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ANALYSIS OF RAY TRACING (BELLHOP) PROPAGATION MODEL IN NORTH NATUNA SEA WATERS

Analisis Model Propagasi Ray Tracing (Bellhop) di Perairan Laut Natuna Utara

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ABSTRACT

The waters of the North Natuna Sea are one of Indonesia's areas prone to conflict and traversed by foreign vessels due to their direct bordering with several neighboring countries, demanding effective maritime security assurances. To ensure this security, careful maritime control and monitoring are necessary, especially through the use of monitoring tools such as SONAR to detect foreign objects traversing or entering the waters of the North Natuna Sea. This research aims to analyze the characteristics of underwater acoustic wave propagation patterns, particularly in forming shadow zones, using the Bellhop method. Simulations of the Ray Tracing propagation model (Bellhop) were conducted using the AcTUP v2.2L Toolbox. Temperature and salinity data against depth obtained from Marine Copernicus over one year were used in this research, from January 1, 2023, to December 31, 2023, during both the west and east monsoon seasons. Sound propagation speed calculations were based on the Medwin empirical equation, with a focus on a source depth of 10 meters at frequencies of 100 Hz and 1000 Hz in the North Natuna Sea. The simulation results indicate that during the west monsoon season, underwater acoustic wave propagation patterns reach further distances and decline towards the seabed compared to the east monsoon season. The shadow zone is therefore wider during the east monsoon season. Additionally, the transmission loss values at 100 Hz are almost the same in each season, whereas at 1000 Hz, the transmission loss is higher during the west monsoon season, ranging from 40 dB to 75 dB, compared to the east monsoon season, which ranges from 40 dB to 65 dB.

Keywords: North Natuna Sea waters, Sonar, Ray Tracing Propagation Model (Bellhop), Transmission Loss, Shadow Zone

ABSTRAK

Perairan Laut Natuna Utara adalah merupakan salah satu perairan di Indonesia yang rawan konflik dan dilewati kapal asing karena berbatasan langsung beberapa negara tetangga, menuntut jaminan keamanan maritim yang efektif. Untuk memastikan keamanan ini, pengendalian dan pengawasan laut yang cermat diperlukan, terutama melalui penggunaan alat monitoring seperti SONAR untuk mendeteksi benda asing yang melintas atau memasuki perairan laut natuna utara. Penelitian ini bertujuan untuk menganalisis karakteristik pola propagasi gelombang akustik bawah air, khususnya dalam pembentukan daerah senyap atau *Shadow Zone*, menggunakan metode *Ray Tracing (Bellhop).* Simulasi dari model propagasi *Ray Tracing (Bellhop)* dilakukan dengan memanfaatkan *Toolbox AcTUP v2.2L*. Data suhu dan salinitas terhadap kedalaman yang diperoleh dari *Marine Copernicus* selama satu tahun digunakan dalam penelitian ini, mulai dari tanggal 01 Januari 2023 sampai 31 Desember 2023 saat musim barat dan musim timur. Perhitungan kecepatan rambat suara didasarkan pada persamaan empiris Medwin, dengan fokus analisis pada kedalaman sumber 10 meter dengan frekuensi 100 Hz dan 1.000 Hz di Laut Natuna Utara. Hasil simulasi menunjukkan Pada musim barat pola propagasi gelombang akustik bawah air mencapai jarak 4.100 meter lebih jauh daripada musim timur, baik pada frekuensi 100 Hz maupun 1.000 Hz, sehingga daerah *Shadow Zone* lebih luas pada musim timur. Sedangkan nilai kehilangan energi Transmisi (*Transmission Loss*) pada frekuensi 100 Hz hampir sama di setiap musim dan pada frekuensi 1.000 Hz nilai *Transmission Loss* lebih tinggi pada musim barat, yaitu berkisar antara 40 dB sampai 75 dB dan pada musim timur hanya berkisar antara 40 dB sampai 65 dB.

Kata Kunci: Perairan Laut Natuna Utara, Sonar, Model *Propagasi Ray Tracing (Bellhop)*, *Transmission Loss*, *Shadow Zone*

INTRODUCTION

The North Natuna Sea is a sea that has extraordinary potential and is located in the Southeast Asia region. Where there is a lot of natural and mineral wealth that is beneficial for the surrounding countries (Novianto *et al.,* 2020), the North Natuna Sea also has an important role in trade distribution routes and international shipping (Andikara *et al.,* 2021) so it is vulnerable of maritime security threats. Climate-wise, the North Natuna Sea is influenced by the Australian-Asian Monsoon (Ilahude, 1997) or monsoon winds. Monsoon winds are divided into West Monsoon winds and East Monsoon winds. The West Monsoon winds blow in December, January and February, while the East Monsoon winds blow in June, July and August (Fadika *et al.,* 2014 ; Hidayat *et al.,* 2015). The peaks of the West Season and East Season are in January and July respectively (Sudarto, 2011 ; Triadmodjo, 1999).

The existence of the West Season and East Season will of course also influence the characteristics of the water masses in the North Natuna Sea, especially the temperature and salinity, where temperature and salinity data are really needed by underwater acoustic technology in the form of Sonar. Sonar can be used to track submarines and foreign underwater acoustic equipment that infiltrate Indonesian territory through the North Natuna Sea. Infiltration of submarines and foreign underwater acoustic equipment often uses safe or quiet areas of underwater acoustic wave propagation known as Shadow Zone areas (Agustinus *et al.,* 2016). This area is a zone where the temperature and salinity of sea water deflects incoming sound waves so that submarines and foreign underwater acoustic equipment are protected from opposing parties' sonar. One way to anticipate this is through simulating underwater acoustic wave propagation patterns.

Underwater acoustic wave propagation is the process of propagation or transmission of acoustic signals through water media. The sea, along with its materials and boundaries, becomes a complex medium for the propagation of underwater acoustic waves. The physical shape of the ocean, such as the surface and seabed, influences the propagation of acoustic energy under the sea. This is because the surface and bottom of the sea can reflect, scatter and absorb energy from acoustic signals that pass through it. Which in the end can cause transmission energy loss (Transmission Loss) and the formation of a Shadow Zone area (Pravitasari, 2010).

One method of underwater acoustic wave propagation is the Ray Tracing (Bellhop) Method. The Ray Tracing (Bellhop) method is an underwater acoustic wave propagation method based on ray theory and Gaussian beam models which are used to mathematically model the channels used to transmit acoustic signals as information carriers in underwater wireless communication systems. The Gaussian beam equation is useful for modeling range dependent conditions, namely situations where the parameters influencing the propagation of underwater acoustic waves change in value as the distance from the source increases (Wijaya, 2010). The Ray Tracing (Bellhop) method is also capable of producing a variety of useful outputs, including calculations of propagation losses, eigenrays which are rays connecting the source and receiver, arrivals, and received time series. This method also allows for variations in distance at the upper and lower limits, as well as in the sound speed profile. With the addition of input files, this method can also consider source directions and geo-acoustic properties for the surrounding media. In addition, the upper and lower reflection coefficients can also be accommodated.

This research is part of an initial study to analyze the propagation of underwater acoustic waves using the Ray Tracing (Bellhop) method in the form of Transmission loss and Shadow Zone areas in the North Natuna Sea at a source depth of 10 meters with a frequency of 100 Hz and 1000 Hz in the west and east seasons. based on temperature data, salinity from Marine Copernicus for 1 year with a depth of 541 meters.

METHODS

Place and Time

This research comes from Copernicus Marine Secondary Data in the form of oceanographic data which includes temperature and salinity for 1 year from January 1 2023 to December 31 2023 during the west and east seasons. The research location will focus on the North Natuna Sea (Figure 1).

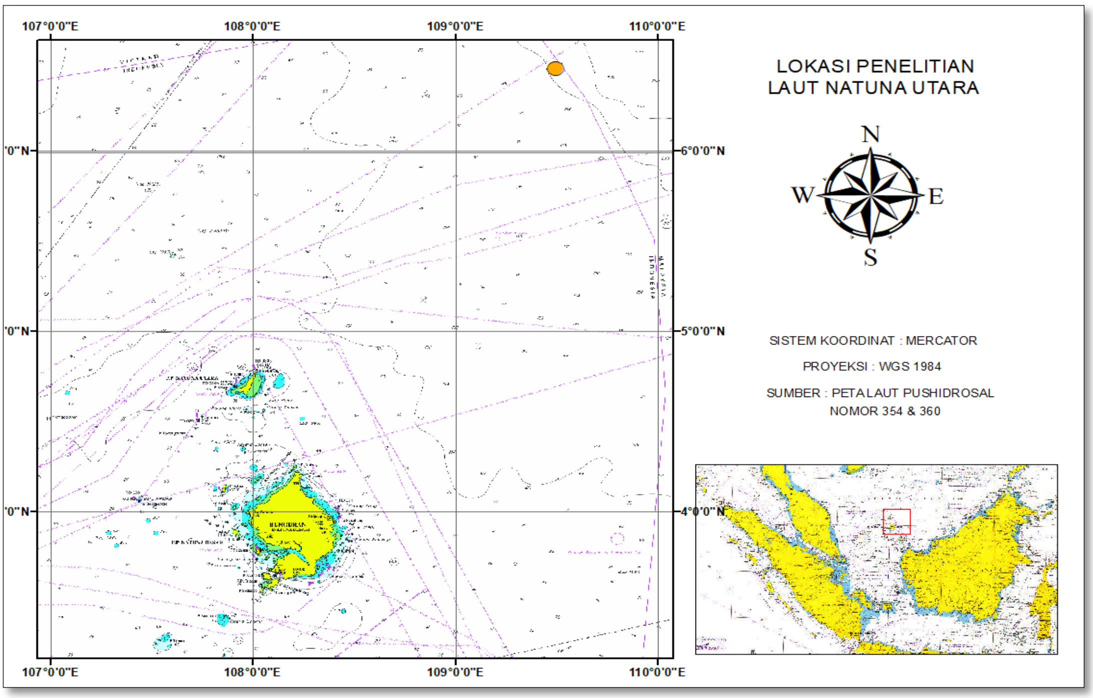

Figure 1. Map of Research Location

Tools and Materials

The tools used are laptops, books and stationery. Meanwhile, the materials used are software including Matlab, ODV and MS Excel.

Research Procedure

Temperature and Salinity data are used to obtain sound speed profile (SVP) values using Medwin's empirical equation (Medwin, 1975). According to (Urick, 1983), the empirical equation for the sound speed profile is divided into three parts, one of which is the Medwin empirical equation, $c = 1449.2 + 4.6 \times T - 5.5 \times 10^{-2}T^2 + 2.9 \times 10^{-4}T^3 + (1.34 - 10^{-2}T) \times (S - 35) + 1.6 \times 10^{-2}z$, with the following constraints:

$0 \leq T \leq 35^{o}C$ (in Celsius)

$0 \leq S \leq 45‰$

$0 \leq z \leq 1000$ meters

Sound speed data is used to obtain underwater acoustic wave propagation patterns using the Ray Tracing (Bellhop) method. This propagation pattern uses the MATLAB toolbox Actup v.2.2L. To run the MATLAB toolbox Actup v.2.2L toolbox simulation, first create an environment followed by entering values in the code dependent and code independent sections. When all the data has been entered, pattern simulation is carried out by running the run propagation function. The results of the simulation will be displayed with the help of images. From the propagation pattern of underwater acoustic waves, the value of Transmission Loss and the Shadow Zone area in the North Natuna Sea will be determined.

Data analysis

Analysis of Temperature, Salinity and Speed of Sound data was carried out using Ocean Data View (ODV) software (Schlitzer, 2022) and Ms Excel. These data are displayed in underwater acoustic wave propagation patterns using the Ray Tracing (Bellhop) method in the North Natuna Sea at a depth of 541 meters in the west and east seasons using the MATLAB toolbox Actup v.2.2L.

RESULT

In the simulation carried out at the Research Station with a depth of 541 meters, a frequency limit in the range of 100 Hz to 1000 Hz was chosen to understand differences in acoustic wave propagation patterns. Lower frequencies have larger wavelengths and can penetrate to greater depths, while higher frequencies have shorter wavelengths and can undergo more rapid reflection or diffraction by underwater obstacles.

Taking into account the location of the transducer depth of 10 meters, simulations were carried out for the west and east seasons. Differences in acoustic wave propagation patterns between the west and east monsoons can be influenced by factors such as wind direction, water temperature, and local geographic characteristics. Therefore, considering both seasons provides a more holistic understanding of the dynamics of the underwater acoustic environment at the site. Simulation results obtained from Ray Tracing (Bellhop) provide an in-depth visualization of how sound waves propagate beneath the water surface at different frequencies and changing seasonal conditions. This data can be used for a variety of applications, including underwater navigation, underwater object detection, and understanding marine ecology. The images resulting from this simulation, namely images 2, 3, 4, and 5, present visual information showing the differences in acoustic wave propagation patterns between the two frequencies and seasons.

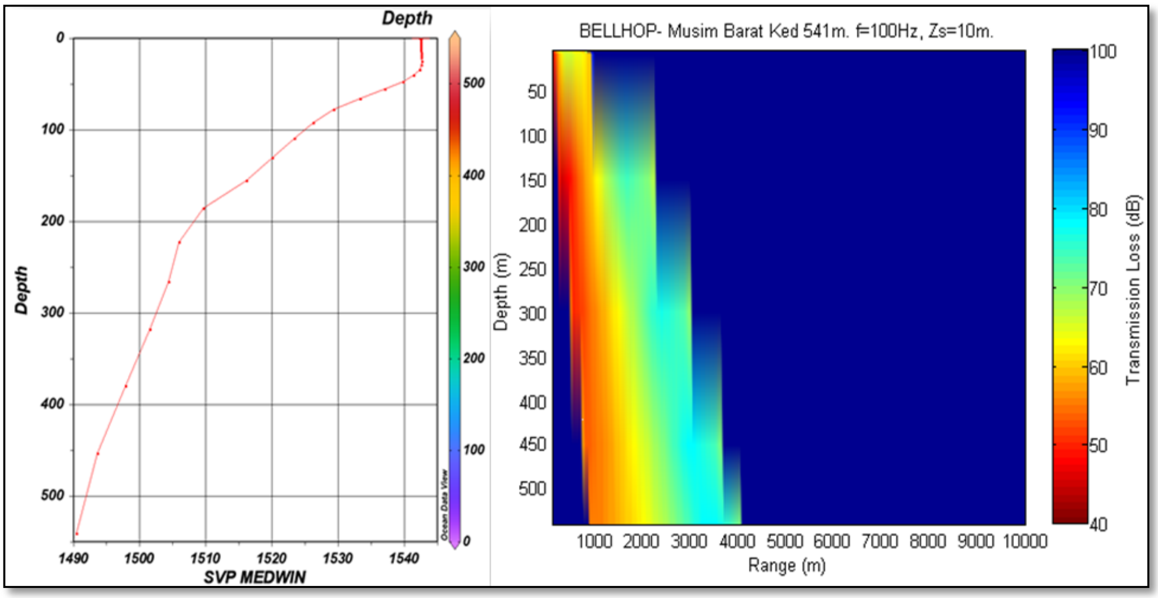

Figure 2. Underwater Acoustic Wave Propagation Pattern Method
Ray Tracing (Bellhop) with a frequency of 100 Hz in the western season

Figure 2 is the result of Matlab Actup 2.2vL simulation in the form of Underwater Acoustic Wave Propagation Pattern Ray Tracing (Bellhop) Method with a frequency of 100 Hz in the west season. It can be seen that as the propagation distance of underwater acoustic waves increases, the transmission energy loss will increase. (Transmission Loss) so that the Transmission Loss value increases as the propagation distance increases. In the simulation of underwater acoustic wave propagation patterns with a frequency of 100 Hz and a source depth of 10 meters using the Ray Tracing (Bellhop) method, the underwater acoustic wave propagation pattern looks quite stable. When sound waves are emitted, their propagation pattern decreases to the bottom of the water with a depth of 541 meters and only reaches a distance of 4,100 meters from the total distance determined at 10,000 meters. When propagating underwater acoustic waves, transmission energy loss (Transmission Loss) is quite large, reaching 100 dB. At a distance of 0 to 2000 meters the Transmission Loss value is between 40 dB to 70 dB and at a distance of 2000 meters to 4100 meters the Transmission Loss value increases between 70 dB to 80 dB.

Shadow Zone area (red circle) in the Ray Tracing (Bellhop) method simulation in Figure 2 Shadow Zone is formed at a distance of 0 – 900 meters at a depth of 250 meters to 541 meters and a distance of 4,100 to 10,000 meters at a depth of 0 to 541 meters with a Transmission Loss value each approaching 90 dB to 100 dB. The emission of underwater acoustic wave propagation reaches around 4 km or 2.4 miles from the acoustic source and a distance of 4.1 km above is a silent area (Shadow Zone) for submarines.

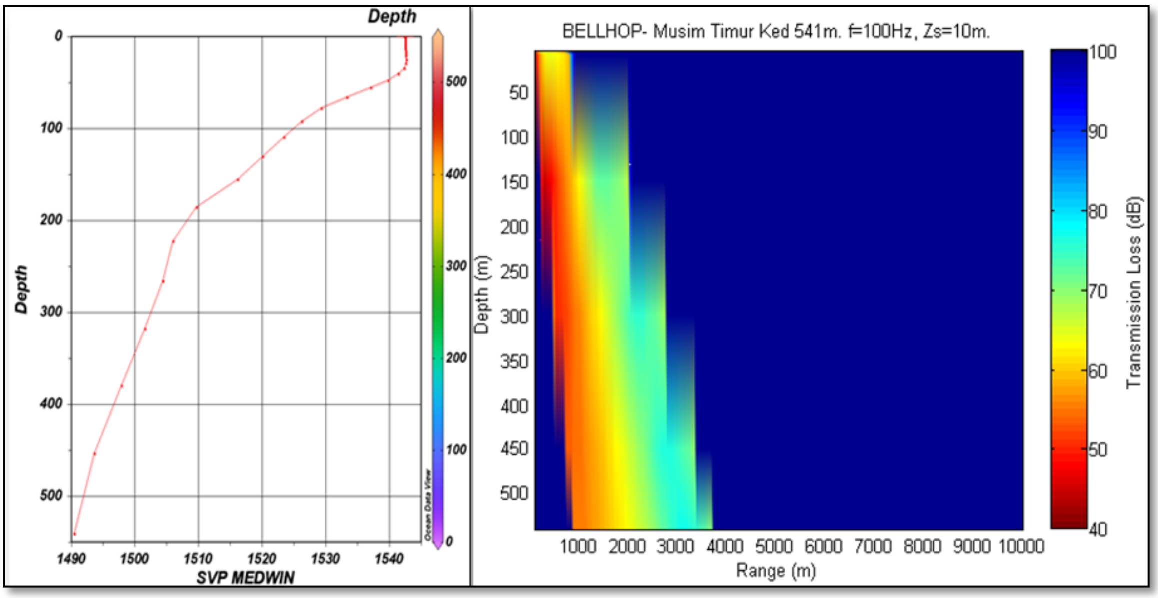

Figure 3. Underwater Acoustic Wave Propagation Pattern Method
Ray Tracing (Bellhop) with a frequency of 100 Hz in the east season

Figure 3 is the result of Matlab Actup 2.2vL simulation in the form of Underwater Acoustic Wave Propagation Pattern Ray Tracing (Bellhop) Method with a frequency of 100 Hz in the east monsoon. It can be seen that as the propagation distance of underwater acoustic waves increases, the transmission energy loss will increase. (Transmission Loss) so that the Transmission Loss value increases as the propagation distance increases. In the simulation of underwater acoustic wave propagation patterns with a frequency of 100 Hz and a source depth of 10 meters using the Ray Tracing (Bellhop) method, the underwater acoustic wave propagation pattern looks quite stable. When sound waves are emitted, their propagation pattern decreases to the bottom of the water with a depth of 541 meters and only reaches a distance of 3,900 meters from the total distance determined at 10,000 meters. When propagating underwater acoustic waves, transmission energy loss (Transmission Loss) is quite large, reaching 100 dB. At a distance of 0 to 2,000 meters, the Transmission Loss value is between 40 dB and 70 dB and at a distance of 2,000 meters to 3,900 meters, the Transmission Loss value increases between 70 dB and 80 dB.

Shadow Zone area (red circle) in the Ray Tracing (Bellhop) method simulation in Figure 3 Shadow Zone is formed at a distance of 0 – 900 meters at a depth of 250 meters to 541 meters and a distance of 3,900 to 10,000 meters at a depth of 0 to 541 meters with a Transmission Loss value each approaching 90 dB to 100 dB. The emission of underwater acoustic wave propagation reaches around 3.9 km or 2.4 miles from the acoustic source and a distance of 3.9 km above is a silent area (Shadow Zone) for submarines.

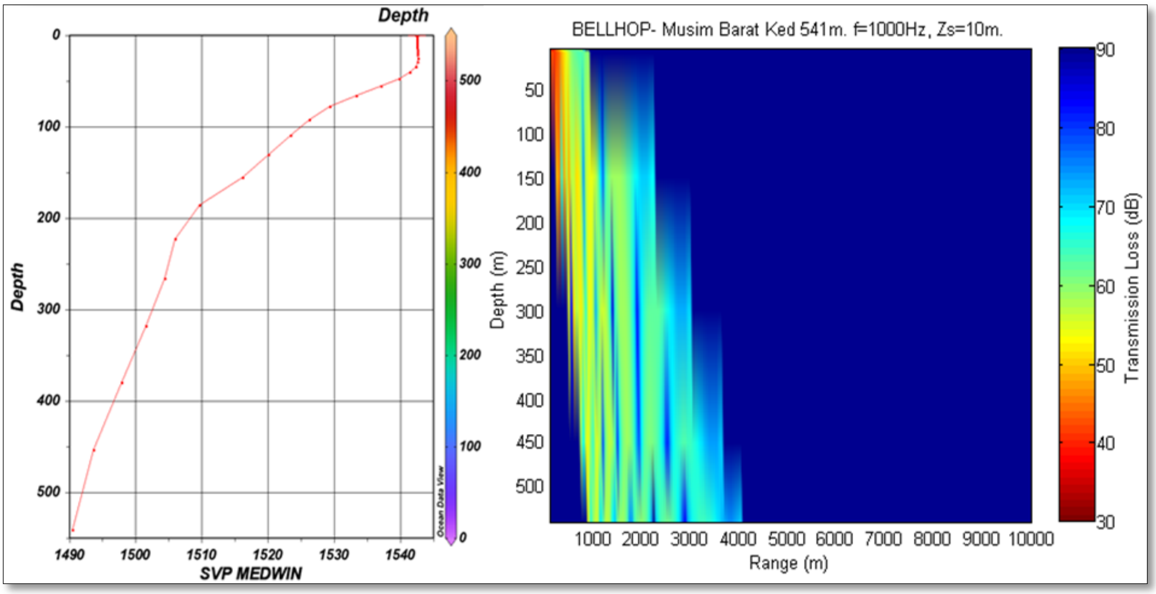

Figure 4. Underwater Acoustic Wave Propagation Pattern Method
Ray Tracing (Bellhop) with a frequency of 1,000 Hz in the western season

Figure 4 is the result of the Matlab Actup 2.2vL simulation in the form of an Underwater Acoustic Wave Propagation Pattern Ray Tracing (Bellhop) Method with a frequency of 1,000 Hz in the west season. It can be seen that as the propagation distance of underwater acoustic waves increases, the transmission energy loss will increase. (Transmission Loss) so that the Transmission Loss value increases as the propagation distance increases. In the simulation of underwater acoustic wave propagation patterns with a frequency of 1,000 Hz and a source depth of 10 meters using the Ray Tracing (Bellhop) method, the underwater acoustic wave propagation pattern looks quite stable. When sound waves are emitted, their propagation pattern decreases to the bottom of the water with a depth of 541 meters and only reaches a distance of 4,100 meters from the total distance determined at 10,000 meters. When propagating underwater acoustic waves, transmission energy loss (Transmission Loss) is quite large, reaching 90 dB. At a distance of 0 to 500 meters the Transmission Loss value is between 40 dB to 50 dB and at a distance of 500 meters to 4,100 meters the Transmission Loss value increases between 50 dB to 70 dB.

Shadow Zone area (red circle) in the Ray Tracing (Bellhop) method simulation in Figure 4 Shadow Zone is formed at a distance of 0 – 900 meters at a depth of 250 meters to 541 meters and a distance of 4,100 to 10,000 meters at a depth of 0 to 541 meters with a Transmission Loss value each approaching 80 dB to 90 dB. The emission of underwater acoustic wave propagation reaches around 4.1 km or 2.5 miles from the acoustic source and a distance of 4.1 km above is a silent area (Shadow Zone) for submarines.

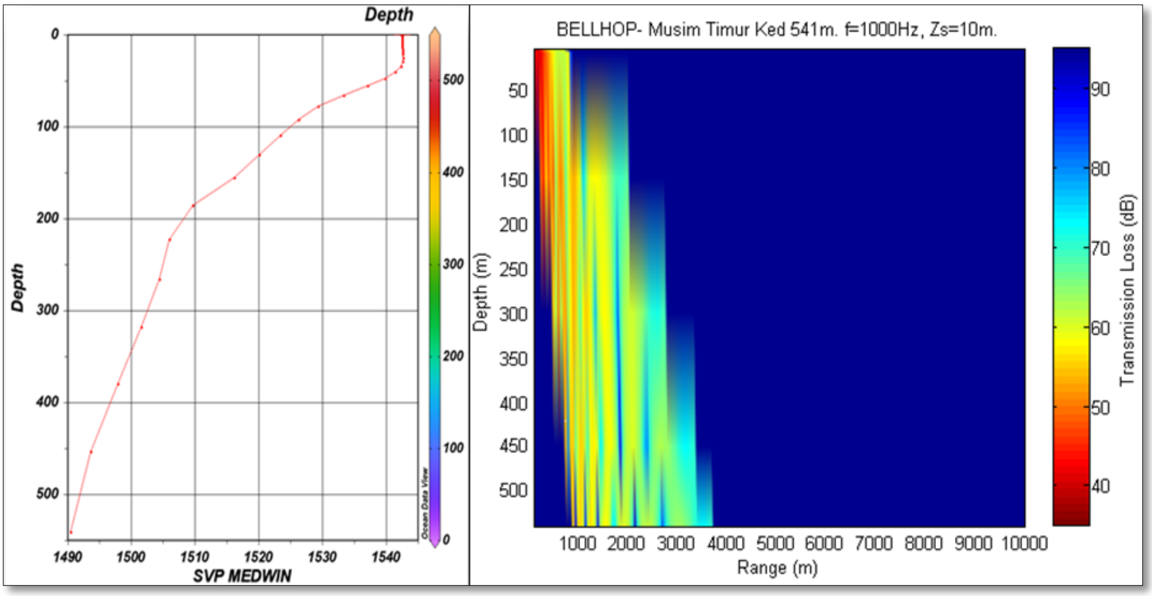

Figure 5. Underwater Acoustic Wave Propagation Pattern Method
Ray Tracing (Bellhop) with a frequency of 1,000 Hz in the east season

Pada gambar 5 merupakan hasil simulasi Matlab *Actup 2.2vL* berupa Pola Propagasi Gelombang Akustik Bawah Air Metode *Ray Tracing (Bellhop)* dengan frekuensi 1.000 Hz pada musim timur, terlihat bahwa seiring dengan bertambahnya jarak propagasi gelombang akustik bawah air, maka akan semakin mengalami kehilangan energi transmisi (*Transmission Loss*) sehingga nilai *Transmission Loss* semakin bertambah seiring dengan bertambahnya jarak propagasi. Pada simulasi pola propagasi gelombang akustik bawah air dengan frekuensi 1.000 Hz dan sumber kedalaman 10 meter metode *Ray Tracing (Bellhop)*, pola propagasi gelombang akustik bawah air terlihat cukup stabil. Pada saat gelombang suara dipancarkan, pola propagasinya mengalami penurunan hingga dasar perairan dengan kedalaman 541 meter dan hanya mencapai jarak 3.900 meter dari total jarak yang ditentukan sebesar 10.000 meter. Pada propagasi gelombang akustik bawah air, mengalami nilai kehilangan energi transmisi (*Transmission Loss*) yang cukup besar mencapai 90 dB keatas. Pada jarak 0 sampai 500 meter nilai *Transmision Loss* antara 40 dB sampai 50 dB dan jarak 500 meter sampai 3.900 meter nilai *Transmission Loss* semakin membesar antara 50 dB sampai 70 dB.

Daerah *Shadow Zone* (lingkaran merah) pada simulasi metode *Ray Tracing (Bellhop)* pada Gambar 5 *Shadow Zone* terbentuk pada jarak 0 – 900 meter di kedalaman 250 meter sampai 541 meter dan jarak 3.900 sampai 10.000 meter di kedalaman 0 sampai 541 meter dengan nilai *Transmision Loss* masing masing mendekati 85 dB sampai 95 dB. Pancaran propagasi gelombang akustik bawah air mencapai sekitar 3,9 km atau 2,4 mil dari sumber akustik dan jarak 3,9 km keatas merupakan daerah senyap (*Shadow Zone*) bagi kapal selam.

DISCUSSION

The relationship between sea water characteristics (salinity, temperature, density to depth) and the sound speed profile in the sea which affects the acoustic ray path or underwater acoustic wave propagation pattern (Hutabarat & Evans, 1985). Each image resulting from the simulation of underwater acoustic wave propagation patterns will display a vertical profile of the speed of sound. Simulation results of underwater acoustic wave propagation patterns using the Ray Tracing (Bellhop) method at a depth of 541 meters show that there are differences in transmission energy loss at frequency and season. From the simulation of acoustic wave propagation patterns, it shows a decrease in transmission energy as the propagation distance increases, this is because the shape of the propagation path of underwater acoustic waves is influenced by the sound speed gradient. The sound speed gradient is a change in the propagation of underwater acoustic waves caused by changes in the speed of sound in water. According to Defrianto & Pratama (2019), changes in sound speed with depth cause biased sound propagation when it moves between areas of different sound speeds, bending or refracting towards areas with lower sound speeds. If the sound speed gradient between regions is greater, the greater the amount of refraction. When the gradient conditions are negative, the speed of sound will decrease with the depth of the water (Harinto *et al.,* 2020). Simulation Results The emission of underwater acoustic wave propagation reaches around 4 km or 2.4 miles from the acoustic source so that a distance of 4 km above is a silent area (Shadow Zone) for submarines.

At a frequency of 100 Hz, the simulated underwater acoustic wave propagation pattern shows a transmission energy loss (Transmission Loss) that is greater than at a frequency of 1,000 Hz. The Transmission Loss Value for a frequency of 1,000 Hz reaches 40 dB to 80 dB, while at a frequency it has a Transmission Loss value of 40 dB. up to 70 dB, this is due to absorption by sediment and sea water medium. Apart from that, at a frequency of 1,000 Hz, the Transmission Loss value obtained is more fluctuating with a tendency to increase if you move away from the sound source (Darmawan, 2022). Shallow water depths are more effective when using high frequencies with a depth criterion of less than 100 meters, while deeper depths with a depth criterion of more than 100 meters are more effective when using low frequencies in sound wave propagation (Jensen *et al.,* 1994). For the Shadow Zone area, the frequency of 100 Hz is almost the same as the Shadow Zone area, the frequency is 1,000 Hz. At frequencies of 100 Hz and 1,000 Hz, the Shadow Zone area is formed at a distance of 0 to 900 meters at a depth of 250 meters to 541 meters and a distance of 4,100 to 10,000 meters at a depth of 0 up to 541 meters, but judging from the Transmission Loss value, the 100 Hz frequency has a higher Shadow Zone area than the 1,000 Hz frequency, the Transmission Loss value for the 100 Hz frequency reaches 90 dB to 100 dB while the Transmission Loss value for the 1,000 Hz frequency only reaches 80 dB up to 90 dB. According to Suharyo (2018), transmission energy loss above 90 dB or 40% of the Source Level (SL) is designated as a silent area (Shadow Zone).

In the west season, the simulation of underwater acoustic wave propagation patterns shows that the propagation distance of underwater acoustic waves is higher than in the east season. The propagation distance of underwater acoustic waves in the west season reaches 4.1 km or 2.5 miles from the acoustic source, while the propagation distance Underwater acoustic waves in the east season reach 3.9 km or 2.4 miles from the acoustic source. This is because differences in seasons cause differences in salinity and water temperature values. Salinity and temperature together with depth influence the speed of sound (Winanta *et al.,* 2015) which propagates in water (Supiyati & Romauli, 2016) which in this case is also called the speed of underwater acoustic waves. The acoustic wave speed value or sound speed value is directly proportional to temperature and inversely proportional to salinity and depth (Agustinus *et al.,* 2023) and is influenced by currents, depth, geographical location, seasons and even water mass exchange (Badhi, 2021). For the western season, the Shadow Zone area is smaller than the eastern season. In the western season, the Shadow Zone area is formed at a distance of 0 to 900 meters, at a depth of 250 meters to 541 meters and a distance of 4,100 to 10,000 meters, while in the eastern season, the Shadow Zone area is formed at a distance of 0 to 900 meters. meters at a depth of 250 meters to 541 meters and a distance of 3,900 to 10,000 meters at a depth of 0 to 541 meters.

From the differences in simulation results of underwater acoustic wave propagation, it shows that transmission energy loss (Transmission Loss) which is influenced by frequency and season plays an important role in the formation of the Shadow Zone area. Transmission energy loss refers to the reduction in sound intensity caused by several factors, including spreading loss, absorption by the medium through which it passes, and reflection loss. Thus, transmission energy loss reflects the ability of a material to block the propagation of underwater acoustic waves in decibels (dB) at certain frequencies (Irwan & Syam, 2013).

CONCLUSION

Based on the simulation results of underwater acoustic wave propagation patterns using the Ray Tracing (Bellhop) method at a depth of 541 meters, it can be concluded that sea water characteristics such as salinity, temperature and depth have a significant influence on the speed of sound in water. Seasonal differences also play an important role in variations in salinity and water temperature values, which in turn influence acoustic wave propagation patterns. The frequency of acoustic waves also affects transmission energy loss, with a frequency of 100 Hz tending to experience a greater reduction in transmission energy than a frequency of 1,000 Hz. The Shadow Zone area, where the transmission energy decreases significantly, is formed at a certain distance from the sound source and is influenced by factors such as the sound speed gradient, the frequencies used and seasonal conditions.

Simulation results of underwater acoustic wave propagation patterns show that low frequencies tend to have higher transmission losses, while shallow depths are more effective for high frequencies and deeper depths are more effective for low frequencies. Seasonal differences affect the salinity and temperature values of the water, which then affect the speed of sound in water. This variation in sound speed creates a different Shadow Zone area between the West and East seasons, where the Shadow Zone area in the West season tends to be smaller than in the East season, with characteristics determined by the depth of the water and distance from the acoustic source.

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