

High-Resolution GNSS-TEC Characterization of Ionospheric Disturbances Induced by Natural Hazards

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S9: Troposphere and ionosphere
XI Hotine-Marussi Symposium



SAPIENZA
UNIVERSITÀ DI ROMA

Genova
September 11th , 2026

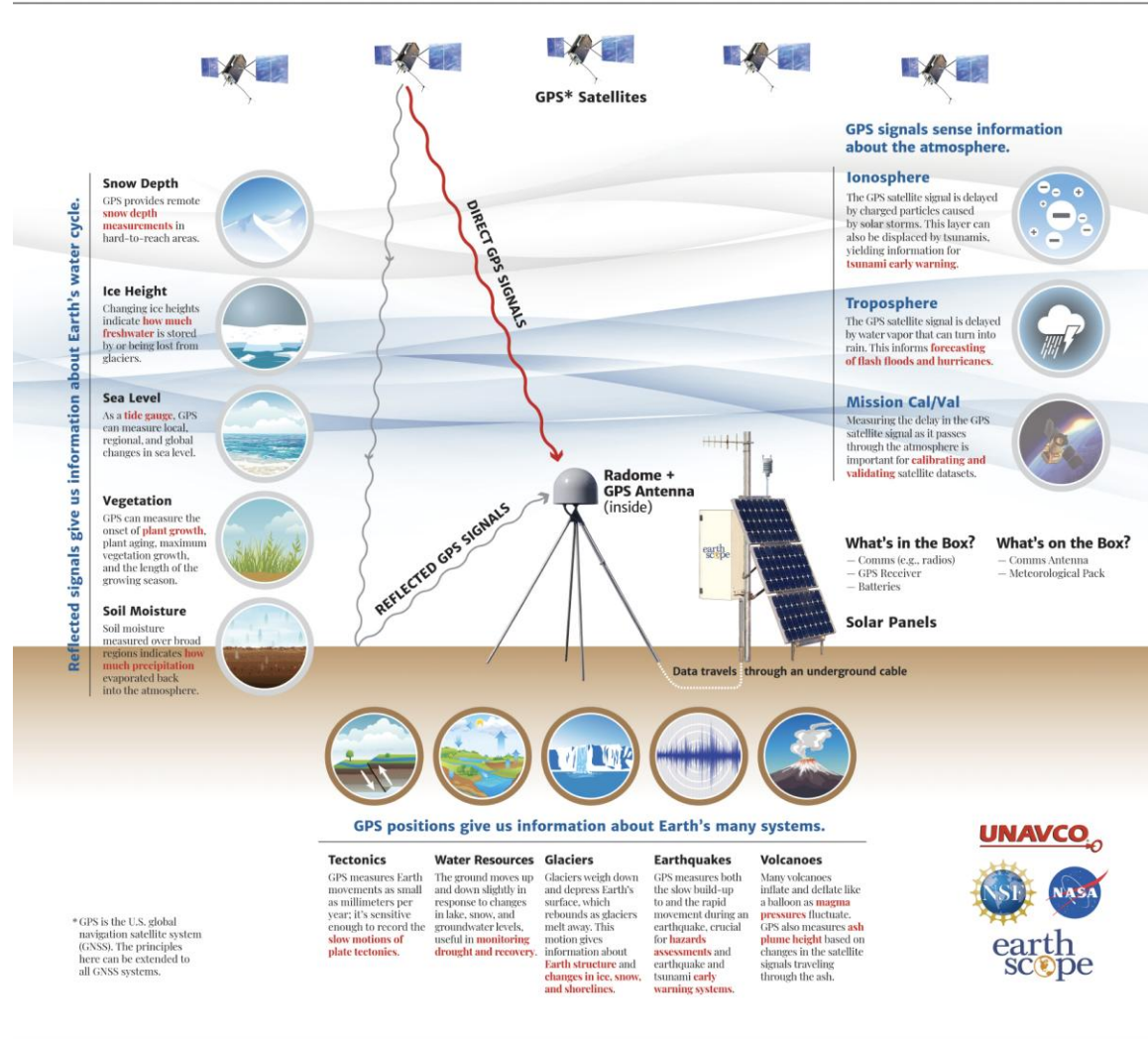


GNSS

GNSS

Can Tell Us About Earth

High-precision GPS stations measure natural phenomena and hazards.



GNSS Ionospheric Sounding

Ground-based dual-frequency GNSS receivers allows to compute TEC

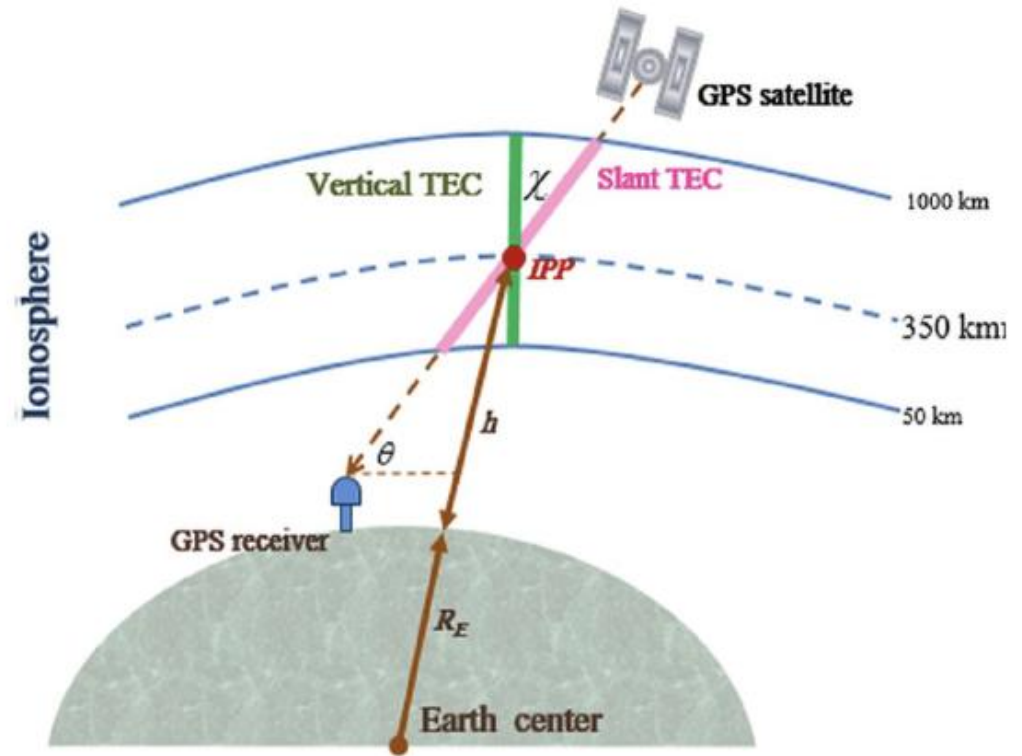


Total Electron Content

The ionosphere acts like a **dispersive medium** for the GNSS signal

$$sTEC = \frac{1}{40.3} \left(\frac{f_1^2 f_2^2}{f_1^2 - f_2^2} \right) (L_{4R}^S - \Delta N_R^S + res)$$

Slant Total Electron Content is the total electron content along the straight line between the satellite and the receiver

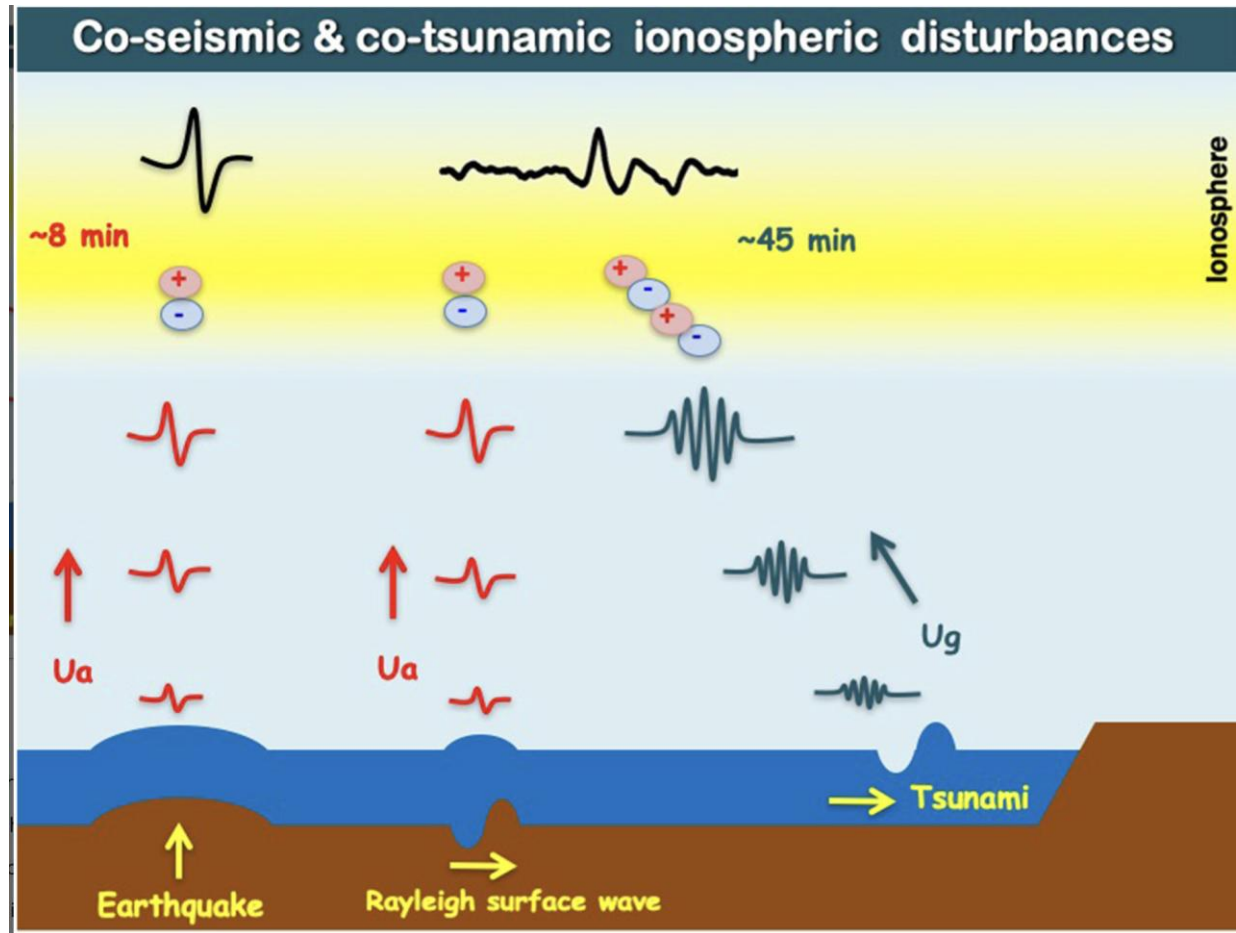


From Siwal et al., 2021

The physical phenomenon

Earthquakes & Local Tsunamis:

- Magnitude (M_w/M_s)
- Vertical displacement?
- Tsunami-genesis (e.g., *Manta et al., 2020*)
- Source dimension/structure (*Astafyeva et al., 2013*)



Astafyeva, 2019

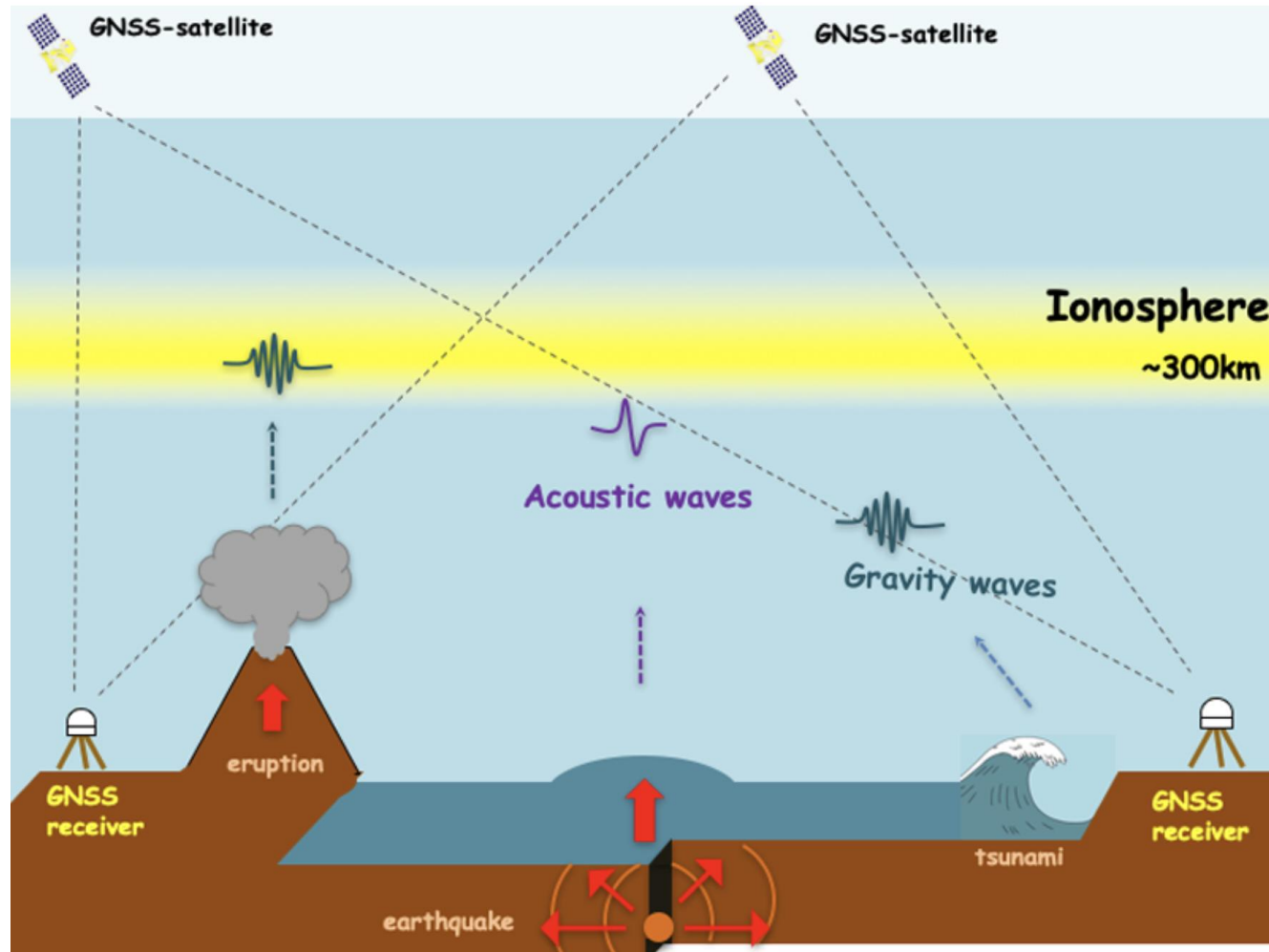
Distant Tsunamis:

- track tsunami propagation offshore
- Independently on the origin (non-seismic OK)
- Propagation speed
- Wave heights (demonstration was done by *Rakoto et al., 2018*, but not NRT yet)

The ionosphere is a natural sensor for geophysical phenomena

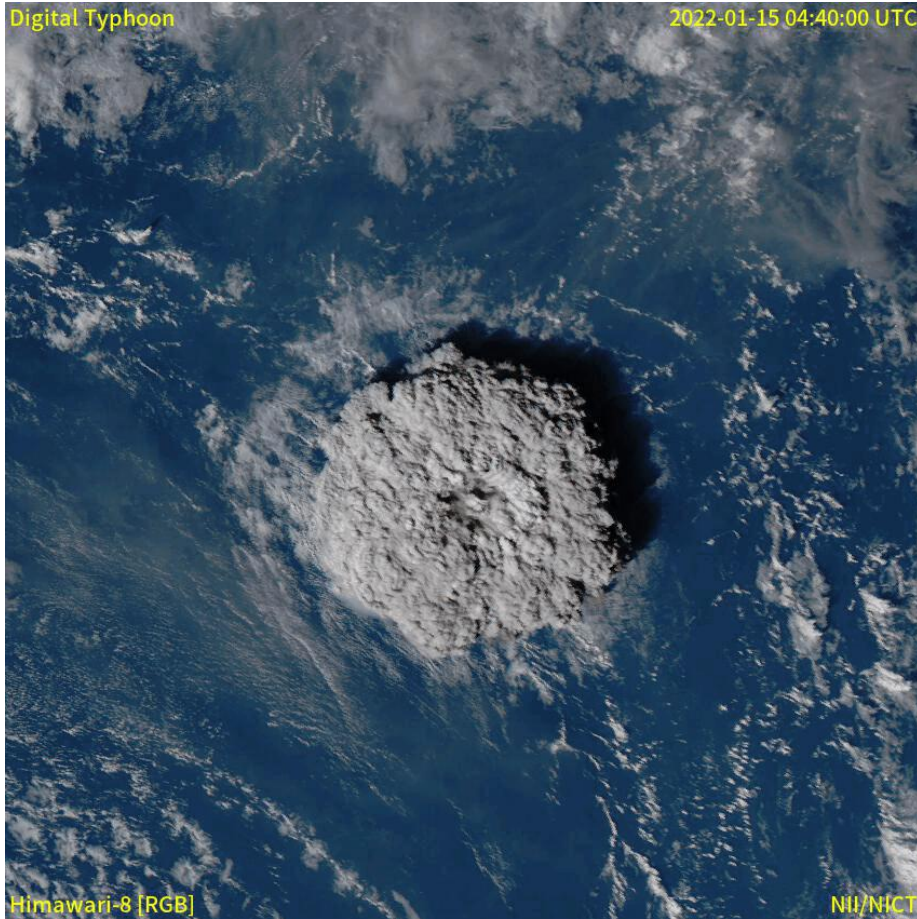
Ionospheric perturbations

1 GNSS-receiver =
20-60 satellites
= 20-60 GNSS-TEC
time series



Credits to E. Astafyeva

2022 Tonga volcanic eruption



Himawari satellite/Japan Meteorological Agency

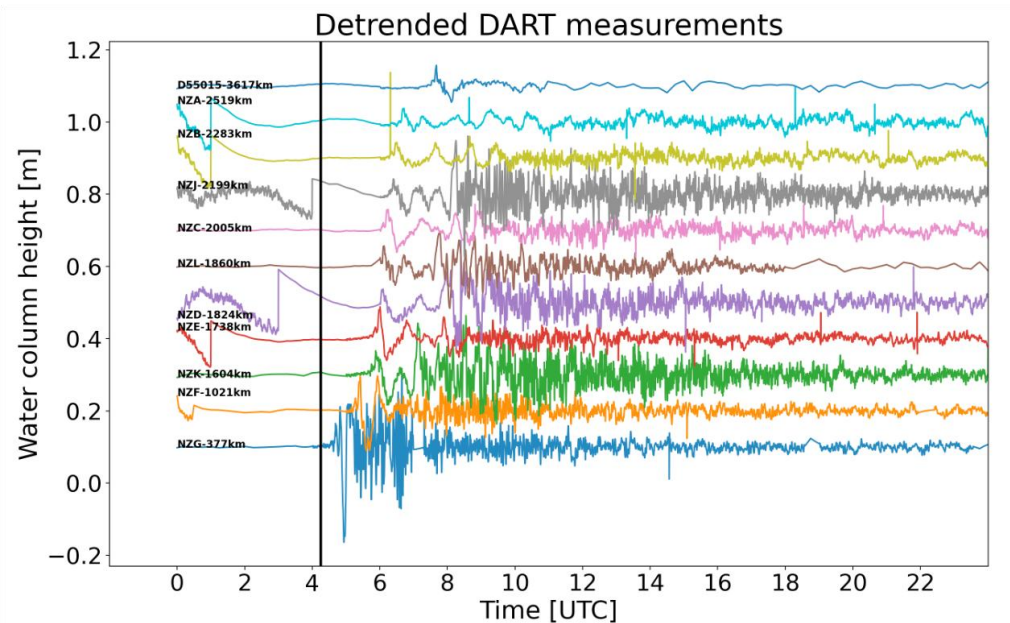
2 tsunamis

- Near-surface propagating Lamb wave caused a small tsunami in the ocean ([air-sea wave](#))
- Tsunami generated by the collapse of the caldera

2022 Tonga volcanic eruption

OCEAN

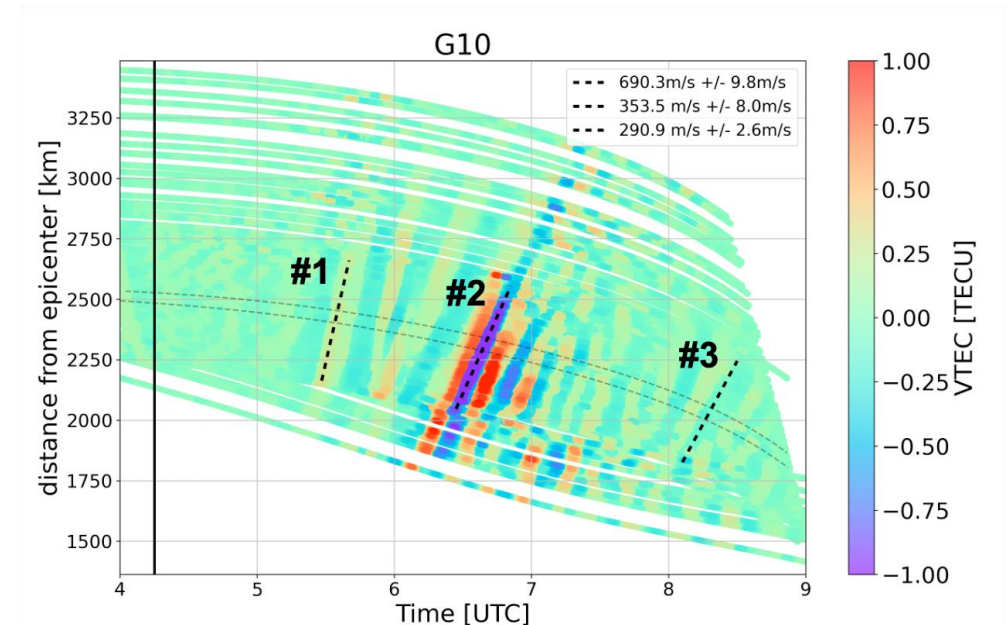
- Near-surface propagating Lamb wave caused a small tsunami in the ocean ([air-sea wave](#))
- [Eruption-generated tsunami](#) showed significant wave heights in the ocean



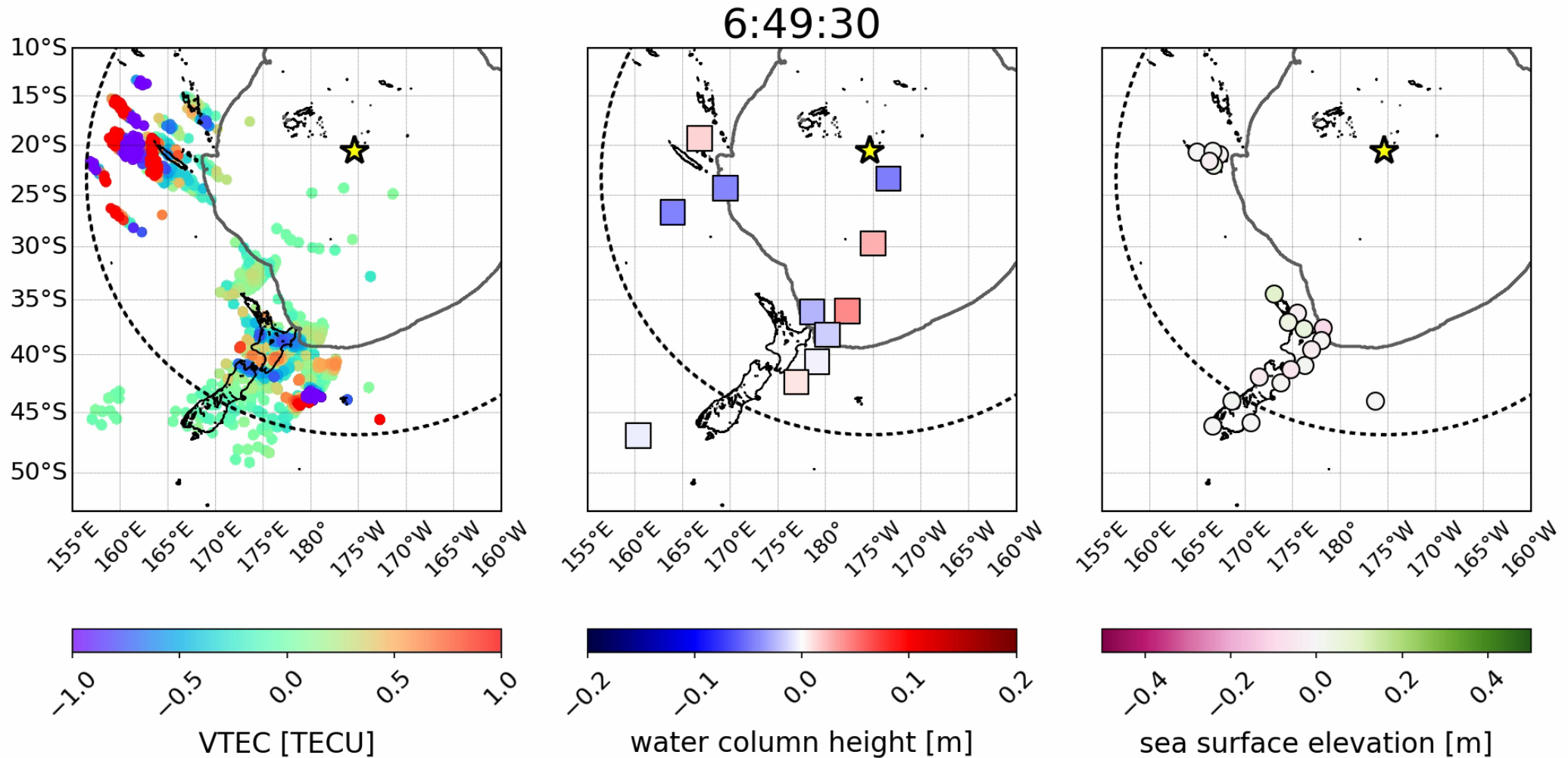
Ravanelli et al. (2023)

IONOSPHERE

- Strong [Lamb-wave](#) induced disturbances in the ionosphere
- Smaller ionospheric response of eruption-generated tsunami



2022 Tonga volcanic eruption

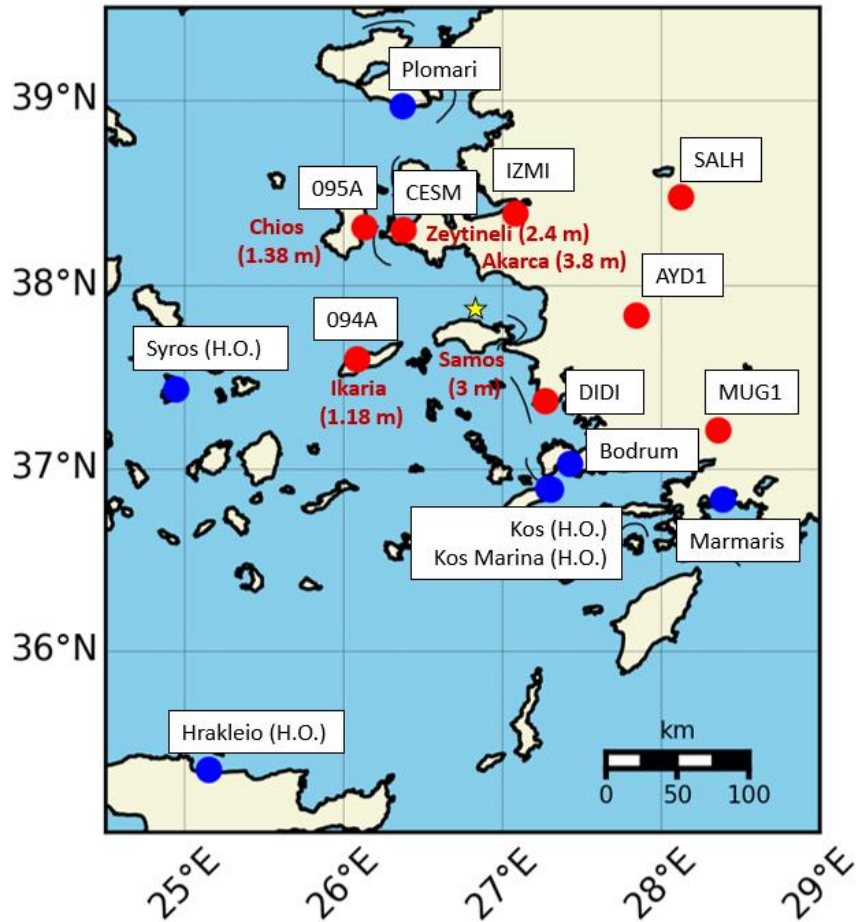


Ravanelli et al. (2023)

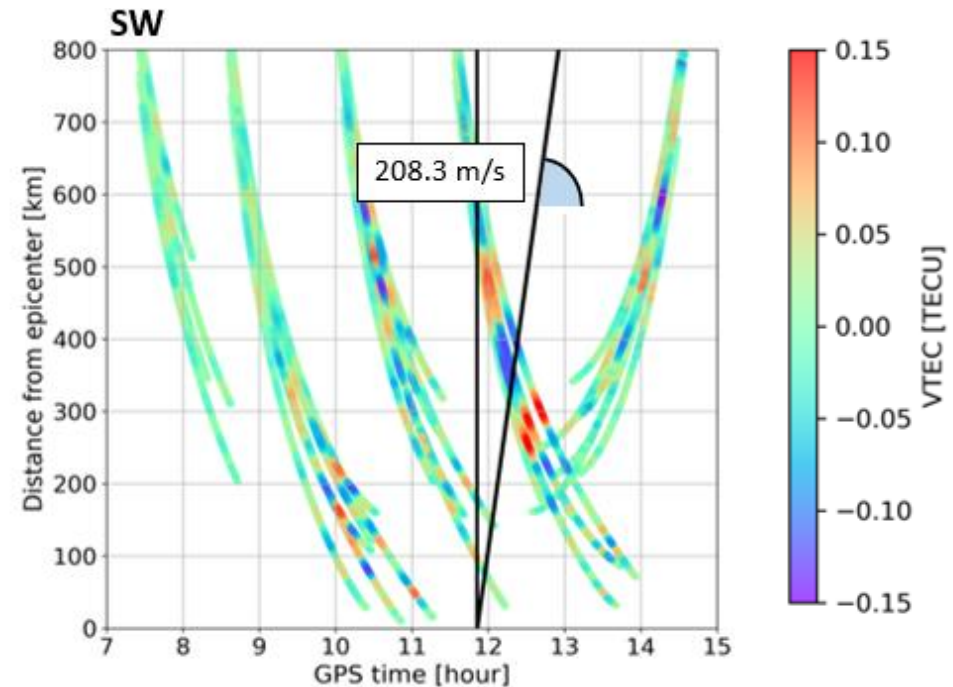
The 2020 Aegean Sea earthquake & tsunami

Mw 7.0 earthquake

GNSS observations & Tide gauges data

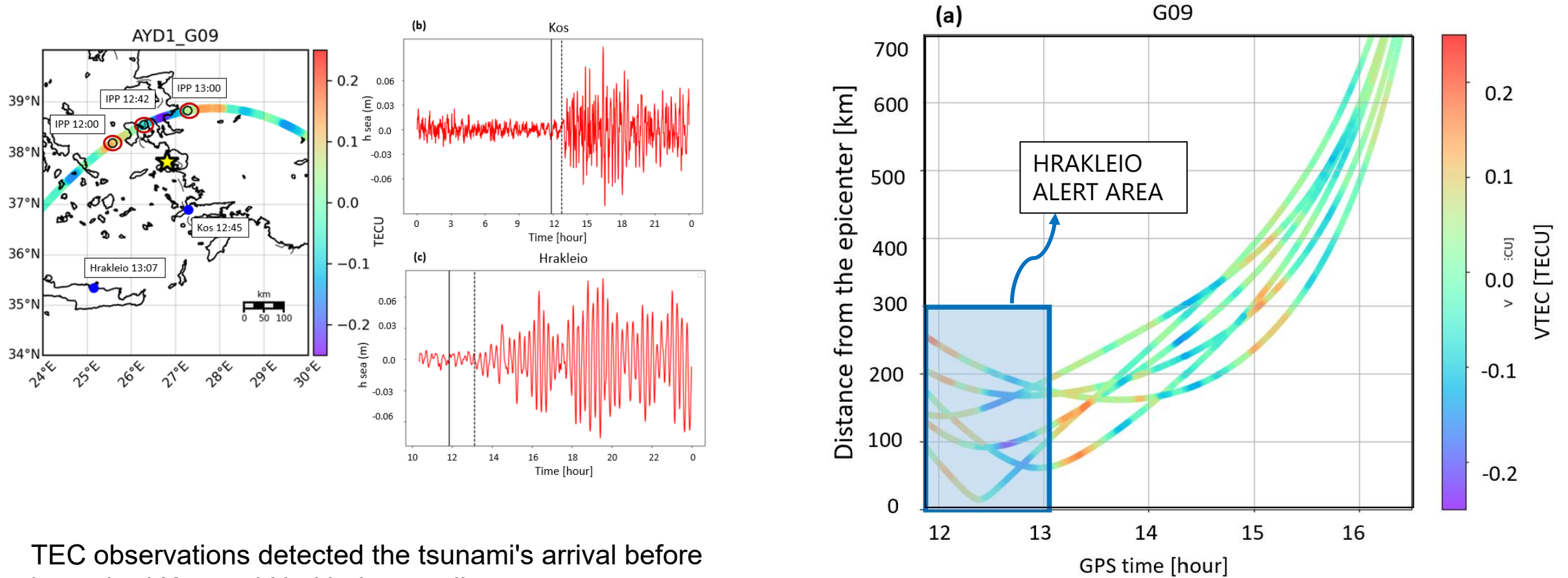


TEC data reveals **internal gravity waves** propagating from the small-scale tsunami in the Aegean Sea (up to 3 m)



Fuso & Ravanelli (2024)

The 2020 Aegean Sea earthquake & tsunami



TEC observations detected the tsunami's arrival before it reached Kos and Hrakleio coastlines

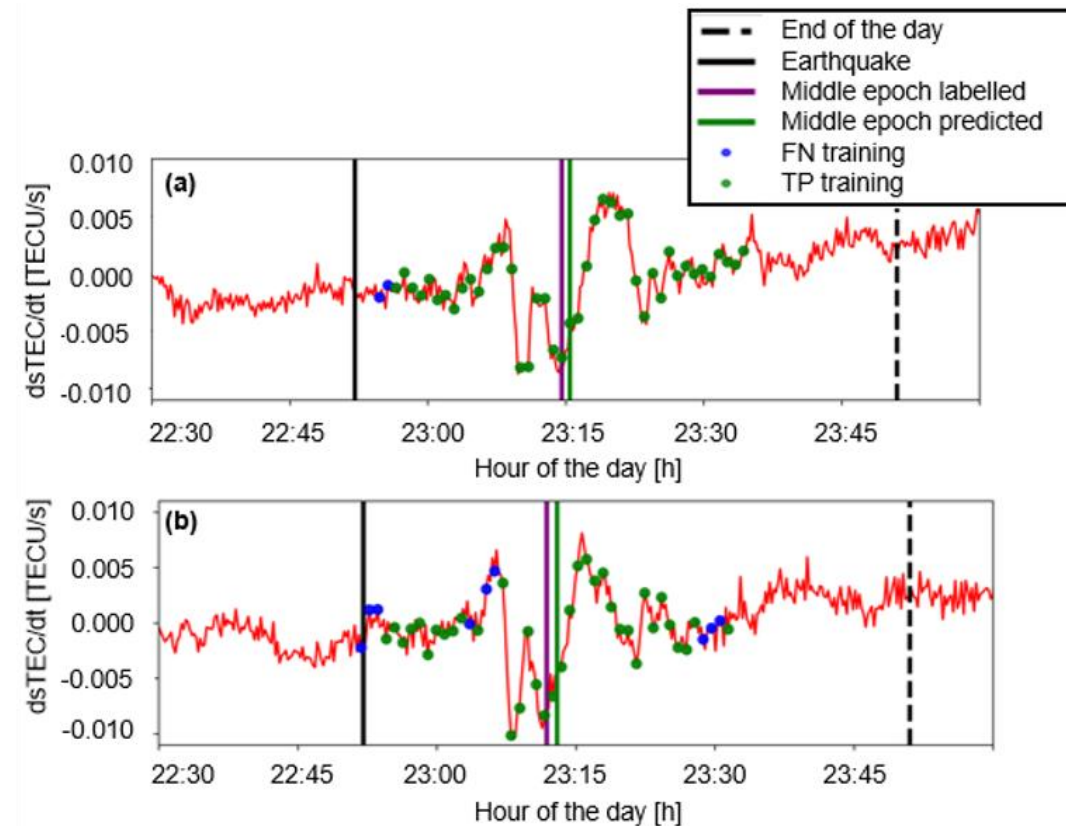
Fuso & Ravanelli (2024)

Artificial intelligence investigation

Automatic real-time detection of ionospheric perturbations induced by earthquakes and tsunamis

- Single event approach: the 2015 Illapel earthquake
- Supervised binary classification task
- Classification with Machine Learning
 - Random Forest
 - XGBoost

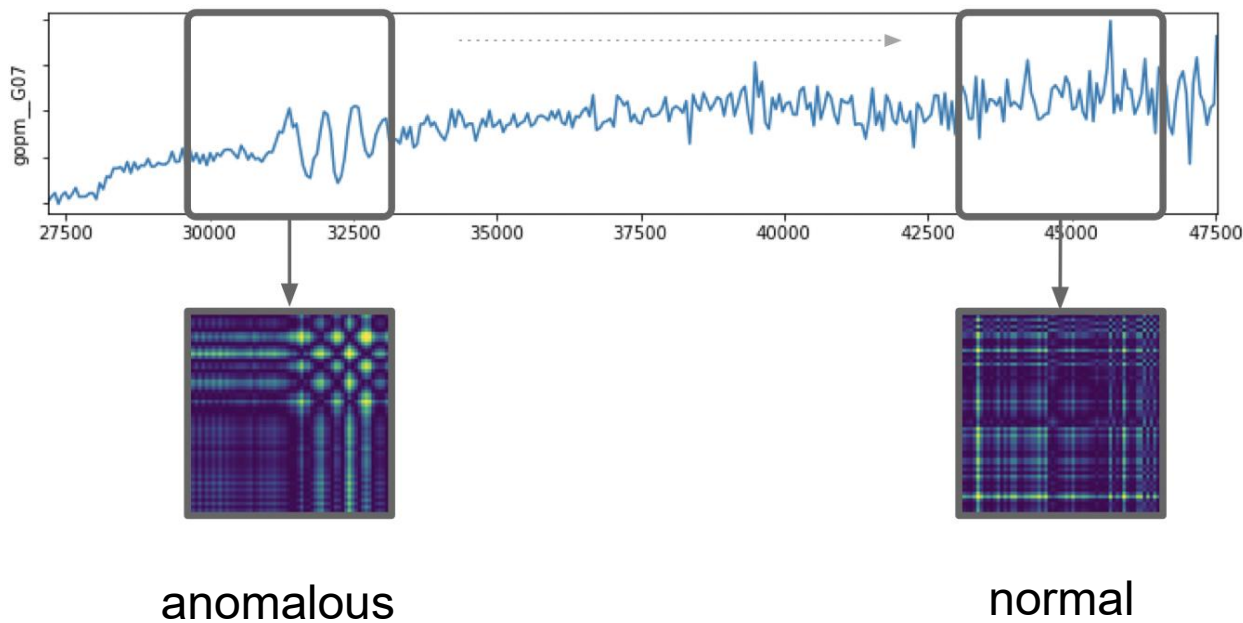
	XGBoost (XGB)		Random forest (RF)	
Elevation cut-off	15°	25°	15°	25°
Added feature(s)	Value range	Variance	Value range	Value range Variance
Accuracy train	0.98	0.99	0.99	0.99
Accuracy test	0.97	0.96	0.96	0.95
Precision	0.80	0.78	0.99	0.98
Recall	0.74	0.78	0.46	0.53
F1 score	0.77	0.78	0.63	0.69



Fuso et al. (2024)

Artificial intelligence investigation

Automatic real-time detection of ionospheric perturbations induced by earthquakes and tsunamis



Ravanelli et al. (2024)

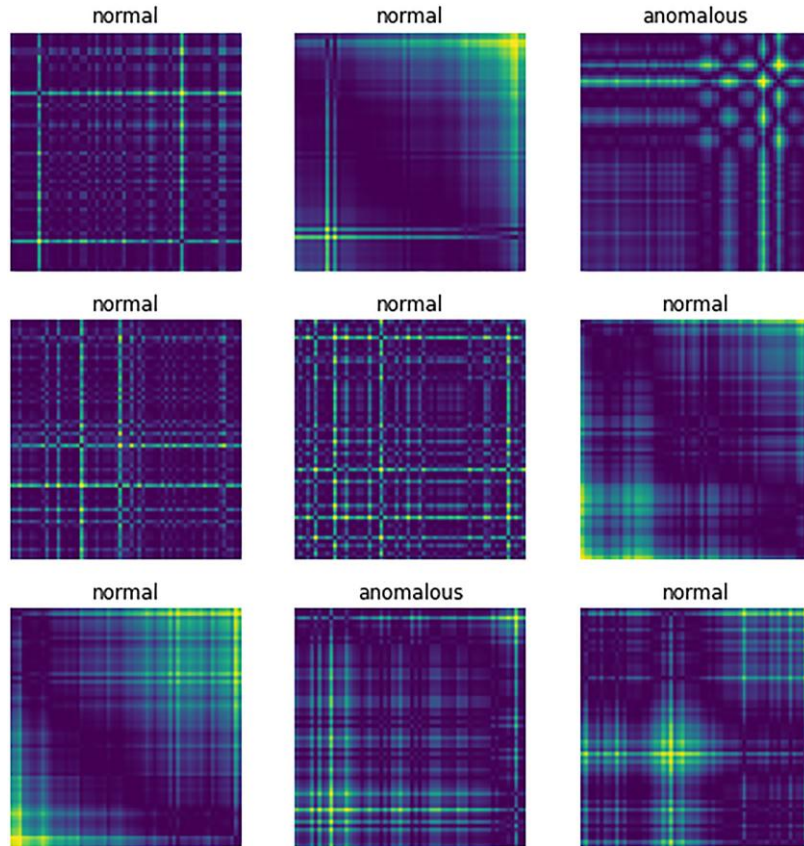
- Multi-event approach in The Pacific area:
 - the 2010 Maule earthquake
 - the 2011 Tohoku earthquake
 - the 2012 Haida-Gwaii
 - the 2015 Illapel earthquake
- **Gramian Angular Difference Fields** that transforms timeseries into images

Advantages

- Preserves Temporal Dependence
- Bijective Matrix
- Detectable Temporal Correlations
- Robust to Missing Data
- Leverages Image-based Deep Learning
- Visually Interpretable

Artificial intelligence investigation

Automatic real-time detection of ionospheric perturbations induced by earthquakes and tsunamis



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Table 4

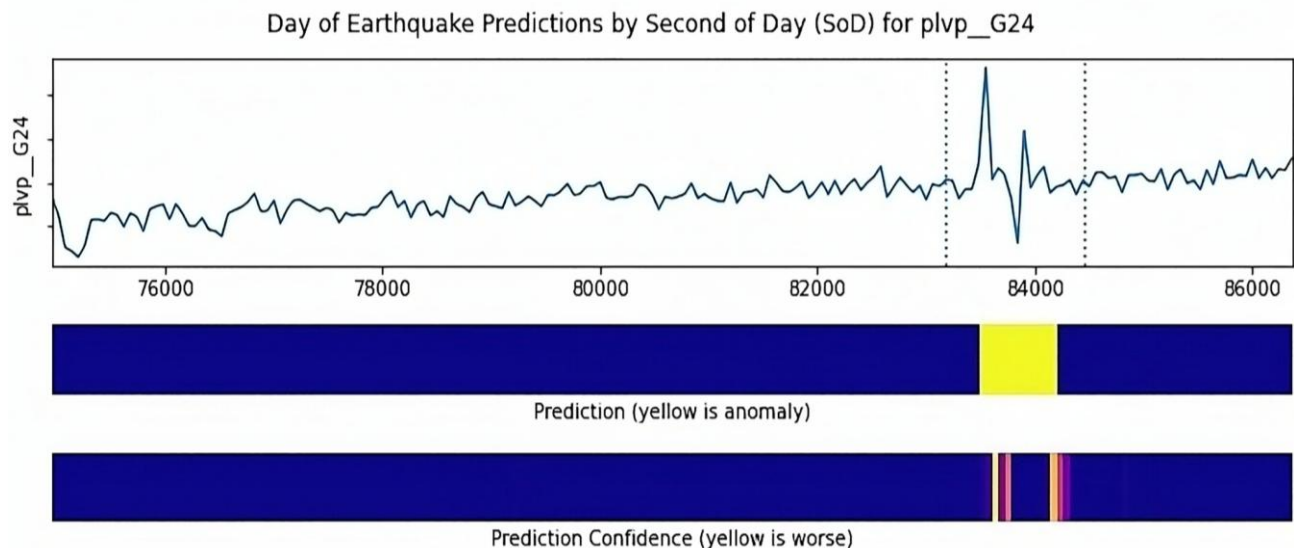
Performance Metrics From Various Stages of the Experiment

Metrics	
validation (false positive mitigation)–recall	84.6.%
validation (false positive mitigation)–precision	100.0%
validation (false positive mitigation)–F ₁ score	91.7%

Ravanelli et al. (2024)

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Ravanelli et al. (2024)

total variability for tsunami hazard estimation

ALTRUIST is one of the eight projects selected worldwide for the Joint Call by the **AXA Research Fund & IOC-UNESCO on Coastal Livelihood** within the framework of **the United Nations Ocean Decade**



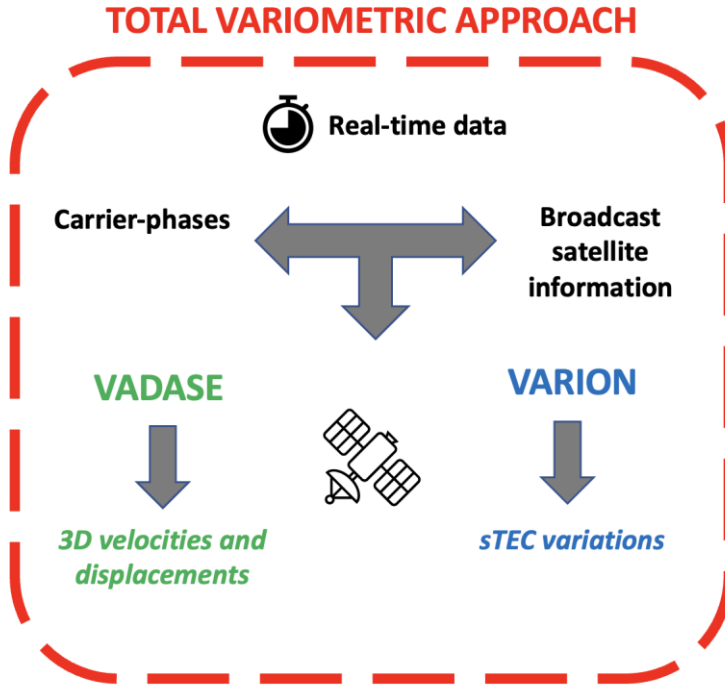
Goals

- Using **real-time GNSS stream** to simultaneously monitoring ground and ionospheric (Total Variometric Approach) observations
- Currently deployed on selected IGS stations and in the GNSS network of Guadeloupe (Caribbean) as a regional testbed
- To test the utilities of multi-layer GNSS observations for tsunami hazard

Ravanelli et al., in prep

The Total Variometric Approach

Using the same GNSS data



Ravanelli et al. (2021)

Total → for a **complete characterization** of the natural hazards or man-made event from ground to the ionosphere in real-time

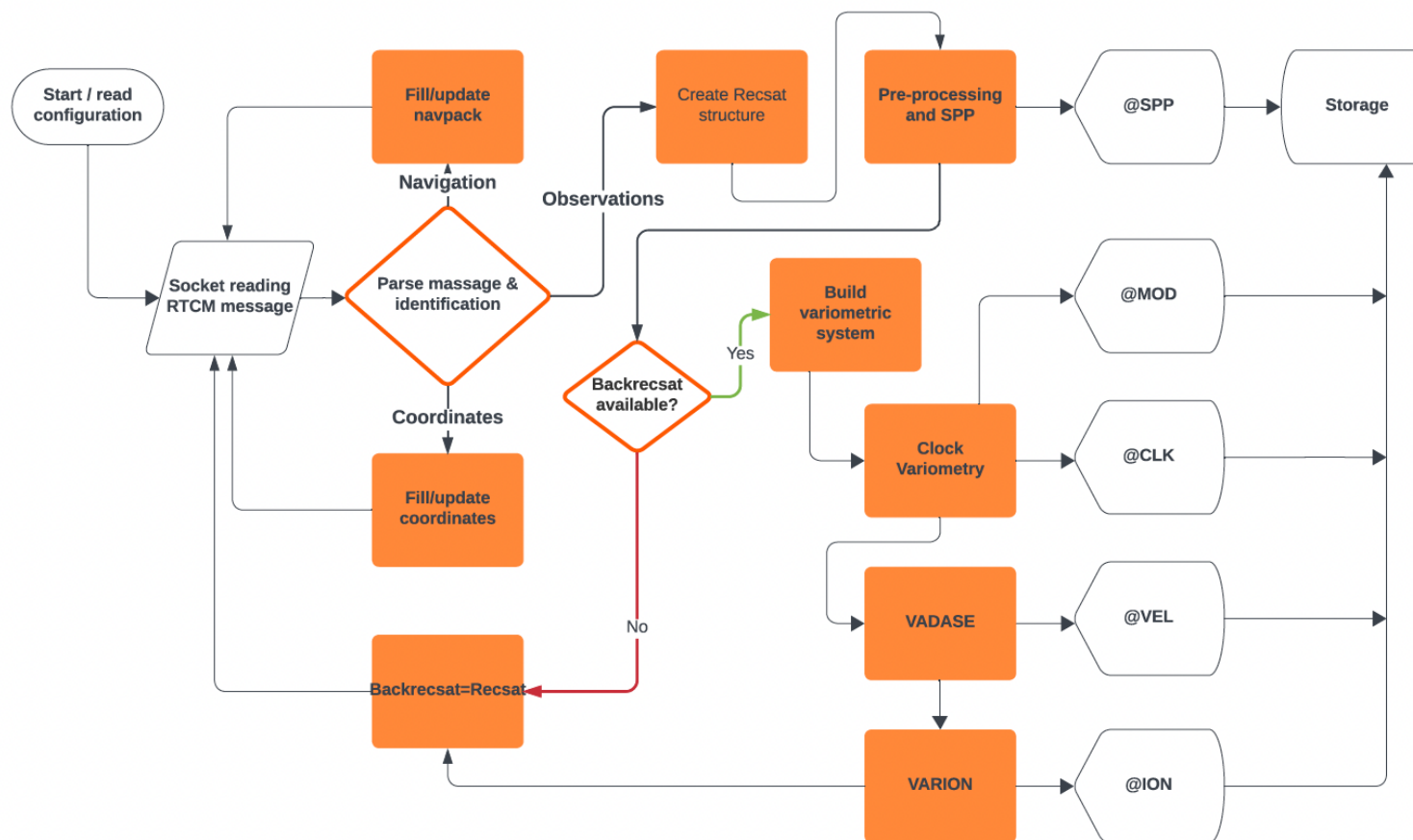
Variometric → based on the Variometric approach

- Based on single time differences of suitable linear combinations of GNSS carrier-phase observations
- Using a stand-alone GNSS receiver and standard GNSS broadcast products (orbits and clocks corrections)
- Working in actual real-time

Total Variometric Approach allows for real-time estimation of a tsunami genesis, potentially suitable to support the classic method for tsunami early warning systems

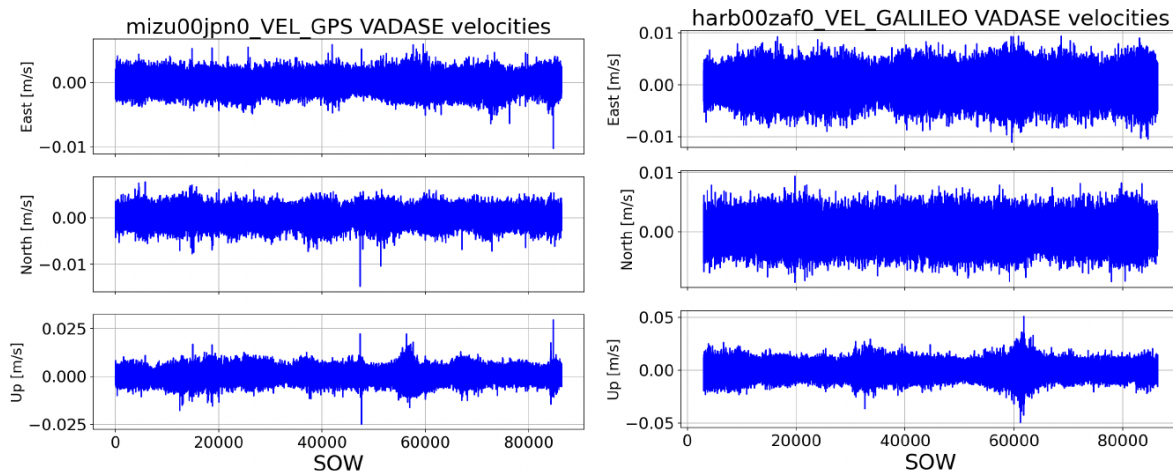
total variometry for tsunami hazard estimation

*The engine: the ALTRUIST project is also based on **GNSS Varioppy***



Ravanelli & Mazzoni, in prep

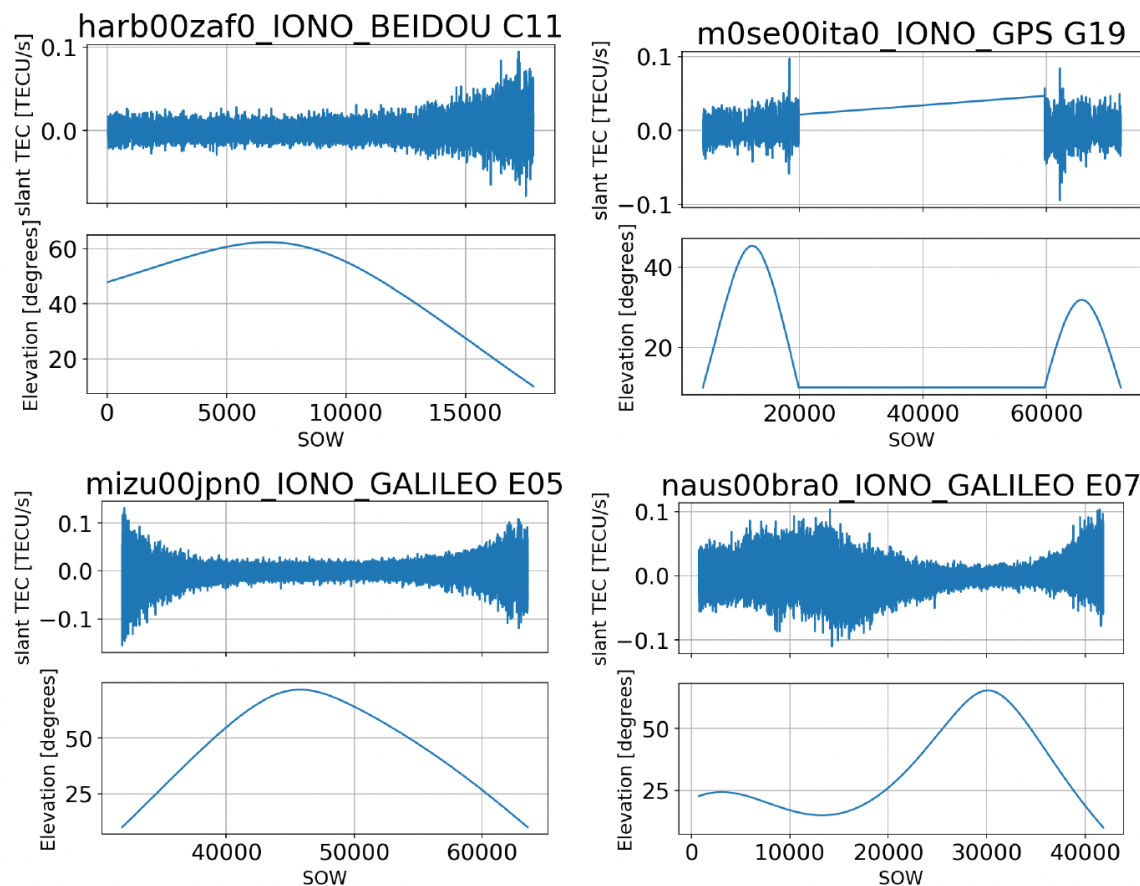
total variomeTry foR tsUnaml hazard eStimaTion



Date	Station	Const.	mean E	std E	mean N	std N	mean U	std U
2026-04-12	ac2400usa0	BeiDou	-1.3252e-05	0.0018	1.4406e-05	0.0026	-7.0142e-06	0.0043
		Galileo	4.5985e-05	0.0019	1.9077e-05	0.0026	9.4038e-05	0.0046
		GPS	5.4289e-07	0.0008	2.0265e-05	0.0013	2.1440e-05	0.0024
	alic00aus0	BeiDou	-2.1839e-05	0.0031	-1.1307e-06	0.0026	-3.0176e-05	0.0085
		Galileo	5.2387e-05	0.0030	-1.6226e-05	0.0025	3.4059e-05	0.0084
		GPS	-5.0055e-05	0.0012	-3.1947e-05	0.0014	5.5411e-05	0.0037
	brux00bel0	BeiDou	6.6732e-06	0.0024	-6.1613e-07	0.0035	1.0786e-04	0.0051
		Galileo	6.5814e-05	0.0020	3.6193e-05	0.0027	1.1068e-04	0.0052
		GPS	3.5441e-05	0.0010	5.4463e-05	0.0014	8.9016e-05	0.0026
	cuib00bra0	BeiDou	-6.6671e-05	0.0021	1.1917e-05	0.0018	-6.0940e-05	0.0052
		Galileo	-1.8775e-06	0.0022	2.9356e-07	0.0018	-2.8875e-05	0.0051
		GPS	-7.6261e-05	0.0010	-9.0315e-06	0.0009	1.1664e-05	0.0026
	harb00zaf0	BeiDou	-3.1147e-04	0.0024	1.1853e-05	0.0022	-2.4626e-05	0.0062
		Galileo	-1.9962e-04	0.0023	-1.3553e-05	0.0020	-1.2799e-05	0.0061
		GPS	-2.2940e-04	0.0011	1.1448e-05	0.0012	3.1005e-05	0.0028
	m0se00ita0	BeiDou	-3.9479e-05	0.0031	2.2346e-05	0.0036	1.0322e-04	0.0071
		Galileo	3.5827e-05	0.0021	4.4898e-05	0.0023	1.0763e-04	0.0054
		GPS	1.6372e-05	0.0012	5.9771e-05	0.0015	7.6953e-05	0.0030
	mizu00jpn0	BeiDou	-7.3415e-05	0.0025	1.1910e-04	0.0029	5.1197e-04	0.0066
		Galileo	1.6196e-05	0.0023	1.5373e-04	0.0027	4.7237e-04	0.0063
		GPS	-1.0308e-04	0.0011	1.6044e-04	0.0015	6.0819e-04	0.0029
	nklg00gab0	BeiDou	-1.6389e-04	0.0029	-3.0308e-05	0.0030	1.0085e-05	0.0076
		Galileo	-8.5103e-05	0.0035	-4.9826e-06	0.0033	-9.3297e-06	0.0085
		GPS	-1.9794e-04	0.0018	6.1660e-05	0.0017	-5.7907e-05	0.0053
	samo00wsm0	BeiDou	-5.4426e-05	0.0023	7.4143e-05	0.0021	-5.4107e-05	0.0054
		Galileo	-3.0356e-06	0.0026	6.1057e-05	0.0027	-5.8329e-05	0.0082
		GPS	-3.7931e-05	0.0015	5.6142e-05	0.0016	8.1472e-05	0.0043
	urum00chn0	BeiDou	1.0721e-04	0.0084	1.4719e-05	0.0053	-7.1561e-05	0.0102
		Galileo	1.6413e-04	0.0078	3.3254e-05	0.0031	4.3946e-05	0.0068
		GPS	6.8781e-05	0.0087	1.6263e-05	0.0024	3.7502e-05	0.0047

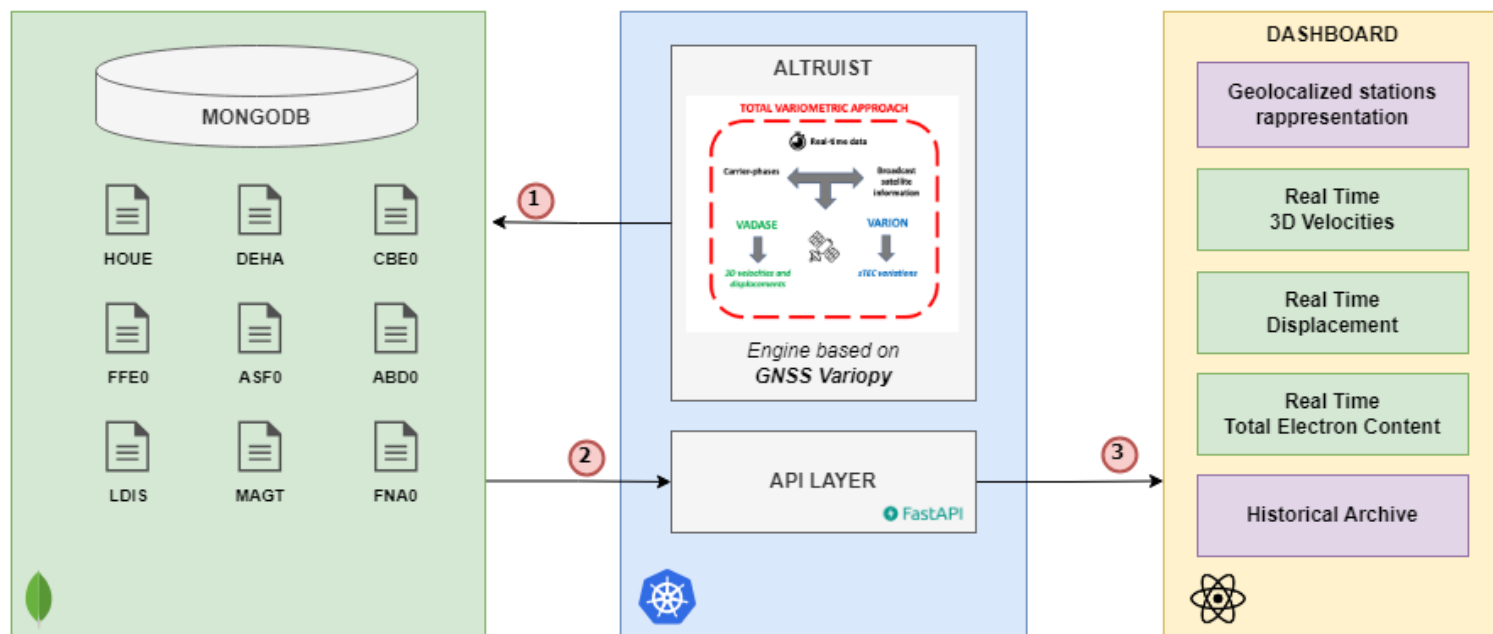
Ravanelli & Mazzoni, in prep

total variomeTry foR tsUnaml hazard eStimaTion



Ravanelli & Mazzoni, in prep

total variometric approach for tsunami hazard estimation



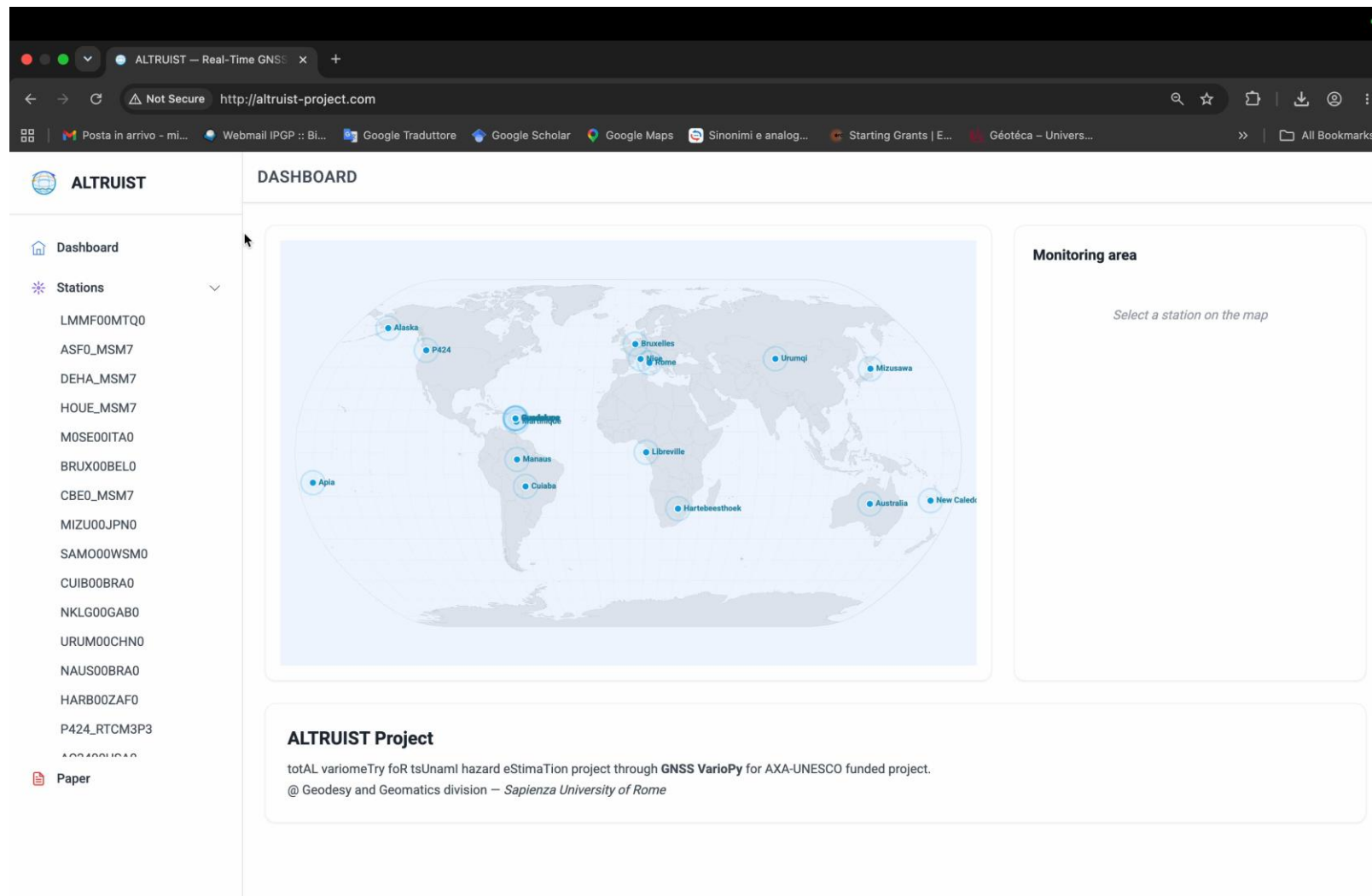
- ① ALTRUIST analyses GNSS observations and store real-time TVA solutions in a database
- ② An API Layer is used to expose data and provide it through a REST protocol in JSON format
- ③ A live dashboard shows real-time TVA solutions on dynamic plots and provide historical solutions using APIs

- Front-end dashboard allows for interactive and real-time data visualization
- Back-end layer allows for real-time and historical data management
- **Modular and scalable**, being suitable to plug external modules to enhance ALTRUIST's capacity
- **Inclusion of every RTCM3 GNSS data stream**

Ravanelli et al., in prep

The ALTRUIST project

total variomeTry foR tsUnaml hazard eStimaTion



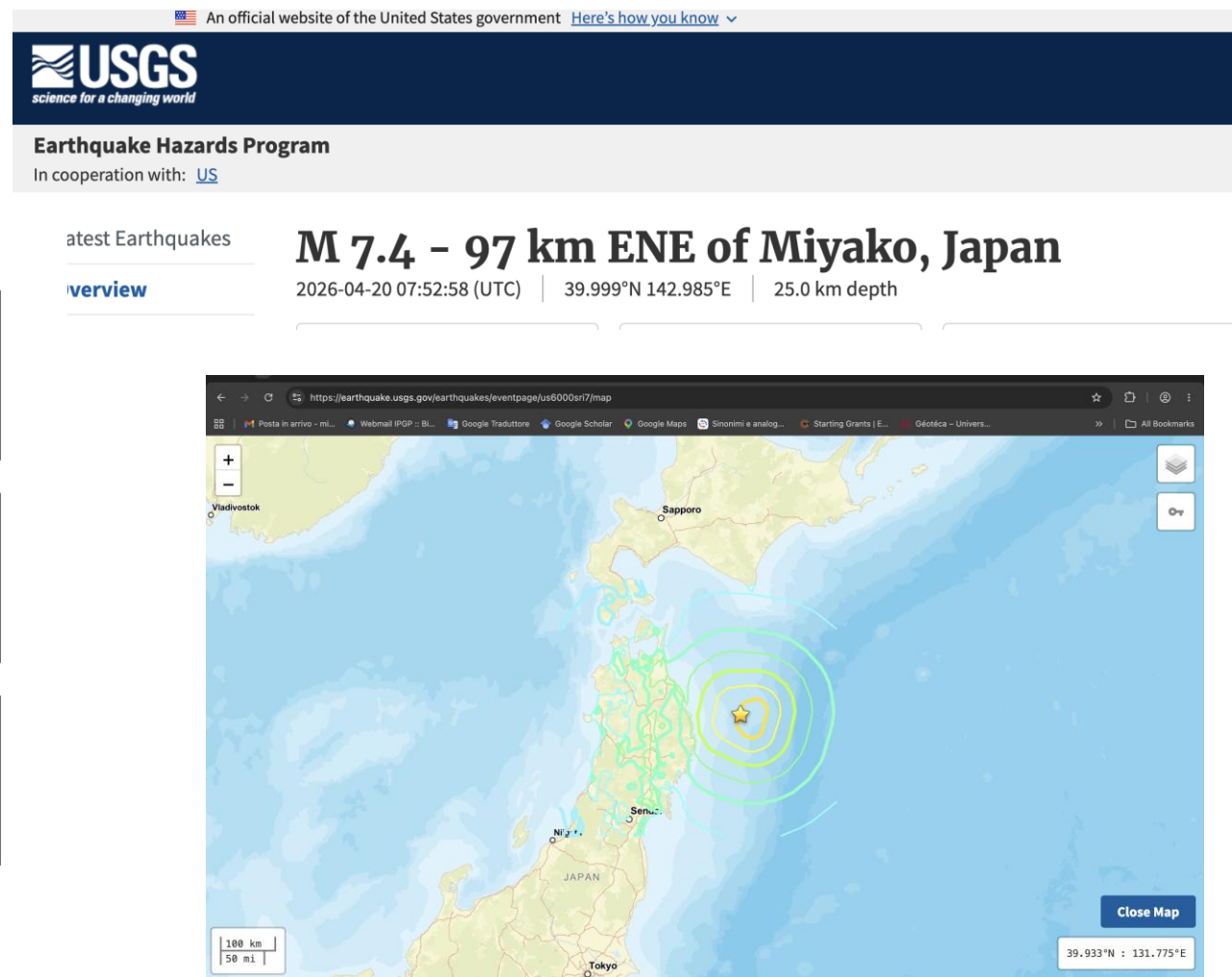
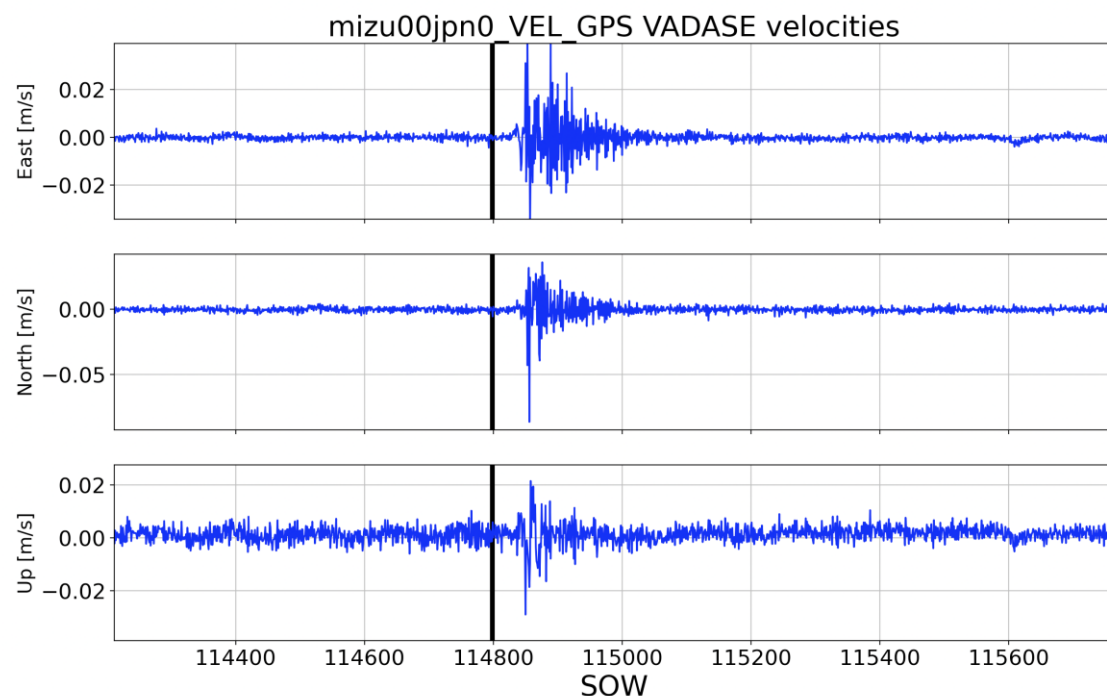
The screenshot shows a web browser window with the URL <http://altruist-project.com>. The page title is "ALTRUIST — Real-Time GNSS". The dashboard features a sidebar with a navigation menu including "Dashboard", "Stations", and "Paper". The "Stations" list includes codes like LMMF00MTQ0, ASF0_MSM7, DEHA_MSM7, etc. The main content area is titled "DASHBOARD" and contains a world map with various stations marked (Alaska, P424, Bruxelles, Rome, Urumqi, Mizusawa, Apia, Manaus, Cuiaba, Libreville, Harthebeesthoek, Australia, New Caledonia). A "Monitoring area" section prompts the user to "Select a station on the map". At the bottom, there is a section titled "ALTRUIST Project" with a description: "total variomeTry foR tsUnaml hazard eStimaTion project through GNSS VarioPy for AXA-UNESCO funded project. @ Geodesy and Geomatics division — Sapienza University of Rome".

<https://altruist-project.com/>



total variomeTry foR tsUnaml hazard eStimaTion

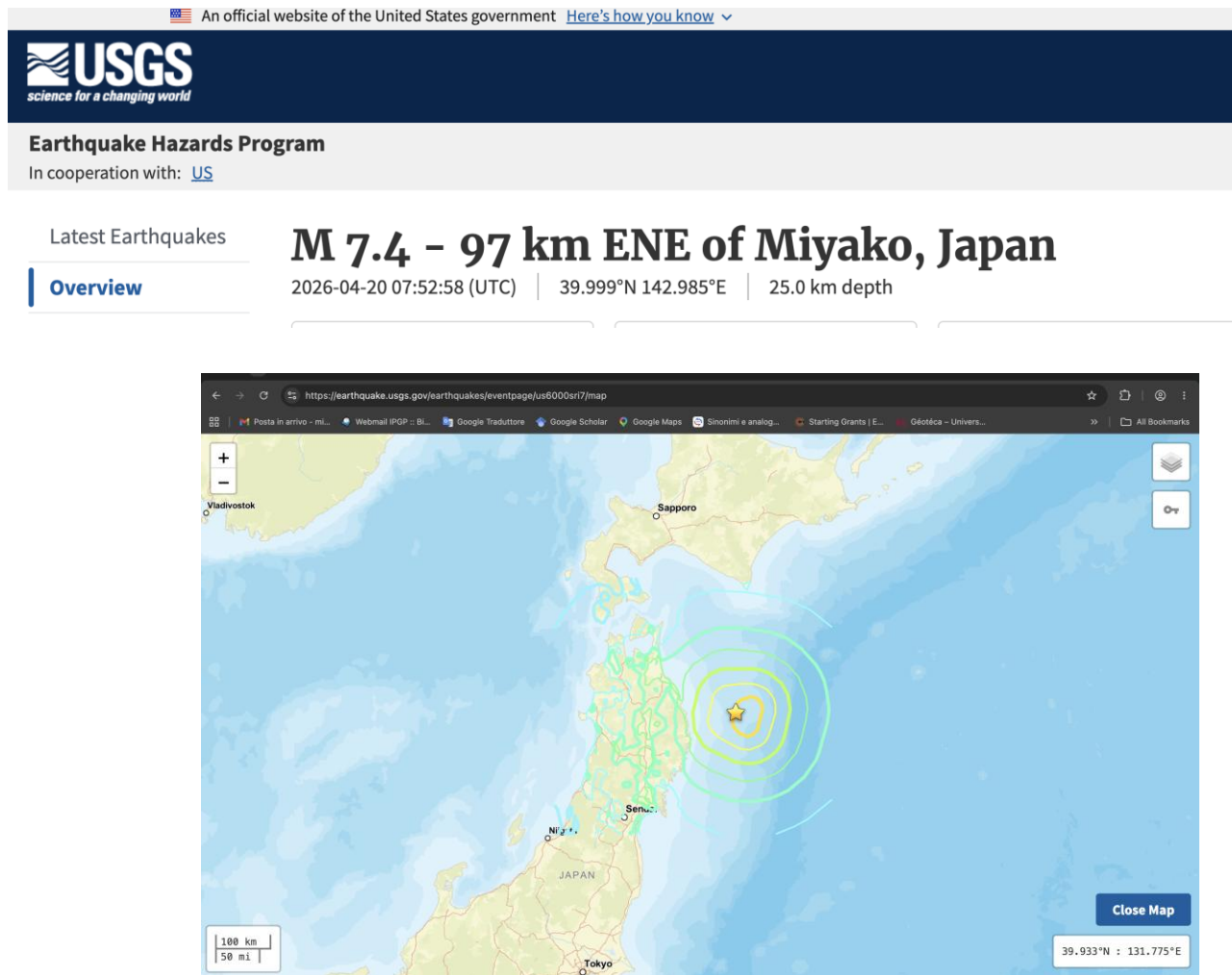
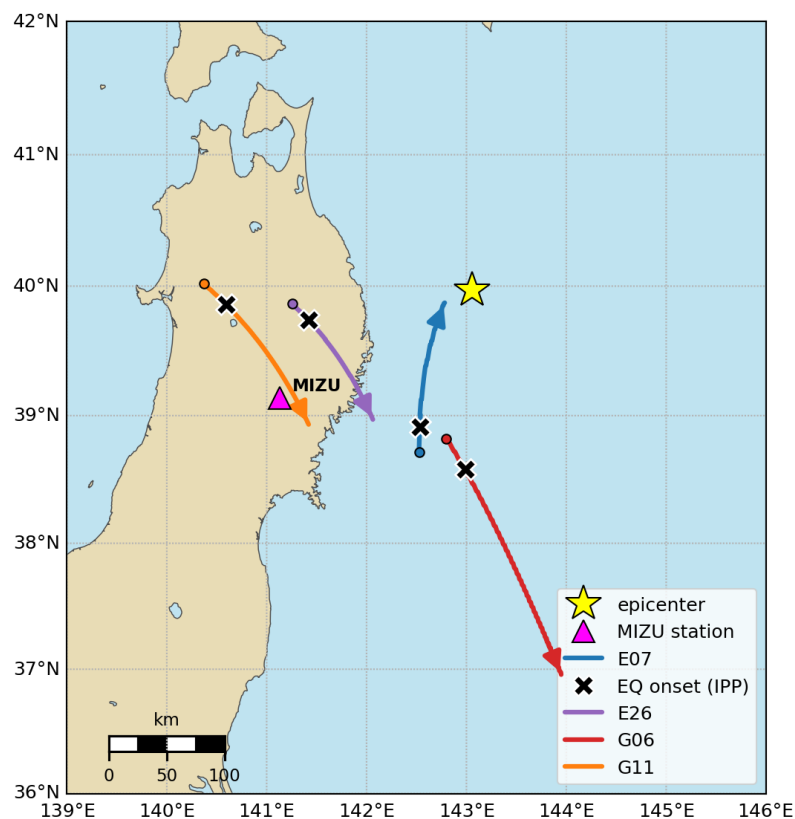
A real-time earthquake: 20 April 2026 earthquake



Ravanelli & Mazzoni, in prep

total variomeTry foR tsUnaml hazard eStimaTion

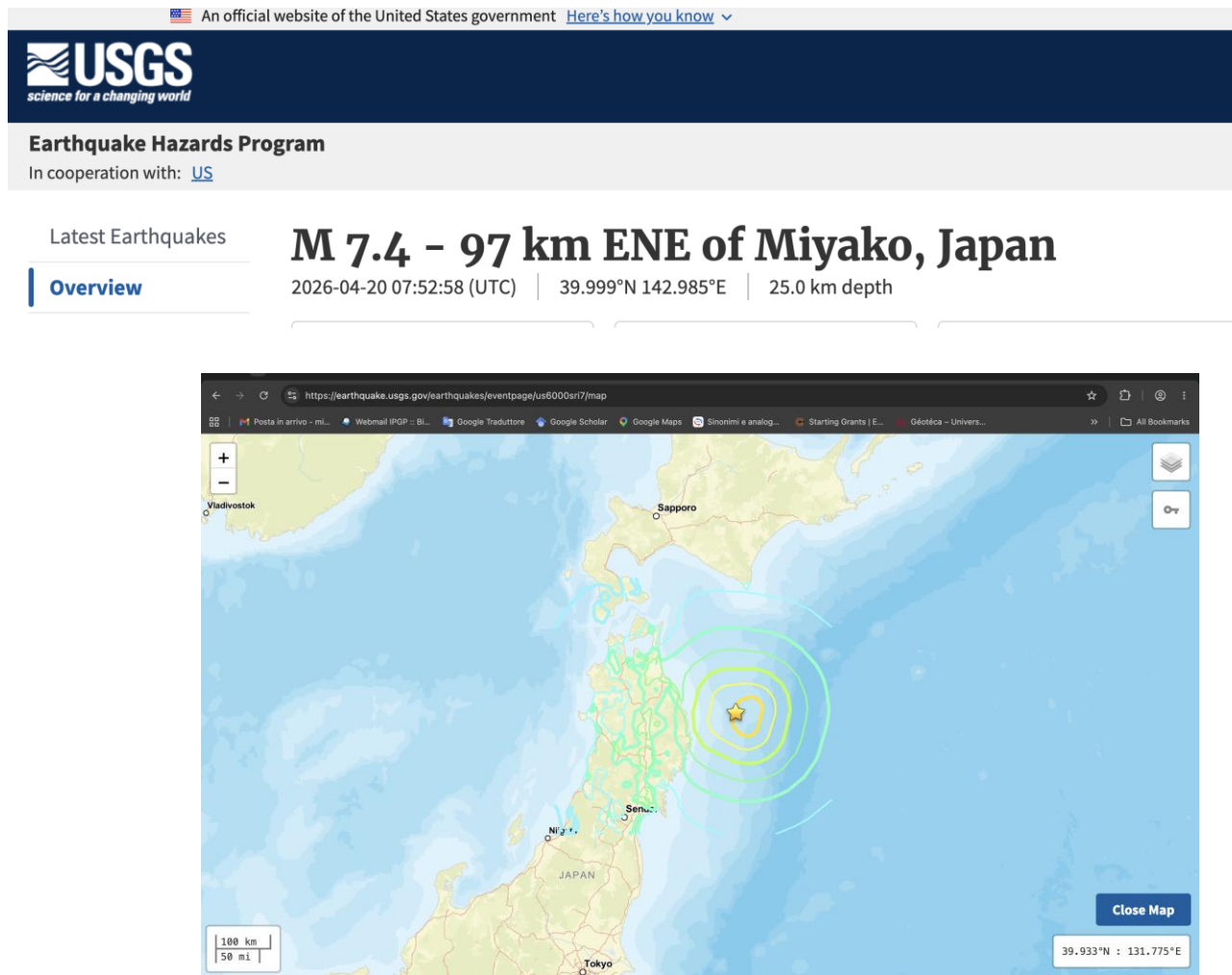
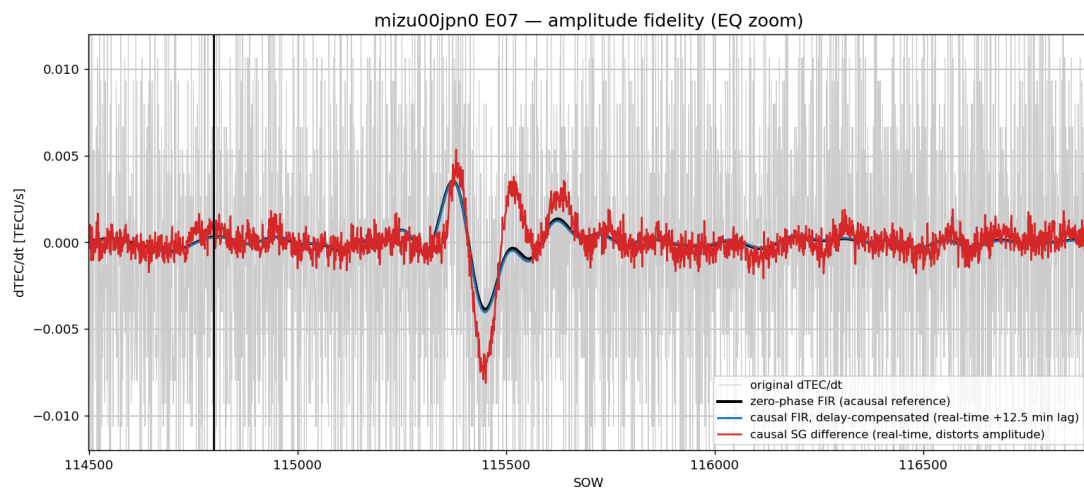
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Ravanelli & Mazzoni, in prep

total variomeTry foR tsUnaml hazard eStimaTion

A real-time earthquake: 20 April 2026 earthquake



Ravanelli & Mazzoni, in prep

GO-EUREKA

- The GNSS-observation-based European system for earthquake and tsunami risk assessment (“GO-EUREKA”) → <https://go-eureka.eu/>
- cooperation of several research institutes from France, Italy, Norway, Brazil, Japan and Chile. GO-EUREKA
- use quasi-continuous observations of ionospheric total electron content (TEC) from ground-based and ship-based dual-frequency GNSS-receivers, to assess earthquake and tsunami related hazards
- Its final aim is to improve the existing tsunami early warning systems.



Conclusions & Outlook

- GNSS-TEC enables improved understanding of **rapid geophysical processes hazard dynamics** and real-time tsunami monitoring
- GNSS-TEC consistently reveals ionospheric dynamics that seismic and sea-level networks miss, on timescales relevant to hazard response
- ***GNSS-TEC is a natural extension of geodesy's role in hazard science***
 - GNSS networks are increasingly multi-purpose sensing systems
- GNSS-TEC monitoring has moved from a retrospective research tool to a credible, **near-real-time** complement to seismic and sea-level networks in multi-hazard early-warning systems — with network geometry, receiver density, and streaming infrastructure now the key levers for operational deployment

Grazie per l'attenzione!

References

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➤ <https://doi.org/10.1029/2022GL101465>
- Ravanelli, M., Occhipinti, G., Savastano, G., Komjathy, A., Shume, E. & Crespi, M. (2021), "GNSS total variometric approach: first demonstration of a tool for real-time tsunami genesis estimation", *Scientific reports*, 11(1), 3114, pp. 1-12, doi:
➤ <https://doi.org/10.1038/s41598-021-82532-6>
- ALTRUIST: <http://altruist-project.com/>
- ALTRUIST <https://axafoundation.org/en/science/funded-projects/climate-environment/mitigating-tsunamis-threats-and-destructive-impacts-through-enhanced-navigation-satellite-system>

Conclusions & Outlook

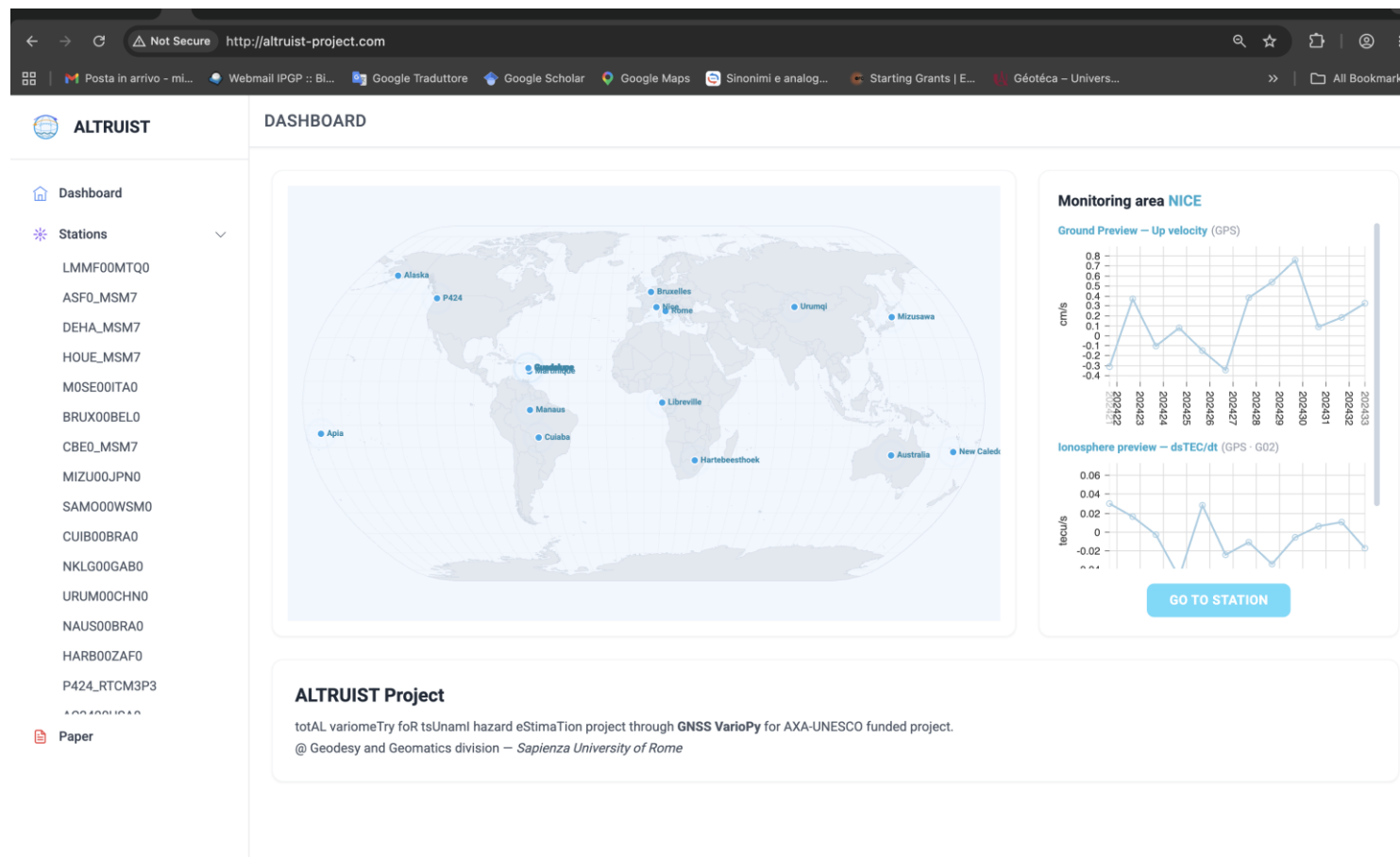
GNSS-TEC as a powerful tool for

- high-resolution probing of ionospheric variability
- atmosphere–ionosphere coupling

***It enables improved understanding of rapid geophysical processes
hazard dynamics and real-time tsunami monitoring***

The ALTRUIST project

total variomeTry foR tsUnaml hazard eStimaTion



<http://altruist-project.com/>



Ravanelli et al., in prep

Conclusions & Outlook

- GNSS-TEC sensing constitutes a disruptive technology for tsunami monitoring and detection
- GNSS-TEC could significantly strengthens next-generation tsunami early warning systems
- ALTRUIST and GO-EUREKA as engine of the transitions!

GNSS-TEC as a powerful tool for high-resolution probing of ionospheric variability and atmosphere–ionosphere coupling, enabling improved understanding of rapid geophysical processes and hazard dynamics.