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MINISTERIO DE TRANSPORTES, MOVILIDAD Y AGENDA URBANA
INSTITUTO GEOGRÁFICO NACIONAL

# GNSS techniques for natural hazards detection and monitoring in the Iberian region

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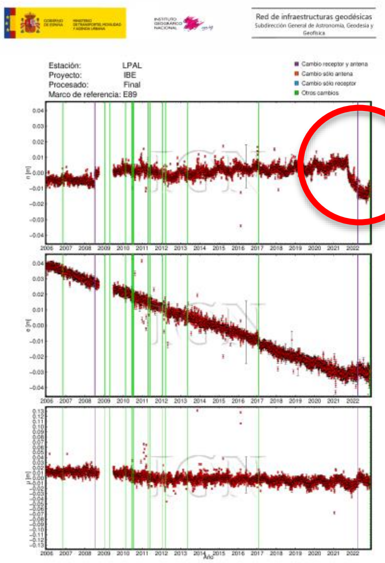
# Contents

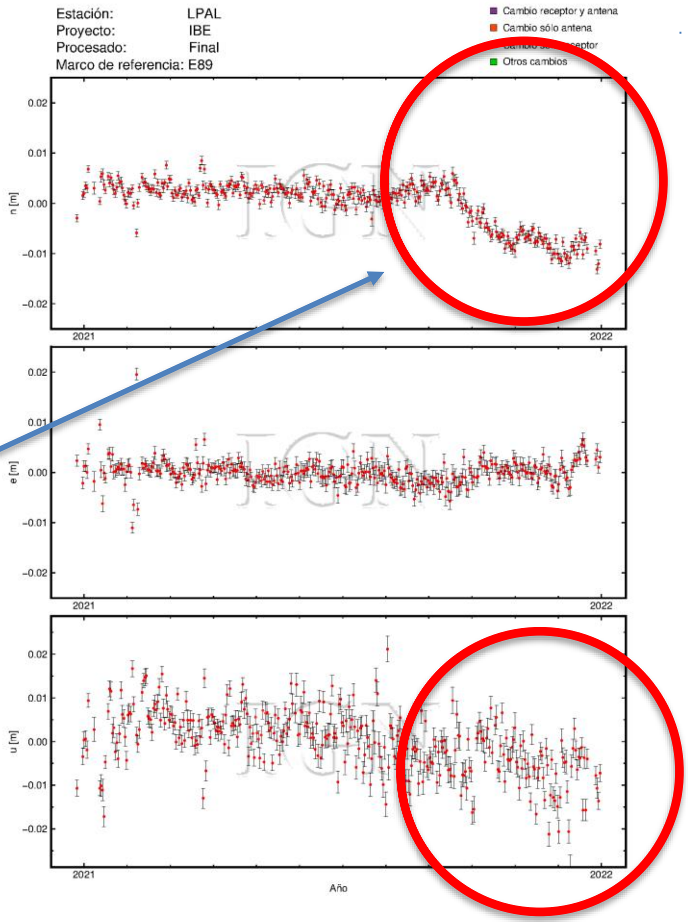
- Volcanic monitoring service.
- Real-time multi-GNSS solutions for earthquakes.
- Tsunamis alert system through GNSS determination of the perturbations in the ionosphere.
- GNSS-R for sea level monitoring.

# Volcanic Monitoring Service in Canary Islands

- LPAL00ESP: IGS & EPN station in La Palma (Canary Islands).

- Trend in coordinates from September, 2021, mainly in the north component < 2 cm.



…on September, 19th, started an eruption in La Palma Island, until December, 13th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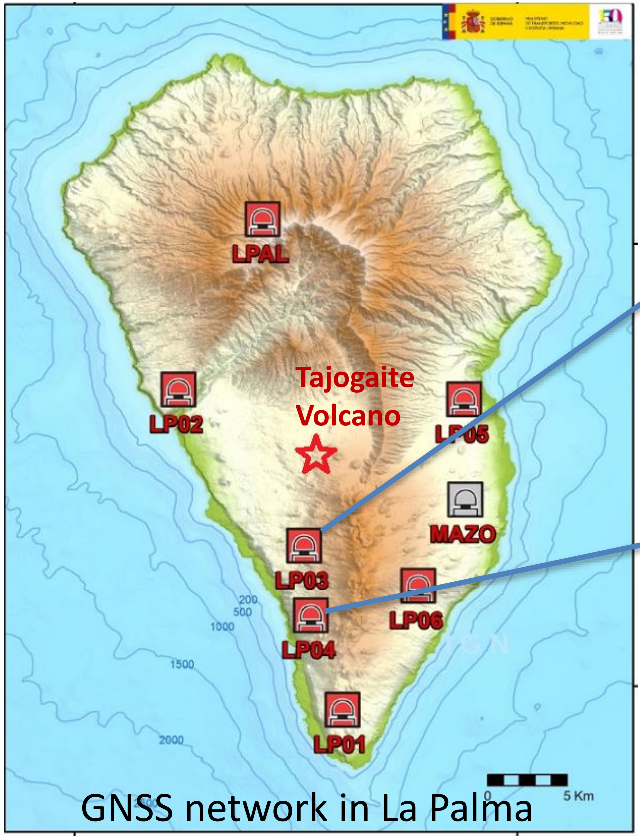
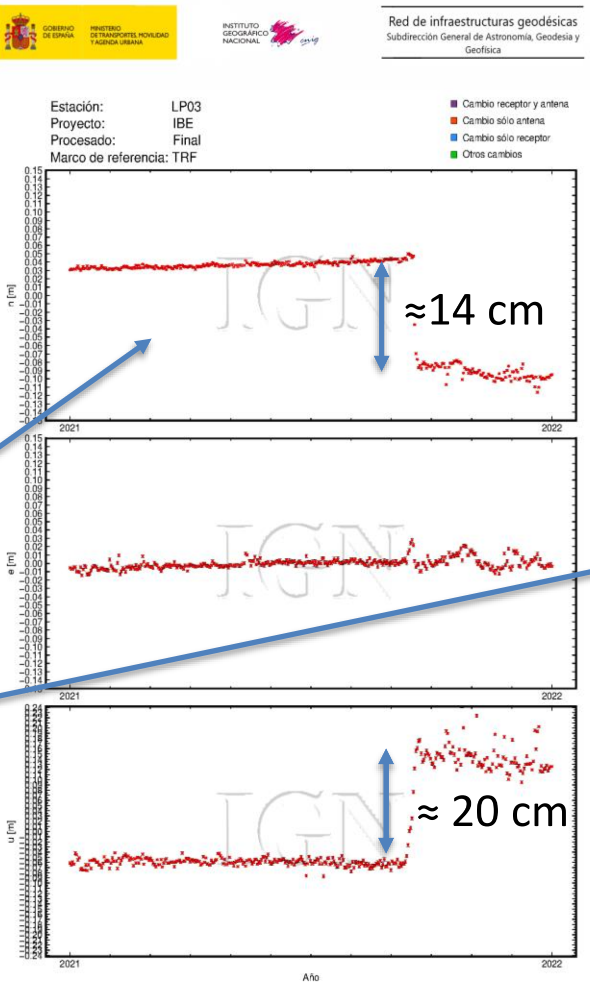
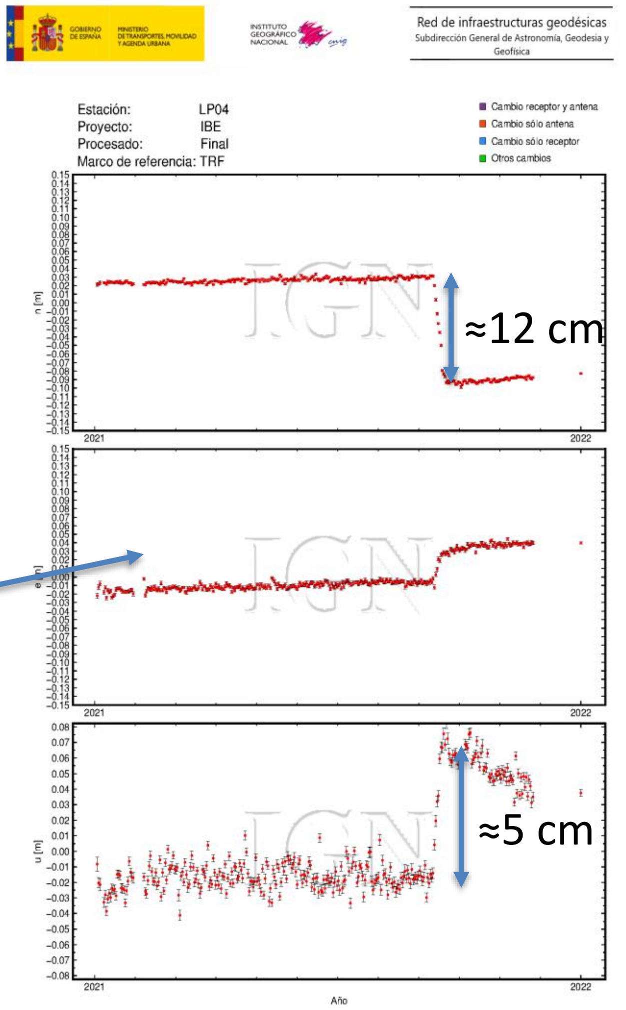
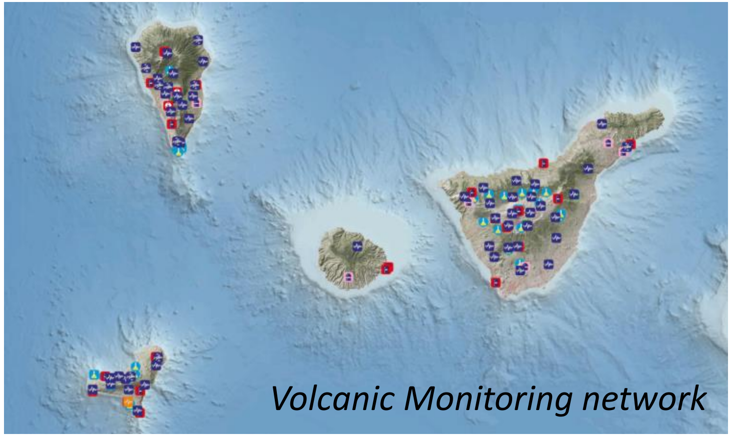


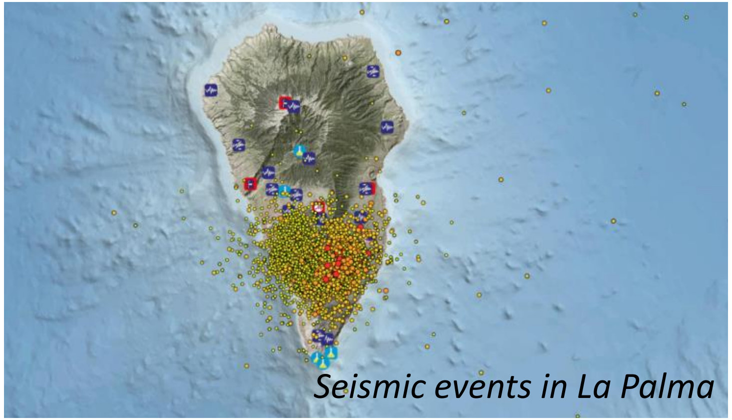



# GNSS network in Canary Islands: a case of usefulness

- A complete network of sensors (GNSS, sismometers, accelerometers, tiltmeters, thermic cameras…) were installed many years before in the Islands, specially in Tenerife, La Palma and El Hierro.
- Hourly & daily processing of GNSS data.
- Deformation was noticed in GNSS time series 6-7 days before the eruption.
- Together with other precursor signals, like seismic events, **<u>the eruption was anticipated / expected.</u>**
- Currently IGN is deploying a network in Decepcion Island, Antarctica.



*Volcanic Monitoring network*



*Seismic events in La Palma*

# Real-time multi-GNSS solutions for earthquakes

- GNSS have been widely applied for deformation monitoring in the interseismic and postseismic phases of the earthquake cycle.

- GNSS high-frequency measurements are becoming an important contribution for earthquake source determination.
  - Complement to the traditional seismic methods.
  - The ground motion measured by GNSS is not affected by the saturation problem.
  - Very high-rate measurement capability (50 Hz, 100 Hz).

- Although there is no area of large earthquakes, the seismic activity in the Iberian Region is relevant and there have been earthquakes Mw < 7 capable of causing serious damage.
  - Contribution to the GGOS Geohazards Focus Area.

# Variometric approach: fundamentals

- VADASE method, proposed by Colosimo et al. (2011).
- It relies on measuring the relative variation of the GNSS phase measurements.
  - Phase measurement at epoch *t*:

$$L_{1i}^{j}(t) = r_i^j(t) + c\left[\delta t_i(t) - \delta t^j(t)\right] + T_i^j(t) - I_i^j(t) + N_1 + c\left(b_{1i} - b_1^j\right)$$

  - Phase measurement at epoch *t+1*:

$$L_{1i}^{j}(t+1) = r_i^j(t+1) + c\left[\delta t_i(t+1) - \delta t^j(t+1)\right] + T_i^j(t+1) - I_i^j(t+1) + N_1 + c\left(b_{1i} - b_1^j\right)$$

  - Phase measurement difference:

$$L_{1i}^{j}(t+1) - L_{1i}^{j}(t) = \Delta r_i^j(t,t+1) + c\left[\Delta\delta t_i(t,t+1) - \Delta\delta t^j(t,t+1)\right]$$

# Variometric approach: fundamentals

- Hypotheses:
  - No cycle slip between *t* and *t*+1.
  - Ionosphere and troposphere delays are considered constant for 1 s.
  - Knowledge of the satellites orbit and clock error.

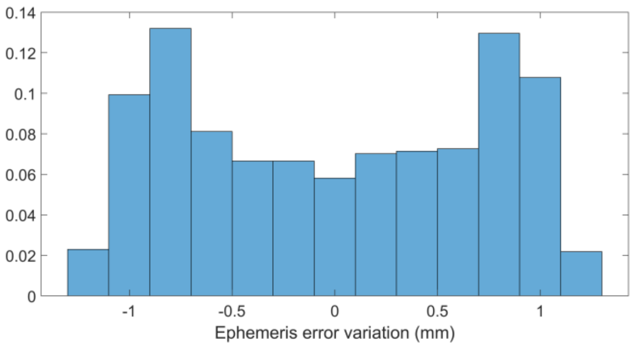
- Displacements and clock receiver computation through least squares fitting:

$$\begin{bmatrix} \frac{x^1-x_i}{r_i^1} & \frac{y^1-y_i}{r_i^1} & \frac{z^1-z_i}{r_i^1} & 1 \\ \frac{x^2-x_i}{r_i^2} & \frac{y^2-y_i}{r_i^2} & \frac{z^2-z_i}{r_i^2} & 1 \\ \dots & \dots & \dots & \dots \\ \frac{x^j-x_i}{r_i^j} & \frac{y^j-y_i}{r_i^j} & \frac{z^j-z_i}{r_i^j} & 1 \end{bmatrix} \begin{bmatrix} \Delta x_i \\ \Delta y_i \\ \Delta z_i \\ \Delta \delta t_i \end{bmatrix} = \begin{bmatrix} L_i^1(t+1) - L_i^1(t) - \Delta r_i^1(t,t+1) + c\Delta\delta t^1(t,t+1) \\ L_i^2(t+1) - L_i^2(t) - \Delta r_i^2(t,t+1) + c\Delta\delta t^2(t,t+1) \\ \dots \\ L_i^j(t+1) - L_i^j(t) - \Delta r_i^j(t,t+1) + c\Delta\delta t^j(t,t+1) \end{bmatrix}$$

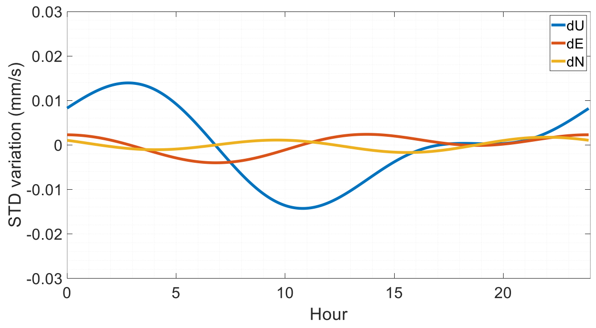
- One row (measurement) per satellite and frequency.

Example of other negligible variables influence: variation of orbits or solid tide

- Ephemeris error variation over 1 s:



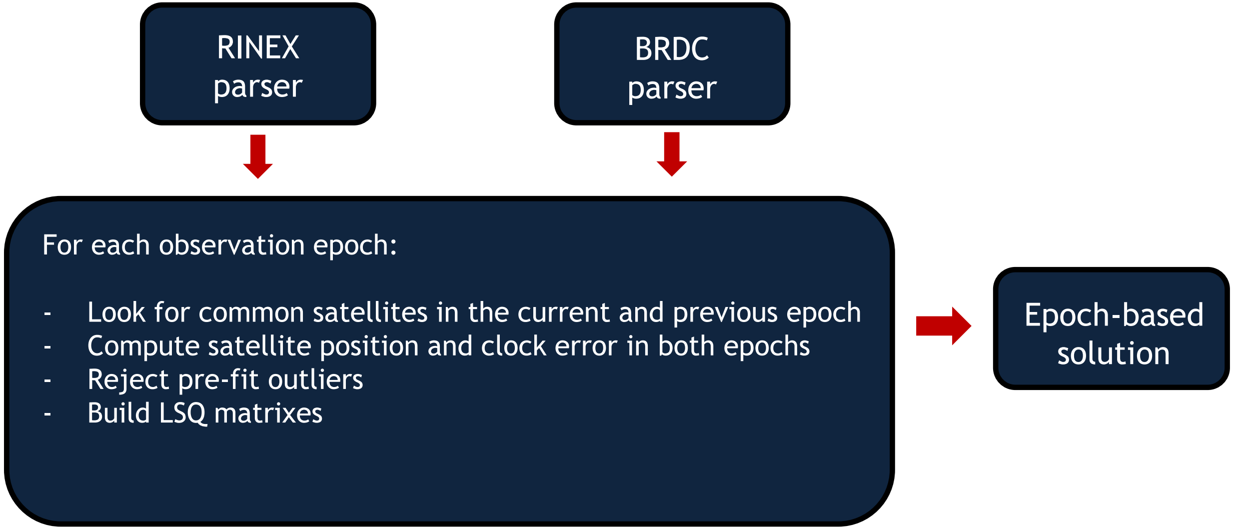

- Solid tide displacement (STD) variation over 1 s:



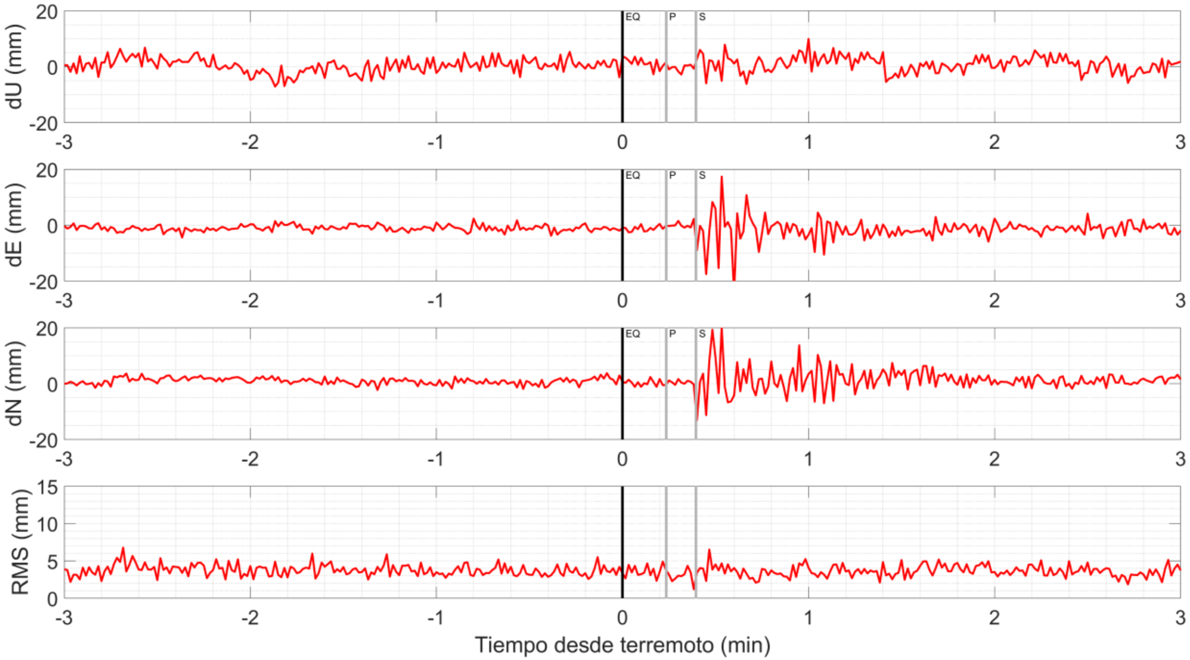
# Variometric approach: study cases

| Earthquake | Date and UTC time | Mw | Depth (km) | GNSS station | Distance (km) |
|---|---|---|---|---|---|
| Alborán Sur | 25/01/2016 04:22:01 | 6.3 | 12.0 | MELI | 85 |
| Lorca | 11/05/2011 16:47:26 | 5.1 | 4.0 | LORC | 7 |
| Ossa de Montiel | 23/02/2015 16:16:31 | 4.7 | 17.0 | ALBA | 67 |
| Navarra | 30/09/2020 22:02:31 | 4.5 | 1.0 | UPNA | 14 |
| Granada | 23/01/2021 11:15:24 | 4.4 | 0.0 | GRA1 | 11 |

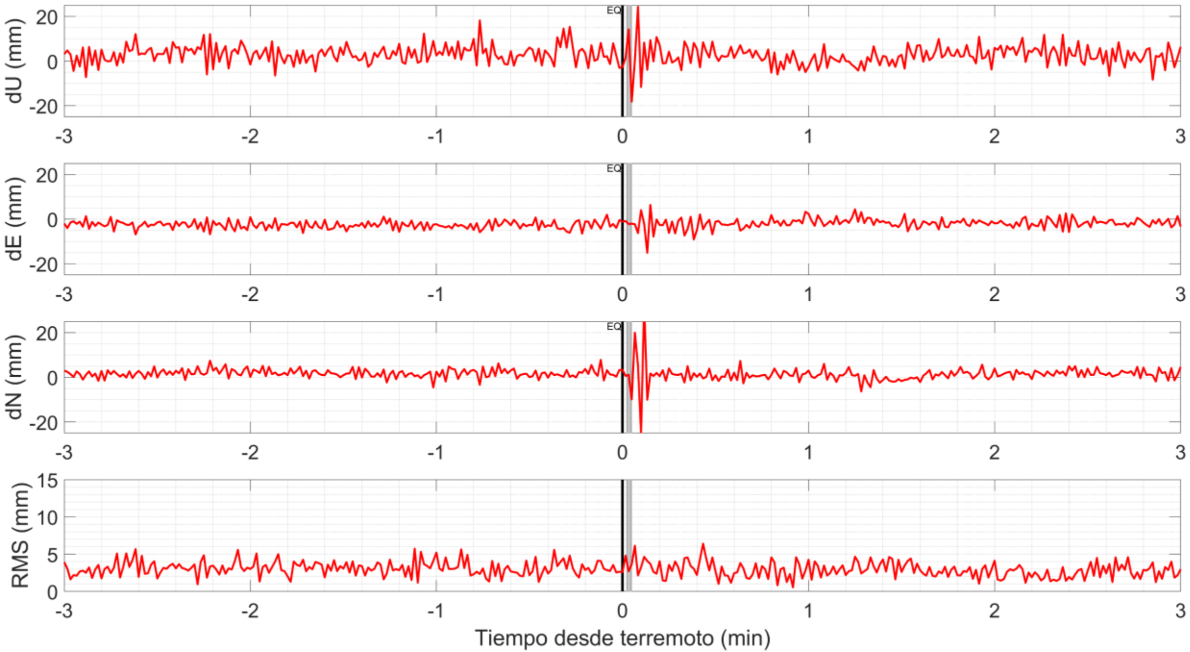
# Variometric approach: computation flow



# Variometric approach: Alborán Sur results (Mw = 6.3)

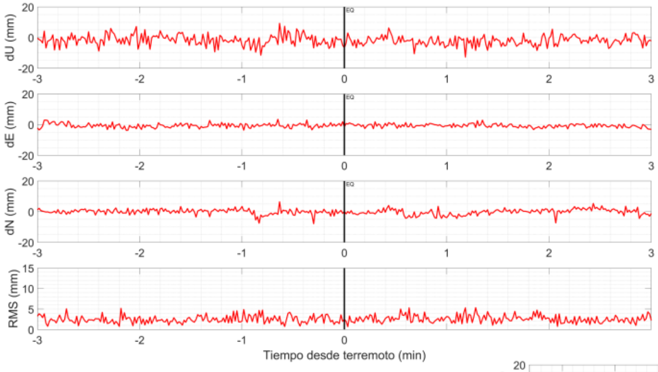


# Variometric approach: Lorca results (Mw = 5.1)

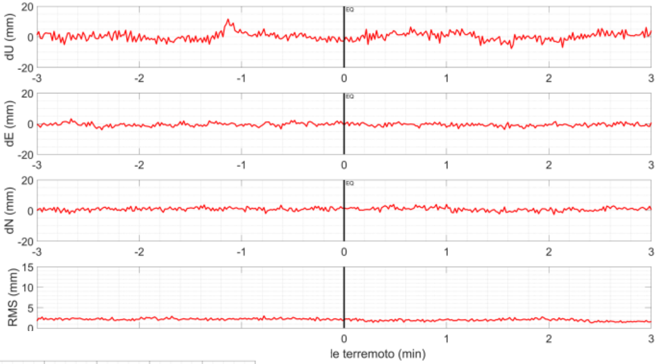


# Variometric approach: other results (Mw = 4.4 to 4.7)

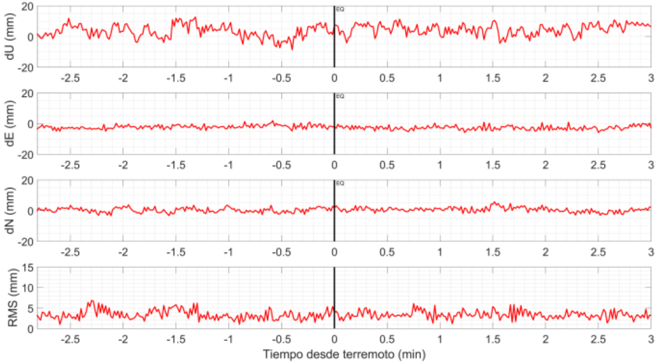
Granada




Ossa de Montiel




Navarra



# Kalman Filter approach tunning: fundamentals

- The previous method can be refined by a KF algorithm, reducing the noise of the observations.
- KF works by a recursive two-phase process:
  1) Prediction step: the state vector is propagated based on a model.
  2) Innovation step: the value predicted in the previous step is corrected using observations.

**Prediction step**

$$\boxed{x_{k|k-1}} = F \cdot x_{k-1|k-1}$$

$$\boxed{P_{k|k-1}} = F \cdot P_{k-1|k-1} \cdot F^T + Q_k$$

**Innovation step**

Input measurements

$$y_k = \boxed{z_k} - H_k \cdot \boxed{x_{k|k-1}}$$

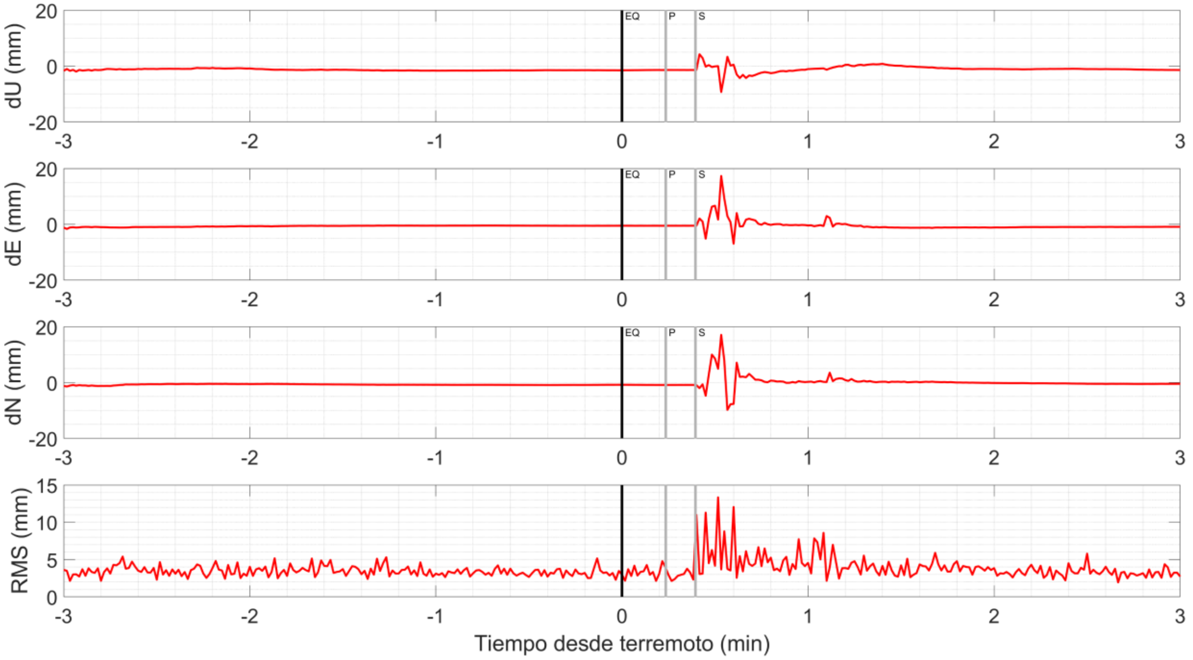
$$S_k = H_k \cdot P_{k|k-1} \cdot H_k^T + R_k$$

$$K_k = \boxed{P_{k|k-1}} \cdot H^T \cdot S_k^{-1}$$

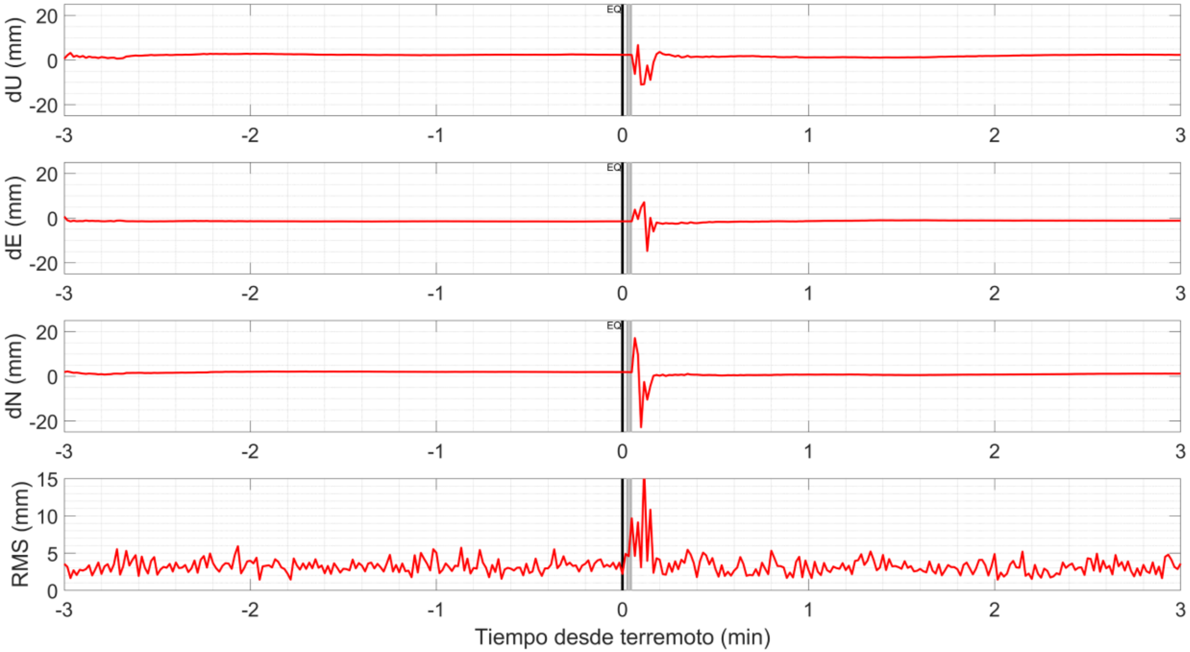
$$x_{k|k} = x_{k|k-1} + K_k y_k$$

$$P_{k|k} = (I - K_k \cdot H_k) P_{k|k-1}$$

# Kalman Filter approach: Alborán Sur results



# Kalman Filter approach: Lorca results

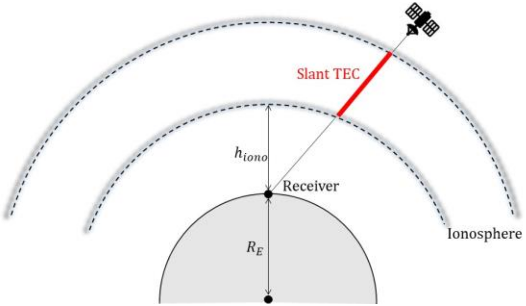


# Real time monitoring feasibility and applications

- The tool developed is ready to be run on a continuous basis.
- Input data:
  - Hourly RINEX files for a NRT solution.
  - Data from public casters for a RT solution (latency of a few seconds).
- Input orbit and clocks:
  - Broadcast GNSS navigation messages.
  - Predicted products from IGS-MGEX project.
- Displacements triggered by eartquakes **Mw > 5 are successfully detected** by means of GNSS.
- The proposed Kalman Filter reduces significantly the measurement noise before/after the event.
- Detection of local perturbations that might affect the stability of the stations.
- Characterization of the measurement noise of sites and antenna/receiver models.

# Tsunamis alert system through GNSS ionosphere perturbations

- Tsunamis generate **gravity** and **sound waves** that propagate up to the ionosphere from the epicenter.
- Slant TEC disturbances are analyzed using the VARION method in a real-time scenario.




*Satellite-receiver geometry*

# Fundamentals: VARION Method

- Carrier-phase observation, in length units:

$$L_{iR}^{S}(t) = \rho_R^S(t) + c(\delta t_R(t) - \delta t^S(t)) + T_R^S(t) - I_{iR}^S(t) + \lambda_i N_{iR}^S(t) + p_R^S(t) + m_{iR}^S(t) + \epsilon_R^S(t)$$

- Differentiating with respect to time between **two consecutive epochs** and applying the geometry-free combination ($L_4$):

$$L_{4R}^{S}(t+1) - L_{4R}^{S}(t) = \frac{f_1^2 - f_2^2}{f_2^2}\left[I_{1R}^S(t+1) - I_{1R}^S(t)\right],$$

where $f_1 = 1575.42$ MHz and $f_2 = 1227.60$ MHz for GPS.

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# Fundamentals: VARION Method

- Considering the ionospheric refraction along the geometric range, the STEC **variations** between two consecutive epochs are:

$$\delta TEC(t) = \frac{f_1^2 f_2^2}{A(f_1^2 - f_2^2)} \; L_{4R}^S(t+1) - L_{4R}^S(t)$$

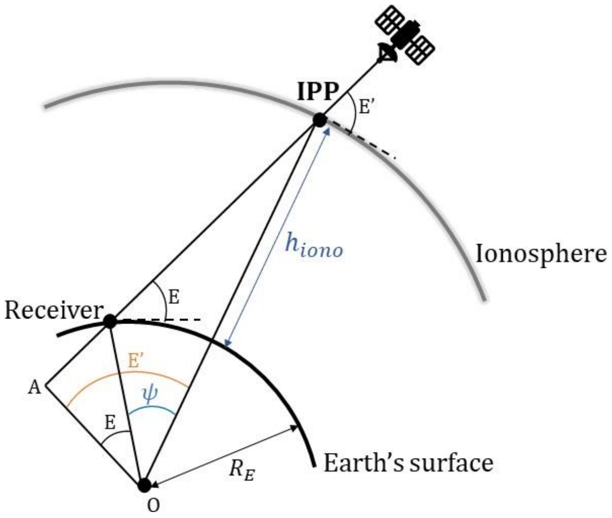
where $A = 40.3082 \cdot 10^{16}$ $m^3/s^2$

- Estimation of slant TEC variations through the Trapezoidal Rule:

$$\Delta TEC(t_f, t_0) := \int_{t_0}^{t_f} \delta TEC\,(t)\, dt \approx \sum_{k=1}^{N} \frac{\delta TEC(t_{k-1}) + \delta TEC(t_k)}{2} \Delta t_k.$$

being $\Delta t_k = t_k - t_{k-1}$ the time grid spacing

# Ionospheric Pierce Point (IPP) coordinates determination




Assuming the estimated TEC is mainly due to the $F_2$ region, the IPP is defined as the intersection of this 350 km height layer and the line of satellite.

Coordinates of IPP are:

$$\begin{cases} \Phi_{IPP} = \Phi_r + \psi \cos A \\ \lambda_{IPP} = \lambda_r + \dfrac{\psi \sin A}{\cos \phi_{IPP}} \end{cases}$$

$(\Phi, \lambda)$, ellipsoidal receiver coordinates in GRS80,
A, azimuth angle of the satellite
$\Psi$, offset angle.

# Threshold distance for Ionospheric Pierce Points

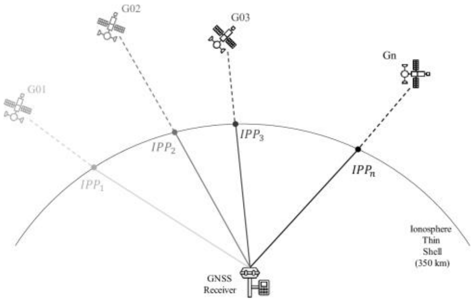
- Depending on the earthquake's magnitude, it is defined a threshold distance, κ, for those satellites whose IPPs are closest to the epicenter (Kamogawa et al., 2016).

If Mw $\geq 8.4$, $\Rightarrow \kappa = 100$ km.

If Mw $< 8.4$, $\Rightarrow$ $\kappa = 50$ km.

Candidate satellites verify the circle equation centered in the epicenter at $F_2$ layer (350 km height).

$$(\phi_{IPP} - \phi_{epi})^2 + (\lambda_{IPP} - \lambda_{epi})^2 \leq \kappa^2.$$



## Real cases of tsunami

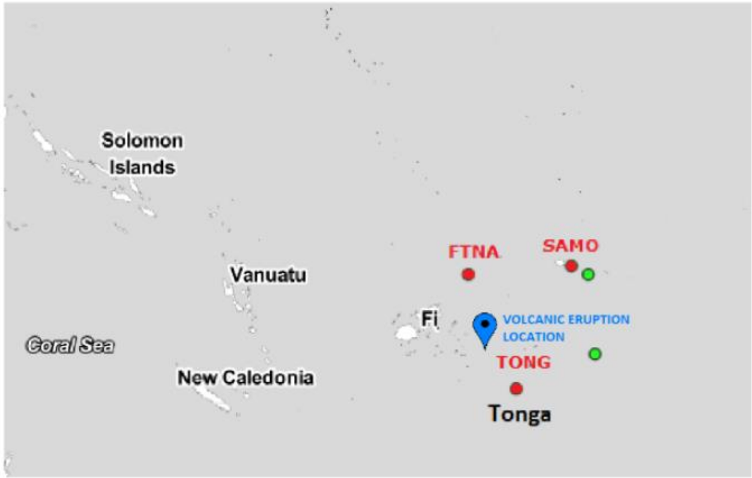
**Tohoku** region, Japan. 11$^{th}$ March 2011.
**Tonga**, Oceania. 15$^{th}$ January 2022.

| | $\phi_{epi}$ | $\lambda_{epi}$ | UTC time | Magnitude (Mw) |
|---|---|---|---|---|
| Tohoku | 38.°297N | 142.°373E | 5:46:24 h | 9.0 |
| Tonga | 20.°546S | 175.°390W | 4:14:45 h | 7.3 |

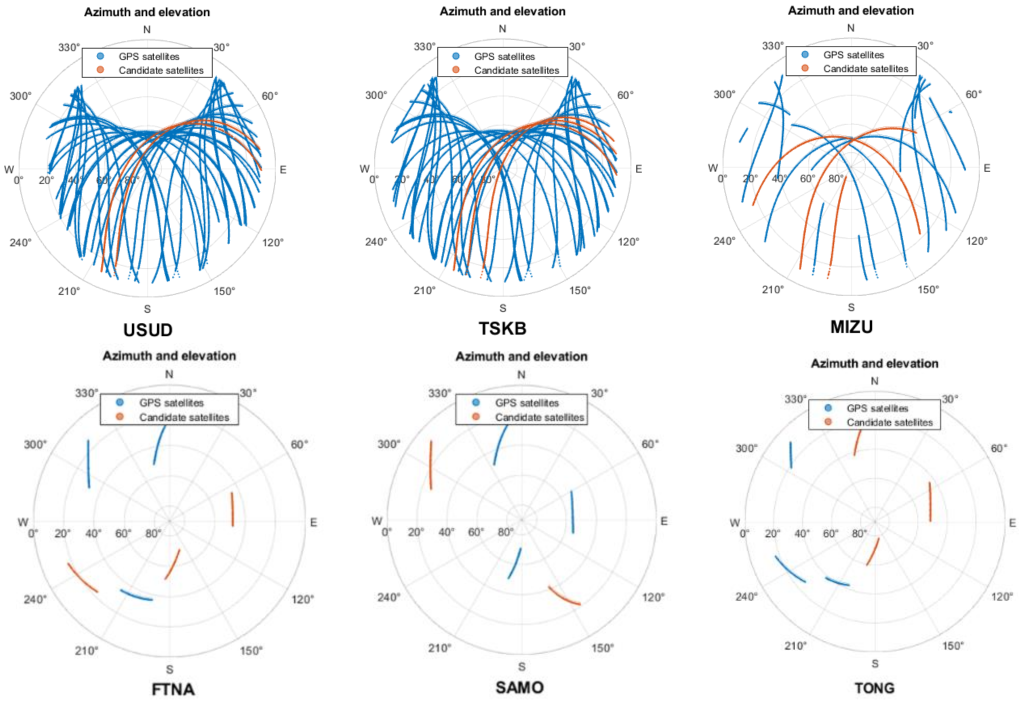
TOHOKU


TONGA

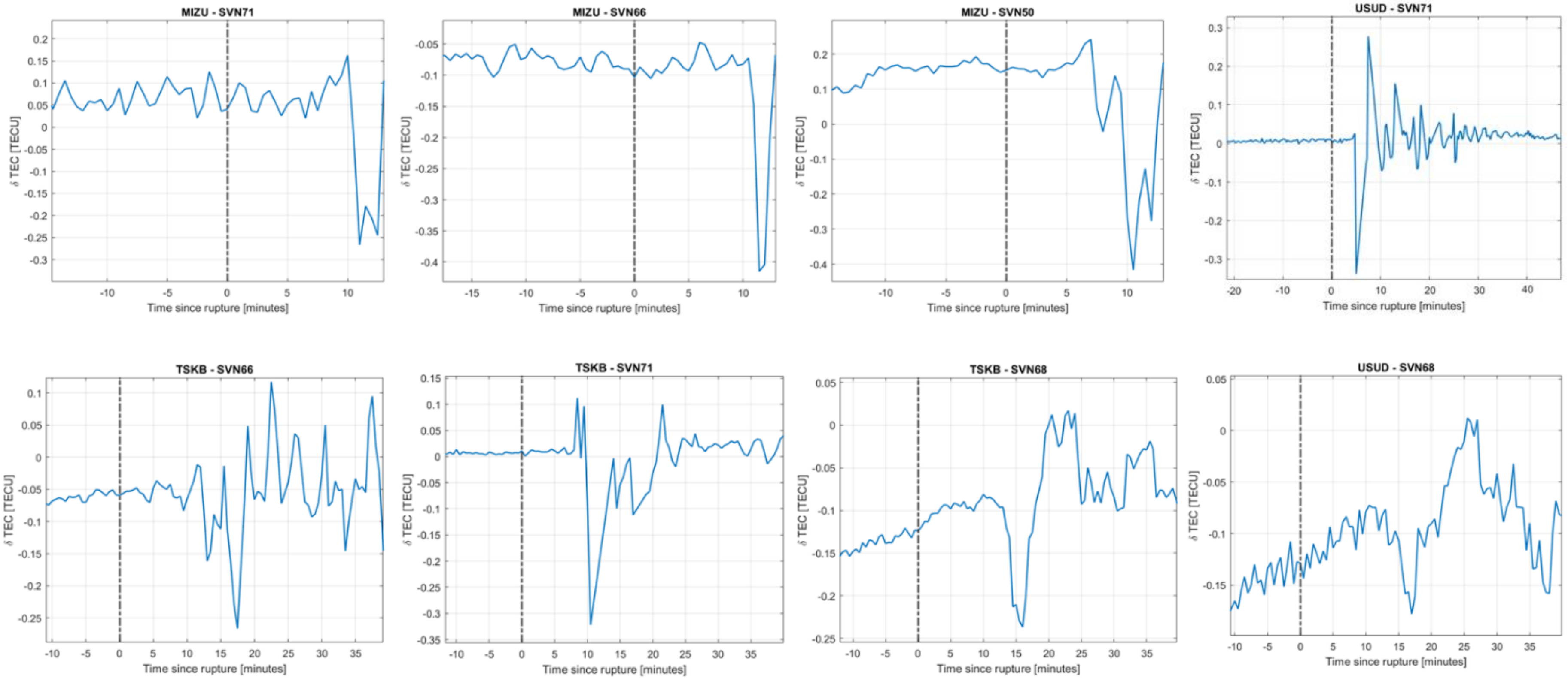

IGS stations selected

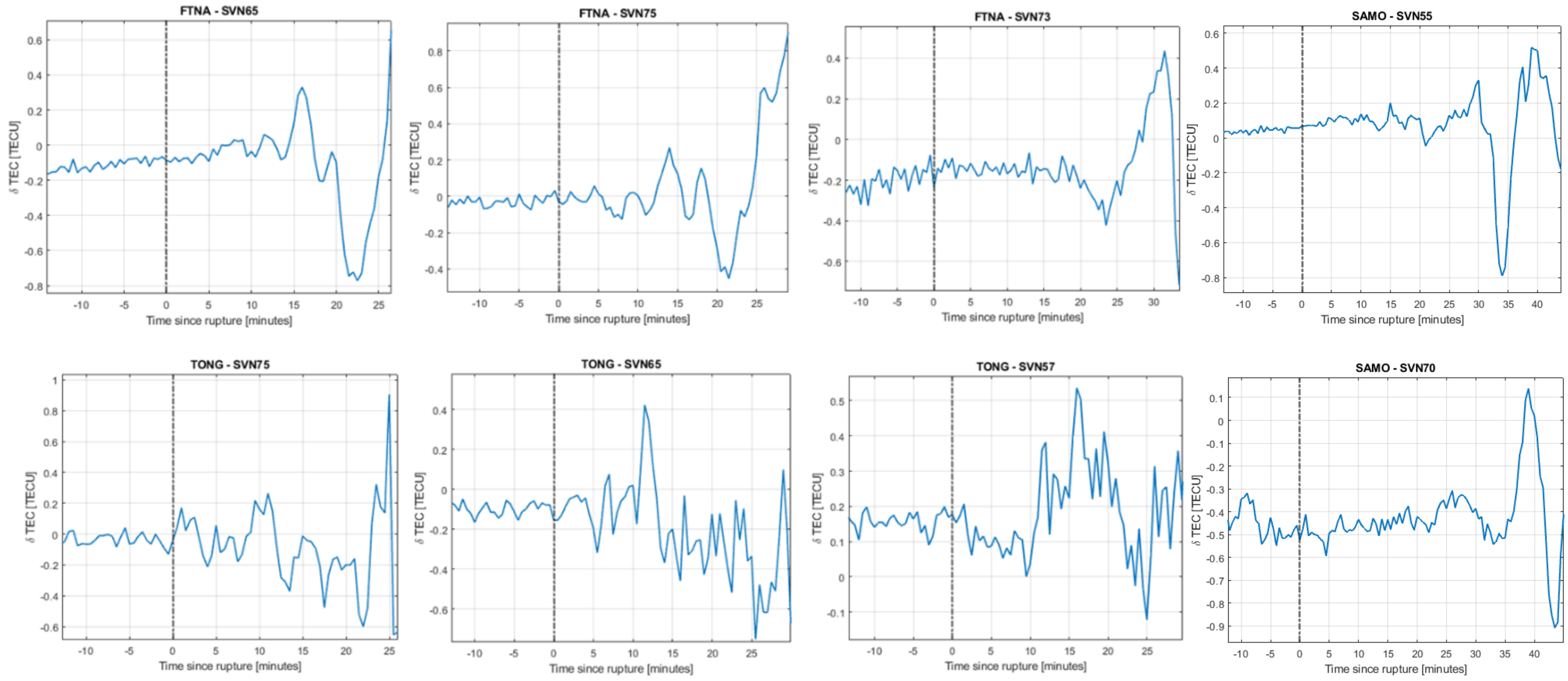
# Azimuth and elevation of the satellites




Search for the tracking satellite candidates due to the elevation and azimuth




Slant TEC time series (GPS) for Tohoku



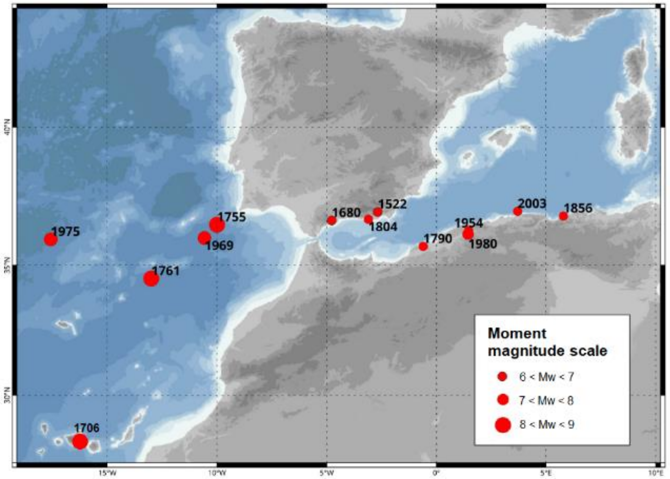

Slant TEC time series (GPS) for Tonga

## Spanish Tsunami Warning System (STWS)

- IGN implemented STWS and it operates since some years ago mostly based in the seismic network.
- Integration of the measurements of ionospheric disturbances into the STWS based on this method.
- Low cost implementation and low computational time: DART buoys, expensive and high maintenance.
- No need of additional infrastructure to install.

## Uncertainties in tsunami’s prediction

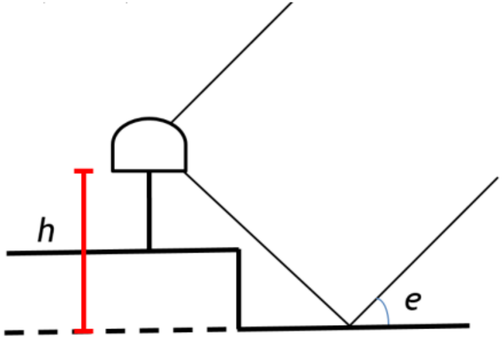
- Estimation of the hypocentral location and its magnitude.
- There is no direct match between earthquake’s size and tsunami’s severity.
- Other anomalies affect the ionosphere, such as solar radiation, geomagnetic activity and strong meteorological events.




*Historical tsunamis affecting near the coast of the Iberian Peninsula*

# GNSS-R for long-term sea level variation

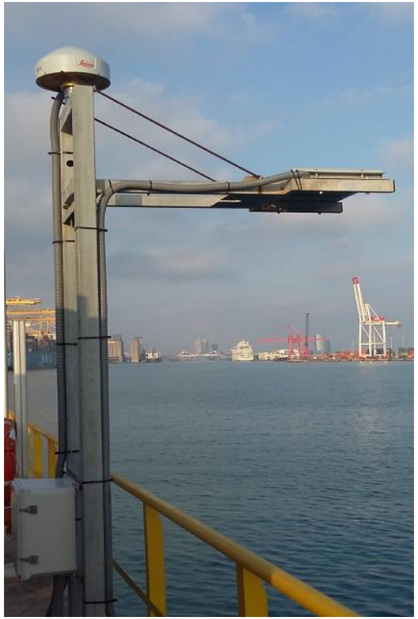
- GNSS-R: sensor of near-field environment of a GNSS station based on the usage of reflected signals.
- Data: SNR, azimuth, elevation.
- Applications: sea level, soil moisture, snow depth…
- Methodology:
  1. Define azimuth and elevation range of interest
  2. Extract SNR from RINEX files
  3. Select satellite passes fulfilling azi and ele
  4. Convert SNR to linear units and remove temporal trend
  5. Sea level height computation:
     - LSP method: spectral analysis of SNR using Lomb-Scargle Periodogram
     - IM method (Strandberg, 2016): Inverse Modelling using non-linear least squares estimation
       (Advantage: multiconstellation)




$$\delta SNR = A \sin\left(\frac{4\pi h}{\lambda}\sin e + \varphi\right)$$

$$\partial \mathrm{SNR(e)} = \left[\mathrm{C}_1 \sin\frac{4\pi h}{\lambda}x + \mathrm{C}_2 \sin\frac{4\pi h}{\lambda}x\right] \mathrm{e}^{-4k^2 \Lambda x^2}$$

| Method | Standard deviation (cm) | Correlation |
|---|---|---|
| LSP GPS, L1 | 5.3 | 0.91 |
| LSP GPS, L2 | 7.7 | 0.83 |
| LSP GLONASS, L1 | 5.5 | 0.90 |
| LSP GLONASS, L2 | 5.4 | 0.90 |
| LSP GALILEO, E1 | 7.4 | 0.84 |
| LSP GALILEO, E5 | 12.5 | 0.62 |
| **IM (GPS+GLO+GAL+BDS)** | **3.2** | **0.96** |



Comparison between methods: one year data of **BCL1** station and comparison with RADAR tide gaude euref

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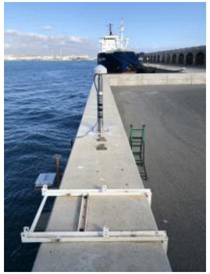
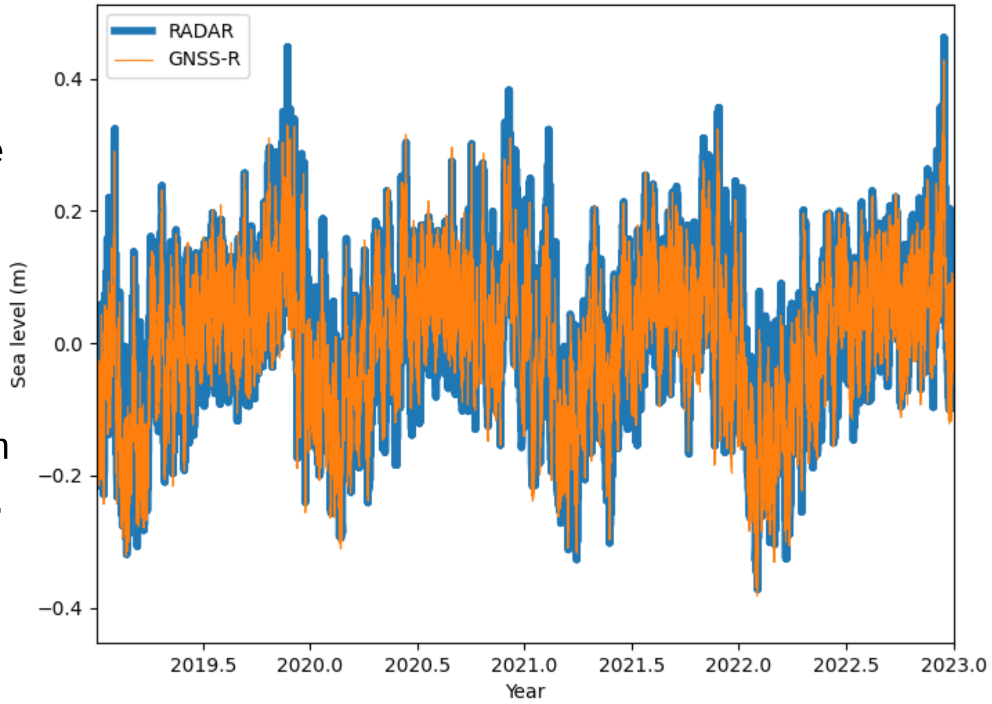







## GNSS-R results

- Direct sea level – ITRF link.
- Sea level measurement if not tide gauge available: low cost.
- Direct discrimination of ground sink vs. sea level variation.
- Check possibility in GNSS and tide gauge co-location.
- IM method shows an accuracy of few cm
- Ii can be implemented for real-time data.
- Worse accuracy than tide gauges ☹




*Example: 4 years analysis in BCL1 station*

## IMPORTANT NOTICE

Despite this presentation, please, dont worry, Spain is a safe place to stay on holidays, so please, come and enjoy !!

# Thank you for your attention

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