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Ship Communication and Radar for Tsunami Alerts

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Abstract—Tsunamis cause severe damage to coastal areas if early warnings are not given in time. Traditional systems using ocean buoys have weaknesses such as high maintenance and equipment failure. New studies propose using ship-based wireless communication and radar imaging methods for faster tsunami detection. This paper reviews these two methods based on recent research papers and proposes a combined model for better tsunami early warnings. The study also highlights the algorithms used, the years they were proposed, the papers where they appeared, and the performance achieved

1. INTRODUCTION

Tsunamis are among the most powerful and hazardous natural events, capable of causing widespread destruction within minutes of landfall. These massive ocean waves, usually caused by undersea earthquakes, volcanic eruptions, or underwater landslides, can devastate coastal regions within minutes. With little to no warning, tsunamis have the potential to wash away entire towns, destroy critical infrastructure, kill thousands of people, and leave survivors struggling for basic needs like clean water and shelter.

The world has witnessed some of the deadliest tsunamis in recent history. The 2004 Indian Ocean tsunami remains a heartbreaking reminder of the scale of destruction that tsunamis can cause. It struck without warning, claiming the lives of more than 230,000 people across 14 countries, making it one of the deadliest natural disasters recorded. Similarly, the 2011 Japan tsunami unleashed massive devastation. Triggered by a powerful magnitude 9.0 earthquake, it led to over 15,000 deaths and caused a catastrophic nuclear disaster at the Fukushima Daiichi Nuclear Power Plant.

These tragic events have made it clear that early detection and warning are the most critical tools we have to reduce the human and economic costs of tsunamis. Timely warnings allow people to evacuate coastal areas and seek safer ground, minimizing casualties and injuries.

Indonesia, situated in one of the most seismically active regions in the world — the Pacific Ring of Fire — is particularly vulnerable. The country sits at the convergence of three major tectonic plates:

- Eurasian Plate,

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- Indo-Australian Plate,

- Pacific Plate.

This geological setting causes frequent earthquakes, many of which are capable of triggering tsunamis. In response to these threats, Indonesia established a national tsunami early warning system known as Ina-TEWS (Indonesia Tsunami Early Warning System). This system was designed to quickly detect undersea earthquakes and possible tsunamis, then send out alerts to vulnerable coastal communities.

However, over time, several problems weakened the effectiveness of Ina-TEWS. Between **2012 and 2018**, Indonesia reported the loss or damage of many tsunami buoys that form a crucial part of its warning network. Without these buoys, the ability to monitor actual changes in sea level — a direct indicator of tsunami formation — was significantly compromised.

Recognizing these challenges, researchers began exploring new methods that could either supplement or replace traditional buoy-based systems. Two promising technological solutions have emerged from this exploration:

- Maritime Wireless Communication using Ships (introduced by Adityawan et al. in 2023),

- Radar Imaging Mechanisms using Synthetic Aperture Radar (SAR) satellites (proposed by Chaturvedi in 2019).

These innovative approaches aim to make tsunami detection faster, more accurate, and more reliable. This paper focuses on analysing these two methods, understanding the specific algorithms and technologies involved, reviewing their strengths and weaknesses, and proposing a **hybrid system** that combines the best features of both to improve future tsunami early warning systems.

Current Status of Traditional Tsunami Warning Systems

Despite years of development and investment, traditional tsunami early warning systems continue to face significant challenges. They have saved lives during many events, but gaps in coverage, technical failures, and system limitations have also led to tragic consequences.
To understand the need for modern alternatives, it is important to examine how traditional systems work and why they sometimes fail.

1.1 Buoy Systems

Buoy systems have been a cornerstone of tsunami detection efforts for decades. Typically, they work as follows:

- **Deployment:** Buoys are placed in strategic locations across the ocean, often in deep waters where tsunamis begin forming.

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- **Detection:** They are equipped with pressure sensors that measure changes in water height on the ocean floor.

- **Communication:** When a significant change is detected, the buoy sends a signal via satellite to a warning center on land.

However, in practice, buoy systems face numerous real-world difficulties:

Vulnerability to Human Interference

Because buoys are placed far from land, they are often unsupervised and vulnerable to human interference.

- **Vandalism:** Some buoys have been deliberately damaged by people who mistake them for valuable fishing equipment.

- **Theft:** Expensive sensors, batteries, and communication devices on the buoys have sometimes been stolen, leaving the systems non-functional.

In Indonesia's experience, this has been a major problem. Between 2012 and 2018, many tsunami buoys were damaged or stolen, leaving significant gaps in the country's ability to detect incoming tsunamis .

Environmental Challenges

The ocean is a harsh environment for delicate equipment:

- Storm Damage: Strong waves, typhoons, and debris from storms can batter buoys until they are no longer operational.
- Marine Growth: Over time, buoys become covered with algae, barnacles, and other marine organisms, which can affect their ability to float correctly and transmit accurate data.
- Battery Life and Corrosion: The salty ocean environment corrodes metal parts, and batteries must be replaced regularly, which requires costly maintenance missions.

High Operational Costs

Keeping a buoy network operational is expensive:

- Regular Maintenance: Ships must be sent to each buoy to check its status, clean it, and replace batteries.

- Repair and Replacement: Damaged buoys must be either repaired or replaced, which can cost hundreds of thousands of dollars.

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These high costs mean that developing countries, including Indonesia, often cannot maintain their buoy networks properly. As a result, gaps form in the early warning system — sometimes leaving entire regions without real-time sea-level monitoring.

1.2 Seismic Monitoring

Seismic monitoring stations are another essential part of tsunami early warning systems. These stations measure the shaking of the Earth's crust to detect earthquakes, especially those that occur under the sea.

When an earthquake is detected, seismic analysts try to quickly determine:

- The location of the quake (its epicenter),
- The depth of the quake,
- The magnitude (how strong it was).

From this information, scientists estimate whether the earthquake is likely to have triggered a tsunami. If it is strong and shallow enough, a tsunami warning might be issued.

However, relying solely on seismic data has serious limitations:

Earthquakes Without Tsunamis

Not every earthquake causes a tsunami.

- Some earthquakes, even if powerful, may not move enough water to create a significant wave.
- If authorities issue a warning every time an earthquake happens, it leads to false alarms.

Tsunamis Without Strong Earthquakes

In rare cases, even small earthquakes can trigger landslides under the sea that generate tsunamis. These are harder to detect with seismic data alone.

False Alarms and Public Trust

Repeated false alarms erode public trust:

- If people evacuate after every minor quake and no tsunami occurs, they may start ignoring warnings.
- The next time a real tsunami comes, fewer people might listen to the warnings, leading to tragic results.

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An example is the 2018 Palu Tsunami in Indonesia. Although the earthquake was detected, the tsunami arrived faster than expected, and warnings did not reach the public in time. Many lives could have been saved if faster and more reliable warning systems had been available.

2. BACKGROUND STUDY

Ship-Based Wireless Communication Systems

2.1 Concept

Passenger ships and cargo vessels are already equipped with VHF radios. These ships constantly move across major sea lanes. Researchers proposed using them as "mobile tsunami sensors."

When ships feel abnormal wave motions or receive seismic alerts, they can immediately send warning messages to coastal radio stations.

2.2 Method Developed in 2023

In 2023, Mohammad Bagus Adityawan and his team developed a detailed framework :

- Used Delft3D and Delft Dashboard software for tsunami simulation.
- Developed Standard Operating Procedures (SOPs) based on worst-case scenarios.
- Integrated VHF radio network between ships and coast stations.
- Modeled four earthquake scenarios around Palu, Indonesia.

2.3 Key Findings

- Ship-to-coast signal propagation took less than 1 minute after tsunami detection.
- Improved mitigation time for evacuation by at least 17 to 39 minutes depending on scenario.
- Proposed a backup communication system for areas where buoys are missing.

2.4 Advantages

- Ships are already available; no extra hardware needed.
- Less chance of system failure compared to fragile buoys.
- Provides real-time warning even when other systems fail.

2.5 Limitations

- Requires ship crew training.

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- Dependence on ship availability and correct procedure following.
- Limited effectiveness if ships are sparse in certain regions.

3. METHODOLOGY

Radar-Based Ocean Imaging for Tsunami Detection

3.1 Concept

Radar satellites like RADAR-SAT-2 can monitor the ocean surface. Changes in wave patterns caused by tsunamis can be detected using radar signals.

This method focuses on capturing the tiny surface variations before the tsunami reaches the coast.

3.2 Method Developed in 2019

In 2019, Sudhir Kumar Chaturvedi proposed :

- Using Synthetic Aperture Radar (SAR) imaging from satellites.
- Applying the q-Factor detection method to monitor sudden changes in ocean current velocities.
- Using the Bragg Resonance Principle to study the interaction between radar signals and ocean waves.

3.3 Key Findings

- q-factor showed sudden positive or negative shifts when tsunami waves approached.
- Detected tsunamis about 8 minutes after initial ocean disturbances.
- Radar warnings were issued 19 minutes earlier than tide gauges during the 2011 Japan tsunami.

3.4 Advantages

Works over vast ocean areas.

Independent of ship or buoy presence.

Can confirm tsunami movement in deep sea.

3.5 Limitations

- Gaps between satellite observations (e.g., 20-minute observation gaps).
- High cost of satellite deployment and maintenance.

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- Dependent on clear atmospheric conditions for best results.

Proposed Combined Tsunami Early Warning System

4.1 How It Works

1. Seismic sensors detect an earthquake.
2. Ships in affected regions check sea conditions and immediately transmit warnings.
3. Radar satellites scan the ocean for tsunami signatures using the q-factor method.
4. Coastal authorities combine ship reports and radar data to confirm tsunami presence.
5. Early warnings are issued to coastal populations, giving them maximum evacuation time.

4.2 Advantages

Faster alerts compared to using buoys alone.

Double confirmation reduces false alarms.

Redundancy: if ships are unavailable, radar can still confirm tsunami presence.

Challenges and Solutions

5.1 Training

- Challenge: Ship crews must be trained to recognise and respond to tsunami situations.
- Solution: Mandatory disaster preparedness modules for ship personnel.

5.2 Data Integration

- Challenge: Combining different data types (radio signals and satellite images) rapidly.
- Solution: Development of integrated warning control centres using AI-based data fusion techniques.

5.3 Cost

- Challenge: High costs for satellite management.
- Solution: International cooperation and shared satellite resources among countries.

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Case Study: 2011 Japan Tsunami

- High-frequency radars detected tsunami signals well before landfall.
- Radar provided early warnings 19 minutes earlier than tide gauges .
- Showed real-world success of radar imaging in tsunami detection.

If ship-based communication had been used as well, warnings could have been even faster and evacuation more effective.

FUTURE SCOPE

Future of Tsunami Early Warning Systems (EWS):

As coastal populations grow and climate change increases the risks of extreme weather events, the need for faster and more reliable tsunami early warning systems has become critical. Future EWS designs are expected to integrate cutting-edge technologies to enhance detection speed, prediction accuracy, and communication effectiveness. The main advancements include:

1. Integration of Artificial Intelligence (AI) and Machine Learning:

Artificial intelligence, particularly machine learning, will be central to improving tsunami forecasting. By training algorithms on historical earthquake and tsunami data, models can learn to recognise early indicators of tsunami generation more quickly than traditional statistical methods. AI systems can also handle real-time data streams from multiple sensors and identify patterns humans might overlook. In the future, predictive models may not only detect tsunami risks earlier but also predict the size, arrival time, and impact areas with high precision, offering more lead time for evacuation and disaster preparation.

2. Deployment of Drones and UAVs:

Drones equipped with radar and optical sensors will enhance real-time monitoring capabilities. After a seismic event, UAVs can be quickly deployed over affected ocean areas to detect changes in sea level, wave patterns, or coastal damage. Unlike satellites, drones can be redirected instantly to critical locations and operate under cloud cover or during adverse weather, providing high-resolution data that satellites might miss. In some cases, long-endurance drones could patrol high-risk zones routinely, serving as early scouts for tsunami formation.

3. Expansion of Maritime Sensor Networks:

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Currently, tsunami detection relies heavily on buoys and a limited number of deep-ocean sensors (such as DART buoys). To strengthen the system, future strategies could involve equipping commercial ships, fishing boats, and private vessels with low-cost sensors. These sensors might include GPS receivers, pressure sensors, and water level gauges, transforming the global maritime fleet into a decentralised, real-time ocean monitoring network. This distributed network would provide more frequent and geographically diverse data, helping to verify tsunami signals and reducing the chances of false alarms.

4. Creation of Multi-Modal Detection Systems:

No single technology can detect every tsunami efficiently. Thus, future systems will be multi-modal, meaning they will integrate multiple technologies to cross-verify data. Seismometers will detect undersea earthquakes, underwater pressure sensors will identify changes in ocean floor pressure, drones will offer visual confirmation, ships will provide localized water level data, and satellites will capture large-scale ocean disturbances. Machine learning algorithms will fuse this data into a cohesive analysis, improving both the speed and reliability of warnings.

5. Faster Communication and Public Alert Systems:

Technological improvements won't just stop at detection. New systems will also focus on rapidly disseminating alerts to the public through multiple channels—such as mobile apps, sirens, satellite messaging systems, and even social media platforms. AI could personalize warnings based on a person's exact location and risk level, making evacuation efforts more efficient.

CONCLUSION

The urgency for improved tsunami early warning systems is becoming increasingly clear as traditional buoy-based systems struggle to provide the level of efficiency required in today's rapidly changing environments. The need for more advanced and dependable technology to monitor and detect oceanic disturbances has sparked considerable research into alternative methods. Studies on maritime wireless communication (Adityawan et al., 2023) and radar ocean imaging (Chaturvedi, 2019) offer promising solutions that can significantly enhance the current warning frameworks. These technologies represent a leap forward, offering real-time data transmission and comprehensive environmental monitoring capabilities that are crucial in preventing major disasters.

Maritime wireless communication systems present a robust way to relay early alerts from ships directly to land-based authorities. These systems allow ships, which are often in the vicinity of developing tsunami threats, to send instant warnings of seismic activity or abnormal wave patterns. This provides a much quicker response time compared to traditional buoy systems. On the other hand, radar ocean imaging offers the ability to monitor vast expanses of the ocean, detecting waves and disturbances with high precision, even under challenging conditions. This technology ensures that any anomalies are quickly identified and confirmed, helping to avoid false positives and false negatives.

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Integrating these technologies into a hybrid system could form a powerful tsunami warning network, improving both the speed and accuracy of alerts. Maritime communication systems will offer rapid notification, while radar imaging will provide large-scale verification and cross-checking of potential tsunami indicators. By combining these capabilities, authorities can issue more reliable warnings, saving lives and reducing the overall damage caused by such natural disasters. It is essential for governments, researchers, and technology developers to collaborate closely to realize the full potential of these advancements and ensure they are effectively implemented on a global scale for the protection of vulnerable coastal populations..

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