Review Article

Radar-Based Tsunami Detection: A Comprehensive Review

Tjahjo Adiprabowo[1,2*], Dani Ramdani[1], Pamungkas Daud[1,2], Andriana[1], Erfansyah Ali[3,4], Nanang Nasrullah[1], Zulkarnain[1]

[1]Langlangbuana University, Bandung, Indonesia,
[2]Badan Riset dan Inovasi Nasional (BRIN), Bandung, Indonesia,
[3]National Taiwan University of Science and Technology (NTUST), Taipei, Taiwan,
[4]Telkom University (TelU), Bandung, Indonesia;

* Corresponding Author: tjahjo.adiprabowo@unla.ac.id

Abstract: Tsunamis can happen anytime and anywhere, and the timing is unpredictable, the biggest problem is if coastal areas are affected, it becomes the biggest risk in life. Tsunamis should at least be able to be detected quickly, and give people in coastal areas time to move quickly. Tsunamis occur due to seaquakes, because there is a plate fault that causes a shock that shoots sea water ashore as strong as possible, the resulting impact is very extraordinary, including the destruction of infrastructure in the coastal area. Radar is one of the technologies that can be proposed for remote object detection, even this Radar can be connected using the Internet of Things, specifically HF Radar, this research talks more deeply into DART (Deep Ocean Assessment and Reporting of Tsunamis) Radar, and this DART is specifically designed for Tsunami wave detection, the shortcomings of DART are quite complex infrastructure and require large funding, but in this research we know the concept of detecting ocean waves against the possibility of Tsunami which plays a big role in the process of future progress.

Keywords: Tsunami; tsunami detection; HF radar; DART radar; tsunami early warning system

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1.Introduction

Tsunamis can occur due to disturbances at the bottom of the ocean, be it an earthquake on or on the ocean floor a volcanic eruption, or for example large objects falling into the water. Tsunamis travel from 600-900 km per hour in the ocean. When approaching land the speed will decrease, in this context, it is very dangerous for residents and infrastructure around the coast, some technology has been developed in several countries, for example countries that often occur Tsunamis such as Japan, but there needs to continue to be a big breakthrough for this Tsunami countermeasure with a fast and accurate Tsunami detection system. This is done to reduce the great risk and impact caused by this Tsunami. The researchers' step is how to develop a system that can read Tsunamis with the latest technology [24,25,26,27,28,29,30] such as HF Radar and DART (Deep Ocean Assessment and Reporting of Tsunamis).

Tsunamis can be detected using several methods, for example by using ocean wave pressure or Buoys, by using an Algorithmic approach, and by using Radar. The focus here is on tsunami detection methods using HF (High Frequency) radar and DART (Deep Ocean Assessment and Reporting of Tsunami) radar. The algorithm used by the High-Frequency Tsunami Radar is to use the Detection Algorithm using orbital velocity and the appearance of Tsunami waves [31,32,33,34,35,36,37]. HF radar can measure the arrival time to land or coast. And can provide confirmation or estimation of time and also other more comprehensive telemetry systems. Resolution settings are also used in the detection process so that the radar can detect correctly.

HF Radar works with a frequency of 3-30 MHz and can detect up to hundreds of km. in this context, if combined with its ability to detect tsunamis, it becomes a high benefit. As in Indonesia, the Tsunami detection [38,39,40,41,42,43] process uses existing data such as Buoy data, a data conversion system is needed to determine a certain point has a certain height, and then from the results of processing buoy data can be developed towards the Internet of Things (IoT) to create realtime data, as developed in previous research, namely using the 77 GHz OPS Radar. This radar has a short distance of up to 100 meters, and low power, with a system integrated with a WiFi module that can be integrated into the Internet of Things (IoT) to obtain special movement data on patient breathing. And it has worked well.

The HF radar integration system for the Tsunami detection system with Buoy requires a complex integration system, in Indonesia there are several Buoy points installed in Indonesia, especially Tsunami-prone areas in Indonesia, but this is also a new challenge, where the Buoy system built needs routine and intense maintenance, and this DART Buoy needs to be continuously developed with an integration system, for example with Realtime Radar data such as IoT - Radar for faster data needs. The DART network is globally installed at several Tsunami hotspots in the Pacific, Atlantic, and Indian Oceans. The DART network is capable of accurate detection at designated vulnerable points, and this real-time challenge is still hindered by an unstable Internet connection system. In terms of data updates, the Internet is currently using satellite assistance from Starlink which can be integrated into the Internet of Things for real-time data needs.

DART transmits real-time ocean wave data from transmitter to receiver, then returns to the receiving station, so that the possibility of obtaining comprehensive Tsunami data can be achieved. This research is more of a review of DART for Tsunami detection, the analysis system of DART is complex, and there are several sections in this paper, the core chapter is how the analysis system of RF Radar on the DART system specifically for Tsunami detection [44,45,46,47]. The detection process requires novelty and GAP Research that has been completed by researchers.

2. Radar Characteristics

Radar works by using electromagnetic radio waves that are emitted to the sea surface then reflected from the surface called the echo signal from the surface of the sea water, and received back by the Radar. The movement of electrons on the surface of the seawater causes the movement of the surrounding magnetic field which in turn causes changes in the surrounding electric field, and so on so that it can be said that the surface of the seawater is a source of electromagnetic waves which are also radiated in all directions and some will lead back to the radar. radar can determine the characteristics of electromagnetic waves generated from reflections from the surface of seawater, information from this radar can be detailed about the speed, direction, and period of sea waves. HF Radar for Tsunami Detection can be seen in Figure 1 and Electromagnetic Radar Signal Transmission and Reflection can be seen in Figure 2.

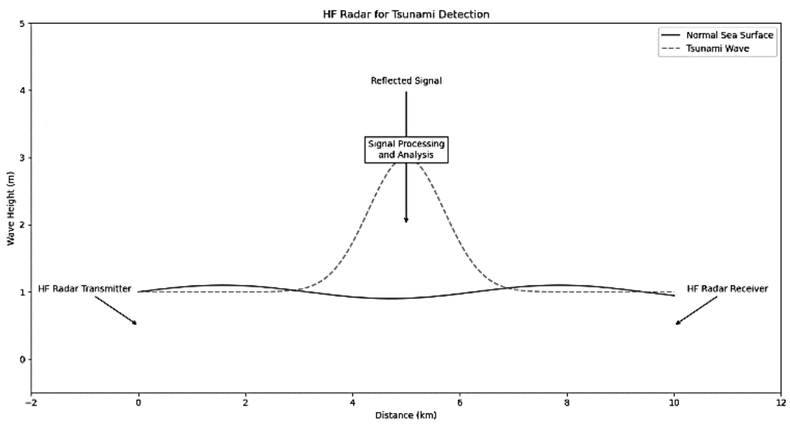

Figure 1. HF Radar for Tsunami Detection

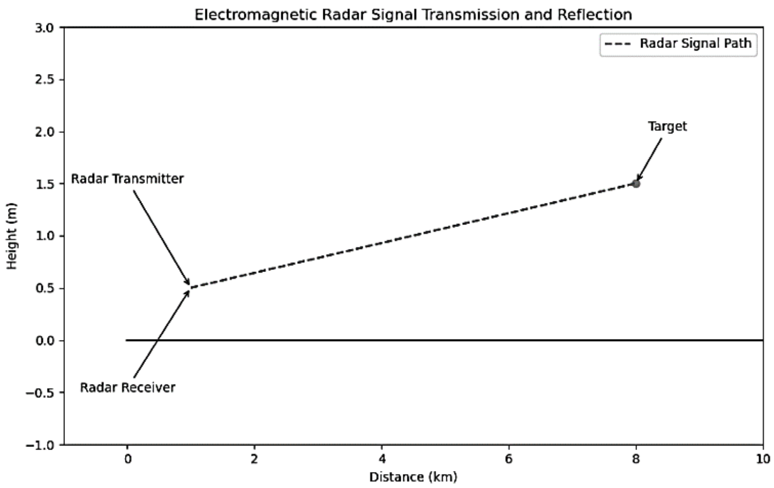

Figure 2. Electromagnetic Radar Signal Transmission and Reflection

$$P_r = \frac{P_t G_t G_r \lambda^2 \sigma}{(4\pi)^3 R^4} \quad (1)$$

The reflection of electromagnetic waves is expressed by the following equation 1. In this expression, P_r is the received transmitted power in watts. P_t is the peak transmitted power in watts. G_t is the gain of the transmit antenna. G_r is the gain of the receive antenna. λ is the carrier wavelength in meters. σ is the mean RCS of the target in square meters. R is the range from the radar to the target in meters. Equation 1 shows the performance of the receiver side and can be a reference for analyzing or comparing real measurements.

Furthermore, in a radar system for detecting tsunamis, the time delay between the electromagnetic waves emitted by the radar and the electromagnetic waves reflected by the sea surface can be used to determine the distance of the tsunami from the radar. The time delay measurement formula is as follows equation 2.

$$\Delta T = \frac{2R}{c} \quad (2)$$

In this expression, ΔT is a time delay. R is the range from the radar to the target in meters. And c is the speed of light in meters per second. In the time delay formula above, the distance component R is multiplied by a factor of 2, because this delay time is the time taken by the electromagnetic wave to transmit from the radar antenna to the target followed by retransmission from the target to the radar antenna with the same travel distance between them, namely R. If from radar measurements the time delay ΔT is obtained, then the target distance, which in this case is the distance of the tsunami wave from the coast, can be obtained from the calculation in the equation 2.

In a radar system for detecting tsunamis, changes in the frequency of radio waves reflected by the sea surface can be used to determine the speed of the tsunami. When the radar sends electromagnetic waves, the waves will bounce back to the radar after colliding with the target. The relationship between the frequency of the reflected wave received by the radar (fr) and the moving speed of the radar target (v) can be explained by the Doppler effect. The formula for calculating frequency changes due to the Doppler effect is as follows Equation 3.

$$f_r = \left(\frac{1+\frac{v}{c}}{1-\frac{v}{c}}\right)\mathrm{f} \tag{3}$$

In this expression, f_r is the received echo frequency in hertz. f is the transmitted frequency in hertz. v is the velocity of the moving target in meters per second. c is the speed of light in meters per second. In equation 3, v has a positive value if the target moves closer to the radar and a negative value if the target moves away from the radar. This will result in fr being greater than f if the target is moving closer to the radar and fr being smaller than f if the target is moving away from the radar. If from radar measurements the echo frequency fr is obtained, then the target speed, which in this case is the speed of the tsunami wave as it approaches the coast, can be obtained from the calculation in equations 3. The signals received by the radar are then processed to produce useful information, such as distance, speed, and direction of objects. This signal processing can be carried out using various techniques, including digital processing and Fourier transform.

The first process is sampling. In this process the received signal is usually sampled at different time intervals, using an Analog Digital Converter (ADC), which quantizes the analog signal into a signal discrete in time and amplitude. The quantization time corresponds to the ADC sample time, while the amplitude quantization depends on the number of bits (binary digits) of the ADC and the full-scale voltage of the signal being processed. The time between samples can be calculated from the sample frequency. To achieve correct detection, the sampling frequency should not be less than twice the highest frequency of the signal being measured. This is governed by the Nyquist sampling theorem. One of the Nyquist sampling theorems says that the maximum frequency that can be unambiguously measured is half the sampling rate. This is necessary so that the original signal can be recovered correctly using the existing sample data. The ADC output, which is binary data, is typically stored in memory as a three-dimensional matrix of complex voltage samples and is referred to as a radar Datacube. A radar datacube is a three-dimensional representation of the time-space processing of radar signals, which consists of Fast Time, Slow Time, and spatial dimensions.

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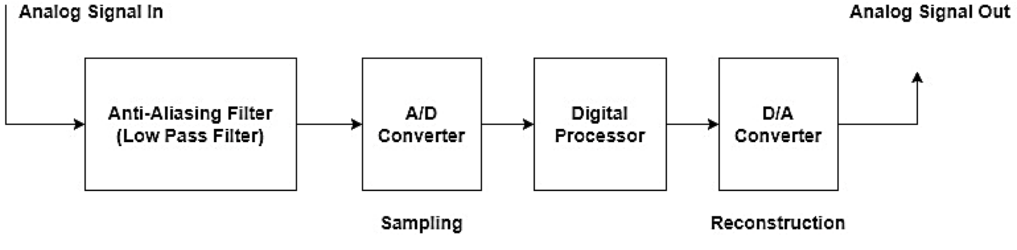

Figure 3. Signal Processing block diagram

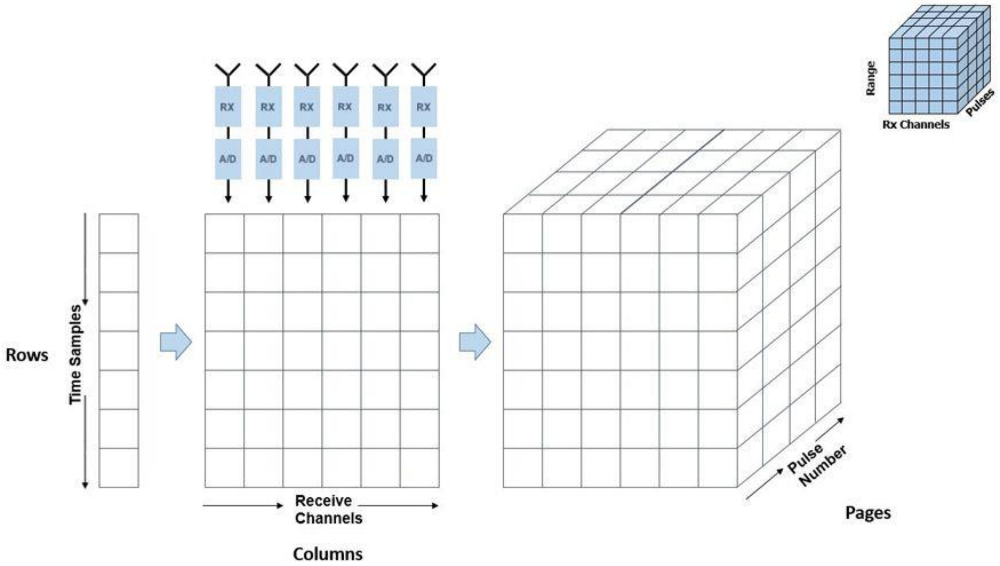

Figure 4. A Radar Data Cube (Sources: MathWorks)

The ADC output, which is binary data, is typically stored in memory as a three-dimensional matrix of complex voltage samples and is referred to as a radar Datacube, a Radar Data Cube can be seen in Figure 4. A radar datacube is a three-dimensional representation of the time-space processing of radar signals, which consists of Fast Time, Slow Time, and spatial dimensions. Fast Time refers to the fast time dimension, namely the time between adjacent radar pulses, while Slow Time refers to the slow time dimension, namely the time between different radar pulses. The spatial dimension is a dimension that refers to the spatial position of the radar signal in space.

The next process is the Fast Fourier Transform (FFT) of the data in the datacube radar. FFT first converts the datacube radar data from the time domain to the frequency domain. This is done by calculating the Fourier transform of the datacube radar data. The FFT then calculates the frequency spectrum of the datacube radar data. Frequency spectrum is a datacube representation of radar data in the frequency domain. The FFT then analyzes the frequency spectrum to obtain information about the targets detected by the radar. This information may include target location, target speed, and target type. The location of the target can be determined by measuring the Doppler frequency of the radar signal reflected from the target. The target's speed can be determined by measuring the change in the Doppler frequency of the radar signal reflected from the target. The type of target can be determined by measuring the strength of the radar signal reflected from the target.

3. Latest Radar Technology for Tsunami Detection

The latest radar technology used to detect tsunamis is HF radar and DART radar (deep ocean assessment and reporting of tsunamis). HF (High Frequency) radar uses high-frequency radio waves (3-30 MHz) to detect tsunamis. The way it works is divided into 4 (four) stages, namely: Signal transmission, signal reception, data analysis, and tsunami early warning. In the signal transmission stage, the HF radar antenna emits radio waves towards the sea. These radio waves propagate on the sea surface and some are reflected to the antenna. Next, in the signal reception stage, the HF radar antenna receives reflected signals from the sea surface. These reflected signals contain information about ocean wave patterns, including changes caused by tsunamis. The next stage is data analysis, here special software is used to analyze the reflected signal data which consists of identifying changes in wave patterns that indicate a tsunami, estimating the direction and speed of tsunami waves, and calculating the height of tsunami waves on the coast.

Tsunamis can be detected by analyzing changes in the frequency and amplitude of the reflected signals. When a tsunami approaches the radar, the signal frequency and amplitude of the reflected signal will increase. The final stage is the tsunami early warning. If a tsunami is detected, the system will issue an early warning to communities in threatened coastal areas. 4 methods can be used to detect tsunamis using HF radar, namely: Backscatter, Doppler, Interferometry, and Polarimetry.

The Backscatter method utilizes the reflection of radio waves from the sea surface. Tsunamis change the reflection pattern of radio waves, which can be detected by HF radar. The backscatter method is effective for detecting tsunamis in the deep sea. The Doppler method measures changes in the frequency of radio waves reflected from the sea surface. Tsunamis cause changes in Doppler frequencies, which can be detected by HF radar. The Doppler method is effective for detecting tsunamis in shallow seas and near the coast. The Interferometry method uses two or more HF radar antennas to measure the phase differences of radio waves reflected from the sea surface. Tsunamis cause interferometric phase changes, which can be detected by HF radar. The interferometry method can produce more accurate information about the height and speed of tsunami waves. The polarimetric method measures the polarization of radio waves reflected from the sea surface. Tsunamis cause polarization changes, which can be detected by HF radar. The polarimetric method can help differentiate tsunamis from other ocean waves.

Often, several methods are combined to increase the accuracy of tsunami detection. A combination of methods can provide more complete information about tsunamis, such as direction, speed, and wave height. Research continues to be carried out to develop new methods and improve the accuracy of tsunami detection with HF radar. New methods such as Synthetic Aperture Radar (SAR) and Moving Target Indication (MTI) show potential to improve the performance of HF radar in detecting tsunamis. Meanwhile, four algorithms can be used by HF radar to detect tsunamis, namely: Change Detection Algorithm, Pattern Recognition Algorithm, Tsunami Parameter Estimation Algorithm, and Data Integration Algorithm. The Change Detection Algorithm compares current ocean reflection signal data with previous data to look for changes that indicate a tsunami. This algorithm can detect changes in wave patterns, such as increases in wave height or changes in Doppler frequency. The Pattern Recognition algorithm uses machine learning techniques to learn patterns of ocean reflection signals associated with tsunamis. This algorithm can detect tsunamis with higher accuracy than change detection algorithms.

The Tsunami Parameter Estimation Algorithm estimates tsunami parameters, such as direction, speed, and wave height, from ocean reflection signal data. This algorithm helps predict the arrival time of a tsunami on the coast and estimates the impact of a tsunami. The Data Integration algorithm combines data from HF radar with data from other sensors, such as seismographs and tide gauges, to improve tsunami detection accuracy. This algorithm allows the tsunami early warning system to provide more complete and accurate information to the public. HF radar uses various algorithms to detect tsunamis. Algorithm combinations and new algorithm developments continue to be carried out to improve the accuracy and effectiveness of tsunami detection. New algorithms such as deep learning and adaptive filtering show potential to improve the performance of HF radars in detecting tsunamis. HF radar system for tsunami detection can be seen in Figure 5. The DART system can be seen in Figure 6.

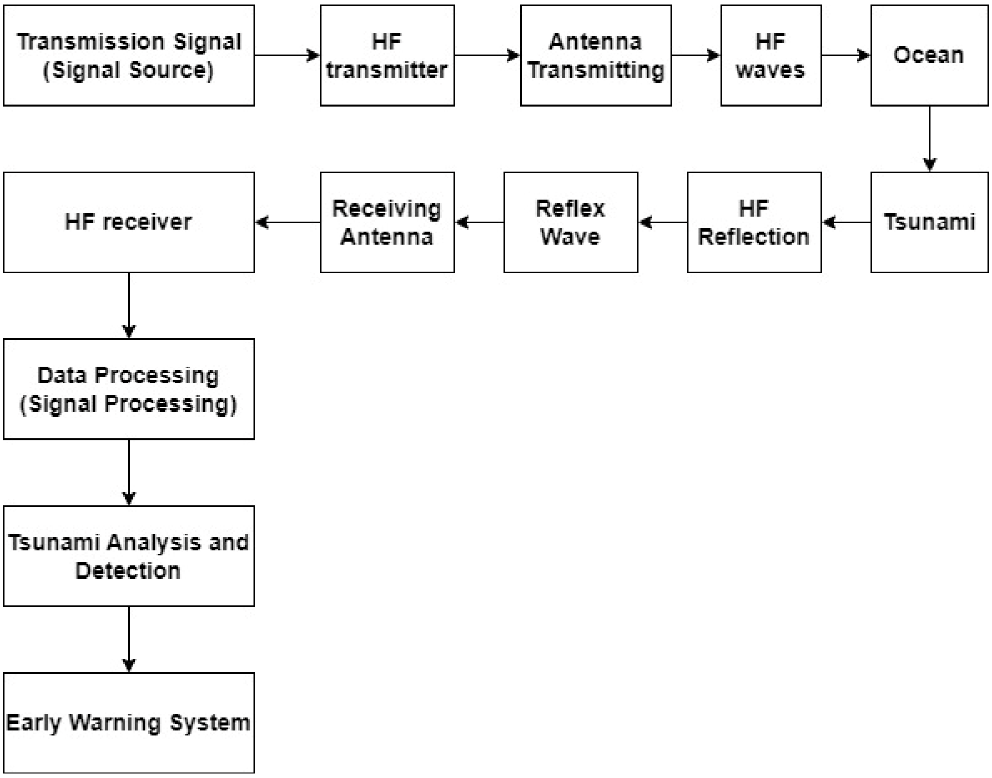

Figure 5. HF radar system for tsunami detection

The DART stands for Deep Ocean Assessment and Reporting of Tsunamis. The DART radar is designed to detect tsunamis in the deep sea, long before they reach the coast. This allows for longer evacuation times for residents in coastal areas. The DART radar works at an operating frequency of 450 MHz for data communications. This frequency was chosen for several reasons, namely: seawater penetration, communication range, and availability. The 450 MHz frequency can penetrate seawater well, allowing it to reach the seabed and measure the height of tsunami waves. In terms of communication range, the 450 MHz frequency can reach long distances, allowing DART to be deployed in the deep sea. In terms of availability, the 450 MHz frequency is available internationally for maritime use. The DART system consists of two main parts, namely: the sea surface and the seabed. At sea level, a buoy is anchored in the deep sea. This buoy is equipped with sensors to measure sea wave height and atmospheric pressure. On the seabed, an acoustic transponder is installed there. This transponder receives signals from the buoy and sends them back to the surface. The acoustic frequency used is 10 kHz.

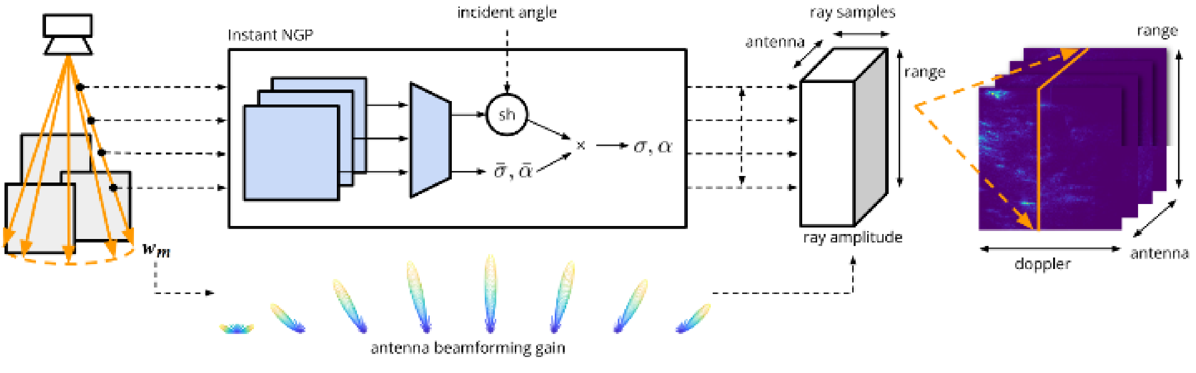

Figure 6. DART system (Sources: wiselabcmu.github.io/dart/)

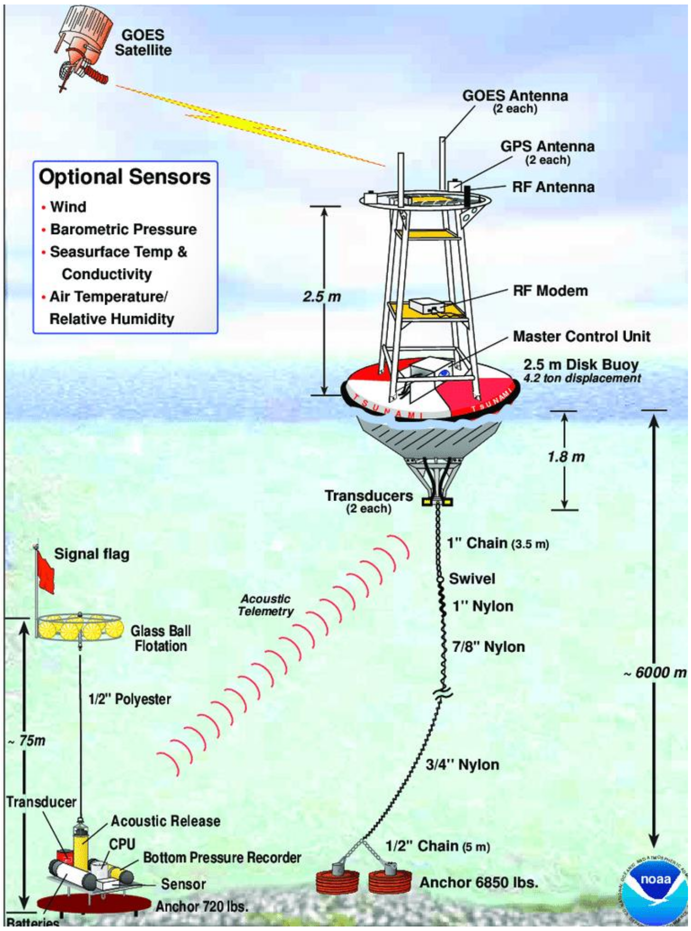

Figure 7. DART Mooring System (sources: E. N. Bernard, Survival Capsule LLC. BSc Physics, MS Oceanography, PhD Oceanography, 2021)

When a tsunami is detected, the buoy will sense changes in sea surface height from the seabed which are measured using sensors and acoustic transponders. Data on changes in sea level height is then transmitted to a transponder on the seabed, which is then forwarded to a land station. The ground station then analyzes the data and issues a tsunami warning if necessary.

DART Radar (Deep Ocean Assessment and Reporting of Tsunamis) uses a seawater pressure measurement method to detect tsunamis with the following stages: Seabed Pressure Sensor, Real-Time Data Transmission, Data Analysis, Tsunami Early Warning. Seabed Pressure Sensors are placed on the seabed in tsunami-prone areas. This sensor measures changes in seawater pressure caused by a tsunami.

Real-Time Data Transmission transmits real-time sea water pressure data to receiving stations on land via satellite. Data Analysis uses special software to analyze sea water pressure data which results in identifying pressure changes that indicate a tsunami, estimating the direction and speed of tsunami waves, and calculating the height of tsunami waves on the coast. If a tsunami is detected, the Tsunami Early Warning system will issue an early warning to communities in threatened coastal areas. DART (Deep-ocean Assessment and Reporting of Tsunamis) Radar is a system used to detect tsunamis in the deep sea. The algorithm used by the DART radar to detect tsunamis involves several key steps, namely: Wave Measurement, Real-Time Data Analysis, Signal Sending, Verification and Confirmation, and Advanced Monitoring.

In Wave Measurement, the DART radar uses sensors installed on the seabed to continuously monitor ocean waves. These sensors detect changes in water pressure or reflected waves, which could indicate the presence of a tsunami. In Real Time Data Analysis, the data collected by sensors is analyzed in real-time by a computer system.

Algorithms in computer systems check for suspicious patterns and trends in water pressure or ocean wave data. This includes looking for sudden changes in water pressure levels that might signal an ongoing tsunami. In Signal Sending, if the system detects indications of a tsunami, such as a sudden change in seawater pressure, the system will send a signal or warning via the available communications network. These alerts can be sent to government agencies, disaster control centers, or nearby maritime authorities.

Verification and confirmation need to be done because the DART radar does not only rely on data from one sensor but also takes into account information from other stations in the relevant area. This helps in verifying and confirming the existence of a tsunami and helps in predicting its impact. Follow-up monitoring needs to be carried out, namely after detecting a tsunami, the DART radar continues to monitor the waves to measure the strength and movement of the tsunami. This information is used to provide additional updates and warnings to areas that may be impacted. These algorithms work together to detect, verify, and provide early warning about tsunamis, helping communities and authorities to take appropriate action in the face of the threat.

4 Discussion

The first advantage of HF radar in detecting tsunamis is that it has a wide range because HF radar can detect tsunamis up to 200 nautical miles. This is possible because HF radio waves have the characteristic of being able to propagate above the sea surface and be reflected by the ionosphere so that their range can exceed the distance of the sea horizon from the shoreline. Then HF radar can operate in all weather because HF radio waves are more resistant to wave depolarization caused by weather. Apart from that, the detection time is also fast. HF radar can detect tsunamis in minutes. In terms of costs, it is also relatively cheap. HF radar is cheaper to install and operate than traditional tsunami detection systems.

The first disadvantage of HF radar in detecting tsunamis is that the data produced by HF radar is complex and requires careful analysis to detect tsunamis. In addition, HF radar can be interfered with by other signals, such as radio interference and ocean waves. Also, HF radar has limited accuracy. HF radar is not as accurate as traditional tsunami detection systems in determining the height and arrival time of a tsunami. Currently, research and development is being carried out to improve the ability of HF radar to detect tsunamis. Some ongoing research areas include the development of new algorithms for data analysis, the development of multi-static HF radar systems, and the development of HF radar systems that are integrated with other tsunami detection systems, such as seismographs and tidal sensors to provide more comprehensive tsunami warnings.

The first advantage of the DART radar is for early tsunami detection. DART radar can detect tsunamis up to an hour before they reach the coast. The next advantage is its wide reach. The DART radar can detect tsunamis in the deep sea up to a distance of 500 km from the coast. Also all-weather capability. The DART radar can operate in all weather. The first disadvantage of DART radar is in terms of cost. DART radars are expensive to install and operate. Next is the limited number. Currently, there are only a few DART radars installed worldwide. Also ranged from interference. DART's radar can be disrupted by marine activity, such as earthquakes and volcanoes.

Current research and development on the DART radar includes enhancing the capabilities of the DART radar. Some ongoing research areas include the development of new algorithms for data analysis, the development of multi-static DART radar systems, and the development of DART radar systems that are integrated with other tsunami detection systems.

Table 1. Use and analysis of HF Radar for Tsunami detection and DART radar system from recent research to obtain Research GAP.

No	Research Topic	Methods used	Analysis obtained	Interviewee or Researcher, year	Source on reference
1	Tsunami generation and propagation	inform preparedness efforts and guide recommendations for infrastructure development in the Palu Bay area.	tsunami waves on September 28, 2018, reflect a T-EL-type tsunami source, while the T-L type source produces tsunami waves with longer periods compared to earthquake-generated tsunamis (T-EL).	Wiko Setyonegoro, et.al, 2024	[1]
2	Modeling and analysis of the Tsunami generated by the 2024 Noto Peninsula earthquake on 1 January: Wave characteristics in the Sea of Japan	provides a comprehensive analysis of the geological context, faulting mechanisms, and tsunami propagation of this event to gain insights into the complex dynamics of tsunami generation and amplification.	involves simulation models based on two fault scenarios provided by the Geospatial Information Authority of Japan (GSI) and the United States Geological Survey (USGS), coupled with Fourier spectral and modal analyses.	Kwanchai Pakoksung, et. al, 2024	[2]
3	Island-based GNSS-IR network for tsunami detecting and warning	GNSS Interferometric Reflectometry (GNSS-IR)	The newly designed GNSS-IR network could work equally well as the cabled OBP network in detecting tsunamis if the stations are built in strategically chosen locations.	Linlin Li, et. al, 2024	[3]
4	Coral reef response in the Maldives during the 2004 Indian Ocean tsunami	Reproduce the tsunami hydrodynamic characteristics along the Maldivian shores using the TUNAMI-N2 model.	Develop fragility curves for the reefs that have been impacted by the tsunami, based on the Global Earthquake Model (GEM) guidelines.	E. Lahcene, et.al, 2023	[4]
5	Evaluation of tsunami inundation in the plain of Martil (north Morocco): Comparison of four inundation estimation methods	A digital terrain model of the plain was used to explore four methods of inundation mapping	Using four hazard mapping methods to create inundation maps for two scenarios of tsunamis generated by extreme submarine mass failure (SMF)	E. Basquin, 2023	[5]
6	A multi-proxy approach to assess tsunami hazard with a preliminary risk assessment: A case study of the Makran Coast, Pakistan	The coastal hazard, particularly tsunamis, is evaluated by integrating five approaches: (i) probabilistic tsunami hazard assessment (PTHA); (ii) deterministic tsunami hazard assessment (DTHA); (iii) geophysical-seismic (2-D thermal modeling), (iv) sedimentary tsunami deposits (tsunamis); and (v) the historical record.	Based on the above five approaches, the hazard analysis helped to shortlist four-wave scenarios (3, 7, 10, and 15 m).	Rashid Haider, et. al, 2023	[6]

No	Research Topic	Methods used	Analysis obtained	Interviewee or Researcher, year	Source on reference
7	A comprehensive review of tsunami and palaeotsunami research in Chile	Show the spatial and temporal distribution of tsunami deposits affected by their preservation in different climate zones. also seek to assess the interpretation of each deposit by comparing information provided from a variety of sources and analyses.	developed by the consideration of five criteria that include the use of multiproxy analyses, the correlation of a site with other deposits, comparisons with numerical simulations or historic counterparts, discrimination of the deposit from other possible processes, and a critical evaluation of the data in the original publication.	Tomás León, et.al, 2023	[7]
8	Extreme events in the Indian Ocean: Marine heatwaves, cyclones, and tsunamis	Review the current knowledge on high-impact oceanic extremes in the Indian Ocean, namely, marine heatwaves (MHWs), tropical cyclones (TCs), and tsunamis.	MHWs and TCs are both modulated by Indo-Pacific climate variability, in particular, the El Niño-Southern Oscillation and the Indian Ocean Dipole	Ming Feng, et. al, 2024	[8]
9	Coastal emergency managers' risk perception and decision making for the Tonga distant tsunami	1) how risk can be communicated most effectively and 2) how risk perceptions associated with "distant" tsunami alerts and warnings affect EMs' willingness to issue emergency alerts.	Interview transcripts were deductively coded and thematically analyzed	Ashley Moore, et. al, 2024	[9]
10	Synchronous observations of traveling ionospheric disturbances by the multipoint Doppler sounding, ionosonde and the incoherent scatter radar: Case study	first time we used data obtained from Kharkiv incoherent scatter (IS) radar, ionosonde, and coherent Doppler HF sounding system to detect and investigate traveling ionospheric disturbances (TIDs).	The periods close to the winter solstice and autumn equinox in 2018 were analyzed. The dominant periods and horizontal phase velocities of registered TIDs were 45–80 min and 230–460 m s−1, respectively.	Kateryna D. Aksonova, et.al	[14]
11	Land subsidence analysis using synthetic aperture radar data	This research has gathered datasets consisting of 80 Sentinel-1A ascending and descending SLC images from July 2017 to July 2019. This dataset, concerning InSAR and PS-InSAR, is processed with SARPROZ software to determine the land subsidence in Gwadar City, Balochistan, Pakistan.	This technique requires multiple images acquired of the same place at different times for estimating surface deformation per year, along with surface uplifting and subsidence. The InSAR results showed maximum deformation in the Koh-i-Mehdi Mountain from 2017 to 2019.	Rida Bokhari, et. al, 2023	[12]
12	A review of onshore tsunami deposits along the Atlantic coasts	The central aim of the paper is to offer a broad overview of the main deposits and key localities that have been documented along the Atlantic coastlines, and which attest to the local or regional impact of tsunamis during historical, pre-historical, and recent geological times.	The paper also discusses the relationships between the different tsunamigenic sources that contributed to the formation of the deposits, as well as critical information on magnitude and frequency, as inferred from the sedimentary	P.J.M. Costa, et. al, 2021	[13]

No	Research Topic	Methods used	Analysis obtained	Interviewee or Researcher, year	Source on reference
			responses preserved in the sediment archives		
13	Rapid tsunami loss estimation using regional inundation hazard metrics derived from stochastic tsunami simulation	Using a probabilistic tsunami loss model for the Tohoku region of Japan, rapid tsunami loss estimation models are developed by regressing predicted tsunami losses against regional inundation hazard parameters, which are derived for coastal cities and towns in Miyagi Prefecture from 4000 stochastic tsunami simulations.	Performances of the new approaches are compared with conventional methods that are based on earthquake magnitude, source-to-site distance, and offshore tsunami wave profiles.	K. Goda, et. al, 2019	[16]
14	Triggers and consequences of landslide-induced impulse waves – 3D dynamic reconstruction of the Taan Fiord 2015 tsunami event	This paper comprises a detailed study of both the landslide evolution and the wave dynamics of the October 2015 Taan Fiord (Alaska) tsunami event, which represents a highly valuable case study for generic methodology development of single code applications using the numerical software Flow3D and testing its applicability for cascading wave hazard evaluation.	The reconstructed landslide volume is estimated to be 49.4 Mm^3, where 26 Mm^3 entered the fiord and triggered the tsunami. Second, wave dynamics are recreated with Flow3D.	A. Franco, et. al, 2021	[17]
15	A comparative study of earthquake source models in high-order accurate tsunami simulations	The two-fold goal of this work is a comparative study of dynamic and static tsunami generation by seabed displacement and the careful validation of these source models.	The numerical results show that the impact of the choice of seabed displacement model can be significant and that using a static approach may result in inaccurate results.	M. Hajihassanpour, 2019	[18]
16	Tsunami hazard and risk assessment for Alexandria (Egypt) based on the maximum credible earthquake	In this work, for each tsunamigenic source, i.e., West Hellenic Arc, East Hellenic Arc, and Cyprian Arc, the maximum credible earthquake (MCE) is defined and then modeled with NAMI-DANCE.	The aggregated tsunami inundation map for Alexandria defines the furthest boundary between inundated and non-inundated lands and is associated with hazard levels based on water heights.	H. M. Hassan, 2020	[19]
17	Tsunami earthquakes: Vertical pop-up expulsion at the forefront of subduction megathrust	Published slip distribution models, based on geodetic, seismological, and tsunami data, of the Mw 7.8, 2010 Mentawai tsunami earthquake offshore south-central Sumatra, suggest that the large tsunami wave was generated by a narrow swath of high seafloor uplift along the accretionary wedge front, implying higher vertical throw than that consistent with slip on	Tsunami simulations show that such combined deformation, i.e. the broad-scale seafloor displacement caused by slip on the megathrust and the localized 8–10 m seafloor uplift across a 6–9 km-wide pop-up belt involving up to three pop-ups, can reproduce the 2010 tsunami amplitude measured by a DART buoy, and observed	N.D. Hananto, 2020	[20]

No	Research Topic	Methods used	Analysis obtained	Interviewee or Researcher, year	Source on reference
		the shallow-dipping megathrust.	run-up heights in the Mentawai Islands.		
18	Numerical modeling of tsunamis generated by iceberg calving validated with large-scale laboratory experiments	A novel numerical methodology and unique large-scale laboratory experiments are presented to investigate the generation and propagation of such IBTs. In the laboratory, the IBTs were generated with rigid blocks in a 50 m × 50 m basin.	An analytical solution of the radiated waves by a heaving sphere in still water, a vertically falling, and an overturning block experiment are used to validate the numerical model.	F. Chen, et. al, 2020	[21]
19	Volumetric change analysis of the Cauvery delta topography using radar remote sensing	The availability of DEM allows the analysis of landscape morphology and related processes in terms of geomorphometry. DEM of Difference (DoD) techniques are used to estimate the elevation variations and volumetric changes over time.	A detailed assessment of individual DEM's errors and propagating errors into the DoD are estimated using the field elevation points measured by Real-Time Kinematic (RTK) Global Positioning System (GPS).	S. Rajakumari, et. al, 2022	[22]
20	Detecting urban changes using phase correlation and ℓ1-based sparse model for early disaster response: A case study of the 2018 Sulawesi Indonesia earthquake-tsunami	we intend to identify changes between images that are not co-registered. The proposed procedure is based on the use of phase correlation, which shows different patterns in changed and non-changed areas.	Pairs of visible and near-infrared (VNIR) spectral bands of medium resolution were used to compute the phase correlation to set feature space. The phase correlation-based feature space consisted of 484 features. We evaluate the proposed procedure using a damage inventory performed from visual inspection of optical images of 0.5-m resolution.	L. Moya, 2020	[23]

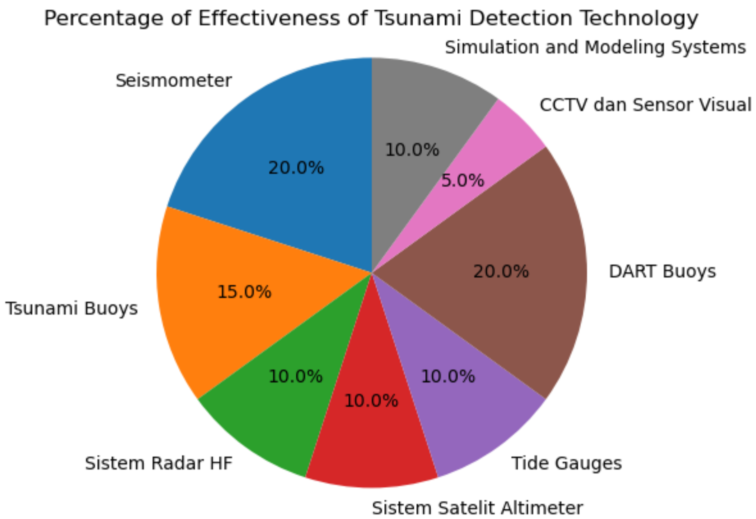

Figure 7. Percentage of Effectiveness of Tsunami Detection Technology

5 Conclusions

Radar could be one of the technologies that can be chosen to detect tsunamis. Two radar technologies that are widely used for tsunami detection are HF radar and DART radar. HF radar and DART radar have their respective advantages and disadvantages. The combination of these two types of radar can provide a more comprehensive solution for tsunami detection. Further research is needed to improve the performance and reliability of radar-based tsunami detection systems. In the future, it is necessary to develop new algorithms to increase the accuracy and efficiency of tsunami detection. Apart from that, increased international cooperation is also needed to share radar data and technology.

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