Data Assimilation for Tsunami Forecast with Shipborne GNSS Data in the Cascadia Subduction Zone

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Introduction

Data assimilation (DA) is a technique that incorporates observations into a numerical model to improve forecasts. It has been used in weather forecasting for many years. It has also been used to study air quality, soil moisture, ocean temperature etc.

In general, the existing tsunami forecast systems are based on high quality data from the DART buoy and/or GPS buoy system which are very expensive, not affordable by developing countries.

As an alternative, we explore a cheaper option of using ship-borne GNSS data in data assimilation modeling to forecast tsunamis in the Cascadia subduction zone. Ship positions are continuously tracked globally through the Automatic Identification System (AIS) under International Maritime Organization.

The AIS system provides information including date, time, MMSI (Maritime Mobile Service Identity), ship type, ship name, ship position (latitude/longitude), speed over ground (SOG), course over ground (COG), and ship heading (HDG). HDG, SOG and COG are used to calculate velocity data.

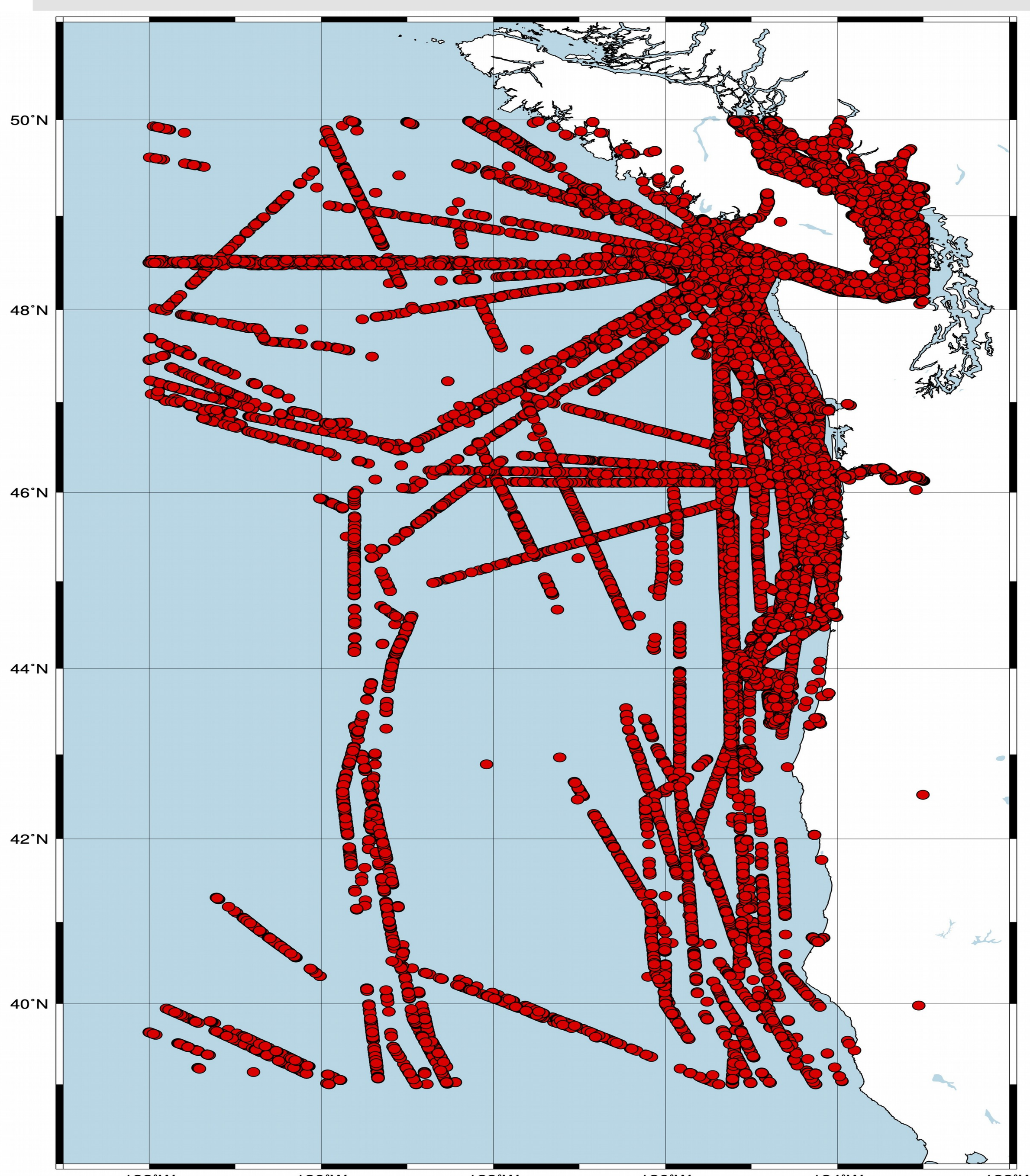

Figure 1: Track of ships traveling on June 16, 2018. Ship data is obtained from a company, named 'Spire global, Inc'.

Methodology

- In this study, we apply a sequential data assimilation based on optimal interpolation outlined in Maeda et.al 2015. The method is seeded with synthetic tsunami height and velocity data at ship positions.
- The synthetic tsunami height and velocity is simulated using a forward model ***M(x),*** a linear tsunami propagation model that solves the 2-D linear long wave (LLW) equations in spherical coordinates using a finite difference scheme.
- We create synthetic observations (elevation, velocity) at the real ship locations using output from JAGURS (a numerical model) run with the tsunami source (Figure 2, right).

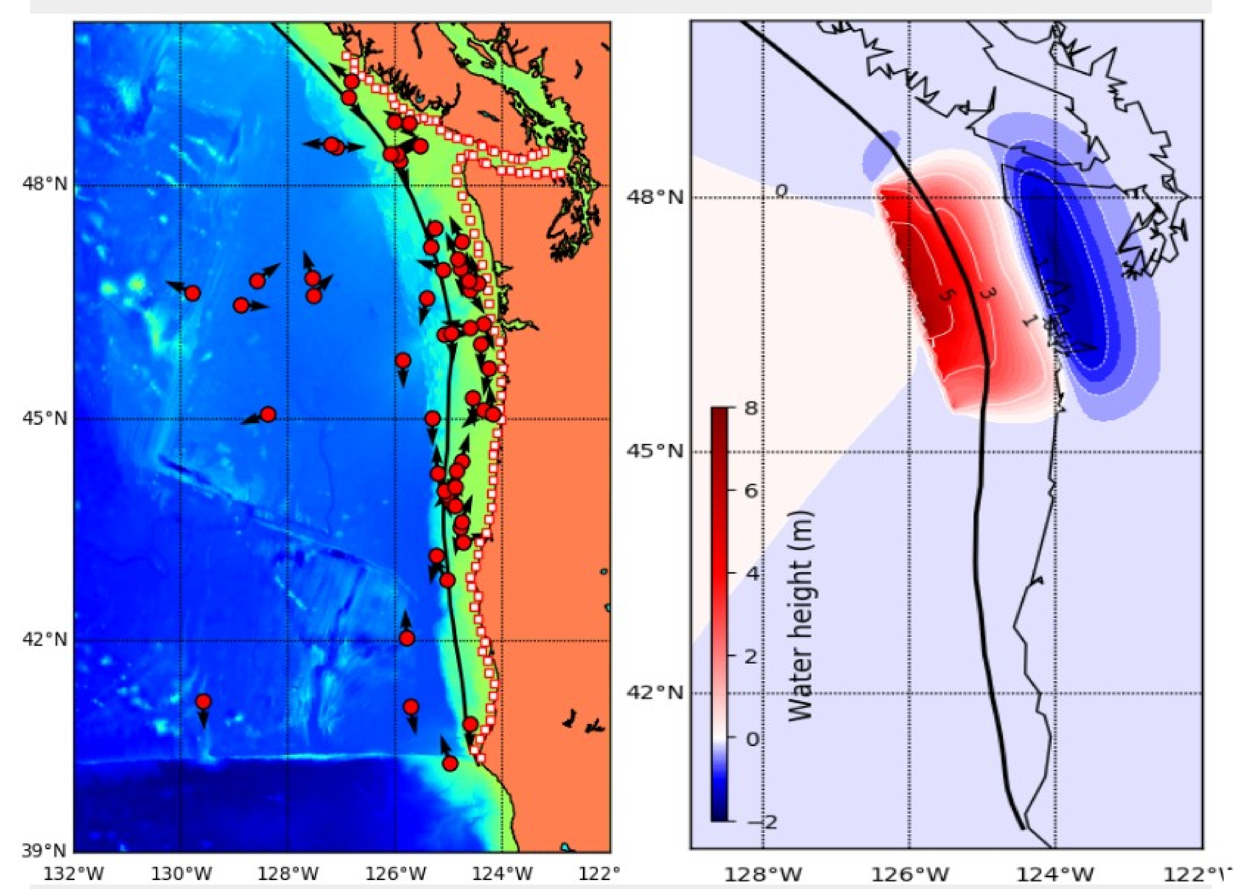

Figure 2: 55 real Ship locations (left) and tsunami source model (right) used for simulation.

- There are two steps in DA system. In the first step (forecast step), the tsunami wave-field is calculated by the forward numerical simulation, $x^f_n = M(x^a_{n-1})$. In the second step (analysis step), the wave-field is updated by integrating observations with simulated waveforms as

$$x^a_n = x^f_n + W(y_n - H x^f_n)$$

Where y_n is the synthetic observed waveforms extracted at the ship locations at 30 sec time interval. To produce more realistic tsunami waveforms at the ship locations, we add noise as suggested by Inazu et al. (2016)

- The weighting matrix ***W*** is calculated using background error covariance and observation error covariance matrices.
- To evaluate the performance of the DA system, we used a formula

$$\mathrm{Accuracy}(\%) = \left\{ 1 - \frac{\sum_{i=1}^{N}(w_i^s - w_i^r)^2}{\sum_{i=1}^{N}(w_i^r)^2} \right\} \times 100\%$$

Results:

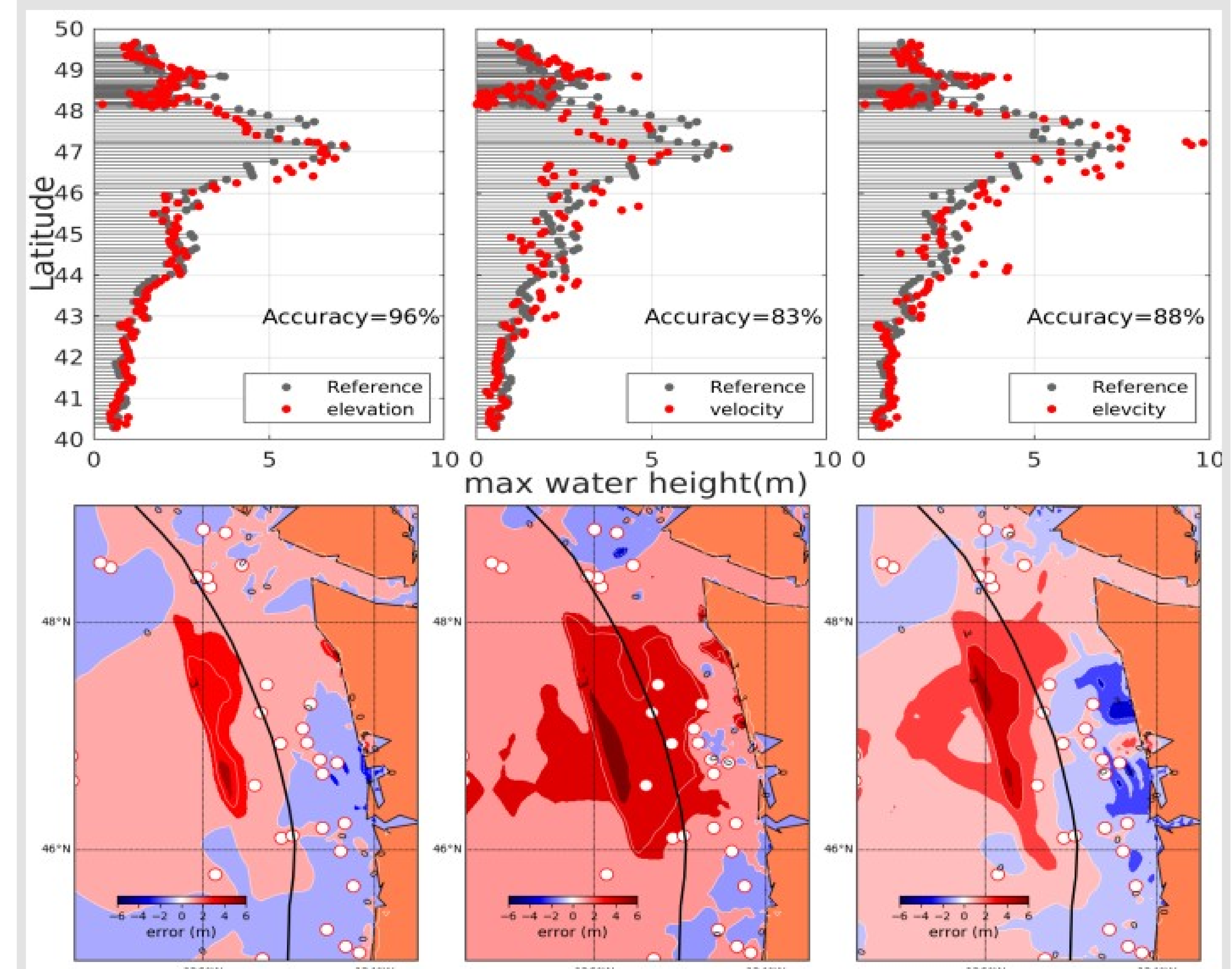

Figure3: Comparison of maximum water height at coast points from assimilated and reference model. Fixed observation are used. Elevcity refers to models where both elevation and velocity data are used.

Performance of DA method with different ship distribution:

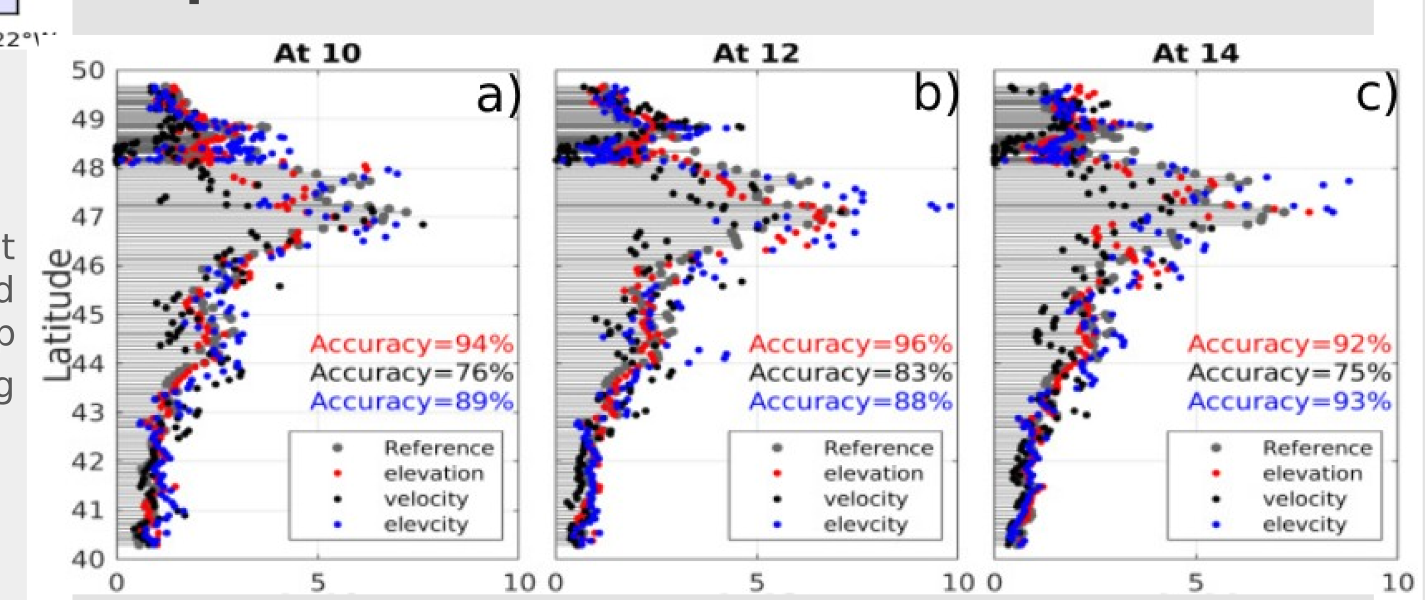

Figure 4: Comparison of maximum coastal water height extracted from reference and assimilated wavefield with ship distributions from three different times (10, 12, and 14 UTC) of the same day.

hours	No of Ships	Elevation (%)	Velocity (%)	Elevcity (%)
10–11	74	94	76	89
11–12	58	94	79	90
12–13	55	96	83	88
13–14	42	94	84	89
14–15	46	92	75	93
15–16	40	93	75	96

Table 1: Performance of ship distribution at different hours of operation on June 16, 2018 offshore Cascadia Subduction Zone.

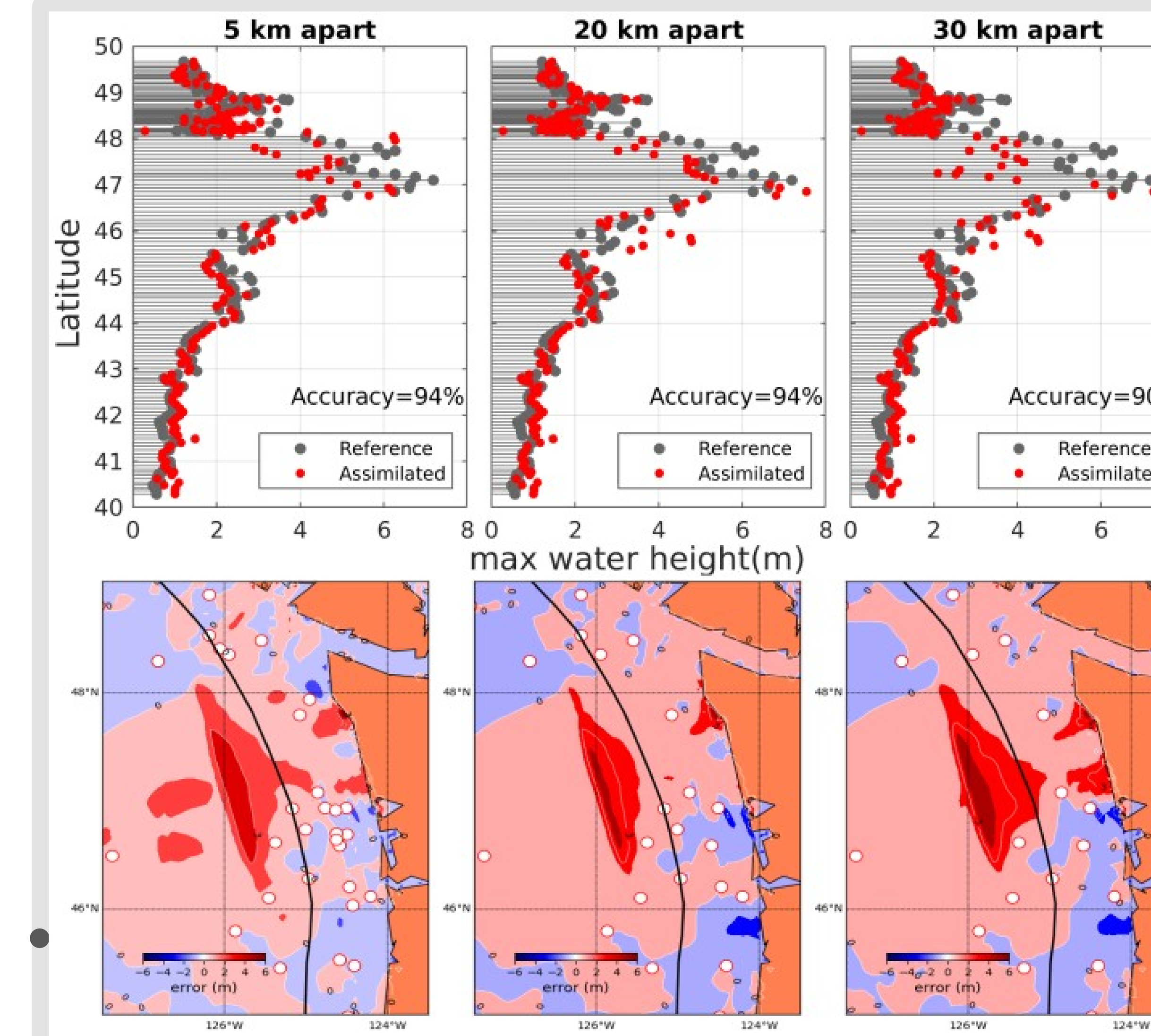

Figure 5: Accuracy of DA simulated model with different minimum spacing between ships. Ship elevation data, but not velocity, is used in these simulations. Left panel shows the result with a 5 km gap between ships, middle panel 20 km, and right one 30 km gap between ships.

Conclusion

- Data assimilation method has been implemented with synthetic ship data at the real ship locations.
- We considered three types of ship data: elevation, velocity and elevation plus velocity, all extracted from numerical simulations with an assumed tsunami source.
- Our result shows that DA method with ship elevation data can recover the reference wavefield with higher accuracy (94%).
- We found that elevation data always outperforms the velocity data irrespective of ship distribution.
- Our sensitivity study shows that a minimum of 20 km gap between ships in regions with high ship density is sufficient to recover the reference model

References

Maeda, T., Obara, K., Shinohara, M., Kanazawa, T., & Uehira, K. (2015). Successive estimation of a tsunami wavefield without earthquake source data: A data assimilation approach toward real-time tsunami forecasting. Geophysical Research Letters, 42 (19), 7923–7932

Inazu, D., Waseda, T., Hibiya, T., & Ohta, Y. (2016). Assessment of GNSS-based height data of multiple ships for measuring and forecasting great tsunamis. Geoscience Letters, 3 (1), 25