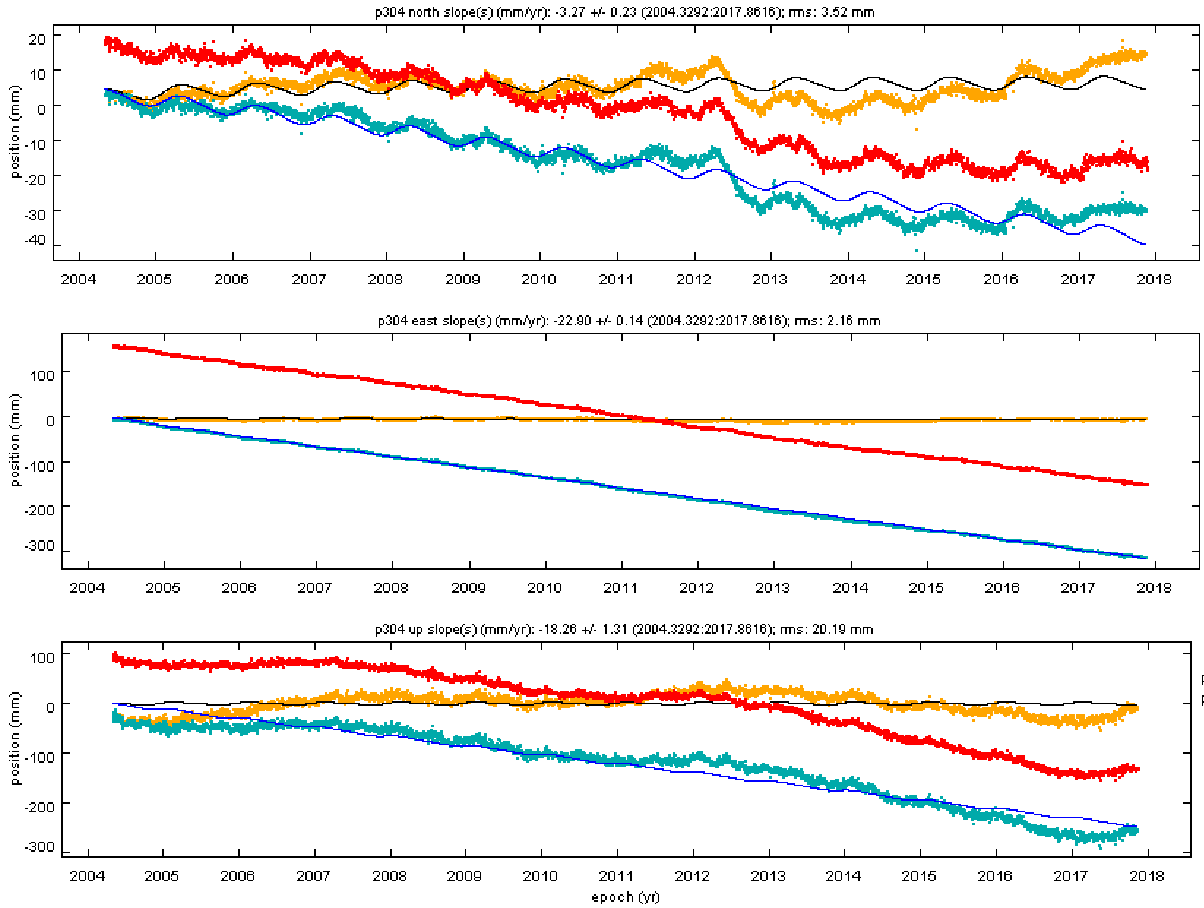


Figure 9. Non-uniform subsidence at PBO station P304 near Mendota in the Central Valley totaling about 0.7 feet starting in 2007, leveling off in 2011, accelerated subsiding since 2012 due to drought conditions, and leveling off in 2017. The pattern of slope changes in the north component mirrors the pattern in the up component. The red lines indicate the raw displacements, the turquoise lines are the trended modeled displacements, the orange lines are the detrended model displacements (the best-fitting slopes have been removed), blue lines are the trended model traces and the black lines are the detrended model traces. Source: GPS Explorer Time Series Applet (http://geoexp01.ucsd.edu/gridsphere/gridsphere).

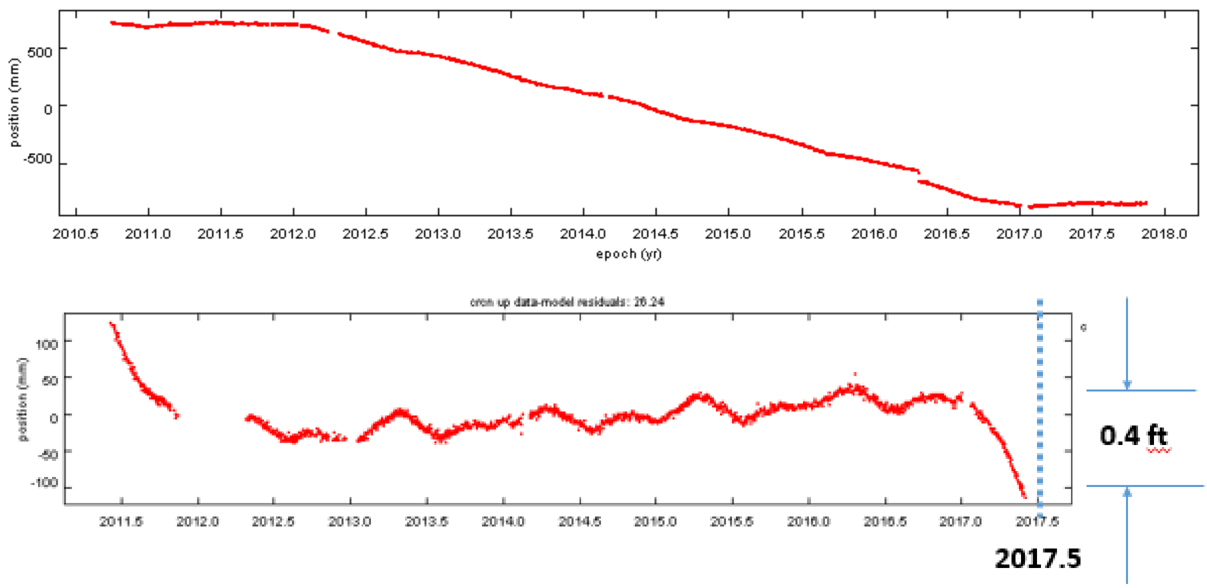


Figure 10. (Top) Raw up time series for CVSRN station CRCN in the southern part of the Central Valley. (Bottom). Residuals after fitting the up time series with a single slope. The residuals diverge at the ends because of the change in subsidence rate at about 2012.3 and at about 2017.0. Source: GPS Explorer Time Series Applet (http://geoexp01.ucsd.edu/gridsphere/gridsphere).

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