High-Accuracy GNSS on Ships to Monitor Tsunami

An opportunity to improve hazard mitigation through public-private collaboration

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Recent tsunamis are responsible for the loss of 100’s of thousands of lives and 100’s of billions of dollars in damage and economic losses. Evacuating coastal zones can cost 10’s of millions of dollars.

Q: How can we cost-effectively acquire spatially dense observations of tsunamis to improve warnings?

A: Use the vast existing infrastructure provided by commercial ships!
Example of tsunami detection from a ship: Maule EQ tsunami, Feb 2010

The R/V Kilo Moana was underway from Hawaii to Guam when the tsunami from the Maule earthquake passed the ship. The predicted amplitude of the wave was ~10 cm.

University of Hawaii Research Vessel *Kilo Moana* is equipped with twin dual-frequency GPS systems.
Sea surface height perturbations

Post-processing of the GPS data revealed sea-surface perturbations very similar to the predictions from numerical models of the tsunami. This was further explored by cross-correlation with a “matched-filter” formed from the first 60-min of the predicted wave field.

By perturbing (rescaling the period and amplitude) the initial model prediction to find a best fitting version, a new model can be used to measure primary characteristics of the tsunami. These estimates can be used to nudge forecasts, or re-ingested by the model to update its prediction.
Ship-based tsunami detection network

Ship tracks provide excellent coverage of tsunami source regions. We have demonstrated that geodetic GPS on ships can detect open ocean tsunamis. Ship tracks are at their most dense along coast-lines: exactly where additional observations to augment existing tsunami detection systems are needed.

There are ~15,000 large container ships active. Instrumenting just 10% (similar to the Voluntary Observing Ship program uptake) would give ~1500 new tsunami and IPW detection systems at sea at any given time.
Ship-based detection offers the opportunity to directly detect the sea-surface perturbation in, or near, the source zone.

GNSS signals + high-accuracy satellite orbits and clock solutions transmitted to ships allows for Precise Point Position solution.

Position time-series transmitted to land analysis center.

Trimble RTX service provides ~5 cm RMS vertical.
Ships as tsunami sensors

- **GPS**: Trimble NetR9 receiver w/ RTX positioning service & GLONASS enabled
- **Satellite Comms**: miniVSAT + 2GB/month (pooled) data plan
- **Data Flow**: Corrections streamed to GPS receiver via internet. Position solutions streamed to UH

- Low-pass (or band-pass) filter to remove wave field
- Ships acts as passive marker for tsunami period sea-surface perturbations
Pilot Network

A 10-ship pilot network was built by the University of Hawaii, collaborating with Matson, Maersk, and the World Ocean Council, with funding from NOAA.

<table>
<thead>
<tr>
<th>Matson Ships</th>
<th>Maersk Ships</th>
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<tbody>
<tr>
<td>Total Round Trip</td>
<td>~63 days</td>
</tr>
<tr>
<td>Port calls</td>
<td>11 days</td>
</tr>
<tr>
<td>Underway</td>
<td>52 days (82%; &gt;60% open Pacific)</td>
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</tbody>
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Underway: 52 days (82%; >60% open Pacific)
Model predictions for the tsunami generated indicated that the maximum amplitude at the ship locations was too small (< 1 cm) for our system to detect.
Basic Performance Statistics

- Collected total of 2,396,186 km of track data, representing 13.3 ship years.
- Data recovery was 57% (*losses primarily due to the satellite communications mask*).
- Ships were underway ~70% of the time (*conservative estimate due to satellite communications mask*).

Null test signal detection (20-60 min period wave) indicates a non-trivial likelihood of a single ship recording a false positive event (occurrence rate per ship per day is almost the same).

Std-dev of filtered vertical solutions = **5.6 cm**. (*c.f. Land-based static std-dev ~3.5 cm*)
Summary

- 10-ship pilot network has demonstrated ship-based GNSS system for tsunami detection.
- Network was live at the time of the 24 Apr 2017 Valparaiso event and the 2015 Illapel event: no signal detected, nor expected, by ships.
- Overall std-dev of vertical perturbations is ~5.6 cm
- With multiple ships in vicinity of source zone, network could reliably detect event with amplitude > 20 cm
- Current biggest practical constraint is real-time communications.
Going Big... What is needed to scale up to a network with 1000+ ships?

- More cost-effective equipment package, with more optimal installation locations (on top of mast)
- On-board processing to reduce bandwidth while estimating IPW and other products (e.g. TEC for space weather)
- Reduced communications costs
- Active partnerships between commercial shipping companies and government/academic/international agencies
Three for the price of one!

Ship-based GNSS generates precise positions, atmospheric delays, and ionospheric electron content. These real-time products would support tsunami detection, meteorology and numerical weather prediction, and space weather.

Equipping 10% of largest class commercial vessels would establish a network of ~1500 GNSS stations.

Ship-based GNSS can detect tsunamis through direct measurement of the sea surface perturbations (Left: Kilo Moana records passage of 10 cm open ocean tsunami from Maule earthquake, Feb 2010) and through detection of the ionospheric gravity wave it generates (Right: TEC perturbations observed by Big Island GPS sites as the small tsunami from the Haida Gwaii earthquake (2012) arrives. [image modified from Savastano et al., 2017]. Ship-based data would improve the limited coverage and resolution available from land-based networks).

Ship-based GNSS meteorology provides all-weather, high spatial and temporal resolution data that complements satellite observations. Importantly ship tracks are most dense near coasts. Left: Precipitable water showing “Pineapple Express” atmospheric river transporting moisture to the Pacific Northwest. Right: IPW timeseries from this period from two commercial ships and a research vessel.
Extras
System Performance

Data can be used (as above) to verify/refine predicted events, but can also be used as a stand-alone detection system. A single-ship system would generate a significant number of false-alarms, multiple ships greatly reduce that likelihood. Including geographic constraints (neighboring ships move together) would reduce this further.

Null test signal detection using a sine wave (20-60 min periods) indicates a non-trivial likelihood of a single ship recording a false positive event (histogram for occurrence rate per ship per day is almost the same)

Treating the network of ships as an integrated sensing network we can test the likelihood of more than one ship recording a “false detection” within a characteristic time-window (10 mins).
Tsunami Monitoring Augmentation
Singapore, 22 August 2019

Current Tsunami Detection Systems

Seismic

**Advantages:**
- Extremely rapid detection and location estimation of large earthquakes
- Fault plane (conjugate planes) can be estimated

**Disadvantages:**
- For very large/slow slip events ground motion may be under-predicted
- Uncertain estimation of energy transferred into water column

Tide Gauges

**Advantages:**
- Direct measurement of runup

**Disadvantages:**
- Limited to land sites – sparse and uneven coverage
- Runup strongly dependent on complex interplay between tsunami source and local bathymetry
- May be destroyed by tsunami, limiting information recovered

DART system

**Advantages:**
- Accurate point measurements of ocean depth perturbations

**Disadvantages:**
- Expense limits the number that can be deployed and maintained (25-30% offline at any given time)
- Network based on current best-estimate of hazard… may not be accurate
- Local bathymetry may perturb signal