Ship-based GNSS Contribution to Tsunami Warning in Europe and the Mediterranean

Schiffsgestütztes GNSS als Beitrag zur Tsunami-Warnung in Europa und im Mittelmeer

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Summary

Geodetic GNSS measurements from ships have been shown to be capable of detecting the perturbation from tsunamis in the open ocean. We propose that a network of ships, based on voluntary participation of cargo and tanker vessels, could contribute to tsunami warning, augmenting the existing systems. Two case studies based on tsunamis generated at the location of historical events are examined based on the distribution of ships that would be expected from such a network. We find that ships are likely to be in position to be the first sensors reached by these tsunamis. We note, however, that the relatively high noise characteristics previously found in ship-based GNSS data requires four or more ships before an unambiguous detection can be made based only on the ship data which may increase the detection time for such a network. In this case a ship-based detection might be delayed compared to the current tide-gauge network, however, ships would still make a contribution to the characterization of an event as they would provide observations from otherwise unsampled locations. The cost of operating such a ship-based network could be mitigated by taking advantage of the additional products that their GNSS systems could provide: estimates of water vapor for weather models and ionospheric observations for space weather.

Keywords: tsunami, cargo ships, tankers, GNSS, natural hazards, NEAM region

Zusammenfassung

Geodätische GNSS-Messungen von Schiffen haben gezeigt, dass sie in der Lage sind, die Störung durch Tsunamis im offenen Ozean zu erkennen. Wir schlagen vor, dass ein Netzwerk von Schiffen, das auf der freiwilligen Teilnahme von Fracht- und Tankschiffen beruht, zur Tsunamiwarnung beitragen und die bestehenden Systeme ergänzen könnte. Zwei Fallstudien, die auf Tsunamis am Ort historischer Ereignisse basieren, werden anhand der Verteilung der Schiffe, die von einem solchen Netzwerk zu erwarten wäre, untersucht. Wir gehen davon aus, dass die Schiffe die ersten Sensoren sein werden, die von diesen Tsunamis erreicht werden. Es ist zu beachten, dass die relativ hohen Rauscheigenschaften, die bisher bei schiffsbasierten GNSS-Daten festgestellt wurden, vier oder mehr Schiffe erfordern, bevor eine eindeutige Erkennung nur anhand der Schiffsdaten erfolgen kann, was die Erkennungszeit für ein solches Netzwerk erhöht. In diesem Fall könnte sich eine schiffsbasierte Erkennung im Vergleich zum aktuellen Pegelnetz verzögern, aber die Schiffe würden einen Beitrag zur Charakterisierung eines Ereignisses leisten, da sie Beobachtungen von ansonsten nicht erfassten Orten liefern würden. Die Kosten für den Betrieb eines solchen schiffsbasierten Netzwerks könnten durch die Nutzung der zusätzlichen Produkte, die ihre GNSS-Systeme liefern, gemildert werden, wie etwa Schätzungen des Wasserdampfs für Wettermodelle und Beobachtungen der Ionosphäre für das Weltraumwetter.

Schlüsselwörter*: Tsunami, Frachtschiffe, Tanker, GNSS, Naturgefahren, NEAM Region*

1 Introduction

Although we most commonly associate tsunamis with the Pacific Ocean and its famous Ring of Fire, deadly tsunamis have occurred in all ocean basins (NGDC/World Data Service 2024). The tsunami on 26 December 2004, in which over 250,000 lives were lost around the Indian Ocean region, was a tragic reminder of this, and prompted the development of tsunami warning systems both in the Indian ocean and for the North-east Atlantic and Mediterranean (NEAM) region. The Mediterranean Sea, in fact, is the second most active ocean for tsunamis (NOAA-NCEI 2024). In addition to the loss of life, tsunamis can lead to extreme economic costs due to direct infrastructural damage as well as the expense and loss of economic productivity during coastal evacuations. Minimizing both the fatalities and costs of tsunamis requires timely and accurate characterization of their predicted impacts. The lower frequency of damaging events in the Mediterranean Sea and around the coasts of Europe than in the Pacific requires a careful analysis of the hazard (Basili et al. 2021) in order to match the investment for tsunami detection and characterization systems against the risk that they present. Most of the biggest and most damaging tsunamis globally are generated by great (M8+) earthquakes on the faults underlying subduction zones, where one tectonic plate is forced under another. In the Pacific Ocean, this has led to the installation of a network of Deep-ocean Assessment and Reporting of Tsunamis (DART) buoy sea-floor pressure sensor systems (Gonzalez et al. 1998, National Research Council 2011) in the deep ocean, off-shore of the sections of the subduction zones considered to present the highest risk. These DART systems provide critical off-shore observations to

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Tab. 1: Source mechanisms for tsunamis in Mediterranean and Northeast Atlantic (NGDC/World Data Service 2024)

Source	Total Tsunamis	Fatal Tsunamis
Earthquake	429	8
Landslide	42	10
Volcano	25	1
Earthquake + Landslide	29	5
Volcano + Earthquake	5	0
Volcano + Landslide	3	0
Meteorological	17	2
Total	**550**	**26**

corroborate the existence and magnitude of tsunamis following the detection of a large earthquake that might have generated one. In Europe and the Mediterranean, the situation is less clear. Although the large majority of recorded tsunamis are from earthquake sources, only a small fraction of these events has caused fatalities. In contrast, although far fewer tsunamis are generated by, or involve, volcanological, meteorological, and landslide sources, these events account for ⅔ of the fatal tsunamis for this region (Tab. 1). This contributes to uncertainties in the hazard assessment, as the science and understanding of the physics of the processes and the locations of potential sources are much less well understood than is the case for the earthquake sources (Behrens et al. 2021). This uncertainty makes it more difficult to cost-effectively deploy tsunami detection systems able to provide effective warnings from any events of these types.

Currently tsunami warning for the coasts of the Mediterranean and Europe is based on the detection of seismic waves (UNESCO/IOC 2022). Although some DART systems are deployed around the Caribbean and off the US northeast coast, and will provide critical data for any large events occurring on the west side of the Atlantic allowing for more accurate predictions of their impacts along European and North African coastlines, there are no DART systems currently deployed within Mediterranean or European waters. Here tide gauges provide the only direct source of measurements of any tsunami wave. Consequently, direct detections of a tsunami event are only possible once it has reached the coast.

There are several new approaches being developed that could contribute towards our ability to detect and characterize tsunamis, and better predict their impacts along our coastlines (e. g. Angove et al. 2019). To be operationally useful for augmenting tsunami detection and characterization, a new data source must 1) be available within the applicable time window, for tsunami warning that would be within minutes of the arrival of a tsunami wave at measurement location; 2) the data must have the accuracy/resolution to add information to the on-going analysis of the event and; 3) data must be in a form that tsunami warning centers can use and assimilate into their operational systems.

A novel approach for the direct detection of the open ocean tsunami signal was recognised in 2010, when a research vessel equipped with geodetic GNSS systems collected data during the passage of a ~10 cm tsunami from the 2010 Mw 8.8 Maule earthquake in Chile. When we examined those data (Foster et al. 2012) we found that the signal from the tsunami was clear in the post-processed kinematic elevation solutions. This led us to propose that the commercial shipping fleet represents a vast, existing infrastructure with excellent spatial coverage which could be exploited to construct a cost-effective tsunami detection network that covers both the deep oceans as well as extensive portions of the near shore region (Thomas et al. 2024). Further work on this concept lead to the deployment of a pilot network in the Pacific to demonstrate that a real-time system based on GNSS-equipped cargo ships could contribute to tsunami warning. We found (Foster et al. 2024) that a network of ships would be able to provide sufficiently robust data that the system could contribute to tsunami detection and characterization.

2 Ship-based GNSS tsunami detection

Tsunami waves in the open ocean can have amplitudes up to several meters close to the source, but are typically less than 1 meter. The scaling effect on the tsunami height when water depth shallows as it approaches the shore means that even modest open ocean amplitudes can translate to large run-ups along the coastline. An open ocean amplitude of 10 cm represents a typical threshold between low-impact events and potentially dangerous ones. The positioning accuracy needed to detect 10 cm vertical perturbations with a GNSS-based system requires high-accuracy real-time solutions. This can be achieved using geodetic grade GNSS equipment with a precise point positioning (PPP) service enabled on the GNSS receiver. Currently available marine positioning services offer real-time positioning with 5 cm accuracy for heights (e. g. Fugro 2024, Oceanix 2024). GNSS receivers with these types of services enabled receive their correction streams over L-Band broadcasts from geostationary satellites, and run the PPP solutions onboard the receiver, producing a high-accuracy kinematic time series.

The most obvious question to ask about using ships to detect tsunamis is how it could be possible to detect such a small amplitude tsunami signal amongst the meter-scale motions of the ships in regular ocean waves. The answer to this lies with the periods of tsunami waves, which range from 10 mins to 2 hours, while ocean waves typically have periods of only 5 to 20 seconds (Fig. 1). This spectral separation between the principal sources of noise and our target signal enables us to employ a simple low-pass filter – such as a running mean – to average out and remove the vertical motions of the ship in the waves.

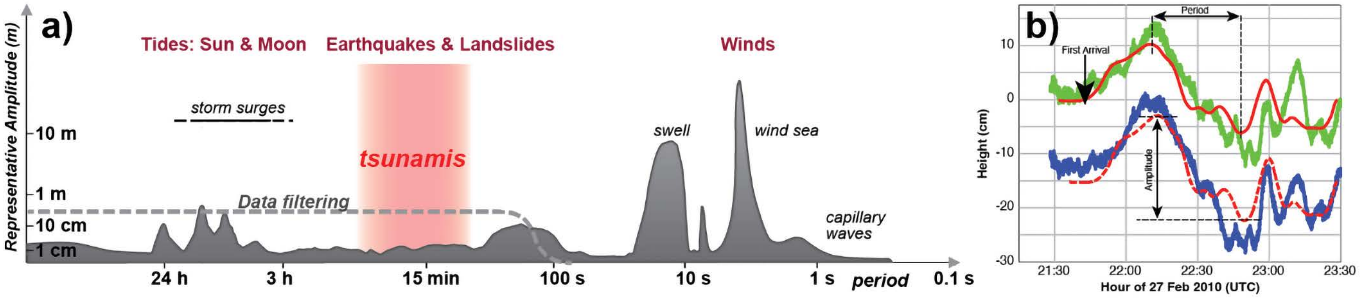

Fig. 1: a) Periodogram of common processes causing vertical motions of the sea surface in the open ocean. Amplitude ranges are rough approximations. Tsunami periods fall between the tidal cycle and the normal wind-generated waves. Ships are designed to have little response to short period waves, but act as passive markers for long-period signals. A low-pass filter can remove the short period wave motions (dashed gray line). b) Figure (from Foster et al. 2012) showing filtered GPS vertical solutions (green and blue) from a ship during the passage of the tsunami from the Maule Mw 8.8 2010 earthquake in Chile. In red are tsunami model predictions for the ship's location.

Our work examining data from our pilot network (Foster et al. 2024) found that, although the accuracy (RMS) of the vertical position solutions from our ships was consistent with the stated 5 cm accuracy of the commercial real-time positioning service we used, there were many significant outliers. The temporal correlation of the time-series meant that these outliers could be mid-identified as tsunami signals. We hypothesize that the origin of these perturbations is from ships adjusting their trim (the ship's forward/afterward inclination) as its speed and the wave conditions change. As these perturbations are not correlated between ships, the likelihood of more than one ship experiencing these perturbations at the same (or any specified) time are greatly reduced. By treating ships equipped with our package as an ensemble system this noise could therefore be mitigated. In this approach, four or more ships providing data simultaneously would have negligible chance of generating a "false-positive" tsunami detection. We are continuing to work to identify the cause of these perturbations: if we can mitigate them this would further improve the robustness of the ship-based data.

3 Proposed ship-based GNSS tsunami network

We propose that a ship-based GNSS tsunami detection network could be created by soliciting participation from the commercial shipping fleets. We use the successful Voluntary Observing Ship (VOS) program which provides observations of marine meteorology (Kent et al. 2010) as a template. It is estimated that 11 % of the commercial fleet are part of the VOS scheme, and so we use 10 % participation as a guideline to explore the potential ship-based contribution. The volunteering vessels would be equipped with a geodetic grade GNSS system running a real-time kinematic PPP service, and a low-cost PC. Our first processing step is to apply a low-pass filter to remove motion from the normal ocean waves (Fig. 1). This is simple to implement, and has the added advantage that the initial position time-series, which is generated at high rate (e. g. 1 Hz) can then be immediately down-sampled. This greatly reduces the volume of data that needs to be returned to the shoreside server. It does however require adding processing capability to the on-board package. A low-cost, fanless PC is capable of handling this initial data processing and transmitting the resulting low-rate position time-series back to shore. For hazard warning, this stream has to be available in real-time (within minutes): this requires a satellite internet connection. This connection is one of the key elements for the system we are proposing. For our pilot network, we deployed our own stand-alone satellite internet units on each ship. In that experiment, the internet connection had to support both the transmission of the GNSS correction stream from shore to the ship, as well as the 1 Hz (or 0.5 Hz) position time-series back to shore. We found that this component of the system proved to be the single biggest source of problems for our data flow, whilst also being the single biggest cost. Based on that experience during the pilot project, our concept for the ship-based package now includes an onboard PC. As the bandwidth required to transmit our decimated data packages is very small, discussions with interested cargo shipping companies have indicated that they may be willing to allow us to use their existing internet connections to transmit our data. This would be a huge advantage, removing that cost from our proposed system, and, as the communications packages deployed on most large commercial ships are typically higher power, and more advantageously located for clear line of sight to the satellites, it would also improve the data-stream reliability.

4 Shipping lines coverage in the NEAM tsunami source region

One focus of our current research efforts is answering the key question: is the distribution of commercial shipping useful for the detection of tsunamis? We are exploring this question by comparing a database of global ship locations with a database of historic tsunami source locations and examining the expected density of ships with the predicted travel time maps for historic tsunamis and the arrival times at exposed coastlines.

All large vessels are required to have an Automatic Identification Service AIS package onboard (IMO 2002). This package includes a navigation grade, single frequency, GNSS system, and it broadcasts regular messages over VHF radio including its coordinates. These AIS messages are received by land-based radio receivers when ships are close to ports, or by low-earth orbiting satellites when further offshore. The AIS messages do not include the height component and so are not themselves suitable for our approach for tsunami detection, but they do enable us to examine the patterns of ship distributions. We use a comprehensive compilation of these data (GMTDS 2024) to generate the mean expected density of cargo ships and tankers (the largest classes of commercial ships, and which typically have satellite internet installed) in the NEAM tsunami warning region at all time (Fig. 2).

Our ship density database was provided in a 1 km × 1 km grid, given in terms of hours of ship crossing per km² for each month of 2023 for cargo ships and for tankers. As our ship-based tsunami detection network concept involves, at least initially, large commercial ships we used the combined density maps of cargo ships and tankers as the basis for our analysis. To convert from ship-hours per month per km2 into a mean ship density we formed the annual total and then normalized by the number of hours in a year to get the mean expected number of ships for each grid square. We then scaled the result to get ships per 100 km2 (Fig. 2) as this number range is easier to visualize. This ship density grid allows us to examine scenarios for a range of historical or possible tsunami sources and determine how many ships would be expected to be in a position to detect such an event as the tsunami propagates away from the source. We present two cases here to illustrate how a ship-based network might contribute to tsunami detection efforts.

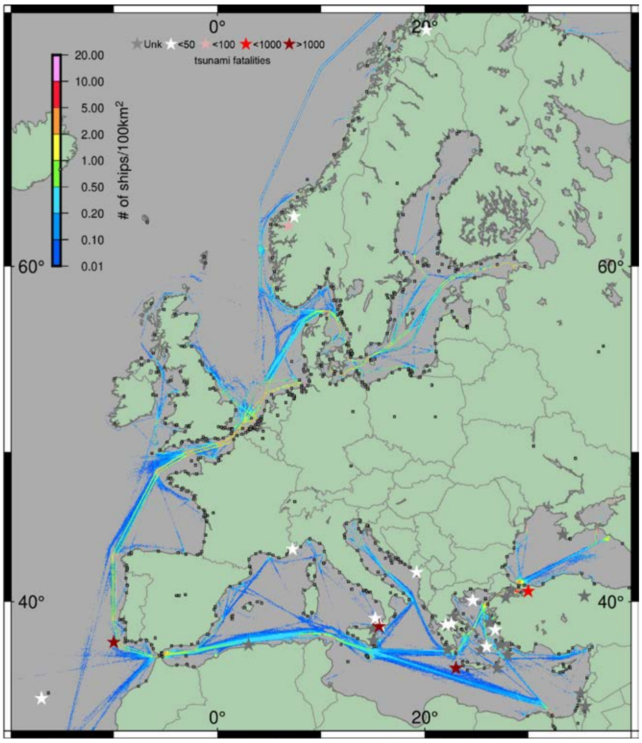

Fig. 2: Ship density for the Northeast Atlantic and Mediterranean area in terms of mean expected number of ships per 100 km² (i.e. within a 10 × 10 km square; GMTDS 2024). Tide gauges (squares; PSMSL 2024) and historical fatal tsunamis (stars; NGDC/World Data Service 2024) coded by number of fatalities are shown.

Case Study 1: Etna Flank Collapse

The southeastern flank of Etna volcano slides into the Ionian Sea at rates of centimeters per year (Urlaub et al. 2018). The balance of forces contributing to the instability of the flank is not fully understood, but the possibility of flank movement evolving into catastrophic collapse has not been excluded, implying that Etna's flank poses a potential tsunami hazard. We examine this scenario by modeling the travel time for a tsunami generated at the location of Etna's submarine flank. We use the Geoware TTT (Tsunami Travel Time) software package to map the first arrival time across the Mediterranean and compare this with the mean ship density grid to determine a cumulative number of ships reached by the tsunami over time. As we envision a 10 % ship participation in a tsunami detection project, we divide the total number of ships by 10 to provide an estimate of the expected number of participating ships. As noted above, our previous work examining the performance of ships for tsunami detection found that the noise within their vertical time series means a minimum of four ships are needed to provide robust detection capability (Foster et al. 2024). So, although we would expect at least one ship to be within 10 minutes travel time of the tsunami, we determine the time until the tsunami has reached at least four participating ships – in this case 20 minutes – and assume that another 10 minutes after the first arrival time are needed for the vertical perturbation to actually be detectable. This gives us an estimate of the time that would be needed for our proposed ship-based network to robustly detect the event. We can then compare that time against the arrival time of the tsunami along the coast lines to map that warning time that would be available. In this scenario, a fully-realized version of our ship-based network concept would need 30 minutes to robustly recognise a significant tsunami wave. We use the "POI" points developed by the NEAM Tsunami Hazard Model (Basili et al. 2021) to represent the warning lead-time this provides (Fig. 3). We find that the coastlines closest to our source - the eastern shore of Sicily and very southern tip of the Italian mainland – would not receive any warning from the ship-based system before the tsunami arrives. However, a ship-based network could contribute to a warning for all other coastlines more than ~200 km from the source. With an expected eight ships within the 30-minute travel time area, they would support increasingly detailed mapping of the tsunami amplitude leading to improved predictions of its impact at key points along most distant coastlines. We note

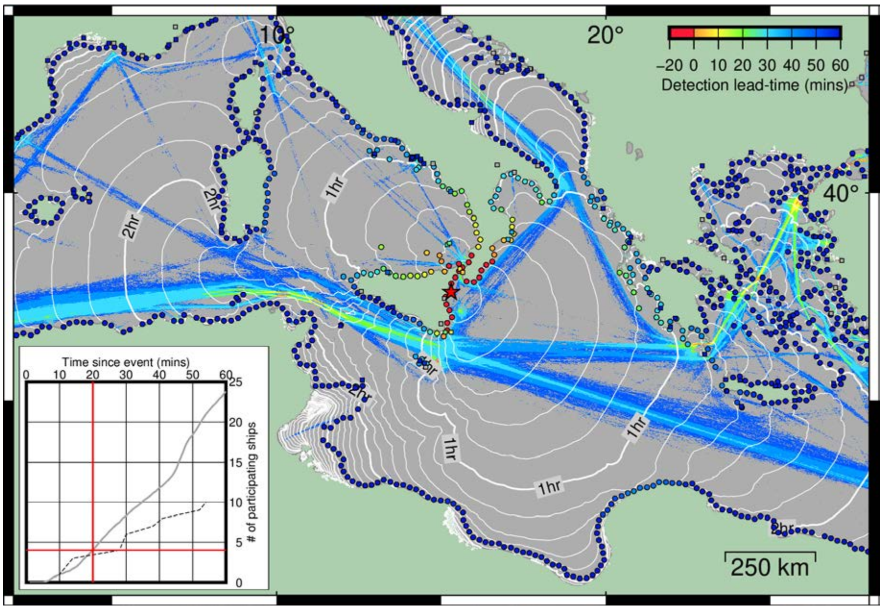

Fig. 3:
Tsunami travel time model for Etna submarine flank source. Ship density as from Fig. 2. White contours show travel time in 10-minute intervals. Colored dots are POIs from NEAM Tsunami Hazard Model, color-coded to the warning lead-time a ship-based tsunami detection network might be able to provide. Inset: cumulative number of ships participating (10 % of all cargo + tankers) in our hypothetical network reached by the tsunami over time. Red line indicates time for the event to reach four ships. Dashed line shows number of tide gauges reached by tsunami.

that the African coast line has virtually no tide gauges. The dense shipping lines between this event and that coast could generate a large number of observations from a region that would otherwise be without sensors.

Case Study 2: Bay of Biscay

On June 5, 1858, a wide range of eye-witness accounts suggest that a tsunami occurred in the North Sea Basin, with run-up values of up to 6 m along the west coast of Denmark (Newig and Kelletat 2011). Based on the arrival time of the first wave the source is interpreted as being in the Biscay region or south of it. The mechanism that generated the event is not known, but thought unlikely to be a simple earthquake source. A similar event could cause significant fatalities, and as it might not be associated with a significant seismic signal, it might – like the 2018 Palu event in Indonesia (Muhari et al. 2018, Syamsidik et al. 2019) – not be well predicted by the existing tsunami systems. We examine this case following the same procedure outlined above (Fig. 4).

For this case, the source is in a region away from the main shipping lines. As a result our proposed ship network would take 48 minutes before the tsunami reached our proposed four ship minimum. This gives no lead-time for the northern coast of Spain based on the ship network. It can be seen though that we would expect the first ship to be reached within 20 minutes, and three ships would be in position to detect the event before it reached the first tide gauge. If the ship noise can be at least partly mitigated, as noted above, the proposed network would once again be able to provide detection warnings for at least some of this coastline. The number of tide gauges reached within the first hour is similar to the ship counts, indicating that ships would be able to contribute to the characterization of the event and improved far-field predictions.

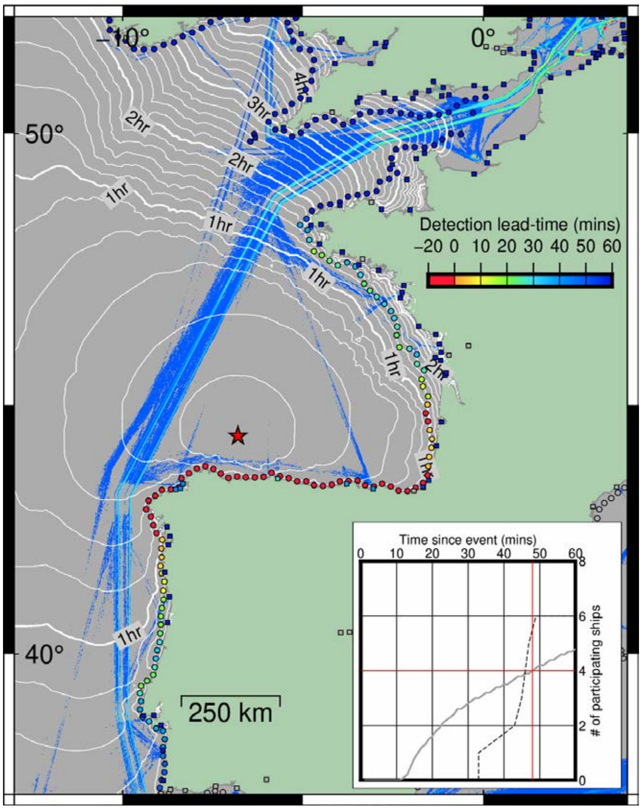

Fig. 4:
Tsunami travel time model for a Bay of Biscay source. Ship density as from Fig. 2. White contours show travel time in 10-minute intervals. Colored dots are POIs from NEAM Tsunami Hazard Model, color-coded to the warning lead-time a ship-based tsunami detection network might be able to provide. Squares indicate tide gauges, with color coded by the arrival time of the tsunami using the same scale as the detection lead time. Inset: cumulative number of ships participating (10 % of all cargo+tankers) in our hypothetical network reached by the tsunami over time. Red line indicates time for the event to reach four ships. Dashed line shows number of tide gauges reached by tsunami.

5 Operational maintenance costs and additional data products

One of the challenges for implementing hazard warning systems for events that might happen only once every few decades – or even less frequently – is the cost of maintaining the system in operational readiness for those rare but critical moments when it is needed. If the system has no other application or product this can be extremely challenging. GNSS has demonstrated its capability to contribute to multiple applications beyond its primary use for positioning, navigation and timing. A prominent secondary use is for land-based GNSS sites providing data that are routinely ingested into numerical weather models. While GNSS is only one component of the many different observational networks that contribute to these efforts, these data have been shown to make positive impacts (Guerova et al. 2016). The existing GNSS networks are land-based however and there is little data contributed from the oceans. Many of the extreme weather events that impact our communities form over the oceans. Satellites provide excellent global coverage, mapping out meteorological fields, but their water vapor observations have limited horizontal resolution, and may be contaminated by clouds and by the land at coastlines, reducing the quality of the data. This impacts the short-term predictions crucial for effective hazard mitigation. Ship-based GNSS meteorology would provide all-weather, high spatial and temporal resolution data that complements satellite observations. Importantly cargo ship tracks are most dense near coasts – exactly where satellite data might be least reliable, and where it can most contribute to improving the accuracy of short-term predictions.

In our modern society space weather can impact electronics, mobile phone communications, electricity supplies, and navigation systems. Space weather-produced effects include loss of radio contact for airplanes on trans-polar flights, astronauts imperiled by radiation, damage to electric grids, and disruption of cell phone service and underwater telecommunication cables, and destruction of satellite electronics. We need accurate models and accurate forecasts to protect modern technology, and as we are currently approaching a maximum in the 11 year solar cycle, these needs have particular relevance. Measurements of the Total Electron Content (TEC), formed through the dual frequency observations made by geodetic GNSS systems are one of the primary data types ingested into models of space weather which help to predict problems and the impacts of processes in our highly dynamic ionosphere (Mrak et al. 2020, IMPC 2024). Observations are currently made by land-based GNSS sites, with only island sites providing TEC observations from the ocean regions (Savastano et al. 2017, Manta et al. 2020). Our proposed ship network would be able to generate dense observations to fill out this gap in ground based ionospheric measurements (Ravanelli and Foster 2020). In addition, as noted above, tsunamis generate ionospheric perturbations that can be detected through the TEC measurements from geodetic GNSS systems. With TEC measurements made by a ship network, an independent tsunami detection approach is made possible, complementing our strategy of direct detection through the sea surface perturbation. By implementing GNSS data streams onboard the ships in our proposed network (Fig. 5), real-time data products could be generated that would

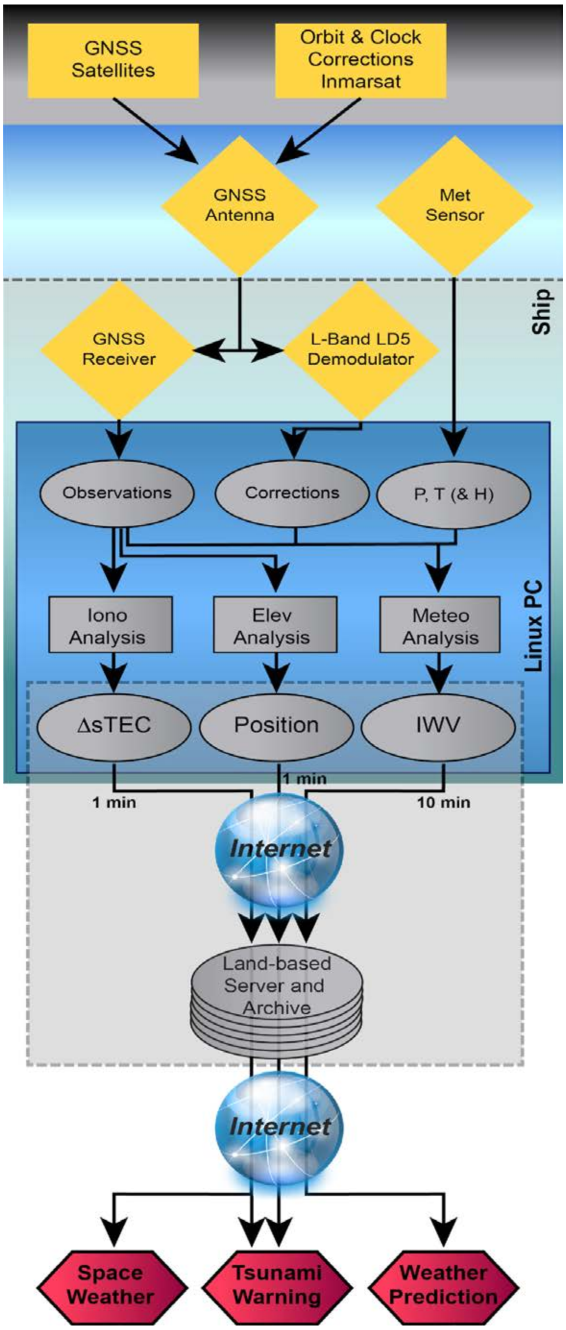

Fig. 5: Schematic of three possible real-time product streams derived from ship-based GNSS system. Our focus here was on the middle strand: high accuracy positions for tsunami detection. Also possible is to derive ionospheric slant total electron content values (left-hand strand). These can be used as an independent tsunami detection system, as well as contributing to space weather efforts. With additional meteorological measurements (right hand strand) real-time estimates of atmospheric integrated water vapor (IWV) can be generated to improve short-term numerical weather forecasts.

provide continuous, valuable, on-going benefits to society even during periods with no dangerous tsunami events.

6 Conclusion

The distribution of the main shipping lanes is a primary control on whether a network of ships equipped with GNSS can augment tsunami detection systems. They can thus contribute useful additional observations to improve warnings. For the cases we examine here, ships would be expected to be the first potential sensors reached by a tsunami. Although they individually provide noisier data than tide gauges, they may be able to provide a detection warning with a similar time to that provided by the tide gauge network. They would also enhance the spatial resolution of the tsunami field, helping to guide and improve predictions of the impact of the event along coastlines further from the source.

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