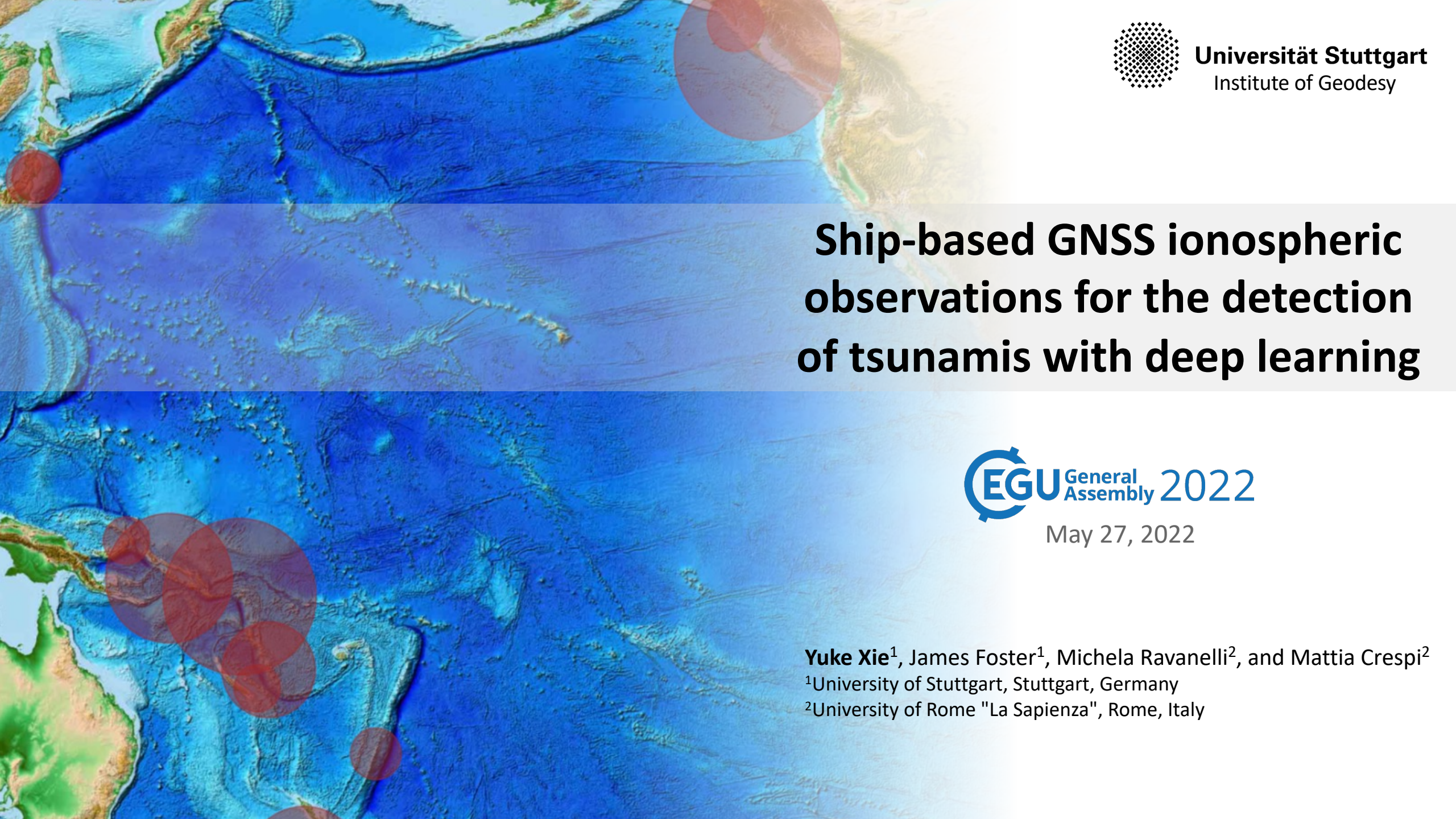


Universität Stuttgart
Institute of Geodesy

Ship-based GNSS ionospheric observations for the detection of tsunamis with deep learning

EGU General Assembly 2022

May 27, 2022

Yuke Xie[1], James Foster[1], Michela Ravanelli[2], and Mattia Crespi[2]
[1]University of Stuttgart, Stuttgart, Germany
[2]University of Rome "La Sapienza", Rome, Italy

Motivation – Detect tsunami-induced TID by GNSS

- Tsunamis are a particularly dangerous natural disaster.
  - Existing tsunami detection systems:
    - DART (bouy system)
    - Seismic
    - Tide Gauges
- Tsunami waves can trigger Internal Gravity Waves (IGW) cause TEC perturbations in the ionosphere known as Travelling Ionospheric Disturbances (TID)
- Tsunami can be detected by GNSS receivers from observed TEC variation
  - 8 minutes early detection using GNSS Network from Hawaiian islands in 2012 Haida Gwaii tsunami event

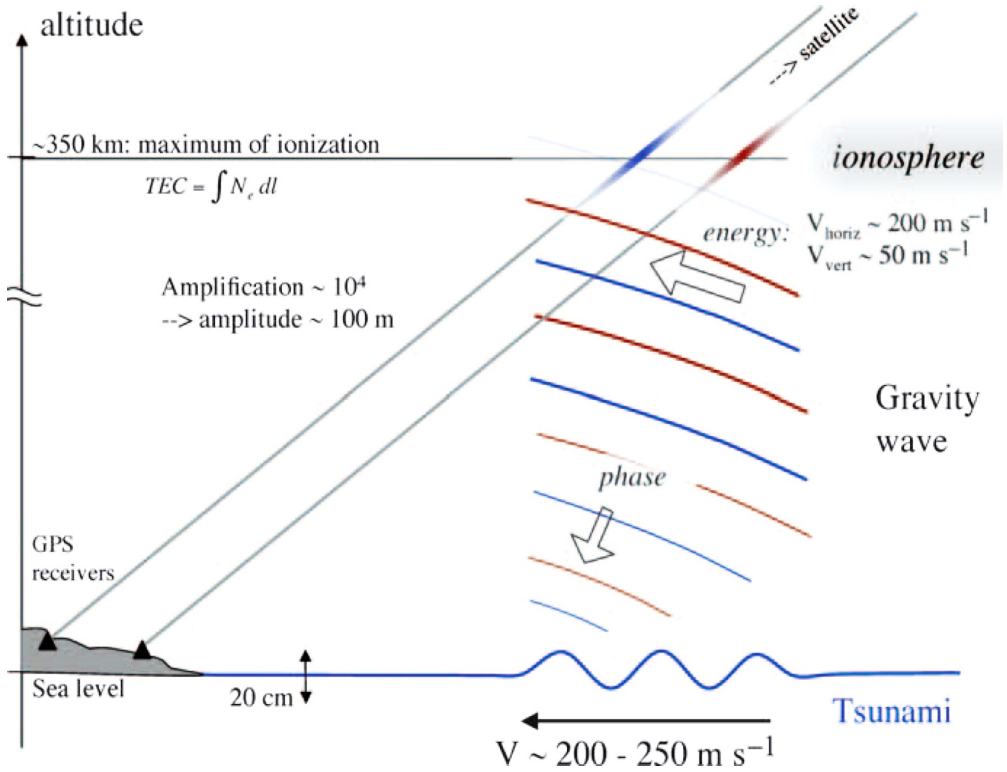


Figure: Principle of tsunami-driven TID [Artru et al., 2015]

VARION algorithm – GNSS ionosphere observation

- Variometric Approach for Real-Time Ionosphere Observation (VARION)
- Developed by Sapienza University of Rome and NASA JPL
- Open-source and fully python based
- Based on single time differences combinations of GPS carrier-phase measurements (L1, L2)
- Based on the geometry-free combination – the ship motion will not affect the TEC estimation.

$$L_{GF}(t+1) - L_{GF}(t) = \frac{f_1^2 - f_2^2}{f_2^2}\left[I_{1R}^S(t+1) - I_{1R}^S(t)\right]$$

$$\delta sTEC(t+1,t) = \frac{f_1^2 f_2^2}{A(f_1^2 - f_2^2)}\left[L_{GF}(t+1) - L_{GF}(t)\right]$$

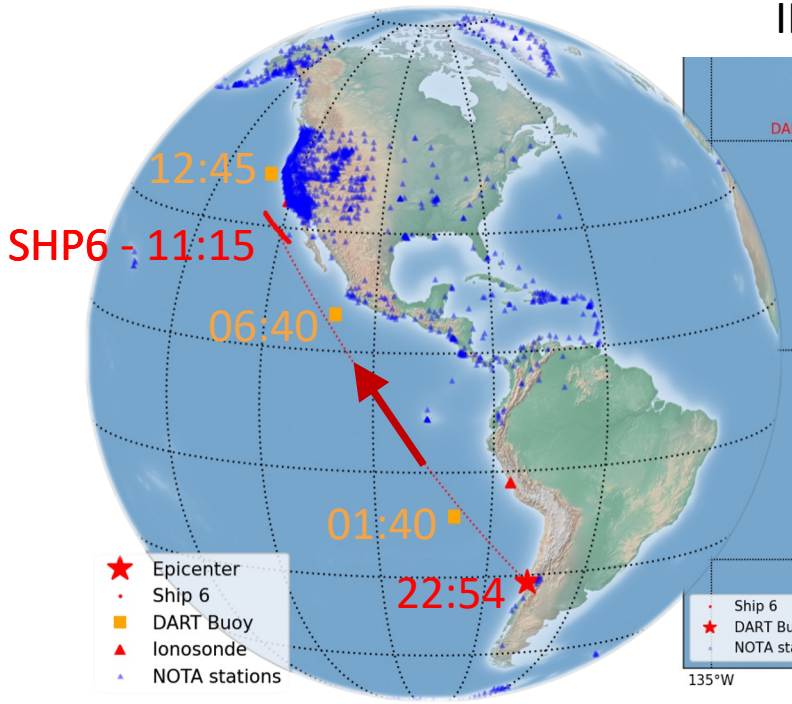
$$\Delta TEC(t_f, t_0) = \int_{t_0}^{t_f} d\ \delta TEC(t, s)$$

Ship-based GNSS observations - network

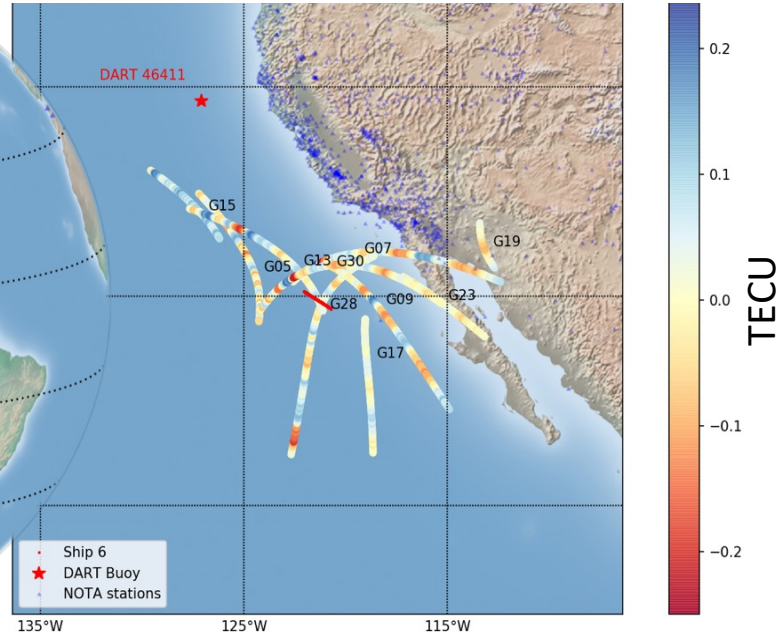
- University of Hawaii in collaboration with Matson, Maersk, and the World Ocean Council, with funding from NOAA
- 10-ship pilot GNSS network with 1s sample rate

Figure: A installed Trimble NetR9 receiver GNSS receiver on the commercial ship [Foster, 2019]

Globe view



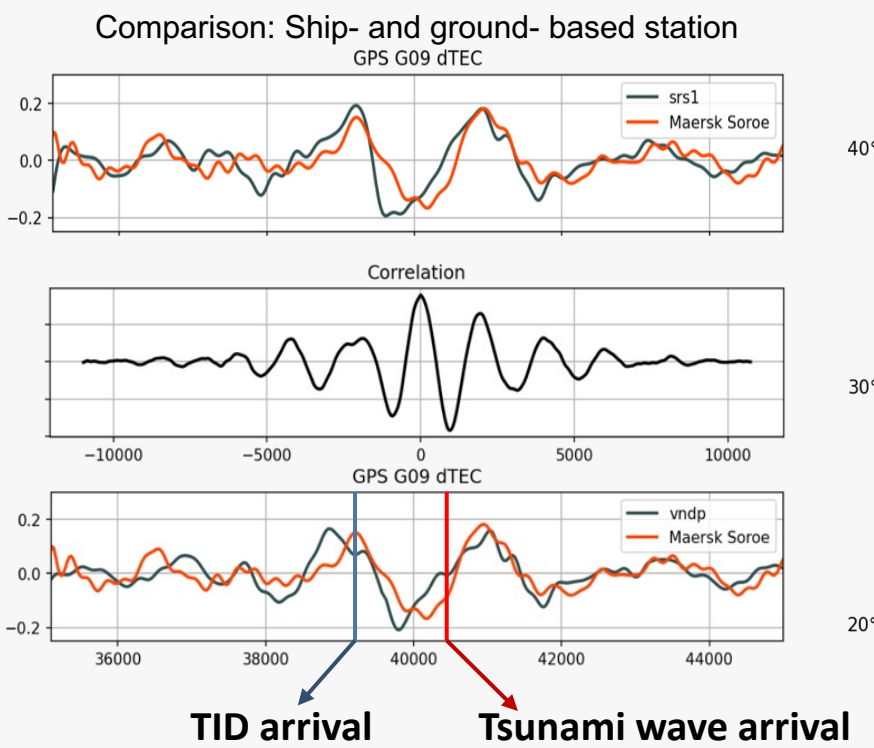
IPP tracks of ship receiver

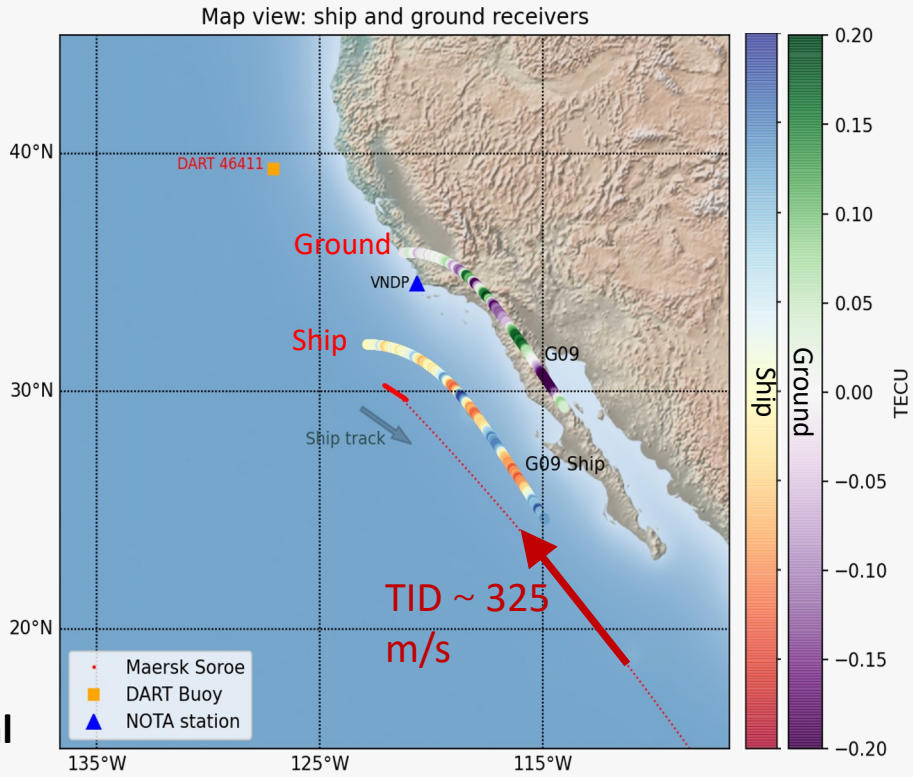


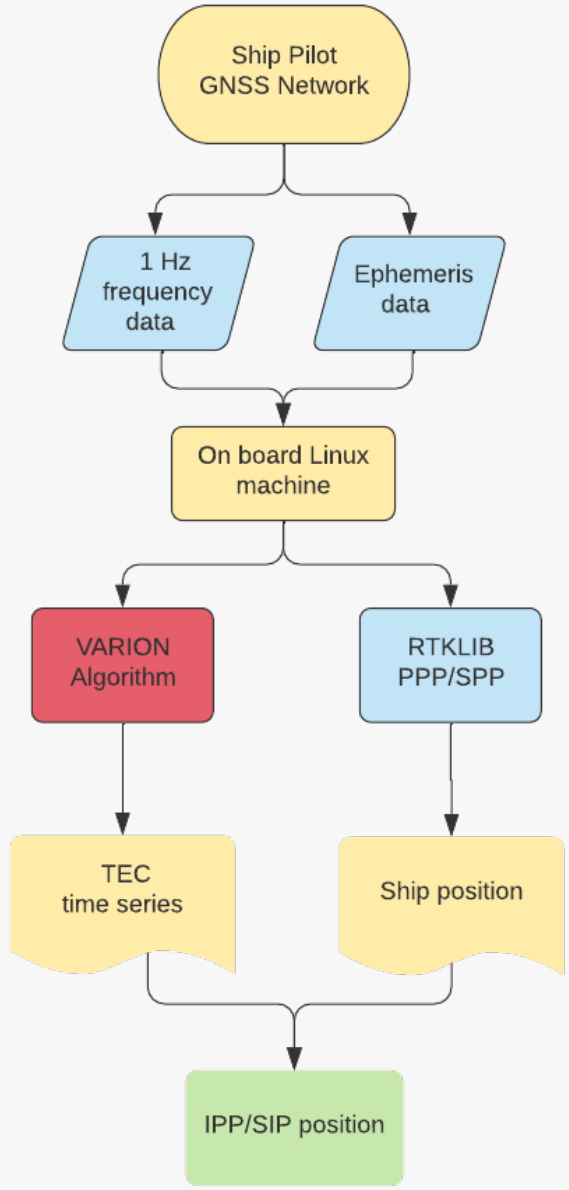
- Ships were active during 2015 Illapel (Chile) Earthquake:
  - System was designed to detect tsunamis using vertical motions, but this event was too small, however ionospheric signal might be sensitive enough…

Ship-based GNSS observations - result

- Comparison between ship- and ground- based stations:
  - Both receivers detected filtered highly correlated TEC perturbation, with the amplitude up to 0.25 TEC units
  - TID arrived 21 minutes earlier than tsunami wave







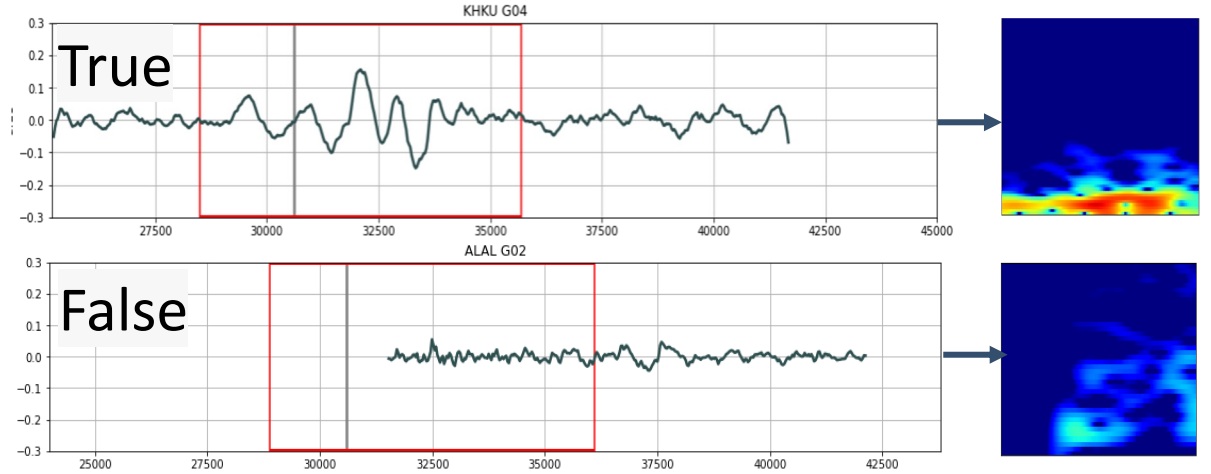
Ship-based GNSS observations

- Tsunami-induced TID detection with CNN
  - Encode time series to Images (STFT) - preserving time information and returning a 2D spectrograms that we can run standard convolutions on
  - 3 events and 61 stations from Hawaiian Islands used for model training
  - Utilized a window size of 60 minutes
  - Zero-padding to fill sample with less than 1 hour
  - Fast prediction (within milliseconds)

Events for training

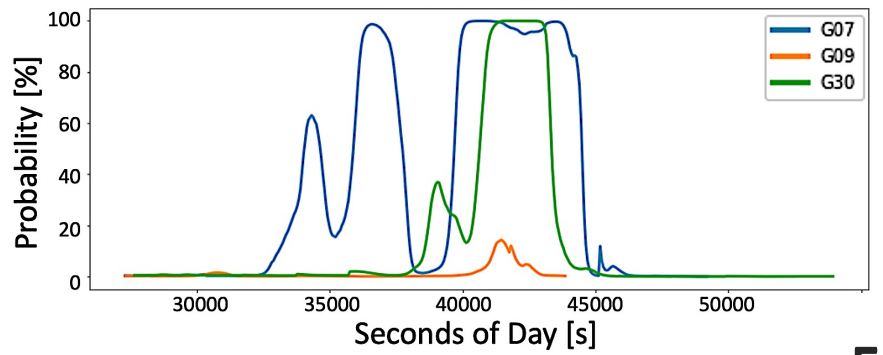
Event location	Date	Magnitude
Maule, Chile	Feb. 27, 2010	Mw 8.8
Tohoku, East Coast of Honshu	Mar. 11, 2011	Mw 9.0
Haida Gwaii, British Columbia	Oct. 27, 2012	Mw 7.8

Training on ground-based station



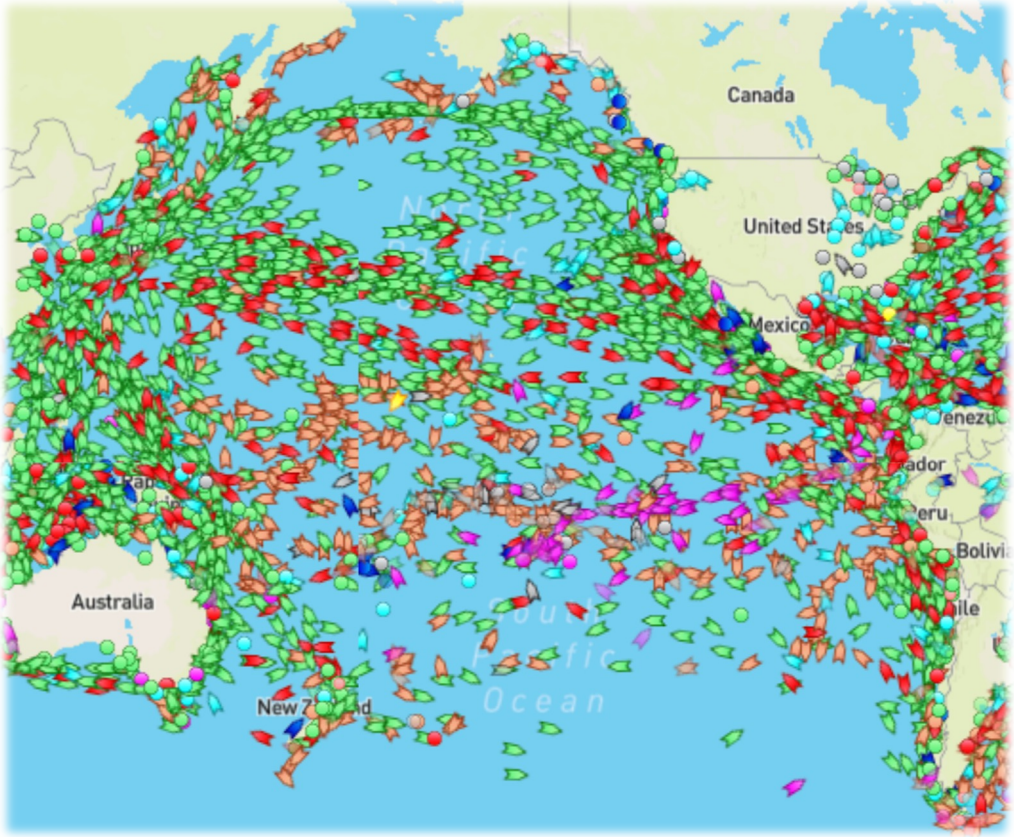
Implementation on ship system

TID Prediction

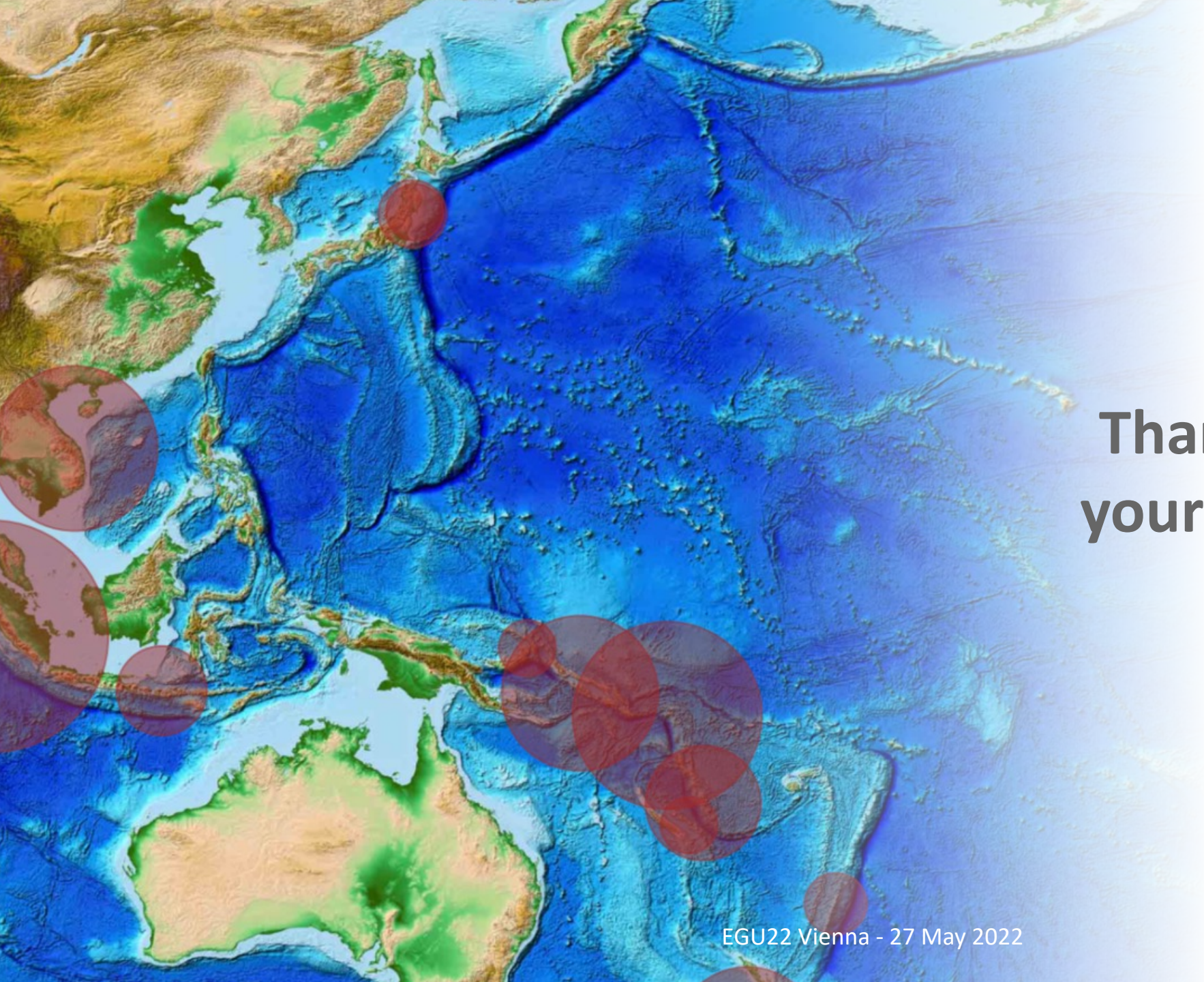


Conclusion

- Large amount of line-of-sight
  - Single ship can provide TEC data from 10-30 lines-of-sight to satellites
- Extending distance
  - With SIPs extending up to 1000 km from the ship
- Addition to existing tsunami warning systems
  - More sensitive than ship motion for some events
- Outlook: opportunity to improve hazard mitigation
  - Real-time implementation
  - Aiming on 1000+ ships network



Ship Traffic Map (Source: MarineTraffic)



Universität Stuttgart
Institute of Geodesy

Thank you for your attention!