# TLALOCNet: A Continuous GPS-Met Backbone in Mexico for Seismotectonic and Atmospheric Research

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## ABSTRACT

The Trans-boundary, Land and Atmosphere Long-term Observational and Collaborative Network (TLALOCNet) is a network of continuous Global Positioning System (GPS) and meteorology stations in Mexico for the study of solid-earth and atmospheric processes. This recently completed network spans most of Mexico with a strong focus on southern and western Mexico. TLALOCNet observations will enable a better analysis of strain accumulation and release processes throughout the Mexican subduction zone and transform faults in the Gulf of California, surface deformation processes, and will provide water vapor estimates that will advance knowledge on atmospheric processes in Mexico. We provide some examples of results generated from TLALOCNet products. For solid-earth applications, we present daily position time-series solutions in contrasting tectonic scenarios and real-time displacement differences for the 8 September 2017 $M_w$ 8.2 Tehuantepec and the 19 September 2017 $M_w$ 7.1 Puebla earthquakes observed from 1-Hz GPS streams that serve as examples of the network performance. For atmospheric applications, we present the evolution of precipitable water vapor and latent heat flux during the North American monsoon season in northwestern Mexico. We finally discuss some of the applications of TLALOCNet for space weather applications in Mexico. TLALOCNet provides open and freely available raw GPS data and high-frequency surface meteorology measurements. Data are available through the TLALOCNet data center (see Data and Resources) that serves as a collection and distribution point. This archive provides a fully queryable and scriptable GPS and surface meteorological data retrieval site. In addition, real-time 1 Hz streams and real-time solutions from selected TLALOCNet stations are available in BINEX and RTCM v.3.1 via the Networked Transport of RTCM via Internet Protocol (NTRIP) for real-time hazard analyses, including seismo-geodesic and weather forecasting applications.

## INTRODUCTION

Mexico is vulnerable to a variety of natural hazards. On short time scales, earthquakes, tsunamis, volcanic eruptions, hurricanes, heavy precipitation, hailstorms, flooding, and landslides all affect Mexico and are high priorities for operational forecasting as well as basic and applied research. Over decadal time scales, ground subsidence induced by aggressive groundwater extraction coupled with climate model projections predict that the currently arid parts of northern Mexico will become even drier (Seager *et al.*, 2007; Karmalkar *et al.*, 2011), and raise concerns about the sustainability of urban development, agricultural production, and manufacturing exports critical to the North American economic region.

The Mexican subduction zone (MSZ; Fig. 1), which extends 1700 km along Mexico's Pacific coast, accommodates 25–80 mm/yr of Rivera and Cocos plate subduction beneath North America's western margin (DeMets and Wilson, 1997; DeMets *et al.*, 2010). The subduction zone geometry varies from subhorizontal below Guerrero and Oaxaca to steeply dipping below Chiapas in southern Mexico and Jalisco/Colima in western Mexico (Pardo and Suárez, 1995; Pérez-Campos *et al.*, 2008; Yang *et al.*, 2009; Melgar and Pérez-Campos, 2011). The current MSZ (including the former Farallon plate subduction) has been the locus of orogeny, terrane accretion, margin truncation, and metamorphic complex exhumation throughout the Cenozoic on the western and southwestern North American plate margin. The proximity of the trench to the coast, averaging 40–60 km along much of its margin, coupled with its shallow subduction angle (10°–12°), the high convergence rate, and strong interseismic coupling for most of the MSZ (e.g., Yoshioka *et al.*, 2004; Correa-Mora *et al.*, 2008; Radiguet *et al.*, 2012) generates large and frequent earthquakes, averaging several $M > 7$ earthquakes per decade for the past century (Singh *et al.*, 1984). The associated Mexican volcanic belt is a unique arc, featuring an oblique orientation with respect to the bathymetric expression of the trench and a complex geochemical record, which includes mantle wedge contamination and several active stratovolcanoes. Large population centers in central Mexico and the Pacific coast are vulnerable to a number of subduction hazard risks, including earthquakes and volcanic eruptions. These characteristics make this region a superb area

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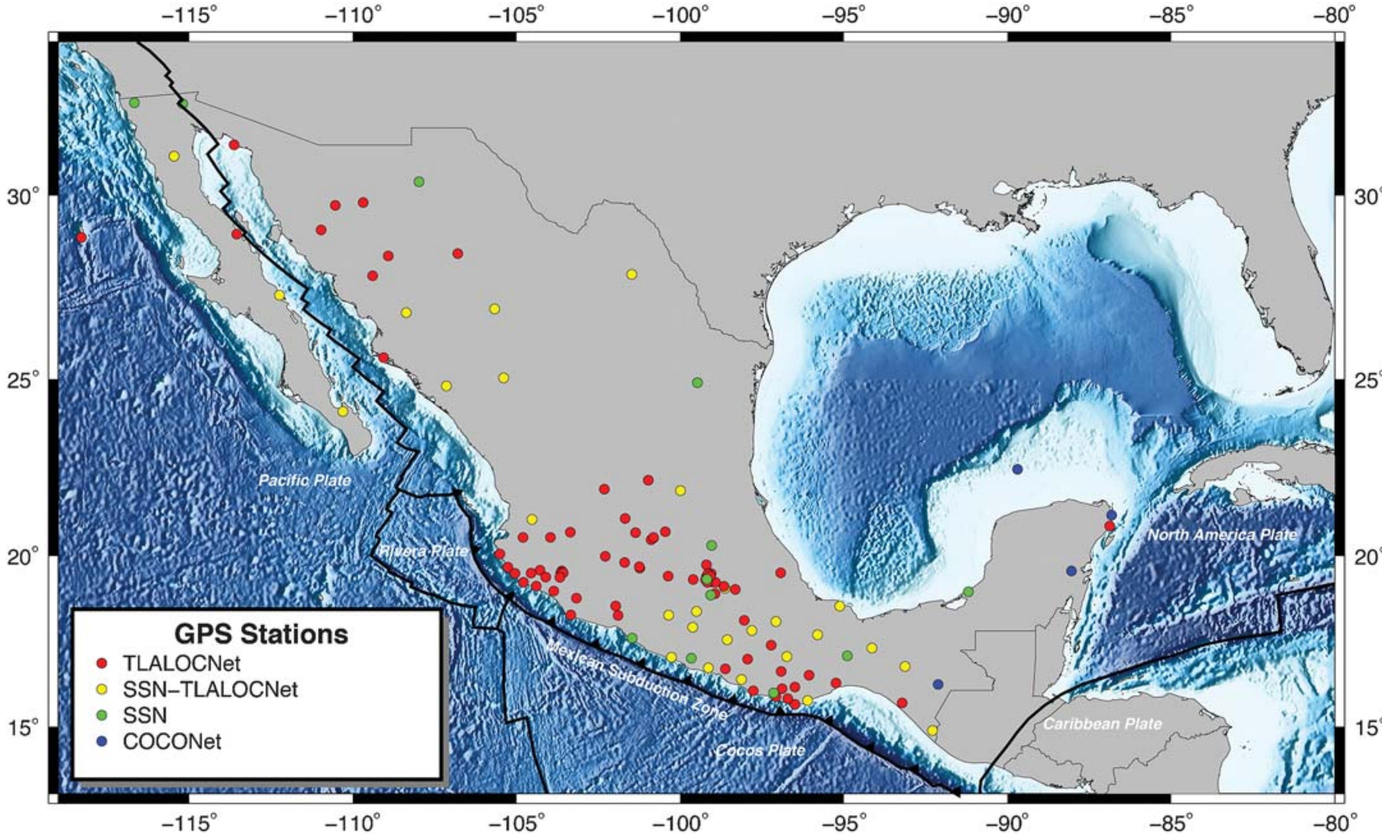



▲ **Figure 1.** Location map for the Trans-boundary, Land and Atmosphere Long-term Observational and Collaborative Network (TLALOCNet), TLALOCNet contributed Servicio Sismológico Nacional (SSN)-TLALOCNet, SSN, and Continuously Operating Caribbean Global Positioning System (GPS) Operational Network (COCONet) currently operational GPS-Met and GPS stations in Mexico.

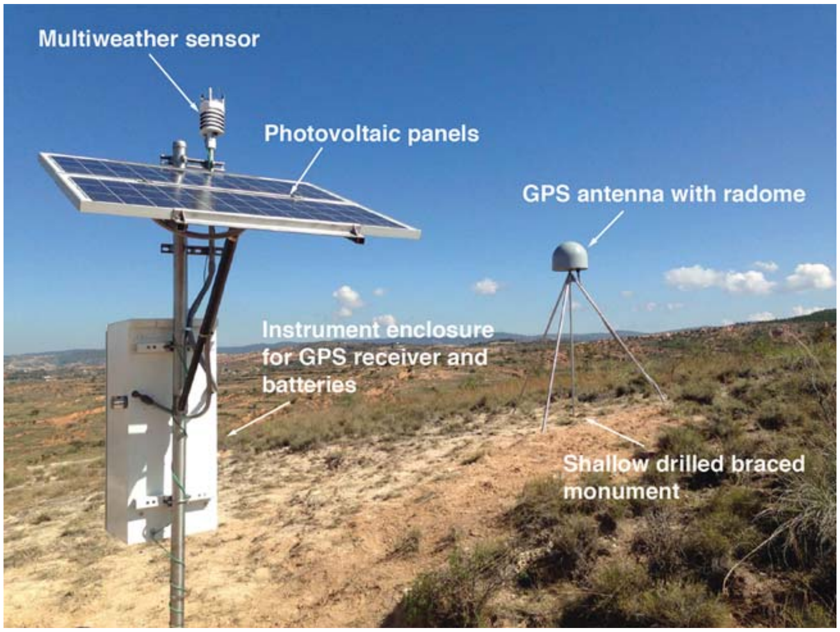
for geodetic and seismic observations of subduction earthquake processes. The study of many of these processes can greatly benefit from continuous geodetic observations hence the development of a nation-wide Global Positioning System (GPS) network that we call TLALOCNet. Moreover, this infrastructure will also be used to augment the existing capability of tsunamigenic earthquake early warning systems in Mexico.

To date, geodetic (primarily from continuous and campaign GPS observations) and seismic measurements have detected a wide range of steady-state and transient deformation phenomena, including slow-slip events every ∼4 yrs in Guerrero ($M \sim 7.5$ equivalent) and every 12–14 months in Oaxaca, tectonic tremor along the majority of the MSZ, postseismic afterslip, and viscoelastic rebound (e.g., Brudzinski *et al.*, 2016; Maury *et al.*, 2016). Future advances in the understanding of the roles of strain accumulation, subduction interface coupling, the various mechanisms of strain release, and its interactions with shallower magmatic systems responsible for volcanic activity within a subduction zone will be enhanced by TLALOCNet.

## RECENT GEODETIC INFRASTRUCTURE DEVELOPMENT IN MEXICO

Since the mid-1990s, campaign and continuous GPS measurements along the MSZ have recorded 4 large subduction earthquakes and recently 2 large intraslab earthquakes and their associated postseismic deformation, at least 11 transient slip events, and secular interseismic strain, representing all phases of the earthquake cycle. Over the last 7 yrs, collaborative GPS studies of these events have resulted in the development of protocols for free and open access to geodetic data. The most recent significant development in these bilateral scientific studies is the construction of the TLALOCNet and the Servicio Sismológico Nacional (SSN)-TLALOCNet, backbone networks in Mexico of collocated continuous GPS and meteorologic stations (cGPS-Met) funded by the United States National Science Foundation (NSF), Mexico's Consejo Nacional de Ciencia y Tecnología (CONACyT) and Universidad Nacional Autónoma de México's Programa de Apoyo a Proyectos de Investigación e Innovación Tecnológica (UNAM-PAPIIT) for the analysis of the earthquake cycle, tectonic processes, land subsidence, and atmospheric processes (Fig. 1).

The combined TLALOCNet and SSN-TLALOCNet continuous GPS-Met networks span most of Mexico and link existing continuous GPS infrastructure in North America (EarthScope Plate Boundary Observatory [PBO]) and similar GPS-Met network distributed across the Caribbean, central and northern South America (Continuously Operating Caribbean GPS Operational Network [COCONet]). TLALOCNet (phase 1; 2014–2017) built and upgraded 40 cGPS-Met sites




▲ **Figure 2.** Photograph of a typical TLALOCNet GPS-Met station (TNNX) in Nochixtlán, Oaxaca.

to the EarthScope PBO standard. The SSN-TLALOCNet (phase 2; 2016–2017) has added 25 more cGPS stations funded through CONACyT. These newly installed geodetic stations, in addition to previously existing cGPS stations, increase our currently operating geodetic infrastructure in Mexico to 104 stations (Fig. 1).

Instrumentation at each TLALOCNet station (Fig. 2) includes a Trimble NetR9 Global Navigation Satellite Systems (GNSS) receiver with L1, L2, and L5 code and phase observations enabled, shallow drilled braced monument built onto a competent rock exposure (or in some cases a rooftop monument design similar to those from COCONet; Braun *et al.*, 2012) with a Southern California Integrated GPS Network (SCIGN) Design 3 style antenna leveling mount, Trimble Choke Ring GNSS antenna, and SCIGN tall radome. Forty percent of the TLALOCNet stations also include a Vaisala WXT520 or WXT536 multiweather sensor that uses the GPS receiver for logging and BINEX real-time data streaming.

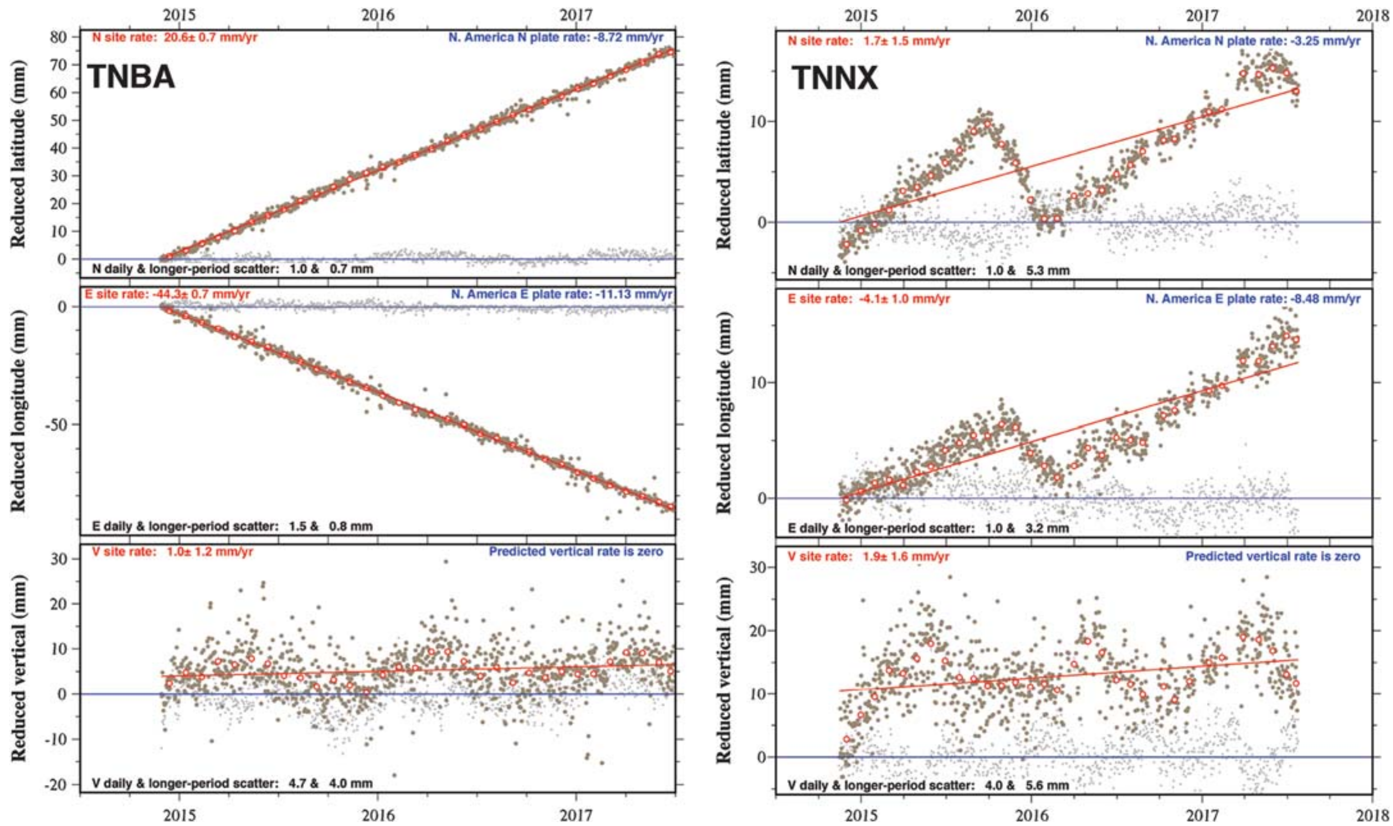
The SSN-TLALOCNet stations instrumentation is mostly Trimble NetR9 receivers, and a smaller number of stations have Trimble NetRS GPS receivers. These installations deploy either Trimble Choke Ring Ti or Zephyr Geodetic II antennas. A subset of the SSN-TLALOCNet station receivers (in Guerrero, Oaxaca, and Chiapas) has been upgraded to multiconstellation GNSS capability and receiver-based Trimble RTX, real-time solution capabilities. Data transmission for most of the TLALOCNet stations depends on cellular networks using Sierra Wireless LS300 cellular gateways; SSN-TLALOCNet and some remotely located TLALOCNet sites use very-small-aperture terminal (VSAT) satellite stations.

## SOLID-EARTH AND SURFACE PROCESSES APPLICATIONS

For solid-earth science, TLALOCNet sustains and enhances continued detailed studies of the earthquake behavior, subduction zone tectonics, and ground subsidence. The MSZ is an ideal natural laboratory for detailed geodetic studies of the subduction earthquake cycle, including coseismic rupture, postseismic fault afterslip and viscoelastic rebound, episodic tremor and slip, and interseismic elastic strain. TLALOCNet provides additional constraints on North America–Pacific plate motion (e.g., DeMets *et al.*, 2014) at a critical transition from oceanic to continental transform faulting and also provides a wealth of observations on the subduction earthquake cycle. In particular, episodic tremor and slip, first discovered a decade ago in Cascadia (Rogers and Dragert, 2003; Dragert *et al.*, 2004; Melbourne *et al.*, 2005) and Japan (Obara, 2002; Obara *et al.*, 2004), are now being studied with the recently enhanced geodetic infrastructure in Mexico to better ascertain the temporal and physical relationship, if any, with the genesis of shallow-thrust earthquakes, which endanger populations living near major subduction zones worldwide.

Recent studies by Graham *et al.* (2015) that use GPS data from stations that are part of TLALOCNet have shown that slow slip below the Guerrero region migrates up-dip into the potentially seismogenic region, presumably accounting for some of the missing slip within the well-described Guerrero seismic gap (Singh *et al.*, 1981). In contrast, slow slip below Oaxaca between 2005 and 2011 occurred mostly down-dip from the seismogenic regions defined by the rupture zones of large thrust earthquakes in 1968 and 1978 and released the entire slip deficit that accumulated in the down-dip region during this period.

Inversions of GPS-derived displacements suggest that large subduction thrust earthquakes in Guerrero, such as the 2014 $M_w$ 7.3 Papanoa earthquake, may be triggered by slow-slip events, either by static stress increases in the hypocentral region or through enhanced weakening of the earthquake hypocentral area. The plate interface in the Guerrero area is highly coupled between slow-slip events, and most of the accumulated strain is released aseismically during the slow-slip episodes (Radiguet *et al.*, 2016); this observation imposes constraints on the mechanical behavior of the Guerrero portion of the MSZ and has important implications for long-term earthquake recurrence in this region. Figure 3 shows two examples from different tectonic environments of estimated position time series for TNBA (Baja California) and TNNX (Oaxaca) relative to North America plate motion; these examples show typical performance of TLALOCNet stations, in which daily and long-term scatter on the horizontal components ranges from 1.0 to 1.5 mm and 0.7 to 5.3 mm, respectively, and from 4.0 to



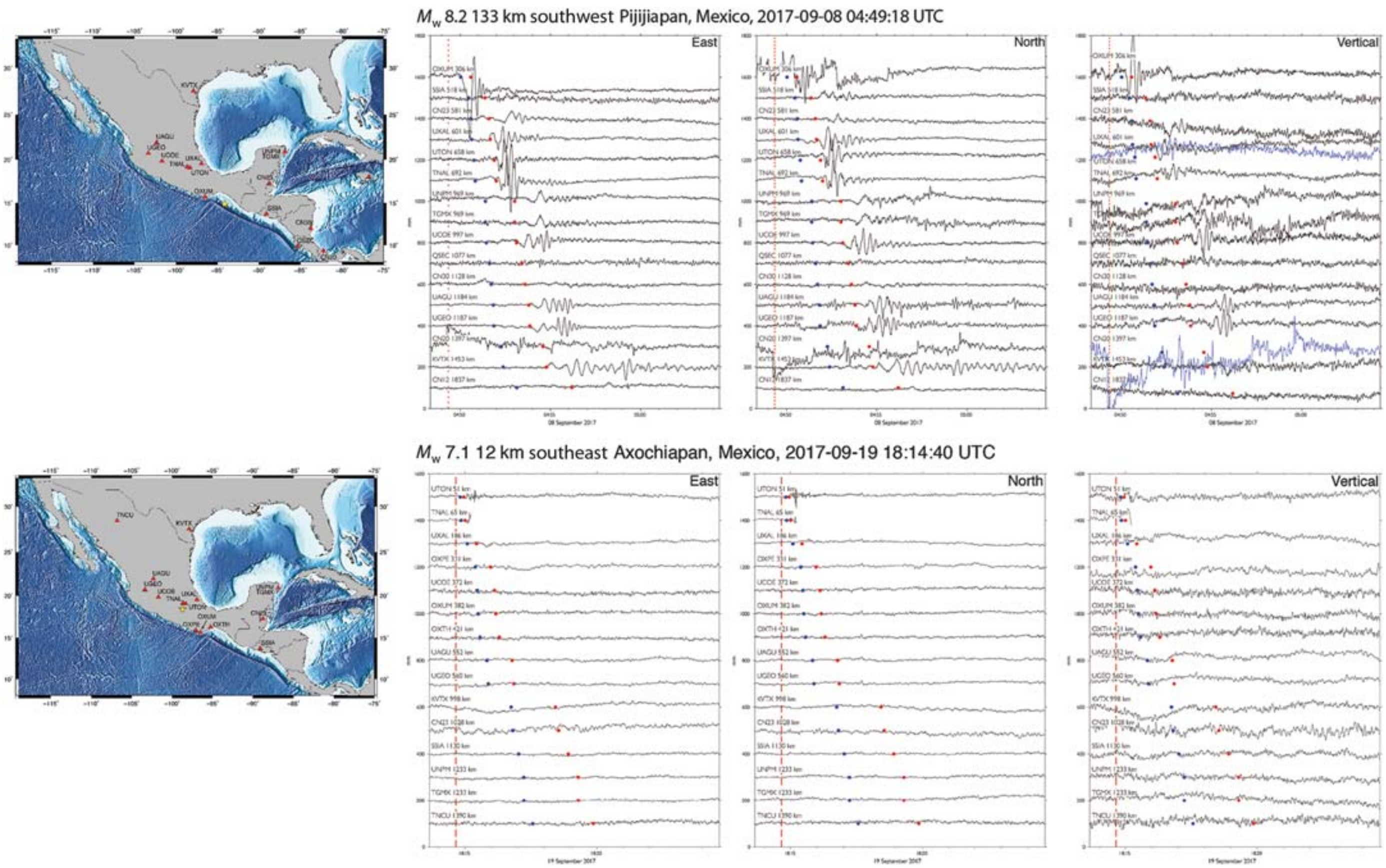

▲ **Figure 3.** Examples of TLALOCNet position time series relative to North America plate motion for stations (left) TNBA in Baja California and (right) TNNX in Oaxaca located at contrasting tectonic environments that show typical performance of TLALOCNet stations. Dark gray dots show daily IGS08 site positions relative to North America and the red circles show 30-day-average site positions. Small light gray dots show daily common-mode noise, which is estimated from the position time series of stable sites far from tectonically active regions and is subtracted from the measured daily site coordinates. Red lines are the best-fitting site velocity, whereas blue lines are predicted plate
14 velocity from MORVEL (DeMets, 2010). TNBA located in Bahía de Los Angeles, Baja California, depicts the steady velocity of the Baja California peninsula. On the other hand, the TNNX time series show common behavior of the Oaxaca region with superimposed signals from the strain accumulation due to the Cocos plate subduction and the interseismic strain release due to slow-slip events, which occur at periodic intervals (~12 month) in this region (e.g., Graham *et al.*, 2015).

4.7 mm and 4.0 to 5.6 mm for the daily and long-term vertical-component scatter, respectively.

During the recent 7 September 2017 $M_w$ 8.2 Tehuantepec and 19 September 2017 $M_w$ 7.1 Morelos-Puebla earthquakes, TLALOCNet and SSN-TLALOCNet stations provided unique observations including 15 s, 1 Hz, and 5 Hz high-rate data from stations in the Tehuantepec isthmus and southern-central Mexico regions. These observations are being used for waveform analysis, inversions of coseismic offset, fault slip distribution, and other analyses of related rupture processes. Two examples of the real-time capabilities of the network during large earthquakes are displayed in Figure 4. This figure shows real-time 1—sample/s precise point positioning
3 displacement in the east, north, and vertical directions for the 8 September 2017 $M_w$ 8.2 Tehuantepec and the 19 September 2017 $M_w$ 7.1 Morelos-Puebla earthquake events derived from 1-Hz GPS streams from TLALOCNet, COCONet, and other GPS stations in the region.

The $M_w$ 8.2 Tehuantepec and $M_w$ 7.1 Morelos-Puebla events on 8 and 19 September 2017, respectively, provided a good test for overall network performance and data transmission during a disruptive event. Typical real-time data latencies for data streams during normal operational conditions range from 1500–3500 ms for VSAT-equipped stations to 1200–1500 ms for cellular equipped stations and 50–500 ms for stations with broadband Internet access.

Because of budget constraints, a large number of TLALOCNet stations rely on cellular modems for daily and real-time data transmission. A smaller number of stations have access to broadband Internet service, with some using a point-to-point radio link. All SSN-TLALOCNet and those stations in remote locations such as Guadalupe (GUAX) and Arrecife Alacrán (CN26) islands rely on VSAT satellite ground stations for data transmission. During the $M_w$ 8.1 Tehuantepec and $M_w$ 7.1 Morelos-Puebla earthquakes, more than 95% of the network stations were logging data, and in these instances all of the VSAT stations operated properly, as did those with broadband access (see Fig. 4). Although cellular links were mostly operational, high cellular traffic right after the event prevented a few from maintaining real-time data streams. In



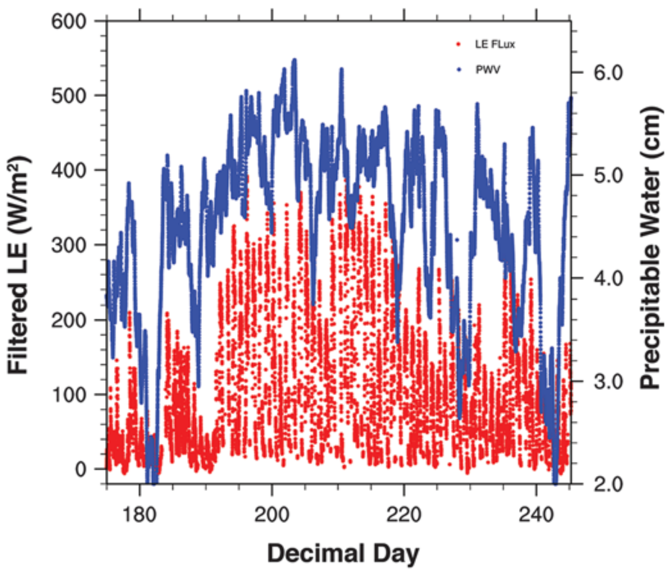

▲ **Figure 4.** Real-time 1—samples/s precise point positioning displacement in the east, north, and vertical directions for (top) the 8 September 2017 $M_w$ 8.2 Tehuantepec and (bottom) the 19 September 2017 $M_w$ 7.1 Puebla earthquakes observed from 1-Hz GPS streams from TLALOCNet, COCONet, and other GPS stations in the region. Vertical red lines show event origin times. Blue dots indicate predicted *P*-wave arrivals and red dots the *S* wave as calculated using the International Association of Seismology and Physics of the Earth's Interior (IASPEI) 1D earth velocity model. Distances beside the site name indicate distance from the epicenter. Time series have been offset vertically for comparison. For the $M_w$ 8.2 event, the vertical traces for UTON and CN20 are in blue for clarity. All solutions were generated using the Trimble RTX processing software.

all cases, automated file transfer protocol (FTP) of 15 s daily files and 1 hr, 1 Hz files resumed a few hours after the event. Direct FTP downloads for 5-Hz high-rate data, which is usually retrieved on an as-needed case-by-case basis was also possible within 24–48 hrs after the event. In the case of TNAL (Fig. 4, bottom panel), the radio link was lost seconds after the 19 September 2017 earthquake as a result of the point-to-point radio antenna motion and resulting misalignment. Overall, the availability of cellular transmission proved better than expected during a disruptive event, and while cellular is not as reliable as VSATs for data transmission, it remains a viable option to support remote station telemetry, if lower cost and simpler installation logistics are desired.

## INTERDISCIPLINARY CAPABILITIES OF THE TLALOCNET INFRASTRUCTURE

One strategy for mitigating the high cost of developing and maintaining high-precision observational networks is to have a multipurpose and interdisciplinary approach for the use of the available sensor data. TLALOCNet generates a suite of measurements to address multiple scientific and operational objectives by providing surface observations of wind speed and direction, barometric pressure, air temperature, humidity, and precipitation collocated with GPS/GNSS observations, which can be used to derive high-frequency (5–30 min) total column precipitable water vapor (PWV) estimates (Rocken *et al.*, 1993) for operational numerical weather forecasting and targeted atmospheric science studies (Adams *et al.*, 2013).

TLALOCNet observations provide critical monitoring across large areas of Mexico, with broad societal implications. Over multidecadal time scales, climate models predict that the currently arid parts of northern Mexico and the southwestern United States will become even drier (Seager *et al.*, 2007; Karmalkar *et al.*, 2011), though individual monsoonal convective storms may actually become more intense (Luong *et al.*, 2017). These regions are at the northernmost edge of a climate hot spot extending into Central America, where some of the largest global increases in surface air temperature and decreases in rainfall are projected to occur by the end of the twenty-first




▲ **Figure 5.** Time series of precipitable water vapor (PWV) from station TNHM in Hermosillo, Sonora, and surface latent heat flux at Rayón, Sonora, measured during the North American monsoon GPS Hydrometeorological Network 2017.

century (Maloney *et al.*, 2014). The northwestern sector of TLALOCNet is designed specifically to provide constraints on atmospheric water vapor over decadal periods within the core North American monsoon region when coupled with constraints from moisture source regions enabled through COCONet, spanning the Caribbean and Central America (Braun *et al.*, 2012). Data from both networks together permit study of the covariance of moisture in the monsoon and source regions on subdaily to century time scales.

Debates over moisture sources for the North American monsoon area in northwestern Mexico and the southwestern United States have resurfaced in recent years. The role of terrestrial surface water vapor flux is a global problem and recent studies have argued for a greater role of Gulf of Mexico, Caribbean, and terrestrial sources in monsoon convective precipitation and regional terrestrial moisture recycling (Dominguez *et al.*, 2008; Hu and Dominguez, 2015; Dominguez *et al.*, 2016). With TLALOCNet and COCONet providing critical observational infrastructure and high temporal resolution, PWV estimates during any weather conditions, new insights may be gained. This GPS-Met backbone infrastructure along with intensive campaigns provide a unique opportunity to advance on quantifying the North American monsoon water vapor source regions, better understanding short-term moisture transport mechanisms, the topographic influence on the diurnal cycle of convection, the formation of mesoscale convective systems, as well as the impact of *in situ* total column water vapor observations on short-term forecasts of monsoon rainfall events (Adams *et al.*, 2014; Serra *et al.*, 2016).

Recently, TLALOCNet and SSN-TLALOCNet served as a GPS-Met backbone and catalyst of more focused observational experiments; for example, the North American monsoon GPS Hydrometeorological Network 2017 consisted of a 3-month campaign in northwestern Mexico during the monsoon season. The northwestern Mexico and Baja California TLALOCNet sites, in addition to 10 campaign GPS meteorological stations, were used to infer large-scale water vapor in the region. Initial results show the evolution of PWV versus latent heat flux in the Hermosillo, Sonora, area (Fig. 5). This figure indicates that seasonally latent heat fluxes (i.e., surface evaporation) and PWV evolve together, although at higher frequencies the relationship becomes less well correlated. Demonstration that PWV and surface latent heat flux are correlated across northwestern Mexico was made possible by TLALOCNet campaign GPS during the 2017 monsoon season. Based on our new campaign observations, we suggest that local terrestrial surface evaporation plays a secondary role in providing water vapor to the atmospheric column.

In addition to tropospheric studies, space weather has become an important hazard assessment element for modern society. TLALOCNet and SSN-TLALOCNet data are a key source of information for space weather studies in Mexico. Earth's ionosphere is very sensitive to space weather phenomena. Vertical total electron content (TEC) is one of the main ionospheric parameters used to estimate the ionosphere state. TEC is the quantity of electrons in a column of unit cross section (from a GPS satellite to the ground; Davies and Hartmann, 1997). TEC is calculated using phase and code delays of GPS signals received by dual-frequency ground receivers. The Mexican Space Weather Service performs continuous TEC monitoring over Mexico using TLALOCNet and SSN-TLALOCNet data in near-real time. Results have already shown a number of distinctive features over Mexico. For example, Gonzalez-Esparza *et al.* (2017) and Sergeeva *et al.* (2017) have identified systematic TEC variations as well as irregular TEC changes during space weather disturbances. Even though TEC values can be obtained from global ionospheric maps produced by the International GNSS Service, global and local phenomena of different origin and scale impact the state of the ionosphere of a particular region on Earth. Consequently, GPS data from local networks are of paramount importance, especially for near-real-time monitoring. These advantages provided by a regional GPS network in Mexico have been shown in Sergeeva *et al.* (2017).

## TLALOCNET DATA ARCHIVE

In 2010, investigators responsible for building and maintaining much of Mexico's GPS research infrastructure over the past 20 yrs convened a workshop jointly sponsored by NSF and CONACyT to discuss the scientific rationale for upgrading and integrating GPS stations in Mexico into a state-of-the-art continuous GPS-Met network for basic and hazards science research in atmospheric, climate, and solid-earth research (Cabral-Cano *et al.*, 2010). One of its outcomes was the memorandum of understanding (MOU) for open GPS data sharing and collaboration, which has now been transformed into a binding legal agreement. The spirit of the MOU for

GPS data exchange in Mexico is realized and implemented through the TLALOCNet data archive that serves as a collection and distribution point (see Data and Resources) for TLALOCNet data, metadata, and derived data products.

The TLALOCNet archive provides open and freely available raw GPS data (as well as GNSS data for a subset of these stations), GPS-derived PWV estimations, surface meteorology measurements including surface rainfall, real-time data streams, time series of daily positions, and a station velocity field to support a broad range of geoscience investigations. This data center is based on UNAVCO's Dataworks-GSAC software
5 (Boler *et al.*, 2015) and can work as part of UNAVCO's seamless archive for discovery, sharing, and access to data. There are currently 104 stations archived using the same protocols and structure as the UNAVCO and other COCONet regional data centers. Through this data archive, the geodetic and seismic communities have the capability of accessing data from academically operated Mexican GPS-Met sites. This archive interface provides a fully queryable and scriptable GPS and meteorological data retrieval point. Additionally, real-time 1 Hz streams from selected TLALOCNet stations are available in BINEX and RTCM v.3.1 formats via the Networked Trans-
6 port of RTCM via Internet Protocol.

## PLANNED EXPANSION FOR THE GEODETIC NETWORK

7 Although the rate of growth for the geodetic infrastructure in Mexico has increased substantially in the last years, the GPS station density is still less than adequate to serve the broad science and operational objectives envisioned during TLALOCNet's inception. The next development phase for TLALOCNet includes collocation of GPS instrumentation at existing SSN sites (at this time, there are ~20 SSN stations that are without GPS) and the addition of GPS infrastructure to existing Red Sísmica Mexicana stations currently in initial development by SSN. This already funded expansion of the geodetic infrastructure in Mexico will add another 45 stations, expanding the installed capability to ~180 GPS stations by 2020, and will achieve more complete coverage across Mexico, with GPS stations located less than 200 km from each other (Pérez-Campos *et al.*, 2018).

## DATA AND RESOURCES

Observational, navigational, and meteorological RINEX files collected by the Trans-boundary, Land and Atmosphere Long-term Observational and Collaborative Network (TLALOC-
8 Net) are open and freely available at the TLALOCNet archive (http://tlalocnet.udg.mx). Real-time data stream broadcasts from some of the TLALOCNet stations are available in both BINEX and RTCM (v.3.1) formats via the Networked Transport of RTCM via Internet Protocol (NTRIP). Access to real-time streaming data must be requested by emailing rtgps@unavco.org. UNAVCO Streaming Global Positioning System (GPS) Data Policy is available at https://www.unavco.org/community/policies_forms/data-policy/DataStreamingPolicy.pdf. Maps for this publication were made using Generic Mapping Tools v.5.4.2 (http://gmt.soest.hawaii.edu; Wessel and Smith, 1998).

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