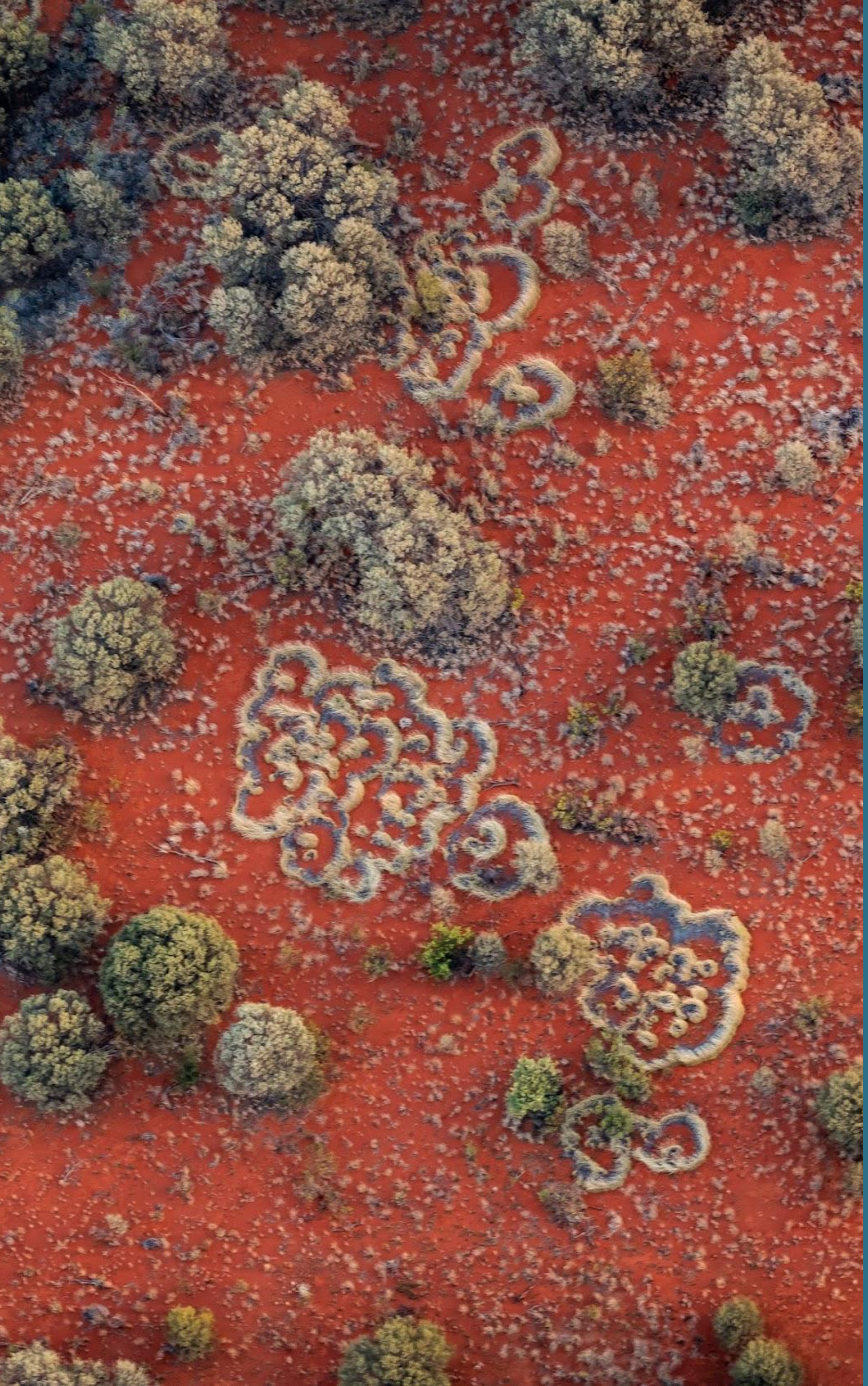


Australian Government
Geoscience Australia

Positioning Australia

Australian perspectives on the use of GNSS for tsunami warning

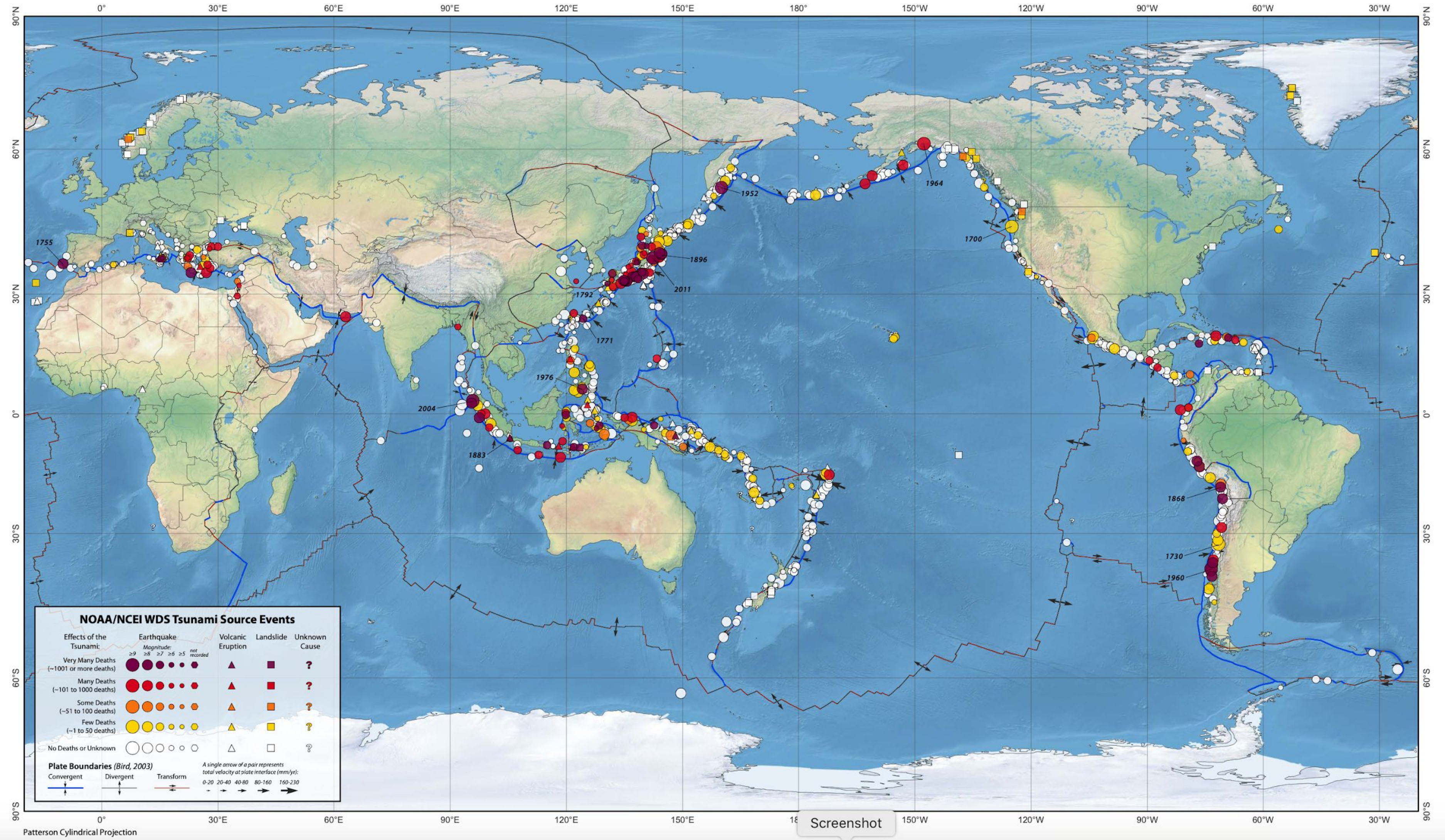
Simon McClusky[1], Adrienne Moseley[1], Phil Cummins[1], Shin-Chan Han[2], John Dawson[1]

(1) Geoscience Australia
(2) University of Newcastle

Presentation Overview

- Tsunami hazard in our region
- Australian Government and tsunami warning system
  - Current capability
  - Ideal capability
- Future Opportunities
  - Real-time GNSS analysis of space based and ground-based infrastructure
    - Australia’s National Positioning Infrastructure (NPIC) GNSS network
    - Australia’s GNSS analysis centre software – Ginan
  - Space-based LEO satellites for Ionospheric Mapping
    - Case Study: Tonga HTHH case study

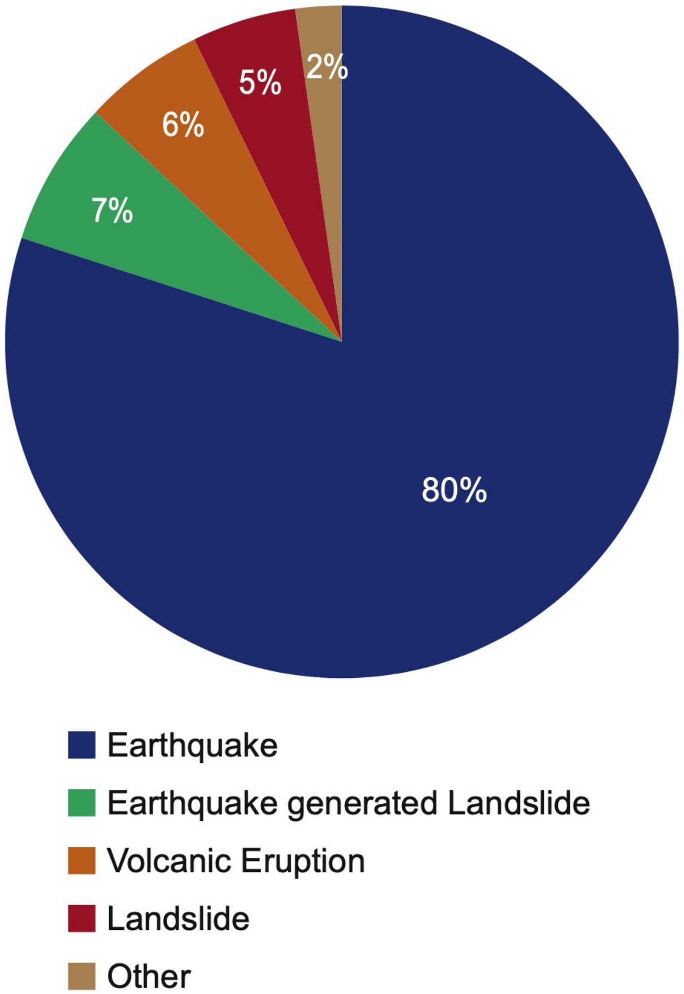
Tsunami Sources 1610 B.C. to A.D. 2022
Earthquakes, Volcanic Eruptions, Landslides, and Other Causes

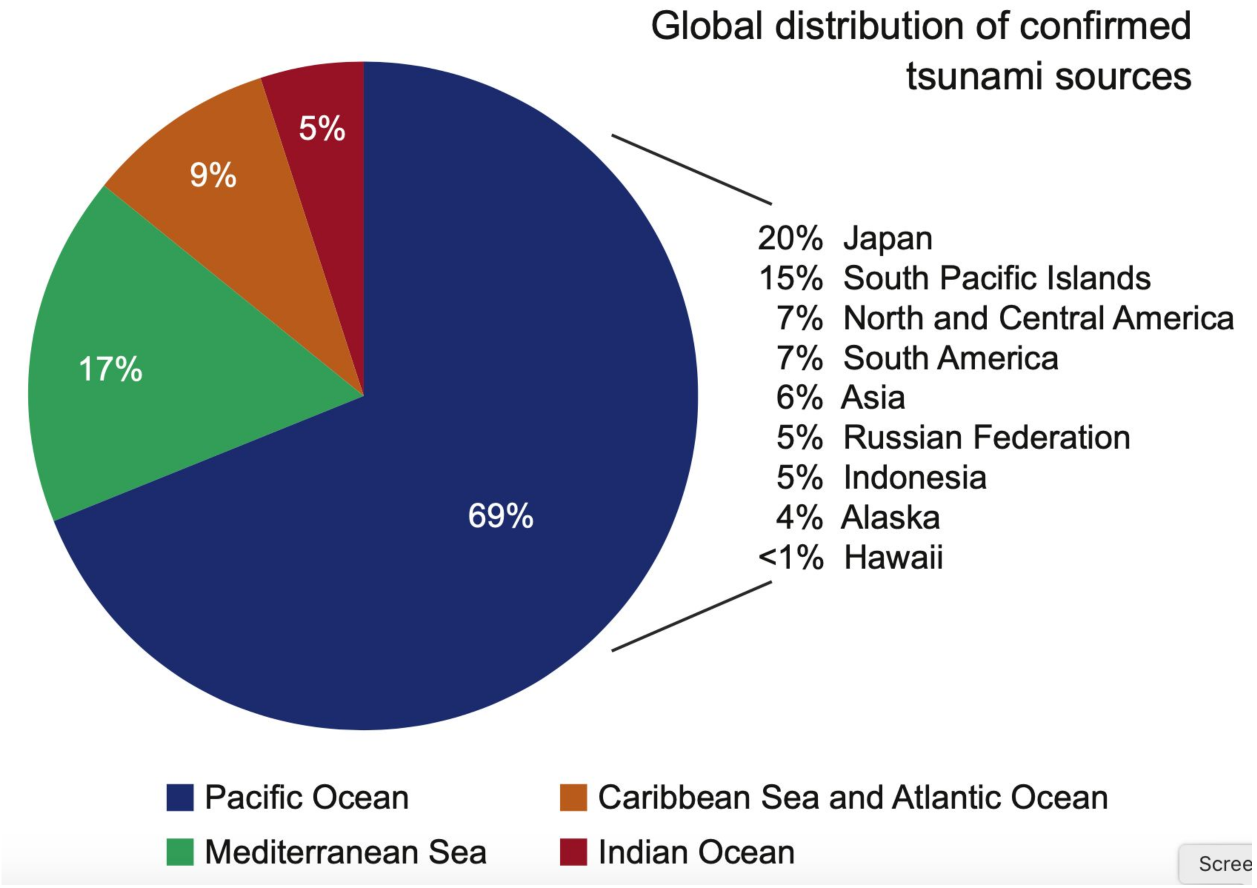


ITIC and NOAA's NCEI, and ICSU World Data Service for Geophysics

- 2,600 events in the NCEI Global Historical Tsunami Database
- Over 1,400 confirmed tsunami source events are displayed on the map
- Total of 264 confirmed deadly tsunamis
- Resulting in over 544,000 confirmed deaths

Global Tsunami Hazard


Distribution of confirmed tsunamis by generation mechanism


Global distribution of confirmed tsunami sources

- >250k deaths from tsunamis since 1980
- ~60k deaths at a distance >1000k from source

Australian Government and Tsunami Warning

- Australia is bounded by 8,000 km of active tectonic plate boundary capable of generating a tsunami (impacts in 2-4 hours, 90-minute requirement for warning)
- Significant vulnerable low-lying areas
- After the December 2004 Sumatra earthquake and tsunami, the need to be able to warn the Australian population was identified.
- Established the National Earthquake Alerts Centre (**NEAC**) operated by Geoscience Australia (GA) and the Joint Australian Tsunami Warning Centre (**JATWC**) is operated by the Bureau of Meteorology (Bureau) and GA
- NEAC and JATWC has a mandate to detect, monitor, verify and warn the community of earthquakes and tsunamis in our region and possible threats to Australian coastal locations and offshore territories

Current Tsunami Warning Capability

Global problem:

- Some countries have dense and sophisticated monitoring systems for early and accurate national warning – most don’t.
- One country’s near-field tsunami can significantly impact distant countries: 1960 Chile, 2004 Indonesia, 2011 Japan

Coordinated tsunami warning systems:

- Regional Tsunami Service Providers (TSPs) and National Tsunami Warning Centres (NTWCs) work together to deliver 24x7 early warnings down to local levels – “coastal forecast zones”
- Australia: Joint Australian Tsunami Warning Centre (JATWC) - both a TSP and a NTWC

Monitoring networks of sparse, point-sources - data sharing is key:

- Australia has a network of ~100 real-time seismic monitoring stations, 6 deep-ocean buoys and a network of coastal tide gauges.
- We rely on global, real-time data sharing - seismic data and sea-level data - in order to detect tsunami sources (earthquakes) and confirm tsunami existence.

Current Tsunami Warning Capability

Current Capability:

- 24x7 real-time earthquake detection and characterisation to define tsunami source parameters
- Estimates of tsunami wave heights and arrival time of first wave at any land-mass are forecast from the source parameters
- Coastal zones under threat are determined
- TSP / NTWC warnings are issued; national warning chains/processes are triggered
- TSPs (and NTWCs) monitor sea-level data for CONFIRMATION that a tsunami has been generated.

Current challenge:

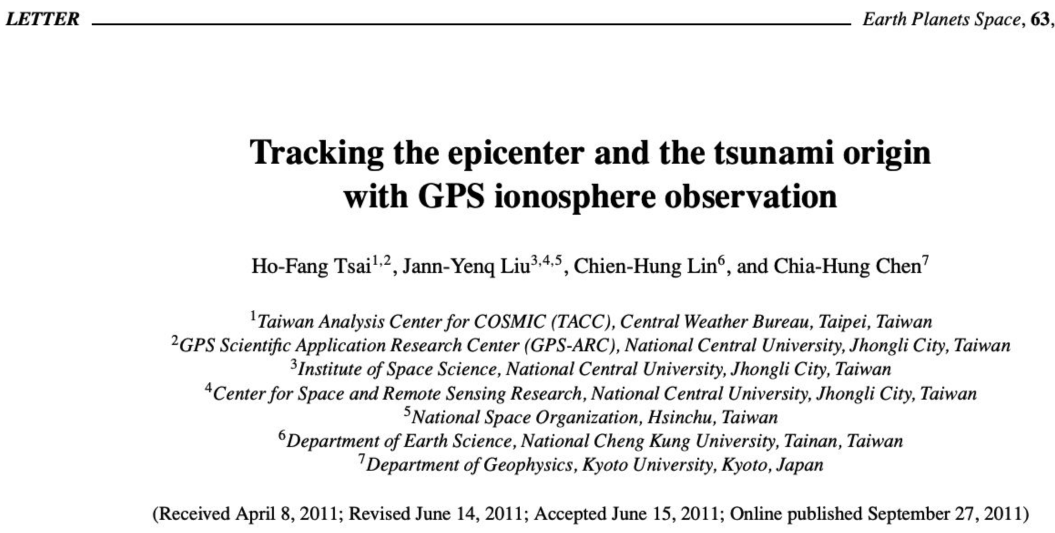
- The accuracy of tsunami early warnings relies on the accuracy of the earthquake [or other] source parameters. Source parameters are derived from inversions which entail assumptions – when well-observed, they're pretty good but they're a PROXY for the phenomenon of interest: the tsunami.
- Direct observation of the tsunami is from generally sparse point sources, only – deep ocean buoys (DART) and coastal tide-gauges.
- Increasing the density of monitoring infrastructure, including SMART cables, can help improve

Ideal Tsunami Warning Capability

Ideal capability:

- 4D observation of the ocean surface with capability to detect and parameterise tsunami continuously, world-wide, 24x7, and in real-time
- Are existing satellite-based technologies the solution? If not, how close can they get us to the ideal state?

Tsunami monitoring with ground-based GNSS derived ionosphere observations



LETTER *Earth Planets Space*, **63**, 859–862, 2011

Tracking the epicenter and the tsunami origin with GPS ionosphere observation

Ho-Fang Tsai[1,2], Jann-Yenq Liu[3,4,5], Chien-Hung Lin[6], and Chia-Hung Chen[7]

[1]*Taiwan Analysis Center for COSMIC (TACC), Central Weather Bureau, Taipei, Taiwan*
[2]*GPS Scientific Application Research Center (GPS-ARC), National Central University, Jhongli City, Taiwan*
[3]*Institute of Space Science, National Central University, Jhongli City, Taiwan*
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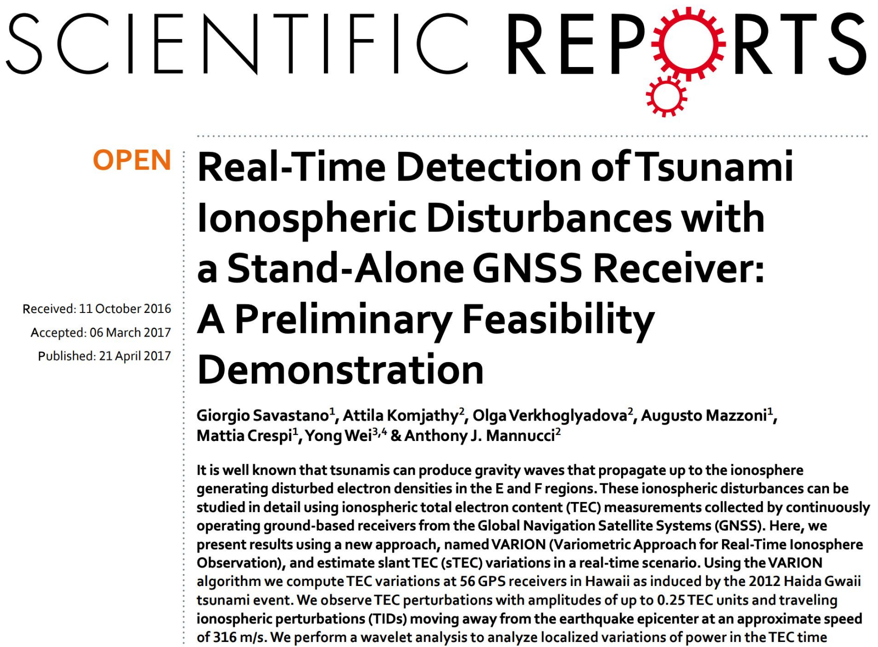
[5]*National Space Organization, Hsinchu, Taiwan*
[6]*Department of Earth Science, National Cheng Kung University, Tainan, Taiwan*
[7]*Department of Geophysics, Kyoto University, Kyoto, Japan*

(Received April 8, 2011; Revised June 14, 2011; Accepted June 15, 2011; Online published September 27, 2011)



SCIENTIFIC REPORTS

OPEN

Real-Time Detection of Tsunami Ionospheric Disturbances with a Stand-Alone GNSS Receiver: A Preliminary Feasibility Demonstration

Received: 11 October 2016
Accepted: 06 March 2017
Published: 21 April 2017

Giorgio Savastano[1], Attila Komjathy[2], Olga Verkhoglyadova[2], Augusto Mazzoni[1], Mattia Crespi[1], Yong Wei[3,4] & Anthony J. Mannucci[2]

It is well known that tsunamis can produce gravity waves that propagate up to the ionosphere generating disturbed electron densities in the E and F regions. These ionospheric disturbances can be studied in detail using ionospheric total electron content (TEC) measurements collected by continuously operating ground-based receivers from the Global Navigation Satellite Systems (GNSS). Here, we present results using a new approach, named VARION (Variometric Approach for Real-Time Ionosphere Observation), and estimate slant TEC (sTEC) variations in a real-time scenario. Using the VARION algorithm we compute TEC variations at 56 GPS receivers in Hawaii as induced by the 2012 Haida Gwaii tsunami event. We observe TEC perturbations with amplitudes of up to 0.25 TEC units and traveling ionospheric perturbations (TIDs) moving away from the earthquake epicenter at an approximate speed of 316 m/s. We perform a wavelet analysis to analyze localized variations of power in the TEC time

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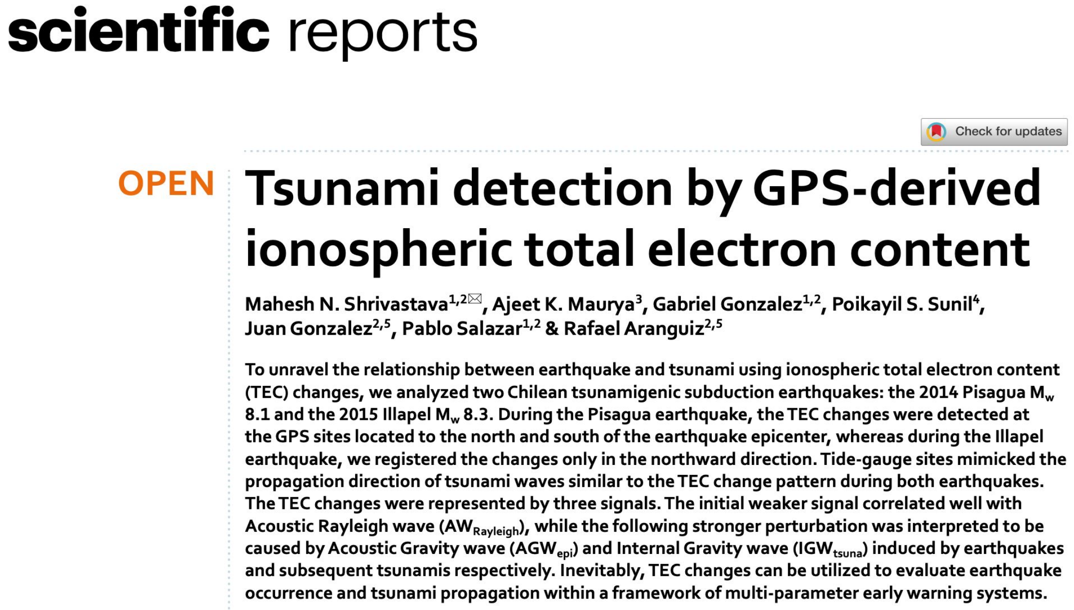

scientific reports

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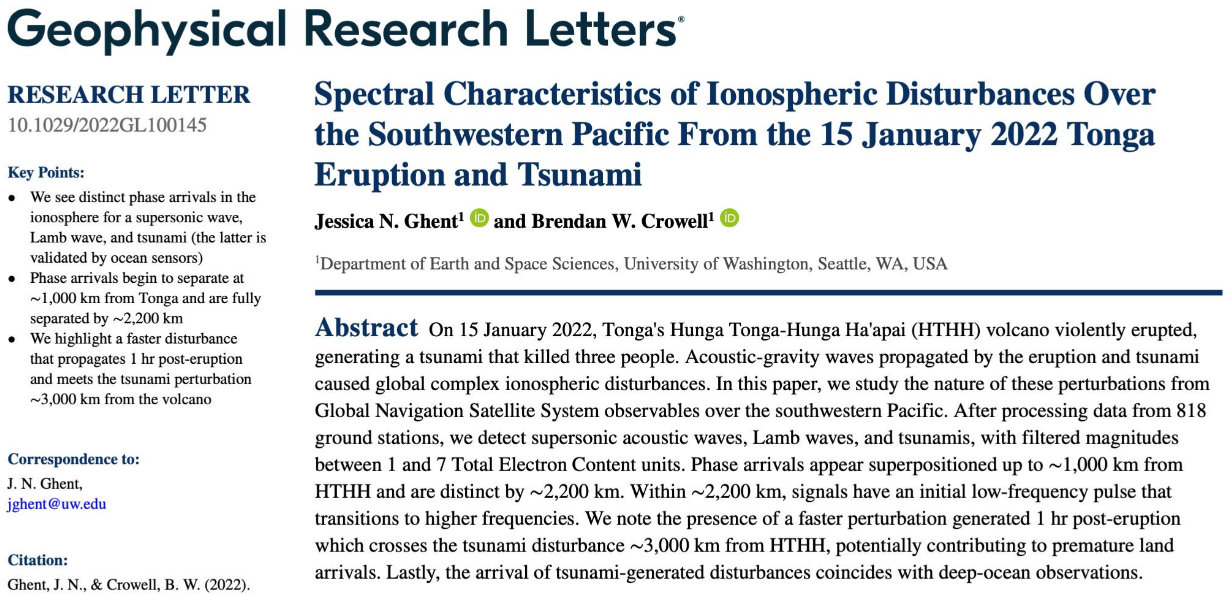
Tsunami detection by GPS-derived ionospheric total electron content

Mahesh N. Shrivastava[1,2]✉, Ajeet K. Maurya[3], Gabriel Gonzalez[1,2], Poikayil S. Sunil[4], Juan Gonzalez[2,5], Pablo Salazar[1,2] & Rafael Aranguiz[2,5]

To unravel the relationship between earthquake and tsunami using ionospheric total electron content (TEC) changes, we analyzed two Chilean tsunamigenic subduction earthquakes: the 2014 Pisagua M_w 8.1 and the 2015 Illapel M_w 8.3. During the Pisagua earthquake, the TEC changes were detected at the GPS sites located to the north and south of the earthquake epicenter, whereas during the Illapel earthquake, we registered the changes only in the northward direction. Tide-gauge sites mimicked the propagation direction of tsunami waves similar to the TEC change pattern during both earthquakes. The TEC changes were represented by three signals. The initial weaker signal correlated well with Acoustic Rayleigh wave ($AW_{Rayleigh}$), while the following stronger perturbation was interpreted to be caused by Acoustic Gravity wave (AGW_{epi}) and Internal Gravity wave (IGW_{tsuna}) induced by earthquakes and subsequent tsunamis respectively. Inevitably, TEC changes can be utilized to evaluate earthquake occurrence and tsunami propagation within a framework of multi-parameter early warning systems.



Geophysical Research Letters®

RESEARCH LETTER
10.1029/2022GL100145

Key Points:

- We see distinct phase arrivals in the ionosphere for a supersonic wave, Lamb wave, and tsunami (the latter is validated by ocean sensors)
- Phase arrivals begin to separate at ~1,000 km from Tonga and are fully separated by ~2,200 km
- We highlight a faster disturbance that propagates 1 hr post-eruption and meets the tsunami perturbation ~3,000 km from the volcano

Correspondence to:
J. N. Ghent,
jghent@uw.edu

Citation:
Ghent, J. N., & Crowell, B. W. (2022).

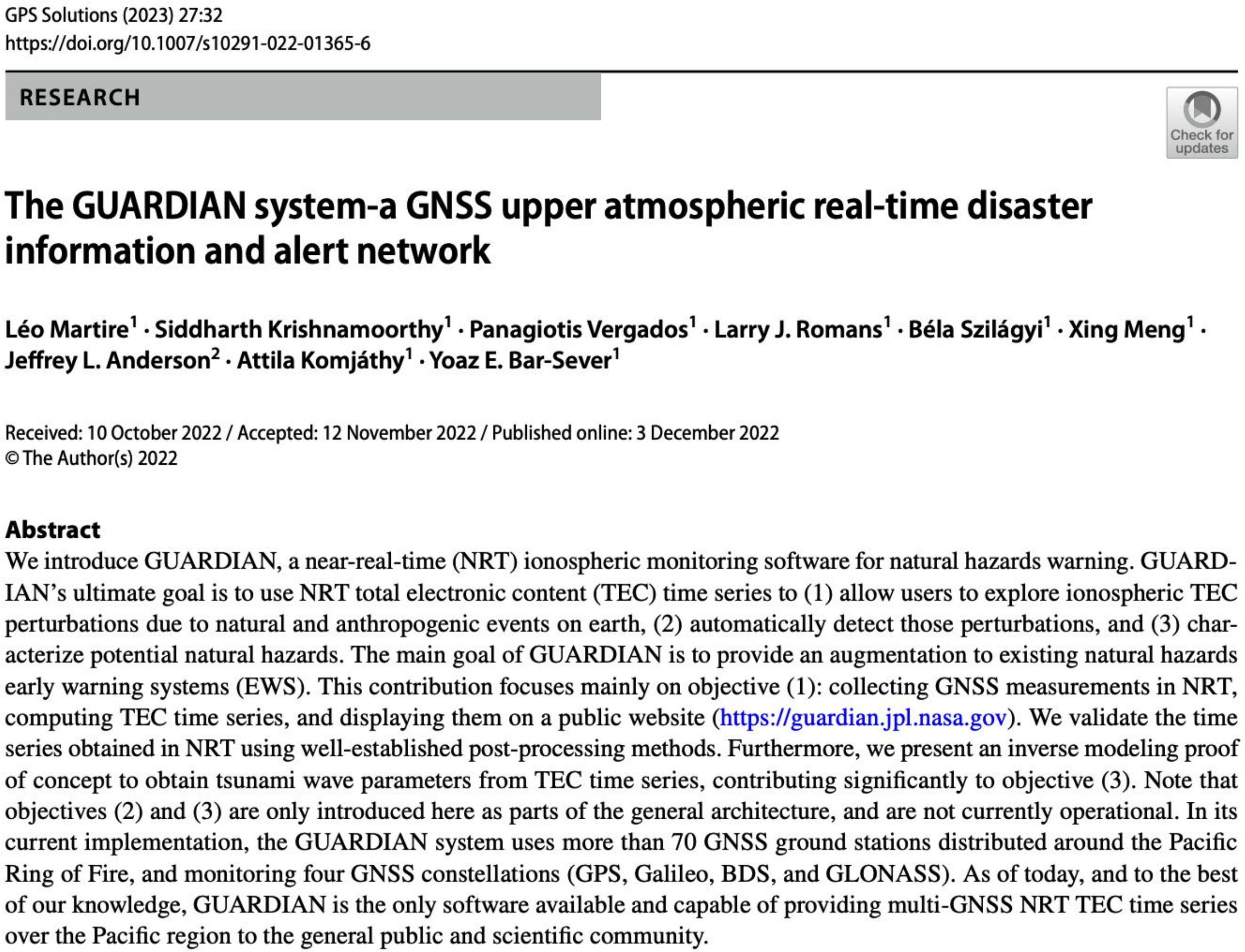
Spectral Characteristics of Ionospheric Disturbances Over the Southwestern Pacific From the 15 January 2022 Tonga Eruption and Tsunami

Jessica N. Ghent[1] and Brendan W. Crowell[1]

[1]Department of Earth and Space Sciences, University of Washington, Seattle, WA, USA

Abstract On 15 January 2022, Tonga's Hunga Tonga-Hunga Ha'apai (HTHH) volcano violently erupted, generating a tsunami that killed three people. Acoustic-gravity waves propagated by the eruption and tsunami caused global complex ionospheric disturbances. In this paper, we study the nature of these perturbations from Global Navigation Satellite System observables over the southwestern Pacific. After processing data from 818 ground stations, we detect supersonic acoustic waves, Lamb waves, and tsunamis, with filtered magnitudes between 1 and 7 Total Electron Content units. Phase arrivals appear superpositioned up to ~1,000 km from HTHH and are distinct by ~2,200 km. Within ~2,200 km, signals have an initial low-frequency pulse that transitions to higher frequencies. We note the presence of a faster perturbation generated 1 hr post-eruption which crosses the tsunami disturbance ~3,000 km from HTHH, potentially contributing to premature land arrivals. Lastly, the arrival of tsunami-generated disturbances coincides with deep-ocean observations.

Real-time ground-based GNSS ionosphere observations



GPS Solutions (2023) 27:32
https://doi.org/10.1007/s10291-022-01365-6

RESEARCH

The GUARDIAN system-a GNSS upper atmospheric real-time disaster information and alert network

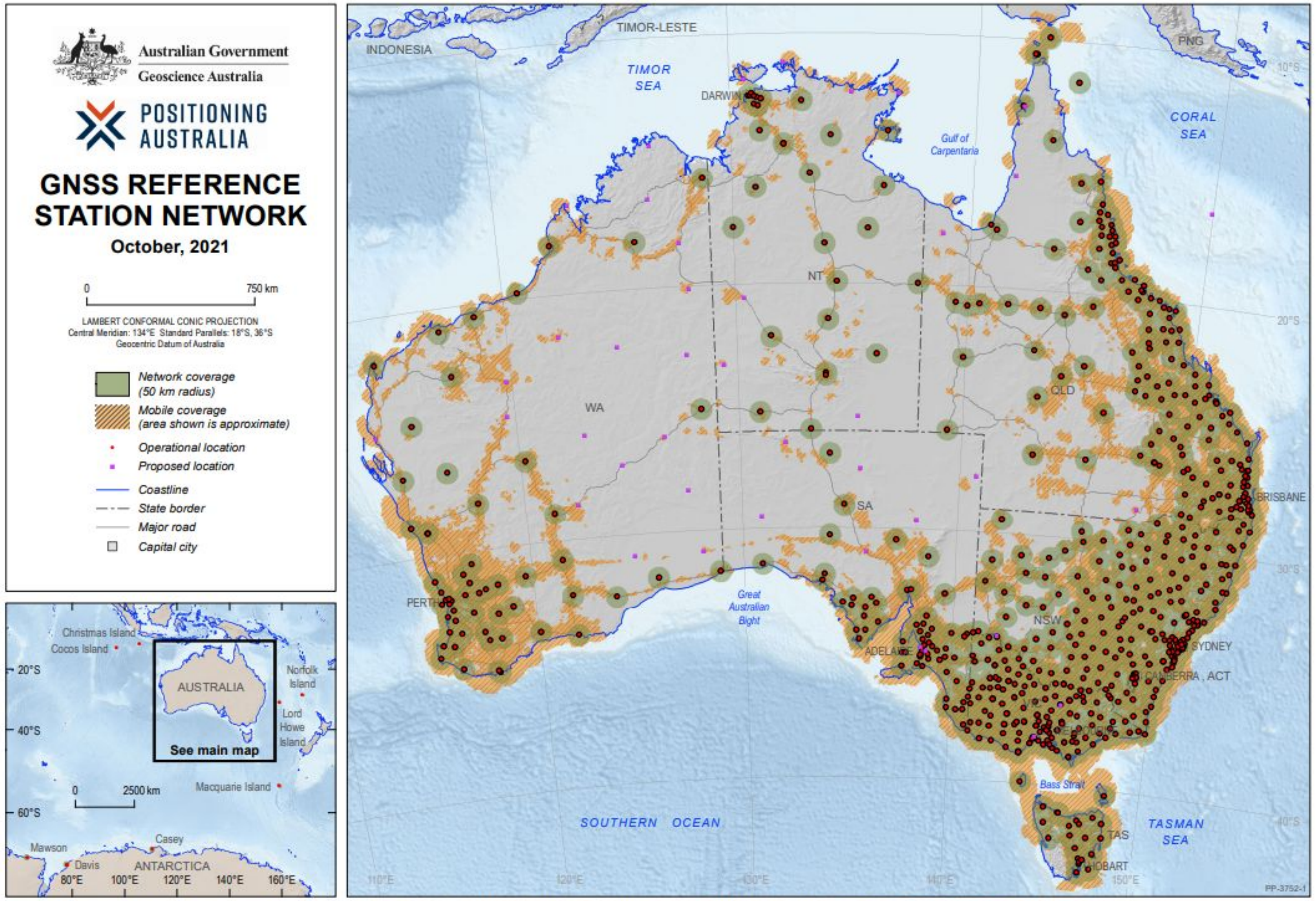
Léo Martire[1] · Siddharth Krishnamoorthy[1] · Panagiotis Vergados[1] · Larry J. Romans[1] · Béla Szilágyi[1] · Xing Meng[1] · Jeffrey L. Anderson[2] · Attila Komjáthy[1] · Yoaz E. Bar-Sever[1]

Received: 10 October 2022 / Accepted: 12 November 2022 / Published online: 3 December 2022

Abstract

We introduce GUARDIAN, a near-real-time (NRT) ionospheric monitoring software for natural hazards warning. GUARDIAN's ultimate goal is to use NRT total electronic content (TEC) time series to (1) allow users to explore ionospheric TEC perturbations due to natural and anthropogenic events on earth, (2) automatically detect those perturbations, and (3) characterize potential natural hazards. The main goal of GUARDIAN is to provide an augmentation to existing natural hazards early warning systems (EWS). This contribution focuses mainly on objective (1): collecting GNSS measurements in NRT, computing TEC time series, and displaying them on a public website (https://guardian.jpl.nasa.gov). We validate the time series obtained in NRT using well-established post-processing methods. Furthermore, we present an inverse modeling proof of concept to obtain tsunami wave parameters from TEC time series, contributing significantly to objective (3). Note that objectives (2) and (3) are only introduced here as parts of the general architecture, and are not currently operational. In its current implementation, the GUARDIAN system uses more than 70 GNSS ground stations distributed around the Pacific Ring of Fire, and monitoring four GNSS constellations (GPS, Galileo, BDS, and GLONASS). As of today, and to the best of our knowledge, GUARDIAN is the only software available and capable of providing multi-GNSS NRT TEC time series over the Pacific region to the general public and scientific community.

Australia's National Positioning Infrastructure Capability (NPIC)



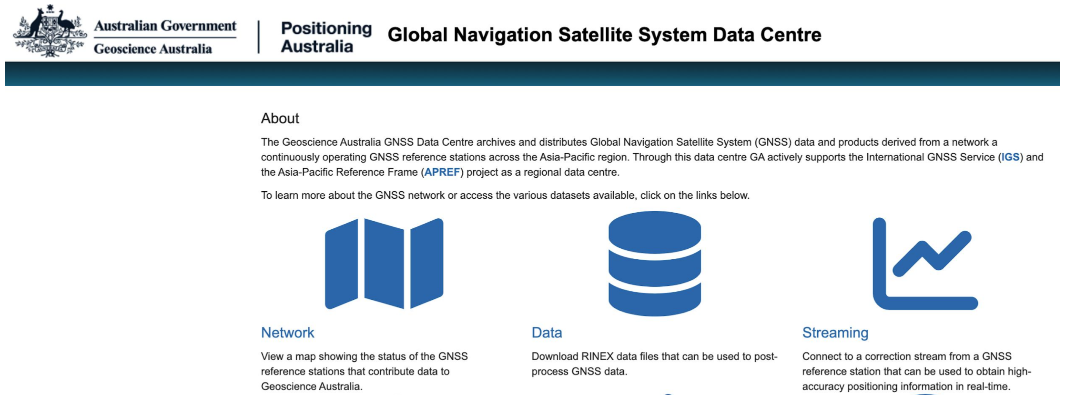
- GA's Positioning Australia program is establishing a national network of continuously operating GNSS reference stations (CORS) that will enable the delivery of 3-5 cm accurate positioning services
- Modernising and expanding Australia's fundamental geodetic GNSS network
- Densifying the network, through partnerships with other government and industry network operators
- Improving the accessibility and reliability of our systems to ensure that the data from the network is accurate and reliable.

NPIC GNSS network Infrastructure

New site build - Oak Valley, Maralinga (remote western SA)

- Standardised systems
- Dual Multi-GNSS receivers
- 1 Hz sampling rate and data streaming
- Real-time comms
- Redundant power

- Upgrading 130 ground reference stations ensure the reliability and resilience into the future
- Installing 70 new ground reference stations to expand the range of the network and fill gaps
- Additionally helps maintain a network of 13 RT GNSS CORS stations in the South Pacific



Global Navigation Satellite System Data Centre

About

The Geoscience Australia GNSS Data Centre archives and distributes Global Navigation Satellite System (GNSS) data and products derived from a network a continuously operating GNSS reference stations across the Asia-Pacific region. Through this data centre GA actively supports the International GNSS Service (IGS) and the Asia-Pacific Reference Frame (APREF) project as a regional data centre.

To learn more about the GNSS network or access the various datasets available, click on the links below.

Network

View a map showing the status of the GNSS reference stations that contribute data to Geoscience Australia.

Data

Download RINEX data files that can be used to post-process GNSS data.

Streaming

Connect to a correction stream from a GNSS reference station that can be used to obtain high-accuracy positioning information in real-time.

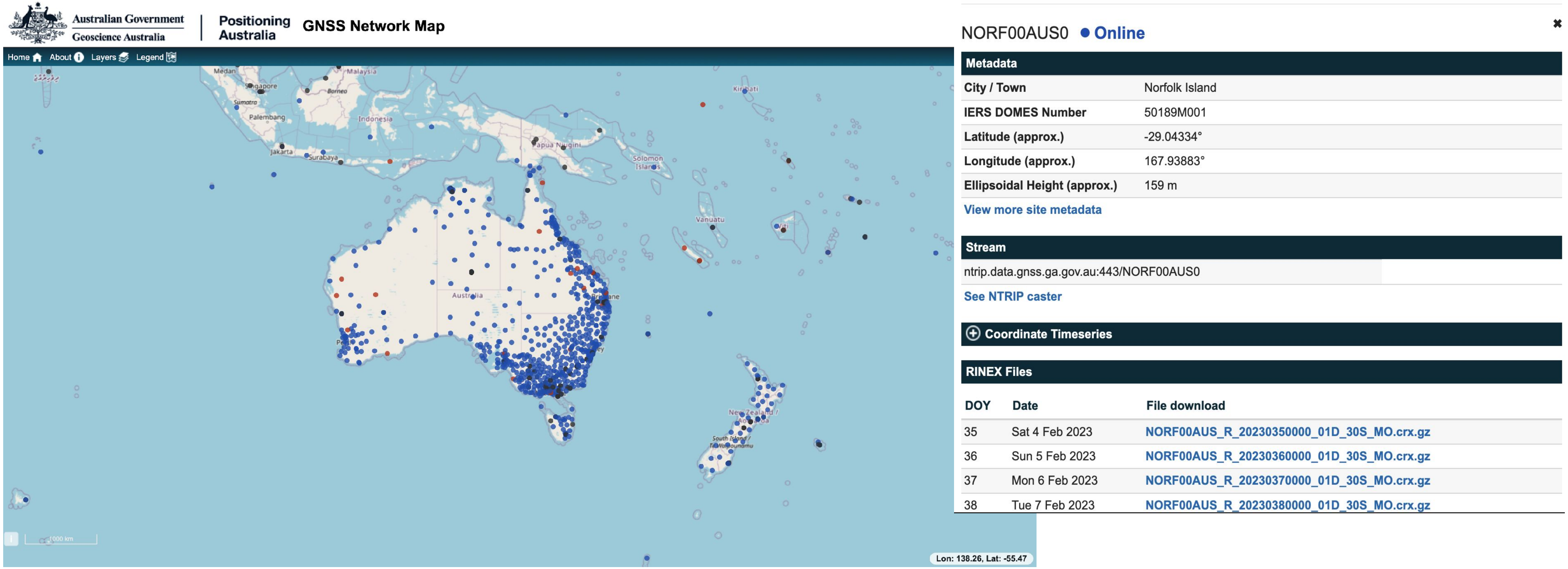
Cloud-Based System

Portal:

- https://gnss.ga.gov.au/

NTRIP Castor:

- ntrip.data.gnss.ga.gov.au



GNSS Network Map

NORF00AUS0 ● Online

Metadata

City / Town	Norfolk Island
IERS DOMES Number	50189M001
Latitude (approx.)	-29.04334°
Longitude (approx.)	167.93883°
Ellipsoidal Height (approx.)	159 m

View more site metadata

Stream

ntrip.data.gnss.ga.gov.au:443/NORF00AUS0

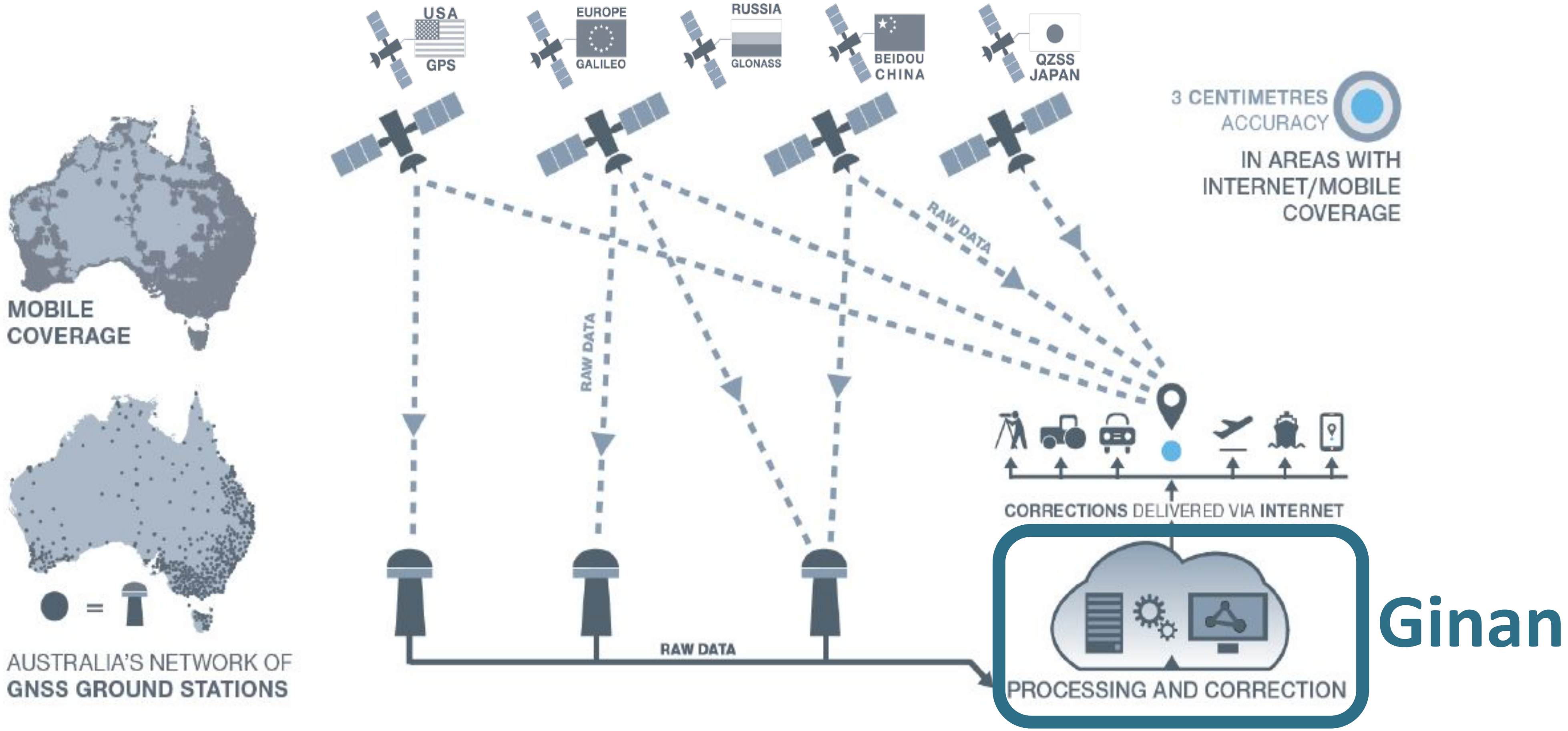
See NTRIP caster

⊕ Coordinate Timeseries

RINEX Files

DOY	Date	File download
35	Sat 4 Feb 2023	NORF00AUS_R_20230350000_01D_30S_MO.crx.gz
36	Sun 5 Feb 2023	NORF00AUS_R_20230360000_01D_30S_MO.crx.gz
37	Mon 6 Feb 2023	NORF00AUS_R_20230370000_01D_30S_MO.crx.gz
38	Tue 7 Feb 2023	NORF00AUS_R_20230380000_01D_30S_MO.crx.gz

Ginan: Geoscience Australia's GNSS Analysis Centre Software



- Multi-GNSS Un-differenced / Un-combined (UDUC) data analysis capability
- Open-source software capable of delivering positioning services for real-time and post processed applications
- Enable centimetre level accuracy positioning in areas with IP (internet) coverage

Ginan Ionosphere observation and modelling capability

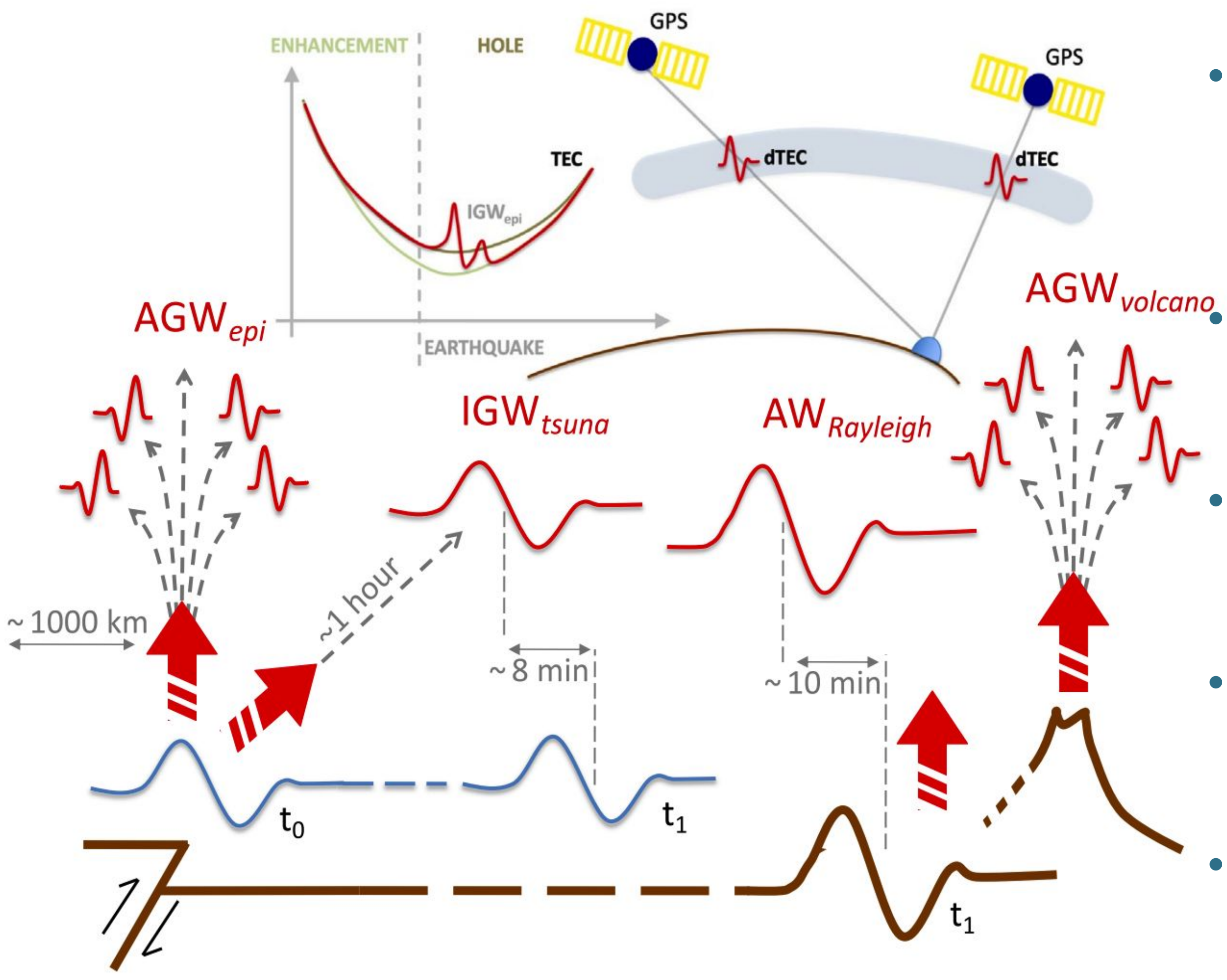
- Ginan is based on the State Space Representation (SSR) methodology.
- The GNSS observation equation terms are mostly parameterized as States in a filter and can be estimated and then transmitted users enabling Precise Point Positioning (PPP)

$$
\begin{aligned}
E(P^{s}_{r,f}) &= \rho^{s}_{r} + c(dt^{q}_{r} - dt^{s}) + \tau^{s}_{r} + \boxed{\mu_f I^{s}_{r}} + d^{q}_{r,f} + d^{s}_{f} \\
E(L^{s}_{r,f}) &= \rho^{s}_{r} + c(dt^{q}_{r} - dt^{s}) + \tau^{s}_{r} - \boxed{\mu_f I^{s}_{r}} + b^{q}_{r,f} - b^{s}_{f} + \lambda_f z^{s}_{r,f} + \phi^{s}_{r,f}
\end{aligned}
$$

- Ionospheric delay is one of the States that can be estimated. Allowing unbiased receiver-satellite Slant Total Electron Content (STEC) extracted at every time step of the filter

- Ginan can use these STEC values to derive station Vertical TEC (VTEC) to produce various models that represent the ionospheric delay that can be broadcast to users for PPP-RTK positioning

Ionosphere monitoring using GNSS



J. Eisenbeis & G. Occhipinti, (2021)

- Ionosphere is an ionized layer @~50 km to ~1000 km altitude that varies in density with time and space.
- Free electrons in the ionosphere are measured in units call Total Electron Content (TEC). 1 TECU = 1×10^{16} electrons per m^2 (assuming electrons are compressed into a single shell).
- GNSS signals are delayed and refracted depending on the TEC of the ionosphere and the frequency of GNSS signals.
- Processes that produce waves in the atmosphere are also produce waves of different types in the ionosphere.
- Using dual frequency GNSS signals the Slant TEC (STEC) between the GNSS ground receiver and the GNSS satellite can be monitored
- In this way waves in the ionosphere called Traveling Ionospheric Disturbances (TIDs) caused by various processes on the Earths surface can be tracked over time using GNSS signals.

Looking to the Sky for Better Tsunami Warnings

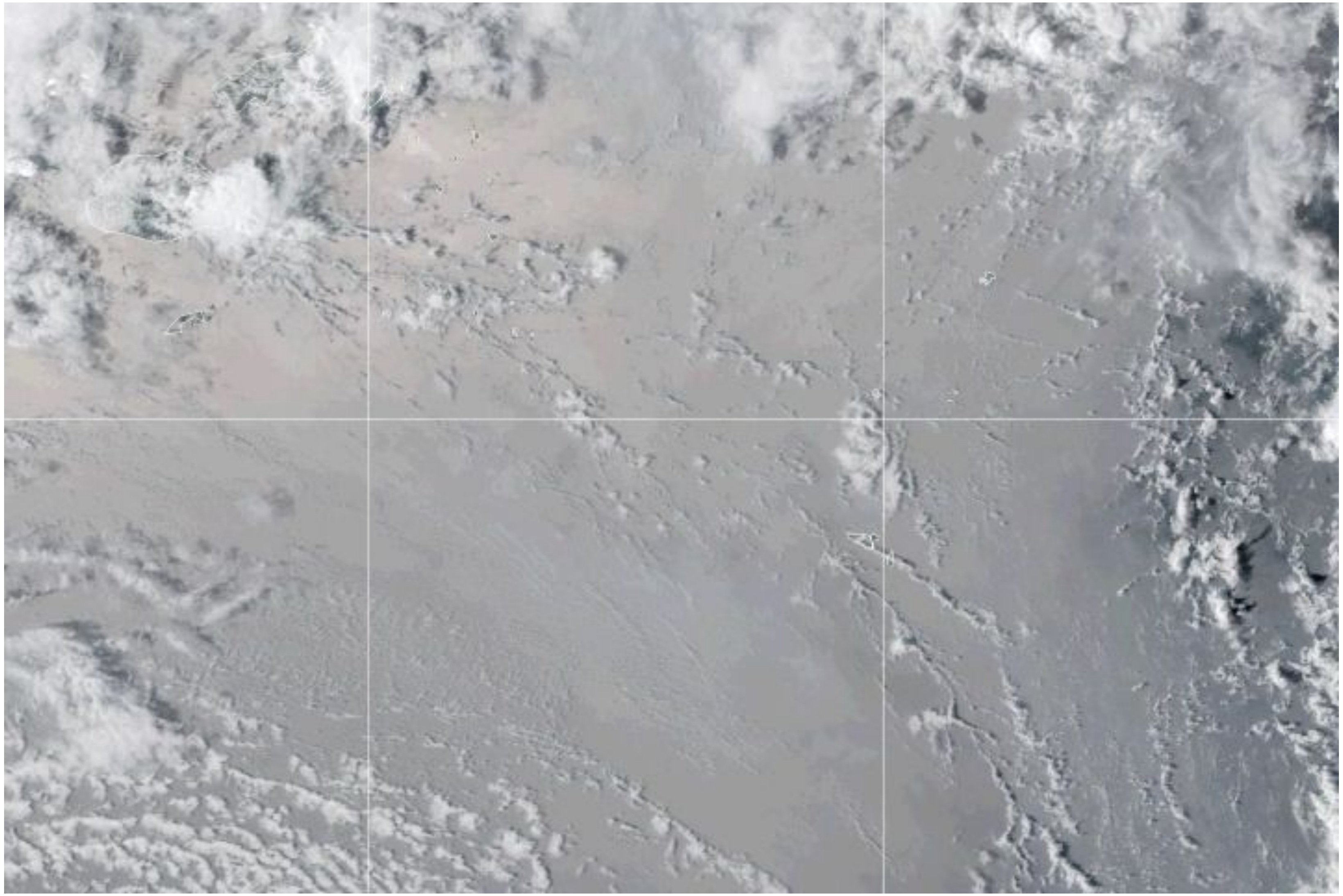
Pairing navigation satellites and CubeSats could provide earlier, more accurate warnings of approaching tsunamis and other impacts of extreme events.

By **Shin-Chan Han**, **Simon McClusky**, **T. Dylan Mikesell**, **Paul Tregoning**, and **Jeanne Sauber**   4 November 2022

A constellation of orbiting CubeSats could help map where atmospheric and tsunami waves are heading before ground-based receivers can detect them. Credit: NASA/JPL-Caltech

https://eos.org/opinions/looking-to-the-sky-for-better-tsunami-warnings

Case Study: Hunga Tonga-Hunga Ha'apai (HTHH) volcano eruption, January 15th 2022 ~04:15 UTC



Credit: NASA Earth Observatory image by Joshua Stevens using GOES imagery courtesy of NOAA and NESDIS

Spire Global Lemur-2 Cubesat Constellation

Spire Global

LEMUR-2

Size: 3U - 10x10x34.5 cm
Mass: < 6 kg
Altitude: 400 – 600 km
Orbit: Sun-Synchronous
Lifespan: ~ 2 years
Number: > 150 launched
GNSS: STRATOS dual freq
GNSS receivers
Zenith POD antenna
Side high gain RO antenna

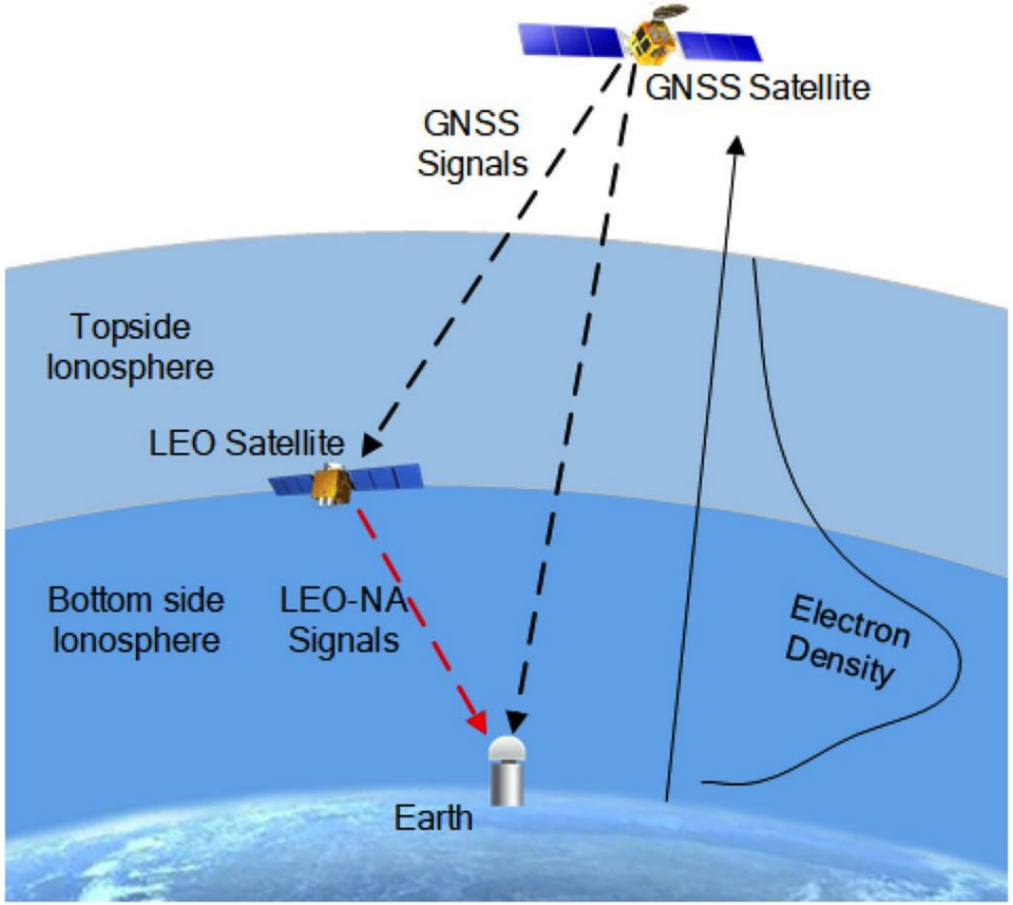


Fig. 1 Principle of ionospheric sensing with LEO-NA signals

T. Li et al., 2021

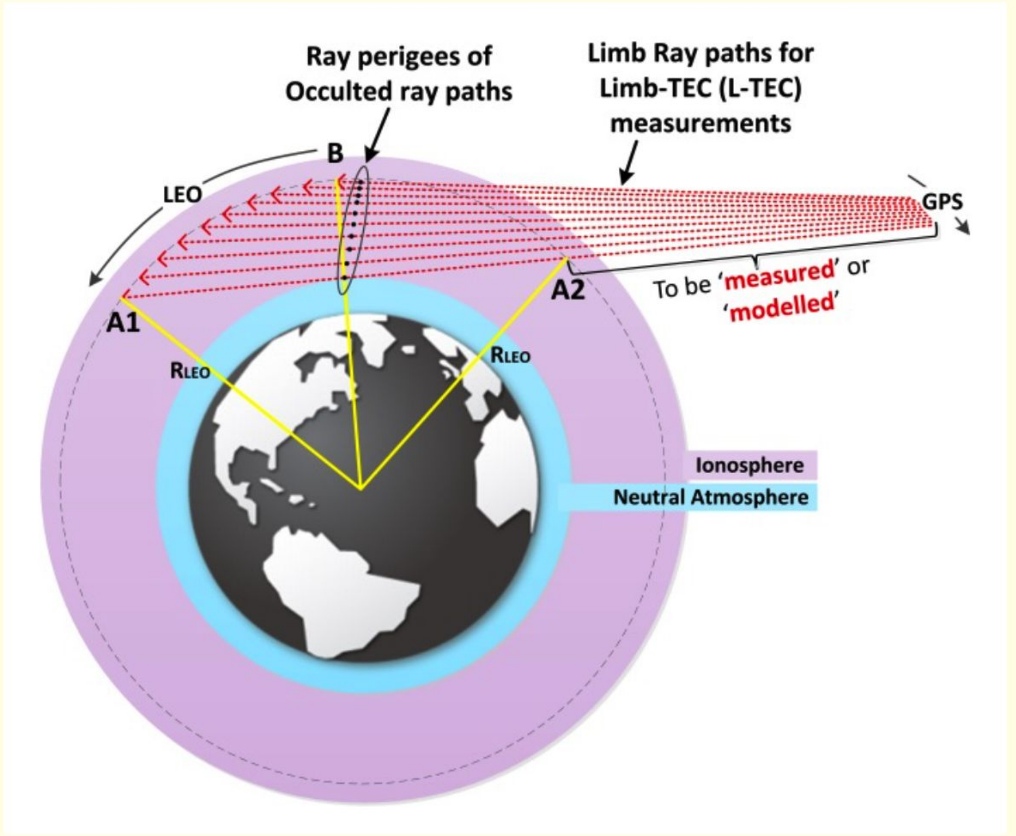
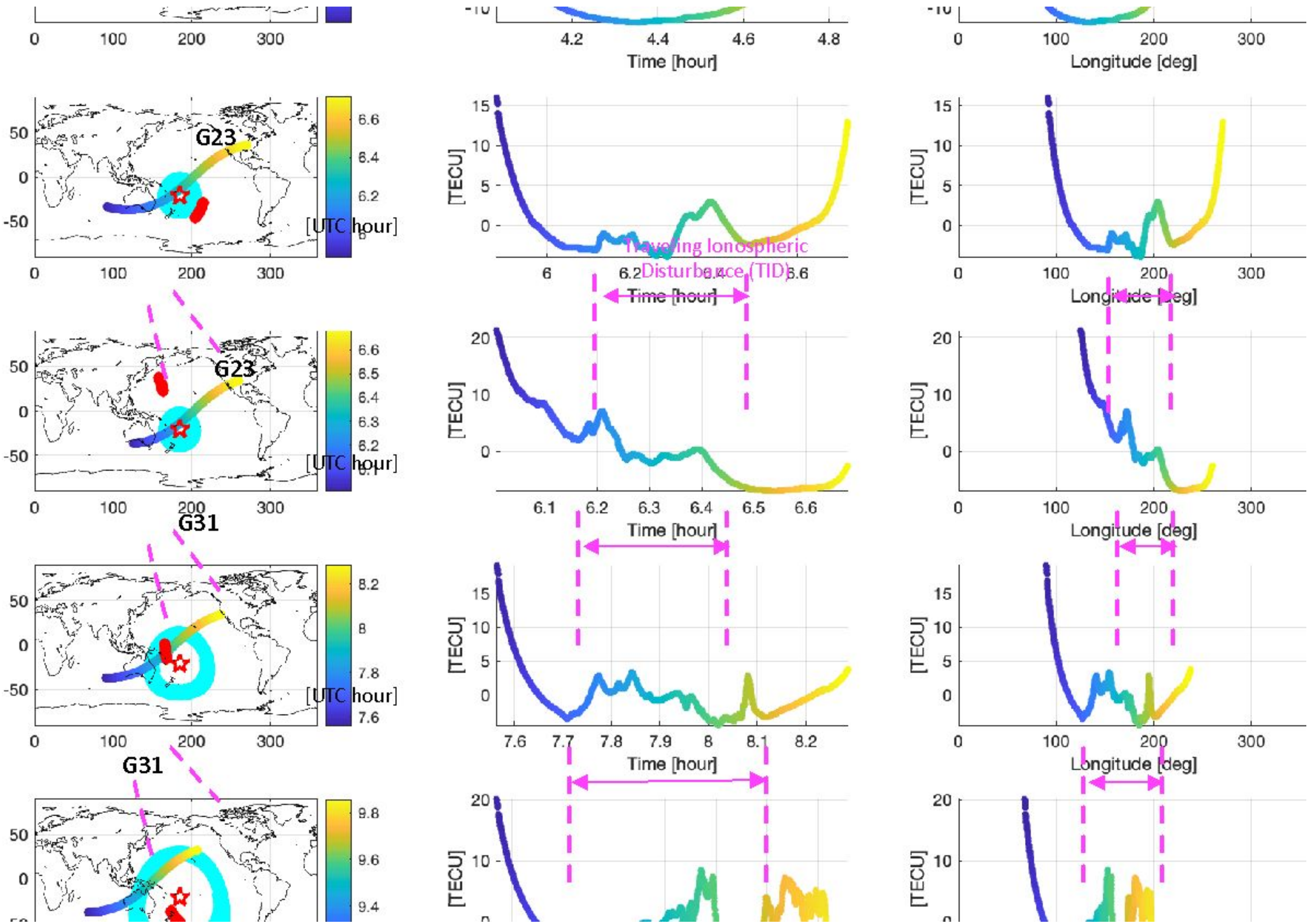


Figure 1.
Limb TEC (LTEC) measurement in the ionosphere using radio occultation technique. A1 and A2 are points defined at opposite sides of LEO orbits around ray perigees (black dots). TEC calculated between A1 and A2 is defined as 'internal orbit LTEC'.

M.M. Shaikh, R. Notarpietro & B. Nava, 2014

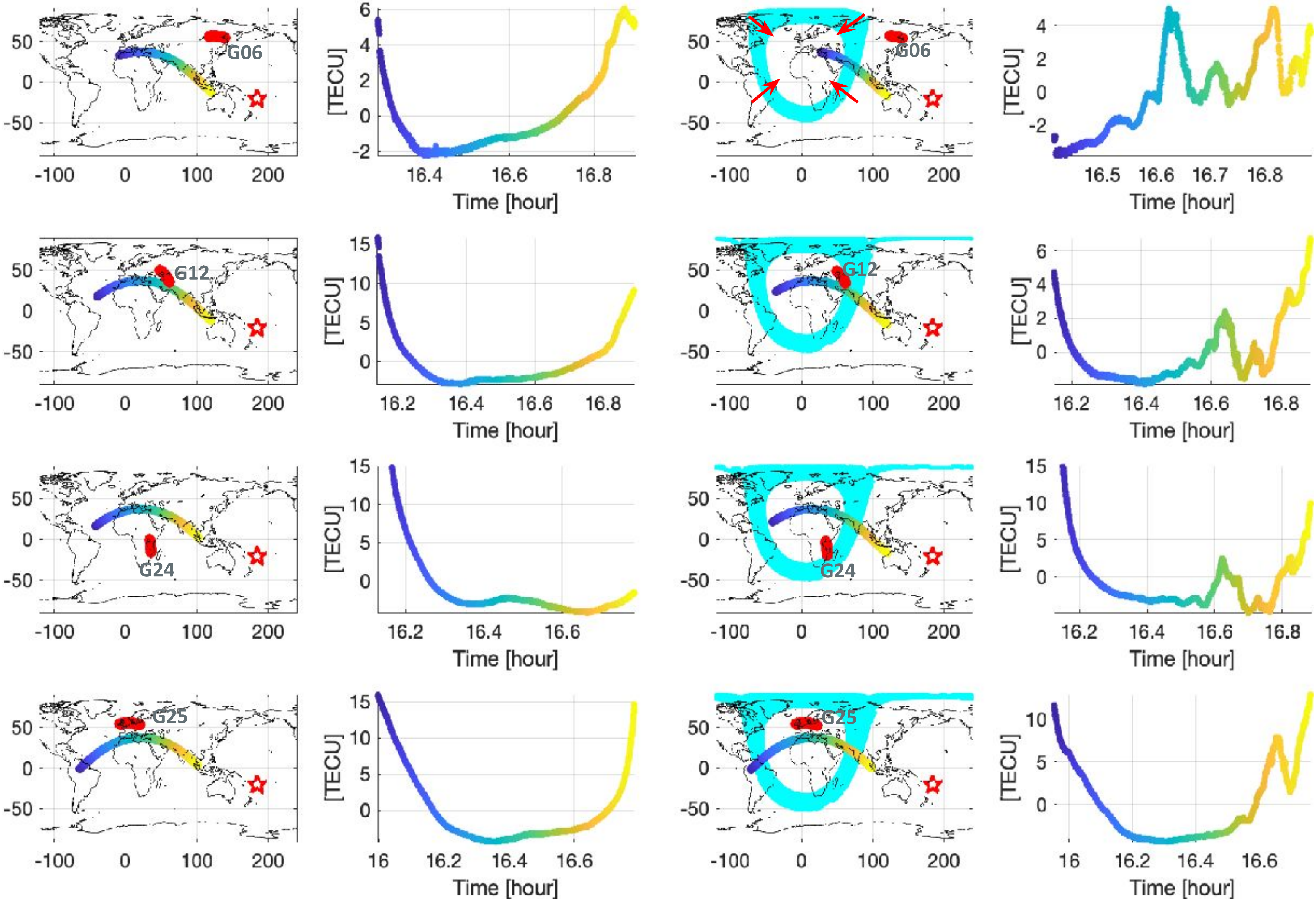
Travelling Ionospheric Disturbances (TIDs) from the CubeSat POD antenna

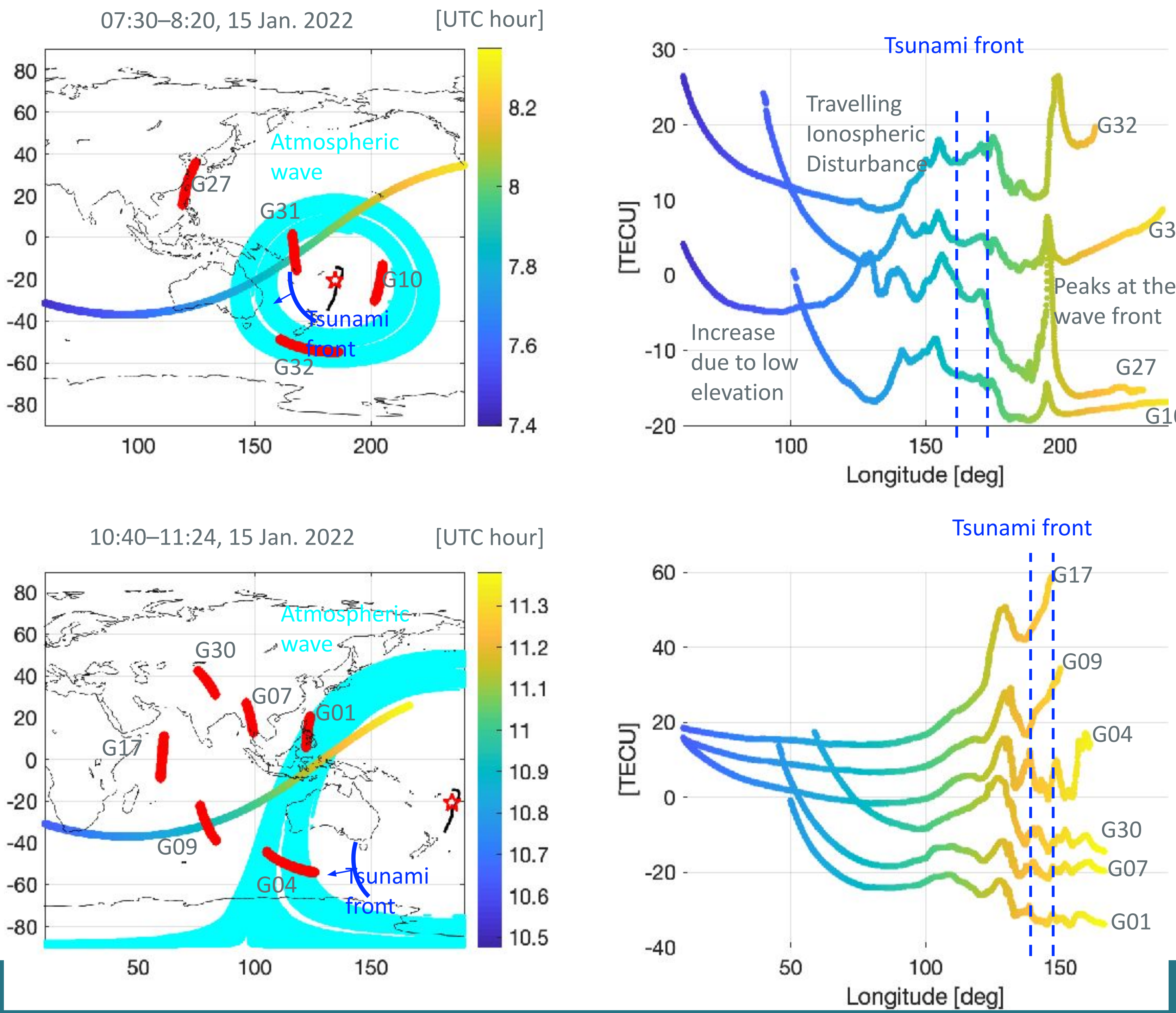


TIDs over distant locations (India)

14 Jan. 2022

15 Jan. 2022





CubeSat GPS POD antenna topside TEC measurements

TEC b/w CubeSat and GPS; high altitude (500 km and above) electron density.

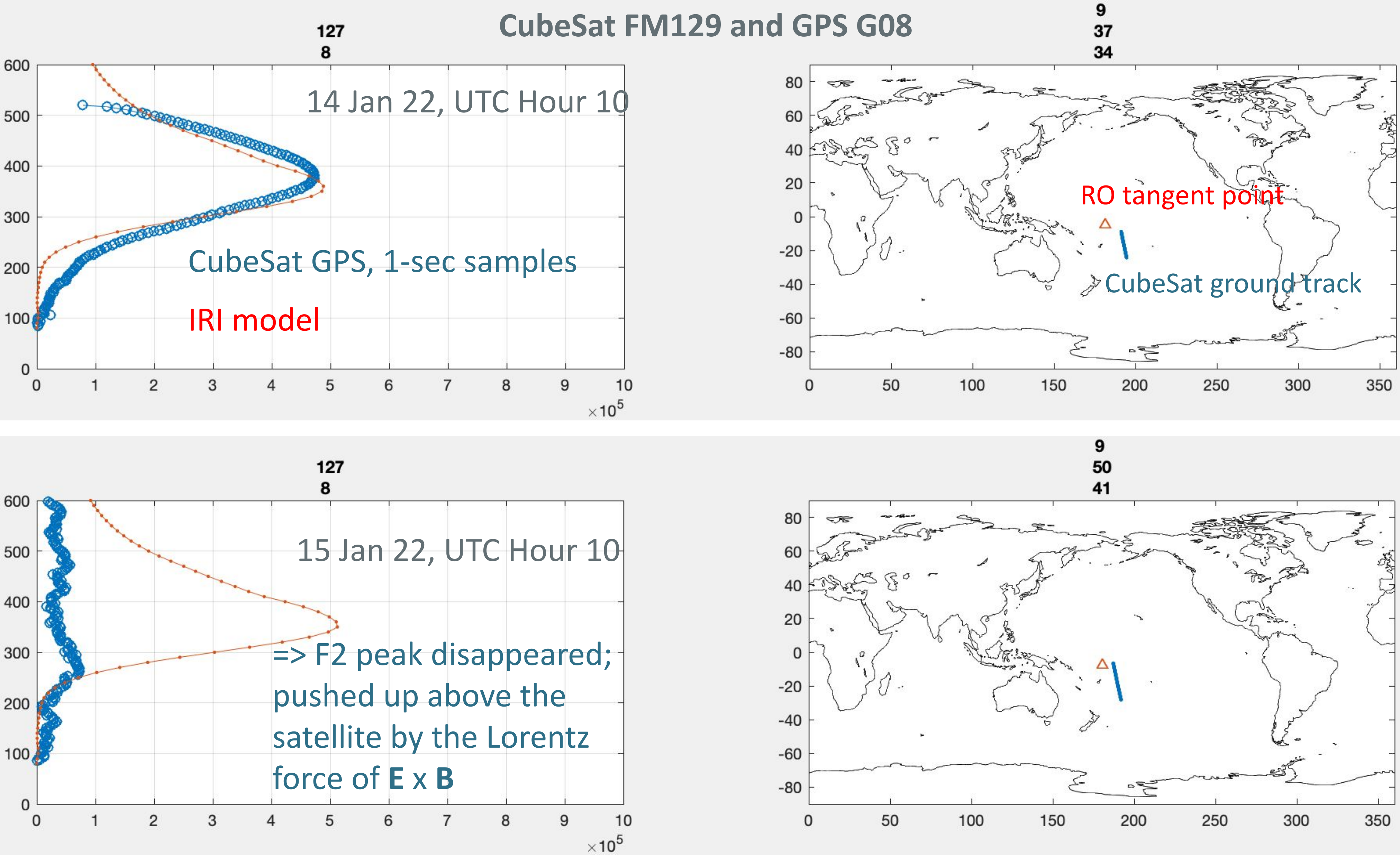
TID was detected by the CubeSats *a few hours before* the tsunami makes its landfall.

Near-real-time operation can lead to additional hours of warning time.

CubeSat constellation for tsunami early warning

Check out our article at Eos.org

CubeSat GPS RO antenna measurements



CubeSat FM129 and GPS G08

14 Jan 22, UTC Hour 10

CubeSat GPS, 1-sec samples

IRI model

RO tangent point

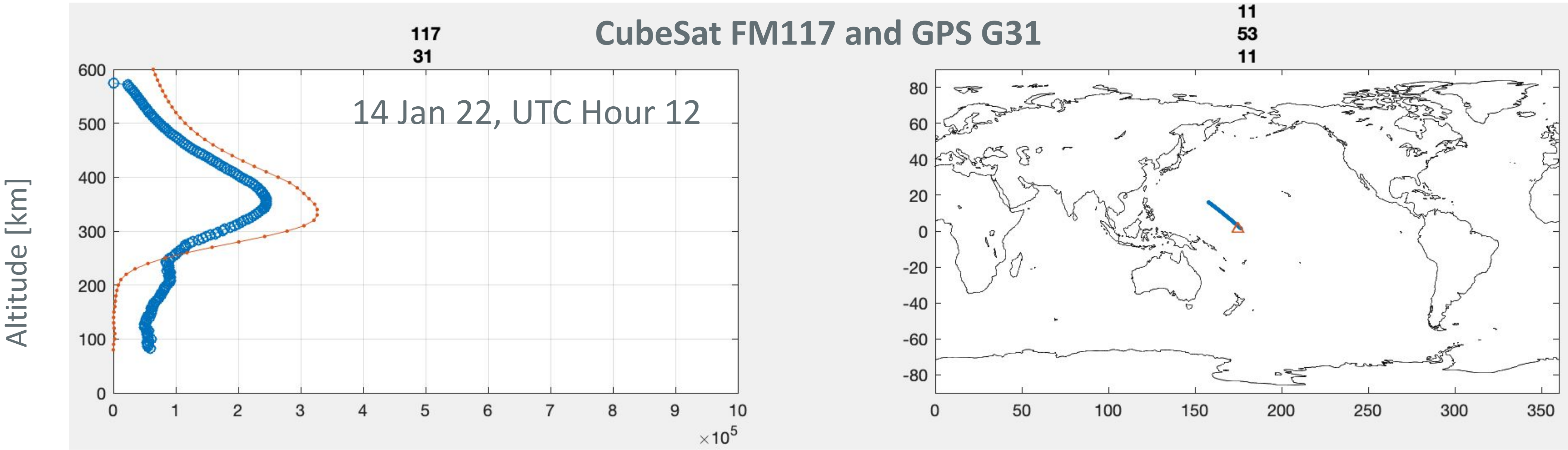
CubeSat ground track

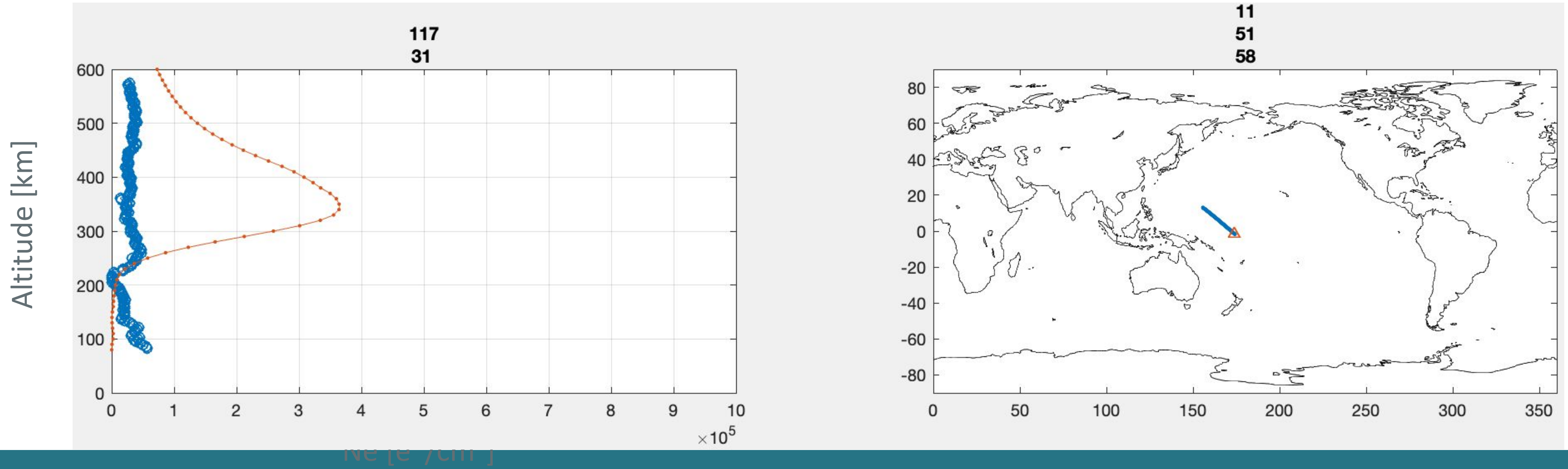
15 Jan 22, UTC Hour 10

=> F2 peak disappeared; pushed up above the satellite by the Lorentz force of **E** x **B**

CubeSat FM117 and GPS G31

14 Jan 22, UTC Hour 12





Tsunami early warning "wish-list"

Tsunami Warning Capability feature (requirement)	Imperative (ie how necessary is it for TSP/NTWC?)
Derived from OPEN, (near)real-time data sources	Essential
(near)real-time production of derived information products* for TSPs/NTWCs	Essential
(near)real-time delivery of derived information to TSPs/NTWCs	Essential
Field of view: early warning	Ideal(TSP)=global (ocean-wide), all of the time. Great(TSP)=~1000km band covering [all] known source zones (tectonic subduction zones; active oceanic volcanoes), all of the time; Great(TSP)=on-demand over any ROI, <30mins of source event (eg earthquake). Good(TSP)=on-demand over any ROI, <60mins… and so on… Good(NTWC)=on-demand over "my ROI", >2hrs TTT to "my coastline". MVP=what have you got?
Field of view: warning accuracy	Ideal(TSP)=~2hr TTT buffer from all coastlines (continental & island nations), all of the time. …scaling to… Great(NTWC)=~2hr TTT buffer from "my coastline", on demand MVP=what have you got?
DETECTION of tsunami	Ideal
CONFIRMATION of tsunami	Essential
Derived "primary" parameters: time of observation; spatial coordinates (e.g. wave(s) crest as geospatial data); number of waves above X cm wave height; wave height (largest wave);	Essential = single point in time; Ideal = series; real-time updates at <1min intervals.
Derived "secondary" parameters: Travel speed (e.g., avg over last X obs); Wave length (e.g., crest-to-crest	Nice to have in addition to "primary" parameters, but not essential.

Thankyou

Click to add text

Click to add text

Further information

Web ga.gov.au
Email simon.mcclusky@ga.gov.au