RIESGO: A NEW SEISMOGEODETIC NETWORK SPANNING THE STATES OF GUERRERO AND OAXACA IN THE MEXICAN SUBDUCTION ZONE

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Resumen

Una red sismogeodésica de veinte estaciones fue instalada a lo largo de la zona de subducción de los estados de Guerrero y Oaxaca (Red Sismoeodésica de Guerrero y Oaxaca, RIESGO). El objetivo de la red es monitorear de forma continua la deformación tectónica de esta parte de la zona de subducción de México. Asimismo, la red sismogeodésica tiene como misión estimar la magnitud de grandes terremotos, con base en la longitud de la ruptura. La red se construyó en dos etapas. Los primeros quince instrumentos se instalaron en el estado de Guerrero y abarcan la brecha sísmica de Guerrero. Este segmento de la zona de subducción no ha experimentado terremotos de magnitud $Mw > 7$ desde principios del siglo XX y ha sido objeto de intenso estudio durante muchos años. La segunda fase de RIESGO se instaló en el estado de Oaxaca, donde cinco instrumentos cubren una gran parte de la zona de subducción. RIESGO genera un flujo de datos de aceleración muestreados a 200 Hz. También, genera datos geodésicos de alta precisión muestreados a 2 Hz, como resultado de la aplicación de una corrección RTX y un filtro de Kalman, que utiliza los datos del acelerómetro como referencia para corregir las señales geodésicas en tiempo real. Una comparación entre los datos geodésicos de alta precisión en tiempo real y los datos procesados posteriormente con el programa GAMIT, muestra resultados prácticamente idénticos. Estos resultados respaldan la utilidad de RIESGO para el monitoreo en tiempo real de la zona de subducción. Hasta la fecha, el único gran terremoto en la zona de subducción mexicana que ha sido registrado por RIESGO es el terremoto de Acapulco del 8 de septiembre de 2021 (*Mw* 7.1). Este evento se registró cuando la red sismogeodésica se encontraba en sus etapas iniciales. Sin embargo, el sismo fue registrado por la estación ubicada en la ciudad de Acapulco, cerca del epicentro. El sismograma de desplazamiento registrado muestra una deformación cosísmica de aproximadamente 20 cm, similar a los resultados obtenidos posteriormente por otros autores mediante interferometría satelital (Interferometric Synthetic Aperture Radar, InSAR), modelado de la fuente y con base en un registro mareográfico. Estos resultados iniciales demuestran que la red sismogeodésica es una herramienta robusta y fiable para monitorizar la zona de subducción en tiempo real y a largo plazo.

Abstract

A seismogeodetic network of twenty stations has been installed along the subduction zone of the states of Guerrero and Oaxaca (RIESGO). The purpose of the network is to continuously monitor the tectonic deformation of the coast along the Mexican subduction zone. Also, the mission of the seismogeodetic network is to estimate the magnitude of large and great earthquakes based on the length of the fault ruptured. The network was built in two stages. The first fifteen instruments were installed in the state of Guerrero and straddle the Guerrero seismic gap. This segment of the subduction zone has not experienced earthquakes of magnitude *Mw* > 7 since the turn of the 20th century and has been the source of intense study for many years. The second phase of RIESGO was installed in the state of Oaxaca, where five instruments cover a large fraction of the subduction zone here. RIESGO outputs an acceleration stream sampled at 200 Hz. A high precision geodetic stream is produced at two samples per second, as a result of the application of an RTX correction and of a Kalman filter that uses the accelerometer data as ground truth to correct the geodetic signals in real time. A comparison between the high-precision geodetic data in real time and the post-processed data using the program GAMIT shows practically identical results. These results support the use of RIESGO in real time monitoring of the subduction zone. To date, the only large earthquake in the Mexican subduction zone recorded by RIESGO is the 8 September 2021 Acapulco earthquake (*Mw* 7.1). This event was recorded when the seismogeodetic network was in the initial stages. Nevertheless, it was well recorded by the station located in the city of Acapulco, onshore of the epicenter. The recorded displacement seismogram shows a co-seismic deformation of ~20 cm, similar to the results obtained later by other authors using satellite interferometry (Interferometric Synthetic Aperture Radar InSAR), modeling of the source, and data from a tide gauge station. These initial results show that the seismogeodetic network is a robust and reliable tool to monitor the subduction zone in real time and in the long term.

1. Introduction

The Guerrero gap has attracted attention for many years, as no major earthquakes (*Mw*>7.5) have occurred along the subduction zone since the early 20th century (Figure 2) (Kelleher et al., 1973; Singh et al., 1981; Suárez et al., 1990; Kostoglodov et al., 2003; Radiguet et al., 2012; Plata-Martinez et al., 2021; Cruz-Atienza et al., 2025). Hence, this segment of the Mexican subduction zone is expected to produce eventually a major earthquake. The seismic energy accumulated in the Guerrero gap is estimated to be large enough to produce potential earthquakes of magnitude between *Mw* 8.1 to 8.4). (e.g., Singh and Mortera, 1991; Valdés-González and Novelo-Casanova, 1998) (Figure 2).

In order to monitor this segment of the subduction zone, presumed to be of high seismic potential, a seismogeodetic network (Red Sismogeodésica de los Estados de Guerrero y Oaxaca (RIESGO) was installed to continually monitor the seismicity and the short and long-term deformation of the Mexican subduction zone. From a civil protection perspective, there are two key objectives in the design of RIESGO. The first one is to estimate the size of very large earthquakes, larger than *Mw* ~7.5, for which the seismic instrumentation of the Seismological Service of Mexico (SSN, Servicio Sismológico Nacional, in Spanish) typically saturates. The advantage of seismogeodetic data over broad-band seismographs in the estimation of magnitude of large and great earthquakes has been extensively demonstrated (e.g., Crowell et al., 2013; Melgar et al., 2013; Chen et al., 2018).

The concept behind this is that, based on the high-quality and high frequency seismogeodetic signal, the deformation of the subduction zone along the coast can be recovered in real time. The estimated fault length based on the deformation of the coast is used as the key parameter to estimate magnitude (*e.g.,* Blewitt et al., 2006). The fault length can be calculated in real time, so magnitude can be estimated within a few seconds after the origin time. Otherwise, the magnitude estimate has to wait for several minutes, until teleseismic data is retrieved. In addition, the length of the fault may be used to estimate areas of potential damage in communities along the coast and neighboring regions.

The second objective, from a civil protection outlook, is to estimate the size of a potential tsunami produced by a major subduction earthquake. Using the deformation of the coast that is observed in real-time by RIESGO, the displacement on the fault defining the interplate contact may be estimated. This information is used to calculate the deformation of the ocean floor and, in turn, calculate the areal extent and inundation height of the potential tsunami. This project is under development and the results would be provided to the Center for Tsunami Alerts, which is under the responsibility of the Mexican Navy (CAT, Centro de Alerta de Tsunamis, in Spanish). The network is relatively low-cost as it operates automatically and the communication links are provided free of charge by CAT.

From a scientific perspective, the network was designed to provide continuous monitoring of the deformation of the coastline, on this portion of the Mexican subduction zone. The geometry and maximum seismogenic depth of the interplate contact in the Middle American trench shows that the largest vertical deformation during subduction events takes place near the coastline (Suárez and Sánchez, 1996). Thus, to capture the pre-seismic, co-seismic, and post-seismic deformation of the coast in real time, RIESGO was built on rocky outcrops as close to the coast as possible. This requirement presented a challenge to find the better suited locations that meet the following criteria: hard rock siting, vicinity to the coastline, sky view without obstruction, and the absence of radio frequency interferences and of reflective surfaces, to avoid signal multipathing. The location of the sites was also designed to complement the existing geodetic stations installed by other projects and the data is being used jointly.

2. Network Description

RIESGO is installed along the coast of Guerrero and Oaxaca in southern Mexico. It consists of twenty stations that have an accelerometer and a GNSS receiver (Figure 1). The accelerometer data is used as ground truth to correct errors in the GNSS receivers using a recursive Kalman filter. As explained below in more detail, the Kalman filter estimates a correction of errors present in the geodetic data to produce a real-time displacement time signal with a 2 Hz frequency. RIESGO was built in two stages. The first phase was designed to monitor the Guerrero seismic gap with fifteen instruments.

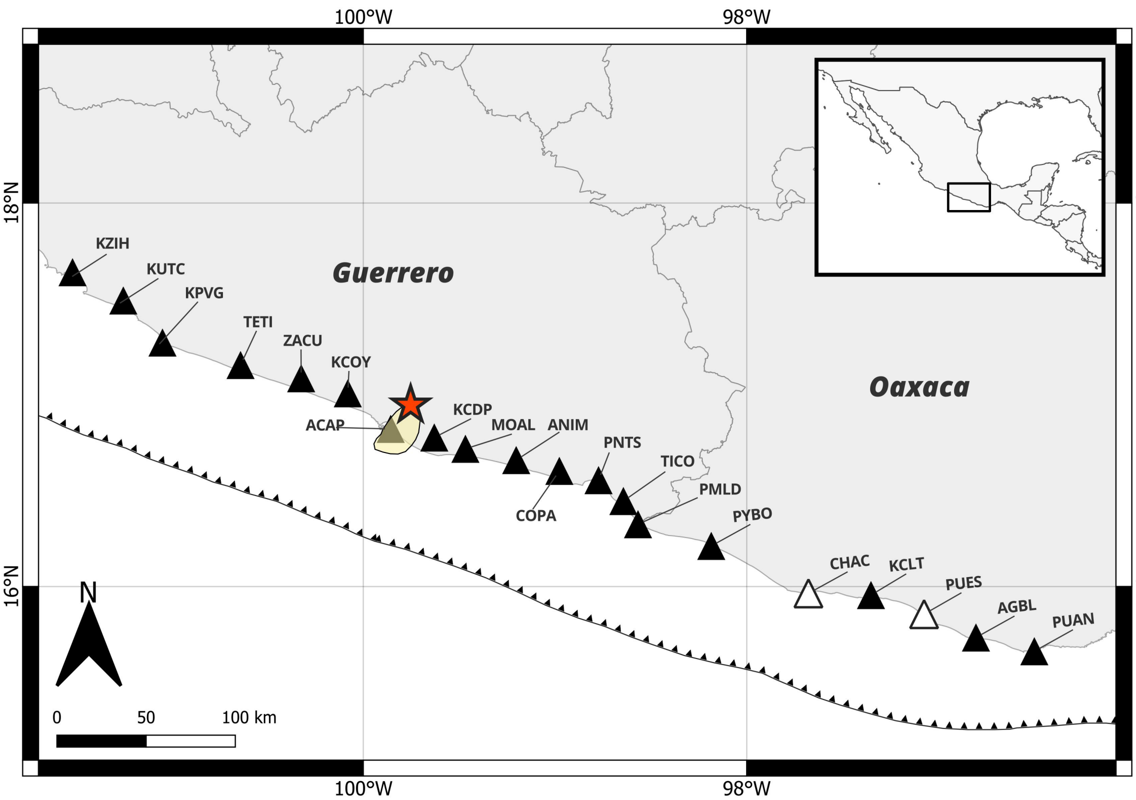


Figure 1. Location of the twenty stations of the Seismogeodetic Network of Guerrero and Oaxaca. The black triangles are operational stations and the two white triangles are the sites that are being built. The rupture zone of the 8 September 2021 Acapulco earthquake is shown as a yellow area. The red star is the epicenter.

In the second phase, RIESGO was extended to the southeast to include the state of Oaxaca, using five additional stations to monitor this part of the subduction zone (Figure 1). At the time of writing this manuscript, permits for two of the five new sites in Oaxaca are still under negotiation; the installation of the twenty stations is expected to conclude in early 2026. The seismogeodetic stations in Oaxaca cover the Ometepec segment of the subduction zone, located at the border of the states of Guerrero and Oaxaca (Figures 1 and 2). This region has been identified as a region of high seismic potential (Singh et al., 1981; Nishenko and Singh, 1987; Mendoza and Martínez-López, 2022; Yan et al., 2022). This segment of the subduction zone near Ometepec region, exhibits an unusually high rate of seismicity, which has been attributed to presence of fluids in the subduction zone (Legrand et al., 2024).

Two earthquakes of moderate magnitude (*Mw* 6.9, 7.0) took place in Ometepec within five hours of each other on 7 June 1982 (Astiz and Kanamori, 1984) (Figure 2). More recently, an earthquake took place in the same region on 20 March 2012 (*Mw* 7.5) (UNAM Seismology Group, 2013). The Oaxaca subduction zone exhibits a complex behavior of seismic ruptures of variable length. Quasi-repeater earthquakes have occurred in recent years where a sequence of four earthquakes took place in 1928 (Singh et al., 2024; Garza-Girón et al., 2025). The region where the event of October 1928 occurred is the only one where no large earthquakes have taken place since, indicating an area that is potentially seismically locked (Garza-Girón et al., 2025; Martínez-López, et al., 2025). No great earthquakes have occurred in the last 96 years, suggesting high accumulation of elastic strain that may generate potentially an earthquake of magnitude *Mw* 7.8.

A great earthquake, *Mw* 8.6, ruptured this segment of the Oaxaca subduction zone in 1787. (Suárez and Albini, 2009; Suárez et al., 2020). This event is the greatest earthquake recorded in the Middle American subduction zone and underlines the variable rupture behavior of under thrusting, interplate events in this region. This seismically complex region in the Oaxaca subduction zone is now covered by seismogeodetic stations of RIESGO in Oaxaca and complements the other seismic and geodetic instruments installed by other agencies.

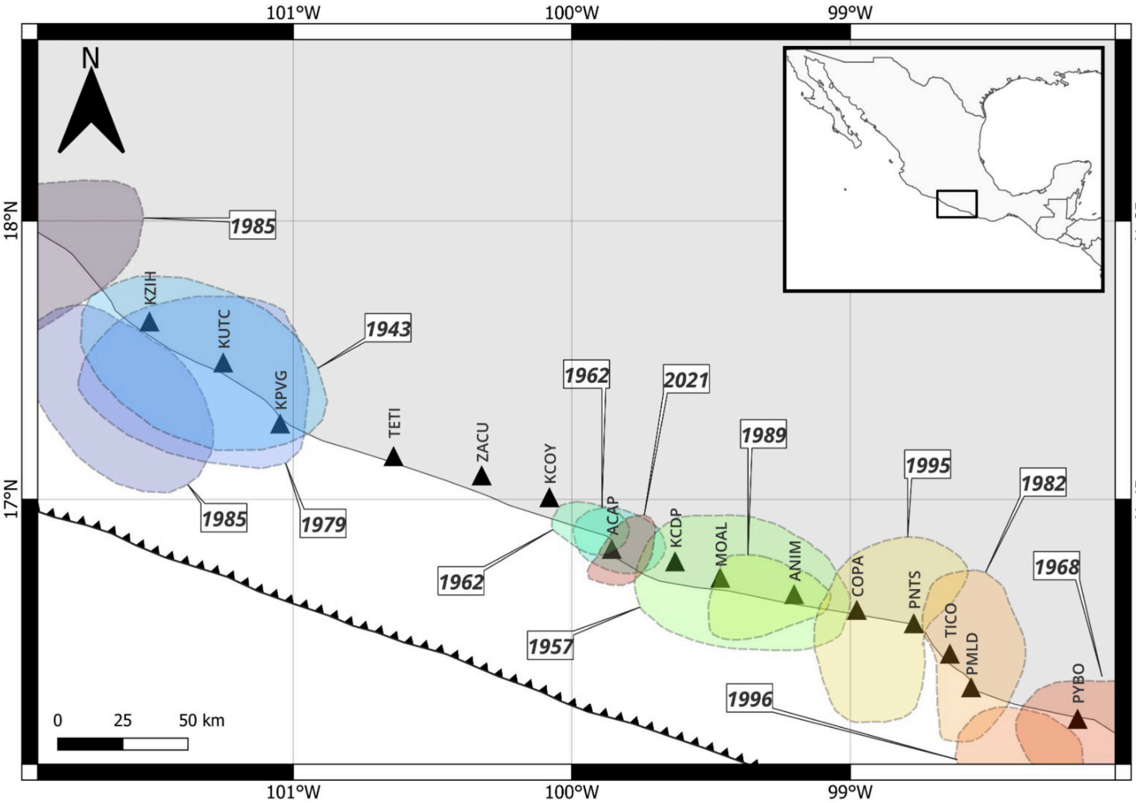


Figure 2. Stations of the Seismogeodetic Network of Guerrero-Oaxaca (triangles) shown together with the rupture areas of the major earthquakes in the region (shaded areas). The dentate line represents the Middle American trench. The Ometepec area is where the 1982 earthquake took place, near the PMLD station and the 1982.

3. Instrumentation and Data Flow

3.1 Instruments Used in RIESGO

The Trimble Kestrel SeismoGeodetic System, SG160-09 was the instrument selected for RIESGO (Passmore et al., 2014). The instrument combines seismic recording of a forced-balance triaxial accelerometer with a 24-bit A/D converter, with a 336-channel GNSS receiver, which tracks the constellations GPS, Galileo, GLONASS, BeiDou, and QZSS. The receiver incorporates GNSS Precise Point Positioning (PPP) using Trimble RTX technology with satellite clock and orbit corrections delivered in real time over the L-Band signal. The

Kestrel system combines the GNSS and the acceleration measurements using the Kalman filter algorithm to create a high rate (200 Hz), real-time displacement with sufficient accuracy and very low latency for earthquake analysis and crustal deformation studies.

The accelerometer data is sampled continuously at 200 Hz. The data stream from the GNSS receiver is corrected using the RTX (Real-Time eXtended) protocol in real time. The RTX protocol delivers real-time, high-accuracy satellite ephemerides to GNSS stations. The correction is a high-precision positioning technique developed by Trimble Inc. that improves raw satellite positioning without requiring a nearby base station. Instead of relying on local differential corrections (like RTK), RTX uses a global network of reference stations and precise satellite orbit and clock models delivered via satellite. The RTX protocol corrects the variations in orbital ephemerides of the satellites, using the data collected by a global network of ground tracking stations, and delivering high-accuracy satellite corrections to the GNSS receivers in real time via satellite, directly to the antenna of the Kestrel instruments.

The GNSS data, that includes the RTX correction, is passed through a Kalman filter, which uses the accelerometer data in real time as the ground truth for displacement of the ground. A Kalman filter is a recursive algorithm used to estimate the position determined by the GNSS instruments. It works in two repeating steps: a prediction, where it uses the accelerometric data to forecast the next state, and an update, where it corrects the position predicted by the GNSS data using these new observations and weighting them according to their uncertainties. Mathematically, it assumes Gaussian noise, producing an optimal estimate in the least-squares sense.

The result is a real-time, data stream of high precision ground motion data, which is transmitted via the satellite links to the central station in Mexico City. The corrected geodetic data is delivered in a 2 Hz data stream (Figure 3). The Kestrel also generates three channels of error estimates. In order to have the capability for post processing the raw GNSS data using different programs, the instruments upload the raw data at the end of the day to an FTP server to the central facility in Mexico City. This allows to process the raw data *a posteriori* to potential users using the program of their choice. Below, we show the comparison between the post-processed data using the program *GAMIT7GLOBK 10.71* and the output of the Kalman filter.

GAMIT is part of the GAMIT/GLOBK package developed at the Massachusetts Institute of Technology (MIT). This software produces high-precision GNSS data. It uses the corrections of satellite orbits and clocks, atmospheric delays, and tropospheric and ionospheric effects determined by various agencies several weeks after the data is collected. Based on these corrections, *GAMIT* performs a least-squares adjustment of the data.

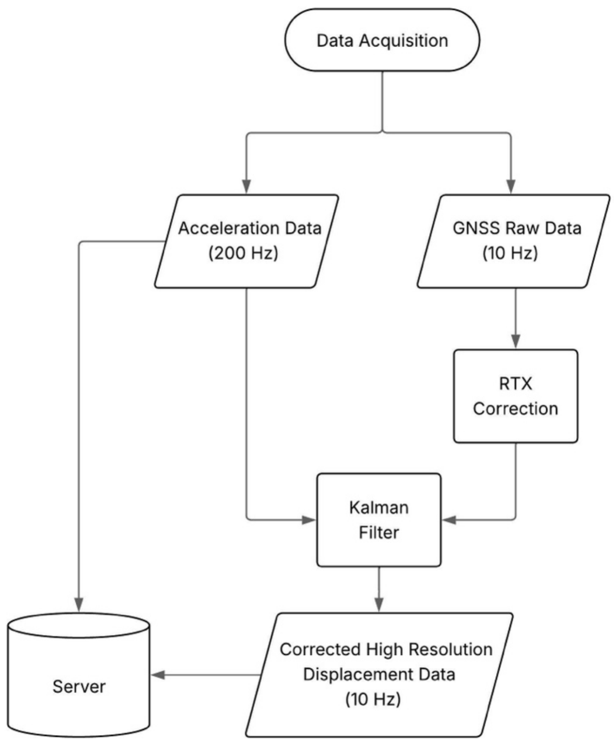


Figure 3. Data flow of the Kestrel seismogeodetic instrument. The acceleration data is sampled at 200 Hz. The incoming GNSS stream is corrected by the RTX protocol and passed through the Kalman filter to obtain a stream of high-quality, real time geodetic data.

3.2 Communications

The locations necessary for this type of network are sites as close to the coastline as possible and anchored on rock. In most cases, the locations selected are relatively isolated and lack internet and telephone connectivity. Also, in most cases, there is no electricity. Therefore, an autonomous communications system was needed to provide reliable real-time and continuous communications based on low power transmitters.

A satellite internet terminal called UNI 3500, manufactured by Hughes Communications, was selected. It is a rugged and compact unit with very low power consumption, capable of sending and receiving IP packets via Ethernet. During the tests conducted in the SSN, the UNI 3500 terminals proved to be a robust and reliable communications link in real time. The sampling of the geodetic signals and of the error channels was reduced from the default 10 Hz to 2 Hz. This sampling rate is sufficient for the scientific purposes of this project and reduces the bandwidth demand on the satellite platform.

The satellite used by the UNI 3500 system is called MEXSAT. MEXSAT provides the communications link on an L-Band platform that is of exclusive use for the military and security services of Mexico. The Mexican Navy, considering that this project contributes to their responsibilities of providing timely tsunami warnings and that it improves the capability of estimating the magnitude of great earthquakes in the subduction zone, generously allowed the use of their platform on the MEXSAT satellite. These satellite internet links provide reliable and effective communication to the central facility at the Instituto de Geofísica, UNAM, in Mexico City. Figure 4 shows a photograph of a typical RIESGO station and its different components.

Figure 4. Seismogeodetic station *Playa Banco de Oro* (PYBO) in the state of Oaxaca (Figure 1). On the vault cover is the solar panel that independently feeds the station. On top of the concrete column the GNSS antenna is protected by a *radome* and on the side of the column is the UNI 3500 L-Band internet terminal (left). The *radome*, short for radar dome, is a protective enclosure that protects the GNSS antenna while allowing electromagnetic signals (radio, GNSS, radar) to pass through with minimal distortion. The concrete vault hosts the Kestrel seismogeodetic instruments, the ethernet switch, the batteries, and the solar charge controller (right).

3.3 Central Recording Facility

The data from the seismogeodetic network are transmitted via the MEXSAT satellite and downloaded at the hub of the national institution that operates the Mexican Satellite System. From there, the data are sent to the Instituto de Geofísica, UNAM via a dedicated internet connection. At UNAM, the data are received in real time by the main server, which stores them on hard disk, and sends it to a second server (mirror). All data are ultimately stored on a high-capacity storage server, allowing access to potential users.

The second server is continuously performing state-of-health analyses using software produced in house, to evaluate the performance of RIESGO. As an example, a helicorder-type record is refreshed every five minutes to monitor gaps in the data from all station (Figure 5). The monitoring and trouble-shooting tools also measure real-time and long-term voltage variations, data availability, the number of operating stations of the network.

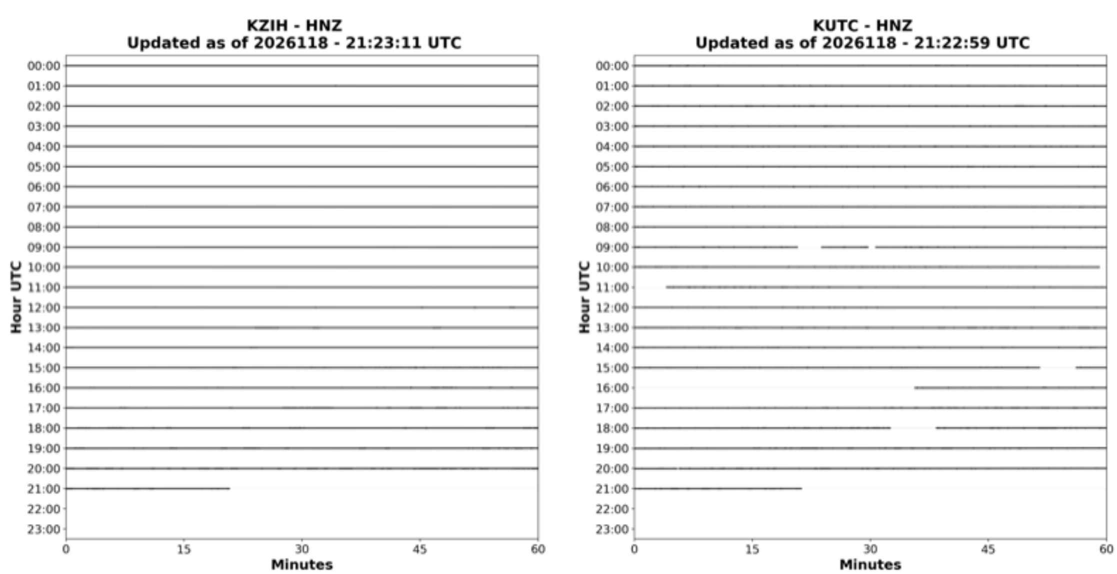


Figure 5. Example of the virtual helicorder records of two stations, KZIH and KUTC (Figure 1). The horizontal lines are one hour long. The graph shows data arrival in real time. As an example, the gaps in station KUTC reflect delays in data arrival. The graph is refreshed every five minutes. The monitoring tools depict the data continuously and for all stations.

4. Evaluation of the Data Quality

One of the key questions was to explore the accuracy of the seismogeodetic data obtained in real time by the Kestrel instruments. To this end, the real time data were compared with the post processed results using the GAMIT software. As mentioned before, to process the raw geodetic data using GAMIT, one has to wait for several days for the final version of the corrections to become available.

Here, we show the comparison of the two data streams, real time locations from the seismogeodetic instruments and the data processed with GAMIT (Figures 6 and 7). Figure 6 shows this comparison for station KUTC, a station in the state of Guerrero, in the rupture area of the 21 September 1985 aftershock of the great Michoacan earthquake of 19 September (see Figures 1 and 2). The comparison clearly shows that the daily averages of the real-time geodetic data are practically identical to the post-processed GNSS stream using the *GAMIT* software package. The geodetic displacements obtained in real time show an accuracy of ~1 cm, similar to the post-processed data. Interestingly, the scatter in the vertical component is smaller in the real time data obtained by the Kestrel, when compared with the data processed several days after, using the GAMIT software.

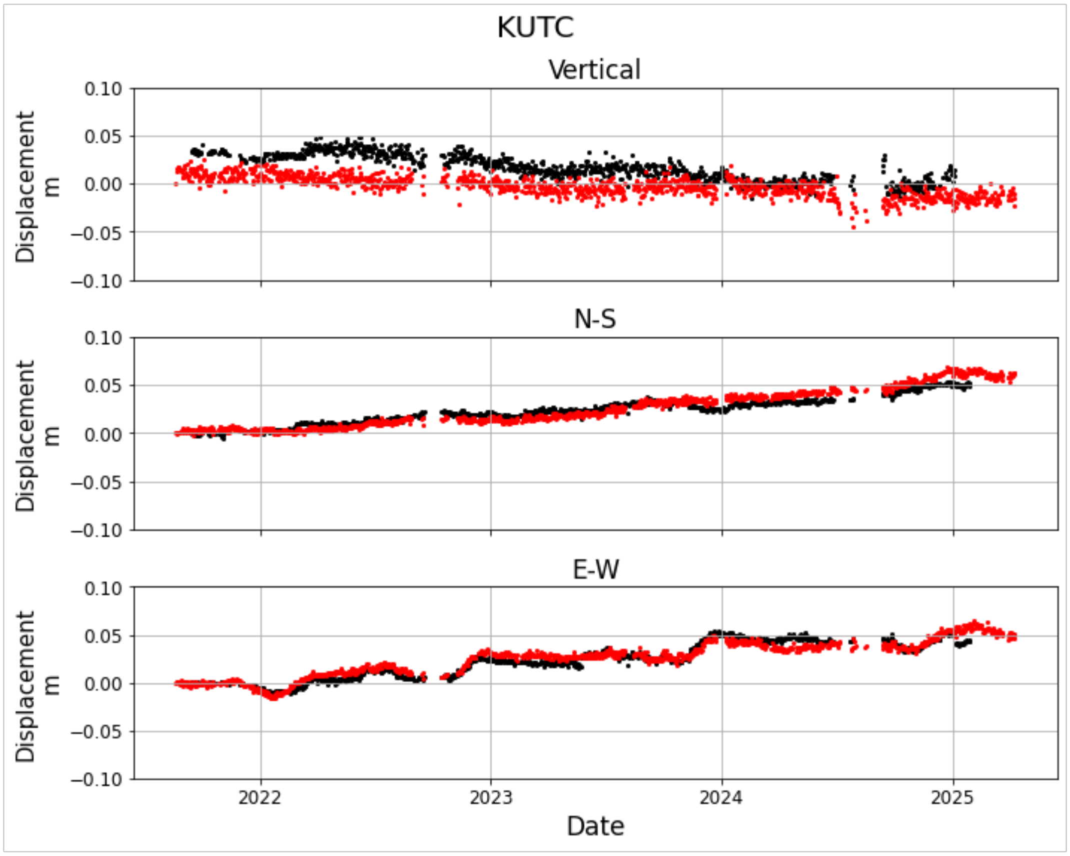


Figure 6. Comparison at station KUTC in northern Guerrero state, between the real time geodetic locations estimated in real time by the seismogeodetic instruments, by applying the RTX correction and the Kalman filter (black dots) and the daily averages resulting by processing the data using GAMIT several days after (red dots).

A similar result is shown for the station ACAP, located in the city of Acapulco (Figure 7). Serendipitously, this station was installed a few weeks before the occurrence of the 8 September 2021 earthquake (*Mw* 7.1) in Acapulco (7 September in local time). The earthquake was recorded by the Acapulco seismogeodetic station, as we show below. The 2021 earthquake is an important event in the context of the Guerrero seismic gap. This is the first earthquake in this segment of the subduction zone since the two large earthquakes (*Mw* 6.7 and 7.0) that took place in 1962 (Ortiz et al., 2000). Some authors interpret the Acapulco earthquake as a possible preamble to the reactivation of this segment of the subduction zone (e.g., Mendoza and Martínez-López, 2021; Iglesias et al., 2022)

Of note is that the post-seismic deformation of the subduction zone is almost identical in both, the real-time output and the data processed using GAMIT. Post-seismic slip of the Acapulco earthquake lasting almost a year after the occurrence of the earthquake is clearly visible in the time series. Again, the results show that real-time data is as accurate and robust as data analyzed with GAMIT afterwards, proving that the locations obtained in real time by the seismogeodetic instruments. These results confirm that the RIESGO may be used for real time monitoring of the seismic behavior of the subduction zone in southern Mexico.

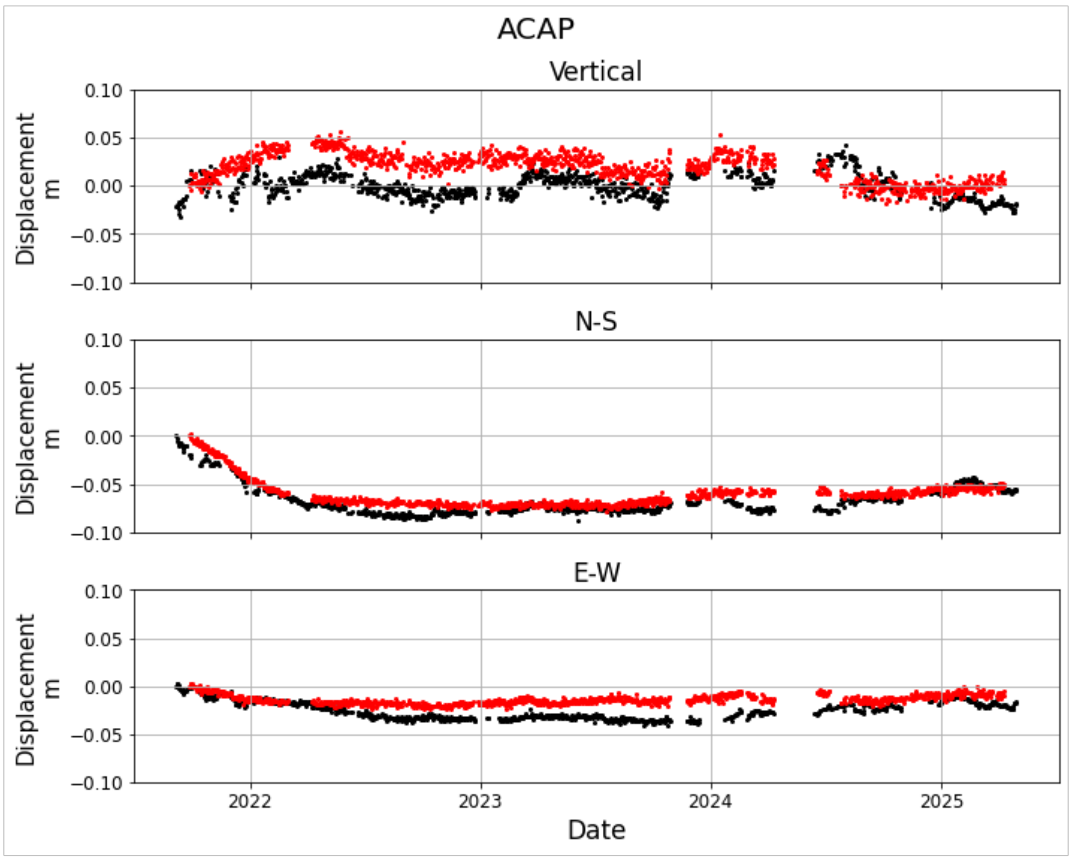


Figure 7. Comparison at station Acapulco (ACAP) between the real time geodetic locations estimated by the seismogeodetic instruments, by applying the RTX correction and the Kalman filter (black dots), and the daily averages resulting by processing the data using GAMIT (red dots), several days after. Notice the post-seismic slip after the 8 September 2021, Acapulco earthquake.

It is illustrating to see the residuals between these two data streams: the real time output of the seismogeodetic instrument and the post processed data using GAMIT. The residuals are defined as the difference between these two observations. These differences are generally less than ~1.5 cm, stressing the value of the seismogeodetic network to monitor the deformation of the subduction zone in real time.

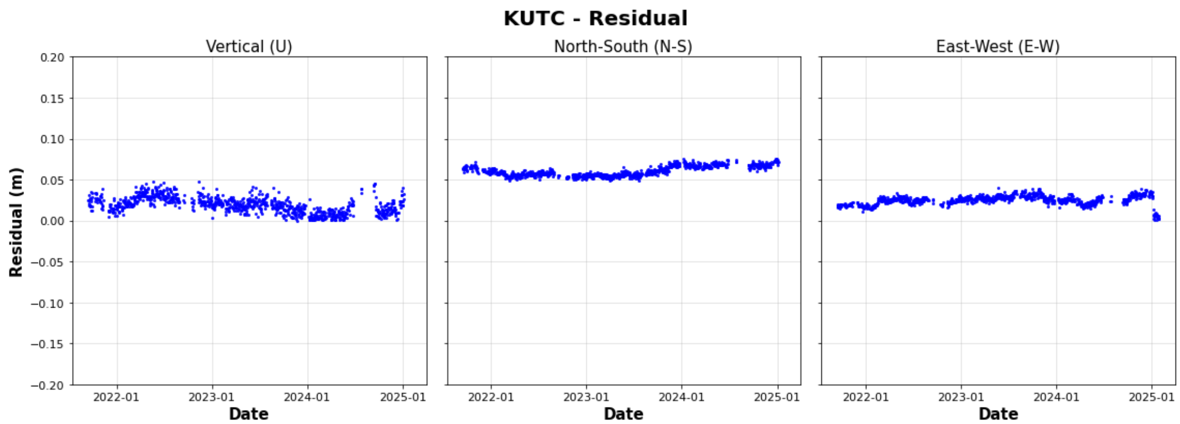
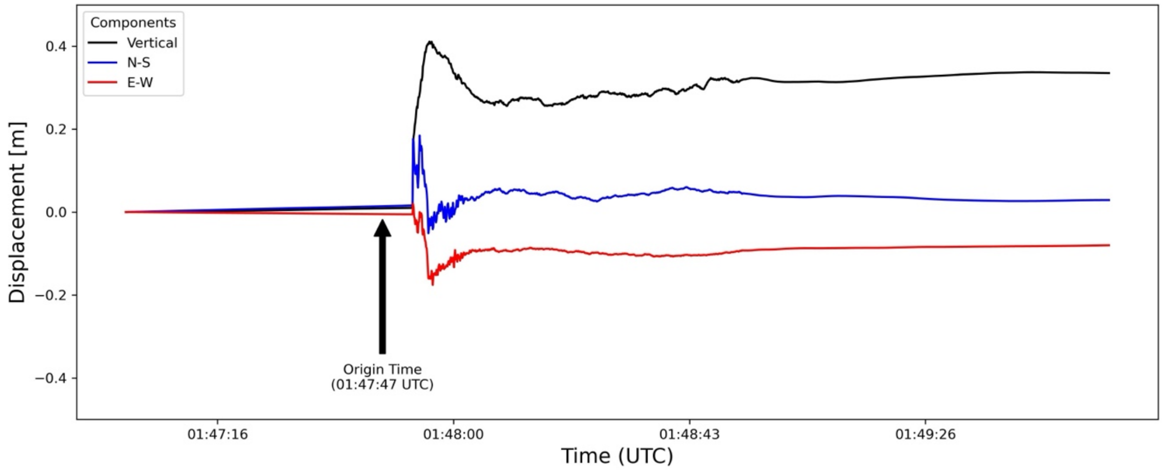


Figure 8. Difference between the real time displacement obtained in real time by the seismogeodetic station KUTC (Figure 1) and the post processed data using GAMIT. This example shows that the difference between these two datasets is less than ~1.5 cm.

5. Displacement Seismogram of the 8 September 2021 Earthquake

On 8 September 2021 an earthquake magnitude *Mw* 7.1 took place in the Middle American subduction zone. The epicenter of the earthquake was located in the city of Acapulco (Figures 1 and 2). ACAP, the seismogeodetic station in Acapulco, was installed a few weeks before the earthquake. It was one of the first stations of the network to be fully operational. The location of the station is very close to the shoreline, on the granitic outcrops surrounding the city (Figures 1 and 2). The earthquake of 8 September provided the first displacement seismogram to be recorded by RIESGO (Figures 8a, b).

a)



b)

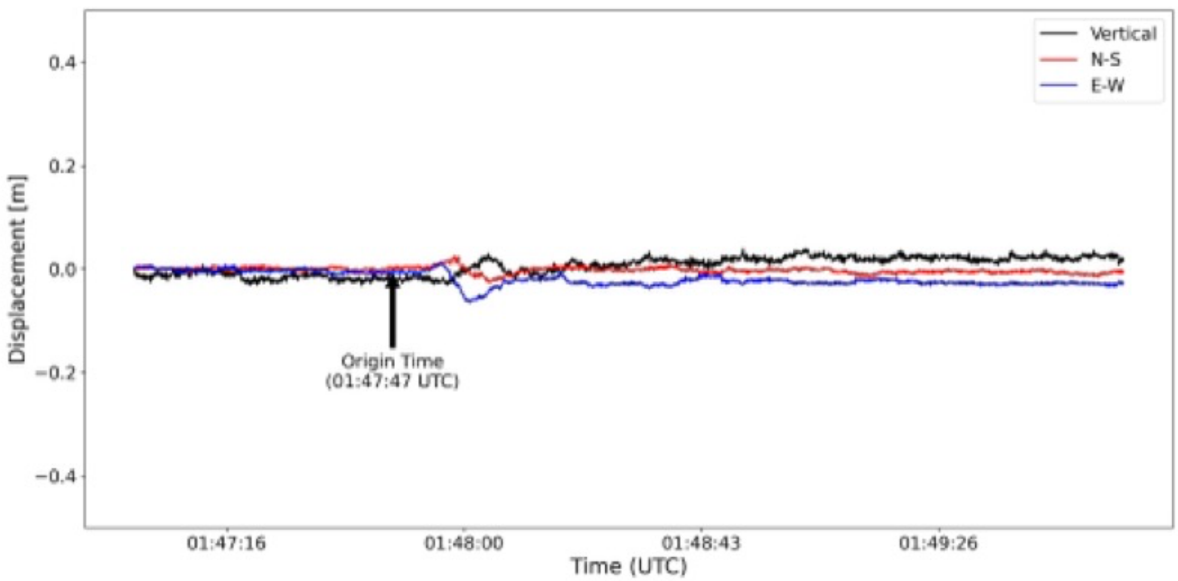


Figure 9. a) Displacement seismogram of the 8 September 2021 Acapulco earthquake (*Mw* 7.1) at station ACAP. The vertical black arrow indicates the origin time of the event, and the three-components of the displacement seismograms are shown as: vertical (black), north-south (blue), and east-west (red); b) Displacement seismogram of the Acapulco earthquake, recorded at station Coyuca (KCOY) (see Figure 1). The co-seismic displacement is within the error of the measurements. However, the P and S waves were recorded by the station.

The Acapulco earthquake ruptured the interplate contact beneath the city of Acapulco (Figure 2). The displacement record of the Acapulco earthquake on the seismogeodetic station Acapulco (ACAP) shows a co-seismic deformation of ~20 cm in the vertical component (Figure 8a). A co-seismic deformation of ~15 cm of to the west also reflects the tectonic rebound of the upper plate; practically no deformation on is observed in the N-S component. The co-seismic deformation of the coast inferred from the InSAR, (Interferometric Synthetic Aperture Radar), shows positive deformation in the Line of Sight of the satellite (LoS) of ~15 to 20 cm, reflecting the uplift of the coast (Melgar et al., 2022; Cruz-Atienza et al., 2025). A tide gauge meter in Acapulco also shows an uplift of the coast of ~16 cm (Arroyo et al., 2025; Melgar et al., 2022). Thus, the deformation reflected by the ACAP seismogeodetic instrument agrees with the other measurements of co-seismic coastal uplift.

The co-seismic static displacement of the upper continental plate was also observed in the two neighboring stations, KCOY y KCDP (Figure 2). However, the observed static deformation of the continental plate at these two stations is of only a few centimeters, as both lie on the edges of the mapped rupture (Melgar et al., 2022; Cruz-Atienza et al., 2025). Station KCOY (Coyuca, Guerrero) is to the north of the rupture area of the 2021 Acapulco earthquake. A co-seismic deformation of ~5 cm is observed in KCOY (Figure8b). The P and S waves were recorded by this seismogeodetic station (Figure 8b). Thus, these first displacement seismograms demonstrate the capacity of the seismogeodetic network to monitor the deformation of the coastline within a few centimeters.

6. CONCLUSIONS

RIESGO has operated continuously since the first stations were installed in late 2021. Despite some data gaps due to the learning curve of the communication modems, the data reflect the continuous deformation of the upper continental plate due to the subduction of the Cocos plate beneath it as evidenced, for example, in station KUTC (Figure 7b).

Since the installation of the RIESGO, several projects have emerged. An algorithm was developed that estimates the magnitude of large and great earthquakes using the length of the rupture zone, determined from the deformation of the coastline (Espinosa-Kuswara, 2025).

In this case, we follow the methodology proposed by Singh et al., (2012). Also, important progress has been made in using the RIESGO to monitor the deformation of the coastline in the subduction zone due to the interaction between the Cocos and North American plates.

Finally, we developed a set of templates of potential large and great earthquakes in the subduction zone, for which deformation of the ocean floor has been mapped in grids. Hypothetical tsunamis produced by earthquakes with ruptures similar to those predicted will be used to estimate tsunami heights and coastal areas likely affected by inundation. The results of these tasks are being prepared for publication.

CONFLICT OF INTEREST

The authors have no conflict of interest in any of the topics included in this manuscript.

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DATA AVAILABILITY

The data is available upon request to the principal author or through the Mexican Seismological Network.

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