Measurement and Analysis of Ocean Current using High-Frequency (HF) Radar Observation in the Bali Strait

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Abstract. High-Frequency (HF) Radar is an instrument using radio waves to measure ocean currents and waves remotely. This technology has many advantages, including has unprecedented spatial and temporal resolution, can operate in any weather condition, and is not dangerous for the environment. However, HF Radar's research is still limited in Indonesia. This research aimed to analyze the tidal and residual current in the Bali Strait in July 2020. Radial velocity from two HF Radar sites is combined to obtain the total currents. Current data from HF Radar were compared with Acoustic Doppler Current Profiler (ADCP) data to investigate its accuracy. Surface current data were analyzed using harmonic analysis to separate tidal and residual currents. Comparison between HF Radar and ADCP data are in good agreement for meridional current with a very high correlation of 0.813 and a small RMSE value of 0.22 m/s. Harmonic analysis shows that the dominant currents are tidal currents. The current direction was northward (southward) at flood (ebb), with maximum northward (southward) velocities are 2.17 m/s (2.97 m/s), respectively. The residual current has a random pattern, slightly faster northward than southward, and has similar spectral with the wind.

1. Introduction
The Bali Strait has an important role in various important sectors such as maritime, transportation, trade, and tourism and its role in connecting the most populous island to the island with the best tourism in Indonesia. Besides, the Bali strait is regarded as an international shipping route, in which this route is getting busier every year with many ships, both locally and internationally, passing this strait. Thus, accurate maritime information is needed, which is expected to reduce the number of ship accidents. Ocean current information is essential for shipping safety, especially in the strait areas where the current velocity is relatively high such as Bali Strait, which connects the Indian Ocean to the Java Sea, has strong currents due to tidal amplification enters a narrow strait [1]. Issuing accurate and reliable information on ocean currents will help the transportation sector run efficiently. The Strong current in
the Bali Strait also can be used as an alternative energy source, such as tidal power plants. The total potential tidal current power plant in the Bali Strait is 1507 MW [2]. Although ocean current data in the Bali Strait is essential, observations of ocean currents in the Bali Strait are still limited. Thus, BMKG, represented by the Maritime Meteorology Center, has made efforts to provide ocean current observation data in Bali by installing HF Radar since 2018.

HF Radar is an instrument that uses high-frequency (3-50 MHz) radio waves to map sea surface currents remotely. HF Radar works on the principle of Bragg-scattering and the Doppler shift of radio waves hitting rough sea to determine the current velocity [3]. HF Radar has many advantages, such as producing near real-time ocean surface current data with a high spatial and temporal resolution, can operate in all conditions, is not harmful to the environment, and low power consumption [4], [5]. HF Radar has been used for coastal and disaster management purposes such as search and rescue, marine pollution management, marine dredging and construction, distribution of fish larvae, also for tsunami early warning [6].

HF Radar has been widely used internationally, and there is even an international organization, the Global HF Radar Network (http://global-hfradar.org/), a new recognized international network that aims to connect world researchers interested in developing this instrument. However, this technology is still very rarely studied and applied in Indonesia. Usually, scientists perform numerical simulations to understand the ocean current, which of course, still have errors and biases. Currently, BMKG has several HF Radar sites installed for research or operational purposes, such as Seasonde CODAR HF Radar (Coastal Ocean Dynamics Applications Radar) in the Bali Strait and Labuan Bajo Waters, WERA (Whelan Radar) in the Sunda Strait, and Southern Yogyakarta waters. Further research needs to be done to find out more details about hf radar capability to map the ocean current in Indonesian waters. This research examines how the HF Radar is used to analyze ocean currents in the Bali Strait.

2. Data and Method

2.1. Data

The data used in this study are sea surface current data from the HF Radar, sea level from the Indonesian Agency for Geospatial (BIG)’s tide gauge, and wind data from BMKG Marine Automatic Weather Station (AWS) at Ketapang Port, Banyuwangi, in July 2020. Two HF Radar units named BOOM and WARU were installed in Banyuwangi, which covers the Banyuwangi-Bali marine transportation route. The HF Radar used in this study has a transmit frequency of 26.275 MHz that can produce current information with a spatial resolution of 500 m and a temporal resolution of every half hour. The accuracy of HF Radar measurements is tested by the Acoustic Doppler Current Profiler (ADCP) data from 24 April to 1 May 2019. Detail location of each data is shown in Figure 1.

Figure 1 Study location. The HF Radar stations named BOOM for the southern station and WARU for the northern station.
2.2. Data processing and analysis

The principle of measuring ocean currents using HF Radar is that by emitting radio waves at a specific frequency, radio waves will hit the rough sea and be reflected in the receiving antenna. The received frequency will experience the Bragg effect and Doppler shift, which produces the movement of water toward or away from the receiver, called the radial velocity. Each radar station measures the radial velocity of the currents. The radial velocity (example of radial velocity in Figure 2) has been processed using the CODAR default manufacturing software [7], [8].

![Figure 2 Example of HF Radar radial velocity: a. BOOM site, b. WARU site.](image)

The current value is obtained from the combination of the radial velocity for at least two HF Radar sites. HF Radar CODAR data has gone through QC tests based on QARTOD, which consists of signal/spectral processing QC, radial components, and total vectors, most of which have been installed on the HF Radar system. Although the data analyzed is for July 2020, the HF Radar current data were verified with ADCP current data for 24 April to 31 May 2019 because of lack of observational data in the Bali Strait. Verification in this study uses the correlation criteria and the Root Mean Square Error (RMSE) as follows:

\[ R = \frac{\sum_{i=1}^{n} (x_i - \bar{x}) - (y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n} (x_i - \bar{x})^2 - (y_i - \bar{y})^2}} \]  

\[ RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (y_i - x_i)^2} \]

R is the correlation coefficient, \( x_i \) is the ADCP data, \( y_i \) is the HF Radar data, \( \bar{x} \) is the temporal mean current ADCP data, \( \bar{y} \) is the temporal mean of HF Radar data, and \( n \) is the number of data used for verification.

The ocean current combines a tidal factor due to astronomic and non-tidal currents (residual currents) due to wind stress or density differences. Harmonic analysis is used to separate tidal currents and residual currents. The tidal current velocity is the sum of the harmonic constant current velocities at a specific frequency which can be written mathematically in the form of the following equation [9]:

\[ v(t) = v_0 + \sum_{i=1}^{n} a_i e^{i\omega_i t} + a_{-i} e^{-i\omega_i t} \]

\( v(t) \) is the total velocity of tidal current, \( v_0 \) is the temporal mean current, \( a_i \) is the amplitude of harmonic constituent \( i \), and \( \omega_i \) is harmonic phase constituent for \( i \).

Harmonic analysis is performed using the t_tide program package in MATLAB software [10]. The harmonic current is compared to tidal data, while the residual current is compared to wind data.
3. Result and Discussion

3.1. Comparison between HF Radar and ADCP Data
Comparison of 3-hour moving average meridional current between HF Radar and ADCP in figure 3 shows a very high correlation of 0.813 with an RMSE of 0.22 m/s. This result is similar to [11] that found the HF Radar RMSE and correlation in Gibraltar Strait were 0.31 to 0.81 and 0.08 to 0.22 m/s. According to [12], the RMSE value of HF Radar ranges from 0.06 to 0.30 m/s depending on the characteristics of HF Radars' location. In contrast to the meridional current, the accuracy for zonal current is not very good. The correlation and RMSE values of zonal currents are 0.235 and 0.402 m/s, respectively. This condition presumably because the meridional current's velocity is very strong and is only measured by two HF radars with a north-south configuration. Thus it may not be easy to separate the meridional and zonal components. According to [13], strong currents can distort the HF Radar antenna pattern. The accuracy will likely be better if there are three HF pairs; one of the HF radars is placed on Bali's side. Also, the possibility of bias can be caused by various things, such as interference of other devices at similar frequencies. For more comprehensive testing, it needs to take a longer time to see the HF Radar's overall accuracy. Several studies have compared the HF Radar data with other instruments for at least three months [7,11,12].

![Figure 3](image-url)

Figure 3 Comparison of meridional current between HF Radar and ADCP: a. Meridional current, b. Zonal current.

3.2. Ocean current in Bali Strait
Although the verification results on 24 April to 1 May 2019 HF Radar against ADCP showed less accuracy in the zonal component, we still used it to describe the overall monthly current characteristics. Because the data studied in this study is for July 2020, we assumed that it is more accurate than the previous one in 2019 because the HF Radar has been maintained every year, such as the antenna pattern calibration. It is necessary to verify again to see how accurate the HF Radar after maintenance.

The mean and standard deviation of surface currents in the Bali Strait in July 2020 showed a high velocity in the middle of the strait with a southward direction. The mean and standard deviation of 1.09
m/s and 0.82 m/s, respectively. The strong current is in the middle because it is the main channel of the Bali Strait waterway. The Indonesian throughflow (ITF) also reaches its peak in July [14] caused the southward current in the Bali Strait. The high standard deviation value indicates that the velocity variation in the middle of the strait is highly varied. The meridional current on the mid-eastern side is southward with a maximum speed of 1.08 m/s, while on the western side is northward with a relatively low speed (max ~0.5 m/s). For the zonal current, the current is more dominant towards the eastern with a maximum speed of 0.66 m/s. The monthly mean of meridional current (figure 4d) shown that the dominant current in the mid-eastern side of the strait is the tidal current, while on the western side influenced by residual current. The distribution of sea surface currents in the Bali Strait (current rose) shows that in July, the current is more dominant to south and southeast for speed of more than 1.00 m/s, while for speed less than 1.00 m/s is distributed in any direction.

Figure 4 Characteristics of current in Bali Strait in July 2020. The colorbar is not the same for all maps for better visualization.
Analysis of harmonic and nonharmonic currents in this research is only carried out for meridional currents because it has better accuracy than zonal currents. Based on the distribution of monthly mean meridional currents (Figure 4d), it can be seen that there is a different current pattern. On the west side, the current is northward (with a relatively small velocity), while on the east side, the current is southward. The pattern is similar to standard deviation maps in figure 4c. Therefore, two points representing these conditions are analyzed (blue and red dot in Figure 4d). The red and blue dot in figure 4d were analyzed for harmonic and residual current, respectively.

3.3. **Harmonic current**

The harmonic analysis of meridional currents in the red dot in figure 4d shows 25 significant harmonic constituents (tested with a significance level of 95%) (Figure 7). The dominant constituent is the principal semi-diurnal constituent (M2) with an amplitude of 1.593 m and the principal lunar diurnal (K1) with an amplitude of 1.0348. The calculated Formzahl number from principal diurnal (K1 and O1) and principal semi-diurnal (M2 and S2) constituent are 0.772, which means the type of the tidal current is the mixed tide prevailing semi-diurnal. For this type, there will be two high and two low with the different speed at the peaks or troughs in a day.

![Figure 5 Harmonic constituent of meridional current. The significant constituent if the amplitude is higher than the green horizontal line (95% significance level).](image)

Based on harmonic analysis, it can be separated between tidal currents and residual currents. The harmonic analysis for meridional currents in figure 6 shows that the dominant current is the harmonic (tidal) currents with speeds reaching -2.97 m/s (negative sign shows that current flow to southward) and 2.18 m/s (for the northward current). The residual currents have random patterns with speeds reaching -0.8 m/s to the south and 0.79 m/s to the north. The harmonic current is stronger when spring tide and weak at neap tide. In contrast, the residual current tend to be stronger when neap tide and weak when the spring tide.
3.3.1. Relationship between tides and harmonic meridional current

The time series plot of meridional current velocity against tidal elevation in figure 7 shows the linear relationship between tides and meridional velocity, which means the current direction is southward at low tide (ebb) and northward when high tide (flood). However, the maximum southward current velocity (-2.95 m/s) at low tide is 26% higher than the maximum northward current (2.18 m/s) at high tide. In July, generally in the Bali Strait, the current direction is southward due to the influence of the Indonesian throughflow (ITF) peak in July [14].

The relationship between tide and tidal current in figure 7 is not that simple. For the northward current (flood condition), the maximum northward velocity is not at the first maximum high tide but the second maximum high tide in one day. There is a lag of 6 hours from the first maximum high tide to the maximum northward velocity current. It is because the tidal current system in the Bali Strait for flood conditions is Hydraulic-current. In this system, the maximum flood current is between the two highest tides (first maximum tide) in a day [15]. There is the second maximum high between the two highest tides for mixed tides prevailing semi-diurnal tides (like Bali Strait). The combination between hydraulic-system and second high tide caused the velocity of the northward flood much higher. In contrast, at ebb condition, the maximum southward velocity is at the lowest tides. The tidal current system at the ebb is a progressive wave system. In the progressive wave system, the maximum ebb (flood) current occurs at the lowest (highest) tide [15].

The tidal current also varied for spring and neap tide conditions. The southward (ebb) and northward (flood) current velocity is 13% and 90% higher in the spring tide than the neap tide. The currents direction is northward (southward) at high (low) tide during the spring tide but is only southward or northward with a small velocity during the neap tide. There is a two-day lag between spring (neap) tide to the increase (decrease) the meridional velocity.
3.4. Residual current

The harmonic analysis was also performed on meridional currents at the blue dot in figure 4d. The residual current is obtained by reducing the harmonic current with the total meridional current. The residual current in figure 8 showed the randomly fluctuated current speed. In contrast to the harmonic current at the blue point, which is faster southward than northward, the residual currents at the red point slightly faster northward than southward. The northward and southward maximum velocity reaches 0.44 m/s and -0.42 m/s (the negative sign shown the southward current). This result is consistent with [16], which found that the residual current in Bali Strait is up to 0.5 m/s. The northward mean current velocity is also faster (0.108 m/s) than southward (-0.106 m/s). The aforementioned is assumed because the dominant wind direction in July 2020, based on the marine AWS data in Figure 9, is south to southwesterly with a maximum speed of up to 8 m/s, which generates the northward currents. Spectrum analysis on residual meridional currents and meridional wind shows a similar spectral. In both data, the strong oscillation period was 0.5-0.6 hours, and 1-hour was found, indicated that wind affected the residual meridional current in the Bali Strait. Residual currents in coastal areas are not only caused by wind but can also be caused by non-linear tides and differences in density [17].
4. Conclusion

HF Radar data verification against ADCP data shows a good agreement for the meridional current but not suitable for the zonal current. Although the accuracy of HF radar needs to be improved, this research shows that the HF Radar data can comprehensively describe the Bali Strait's current characteristics. The dominant current is the tidal currents with different effects from various locations. On the mid-eastern side, it is strongly influenced by harmonic currents in a more dominant southward direction. The velocity pattern of meridional harmonic currents during high tide (flood) and low tide (ebb) is different. The northward maximum current velocity occurs between the two highest tides for high conditions, while at ebb condition, the southward maximum current velocity occurs at the lowest tide. On the western side, the meridional current's velocity is not as large as that of the mid-eastern side, and its direction is more
dominant to the north. The spectral density analysis result showed that the 0.5 and 1-hour oscillation was found in both wind and current data suggested that the wind causes residual current.

5. References

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Acknowledgments

We would like to thank Marine Meteorological Analysis and Prediction (APM) subdivision and the Center for Research and Development team to provide ADCP data used as HF Radar's verifier for this study. We also thank Indonesian Agency for Geospatial (BIG) for providing the online tidal data (http://ina-sealevelmonitoring.big.go.id/).