An Efficient Tsunami Arrival Time Estimator Coupled to Acoustic Gravity Wave Multi-Fault Rupture Solution

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Methodologies

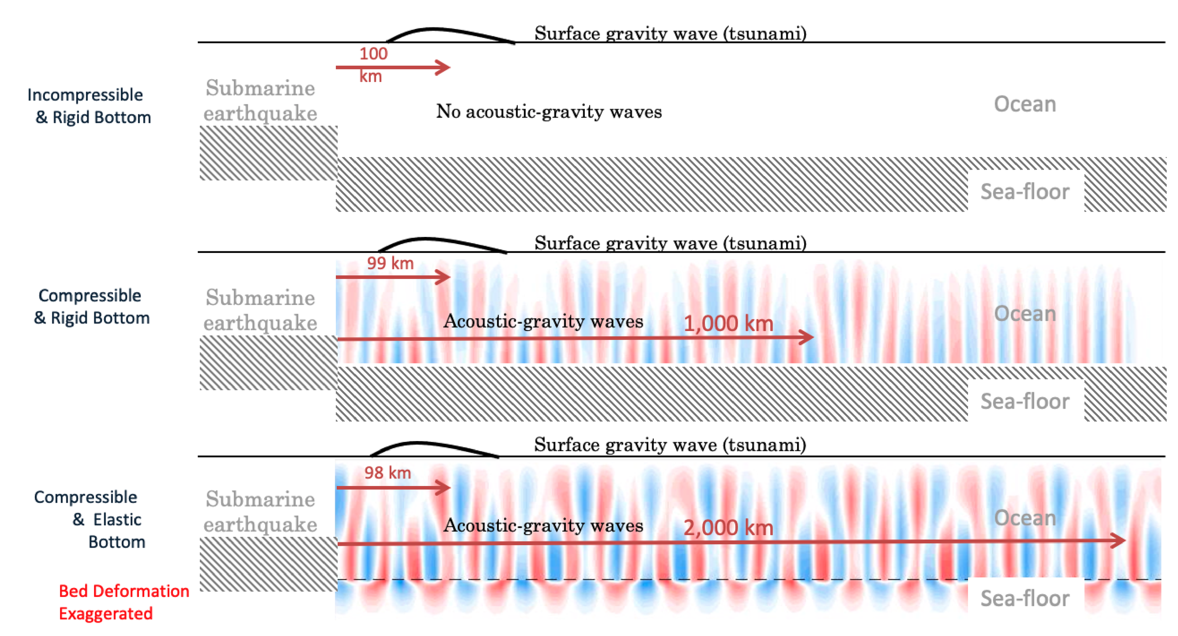

Figure 1: Surface Gravity (tsunami) and acoustics generation and propagation under the incompressible ocean & rigid bottom (upper panel), compressible ocean & rigid bottom (middle panel), and compressible ocean & elastic bottom (lower panel) assumptions.

In this work and within an integrated TEWS, the **Dijkstra's algorithm** is employed to find the shortest paths between the epicenter and all the wet nodes on a global triangular unstructured mesh using the phase speed of surface gravity waves, progressive acoustic modes within the water body, and P and S waves throughout earth. The phase speed estimator takes into account the simultaneous effects of the slight compressibility of water, sea-bed elasticity, and static compression of the ocean under gravity, leading to the precise calculation of the arrival time [4].

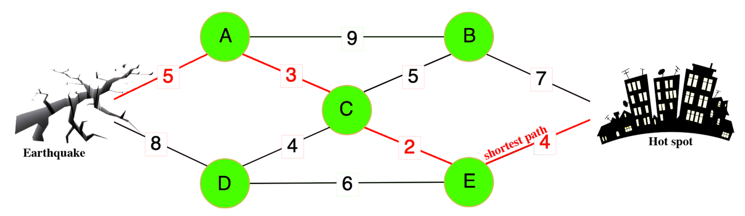

Figure 2: Schematic view of travel time calculation via Dijkstra's algorithm fastest/shortest path.

Employing digital signal processing techniques (DPS), we can analyze sound recordings of underwater earthquakes, that train **artificial intelligence (AI)** algorithms to classify the type of earthquake (i.e. horizontal or vertical) and its moment magnitude (strength) [5]. This is a significant step for a reliable early tsunami warning system since the type of earthquake can dictate if a tsunami will be generated at all. For example, a more horizontal type movement will not generate a tsunami even if the magnitude of the earthquake is relatively large, but the vertical element has a direct relation. Moreover, AI algorithms were coupled with our semi-analytical **inverse model** [3] that calculates the dynamics and geometry of the fault, which in turn can give an estimation of the size of the generated tsunami.

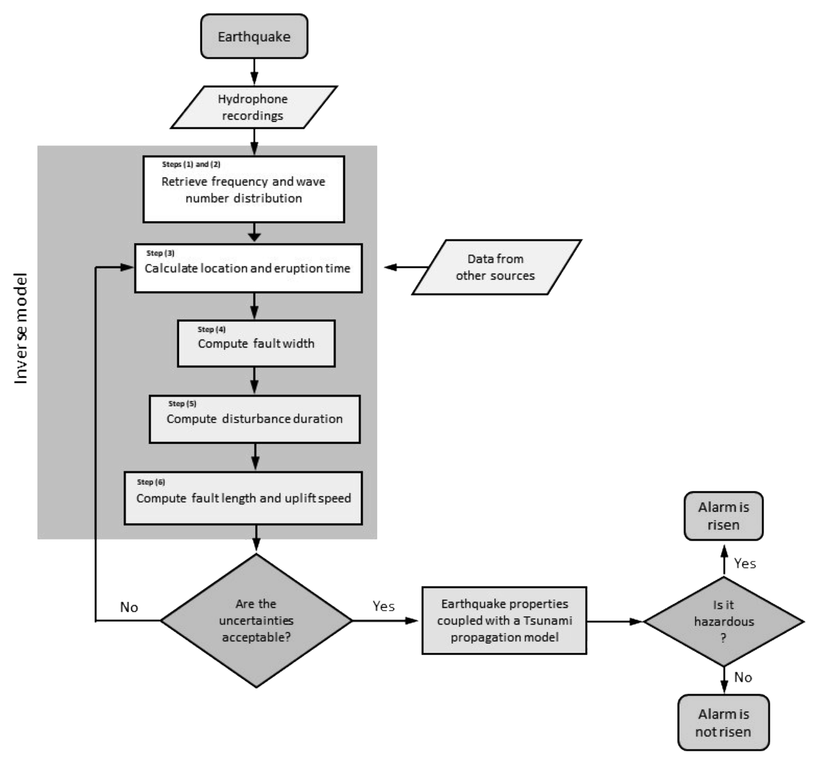

Figure 3: Inverse model application flowchart - from acoustic pressure signal arrival to probabilistic calculation of source properties [3].

Introdcution

Tsunamis have a long history of devastation, costing the lives of thousands of people, causing damage to property and infrastructures. To name a few of them, the deadliest 2004 Sumatra earthquake and tsunami, 2011 Tohoku Oki, and more recently, the 2018 Sulawesi and Palu tsunami. It implies the necessity of having a reliable early warning system [1] Current warning systems rely heavily on the Deep-ocean Assessment & Reporting of Tsunamis (DART network) for tsunami waves and seismic measurements for rupture detection, each within a separate early warning system. Accurate tsunami evaluation from DART buoys may be possible, though depending on particular circumstances (far distance generated tsunamis) there may not be sufficient time for early warning. On the other hand, seismic data provide valuable information on the tectonic movements, earthquake size, and possible epicenter, though with current technology and analysis they fail to assess the tsunami threat. Recently, Acoustic Gravity Waves (AGW), as another precursor of tsunami waves have been considered for the early detection of hazards ([2, 3]). These waves are generated and propagated due to the slight compressibility of the water. AGWs radiate from submarine earthquakes alongside tsunamis and propagate through the liquid or elastic layers. They carry information about the source at relatively high speeds ranging from the speed of sound in water (1500m/s), to Rayleigh waves speed in the solid (3200 m/s) that far exceeds the phase speed of the tsunami (200m/s at 4 km water depth) while compression P (pressure) waves and S (shear) waves propagate at about 6,800 m/s and 3,900 m/s in the solid earth, respectively. The combined effect of water compressibility coupled to elastic earth also improved the accuracy of the numerical models for the prediction of surface gravity waves [4].

Integrated TEWS Workflow

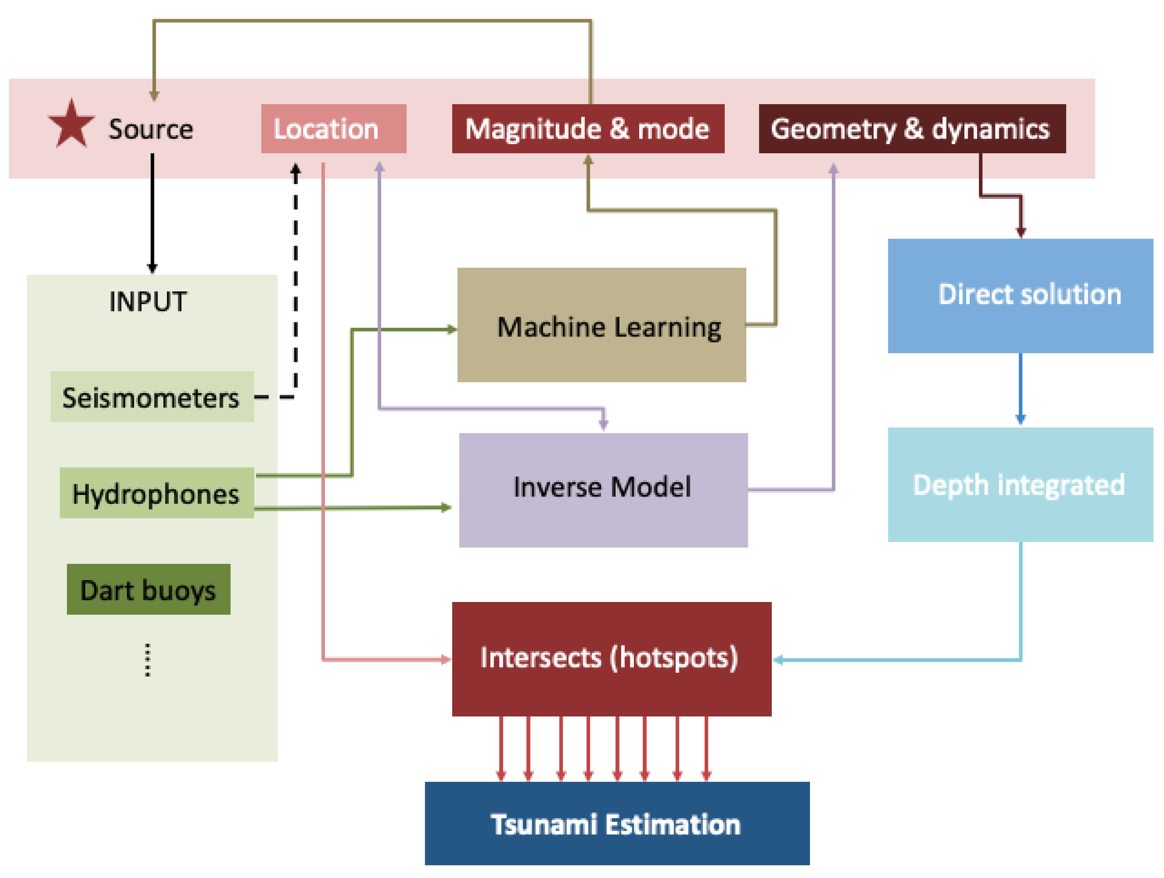

Figure 4: Tsunami Early Warning System (TEWS) workflow.

Acoustic Waves Travel Time

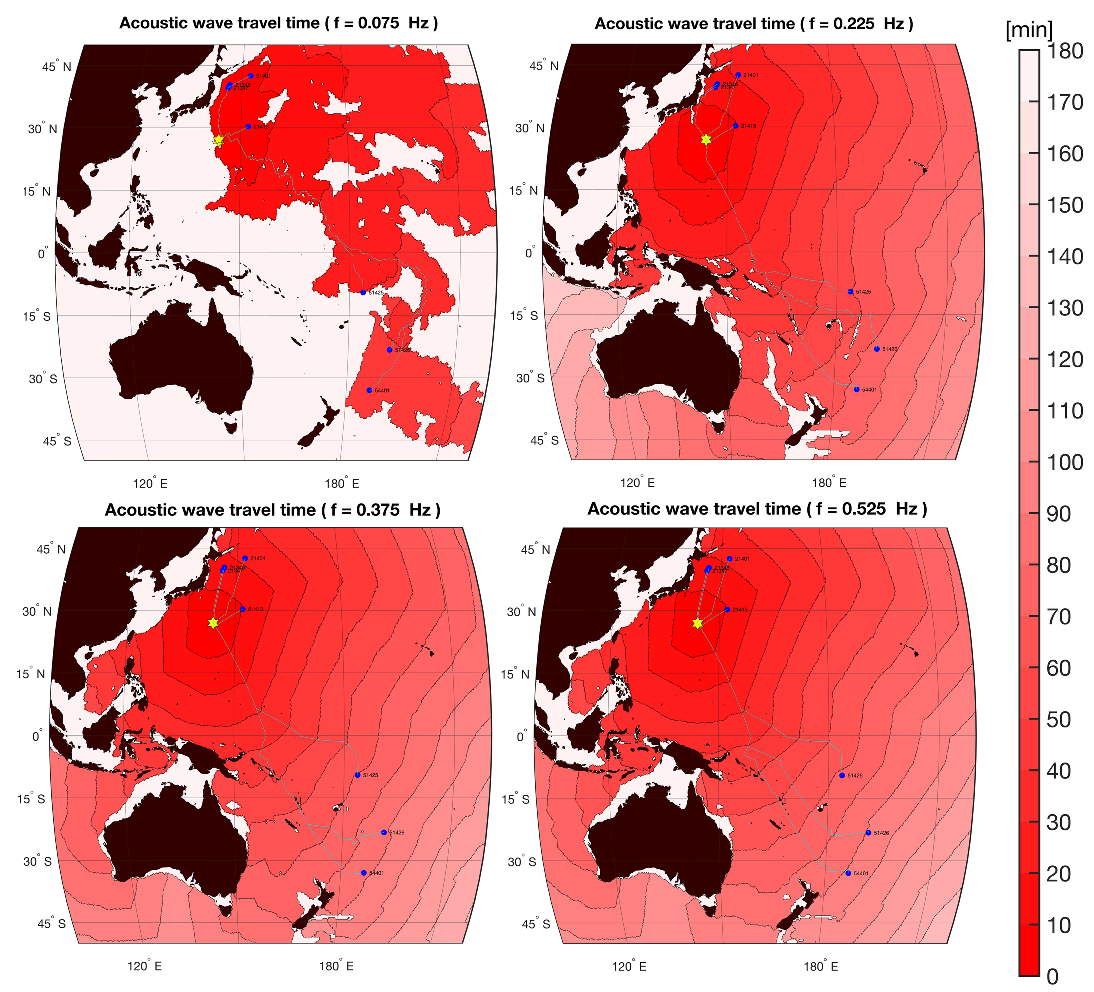

Figure 5: The first 4 dominant acoustic modes (governed by fault depth) travel time for the 21st December 2010 (27.10N, 143.76E) earthquake.

P & S waves Travel Time

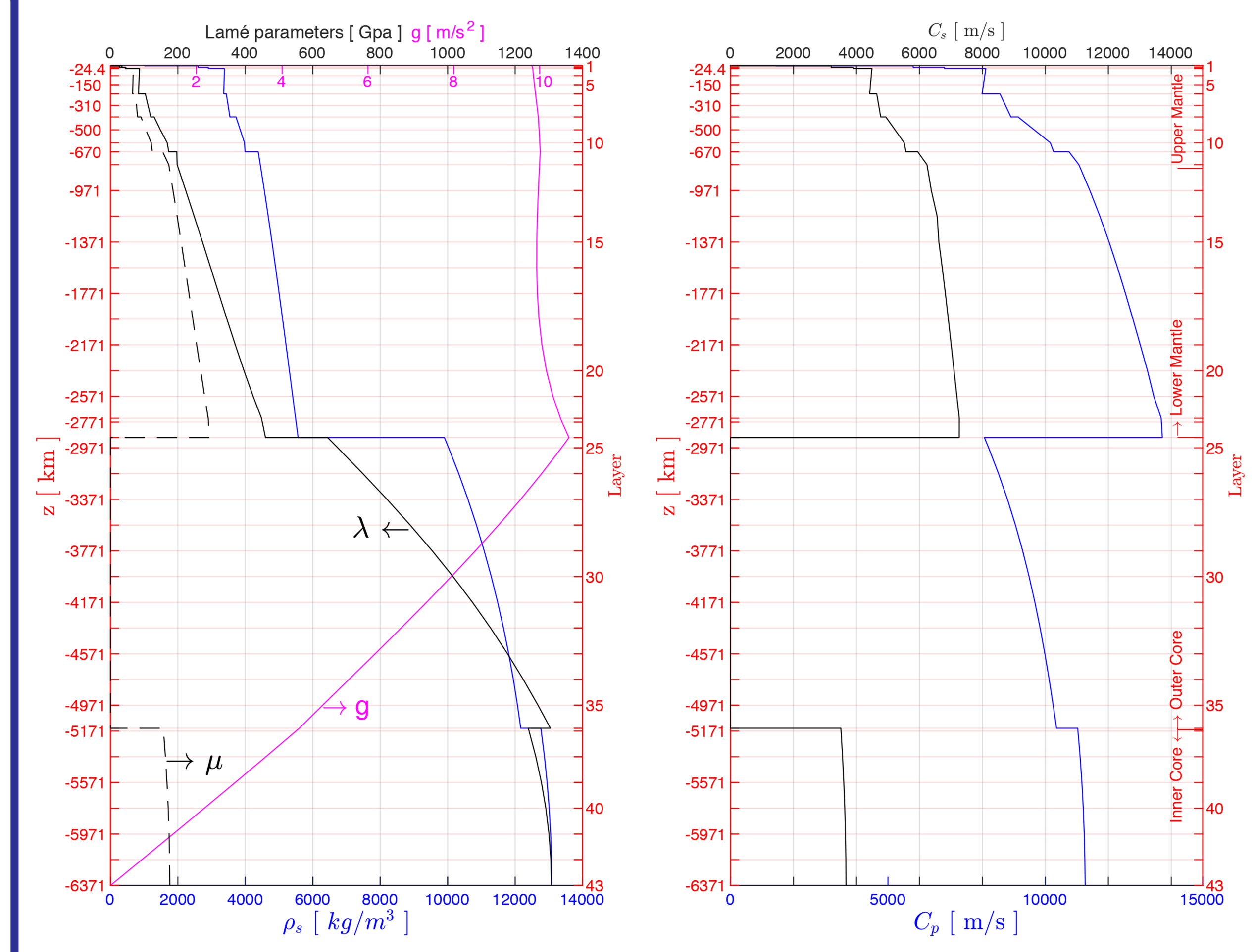

Figure 6: PREM model profile (Dziewonski 1981). Left panel: Lame constant profile, density and gravity (g); Right panel: Compressional wave speed (V_p) and shear wave speed (V_s).

V_p and V_s are the pressure-wave and shear-wave velocities in the n^{th} layer of solid earth respectively. V_p and V_s are related to the Lame's elasticity constants (λ_n, μ_n) and the earth density ($\rho_{s,n}$).

$$V_{p,n} = \sqrt{\frac{\lambda_n + 2\mu_n}{\rho_{s,n}}} \tag{1}$$

$$V_{s,n} = \sqrt{\frac{\mu_n}{\rho_{s,n}}} \tag{2}$$

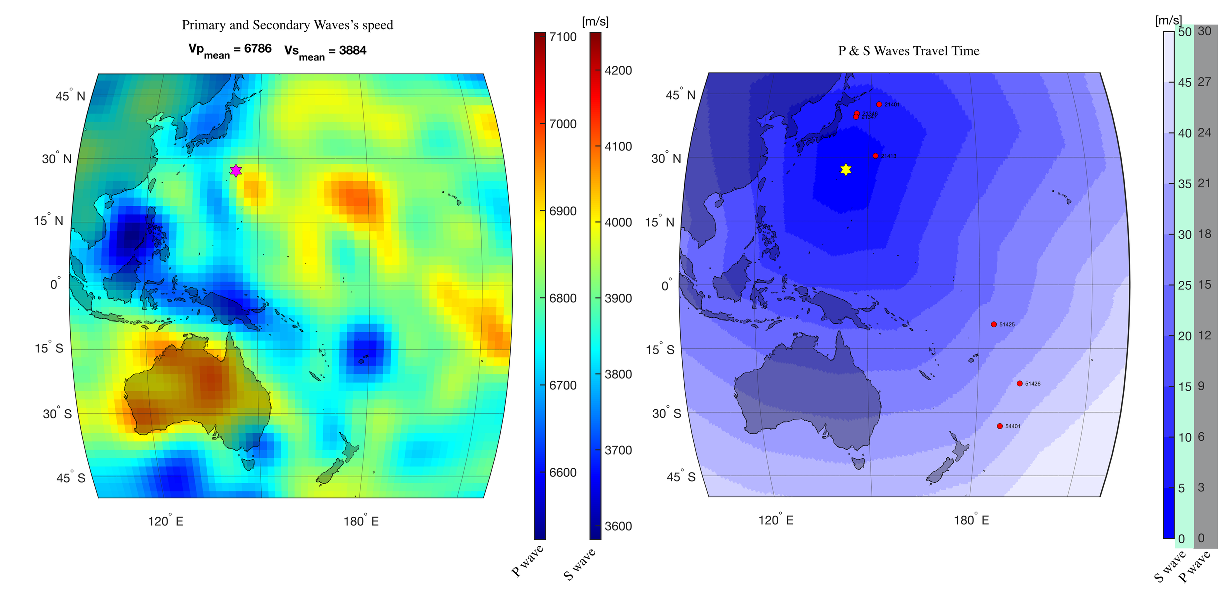

Figure 7: P and S wave speed (left) and travel time (right) from the epicenter for the 21st December 2010 (27.10N, 143.76E) earthquake.

Tsunami Travel Time

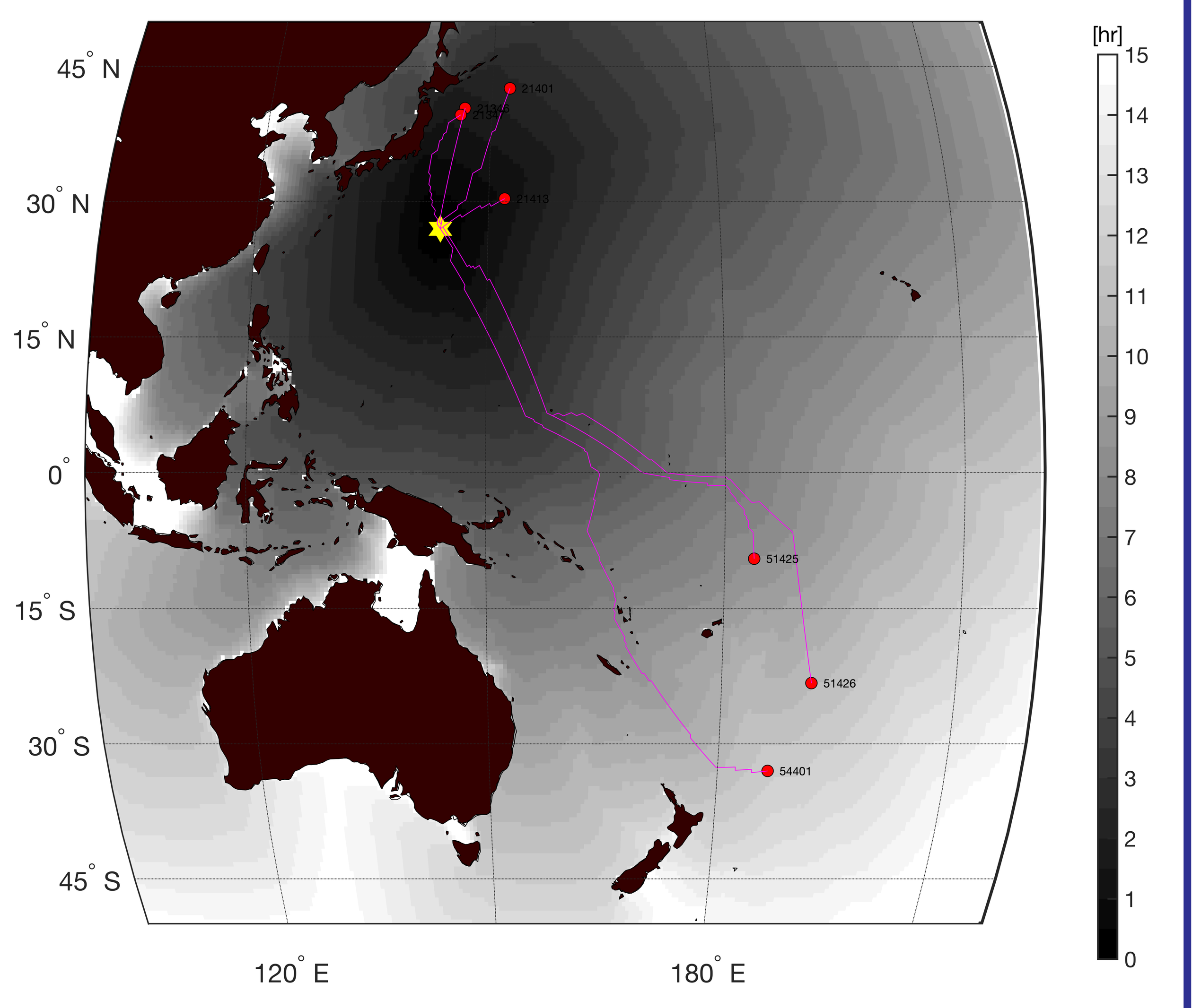

Figure 8: The surface gravity wave (tsunami) travel time for the 21st December 2010 (27.10N, 143.76E) earthquake.

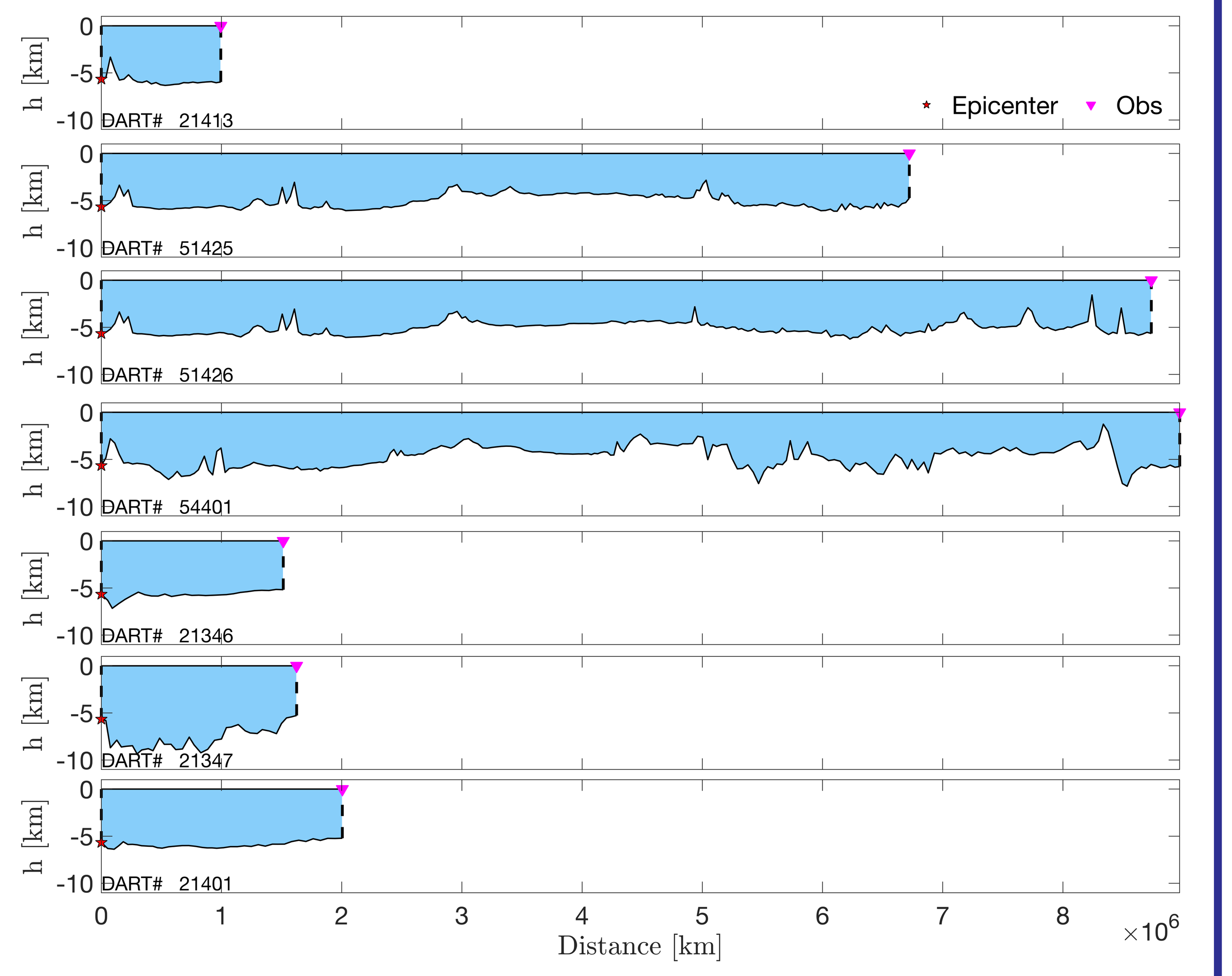

Figure 9: Transect along the shortest path, shown in Figure 8, between the epicenter and selected hotspots (DART stations) for the 21st December 2010 (27.10N, 143.76E) earthquake.

References

[1] Williams, B., Kadri, U., & Abdolali, A. (2021). Acoustic–gravity waves from multi-fault rupture. Journal of Fluid Mechanics, 915, A108. doi:10.1017/jfm.2021.101.

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