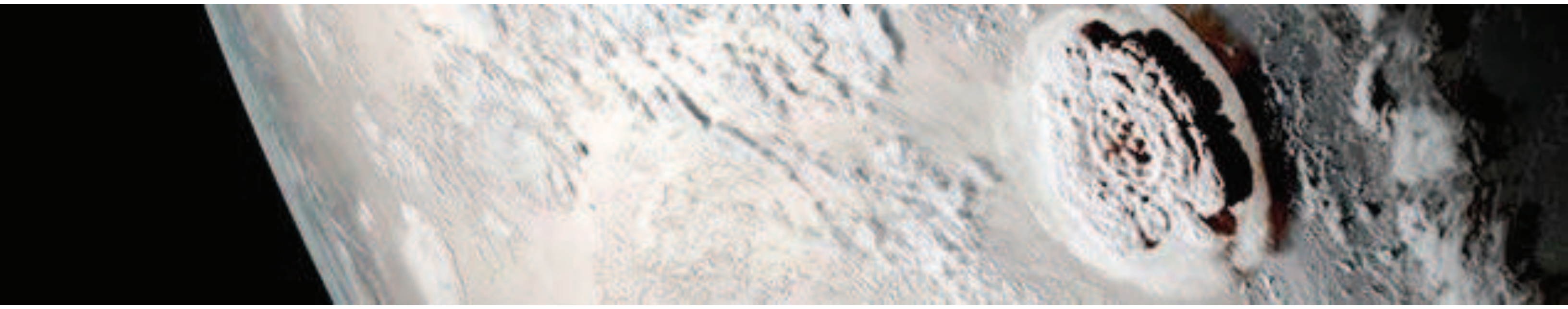


The 15 January 2022 Hunga volcano eruption captured by NOAA's GOES-West satellite. Credit: GOES-West NOAA/RAMMB/CIRA.

Natural Hazards Monitoring using Global Navigation Satellite Systems

By harnessing the power of GNSS and fostering international collaborations, we can greatly enhance our ability to detect and respond to natural disasters effectively, saving countless lives and protecting communities worldwide.

Introduction

Expanding worldwide GNSS infrastructures is an essential and cost-effective endeavour, playing a crucial role in enhancing monitoring and early warning systems for natural hazards, while also contributing to traditional research and geodetic surveying.

Natural hazards, including earthquakes, tsunamis, and volcanic eruptions, pose significant threats to countries and civil infrastructures globally. Tsunamis, in particular, can cause catastrophic damage near coastlines, emphasizing the critical need for robust early warning systems. Current systems, like NOAA's PTWC, employ seismic and water-level instruments to monitor and assess tsunami threats worldwide. However, these methods have significant limitations in terms of accuracy and spatiotemporal coverage.

The integration of GNSS as a complementary component in traditional early warning systems (EWS) enhances their effectiveness by providing invaluable, global-scale, and cost-effective data for monitoring and assessing various threats, including not only tsunamis but also other disasters. Realising this potential necessitates interdisciplinary, multi-stakeholder, and international collaborations, as the complexity and global nature of natural hazards demand collective efforts and diverse expertise to effectively address these challenges.

Global Navigation Satellite Systems (GNSS) are satellite constellations that include the United States' Global Positioning System (GPS), Europe's Galileo, China's BeiDou (BDS), Russia's GLONASS, as well as regional constellations such as Japan's QZSS, and India's NavIC. The most well-known use of GNSS is for positioning, navigation, and timing.

As of today, GNSS is becoming an integral part of natural hazards monitoring and warning systems. These efforts were kick-started in 2015, when the International Union of Geodesy and Geophysics (IUGG) adopted a resolution to use geodesy to enhance and improve the accuracy of early warning systems where large populations are at risk of experiencing tsunamis[1].

[1] "Real-Time GNSS Augmentation of the Tsunami Early Warning System" [International Union of Geodesy and Geophysics (IUGG), 2015].

In such a context, the International GNSS Service (IGS) consistently works to identify and support emerging and novel applications of GNSS for disaster risk reduction, building namely on the work of the International Association of Geodesy's Global Geodetic Observing System (IAG GGOS). Through this work, the IGS fosters a geodesy component to the United Nations Sustainable Development Goals (SDGs) and to the Sendai Framework for Disaster Risk Reduction. Namely and recently, the IGS spearheaded and co-chairs since October 2022 a Task Force on "Applications of GNSS for Disaster Risk Reduction" under the aegis of the United Nations Office for Outer Space Affairs.

Key Points

A. GNSS data is readily available and capable to monitor natural hazards in near-real-time.
B. Ionosphere-based GNSS analyses have an excellent spatial coverage.
C. Single GNSS ground stations are cost-effective and offer several crucial benefits.
D. GNSS analyses are possible without an Internet connection, and are consequently reliable during disconnections from global networks.
E. Stations in the IGS network improve the global coverage and contribute to IGS products.

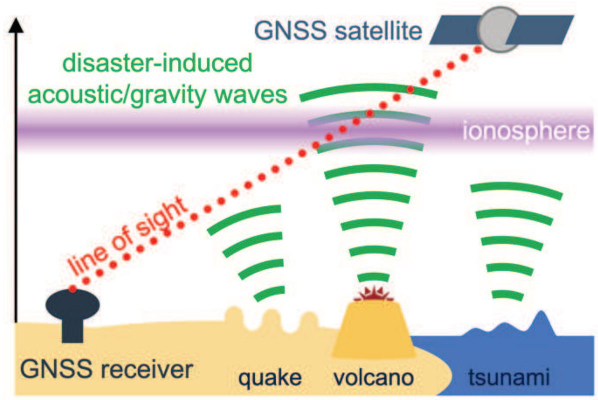
Suggestions for Maximizing Investments in Geodetic Infrastructure for Current and Emerging Applications

1. Ensure multi-GNSS constellation signal tracking for all new GNSS ground stations.
2. Install new GNSS ground stations to fill in existing coverage gaps (see Figure 1).
3. In remote locations, ensure GNSS stations are capable of functioning without the Internet.
4. Include commercially-funded GNSS observables in publicly-accessible IGS products.

Key Point A: Natural Hazards Monitoring in Near-Real-Time

On the ground, networks of GNSS ground stations can be used to detect and monitor changes in the Earth's crust caused by natural hazards. Some monitoring tools already leverage those capabilities, for instance: the GREAT, GATED, and GUARDIAN systems (NASA Jet Propulsion Laboratory, USA), G-FAST (University of Oregon, USA), REGARD (GSI, Japan), or the currently in-development R-CET (GNS Science, New Zealand), *etc.*. The traditional Precise Point Positioning techniques on near-field GNSS stations has already convincingly demonstrated they provide information able to enhance the rapid characterization of significant earthquake events.

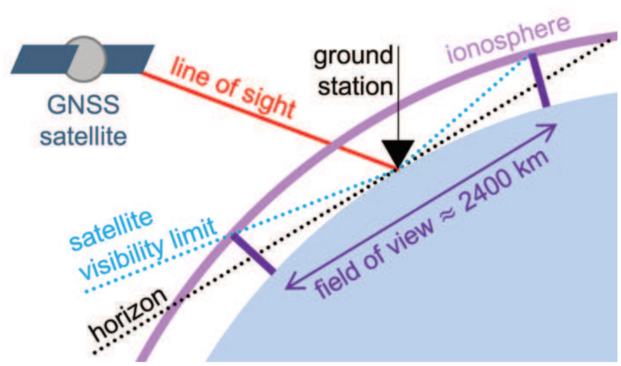
In addition to permanent ground displacements and transient seismic motions, some natural hazards also perturb the Earth's atmosphere. Volcanic eruptions or tsunamis create strong, low-frequency atmospheric waves that can travel up to the ionosphere, a layer in the Earth's atmosphere consisting of electrically charged particles. Because all radio signals are very sensitive to such particles, GNSS signals passing through this medium may be used to visualise the changes in electron densities in the ionosphere, and thus to monitor the rippling atmospheric waves caused by natural hazards.



Other GNSS-based techniques, such as reflectometry and radio occultation, also offer promising prospects for disaster risk reduction and early warnings. While they may require further development for real-time implementation, investing in them and advancing the relevant techniques still bears significant value for the future or disaster monitoring and early warnings.

Key Point B: Excellent Spatial Coverage for Ionosphere-Based Monitoring

Any modern GNSS ground station can record signals from any GNSS satellite (regardless of constellation), as long as it is slightly above the horizon in the sky. Furthermore, each of these GNSS ground stations has an effective field of view of the ionosphere that can reach up to a radius of 1200 km around the station. In combination with the fact that GNSS networks are deployed worldwide, this makes for exceptional spatial coverage to monitor the ionosphere, and subsequently any perturbations propagating through it – similar to dropping a rock into a tub of water and watching the ripples propagate. This configuration reaches its full potential when satellites from multiple constellations can be monitored at the same time, effectively filling the sky with as many measurement points as possible.



Key Point C: GNSS Stations are a Multi-Objective, Multi-Benefit Investment

Worldwide, a plethora of ground GNSS networks are constantly recording GNSS data for a variety of uses. Thanks to the International GNSS Service (IGS), as well as other academic or national partnering institutions, a significant portion of this data volume is made openly accessible and free of charge to the public, financed by contributions from organizations and governments around the world. To improve use potential of GNSS as an operational natural hazard monitoring method, new stations should be installed to fill in gaps in geographically under-represented or hard-to-access locations.

As of today, the cost of a traditional science-grade multi-GNSS ground station stands between \$5,000 and \$20,000 USD. It should however be noted that these values do not account for implementation, maintenance, and surrounding infrastructure costs, which could be high in difficult terrain conditions. Low-cost receivers are also being developed, but their applicability to natural hazards EWS depend heavily on performance. Investments in geodetic infrastructure, starting with GNSS ground stations, yields geodetic data useful in a broad spectrum of applications: raw positioning, autonomous navigation, Earth observation colocation information, precise timing, space weather monitoring, *etc.*. The number and diversity of public benefit applications enabled or enhanced by GNSS is ever-expanding.

Key Point D: Local Analyses in Remote Locations

GNSS-based analysis of natural hazards can be performed even if the station is not currently connected to the internet. The analysis algorithms that analyse GNSS data and turn it into information for disaster risk reduction decision-making can be run using a single computer connected to one or more local GNSS stations. Some of these capabilities are also available onboard of science-grade GNSS ground stations. This works not only for traditional position-based monitoring of ground motion, but also for ionospheric monitoring. This has the potential to significantly benefit disaster risk reduction in remote areas or islands, as they might become disconnected from the Internet following a hazard (see Case Study below), or could suffer from a slow connection or limited bandwidth preventing the reliable use of real-time internet-based (cloud-based) algorithms.

Key Point E: Contributing to Global Data Products

The International GNSS Service (IGS) network gathers data from over 500 GNSS ground stations worldwide (see Figure 1). Through extensive international collaborations in analysis and data dissemination, the IGS also provides openly available geodetic products (https://igs.org/products/) that are crucial for many scientific applications and discoveries. These data-enabled products include satellite orbits, total electron content maps and satellite biases (useful for positioning corrections), tropospheric precipitable water vapor (meteorology), and the IGS reference frame (contributing and providing access to the International Terrestrial Reference Frame). In particular, the real-time IGS products and services derived from regional GNSS networks enable an immediate, real-time, and cost-effective resource for natural hazards monitoring.

Contributing GNSS data to the IGS offers compelling advantages and a strong return on investment. It fosters collaboration and connects stakeholders with GNSS experts, researchers, and practitioners worldwide, accelerating research and building valuable partnerships for effective disaster management. Furthermore, it enables access to the IGS' diverse products, facilitating comprehensive analyses and informed decision-making. The collective knowledge improves data quality, coverage, and reliability, leading to more accurate models and early warning systems.

By joining this effort, contributors demonstrate their commitment to global collaboration, enhancing their reputation, credibility, and potential for partnerships and funding opportunities in disaster risk reduction.

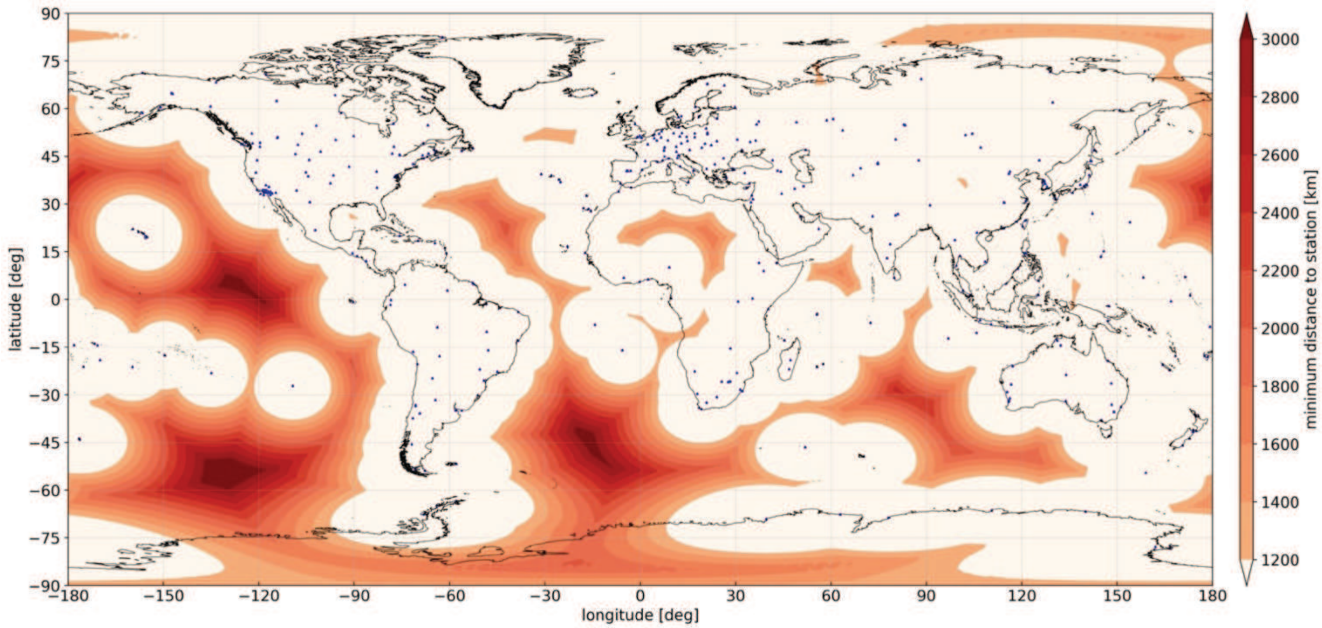


Figure 1: Global ionospheric coverage (see Key Point B) provided by the 515 stations currently available through the International GNSS Service network (see https://network.igs.org/). Some significant land areas are devoid of IGS stations, and could immediately benefit from additions to the network: *e.g.*, Africa, Indonesia, middle China, or Siberia. Coverage of the ocean is intrinsically more difficult; on certain islands, additional stations could however be added to the IGS network to fill critical gaps: *e.g.*, on the Kuna Atoll (United States) to cover the North-western Pacific Ocean, on Tristan da Cunha and the Falkland Islands (British Overseas Territories) to cover most of the Southern Atlantic Ocean, on Île Amsterdam (French Southern and Antarctic Lands) to decrease gaps over the Indian Ocean, *etc.*.

Case Study: The 2022 Hunga Eruption in the Kingdom of Tonga

After a series of relatively weak eruptions, the submerged Hunga Tonga - Hunga Ha'apai volcano in the Kingdom of Tonga eruption on the 15th of January 2022 released a colossal amount of energy, creating signals that in the atmosphere, ocean, and solid Earth that rippled around the globe multiple times. Audible sound was heard over thousands of kilometres, while both volcanic ash and tsunami waves ravaged the islands of Tonga. In fact, traditional seismological methods were incapable of rapidly forecasting these eruption-induced tsunamis, which were only measured much too late by water-level monitoring stations (DART, *etc.*).

Furthermore, the eruption broke the single submarine fibre optic cable linking the Kingdom of Tonga to the rest of the world, as an underwater avalanche buried about 55 kilometres of it, hampering important communications and relief missions. This disconnection also prevented the scientific community – and by extension the local communities – from having local measurements of the magnitude of the event, not only from ionospheric measurements but also from the local seismic and infrasonic networks.

GNSS stations in Tonga's capital and on neighbouring islands were able to record the direct ionospheric perturbations due to the event. A mere five minutes after the main explosion, GNSS signals captured the first ionospheric disturbances, whose amplitude reached more than 40 times the usual background levels. While the initial ionospheric perturbations were due to the initial explosive event and rising of the plume, subsequent gravity waves were also sensed due to the tsunamis propagating away from the eruption site.

Due to the volcano being so close to the Tongan coast, the sound of the eruption was unfortunately the earliest warning the people of Tonga had. In retrospect, for more distant locations and rapid assessment of the eruption, monitoring the ionosphere would have been a particularly viable augmentation to natural hazard monitoring systems. In addition, this shows that GNSS-based methods may enable a monitoring of tsunamis that is independent from the causative source.

Authors

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