Sixteenth Meeting
of the International Committee
on Global Navigation Satellite Systems

Near-Real-Time GNSS-Based Ionospheric Monitoring for Natural Hazards

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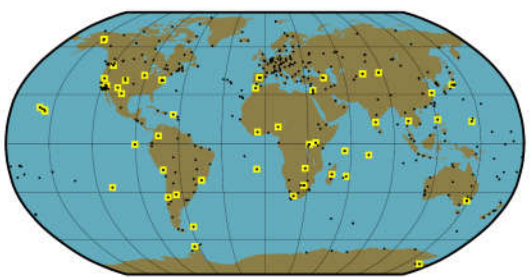
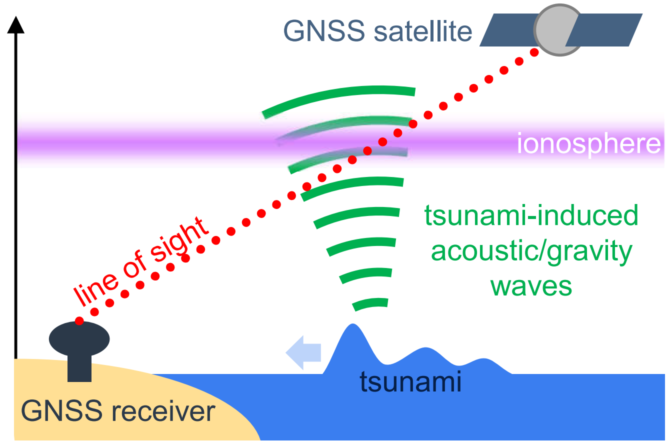
Background

- 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.**

GDGPS Global Network: 200+ Real-Time Sites





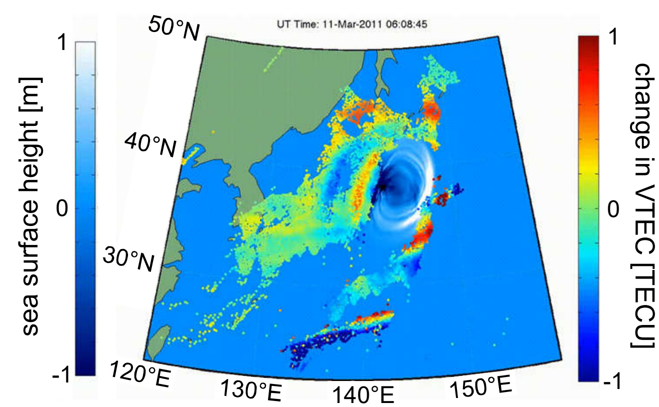
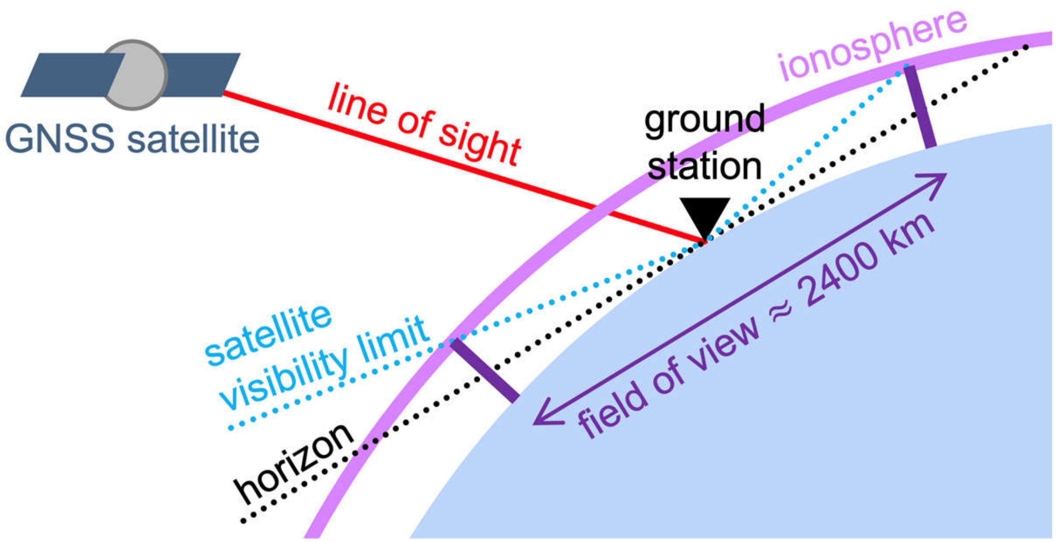


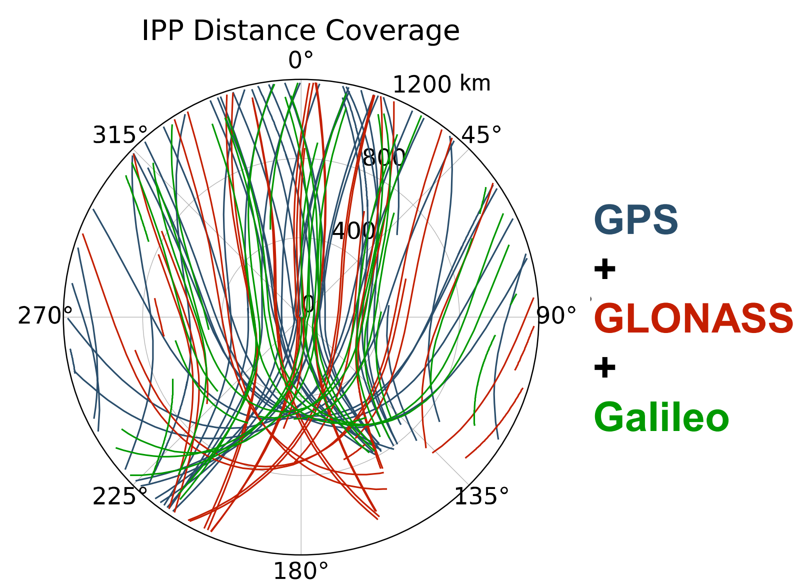
Figure: Ionospheric TEC and sea surface height map for the 2011 Tōhoku-Oki event (Galvan *et al.*, 2012).

Ionospheric Field of View

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



Schematic of the ionospheric field of view enabled by a single ground GNSS station.

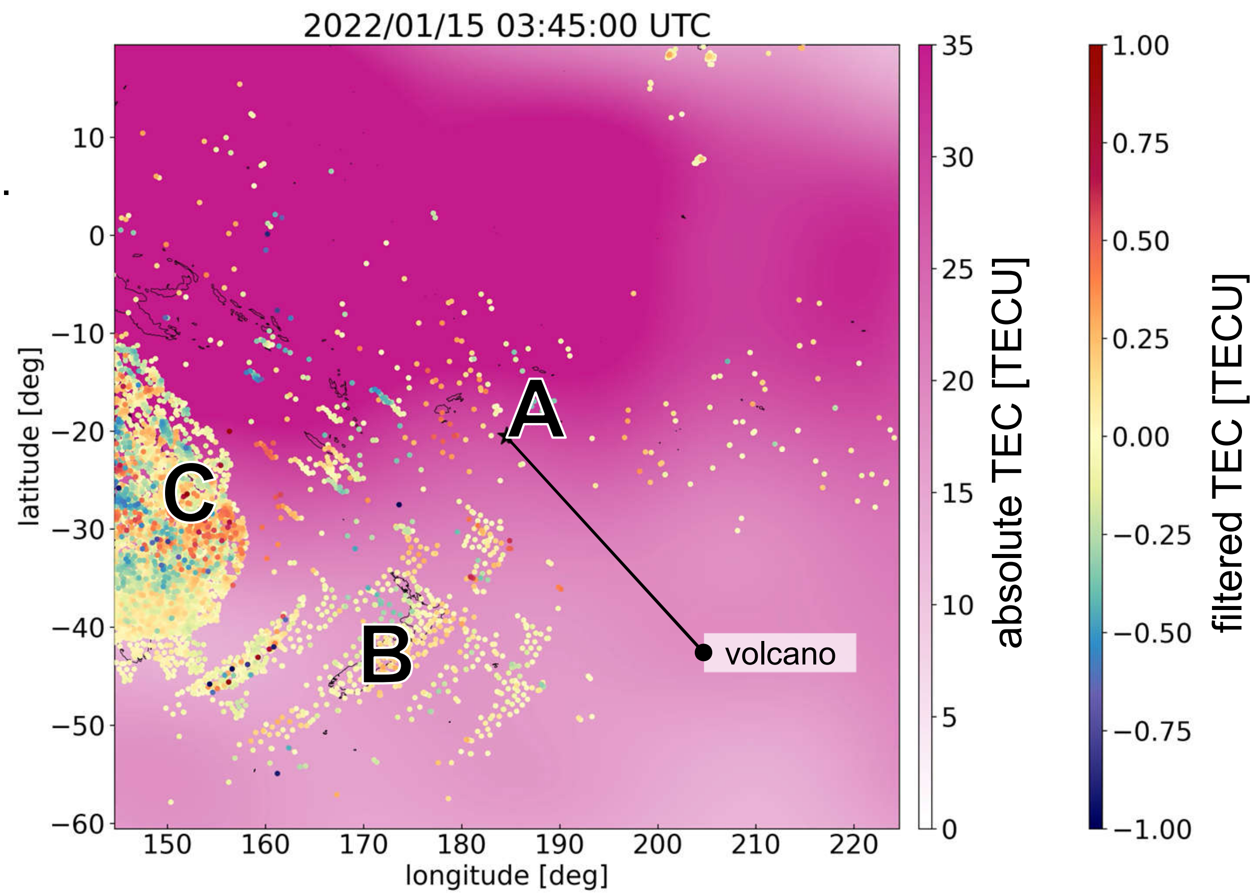


Skyplot: satellite paths above a given GNSS site (here, FTNA), as function of **distance** and **azimuth** relative to the site.

Example: Volcanic Eruption

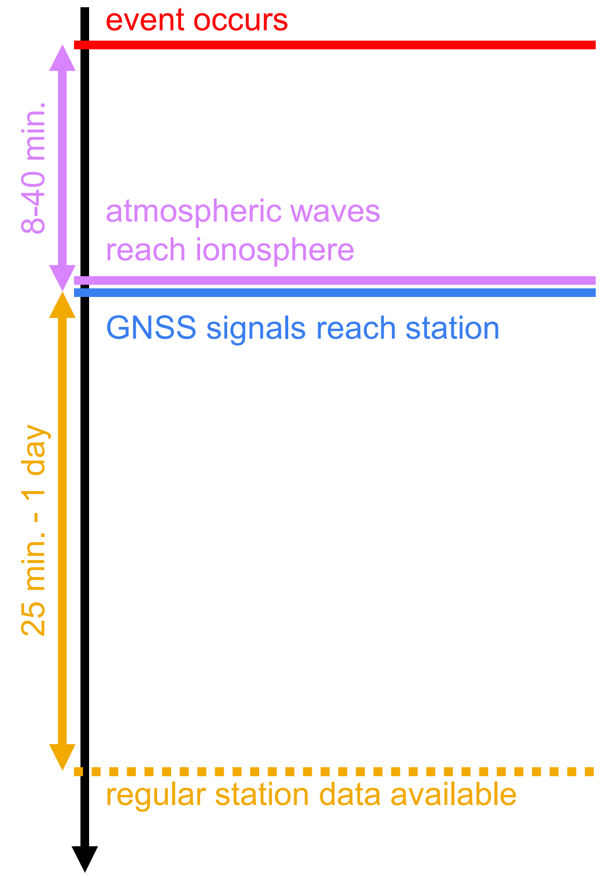
Hunga Volcano, Tonga, 2022

- Background:
  - global ionospheric map (2-min rate),
  - produced using 1000 sites worldwide.
- Foreground:
  - filtered TEC data (periods < 60 min.),
  - for all individual satellite-station links from the stations closest to volcano.
- <u>Clear ionospheric signals:</u>
  - **A. strong depletion**,
  - **B. shock wave**, and
  - **C. enhanced ionospheric activity** (depletion recovery + gravity waves).



Why Real-Time?

- Traditional GNSS stations: data only available the following day.
  - Useful for post-processing past events.
  - **Not ideal for natural hazard warnings**.



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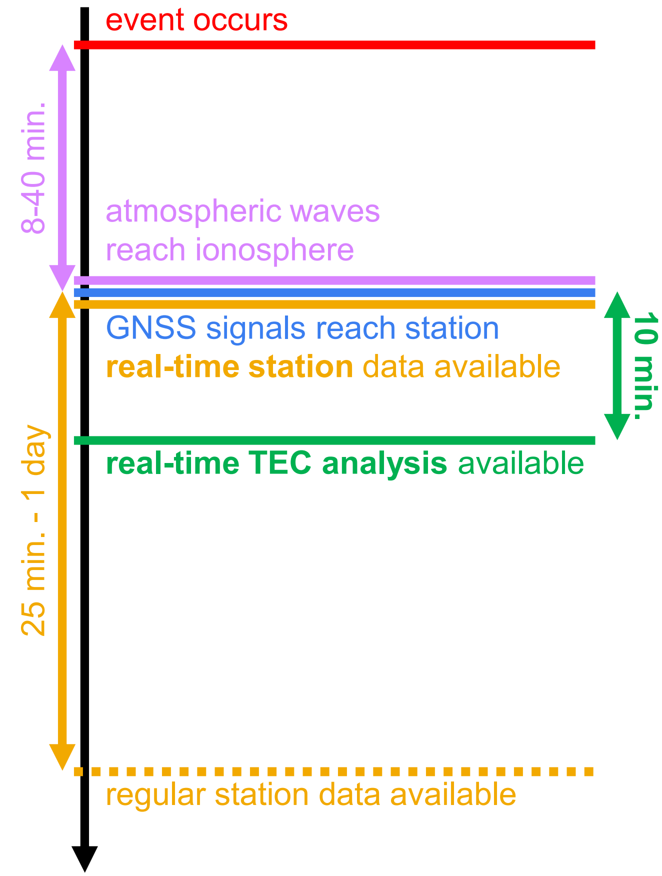
  ⇒ TEC-based analyses available **minutes after the event**.



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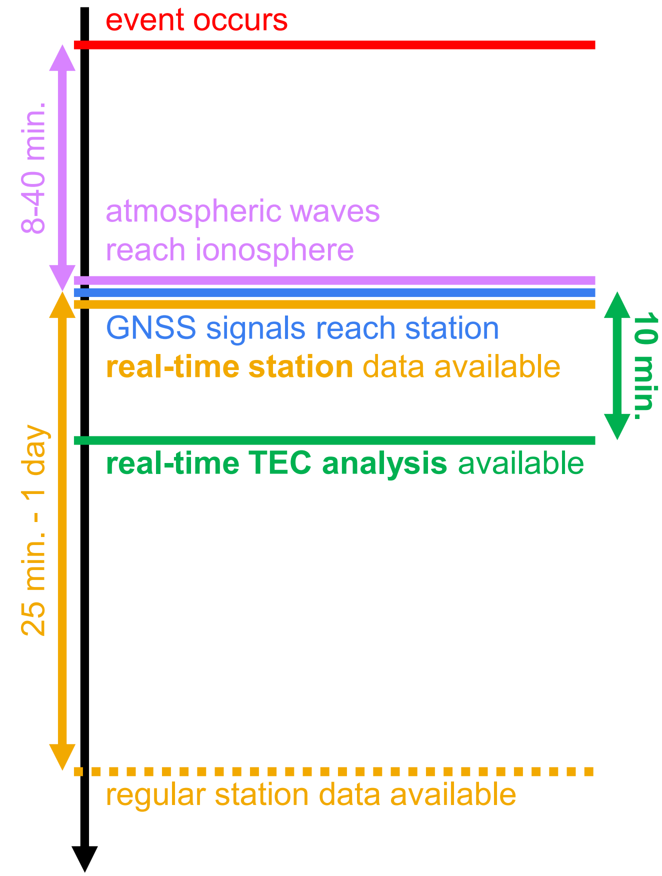
- Ensuring GNSS stations possess **real-time capabilities**:
  ⇒ traditional benefits (positioning, tectonic monitoring, *etc.*),
  ⇒ **real-time products for natural hazards early warning**.



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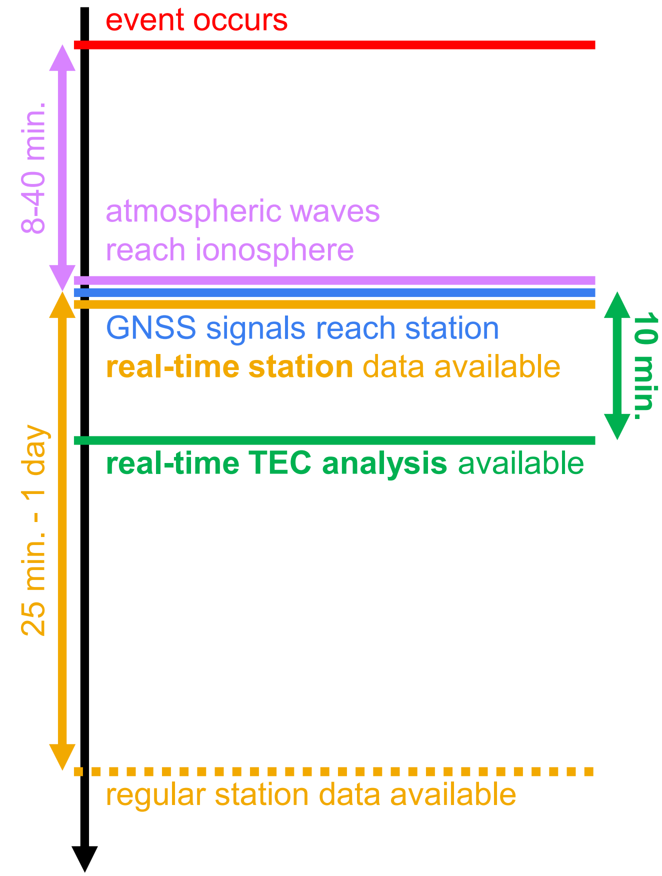
  ⇒ **real-time products for natural hazards early warning**.
- At JPL: currently developing the **GUARDIAN** system, a near-real-time early warning system for natural hazards in the Pacific Ocean (Martire *et al.*, 2022, under review).



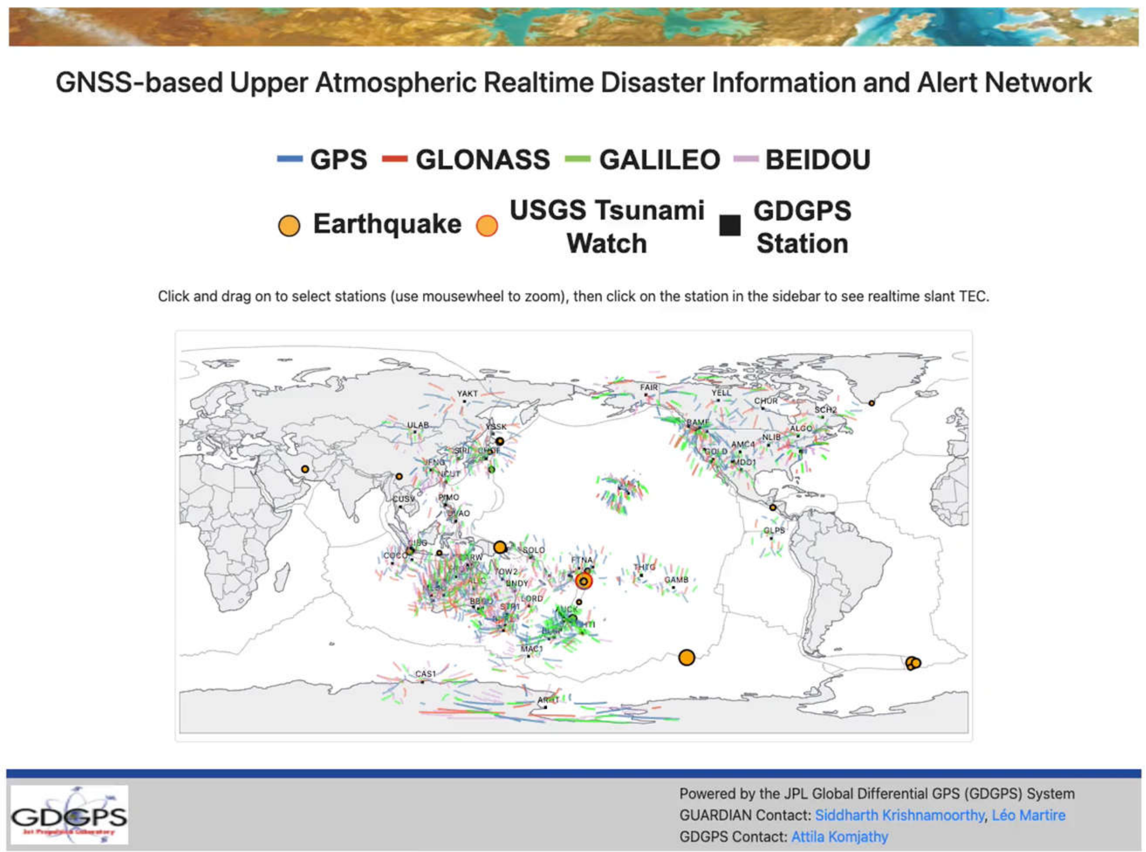
GUARDIAN Demonstration

Hunga Volcano, Tonga, 2022

What a user would have seen at 12:00 UTC on the day of the eruption.

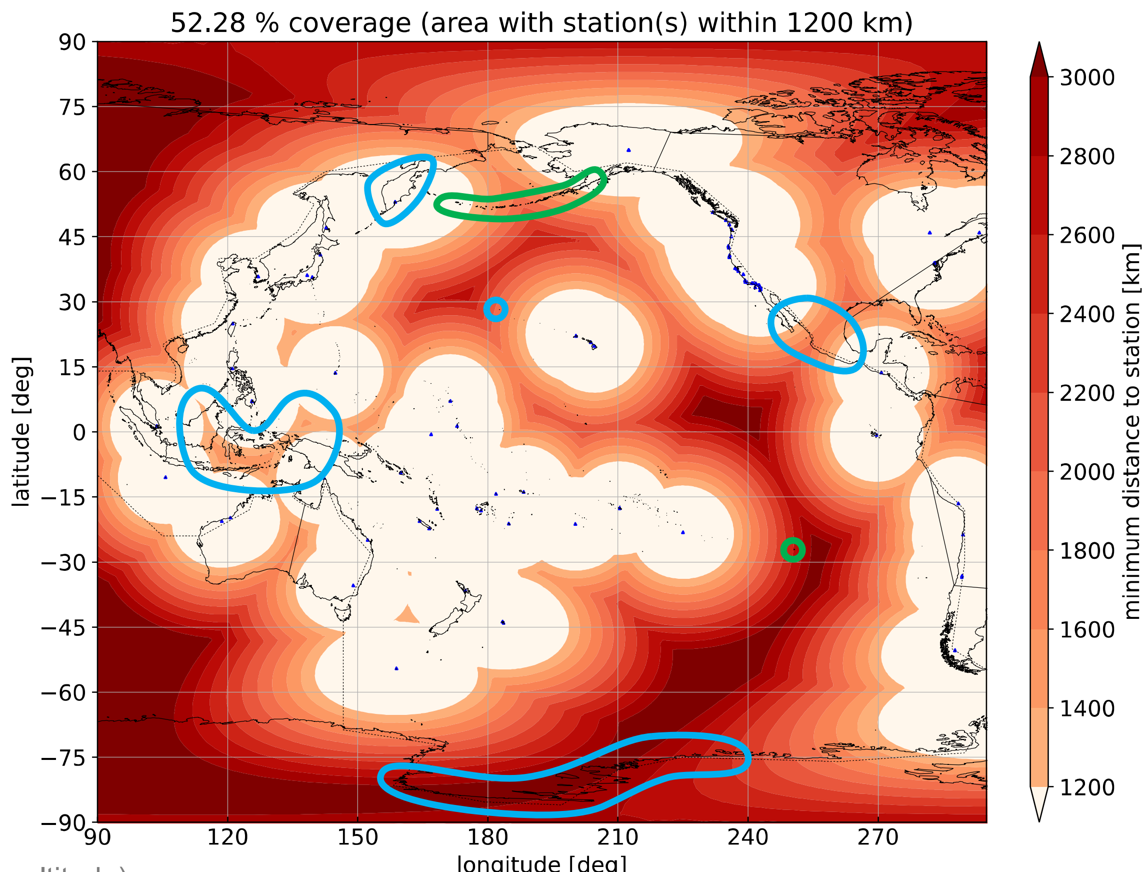
Key points:

- Map is interactive.
- Includes events in USGS catalogue.
- Pacific GDGPS stations selectable.
- Multi-GNSS data available for each GDGPS station.



GUARDIAN - Coverage in the Pacific Ocean

- Maximum possible coverage[1]: 82.05 %.
- Current coverage[1]: 52 % = **64 % of max.**
- With next additions: 57 % = **69 % of max.**
  Easter Island (Chile), continental Chile, Aleutians Islands (USA).
- Strategically important locations:
  Kuna Atoll (USA), South-East Indonesia, Mexico, Kamchatka Peninsula (Russia), Antarctic.



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

Conclusions

- Natural hazards (earthquakes, tsunamis, volcanic eruptions) cause clear ionospheric perturbations.
- Ground-based GNSS signals can be used to scan the ionosphere with an extremely wide field of view.

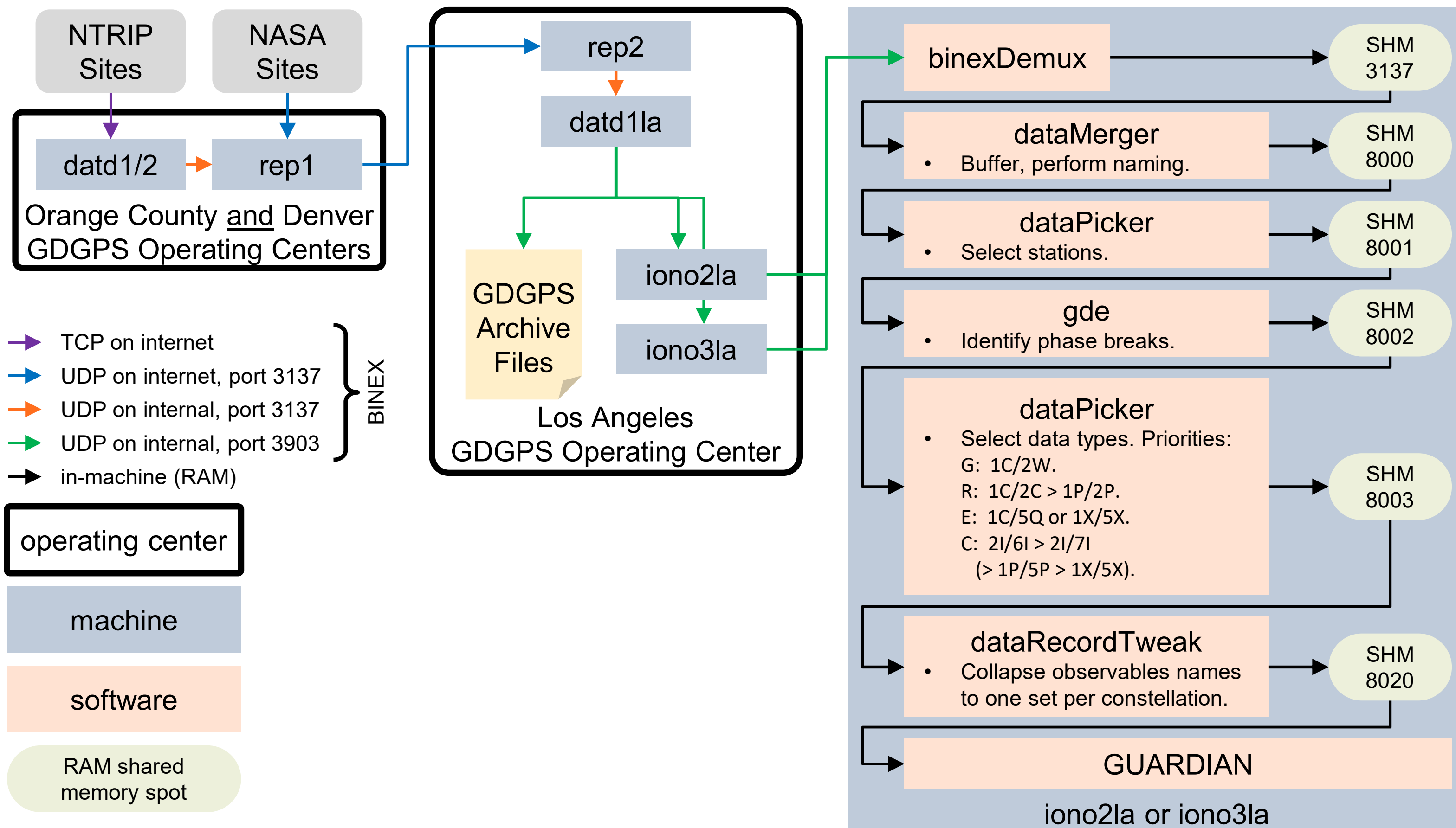
⇒ Networks of ground GNSS sites with real-time capabilities (*e.g.*, JPL's GDGPS) have the potential of achieving a **near-real-time** (<10-min latency) and **high-rate** (1-sec) **monitoring of natural hazards**.

- The development of ionospheric natural hazard early warning systems is **an international collaboration in geodesy involving several key institutions**: the International GNSS Service, NASA's Science Mission Directorate, IUGG's/IAG's Global Geodetic Observing System, the ITU Focus Group on AI for Natural Disaster Management, and the Geodesy4Sendai Pilot Initiative.

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

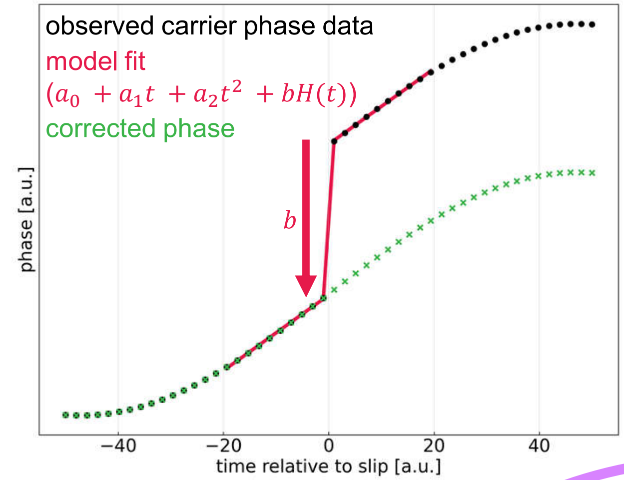
Back-Up Slides

GUARDIAN Detailed Data Pipeline



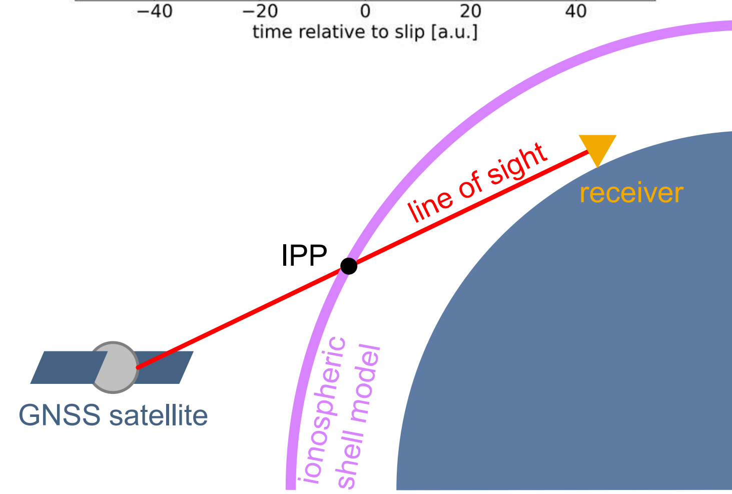
Computation Techniques

- **Cycle slips fixing:**
  - Cycle slips = "jumps" in carrier phase time series, due to phase tracking losing lock and skipping an integer number of cycles.
  - Correct the phase time series before computing TEC.



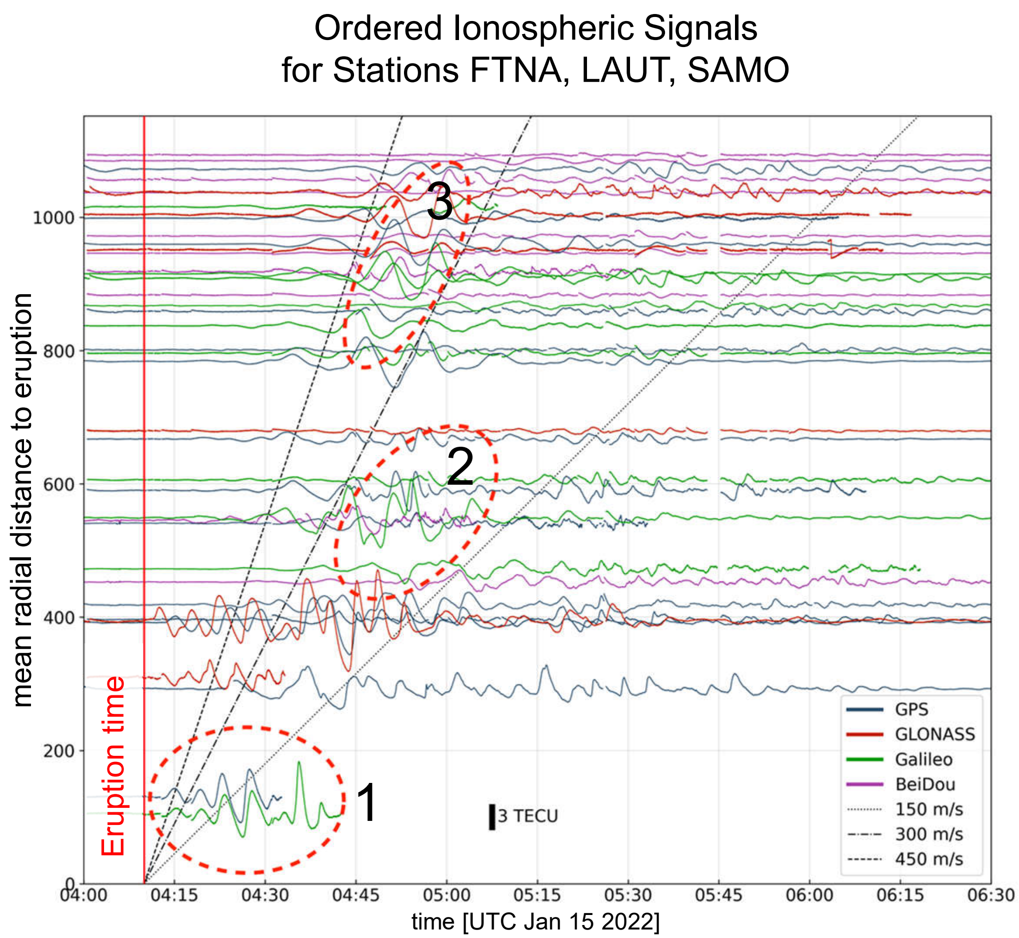
- **TEC computation:**
  - slant TEC = STEC = $\frac{f_1^2 f_2^2}{K(f_1^2 - f_2^2)}(\phi_1 - \phi_2)$

- **IPP** (ionospheric pierce point) **computation:**
  - geometrically intersect line of sight with ionospheric shell



Tonga Case Study

FTNA, LAUT, and SAMO Signals



DART Buoys

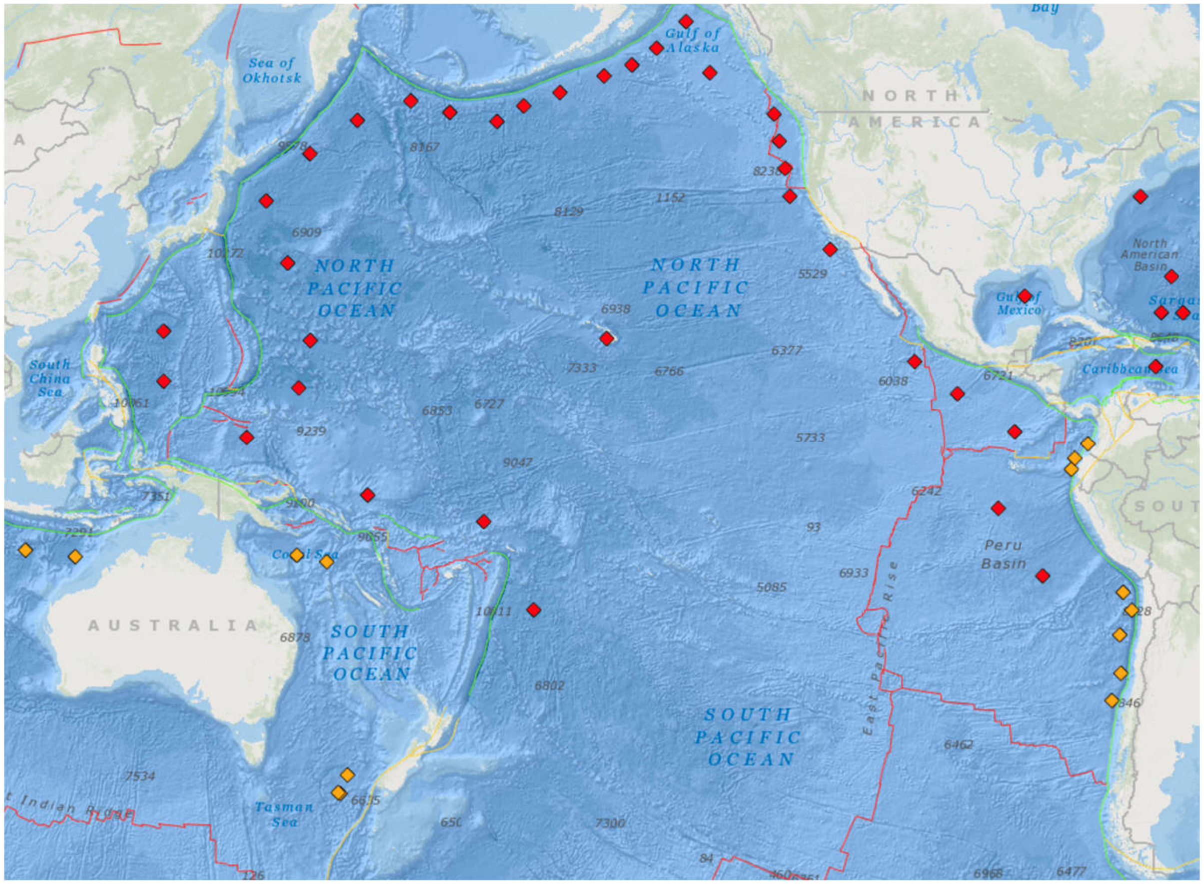


Figure: Currently active DART buoys around the Pacific ocean. Credit: NOAA (www.ncei.noaa.gov/ maps/hazards/).

Example: Volcanic Eruption

Hunga Volcano, Tonga, 2022

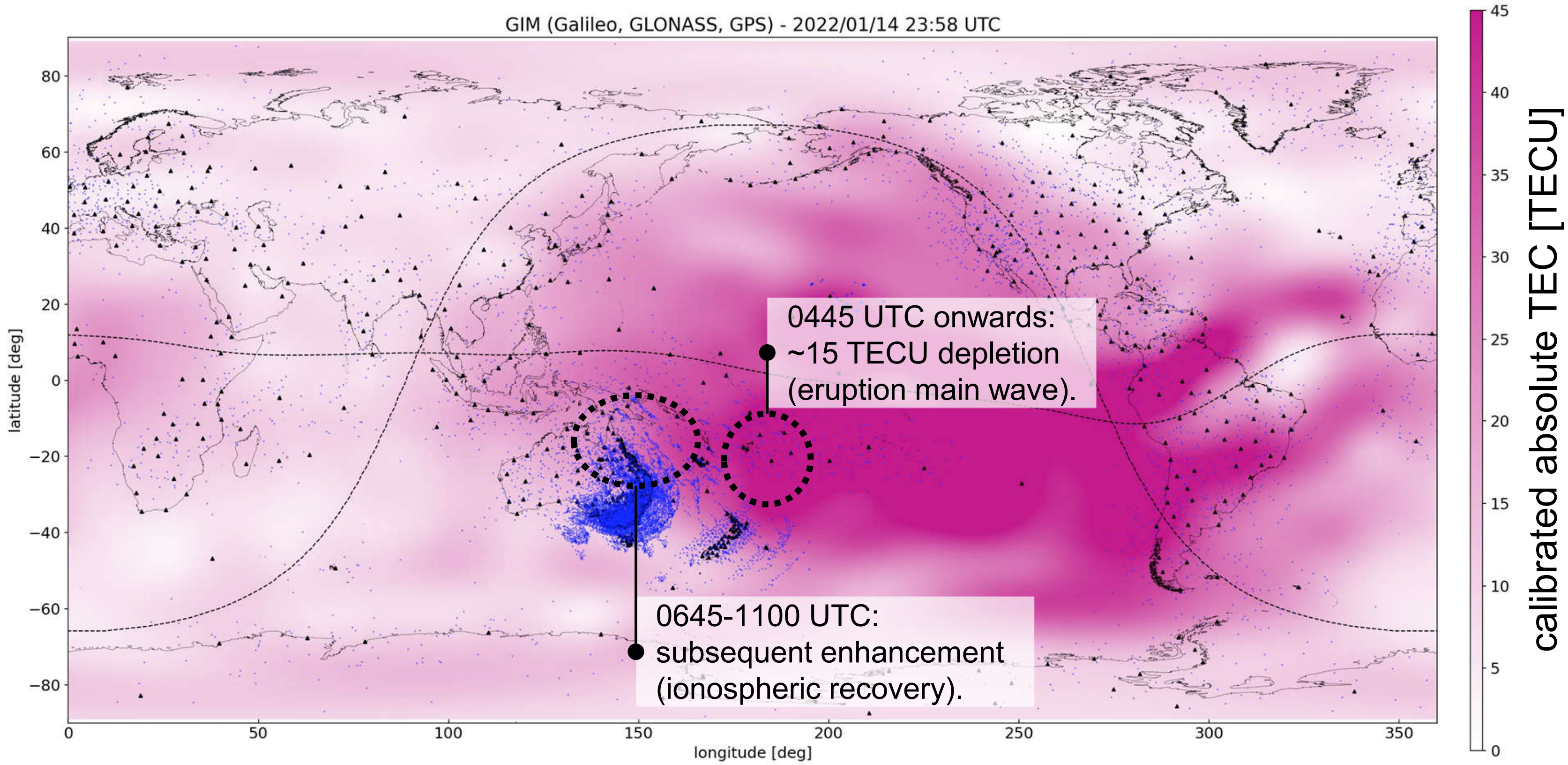
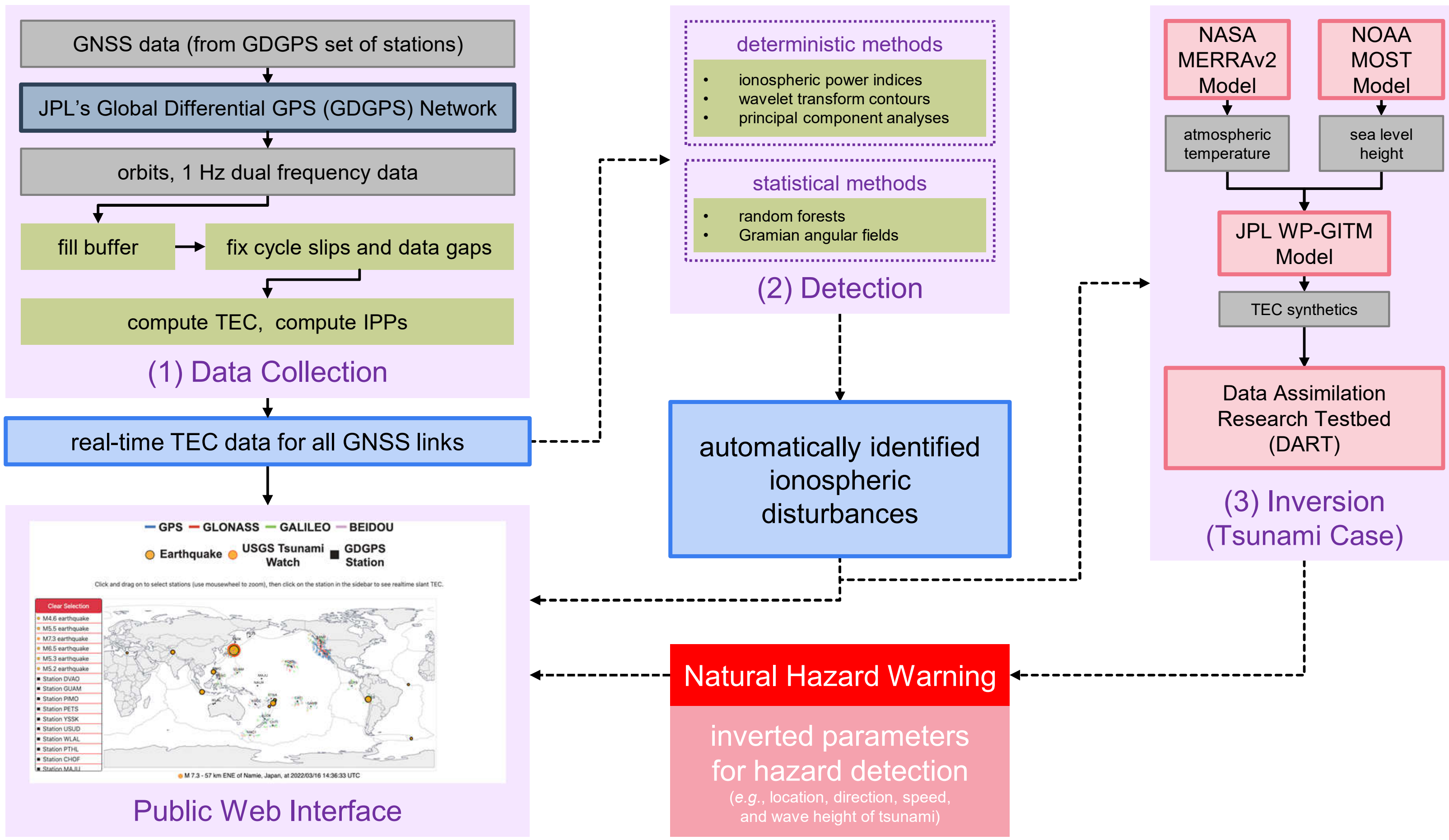


Figure: **Very high-rate** (2-min) **multi-GNSS** (GPS, Galileo, GLONASS) Global Ionospheric Map (GIM) computed with 30-sec data from **1000 GNSS ground stations** distributed worldwide (black triangles), including **621 sites available closest to the eruption**.

GUARDIAN Architecture



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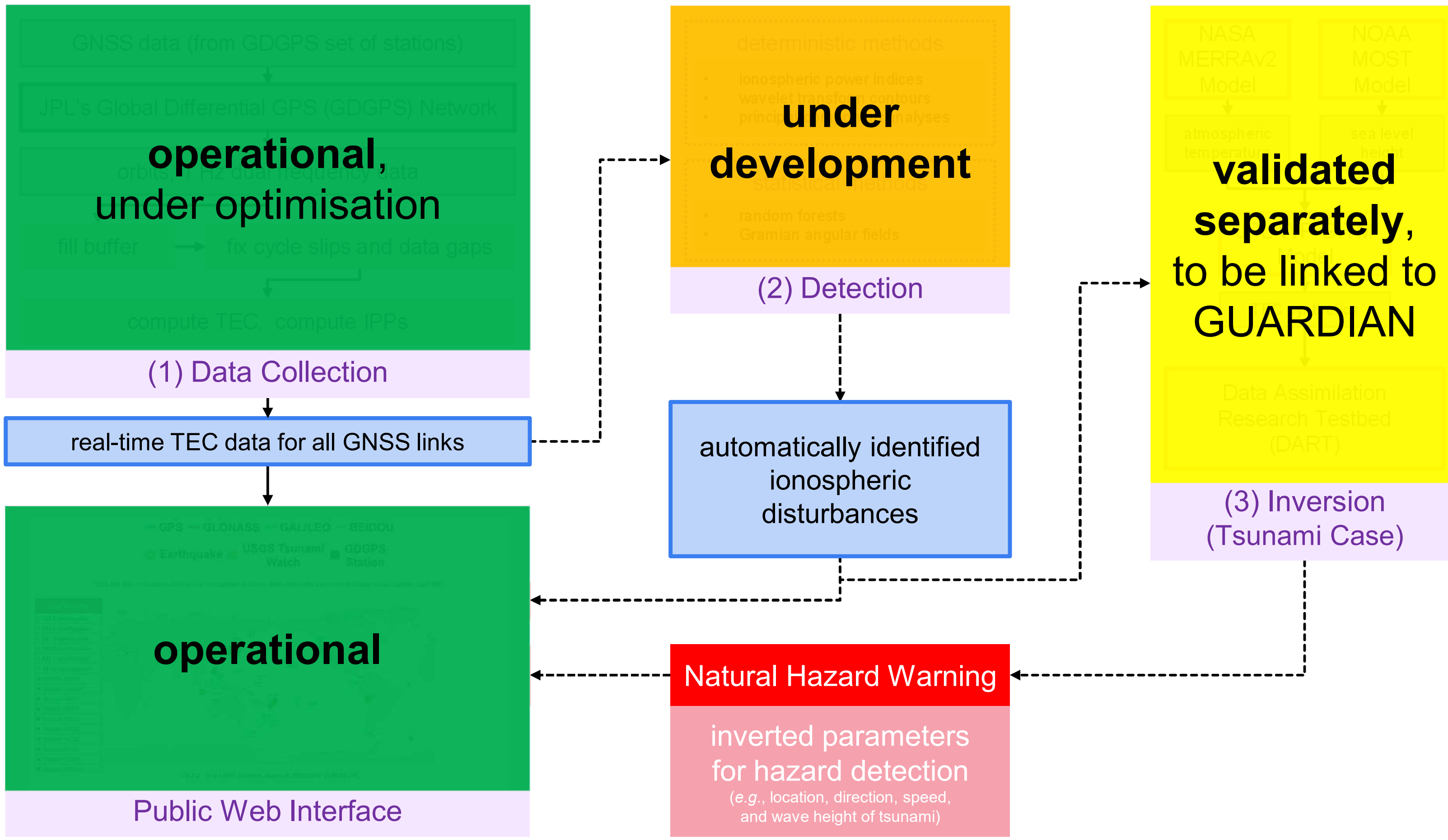


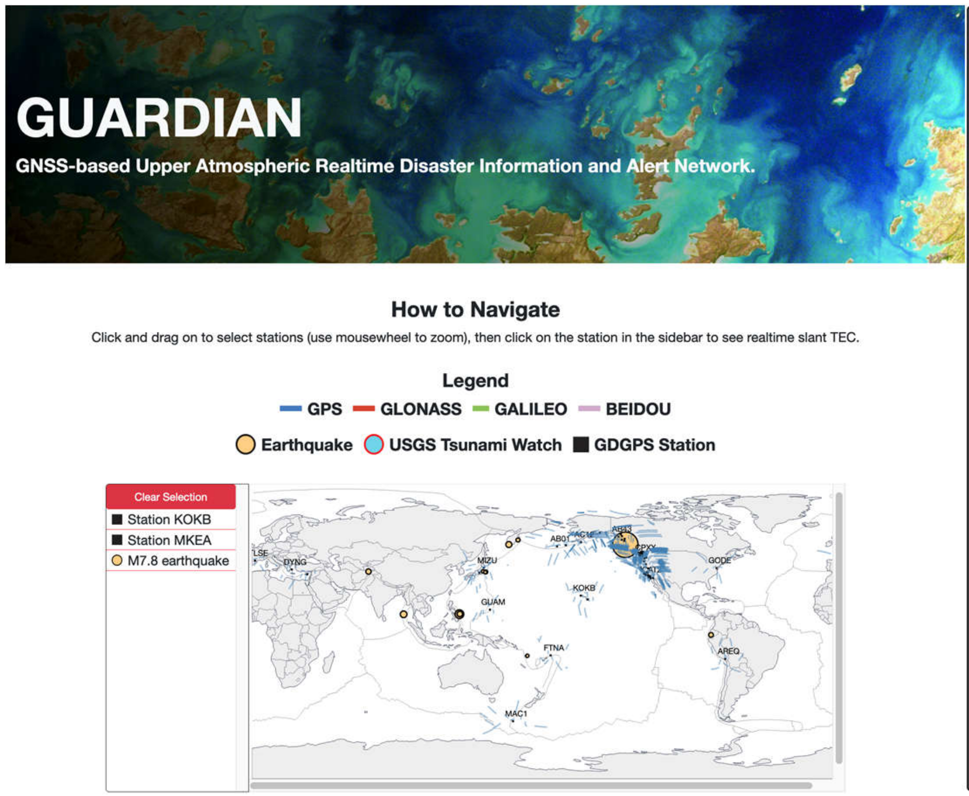
GUARDIAN Demonstration

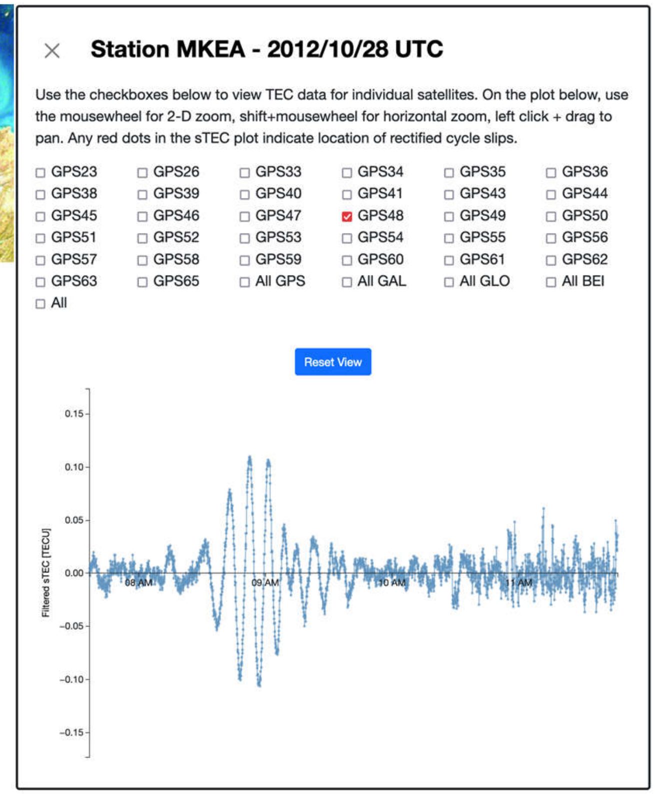
Haida Gwaii, 2012

What a user would have seen at 18:00 UTC on the day of the event.

Key points:

- Map is interactive.
- Includes events in USGS catalogue.
- Pacific GDGPS stations selectable.
- Multi-GNSS data available for each GDGPS station.





GUARDIAN Validation *vs.* Post-Processing

- **GUARDIAN's near-real-time streams are almost identical to post-processed data.**
- RMS differences appear consistently **< 0.1 TECU**, within noise levels.

- Minor differences stem from data availability, shortening arc lengths and thus affecting filtering.
  Advanced mitigation techniques are available in post-processing.