*United Nations*
*Office for Outer Space Affairs*
*International Committee on GNSS*
*17th Meeting*

# Near-Real-Time Anomaly Detection in Total Electron Content for the GUARDIAN Ionospheric Monitor

**Léo Martire**[1, 2], S. Krishnamoorthy[1], F. Luhrmann[3], J. Park[3], A. Komjáthy[1], B. Szilágyi[1], L. Romans[1], P. Vergados[1]

[1] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA
[2] International GNSS Service Central Bureau Deputy Director
[3] Oregon State University, Corvallis, OR, USA

**Jet Propulsion Laboratory**
California Institute of Technology

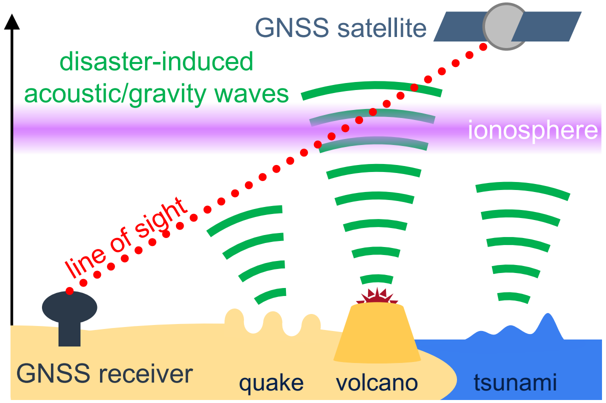
# Outline

- Background
  - Ionospheric Sensing of Natural Hazards
  - Field of View in Ionospheric Monitoring
- GUARDIAN Coverage in the Pacific Ocean
- GUARDIAN Observations
- AI-Based Automatic Detection of Ionospheric Disturbances
- Conclusion

# Background

## Ionospheric Sensing of Natural Hazards

- Natural hazards (tsunamis, earthquakes, volcanoes, meteor impacts, *etc.*) **generate atmospheric waves.**
- Atmospheric waves **propagate up to the ionosphere**, and cause electron density fluctuations.
- Perturbations in total electronic content (TEC) can be **detected using GNSS observations** for each satellite-station pair.
- Objective: use near-real-time GNSS-derived TEC data to **augment natural hazard early warning systems**.



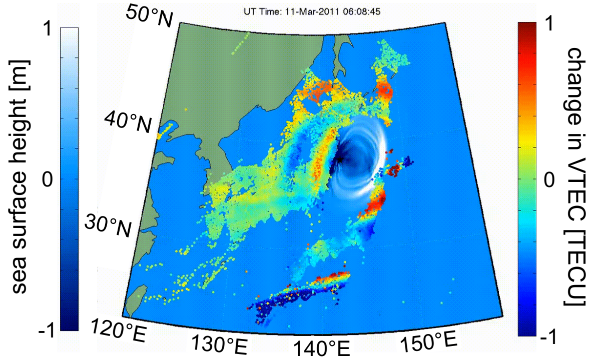
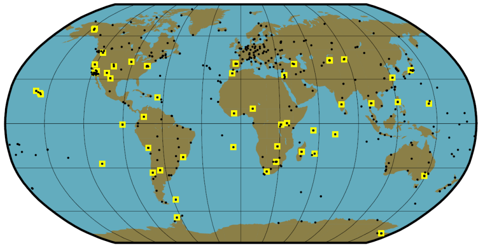




Figure: Ionospheric TEC and sea surface height map for the 2011 Tōhoku-Oki event (Galvan *et al.*, 2012).

GDGPS Global Network:
200+ Real-Time Sites



# Background

## Field of View in Ionospheric Monitoring

- A **single ground-based GNSS station** is sufficient to capture **key signals** up to ≈ **1200 km away**.
- **Multi-GNSS tracking** allows an **even better** coverage of the ionosphere.
- **Simple signal processing methods** are sufficient to distinguish those signals.

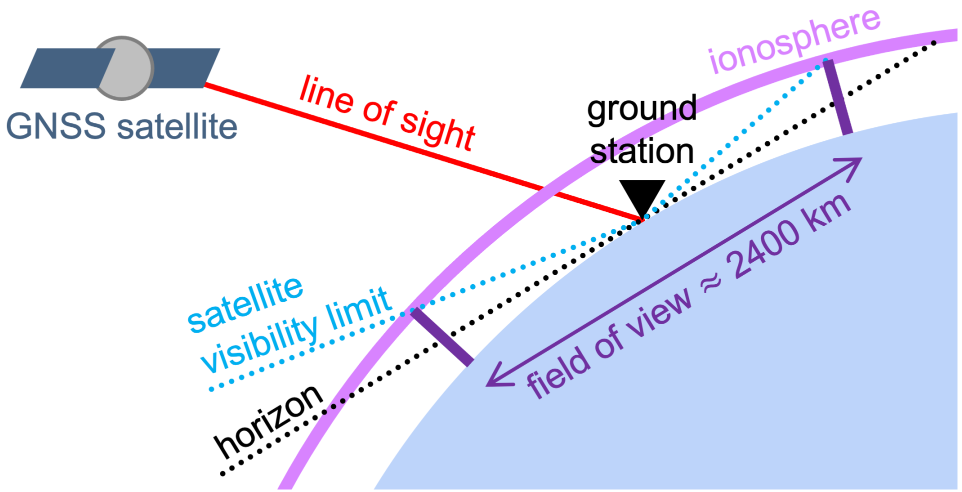



**Figure:** schematic of the ionospheric field of view from a single ground GNSS station.

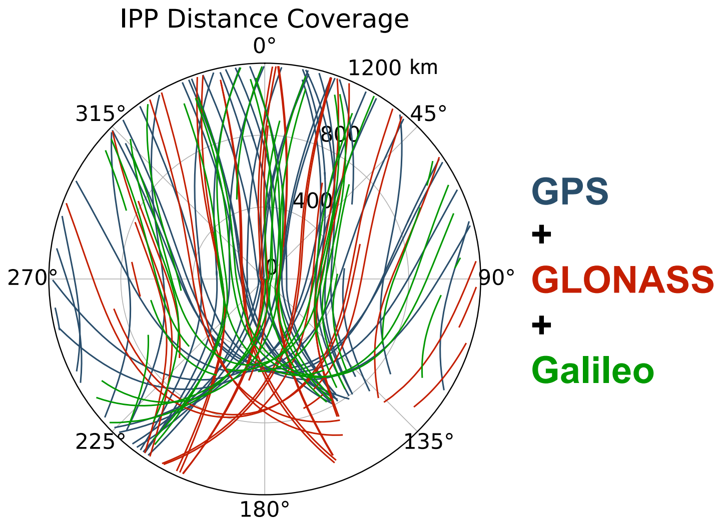
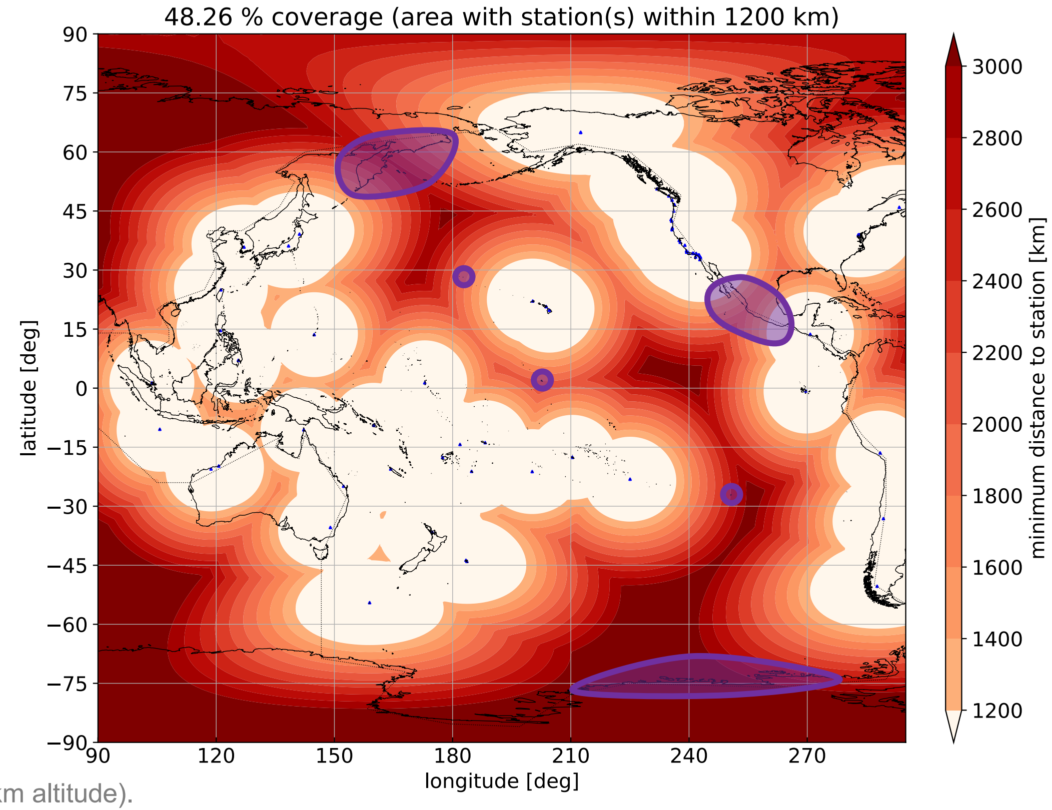



**Figure:** skyplot - satellite paths above a given GNSS site, as function of **distance** and **azimuth** relative to the site.

# GUARDIAN Architecture

## Coverage in the Pacific Ocean

- Maximum possible coverage[1]: 82 %.
- 2022 Coverage[1]: 59 % of max.




[1] Area with stations < 1200 km
(*i.e.*, a 15 degree elevation cut-off for an ionospheric shell at 350 km altitude).

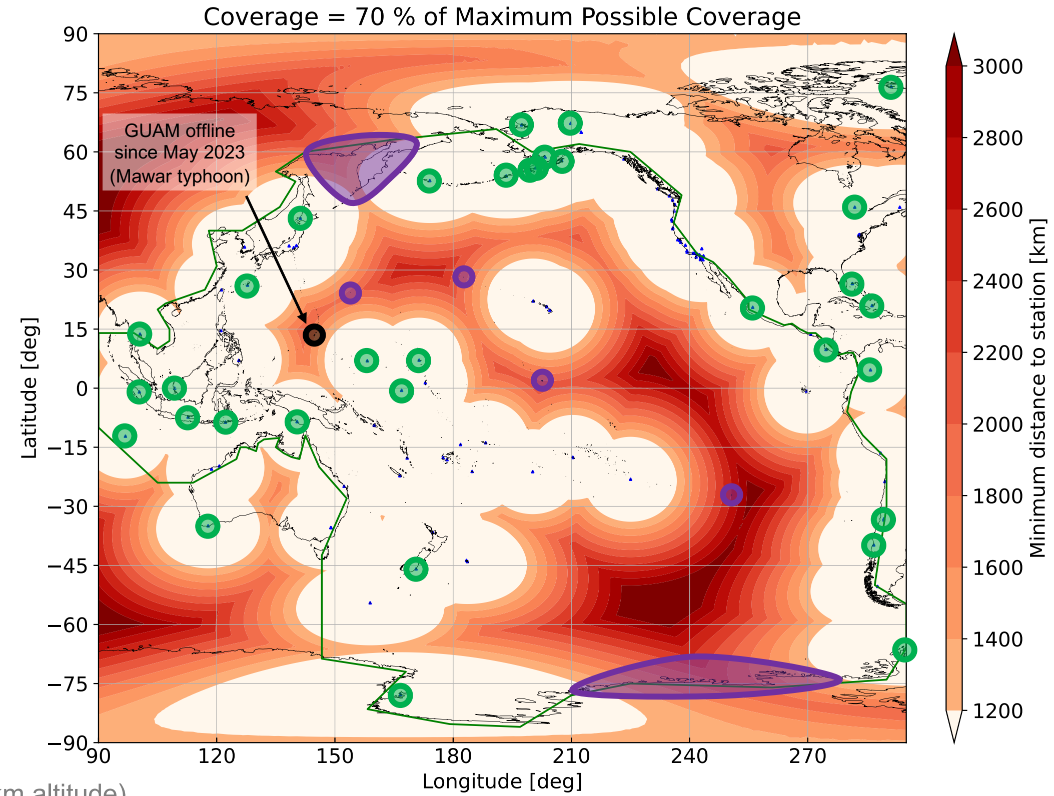
# GUARDIAN Architecture

## Coverage in the Pacific Ocean

- Maximum possible coverage[1]: 82 %.
- 2023 Coverage[1]: **70 % of max** (+11 %).

- Strategically important regions:
  - <u>With existing stations:</u> Kamchatka Peninsula (Russia; PETS, YSSK, MAG0), ~~Indonesia, Micronesia,~~ Minamitorishima Island (Japan; MCIL), Guam (USA; GUAM), Antarctica's Bear Peninsula (BERP), Kiribati (KRTM), Easter Island (Chile; ISPA), Ecuador (SNLR), ~~Mexico, Aleutians Islands~~.
  - <u>Without stations:</u> Midway Atoll (USA).

- With strategic regions covered:
  ⇒ 82% of max.



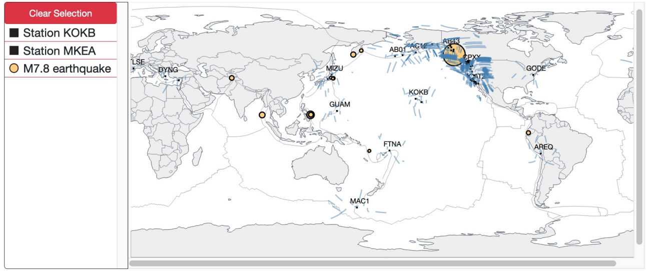

[1] Area with stations < 1200 km
(*i.e.*, a 15 degree elevation cut-off for an ionospheric shell at 350 km altitude).

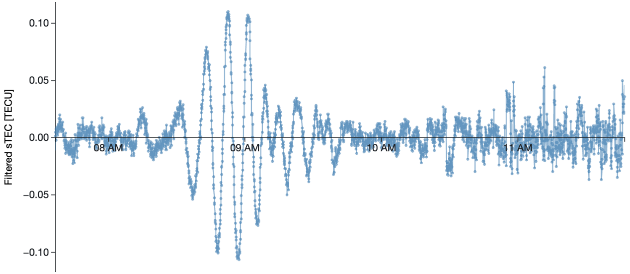
# GUARDIAN Observations

Reminder

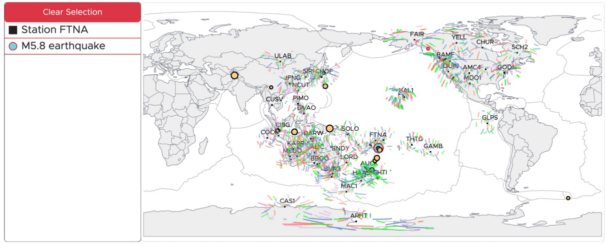
**Existing showcase examples:**

- Tsunami (Haida Gwaii, 2012): https://guardian.jpl.nasa.gov/examples/haidagwaii121028

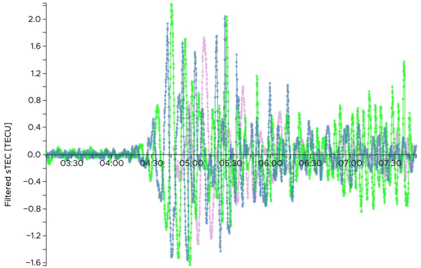



- Volcanic Eruption (Tonga, 2022): https://guardian.jpl.nasa.gov/examples/tonga220115



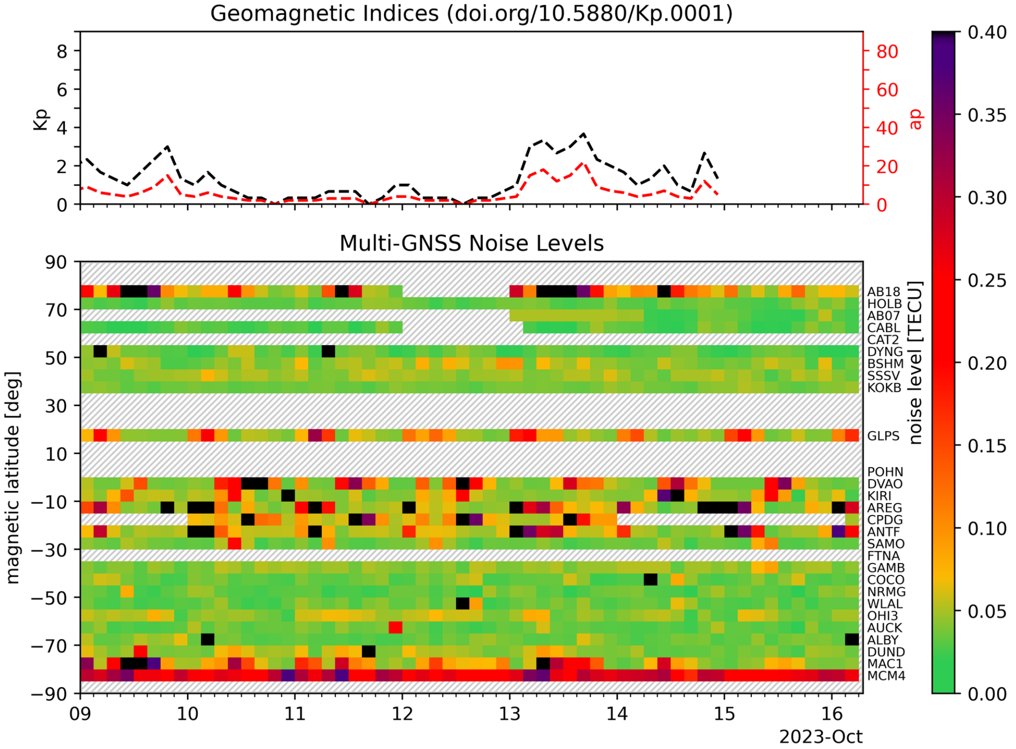

M 5.8 Volcanic Eruption - 68 km NNW of Nuku'alofa, Tonga, on 2022-01-15
Solar Noon: 23:50. **Event: 04:14:45.** Sunset: 06:27. Sunrise: 17:13.



# GUARDIAN Observations

## Use as a Space Weather Proxy

**Near-real-time records of the noise level w.r.t. magnetic latitudes.** https://guardian.jpl.nasa.gov/analysis/spaceWeather



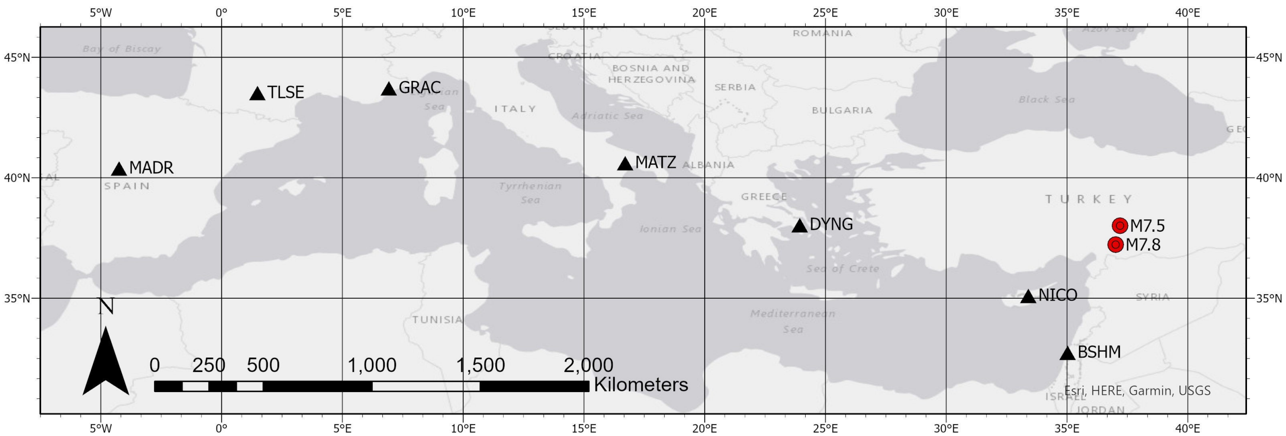

Key points:

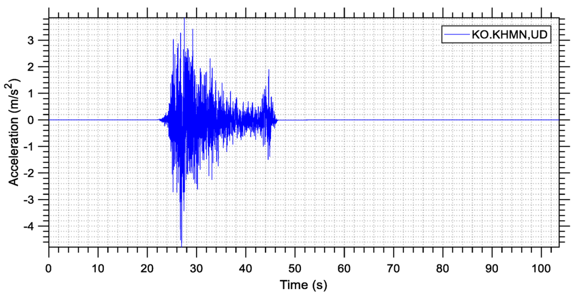
- Noise levels are higher at high latitudes and around the magnetic equator (*e.g.*, auroras, bubbles).
- Ionosphere reacts strongly to geomagnetic storms (*vertical lines*).
- Daily variability is observable.
- Note: monitored stations are mainly around the Pacific Ocean.

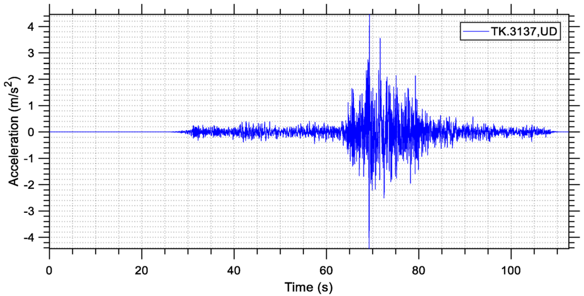
# Automatic Detections of TIDs (Luhrmann *et al.*, 2023, under review)

Study Case

- We study **the 2023 Turkish Kahramanmaraş sequence**.
- **$M_w$=7.8** and **7.5** earthquakes.
- GUARDIAN stations of interest: NICO, BSHM, DYNG, MATZ, GRAC, TLSE, MADR.
- PGAs for the $M_w$=7.8 quake, 30-70 km away: 0.60 to 0.75 g (Papazafeiropoulos and Plevris, 2023).



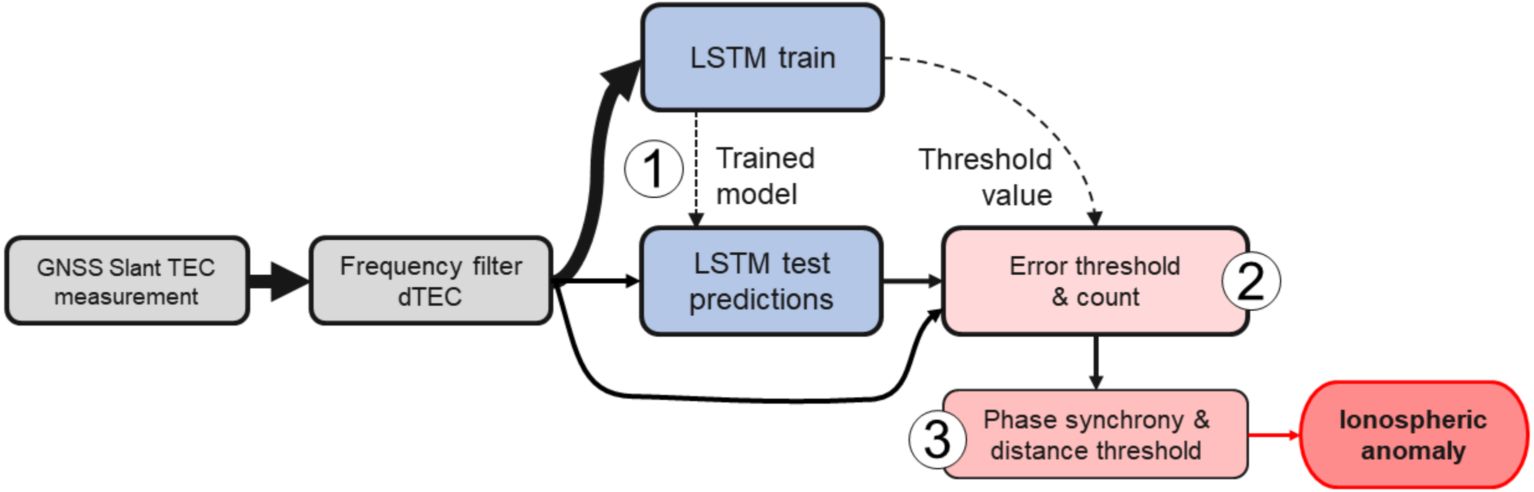



# Automatic Detections of TIDs (Luhrmann *et al.*, 2023, under review)

Method

- Method: **Long Short-Term Memory** (LSTM) deep learning neural network.
- Assumption: The LSTM is able to **learn the temporal dynamics** of differential TEC.
- Expected Outcome: Differences between observations and LSTM-expected dynamics represent **anomalous ionospheric behaviour**.



# Automatic Detections of TIDs (Luhrmann *et al.*, 2023, under review)

Training

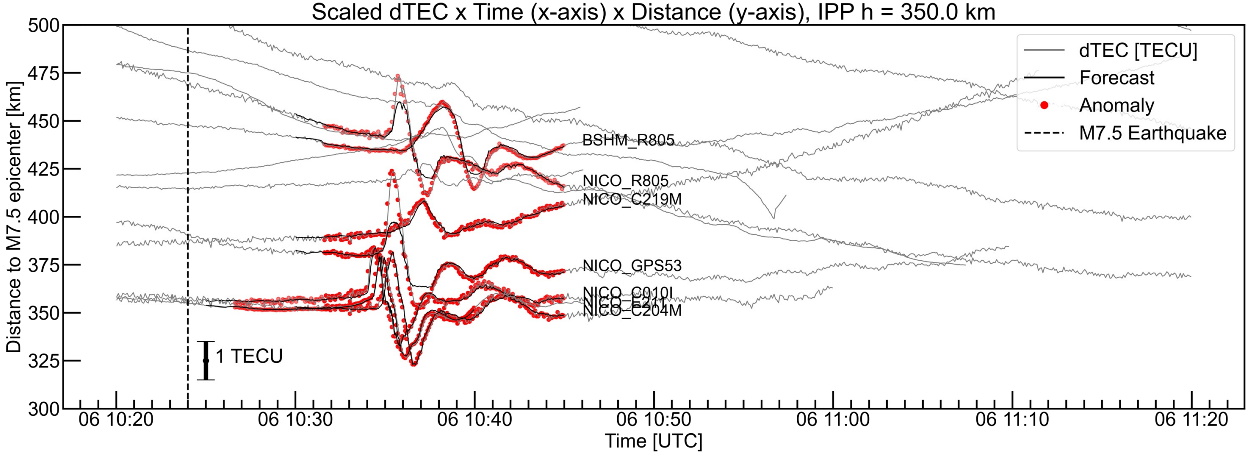
- Inputs are, as expected for future operations, **GUARDIAN-derived TEC time series**.
  - Date Range: 01 Dec 2022 to 31 Jan 2023.
  - Cutoffs: filter out periods longer than 15 minutes, elevations ≥ 30°.
  - Ionospheric Model: single-shell at 350 km, parametrisable.
- Training Stations: subset based on relative position (*e.g.*, the LSTM trained on GRAC data is tested on MADR and TLSE data).
- Training Satellites: C201M for BDS, E203 for GAL, GPS50 for GPS, and R856 for GLO.
- *Test* Date Range: 01-07 Feb 2023 (734 station-satellite pairs).

# Automatic Detections of TIDs (Luhrmann *et al.*, 2023, under review)

Results

- Test Setup: **simulated real-time data ingestion** (same setup as in actual GUARDIAN operations).

**We automatically detected the ionospheric signal due to the $M_w$=7.5 daytime quake.**




- The $M_w$=7.8 quake was not automatically detected: it occurred during *nighttime* (lower ionization levels) and with a *different focal mechanism*.

# Conclusion

- Significance:
  - GNSS-, Ionosphere-based augmentations to EWS can **improve disaster warning time by several hours**.
  - The GUARDIAN System is the first global, high-rate, multi-GNSS system for NRT ionospheric monitoring.

- FY23 Operational Progress:
  - stabilization of the data engine,
  - application to / showcasing of new hazards, and
  - higher-order analytics services provided on the website.

- Main Step Forward: **implementation of a deep learning framework for automated detections**.
  - See (Luhrmann *et al.*, 2023, under review).
  - Input: GUARDIAN-processed data.
  - Output: automated and time-tagged detections of ionospheric anomalies.
  - Demonstration: on the 2023 Turkish Kahramanmaraş earthquake sequence.

- Next Steps:
  - Implement the detection scheme into GUARDIAN operations.
  - Identify the source of the detected ionospheric signatures.

# Acknowledgements

The development of natural hazard early warning systems is **an international collaboration** involving and enabled by **several key institutions**:

- IUGG's/IAG's Global Geodetic Observing System,
- NASA's Science Mission Directorate,
- the International GNSS Service,
- the ITU Focus Group on AI for Natural Disaster Management, and
- the Geodesy4Sendai Pilot Initiative.

Contributions by the JPL authors were made possible through the support from GDGPS funds at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

**Contact information:**
**leo.martire@jpl.nasa.gov**
siddharth.krishnamoorthy@jpl.nasa.gov
attila.komjathy@jpl.nasa.gov